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PROCEEDINGS OF INTERNATIONAL INNOVATIVE RESEARCH AND INDUSTRIAL DIALOGUE 2026

iIRID2026

Advancing Malaysia's Higher Education Transformation: Fostering
AI-Driven University-Industry Collaboration for Smart Manufacturing Excellence

14 – 15 OCTOBER 2026
Universiti Teknikal Malaysia Melaka

THEME:
**"AI-Driven Smart Manufacturing: Advances
in Materials Science, Automation, and
Production Technologies"**

Chief of Editors
ZALEHA MUSTAFA
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PREFACE

The 6th International Innovative Research and Industrial Dialogue 2026 (iIRID 2026), hosted by the Faculty of Industrial and Manufacturing Technology and Engineering (FTKIP), Universiti Teknikal Malaysia Melaka (UTeM), provides an important platform for advancing research, innovation, and collaboration in engineering and technology. The event is jointly organised by FTKIP, the RICE UTeM–Melaka Collaboration Management Centre, and the Centre of Smart Systems and Innovative Design (CoSSID).

Guided by the overarching theme “Advancing Malaysia’s Higher Education Transformation: Fostering AI-Driven University–Industry Collaboration for Smart Manufacturing Excellence,” iIRID 2026 reflects the growing importance of artificial intelligence, digitalisation, and smart manufacturing in strengthening industrial competitiveness. It brings together researchers, academics, industry practitioners, and postgraduate students to exchange knowledge, present research findings, and explore emerging technological developments.

These proceedings, with the focus title “**AI-Driven Smart Manufacturing: Advances in Materials Science, Automation, and Production Technologies,**” feature contributions in materials science, automation, production technologies, and manufacturing. The papers address current developments in advanced materials, intelligent automation, digital manufacturing, production systems, process optimisation, and emerging manufacturing technologies.

Manufacturing is undergoing significant transformation as artificial intelligence, automation, and data-driven technologies become increasingly integrated into industrial operations. At the same time, advances in materials science continue to create opportunities to improve product performance, process efficiency, and environmental sustainability. The contributions presented in these proceedings reflect these developments and demonstrate how research can address real-world industrial needs.

Through its industrial forums and online research presentation sessions, iIRID 2026 promotes meaningful engagement between universities and industry. It encourages translating research into practical applications, supports innovation and commercialisation, and contributes to developing future-ready talent. It is hoped that the research presented in these proceedings will stimulate further studies, encourage technology adoption, and contribute to the development of more efficient, resilient, and sustainable manufacturing systems.

We sincerely thank all authors for sharing their research and the reviewers for their careful evaluation and constructive feedback. Our appreciation is also extended to the editors, session chairs, organising committee members, collaborating institutions, industry partners, and sponsors whose commitment and support have made this publication possible.

Zaleha Mustafa
Effendi Mohamad

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ADVANCED MATERIALS & STRUCTURAL MECHANICS



MODIFICATION OF KENAF NATURAL FILLER SURFACES WITH ALKALINE TREATMENT

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Abstract— Kenaf fibre is widely used in the automotive, construction, and packaging industries. Kenaf has a composition of cellulose (45-70%), hemicellulose (18-30%), lignin (8-22%), and other impurities (3-10%). Non-cellulosic components in kenaf need to be removed to produce kenaf biocomposites with higher mechanical strength. Kenaf fibre needs to undergo treatment to change its surface from smooth to rough, enhancing interfacial adhesion and defibrillation. The aim of the study was to investigate the composition of kenaf after NaOH treatment. The chemical composition and morphological microstructure were evaluated by Fourier transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM). Experimental data show that partial hemicellulose, lignin, pectins, wax, and other impurities were successfully removed after treatment with NaOH solution. This is expected to improve interfacial adhesion and enhance mechanical inter-locking. The treated kenaf fibre composite is promising in the manufacturing sector.

Introduction

Polypropylene (PP) is a useful polymer matrix used in producing natural fibre biocomposites. Waste PP in landfills contributes to pollution and global warming [1]. Natural fibre-reinforced composites have advantages such as being biodegradable, lightweight, low cost and having favourable mechanical properties [2]. Kenaf fibre is used to fabricate components such as dashboards, door panels, and insulation [3]. Its high strength-to-weight ratio and cost-effectiveness make it a premier candidate for replacing synthetic reinforcements [2]. The performance of untreated kenaf is often compromised by its inherent surface chemistry. Lignocellulosic constituents, including waxes, oils, pectin, and lignin, create a smooth, low-energy surface that inhibits effective interfacial bonding with hydrophobic polymer matrices [4]. This incompatibility leads to issues such as fibre pull-out, excessive moisture absorption, and void formation, ultimately reducing the durability and interfacial shear strength of the composite [4]. This research aims to evaluate the effects of alkaline surface treatment on kenaf core particulates. By employing a sodium hydroxide (NaOH) solution, the study seeks to optimise fibre morphology and chemical reactivity [5,6]. The modifications are characterised through FTIR analysis and SEM to validate the removal of non-cellulosic impurities and the enhancement of surface roughness.

Materials and methods

The filler material consisted of kenaf core particulates with a particle size distribution ranging from 100 to 300 microns, which were utilised. To remove absorbed moisture and prevent hydrolytic degradation, 1g of untreated kenaf core particulates was dried in a circulating-air oven at 80 °C for 24 hours. The dried kenaf was immersed in 25 mL of 50% NaOH solution and mixed with 250 mL of distilled water, then mechanically stirred at 25 °C at 500 rpm for 30 minutes. Treated fibres were thoroughly washed and subjected to a secondary drying stage to eliminate residual aqueous content. Chemical functional groups were identified using FTIR spectroscopy across the 4000–600 cm⁻¹ range using a Jasco FT/IR-4X machine.

Surface topography and morphological observations were analysed via SEM at 50× magnification using a JEOL JSM-IT210 Scanning Electron Microscope.

Results and discussion

The FTIR spectra of untreated and NaOH-treated kenaf fibres demonstrate the chemical changes caused by alkali treatment, as illustrated in Figure 1. Both spectra display the characteristic absorption bands of fibres. The O-H stretching band in the range 3300-3400 cm^{-1} shifts to a conspicuous peak, implying enhanced exposure of cellulose hydroxyl groups. It is suggested that the extraction of waxes and other impurities is related to the dressing of the C-H stretching band at approximately 2915 cm^{-1} . The significant reduction or disappearance of the absorption band around 1730 cm^{-1} , attributed to the carbonyl groups of hemicellulose, confirms the effective removal of hemicellulose [7]. Furthermore, the decreased intensity of the lignin-related bands around 1510 cm^{-1} and 1245 cm^{-1} indicates partial delignification. In contrast, the stronger absorption near 1030 cm^{-1} , corresponding to C-O stretching of cellulose, suggests greater exposure of the cellulose structure. Overall, the FTIR results confirm that NaOH treatment successfully removed non-cellulosic components while preserving the cellulose backbone of the kenaf fibre, thereby improving the fibre's surface cleanliness and enhancing its potential for interfacial bonding with polymer matrices.

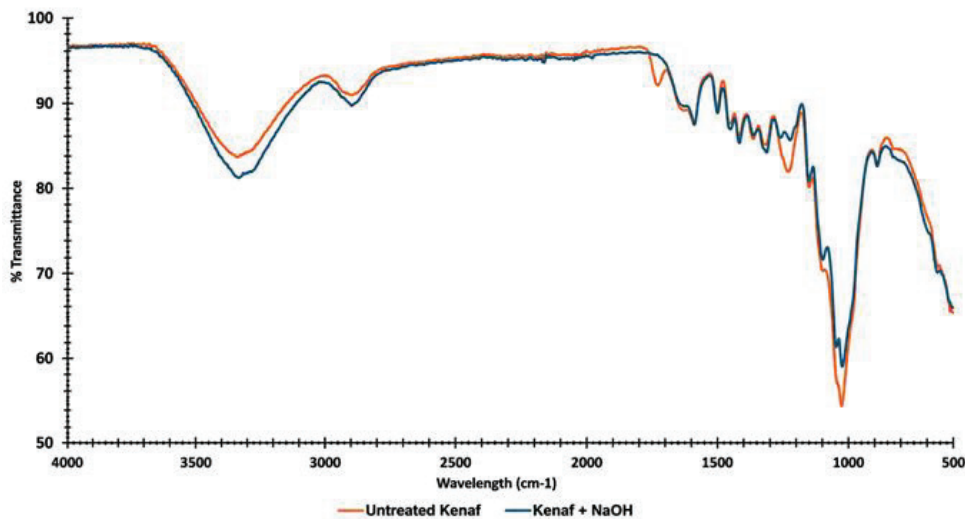


Figure 1 FTIR analysis of untreated kenaf and treated kenaf

Micrographs revealed fibre bundles held together by a natural matrix of hemicellulose and lignin. The fibre surfaces were smooth but coated with debris, waxes, and pectin. While lumens (capillary structures) were visible, the overall surface lacked the necessary topography for mechanical interlocking [7], as shown in Figure 2(a) for untreated kenaf. Figure 2(b) illustrates that the treatment with NaOH resulted in significant surface roughening and the exposure of cellulose fibrils. A critical finding was the exposure of the lumens. Maximising composite performance depends on the polymer matrix's penetration into these capillary structures during compounding. By removing oils and waxes that block these openings, the treatment allows for a "mechanical anchoring" effect.

The fibres become stiffer and exhibit greater potential for load transfer across the fibre-matrix interface due to their larger surface area and fibril exposure, thereby strengthening the interfacial shear strength.

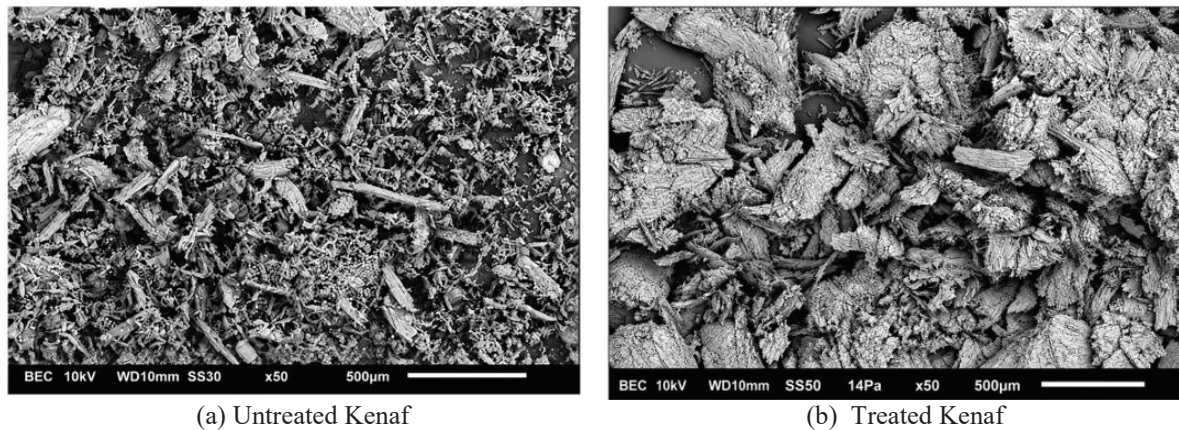


Figure 2 SEM observation at 50x magnification

Conclusions

Alkaline treatment has successfully modified both the chemical composition and surface morphology. FTIR and SEM results demonstrated that the removal of partially hemicellulose, lignin, pectin, and other impurities altered surface roughness and potentially enhanced mechanical interlocking and interfacial adhesion. Treated kenaf with alkali can enhance mechanical properties such as tensile, flexural, and impact strength, particularly in kenaf biocomposites. It is recommended for treated kenaf-reinforced composites.

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A NEW PRODUCT DEVELOPMENT FRAMEWORK FOR MANUFACTURING DEFECT REDUCTION IN COMPOSITE HEADLAMP JIGS

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Abstract—This study proposes a new product development (NPD) framework for improving the fabrication of composite headlamp jigs used in automotive manufacturing. The work was motivated by limitations observed in conventional metal jigs, particularly deformation during repeated exposure to elevated temperature and high-pressure cleaning conditions. A reverse engineering approach was applied to capture the geometry of an existing headlamp jig using a FARO 3D scanning system and to reconstruct the component in a computer-aided design environment. A composite prototype was subsequently developed through master mould preparation and fibre-reinforced resin lamination. The fabrication procedure incorporated carbon-fibre and glass-fibre layers, controlled resin and hardener mixing, curing, demoulding, trimming and finishing. Information collected from workers involved in the production of 40 headlamp jig products was used to identify bubble formation as a significant manufacturing defect. Based on the observed defect mechanism, the proposed NPD framework incorporates additional process controls, including resin degassing, controlled layer consolidation, inspection, repair and final quality checking. The framework provides a structured route for combining reverse engineering with composite jig development and offers a practical basis for improving dimensional stability and manufacturing quality.

Introduction

Reverse engineering (RE) provides a practical means of recovering the geometry and functional information of an existing component when complete original design data are unavailable. In manufacturing, the approach can support redesign, maintenance, remanufacturing and product improvement by converting an existing physical part into a digital engineering representation [1–4]. For jig and fixture development, this capability is particularly useful when an established production component needs to be reproduced or modified without rebuilding the design entirely from the beginning.

Headlamp manufacturing requires accurate positioning and guidance during production operations. The jig must retain its intended geometry while being subjected to repeated thermal and cleaning conditions. The existing metal headlamp jig considered in this study was reported to experience deformation during service. The production environment includes exposure to approximately 120 °C for prolonged periods, together with high-pressure cleaning operations. Such dimensional changes can reduce the effectiveness of the jig, affect process consistency and contribute to deterioration of the finished product [5–7]. The service limitations of the conventional jig therefore indicate a need for an alternative material and manufacturing route.

Fibre-reinforced composite materials are potential alternatives because they can provide a useful combination of strength, low mass and thermal stability [8,9]. Their lower weight may also simplify handling and reduce the mechanical burden associated with repeated jig installation and removal [10]. However, replacing a metal jig with a composite component does not by itself eliminate manufacturing problems. The quality of a laminated composite jig depends strongly on the preparation of the mould, resin handling, fibre placement, consolidation and curing processes. Defects such as entrapped air or bubbles can reduce the integrity of the finished component and must therefore be considered within the product development process.

The integration of RE with NPD provides a systematic route for addressing this problem. RE supplies the geometric information required to reproduce or improve the existing jig, while NPD provides a sequence for evaluating the design, fabricating the prototype and checking its suitability. Accordingly, this study develops a preliminary NPD framework for a composite headlamp jig, with particular attention to manufacturing defects observed during prototype fabrication. The objective is to establish a practical process model that links reverse engineering, composite fabrication and quality inspection for headlamp jig development.

Methodology

Data Collection via Reverse Engineering

The existing metal headlamp jig was first digitised using a FARO 3D laser scanning system. The purpose of scanning was to obtain the geometric information required for reconstruction of the existing jig in a computer-aided design (CAD) environment. The resulting digital representation provides the basis for developing the composite prototype while retaining the geometry of the existing production component.

Composite Prototype Fabrication

The composite prototype was fabricated through a sequence beginning with the preparation of a master female component. An inner framework was formed on the headlamp lens surface using lightweight and readily shaped materials, including foam, cardboard and plywood. An outer framework was then constructed to establish the required form, after which filler material was applied to obtain the intended surface profile. The surface was allowed to dry before finishing operations were performed to prepare the master for subsequent moulding.

A master male component was then produced from the prepared form. For the lamination stage, 100 g of resin was mixed with 30 g of hardener. The resin system was applied to the mould surface before the reinforcement layers were placed. Eight alternating layers of carbon fibre and glass fibre were used to construct the composite structure. The laminated assembly was allowed to cure overnight, followed by an additional lamination stage where required. After the resin had fully solidified, the component was demoulded, trimmed and subjected to final finishing as shown in Fig.2. This fabrication route was used to produce the composite jig shown in the original study.

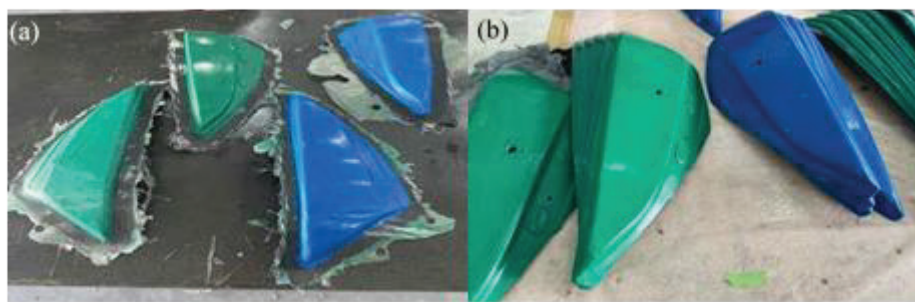


Fig. 2. (a) Demold composite jig from mold. (b) After trimming.

Result and Discussion

Bubble defect

These bubbles in the headlamp jig provide considerable issues because they damage the structural integrity and performance of the finished product. Fig. 3 shows bubble defects from visual inspection.



Fig. 3. After trimming

Bubble formation can occur when air becomes trapped within the resin system or between reinforcement layers during fabrication. The likelihood of entrapment is influenced by resin viscosity, mixing conditions, the distribution of the resin through the reinforcement and the effectiveness of consolidation. Inadequate mixing can introduce or retain air, while insufficient consolidation can prevent entrapped air from being removed before the resin cures [11]. The bagging stage is also important because an ineffective seal or vacuum leakage can reduce the ability of the process to remove air and consolidate the laminate.

The proposed framework is intended as a preliminary model rather than a complete statistical process-control system. Its main contribution is the integration of reverse engineering and composite fabrication controls within the NPD process. By placing defect checks at appropriate stages, the framework can help identify bubble formation before the component reaches final production use and can provide a more systematic approach to improving composite jig quality.

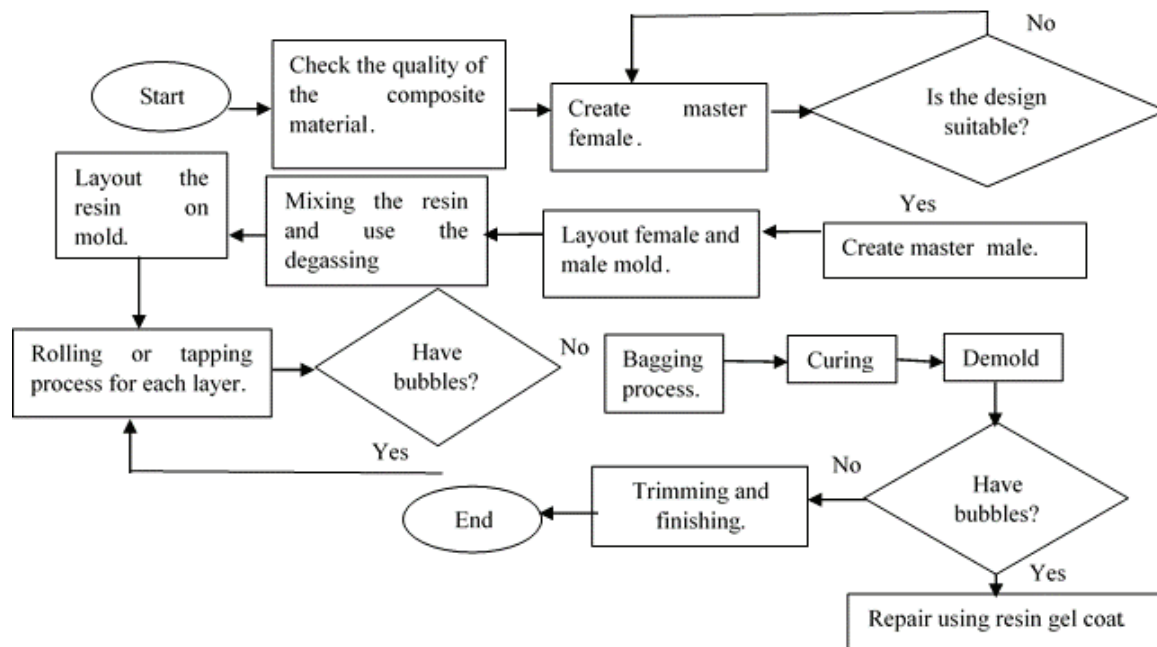


Fig. 4. Proposed NPD model.

Conclusion

The proposed framework therefore incorporates process controls intended to reduce air entrapment, including resin degassing, layer consolidation, intermediate inspection and corrective repair before bagging and curing. Future work should evaluate the proposed framework using quantitative measurements of dimensional stability, defect frequency and jig performance under the actual thermal and cleaning conditions experienced during production.

Such validation would allow the effectiveness of the proposed process controls to be established more rigorously

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Tailoring Morphology and Band Gap of N-CQDs Synthesized from Citrus-based Precursors

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Abstract - Carbon quantum dots (CQDs) derived from natural bio-precursors offer attractive biocompatibility, chemical stability, and photoluminescence (PL) properties. This work presents the green synthesis of nitrogen-doped carbon quantum dots (N-CQDs) via a hydrothermal route using calamansi lime juice and urea. The study focuses primarily on evaluating the optical band gap, PL characteristics, and nanoscale morphology using UV-Vis spectroscopy, PL spectroscopy, FTIR, Zeta potential, FESEM-EDX, and TEM analyses. High-resolution TEM confirms monodisperse, spherical N-CQDs with an average particle diameter of 2.88 nm for Sample 1 and 3.91 nm for Sample 6. Optical analysis reveals excitation-dependent emission with maximum PL intensity reaching 450,000 counts/s for narrower band gap states. These structural and photoluminescent properties highlight the strong potential of calamansi-derived N-CQDs for optoelectronic and bio-sensing applications.

Introduction

Carbon quantum dots (CQDs) are zero-dimensional luminescent nanomaterials that have gained widespread attention due to their non-toxic nature, excellent water solubility, tunable photoluminescence (PL), and high chemical resistance (1, 2). Compared to traditional semiconductor quantum dots containing hazardous heavy metals, green-synthesized CQDs derived from renewable biomass provide an eco-friendly and cost-effective alternative for bio-imaging, optical sensing, and light-emitting devices (3, 5). Surface passivation and heteroatom doping, particularly with nitrogen, effectively modulate the core electronic structure and surface trap states, thereby boosting PL emission efficiency (4). Despite extensive progress, achieving a thorough understanding of the relationship between nanoscale core morphology, crystal structure, and emission behavior in bio-derived CQDs remains crucial (6). The optical performance of nitrogen-doped CQDs (N-CQDs) is governed by quantum confinement effects (particle size) alongside defect-state emissions induced by surface functional groups and heteroatom incorporation (7).

The primary objective of this paper is to investigate the physical morphology, crystallographic/graphitic structure, and PL emission characteristics of N-CQDs hydrothermally synthesized from calamansi lime (*Citrus microcarpa*) juice and urea (9, 11). Advanced characterization techniques including Transmission Electron Microscopy (TEM), XRD/Raman structural evaluation, UV-Vis Tauc-plot analysis, and PL spectroscopy are employed to elucidate core-shell property relationships (11, 12).

Methodology

N-CQDs were synthesized using a sustainable one-step hydrothermal process (4, 9). Natural citric acid extracted directly from calamansi lime juice served as the carbon framework precursor, while commercial urea acted as the nitrogen dopant (11). In a typical preparation, urea was dissolved in distilled water at a 2:1 ratio and combined with filtered calamansi juice at designated precursor volume ratios (1:1 to 1:3) (9, 11). The blended precursor solutions were sealed in Teflon-lined stainless-steel autoclaves and hydrothermally processed at temperatures

between 140 °C and 180 °C for 2 to 4 hours (9). Following reaction completion, the vessels were cooled naturally to room temperature. The liquid product was centrifuged at 10,000 rpm for 15 minutes to eliminate large agglomerates, yielding clear, purified N-CQD liquid supernatants (10, 11).

The optical properties and optical band gaps (E_g) were measured using a Shimadzu UV-Vis spectrophotometer and calculated via direct-transition Tauc plots (10, 11). Photoluminescence emission intensity and lifetime decay profiles were systematically recorded on a Perkin Elmer LS55 Fluorescence Spectrometer (12, 13). Structural functional groups were analyzed using a Bruker FTIR spectrometer (ATR mode) (14). Colloidal surface stability was quantified using a Malvern Zetasizer (15, 16). Particle nanoscale morphology, spatial distribution, and size histograms were gathered using a Talos L120C Transmission Electron Microscope (TEM) operating at 120 kV (2, 11).

Results and Discussion

Structural and Morphological Analysis (TEM)

High-resolution TEM imaging (Figure 1a) reveals well-dispersed, spherical N-CQD particles with no severe aggregation (2). The particle size distribution histogram confirms a narrow Gaussian profile with an average quantum dot diameter of 2.88 ± 0.48 nm for optimized samples (Sample 1) (11). At higher precursor concentrations and elevated synthesis temperatures (Sample 6) (Figure 1b), slightly larger mean particle sizes (3.91 ± 0.71 nm) were recorded alongside minor cluster aggregation. The ultra-small dimension (< 5 nm) ensures strong quantum confinement, which directly influences electron transition pathways and optical band gap broadening (1, 2). High-resolution TEM micrographs and corresponding particle size histograms provide further insight into the nanoscale morphology of the synthesized N-CQDs. Sample 1 displays well-dispersed, highly uniform spherical dots with an average core size of 2.88 ± 0.48 nm. In contrast, Sample 6 exhibits a larger mean particle diameter of 3.91 ± 0.71 nm alongside noticeable cluster aggregation. This increase in size and minor particle agglomeration directly affects the electronic state density, resulting in band gap narrowing (4.65 eV) due to reduced spatial quantum confinement effects.

Photoluminescence Spectral Analysis

The synthesized N-CQDs display bright, excitation-dependent photoluminescence performance (8, 12). As illustrated in Figure 2a, under an excitation wavelength of 500 nm, a dominant broad emission peak is recorded at 554 nm (12). A direct correlation exists between core dimensions, band gap tuning, and PL brightness (11). Sample 6 ($E_g = 4.65$ eV) exhibited a maximum PL intensity count of approximately 450,000 counts/s, significantly higher than wider band gap samples (12, 13). This enhanced emission is attributed to rich surface state defect channels provided by nitrogen functionalization (4, 14). FTIR spectra (Figure 2b) confirm nitrogen incorporation and passivation networks (14). Distinct stretching vibrations at 3283 cm^{-1} (O–H/N–H), 1750 cm^{-1} (C=O), and 1300 cm^{-1} (C–N) confirm the presence of amine and carboxyl surface networks (14). These polar surface groups impart excellent colloidal stability, with measured zeta potentials of -25.5 mV and -24.0 mV (Table 1) (15, 16). EDX chemical mapping confirms significant nitrogen contents (14.0%–42.4% atomic ratio), validating successful heteroatom incorporation into the carbon framework (4, 11).

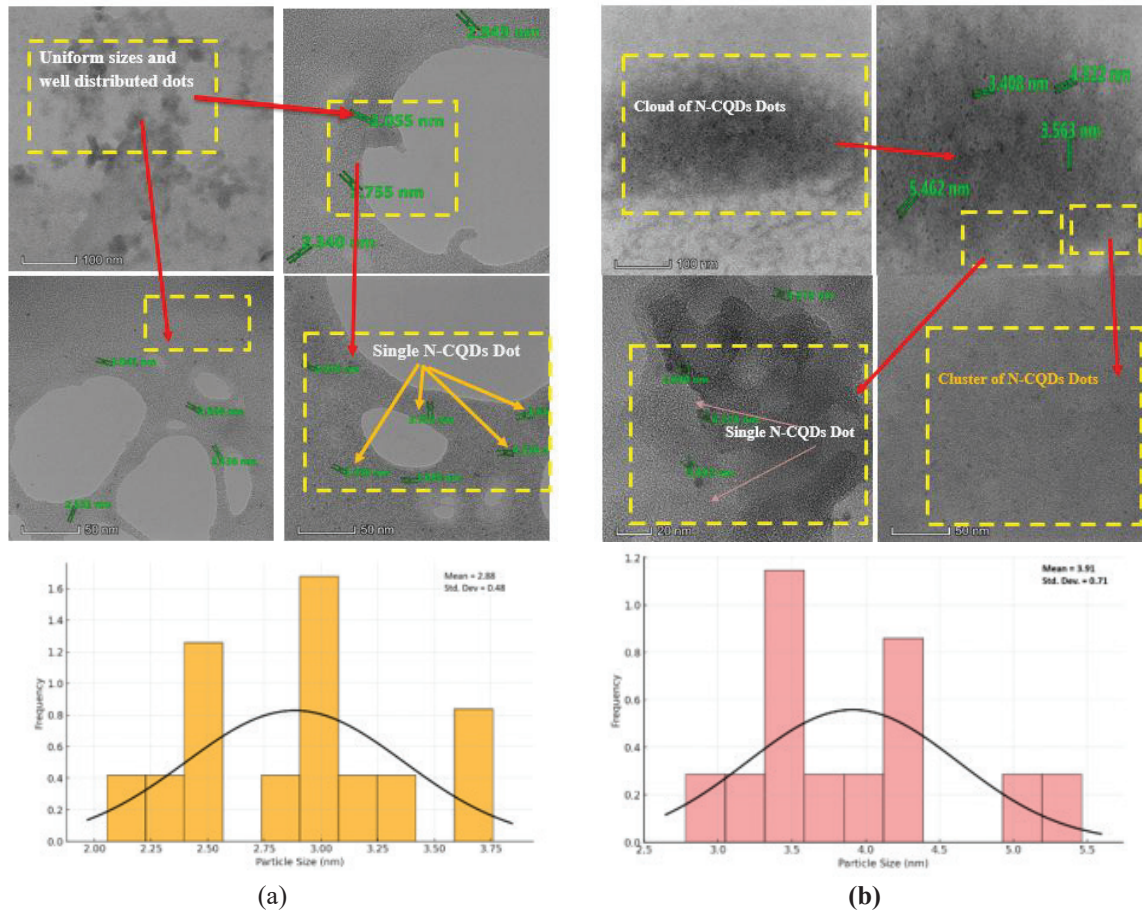


Fig 1. Morphological properties of N-CQDs: (a) TEM micrograph with particle size histogram for Sample 1 (mean = 2.88 nm) and (b) TEM micrograph with particle size histogram for Sample 6 showing cluster aggregation (mean = 3.91 nm).

Table 1: Morphological, Structural, and Optical Properties of Synthesized N-CQDs

Sample Parameter	Particle Size (TEM, nm)	Band Gap (E_g , eV)	Peak PL Emission (nm)	Zeta Potential (mV)
Max Band Gap State (Sample 1)	2.88 ± 0.48	5.81	554	-25.5
Min Band Gap State (Sample 6)	3.91 ± 0.71	4.65	554	-24.0

Table 2: Elemental Composition (EDX) and Surface Functional Groups of N-CQDs

Sample State	Carbon (At. %)	Nitrogen (At. %)	Oxygen (At. %)	Functional Groups Present (FTIR)
Sample 1 (140 °C, 2h)	37.6	42.4	19.3	O-H, N-H, C=O, C-N
Sample 6 (180 °C, 2h)	62.2	14.0	23.6	O-H, N-H, C=O, C-N, C-O

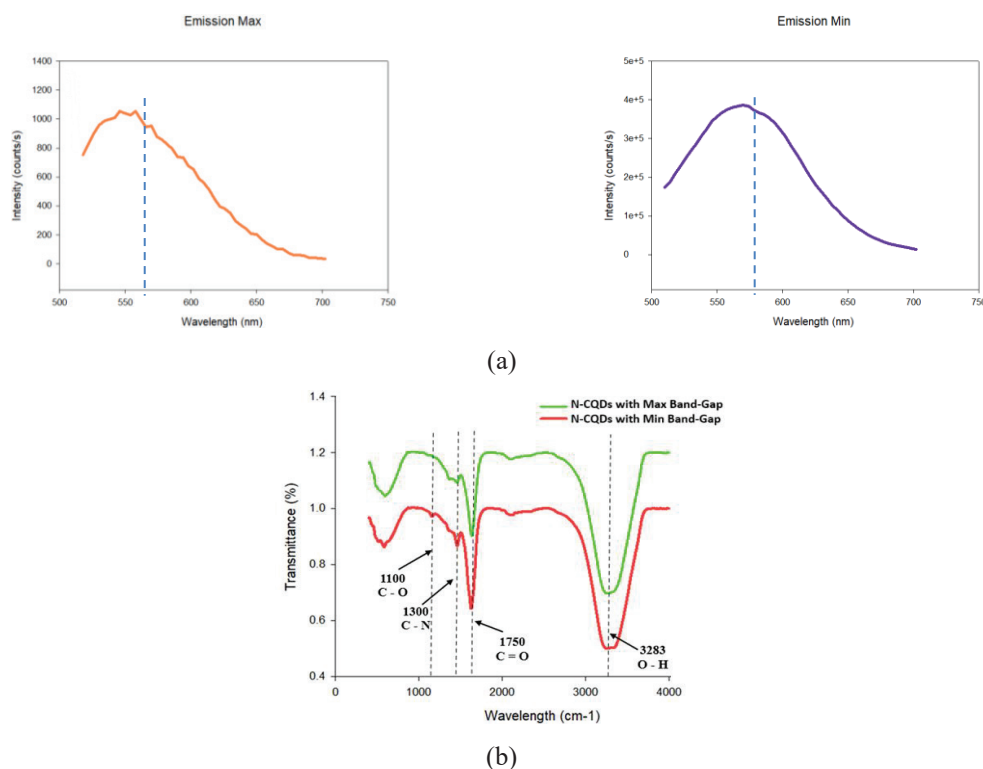


Fig 2: Optical characteristics of N-CQDs: (a) Photoluminescence emission spectra and fluorescence lifetime profiles, and (b) FTIR spectra demonstrating surface passivating groups.

Conclusions

In summary, nitrogen-doped carbon quantum dots were successfully synthesized from calamansi lime juice and urea via a green hydrothermal. TEM analysis confirmed monodisperse spherical dots with mean diameters ranging between 2.88 nm and 3.91 nm. Surface functionalization analysis via FTIR and EDX revealed strong nitrogen incorporation and oxygen-containing passivating groups. Optical testing established strong excitation-dependent photoluminescence (554 nm peak) with emission intensity strongly tied to core sizing and surface defect states.

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Corrosion Performance of TiO₂–ZnO Composite Coatings on Mild Steel under Different Exposure Environments

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Abstract—Corrosion of mild steel remains a major challenge in industrial and marine applications, necessitating the development of effective protective coatings. This study evaluates the effects of TiO₂–ZnO coating composition and exposure environment on the corrosion performance of mild steel using a full factorial design. Mild steel specimens were coated with varying TiO₂–ZnO compositions and exposed to different corrosive environments. Corrosion performance was assessed using the weight loss method, and the experimental data were analysed using analysis of variance (ANOVA) to evaluate the effects of coating composition, environmental conditions, and exposure time. The results showed that the 100 wt.% TiO₂ coating exhibited the lowest corrosion rate, indicating superior corrosion protection. In contrast, increasing the ZnO content resulted in progressively higher corrosion rates, suggesting that ZnO incorporation reduced the protective performance of the coating under the investigated conditions. Although the factorial analysis revealed no statistically significant effects of coating composition, exposure environment, or their interactions at the 95% confidence level ($p > 0.05$), the experimental results demonstrated consistent trends in corrosion behaviour among the coating formulations. The factorial design approach provided a systematic framework for evaluating multiple factors simultaneously and identifying performance trends. These findings indicate that TiO₂ is a more effective coating material than TiO₂–ZnO composites for corrosion protection of mild steel under the conditions investigated and provide useful guidance for the optimization of ceramic protective coatings.

Introduction

Mild steel is used extensively in structural, automotive, marine and industrial applications because of its good mechanical properties, ease of fabrication and low cost of production. However, its vulnerability to corrosion, especially in aggressive environments such as seawater and rainwater, greatly shortens its service life, endangers structural integrity and raises maintenance and replacement costs. Hence, the development of effective protective coatings has become a significant research interest to improve the durability and reliability of mild steel components. TiO₂ and ZnO have been extensively studied as ceramic coating materials because of their excellent chemical stability, corrosion resistance, environmental friendliness and high oxidation resistance, making them promising candidates for corrosion protection applications [1]. Previous studies have shown that TiO₂ and ZnO coatings are effective in enhancing the corrosion resistance of metallic substrates. In particular, TiO₂–ZnO composite coatings have been found with improved protective performance, resulting from the combination of the high chemical stability of TiO₂ and the barrier and passivation properties of ZnO [2]. However, previous studies have mainly investigated the impact of coating composition or corrosion environment individually. The performance of coatings is greatly influenced by the combination of coating composition and exposure environment under actual service conditions [3]. However, few studies systematically investigate the interaction between coating composition and exposure environment. Hence, the optimum TiO₂–ZnO formulation to provide consistent corrosion protection in different corrosive environments is not well established.

To fill this research gap, this study combines a full factorial experimental design and corrosion evaluation to systematically study the combined effects of TiO₂–ZnO coating

composition and exposure environment on corrosion behaviour of mild steel. Unlike the classical one-factor-at-a-time approaches commonly used in the literature, the factorial design enables the simultaneous assessment of the main effects and interaction effects of several variables, while minimising the number of experimental runs and improving the statistical reliability. Corrosion performance was evaluated by weight loss method and analysis of variance was applied to determine the statistically significant factors affecting the corrosion rate. The results demonstrate the capability of factorial design as a robust optimisation tool for the development of corrosion-resistant ceramic coatings, and yield the optimum TiO_2 -ZnO coating formulation for various service environments. This procedure gives practical guidance regarding selection and design of protective coatings for marine and outdoor engineering applications where the environmental conditions are very important for the coating performance.

Materials and Methodology

The substrate material for corrosion evaluation was mild steel sample. Specimens were cut to the same size and ground, cleaned and dried to provide a uniform surface condition before coating. TiO_2 -ZnO coatings of approximately 80 μm thickness were deposited by the plasma spray process with the following compositions: 100 wt.% TiO_2 -0 wt.% ZnO, 90 wt.% TiO_2 -10 wt.% ZnO, and 80 wt.% TiO_2 -20 wt.% ZnO. The control specimen was uncoated mild steel. All non-test surfaces were painted with a protective coating to prevent undesirable corrosion. The specimen weight and surface roughness were measured before the immersion test.

The corrosion performance was evaluated by the immersion weight loss method in rainwater and seawater for an exposure period of 10, 20 and 30 days. The experiments were performed in triplicate ($n=3$) to guarantee the reliability of the results. After each period of immersion, the specimens were cleaned, dried and weighed to determine loss of mass. The corrosion rate (mm/year) was calculated from the measured weight loss, exposed surface area, immersion time and material density using the ASTM weight loss equation.

A full factorial experimental design was used to investigate the effect of coating composition, exposure environment and immersion time on the corrosion rate. The experimental data were analysed by regression analysis, main effects plots, interaction plots and analysis of variance (ANOVA) using Minitab 22. The assumptions of normality, independence and homogeneity of variance were tested prior to ANOVA to ensure that the statistical analysis was valid. The results of these analyses were used to identify the significant factors and interactions affecting the corrosion performance and to optimise the TiO_2 -ZnO coating formulation.

Results and Discussion

The corrosion behaviour of mild steel coated with different compositions of TiO_2 -ZnO was evaluated by the immersion weight loss method in the rainwater and seawater environments. The corrosion rates after 10, 20 and 30 days are shown in Table 1. Generally, the corrosion rate of the samples exposed to seawater was higher than the samples exposed to rainwater because of the higher chloride ion concentration and electrolyte conductivity of seawater which accelerate electrochemical corrosion reactions [4]. In most cases, the 100 wt.% TiO_2 coating showed lower corrosion rates than the TiO_2 -ZnO composite coatings, which indicated a better corrosion protection. The addition of ZnO (10–20 wt.%) tended to increase the corrosion rate, indicating that higher ZnO content might reduce the compactness of the coating or promote the formation of defects that help the electrolyte penetration. As observed in previous studies [5,6], better corrosion resistance was obtained due to higher chemical stability and dense protective barrier of TiO_2 -rich coatings.

Table 1: Corrosion rate (mm/year) for sample for 10 days, 20 days and 30 days.

Samples name / days of Immersion	Corrosion rate (mm/year)					
	Rain water environment			Sea water environment		
	10 days	20 days	30 days	10 days	20 days	30 days
Uncoated mild steel	2.9113	45.7802	30.2238	26.3347	35.5019	30.0757
100% TiO ₂ coating	17.3342	25.5569	15.5564	17.4454	28.6682	12.2969
90% TiO ₂ - 10% ZnO coating	139.2296	11.8895	3.1483	64.0034	32.2795	16.4083
80% TiO ₂ - 20% ZnO coating	133.7848	30.6683	16.4823	57.7808	21.8345	23.705

A full factorial design was used to further investigate the effects of coating composition, exposure environment and immersion time. The main effects plot (Fig. 1) indicated that the immersion time had the largest effect on the corrosion rate, then the coating composition and exposure environment. ANOVA analysis found that the factors and their interactions were not statistically significant at the 95% confidence level ($p > 0.05$). The experimental results clearly showed differences in corrosion rates, but the lack of statistical significance is likely due to the relatively high variability in weight loss measurements and the limited number of experimental replicates, which reduced the statistical power of the analysis. However, in both exposure environments the trends were always in favour of better corrosion resistance of the 100 wt.% TiO₂ coating.

The interaction plots showed weak interactions between the investigated factors, indicating that the influence of coating composition was relatively constant under rainwater and seawater conditions. In general, the factorial design provided a systematic methodology for evaluating the individual and combined effects of several variables, and the experimental tendencies suggest that TiO₂-rich coatings are more promising for corrosion protection. It is suggested that further work with a larger sample size and additional characterisation techniques such as SEM and electrochemical corrosion testing be carried out to validate the statistical findings and to improve the reliability of the conclusions.

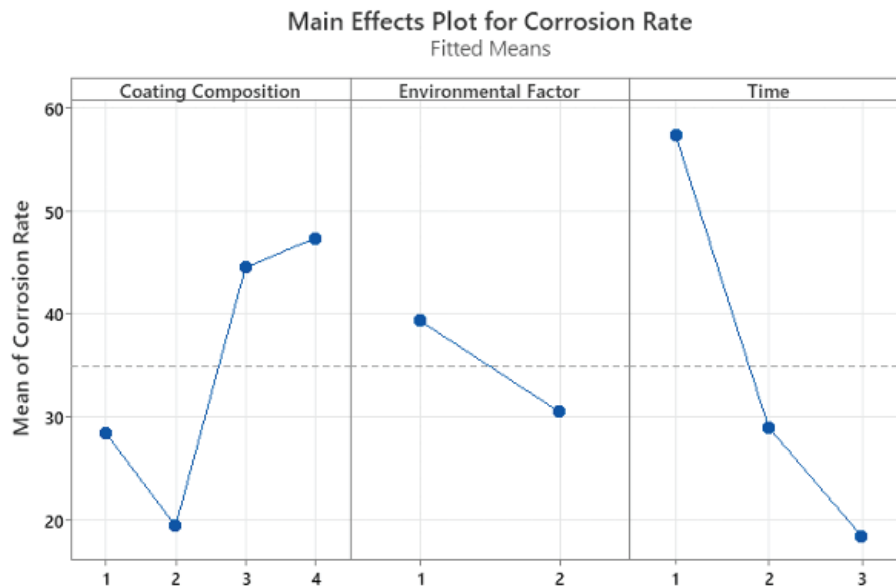


Fig. 1 Main Effects Plot for Corrosion Rate factors

Conclusion

In this study, the effect of TiO₂-ZnO coating composition and exposure environment on the corrosion behaviour of mild steel was investigated using a full factorial design. The results

showed that the minimum corrosion rate of the coatings was 100 wt. % TiO₂ which meant the better corrosion protection of the TiO₂-ZnO composite coatings. The corrosion rates increased with immersion time. The corrosion in seawater was higher than in rainwater due to higher concentration of chloride ion. The factorial design approach was an effective approach to systematically evaluate the effects of multiple factors and to identify the coating formulation with the best corrosion performance. Future work should explore a broader range of TiO₂-ZnO compositions and coating parameters, such as coating thickness and deposition methods, to enhance corrosion resistance further. Moreover, longer immersion duration, additional corrosive media and advanced characterisation techniques such as SEM, EDS and electrochemical impedance spectroscopy (EIS) are recommended to facilitate a more comprehensive understanding of the coating degradation and corrosion mechanisms, thus contributing to the creation of more resistant protective coatings for industrial application.

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Composition Dependent Morphology and Crystallinity of Chemically Reduced Nickel- Cobalt Alloy Nanoparticles

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Abstract— Nickel–cobalt (Ni–Co) alloy nanoparticles have attracted considerable attention due to their tunable magnetic, catalytic, and electrical properties, which are strongly influenced by alloy composition. However, systematic understanding of how different Ni:Co precursor ratios affect particle morphology and crystallinity during chemical reduction remains limited. This study investigates the effect of the Ni:Co precursor ratio on the morphology and crystallinity of chemically reduced Ni–Co nanoparticles. The nanoparticles were synthesized via chemical reduction using nickel chloride and cobalt chloride precursors with hydrazine hydrate as the reducing agent in 5 M NaOH. Four precursor ratios (Ni:Co = 100:0, 50:50, 30:70, and 0:100) were prepared and characterized using field emission scanning electron microscopy (FESEM) and X-ray diffraction (XRD). FESEM analysis revealed that pure Ni and Co nanoparticles exhibited relatively uniform quasi-spherical morphologies with average particle sizes of 0.034 μm and 0.052 μm , respectively. In contrast, the alloy samples showed larger agglomerated particles ranging from 0.301 μm to 0.321 μm , indicating altered nucleation and growth behaviour during co-reduction. XRD analysis demonstrated a significant decrease in crystallite size with increasing Ni content, reaching 0.1336 nm for pure Ni, while cobalt-rich compositions exhibited substantially bigger crystallites. These findings confirm that the precursor composition plays a critical role in governing particle morphology and crystallization behaviour. The study provides valuable insight into the composition-controlled synthesis of Ni–Co nanoparticles for potential applications in catalytic, magnetic, and electronic materials.

Introduction

Nickel–cobalt (Ni–Co) alloy nanoparticles have attracted sustained interest because their ferromagnetic, catalytic and electrical behaviour can be adjusted continuously by varying the relative proportion of the two constituent metals [1]. This tunability, combined with the relative abundance and low cost of nickel and cobalt, has motivated the use of Ni–Co-based nanomaterials in supercapacitor and battery electrodes [8], electrocatalysis [10], chemical sensing [1,6], and biomedical platforms [4]. A range of synthesis routes has been reported for Ni–Co nanoparticle systems, including biogenic and green synthesis using plant or microbial extracts [6,10], polyol and hydrothermal processing [7,8], and pulsed laser ablation in liquid [2]. Among these, chemical reduction with hydrazine remains one of the most widely used routes because it is simple, inexpensive, scalable and operable at moderate temperature [4,9,11,12, 14]. However, because Ni^{2+} and Co^{2+} are reduced by hydrazine at different rates, and because nanoparticle nucleation is highly sensitive to solution alkalinity, the chemical reduction of Ni–Co systems is considerably harder to control than that of the single-metal [7, 14].

The role of synthesis parameters such as NaOH concentration and precursor ratio in governing nanoparticle size and crystallinity has been demonstrated repeatedly across related transition-metal and metal-oxide nanoparticle systems [7,14], and composition has likewise been shown to control crystallite size and electrochemical performance in Ni–Co oxide and alloy nanocomposites [3,5,8]. In directly comparable Ni and Co nanoparticles prepared by chemical reduction, crystallite sizes on the order of 12–18 nm are typically reported [3], providing a useful benchmark against which the present alloy system can be assessed. Nevertheless, comprehensive studies correlating particle morphology and crystallinity over a wide range of Ni:Co compositions are still limited. This study addresses that gap by (1) determining the effect of the Ni:Co precursor molar ratio on nanoparticle morphology using FESEM, and (2) characterizing the corresponding structural and crystallinity changes using

XRD, providing a practical basis for the composition controlled design of Ni–Co nanomaterials for catalytic, magnetic and electronic applications.

Methodology

Ni–Co alloy nanoparticles were synthesized by chemical reduction of nickel chloride (NiCl_2) and cobalt chloride (CoCl_2) dissolved in 40 mL of distilled water at four nominal Ni:Co molar ratios: 100:0, 50:50, 30:70 and 0:100. Hydrazine hydrate (N_2H_4 , 0.1 M) was used as the reducing agent, and sodium hydroxide (NaOH) was added to fix the solution alkalinity at 5 M for this ratio series. The reaction mixture was heated to 80 °C and continuously stirred at 300 rpm for 5 hrs, during which a visible colour changes confirmed nanoparticle formation.

Following synthesis, the suspension was centrifuged at 8000 rpm with two cycles of 15 min. The precipitate was washed repeatedly with distilled water and ethanol to remove residual reactants and dried in an oven at 60 °C for 24 hrs. Surface morphology and particle size were examined by field emission scanning electron microscopy (FESEM), while phase composition and crystallinity were determined by X-ray diffraction (XRD); crystallite sizes were estimated from the broadening of the XRD peaks using the Scherrer relation. Particle size analysis was performed using ImageJ where approximately 100 individual nanoparticles were measured to obtain the representative size distribution.

Results and Discussion

FESEM imaging (Fig. 1) revealed a clear composition dependent trend in particle morphology. The pure nickel and pure cobalt samples formed compact, quasi-spherical particles with the smallest average sizes of 0.034 μm and 0.052 μm , respectively (Table 1). In contrast, both mixed compositions produced substantially larger particles with irregular, agglomerated shapes (0.321 μm for Ni (50%) – Co (50%) and 0.301 μm for Ni (70%) - Co (30%)). The differing reduction rates of Ni^{2+} and Co^{2+} by hydrazine likely result in a heterogeneous population of nuclei during co-reduction, with subsequent growth proceeding via preferential deposition of one metal onto nuclei already rich in the other. This mechanism plausibly explains the coarser, more agglomerated morphology observed for both alloy compositions relative to either pure metal. The influence of composition on particle agglomeration has also been reported in other alloy nanoparticle systems, where variations in metal ratio alter the reduction kinetics [2,3].

Figure 2 shows the XRD patterns of the nanoparticles synthesized at four different Ni:Co molar ratio. The observed diffraction peaks correspond to the Ni and Co containing phase with different in peaks intensity and broadening among the samples. The Ni (30%)- Co (70%), exhibit the largest reported crystallite size of 2.4465 nm, followed by the Ni (50%)- Co (50%) with 2.1146 nm. In comparison, the reported crystallite sizes of the pure Co and pure Ni samples were substantially smaller, at 0.2990 nm and 0.1336 nm respectively (Table 2). This indicates that the precursor composition does not produce a simple linear relationship between Ni content and crystallite size. Instead, the presence of both Ni and Co appears to influence the nucleation and subsequent crystal growth behaviour during the reduction process [1,11]. The larger particle size observed for the mixed Ni-Co composition maybe associated with the more complex nucleation and growth conditions resulting from the simultaneously reduction of Ni^{2+} and Co^{2+} ions. The presence of two metal precursors may alter the rate at which nuclei are formed and developed, leading to interactions between newly formed particles and promoting particle - particle attachment. As a result, relatively small crystalline domains can form larger agglomerated structures, which is consistent with the FESEM observations.

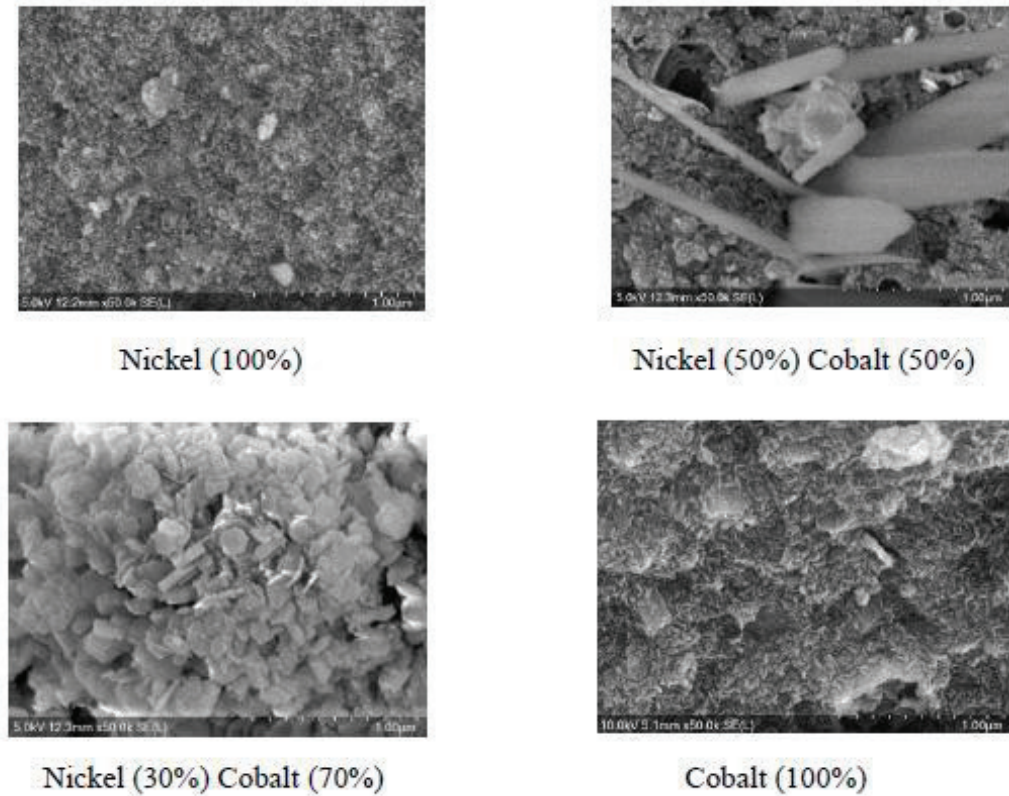


Fig. 1 FESEM images of nanoparticles synthesized at Ni: Co molar ratios of 100:0, 50:50, 30:70 and 0:100 in 5 M NaOH.

Table 1: Average particle size as a function of Ni:Co molar ratio

Ni:Co molar ratio	Average particle size (μm)
Nickel (100%)	0.034
Nickel (50%) – Cobalt (50%)	0.321
Nickel (30%) – Cobalt (70%)	0.301
Cobalt (100%)	0.052

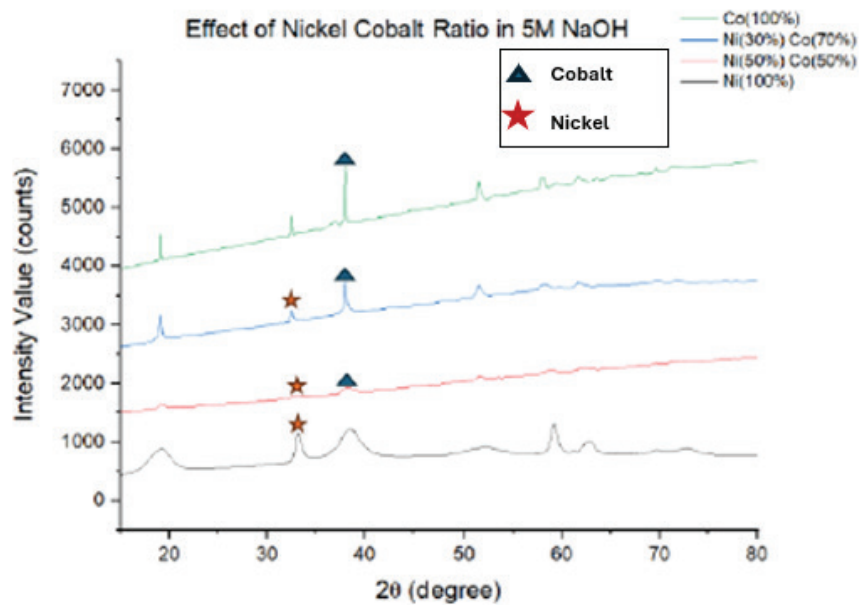


Fig. 2 XRD patterns of nanoparticles synthesized at Ni: Co molar ratios of 100:0, 50:50, 30:70 and 0:100 in 5 M NaOH.

Conclusion

This study demonstrates that the Ni: Co precursor molar ratio is a decisive parameter governing both the morphology and the crystallinity of nanoparticles produced by hydrazine-based chemical reduction. Pure nickel and pure cobalt yield small, well-defined quasi-spherical particles, whereas mixed Ni: Co compositions produce larger, agglomerated and irregularly shaped particles, consistent with competing nucleation kinetics between the two metal ions during co-reduction. Crystallite size increases sharply with Nickel content, indicating that composition also controls the degree of crystalline ordering achieved during synthesis. A practical implication is that single-metal-dominant compositions may be preferable where fine, well-dispersed particles are required (e.g., catalysis), whereas nickel-rich compositions should be favoured where enhanced crystallinity is the primary design target.

Acknowledgement

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A BEN Framework for Comparing AHP–MOORA and AHP–TOPSIS in Sustainable Natural Fiber Selection

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Abstract— The increasing demand for lightweight and sustainable materials has encouraged the use of natural fiber composites in electric vehicle (EV) applications. However, selecting the most suitable natural fiber is a complex multi-criteria decision-making (MCDM) problem involving mechanical, environmental, and economic considerations. This study proposes the BEN (Balance–Evaluation–Normalization) framework to compare the performance of two hybrid MCDM methods, namely AHP–MOORA and AHP–TOPSIS, for sustainable natural fiber selection in EV strut bar applications. Seven decision criteria derived from the Product Design Specification (PDS) were weighted using the Analytic Hierarchy Process (AHP) and applied consistently to both ranking methods. Fourteen natural fiber alternatives were evaluated within the proposed framework. The results showed that both methods consistently identified coir as the most suitable material, followed by kenaf and oil palm. The AHP–TOPSIS method produced the highest closeness coefficient ($CC = 0.576$) for coir, while the AHP–MOORA method yielded the highest assessment value ($Y_i = 0.2004$). The consistency between both ranking methods was verified using Spearman's rank correlation coefficient ($\rho = 0.96$), indicating a very strong positive correlation. These findings demonstrate that the proposed BEN framework provides a reliable and systematic approach for comparing hybrid MCDM methods while supporting sustainable material selection for lightweight automotive applications.

Introduction

The rise of electric vehicles constitutes the primary catalyst for lightweight and sustainable materials which enhance vehicle efficiency and reduce environmental impact. The strut bar functions as a critical structural component which enhances vehicle handling and reinforces chassis rigidity. Steel and aluminium serve as primary materials for this component because of strength and stiffness although they require energy-intensive manufacturing and contribute to increased mass. The interest in natural fibre reinforced composites arises because of low density and renewability and environmental benefits, although selecting optimal natural fibres remains complex because of simultaneous mechanical performance and environmental and economic requirements. [1].

Multi-criteria decision-making (MCDM) methods support engineering material selection when several conflicting criteria are involved. The Analytic Hierarchy Process (AHP) [2] is commonly used to weight decision criteria, while Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are often used to rank material alternatives [3][4]. Both hybrid methods have been applied to material selection, but few studies compare their performance under the same criteria and weighting structure. This study proposes the BEN (Balance–Evaluation–Normalization) framework to compare AHP–MOORA and AHP–TOPSIS for sustainable natural fiber selection in EV strut bar applications [5].

AHP–MOORA and AHP–TOPSIS have both been widely applied in engineering material selection, but previous studies have mainly used a single hybrid MCDM method or reported individual ranking results. As a result, the consistency and decision-making behaviour of these methods under identical evaluation criteria remain insufficiently explored [6]. To address this gap, this study proposes the BEN (Balance–Evaluation–Normalization) framework, which gives a unified structure for weighting decision criteria, standardizing material evaluation, and comparing ranking outcomes using identical criteria weights and material datasets. Unlike previous studies, the proposed framework allows a fair comparison between AHP–MOORA

and AHP–TOPSIS, since any differences in ranking can be attributed to the decision-making algorithms rather than to variations in the evaluation setup [7]. Consistency between the two methods is further verified using Spearman's rank correlation coefficient. This study therefore offers a transparent, systematic framework for comparative hybrid MCDM analysis in sustainable natural fiber selection [8].

Methodology

This study uses the proposed BEN (Balance–Evaluation–Normalization) framework to compare two hybrid multi-criteria decision-making (MCDM) methods, AHP–MOORA and AHP–TOPSIS, for sustainable natural fiber selection in electric vehicle (EV) strut bar applications. Figure 1 illustrates the overall research methodology. The framework has three sequential phases, Balance, Normalization, and Evaluation, which together give a unified structure for weighting decision criteria, processing material data, and comparing ranking results. Seven decision criteria were extracted from the Product Design Specification (PDS) for EV strut bar applications, covering mechanical, environmental, and economic requirements (Fig. 2)

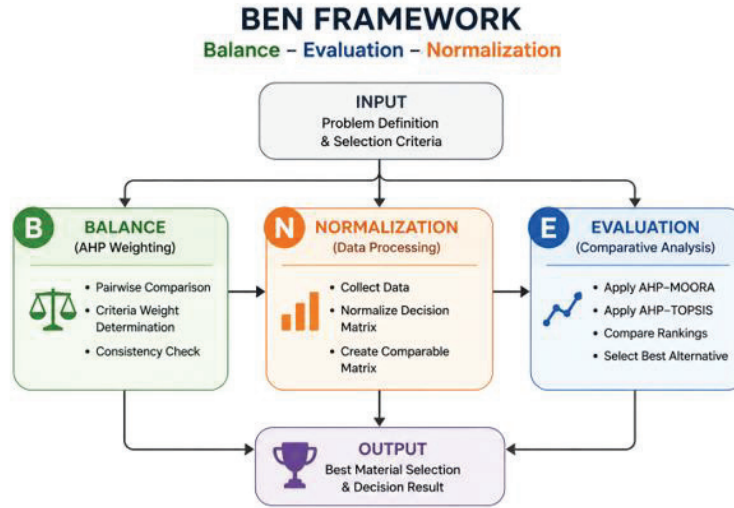


Fig. 1 BEN Framework



Fig. 2 Electric Vehicle Strut Bar Product Design Specification

The Balance phase used AHP to determine the relative importance of the seven criteria. The consistency of the pairwise comparison matrix was checked using the Consistency Ratio (CR < 0.10). The weighting process includes matrix normalization, priority weight calculation, and consistency verification to ensure reliable expert judgments.

$$a_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} \quad (1)$$

where a_{ij} is the normalized value of criterion j for alternative i , and x_{ij} represents the original value in the pairwise comparison matrix.

$$w_i = \frac{1}{n} \sum_{j=1}^n a_{ij} \quad (2)$$

where w_i is the priority weight of the i^{th} criterion. The resulting weights represent the relative importance of each decision criterion and are subsequently applied in both the AHP–MOORA and AHP–TOPSIS methods. The formula for Consistency Index and Consistency Ratio is:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

The validated criteria weights from the Balance phase were then carried into the Normalization phase for both integration methods. After the pairwise comparison and consistency verification, the priority weights for each decision criterion (Figure 2) were obtained using the AHP method.

In the Normalization phase, fourteen natural fiber alternatives were evaluated using the same decision criteria, and the AHP-derived weights were integrated into both hybrid MCDM methods. MOORA used ratio-based normalization to maximize beneficial criteria and minimize non-beneficial criteria, while TOPSIS used vector normalization, followed by determining the positive and negative ideal solutions, to calculate the relative closeness of each alternative.

Table 3: The Material Assessment Equation.

Alternative	MOORA	TOPSIS
Normalize	$x_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$	$v_{ij} = w_j r_{ij}$
Assessment	$Y_i = \sum_{j=1}^g X_{ij}^* - \sum_{j=g+1}^n X_{ij}^*$	$CC_i = \frac{D_i^-}{D_i^+ + D_i^-}$

Finally, the Evaluation phase compared the ranking outcomes from AHP–MOORA and AHP–TOPSIS. Spearman's rank correlation coefficient (ρ) was used to assess the consistency between the two ranking methods. This comparison shows how each hybrid MCDM approach behaves methodologically and identifies the most suitable natural fiber for sustainable EV strut bar applications.

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

where ρ is Spearman's rank correlation coefficient, d_i is the difference between the rankings of the i^{th} alternative obtained from AHP–MOORA and AHP–TOPSIS, and n is the total number of alternatives. A coefficient value closer to 1 indicates a stronger agreement between both ranking methods.

Results and Discussions

The proposed BEN framework was implemented using identical AHP-derived criteria weights in both hybrid methods. The comparative ranking results for the fourteen natural fiber alternatives are shown in Table 4. It can be observed that both AHP–MOORA and AHP–TOPSIS ranked coir as the best natural fiber, followed by kenaf, with only minor differences among the middle-ranked alternatives. These variations mainly stem from the different ranking mechanisms used by the two methods. The calculated Spearman's rank correlation coefficient ($\rho = 0.96$) shows very strong agreement between the two sets of rankings, confirming that the

proposed BEN framework is a consistent and reliable approach for comparing hybrid MCDM methods in sustainable natural fiber selection.

Table 4. Comparative ranking results of AHP–TOPSIS and AHP–MOORA

Natural Fiber	AHP–TOPSIS (CC)	Rank	AHP–MOORA (Yi)	Rank
Coir	0.576	1	0.2004	1
Kenaf	0.559	2	0.1758	2
Flax	0.528	3	0.1624	4
Oil Palm	0.437	4	0.1694	3
Sugar Palm	0.420	5	0.1607	5
Pineapple	0.349	6	0.1263	6
Abaca	0.307	7	0.1018	7
Hemp	0.275	8	0.0632	11
Ramie	0.274	9	0.0597	13
Jute	0.272	10	0.0733	10
Banana	0.256	11	0.0880	8
Cotton	0.241	12	0.0747	9
Sisal	0.218	13	0.0484	14
Bamboo	0.186	14	0.0615	12

Conclusion

This study proposed the BEN framework for comparing AHP–MOORA and AHP–TOPSIS in sustainable natural fiber selection. Both methods consistently identified coir as the best alternative, and Spearman's correlation coefficient ($\rho = 0.96$) confirmed very strong agreement between the ranking results. The proposed framework offers a reliable approach for comparative MCDM analysis and can be extended to other engineering material selection problems.

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Enhancing the Tribological Performance of Reclaimed EV Transmission Oil Using hBN Nanoparticles

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Abstract— Electric vehicle (EV) gearbox fluids undergo severe thermal and mechanical stress during service, which results in oxidation, depletion of additives and contamination. These degradation processes result in higher friction and wear and thus lower drivetrain efficiency and shorter service life of components. In this study, the potential for recycling EV gearbox fluid by means of filtration and re-additives with hexagonal boron nitride (hBN) nanoparticles is investigated. The Taguchi L9 orthogonal array was used to study the effects of hBN concentration, homogenization time and homogenization temperature on the tribological performance. Under boundary-lubrication conditions, the coefficient of friction (COF) and wear scar diameter (WSD) were measured using a four-ball tribometer. The results show that hBN-enhanced recycled oil significantly improves tribological performance. The best condition of 0.75 wt. % hBN, 40 min homogenization time and 80 °C homogenization temperature resulted in a minimum COF of 0.107 and WSD of 0.287 mm. The results indicate the promising potential of hBN nanoparticles re-additives as an eco-friendly method to prolong the service life and enhance the tribological properties of recycled EV gearbox fluids.

Introduction

The gearbox fluids must withstand high torque, wide speed ranges, and continuous thermal loading. Thus, EV lubricants need to offer better oxidation stability, thermal management, electrical insulation and wear protection and proper viscosity in their service life [1]. Gearbox fluids deteriorate over time due to thermal oxidation, mechanical shear, additive depletion, and contamination by wear debris, which increases friction and wear, reduces train efficiency, and shortens component life [2]. Used gearbox oil must be treated properly to achieve a sustainable reduction in lubricant waste and operating expenses, while restoring tribological performance to allow re-use. Nanoparticle additives have received much interest in improving lubricants due to their ability to reduce friction and wear through various mechanisms such as tribofilm formation, surface repair, asperity polishing and reduced metal-to-metal contact [3]. Among these, hexagonal boron nitride (hBN) is a promising candidate because of its layered crystal structure, low shear strength, high thermal conductivity, excellent thermal stability and chemical inertness that can facilitate the formation of stable protective tribofilms under harsh operating conditions [4].

Therefore, the present work examines the tribological performance of the reclaimed EV gearbox oil modified with hBN nanoparticles following the filtration treatment. The effects of hBN concentration, homogenization time, and homogenization temperature were investigated using a Taguchi L9 orthogonal array. Tribological performance was evaluated using a four-ball tribometer based on the coefficient of friction (COF) and wear scar diameter (WSD) to determine the optimal processing conditions for recovering the performance of the reclaimed EV gearbox fluid.

Methodology

The base lubricant used in this work was a commercial Castrol ON EV Gearbox Fluid D2. The fluid was collected after service, reclaimed by filtration, and modified with hexagonal boron nitride (hBN) nanoparticles. Castrol ON EV Gearbox Fluid D2 is a fully synthetic gearbox fluid specifically designed for electric vehicle (EV) drivetrains where lubricants are required to provide effective lubrication, thermal management, oxidation resistance and electrical

insulation under high-speed, high-torque operating conditions. The physicochemical properties of the fresh Castrol ON EV Transmission Fluid D2, as provided by the manufacturer, are given in Table 1.

Table 1. Typical properties of Castrol ON EV Transmission Fluid D2.

Property	Test Method	Unit	Value
Density at 15 °C	DIN EN ISO 12185	g/mL	0.852
Kinematic viscosity at 40 °C	ASTM D445	mm ² /s	32.2
Kinematic viscosity at 100 °C	ASTM D445	mm ² /s	6.3
Viscosity Index	ISO 2909	—	154
Brookfield viscosity at -40 °C	DIN 51398	mPa·s	10,000
Pour point	ISO 3016	°C	-57
Flash point (COC)	ISO 2592	°C	226

The nano-additive used to improve the tribological performance of the reclaimed EV gearbox oil was hexagonal boron nitride (hBN) nanoparticles. The manufacturer stated the average particle size of the nanoparticles as 70 nm. The hBN nanoparticles were received as a white powder with a hexagonal crystal structure and density of 2.3 g cm⁻³. The material has a high decomposition temperature of ~3000 °C, a maximum service temperature of 1000 °C in air and a thermal conductivity of ~27 W m⁻¹ K⁻¹, which allows stable operation at elevated operating temperatures.

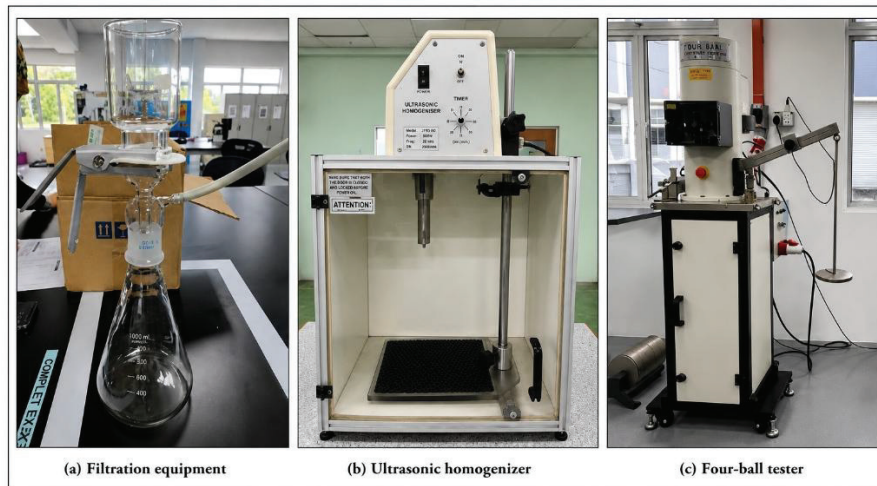


Fig. 1 (a) filtration equipment, (b) ultrasonic homogenizer, and (c) four-ball tester

Used EV gearbox oil was recovered by filtration in accordance with ASTM D7317 to remove suspended contaminants, oxidation products, sludge and metallic wear debris, providing a clean, consistent base lubricant for nanoparticle modification. The filtration, ultrasonic homogenizer and Four-Ball tribometer used in this study are shown in Fig. 1. Hexagonal boron nitride (hBN) nanoparticles were dispersed in 50 mL of filtered gearbox oil at the concentrations of 0.25, 0.50 and 0.75 vol.%. The lubricant mixtures were ultrasonicated with a homogenizer to better disperse the nanoparticles and to reduce the agglomeration. The tribological performance was studied using a Taguchi L9 orthogonal array approach to assess the effects of hBN concentration, homogenization temperature (70, 80, and 90 °C), and homogenization time (20, 30, and 40 min). The tribological properties were evaluated by a Four-Ball tribometer under boundary lubrication conditions according to ASTM D4172. The coefficient of friction (COF) was recorded continuously during the test. After the test, the wear scar diameters (WSDs) of the three stationary steel balls were measured by an optical

microscope. The average WSD and COF were chosen as the main response variables for evaluating lubricant performance.

Results and Discussion

The tribological performance for the lubricant formulations chosen as the worst (Sample 3), intermediate (Sample 5) and optimum (Sample 9) cases from the Taguchi L9 experimental design are shown in Table 2 and Fig. 2. Sample 9 with 0.75 vol. The best tribological properties were observed for the 10% hBN mixture homogenized at 80 °C for 40 minutes, with the lowest coefficient of friction (COF) of 0.107 and the smallest worn scar diameter (WSD) of 0.287 mm. Compared to Sample 3, the optimized formulation decreased the COF by 15.1% and the WSD by 15.3%, indicating the effectiveness of hBN nanoparticles in improving the tribological properties of recycled EV gearbox oil. The improvement is due to the higher concentration of hBN nanoparticles that form a stable protective tribofilm between the interacting asperities, hence reducing the direct metal-to-metal contact, the adhesive wear and the abrasive wear [4]. A large body of literature exists on similar friction-reducing processes in layered nanomaterials, where a lower shear strength between layers enables smooth sliding in boundary-lubrication conditions [3]. The better performance at 80 °C than at 90 °C shows that the homogenization temperature is an important factor in nanoparticle dispersion. Moreover, higher temperatures could also promote nanoparticle agglomeration or decrease dispersion stability, limiting the number of active nanoparticles available in the lubricant. However, 40 min of homogenization at 80 °C is sufficient to achieve a uniform dispersion of nanoparticles, which improves the stability of the lubricating film and enhances anti-wear performance. These findings align with other studies indicating that the efficient distribution of nanoparticles significantly affects the tribological properties of nanolubricants [2]. The findings indicate that filtration and the re-addition of hBN nanoparticles can effectively reinstate the friction-reducing and anti-wear characteristics of deteriorated EV gearbox oil, thereby supporting the viability of this method for sustainable lubricant recycling in electric vehicle drivetrains.

Table 2. 2 Experimental conditions and measured tribological responses obtained from the Taguchi L9 design

Test	hBN (vol.%)	Time (min)	Temperature (°C)	COF	WSD (mm)
1	0.25	20	70	0.115	0.351
2	0.25	30	80	0.116	0.318
3	0.25	40	90	0.126	0.339
4	0.5	20	80	0.116	0.296
5	0.5	30	90	0.112	0.291
6	0.5	40	70	0.112	0.344
7	0.75	20	90	0.124	0.32
8	0.75	30	70	0.116	0.309
9	0.75	40	80	0.107	0.287

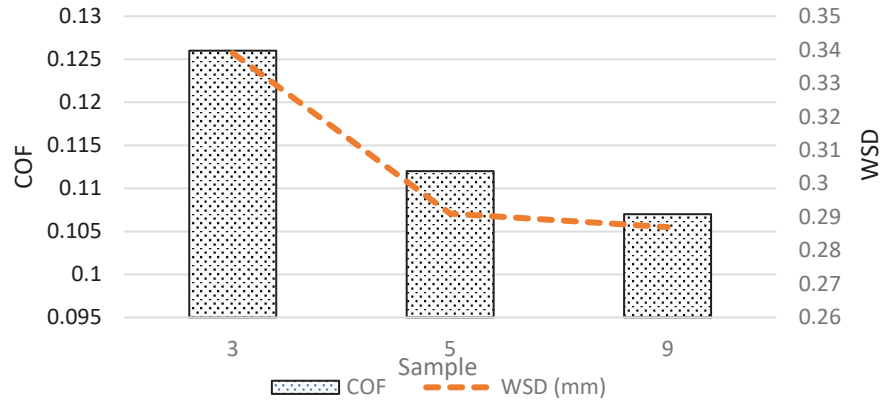


Fig. 2: Three results for optimized (sample 9), moderate (sample 5), and worse (Sample 3) extracted from Table 2.

Conclusion

This study shows that the re-additivation of hBN nanoparticles is a promising strategy to improve the tribological properties of reclaimed EV gearbox oil. The best results in terms of the lowest COF (0.107) and WSD (0.287 mm) were achieved with 0.75 vol.% hBN, a 40 min homogenization time, and a temperature of 80 °C, which were among the tested parameters. Improved nanoparticle dispersion and the formation of a stable protective tribofilm lead to improved tribological performance, which can reduce friction and surface wear. These results highlight the promise of nanoparticle-enhanced lubricant recycling as a sustainable method for extending the service life of EV gearbox fluids while reducing lubricant waste and maintenance costs. Future work should investigate the long-term oxidation stability, rheological and dielectric properties, and durability of the reclaimed hBN-enhanced gearbox fluids under real-world EV operating conditions.

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Particle-Size-Dependent Performance of Kenaf Core–Reinforced Epoxy Composites under Prolonged Environmental Exposure: A Review

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Abstract—The increasing demand for sustainable engineering materials has encouraged the incorporation of agricultural biomass into polymer composites. This review critically examines the influence of kenaf core particle size on the durability, mechanical performance, and physical properties of epoxy thermoset composites under prolonged environmental exposure. Emphasis is placed on particle dispersion, particle–matrix interfacial bonding, stress transfer, moisture absorption, dimensional stability, and degradation mechanisms. Fine particles may promote more uniform dispersion, improved packing, and efficient load distribution; however, excessive size reduction can increase agglomeration and resin demand. Coarse particles may support crack deflection and mechanical interlocking but can also introduce stress concentrations, interfacial voids, and moisture-transport pathways. Prolonged exposure to moisture, temperature fluctuations, ultraviolet radiation, and natural weathering may progressively weaken the interface and reduce mechanical integrity. The literature indicates that particle size cannot be evaluated independently of filler loading, surface treatment, void content, and fabrication conditions. Optimising these interrelated parameters is therefore essential for developing lightweight, durable, and sustainable kenaf core–epoxy composites for non-structural and semi-structural engineering applications.

Introduction

Natural fibre-reinforced polymer composites are increasingly considered sustainable alternatives to conventional synthetic fibre composites [1]. Compared with glass- and carbon-fibre reinforcements, natural fibres offer several advantages, including low density, relatively low production cost, renewability, biodegradability, reduced equipment abrasion, and potentially lower environmental impact [2]. These characteristics make natural fibre composites attractive for lightweight and semi-structural applications in the automotive, construction, furniture, packaging, and consumer-product sectors.

Kenaf (*Hibiscus cannabinus* L.) is a rapidly growing, renewable lignocellulosic crop with favourable specific properties. The kenaf stem comprises an outer bast and an inner woody core. Although bast fibre has been extensively investigated as composite reinforcement, the core, which constitutes approximately 60–70% of the stem biomass, remains comparatively underutilised. Incorporating kenaf core into polymer composites could convert an agricultural by-product into a value-added engineering material, minimise biomass waste, and support circular-economy practices. Despite these advantages, the hydrophilic nature of kenaf core presents a major challenge to the long-term performance of polymer composites [3]. Hydroxyl groups within its lignocellulosic structure promote moisture absorption, which may cause particle swelling, dimensional instability, microcracking, and deterioration of the particle–matrix interface. Prolonged environmental exposure can consequently lead to matrix degradation, interfacial debonding, reduced stress-transfer efficiency, and progressive loss of mechanical properties. Kenaf core particle size influences particle dispersion, interfacial area,

porosity, resin penetration, stress distribution, and moisture-diffusion behaviour. Fine particles may provide more uniform dispersion and a larger contact area with the resin, but they are also more susceptible to agglomeration and increased resin demand. Conversely, coarse particles can retain more of the porous cellular structure, potentially increasing moisture uptake, interfacial void formation, and localised stress concentration. A hybrid particle-size distribution may improve packing and reduce void content, although its effectiveness depends on particle compatibility, filler loading, and fabrication conditions.

Previous investigations of kenaf-based composites have mainly focused on bast fibres, conventional particle sizes, and short-term testing under controlled laboratory conditions [2,4]. Comparatively little attention has been given to coarse kenaf core particles or hybrid particle-size distributions subjected to prolonged environmental exposure. Accordingly, this review critically evaluates how kenaf core particle size affects the durability, mechanical performance, and physical stability of epoxy thermoset composites. Particular emphasis is placed on moisture absorption, thickness swelling, interfacial degradation, mechanical-property retention, and the mechanisms governing long-term performance.

Influence of Particle Size on Mechanical Properties

Natural fibres offer low density, renewability, relatively low cost, low abrasiveness to processing equipment, and the potential to reduce embodied environmental impacts. Nevertheless, their variable composition, moisture sensitivity, and poor compatibility with hydrophobic polymer matrices continue to limit long-term structural applications [5,6]. Unlike the relatively long, cellulose-rich bast fibre, kenaf core comprises short, porous, thin-walled cells. This cellular morphology produces low bulk density and favourable thermal and acoustic characteristics but limits its effectiveness as a high-strength reinforcement. Kenaf core is therefore more appropriately regarded as a lightweight functional filler than as a direct replacement for continuous glass or carbon fibre. During fabrication, the porous core may absorb liquid epoxy. Limited resin penetration can strengthen the particle and improve mechanical interlocking, whereas excessive absorption may locally disturb resin availability and leave insufficient matrix to fill interparticle spaces. Consequently, the effect of particle size must be considered together with resin viscosity, core moisture content, mixing procedure, compaction pressure, and curing conditions [7].

Fine Particles

Reducing particle size generally increases the specific surface area available for interaction with the epoxy matrix. When fine particles are uniformly dispersed and adequately wetted, the larger contact area may improve interfacial stress transfer and restrict local deformation. Fine particles may also occupy spaces between larger particles, producing a more compact structure with lower pore volume. These potential advantages do not imply that progressively smaller particles will continuously improve composite performance. Very fine kenaf core particles may agglomerate because of their high surface energy and interparticle attraction. Such agglomerates behave as irregular defects that can trap air and prevent complete resin wetting. Furthermore, the increased surface area raises resin demand. At a constant resin fraction, inadequate particle encapsulation can generate dry regions, microvoids, and premature fracture.

Fine particles also have a lower effective aspect ratio and are therefore less capable of bridging cracks than longer or coarser particles. Consequently, improvements in stiffness and surface uniformity may not be accompanied by equivalent gains in impact resistance or fracture toughness. Their overall performance is governed by the competing effects of improved dispersion and reduced reinforcement efficiency.

Coarse Particles

Coarse particles retain more of the cellular kenaf structure and may promote crack deflection, crack bridging, and mechanical interlocking. Their lower specific surface area also reduces the amount of resin required for complete coverage. However, large irregular particles can generate heterogeneous stress fields, particularly around sharp edges and poorly wetted regions. Under tensile and flexural loading, coarse particles may act as critical defect sites when interfacial bonding is inadequate. Debonding can initiate at the particle boundary and progress through particle pull-out, matrix cracking, and void coalescence. Coarse particles may also reduce packing uniformity and create larger interparticle spaces. Thus, the benefit of retaining a greater aspect ratio may be offset by increased stress concentration and porosity.

Hybrid Particle-Size Distributions

Combining fine and coarse particles may produce more efficient packing than a single particle-size fraction. Fine particles can occupy spaces between coarse particles, while the coarse fraction retains some capacity for crack deflection and mechanical interlocking. Nevertheless, a hybrid distribution is beneficial only when fine-particle agglomeration is controlled and sufficient matrix is available to wet both fractions. The literature has not yet established a universal fine-to-coarse particle ratio for kenaf core–epoxy composites. Apparent improvements attributed to hybrid particle sizes may instead result from concurrent changes in composite density, void fraction, filler loading, or processing pressure. These variables must therefore be independently controlled before a genuine synergistic effect can be confirmed. The relationships summarised in Table 1 represent mechanistic expectations rather than universally established rankings. Direct quantitative evidence comparing kenaf core size classes in the same epoxy system under identical long-term ageing conditions remains limited.

Table 1. Expected influence of kenaf core particle-size category on composite performance [8,9].

Particle-size category	Potential advantages	Principal limitations	Expected mechanical response	Expected long-term behaviour
Fine particles	High interfacial area; improved surface finish; potentially uniform stress distribution	Agglomeration, high resin demand and reduced crack-bridging capability	May improve stiffness and strength at low-to-moderate loading	Large exposed surface area may increase moisture interaction unless fully encapsulated
Medium particles	Balance between dispersion, aspect ratio, resin wetting and packing	Performance remains sensitive to size distribution and processing	Most likely range for balanced strength and toughness	Potentially better property retention when void content is minimised
Coarse particles	Lower resin demand per unit surface; retained cellular structure; possible crack deflection	Stress concentration, heterogeneous distribution, large voids and particle pull-out	May improve energy absorption but reduce tensile or flexural strength if bonding is inadequate	Greater swelling and interfacial cracking may develop during prolonged exposure
Hybrid distribution	Fine particles can fill spaces between coarse particles; potentially improved packing	Complex wetting behaviour and possible segregation during mixing	Potential balance of stiffness, strength and fracture resistance	Performance depends on whether the mixed sizes reduce or increase connected porosity

Long-term Environmental Durability

Moisture ageing is one of the principal limitations of natural fibre polymer composites. Absorbed water may plasticise the polymer matrix by increasing molecular mobility, thereby reducing stiffness and temperature-dependent performance. Within the reinforcement, water can induce swelling and extract soluble constituents. Repeated swelling and shrinkage generate

interfacial stresses that promote debonding and microcracking, progressively reducing the effective stress-transfer area [8,9]. Elevated temperature accelerates moisture diffusion and may promote post-curing, oxidation, or hydrothermal degradation. A temporary increase in strength can occur after mild thermal exposure because of additional epoxy cross-linking; however, this should not be interpreted as improved long-term durability, as moisture- and temperature-induced degradation may subsequently dominate. Ultraviolet radiation primarily damages the composite surface, causing discolouration, polymer-chain scission, matrix embrittlement, and microcracking. Once cracks develop, moisture penetration becomes more rapid. Outdoor weathering is therefore more complex than water immersion because ultraviolet radiation, temperature, humidity, and rainfall act simultaneously or cyclically.

Studies of kenaf/epoxy and hybrid kenaf composites demonstrate the importance of moisture uptake and interfacial condition; however, most available evidence concerns kenaf bast fibres, woven reinforcements, or hybrid natural–synthetic laminates [10,11]. Although these systems clarify general degradation mechanisms, their quantitative findings cannot be directly applied to kenaf core-filled epoxy composites because of substantial differences in morphology, porosity, and reinforcement efficiency.

Conclusions

Kenaf core particle size plays a critical role in the mechanical, physical, and long-term durability performance of epoxy composites. Fine particles may improve dispersion, packing, and interfacial contact, whereas coarse particles may promote crack resistance but increase porosity, moisture uptake, and stress concentration. Hybrid particle-size distributions could provide a more balanced response; however, systematic long-term studies are still required. Optimising particle size together with filler loading, surface treatment, void content, and fabrication conditions is essential for developing lightweight, durable, and sustainable kenaf core–epoxy composites.

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Development and Long-Term Water-Ageing Assessment of Oil Palm Empty Fruit Bunch–Reinforced Epoxy Thermoset Composites for Circular Economy and Decarbonization: A Work-in-Progress Study

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Abstract -The valorisation of oil palm empty fruit bunch (OPEFB) biomass as reinforcement in epoxy thermoset composites offers a potential route for reducing agricultural waste and dependence on conventional synthetic fillers. This work-in-progress study investigates the effects of OPEFB loading and prolonged water exposure on the mechanical performance, physical stability, and durability of OPEFB–epoxy composites. Untreated OPEFB fibres will be incorporated at 0–70 wt.% in 10 wt.% increments using a compression-assisted hand lay-up process. Following room-temperature curing and laboratory conditioning, the specimens will undergo water immersion for up to 180 days. Tensile, flexural, and notched Charpy impact properties will be evaluated alongside water absorption, thickness swelling, density, and Shore D hardness using the relevant ASTM methods. The experimental design will compare unexposed and water-aged specimens and assess the effects of fibre loading, exposure duration, and their interaction using two-way analysis of variance. Moderate OPEFB loading is anticipated to provide the most favourable balance between reinforcement efficiency and dimensional stability, whereas excessive loading may promote fibre agglomeration, incomplete wetting, porosity, and moisture-assisted interfacial degradation. The study is expected to establish an optimum OPEFB content for durable, resource-efficient epoxy composites and to provide evidence supporting biomass valorisation, circular material use, and composite-sector decarbonization.

Introduction

The continued expansion of the palm oil industry has generated substantial quantities of lignocellulosic biomass, with Malaysia producing approximately 6.93 million metric tonnes of oil palm empty fruit bunch (OPEFB) annually [1,2]. Converting this residue into reinforcement or filler for epoxy thermoset composites could divert biomass from disposal, reduce the consumption of conventional synthetic materials, and create value within a circular material system [3]. OPEFB is lightweight, renewable, and widely available; however, its hydrophilic lignocellulosic structure is inherently incompatible with the comparatively hydrophobic epoxy matrix. This incompatibility can impair wetting and interfacial adhesion, promote void formation, and restrict stress transfer between the reinforcement and matrix [4]. Moisture ingress may further induce fibre swelling, matrix plasticisation, and interfacial debonding, thereby reducing dimensional stability and retained mechanical performance. Although previous studies have established the short-term feasibility of OPEFB-reinforced polymer composites, comparatively limited attention has been given to their behaviour during extended water exposure [5]. This knowledge gap restricts the selection of a fibre loading that simultaneously maximises biomass utilisation and maintains engineering performance. Accordingly, the present conference work-in-progress study is designed to determine the influence of untreated OPEFB loading, ranging from 0 to 70 wt.%, on the mechanical and

physical properties of epoxy composites before and during water immersion for up to 180 days. The study specifically seeks to establish the relationship among fibre content, moisture uptake, dimensional change, and mechanical-property retention, thereby identifying a technically viable composition for resource-efficient and lower-carbon composite applications.

Methodology

The experimental programme will use untreated OPEFB fibres to represent a low-cost and low-energy material-processing route. The fibres will first be manually cleaned to remove soil and residual impurities, dried to minimise moisture-related variability, and shredded to a controlled size. No chemical surface treatment will be applied. Epoxy resin and hardener will be combined at a mass ratio of 2:1 and mixed until visually homogeneous. Eight formulations containing 0, 10, 20, 30, 40, 50, 60, and 70 wt.% OPEFB will be prepared, with OPEFB content defined relative to the total mass of fibre, resin, and hardener. Composite panels will be produced in a mild-steel mould using a compression-assisted hand lay-up process. A thin epoxy layer will first be applied to the mould surface, after which the shredded fibres will be distributed progressively over the wet resin. The fibres will be manually compacted, and the remaining resin mixture will be added gradually to improve impregnation and minimise entrapped air. The mould will then be closed and compressed to obtain a consistent panel thickness. All panels will be cured at room temperature for 24 h, demoulded, and conditioned under controlled laboratory conditions before being machined into specimens of the dimensions prescribed by the relevant test standards.

For durability assessment, specimens from each formulation will be assigned to an unexposed control group and a water-aged group. The latter will be immersed in water for up to 180 days in accordance with the water-absorption procedure of ASTM D570. Mass and thickness will be recorded before immersion and at predetermined exposure intervals. At each interval, specimens will be removed, gently surface-dried with absorbent material, and measured immediately. Water absorption and thickness swelling will be calculated relative to the initial dry mass and initial thickness, respectively. Mechanical characterisation will comprise tensile testing in accordance with ASTM D3039/D3039M, three-point flexural testing in accordance with ASTM D790, and notched Charpy impact testing in accordance with ASTM D6110. Physical characterisation will include water absorption and thickness swelling based on ASTM D570, density according to ASTM D792, and Shore D hardness according to ASTM D2240. Mechanical and physical measurements will be performed on unexposed and water-aged specimens to quantify changes associated with OPEFB loading and prolonged immersion. At least five replicate specimens will be evaluated for each formulation and exposure condition. Results will be reported as mean $\pm$ standard deviation. Following verification of the relevant statistical assumptions, two-way analysis of variance will be used to determine the main and interaction effects of OPEFB loading and exposure duration. An appropriate post-hoc multiple-comparison procedure will be applied at a significance level of $p < 0.05$. Mechanical-property retention will be expressed as the ratio of the aged property to the corresponding mean unexposed property, multiplied by 100.

Anticipated Outcomes and Discussion Framework

The mechanical response is anticipated to improve as OPEFB content increases from a low level to an intermediate optimum, provisionally expected within 20–30 wt.% based on trends reported for comparable natural-fibre composites [6]. Within this range, adequate fibre dispersion, matrix continuity, and interfacial contact may permit efficient load transfer from the epoxy matrix to the OPEFB reinforcement. Above the optimum range, tensile, flexural, and impact performance may decline because the available resin becomes insufficient to wet and encapsulate the fibres uniformly. Fibre agglomeration, entrapped voids, and weak interfacial

regions may consequently act as stress concentrators and initiate premature damage [7]. These trends are hypotheses to be tested by the proposed experimental programme rather than reported findings of the present study.

Increasing OPEFB content is also expected to reduce composite density while increasing water absorption and thickness swelling. Throughout this study, OPEFB loading is expressed consistently as wt.% relative to the total composite mass. The greater concentration of accessible hydroxyl groups in the lignocellulosic phase can promote moisture uptake, particularly through exposed fibres, microvoids, and interfacial pathways [5]. During prolonged immersion, fibre swelling and matrix plasticisation may generate local stresses and progressive interfacial debonding, reducing the retained mechanical properties. The analysis will therefore examine whether the composition that provides the highest initial strength also maintains acceptable dimensional stability and property retention after 180 days. Table 1 summarises literature-based qualitative trends and defines the hypotheses against which the experimental results will subsequently be evaluated. Fig. 1 presents an original schematic developed for this study to summarise the moisture-transport and damage mechanisms relevant to the planned ageing assessment. Water can enter through matrix defects and capillary pathways at the fibre–matrix interface, causing fibre swelling, matrix plasticisation, microcracking, and progressive interfacial debonding [6,9].

Table 1: Literature-based qualitative influence of fibre loading on OPEFB–epoxy composite behaviour [8,9].

Fibre loading (wt.%)	Anticipated mechanical response	Likely physical characteristics
Low (<10%)	Sub-optimal reinforcement	Good dispersion, high matrix dominance
Intermediate (15-30%)	Potential maximum tensile and flexural performance	Efficient stress transfer, good interface
High (>35%)	Possible strength reduction and increased brittleness	Fibre agglomeration, incomplete wetting, and higher porosity

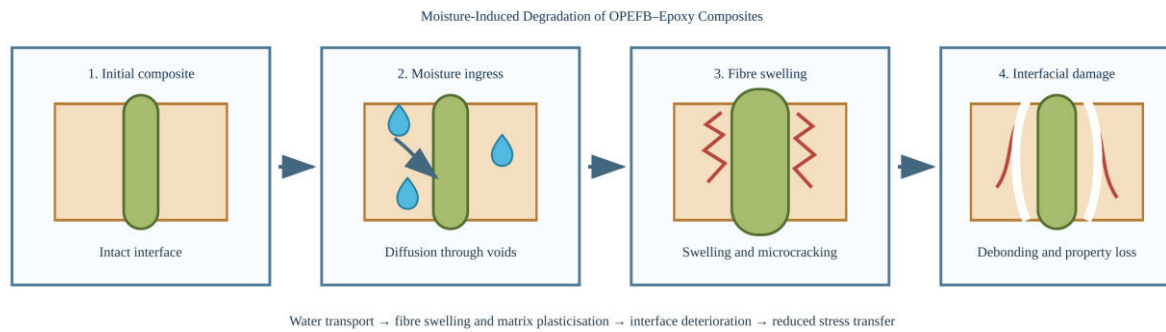


Fig. 1. Schematic of moisture-induced degradation in OPEFB–epoxy composites, showing moisture ingress, fibre swelling, microcracking, and interfacial debonding (Author-generated)

Water absorption will be quantified from the change in specimen mass relative to its initial dry mass. Careful removal of surface water before each measurement will ensure that the recorded mass increase predominantly represents moisture retained within the composite. The resulting absorption and thickness-swelling profiles will be interpreted together with changes in tensile, flexural, impact, density, and hardness properties. This combined analysis will distinguish simple moisture uptake from moisture-induced structural deterioration and will clarify the extent to which OPEFB loading governs long-term performance.

Conclusions

This work-in-progress study establishes an experimental framework for determining how OPEFB loading influences the initial properties and 180-day water-ageing resistance of epoxy

thermoset composites. Moderate fibre loading is hypothesised to provide the best balance between reinforcement efficiency, biomass utilisation, and dimensional stability, whereas excessive loading may increase porosity, moisture uptake, and interfacial degradation. Completion of the experimental programme will identify the optimum composition and quantify mechanical-property retention after prolonged immersion. The resulting evidence will clarify the technical feasibility of OPEFB–epoxy composites as resource-efficient materials that support agricultural-waste valorisation, circular material use, and decarbonization.

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Physical and Environmental Performance of Alkali-Treated Napier Grass Fibre-Reinforced Thermoplastic Cassava Starch/Carnauba Wax Composites

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Abstract— Thermoplastic cassava starch (TPCS) is renewable and biodegradable, but its high-water affinity restricts service in humid environments. This study evaluated whether alkali treatment of Napier grass fibre (NGF), combined with carnauba wax, could regulate the physical and environmental behaviour of TPCS biocomposites. Composites containing 20 wt.% NGF were fabricated using fibres treated with 0, 3, 6, or 9% sodium hydroxide (NaOH), followed by hot pressing at 155 °C for 60 min. Moisture content, density, water absorption, thickness swelling, moisture absorption, water solubility, four-week soil-burial mass loss, and surface morphology were assessed. Alkali treatment increased moisture content, immersed-water absorption, thickness swelling, and soil-burial mass loss, whereas density, five-day moisture absorption, and water solubility showed smaller or non-systematic variations. The untreated composite showed the lowest two-hour water absorption at 155.75% and one-hour thickness swelling at 11.80%, whereas 6% NaOH produced maxima of 251.05% and 26.74%, respectively. Four-week soil-burial mass loss increased from 30.32% without treatment to 55.67% at 9% NaOH. SEM showed progressive cleaning and fibrillation up to 6% NaOH, followed by severe erosion at 9%. Overall, alkali treatment enhanced fibre surface exposure but also increased water sensitivity and biodegradation, indicated that 6% NaOH represented the optimum condition for morphological improvement rather than for overall water resistance.

Introduction

Thermoplastic starch (TPS) is a promising substitute for short-life petroleum-based plastics because starch is abundant, inexpensive, renewable, thermally processable in the presence of suitable plasticisers, and biodegradable. These characteristics make TPS particularly attractive for disposable packaging and other applications in which a short service life and reduced environmental persistence are desirable. However, its main technical limitation is the strong affinity of starch hydroxyl groups for water. Moisture absorption disrupts intermolecular hydrogen bonding within the starch network and promotes additional plasticisation, resulting in dimensional instability, swelling, reduced mechanical performance, and eventual loss of structural integrity under humid or immersed conditions [1,2]. Reinforcing TPS with lignocellulosic fibres can improve stiffness, dimensional stability, and overall resource efficiency while reducing the proportion of polymeric matrix required. Nevertheless, the effectiveness of fibre reinforcement depends strongly on the fibre–matrix interface. A well-bonded interface promotes stress transfer from the starch matrix to the fibres, whereas poor interfacial adhesion, fibre agglomeration, or interfacial voids may instead create preferential capillary pathways for water penetration [2,8]. Napier grass fibre (NGF) is attractive for this purpose because it is rapidly renewable, has a relatively low density, and is widely and locally available, making it a potentially sustainable reinforcement for starch-based composites.

Alkali treatment is commonly applied to natural fibres to remove surface waxes, pectin, hemicellulose, impurities, and part of the lignin fraction, thereby increasing surface roughness, fibrillation, and the availability of cellulose-rich surfaces [4,9]. A moderate treatment may improve fibre dispersion, mechanical interlocking, and interfacial bonding with the polymer matrix. In contrast, excessive alkali exposure may over-remove non-cellulosic constituents, expose additional hydrophilic cellulose, generate surface defects and voids, and damage the fibre wall structure [9]. Consequently, alkali treatment may simultaneously improve interfacial morphology while increasing the susceptibility of the composite to moisture uptake and biodegradation. Recent studies on coconut-fibre/TPCS/wax and water-hyacinth/TPS systems similarly indicate that fibre incorporation strongly influences water affinity, solubility, structural stability, and environmental degradation behaviour [3,10]. Carnauba wax was therefore introduced as a hydrophobic phase to reduce the moisture sensitivity of the starch–fibre

network. This approach is consistent with previous studies on plant-derived waxes, which reported improvements in surface hydrophobicity, water-barrier performance, and resistance to moisture transport [5,7]. The present study therefore aimed to determine how alkali treatment at concentrations ranging from 0 to 9% NaOH affects the moisture response, density, water solubility, soil degradation behaviour, and morphology of TPCS/carnauba wax composites reinforced with 20 wt.% NGF.

Methodology

Cassava starch was plasticised with glycerol at a starch-to-glycerol mass ratio of 100:30, followed by blending with carnauba wax. Water-retted Napier grass was ground, and the fibre was either left untreated or exposed to 3, 6, or 9% NaOH. Each formulation contained 20 wt.% NGF and 80 wt.% TPCS/carnauba-wax matrix. The blended material was compression moulded at 155 °C for 60 min and cooled for 20 min. Test specimens were cut to approximately 10 × 10 × 3 mm. Moisture content was determined after oven drying at 105 °C; density was calculated from mass and specimen dimensions in accordance with ASTM D1895. Water absorption and thickness swelling were determined following immersion in distilled water by calculating the changes in specimen mass and thickness relative to their initial dry-state values. The procedures were adapted from those reported for a comparable alkali-treated TPCS/fibre/wax composite system [4]. Atmospheric moisture absorption was monitored for five days at 35 °C and 75% relative humidity. Water solubility was evaluated after 24 h immersion followed by redrying. For soil burial, triplicate specimens were placed 10 cm deep in a 1:1 soil:sand mixture at 30 °C and were recovered after two and four weeks. Fracture and post-immersion surfaces were examined using a Zeiss EVO 18 scanning electron microscope at 10 kV after gold coating. The results were compared descriptively across the four NaOH treatment levels.

Results and Discussion

Table 1 shows that NaOH treatment increased equilibrium moisture content from 4.56% for untreated material to 6.51 to 6.60% for treated composites. This result is consistent with removal of surface waxes and non-cellulosic material, which exposes hydroxyl-rich cellulose and increases accessible pore volume [9]. Density varied non-monotonically from 0.494 to 0.580 g cm⁻³ without a consistent concentration-dependent trend. The loss of low-density lignin and hemicellulose competed with improved packing and matrix penetration; consequently, surface modification did not translate into a systematic change in bulk compactness.

Table 1: Summary of physical and environmental responses to NaOH treatment

Response	Untreated (0% NaOH)	Principal treated response
Moisture content	4.56%	6.51 to 6.60% (3–9% NaOH)
Density	0.580 g cm ⁻³	0.494, 0.553, 0.515 g cm ⁻³ at 3, 6, and 9%
Water absorption, 2 h	155.75%	Maximum 251.05% at 6%; 219.22% at 9%
Thickness swelling, 1 h	11.80%	Maximum 26.74% at 6%; 25.65% at 9%
Moisture absorption, day 5	13.12%	13.39, 12.64, 12.52% at 3, 6, and 9%
Water solubility, 24 h	39.59%	38.74 to 43.01%; maximum at 9%
Soil-burial mass loss, week 4	30.32%	Maximum 55.67% at 9%

Water immersion amplified the treatment effect. The untreated composite had the lowest two-hour water absorption at 155.75% and one-hour thickness swelling at 11.80%. Both responses peaked at 6% NaOH, reaching 251.05% and 26.74%, respectively. The carnauba wax phase was therefore insufficient to seal the capillary network created by mercerisation. The slight reduction observed at 9% NaOH should not be interpreted as evidence of improved fibre–matrix compatibility. SEM observations instead indicated excessive fibre treatment, characterised by cell-wall erosion and structural damage, which may have reduced the water-retention capacity of the fibre. The maximum water uptake recorded at 6% NaOH was attributed to increased surface roughness and the formation of exposed capillary channels. Although these morphological changes may enhance mechanical interlocking, they can also promote more rapid water penetration into the composite structure [8,9].

In contrast, atmospheric moisture absorption converged after five days to a narrow range of 12.52 to 13.39% across the treatments. Water solubility likewise remained within 38.74 to 43.01%, indicating that variability in the starch-rich matrix dominated the 24-hour leaching response. These findings separate two mechanisms that are often conflated: liquid-water uptake was strongly controlled by fibre porosity and exposed cellulose, whereas equilibrium uptake from humid air and dissolution showed less variation with NaOH concentration. All formulations biodegraded in soil. Four-week mass loss increased from 30.32% for untreated composite to 55.67% at 9% NaOH, supporting the premise that removal of protective lignin/wax layers and increased surface area enhanced microbial access. Similar environmental responsiveness has been reported for other natural-fibre/TPS composites [3,6,10]. SEM observations reinforced the quantitative data: untreated fibres retained a comparatively smooth, impurity-covered surface; 3% NaOH initiated cleaning; 6% produced pronounced fibrillation and the greatest apparent area for mechanical interlocking; and 9% caused deep grooves, severe fibrillation, interfacial gaps, and microcracking. The 2024 review by Schutz et al. [2] emphasises that interface optimisation, rather than maximum fibre exposure, is the decisive design variable in starch-based plant-fibre biocomposites.

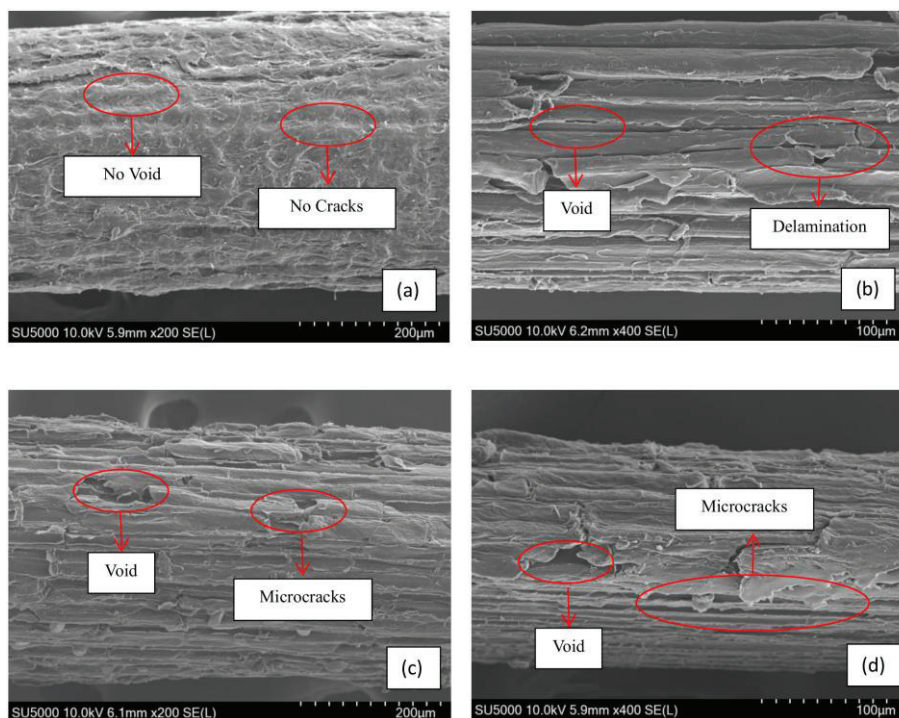


Figure 1: SEM micrographs of Napier grass fibre after (a) 0%, (b) 3%, (c) 6%, and (d) 9% NaOH treatment.

Conclusion

Alkali-treated NGF/TPCS/carnauba-wax composites were successfully fabricated, and NaOH concentration produced marked changes in moisture content, immersed-water absorption, thickness swelling, and soil degradation. However, increasing surface roughness did not produce better water resistance. The untreated composite provided the greatest short-term dimensional stability, while 6% NaOH yielded the clearest fibrillation but also the largest water absorption and swelling. At 9% NaOH, fibre erosion coincided with the highest four-week soil-burial loss. Therefore, 6% NaOH should be described as a morphological surface-modification optimum, not as a comprehensive performance optimum. For moisture-exposed products, fibre–matrix sealing and wax distribution require further optimisation before the material can be considered suitable for packaging; for controlled-degradation products such as nursery pots, the accelerated soil mass loss may be advantageous [6].

Acknowledgement

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SMART SYSTEMS & AUTOMATION



Machine Learning-Based Quality Issue Monitoring with Automated Email Alerts in Automotive Manufacturing

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Abstract— The automotive manufacturing industry generates large volumes of consumer response data, including customer complaints, warranty claims, and service records, which are valuable for quality improvement and decision-making. However, the increasing complexity and volume of these data present challenges in identifying critical quality issues efficiently. This study proposes a machine learning-based predictive framework for quality issue filtration within an automotive manufacturing environment. The framework integrates data preprocessing, feature selection, clustering, and classification techniques to support the identification and prioritization of quality-related issues. K-Means clustering is employed to uncover hidden patterns and categorize quality issues according to their severity levels, while multiple classification algorithms are evaluated to automate issue categorization. The predictive outputs are further integrated into a Power BI dashboard for real-time monitoring and visualization. An automated email alert mechanism is incorporated to notify responsible personnel when critical issues exceed predefined thresholds. Experimental results demonstrate that the proposed framework achieves classification accuracy exceeding 90%, indicating its effectiveness in supporting quality issue management. The integration of predictive analytics, business intelligence, and automated notifications enhances operational responsiveness and facilitates data-driven decision-making in automotive manufacturing.

Introduction

The automotive manufacturing industry generates substantial volumes of consumer response data, including customer complaints, warranty claims, and dealer service reports. These data provide valuable insights into quality improvement and post-market decision-making. However, the increasing volume and complexity of such information make it difficult for organizations to identify critical quality issues efficiently. Traditional approaches that rely on manual assessment are often time-consuming and may delay corrective actions, resulting in inefficient resource allocation and reduced operational responsiveness [1,2].

Machine learning techniques have demonstrated significant potential in improving manufacturing quality management through predictive analysis and automated decision-making. Classification algorithms such as Random Forest and Decision Tree have been widely applied in quality assessment, while clustering techniques such as K-Means are effective in identifying hidden patterns and categorizing quality-related issues [3,4]. Furthermore, Business Intelligence tools have increasingly been integrated with predictive models to support real-time monitoring and operational decision-making [5].

Previous work demonstrated the effectiveness of machine learning and dashboard visualization in supporting consumer response data management within the automotive sector [6]. Building upon this work, the present study extends the framework by incorporating an automated email alert mechanism for real-time notification of crisis-level quality issues. As illustrated in Fig. 1, the proposed framework integrates data preprocessing, clustering, classification, dashboard visualization, and automated email notifications to support proactive quality management. The results demonstrate that the Random Forest model achieved an accuracy of 97.4%, while the integrated alert mechanism enhanced operational responsiveness and decision-making efficiency.

Methodology

The proposed methodology consists of four main phases, namely Business and Data Understanding, Data Preparation, Exploratory Data Analysis and Modelling Validation, and

Data Visualization, Alert System and Data Presentation, as illustrated in Fig. 1. The framework was developed to support quality issue filtration and predictive decision-making using market claim data obtained from an automotive manufacturing company.

Fig. 1 presents the overall research workflow. In Phase 1, business objectives, stakeholder requirements, relevant literature, and data availability were identified to establish the project scope and analytical requirements. Initial exploratory analysis was then conducted to obtain preliminary insights into the dataset.

In Phase 2, data preparation activities were performed, including data cleaning, data formatting, data transformation, and data segregation. Textual attributes, such as Dealer Note and Dealer Solution, were converted into numerical representations through label encoding to enable machine learning model training. Additional exploratory analysis was conducted after preprocessing to ensure data quality and readiness for model development.

Phase 3 focused on predictive modelling and validation. Feature learning and feature selection techniques were applied to identify significant variables influencing quality issues. K-Means clustering was subsequently employed to identify hidden patterns among quality issues. The resulting clusters were interpreted based on issue occurrence frequency and assigned severity labels, which were subsequently used as target classes for supervised classification models. Several machine learning classification algorithms were then developed and evaluated using training and testing datasets to determine the most suitable predictive model. Model performance was evaluated based on classification accuracy.

Finally, Phase 4 involved the deployment of the predictive model through Power BI for real-time visualization and monitoring. A threshold-based automated email alert system was integrated into the framework to notify engineering and quality teams whenever critical consumer response patterns exceeded predefined limits. The analytical outputs were subsequently used to support operational decision-making and formulate recommendations for continuous quality improvement.

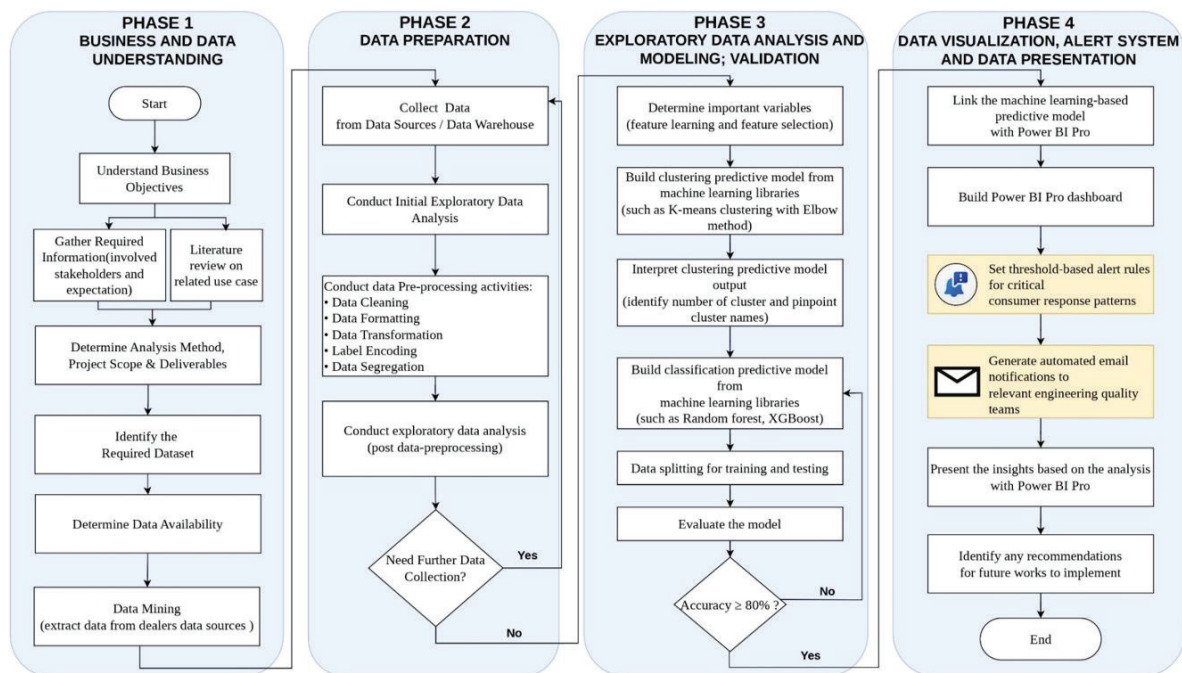


Fig. 1 Flow Chart of Research Structure

Results and Discussion

The proposed framework was evaluated using historical market claim data obtained from an automotive manufacturing company. Following data preprocessing, textual features such as *Dealer Note* and *Dealer Solution* were standardized using mapping functions and converted into numerical representations through label encoding before feature selection and model development. Machine learning models were subsequently trained and validated to classify quality issues according to their severity levels. The selected features used for predictive modelling are presented in Table 1.

Table 1: Selected Features for Predictive Modelling

Feature	Description
Part Description	Component involved
Dealer Note	Complaint description
Dealer Solution	Corrective action
Model	Vehicle category

The processed dataset was subsequently used to develop and evaluate several supervised machine learning classification models. Prior to supervised learning, K-Means clustering was applied to identify recurring quality issue patterns from historical market claim data, where the resulting clusters were interpreted based on issue occurrence frequency. The cluster with the highest occurrence was assigned as the *Crisis* category, while the remaining clusters were assigned to *Intermediate Crisis Levels* according to their relative occurrence frequency before being used as target classes for supervised classification. The performance of six classification algorithms, namely Decision Tree (DT), Support Vector Machine (SVM), Random Forest (RF), K-Nearest Neighbors (KNN), Naïve Bayes (NB), and Gradient Boosting Tree (GBT), is summarized in Table 2. Among the evaluated models, the Random Forest classifier achieved the highest classification accuracy of 97.4%, followed by Gradient Boosting Tree (96.9%), K-Nearest Neighbors (93.0%), Naïve Bayes (89.0%), Decision Tree (88.1%), and Support Vector Machine (82.8%). The superior performance of Random Forest can be attributed to its ensemble learning strategy, which effectively handles heterogeneous market claim data, reduces overfitting, and improves prediction stability. This finding is further supported by the classification report in Fig. 2, where the Random Forest classifier achieved weighted average precision, recall, and F1-score values of 0.98, 0.97, and 0.97, respectively, demonstrating its robustness and balanced predictive performance across different quality issue categories. Consequently, the Random Forest classifier was selected as the final predictive model for integration with the Power BI dashboard and automated email alert system to support real-time quality issue monitoring and decision-making.

	precision	recall	f1-score	support
0	0.99	1.00	1.00	131
1	1.00	0.83	0.91	6
2	1.00	0.90	0.95	10
3	0.77	0.91	0.83	11
4	0.97	0.96	0.96	69
accuracy			0.97	227
macro avg	0.95	0.92	0.93	227
weighted avg	0.98	0.97	0.97	227

Fig. 2. Classification report for Random Forest

Table 2: Classification Performance of Machine Learning

Model	Accuracy (%)
Random Forest	97.4
Gradient Boosting	96.9
K-Nearest Neighbors	93.0
Naïve Bayes	89.0
Decision Tree	88.1
Support Vector Machine	82.8

Fig. 3 presents the Power BI dashboard and automated email alert system developed in this study. The dashboard enables real-time visualization of quality issue trends and performance indicators, while the automated alert mechanism generates notifications whenever predefined thresholds are exceeded. This functionality enhances operational responsiveness and supports timely intervention by engineering and quality management teams. The integration of predictive modelling, dashboard visualization, and automated notifications provides a comprehensive decision-support framework for proactive quality management. The proposed approach contributes to improved monitoring, faster response times, and more effective utilization of organizational resources within automotive manufacturing environments.

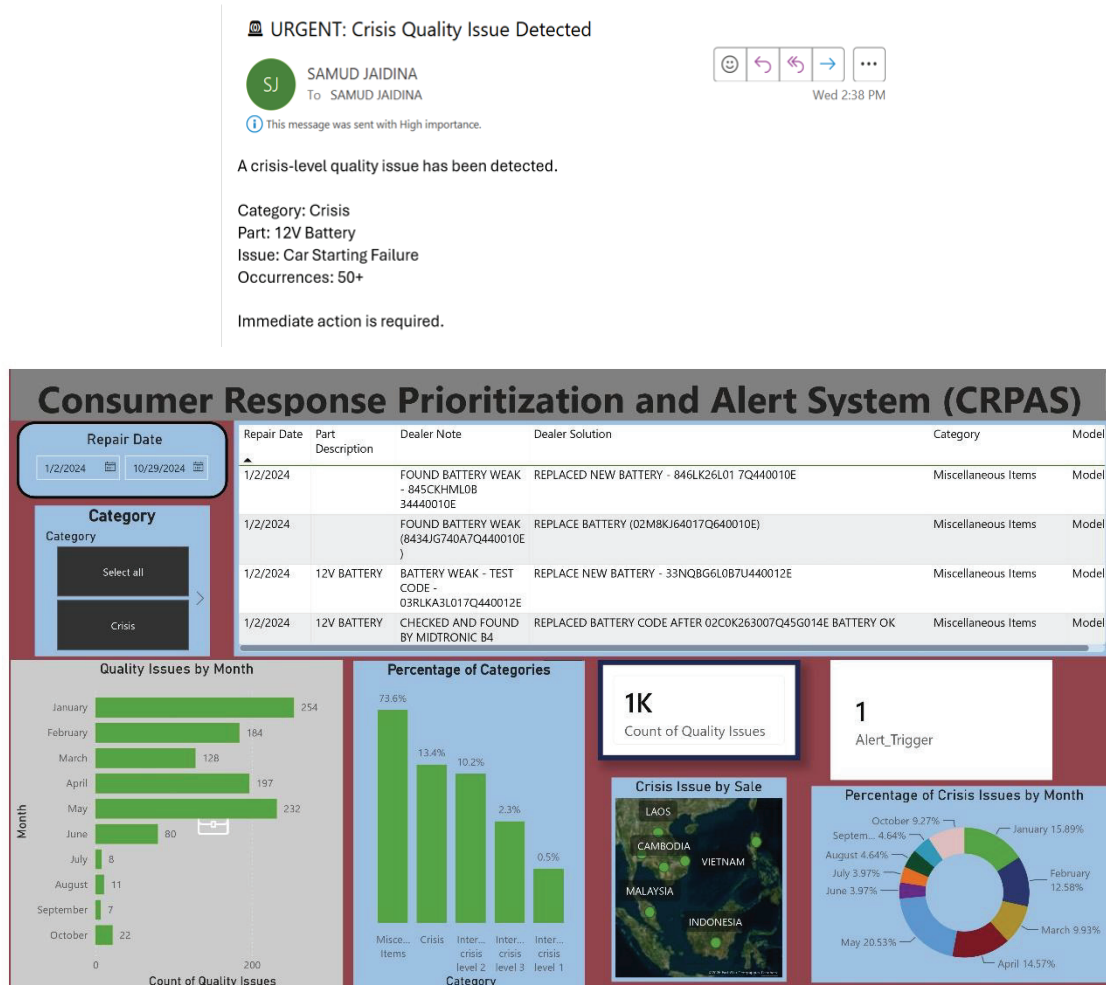


Fig. 3. Automated Email Alert System and Power BI Dashboard

Conclusions

Thus, study proposed a machine learning-based predictive framework for quality issue filtration in an automotive manufacturing company. The framework integrates data preprocessing, clustering analysis, classification modelling, dashboard visualization, and automated email notifications to support proactive quality management. The Random Forest classifier achieved the highest prediction accuracy of 97.4%, demonstrating its effectiveness in classifying quality issues. Furthermore, the implementation of Power BI visualization and automated alert mechanisms. The proposed framework demonstrates the practical integration of machine learning, business intelligence, and automated notifications for sustainable quality management in automotive manufacturing. The proposed framework contributes to data-driven

quality management practices and supports Industry 4.0 initiatives within the automotive manufacturing sector.

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Adaptive Parameters for Genetic Algorithm and Ant Colony Optimization in E-Commerce Last-Mile Delivery Optimization

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Abstract— The rapid growth of e-commerce has increased the need for efficient last-mile delivery, particularly for courier services that must visit many customer locations within a limited operational period. This study proposes an adaptive metaheuristic approach to optimize e-commerce delivery routes by comparing the Genetic Algorithm (GA) and Ant Colony Optimization (ACO) for a Travelling Salesman Problem (TSP) case involving 155 Shopee Express delivery points in Sawojajar, Malang. Adaptive parameter control was applied to important search parameters: pheromone evaporation rate, pheromone trail intensity, and visibility intensity in ACO, as well as crossover rate and mutation rate in GA. The algorithms were implemented in MATLAB using deterministic distance matrices and ten replications for each parameter configuration to obtain stable results. The findings show that adaptive GA produced the shortest route of 34,915 meters with a computation time of 5.44 seconds, while adaptive ACO produced the best route of 61,200 meters with a computation time of 172.51 seconds. These results indicate that adaptive GA provides better routing efficiency and computational performance for the investigated last-mile delivery case. The study contributes to information technology and logistics optimization by demonstrating how adaptive metaheuristic algorithms can support data-driven decision-making in e-commerce distribution.

Introduction

E-commerce logistics has become increasingly important as online purchasing behavior continues to grow and customers increasingly expect fast, reliable, and low-cost delivery services. In online retail, last-mile delivery plays a mediating role in shaping customer experience and satisfaction because it represents the final interaction between the delivery service and the customer [1]. Therefore, route planning becomes a critical operational decision in last-mile delivery, as courier movement directly affects delivery time, fuel consumption, service reliability, operational cost, and customer satisfaction.

The delivery routing problem in this study is formulated as a Travelling Salesman Problem (TSP), where a courier must depart from an origin point, visit each destination once, and return to the starting point while minimizing the total travel distance. TSP is widely recognized as a combinatorial optimization problem, and its complexity increases rapidly as the number of delivery locations grows [2]. Previous TSP studies have used exact, heuristic, and metaheuristic approaches; however, exact search becomes increasingly impractical for larger instances, making metaheuristic algorithms more suitable for obtaining high-quality solutions within reasonable computation time [3]. Among these methods, Ant Colony Optimization (ACO) is frequently used because it imitates the pheromone-based path-searching behavior of ants [4], while Genetic Algorithm (GA) is widely applied because it imitates natural evolution through selection, crossover, and mutation mechanisms [5].

Although ACO and GA have been widely used in routing and optimization problems, their performance strongly depends on parameter settings. Fixed parameters may produce good results in one problem instance but perform poorly in another. Therefore, parameter control is an important issue in evolutionary algorithms because it influences exploration, exploitation, convergence behavior, and the risk of being trapped in local optima [6]. In the context of routing optimization, adaptive ACO has been developed to improve the search process by dynamically adjusting algorithm parameters during the solution process [7]. Similarly, adaptive GA has been applied to TSP by optimizing crossover and mutation-related parameters to

improve solution quality [8]. Furthermore, parameter optimization in ACO has also been shown to improve TSP solution performance by selecting more suitable parameter configurations [9]. Based on this background, this study applies adaptive parameter control to both GA and ACO for optimizing e-commerce last-mile delivery routes.

Methodology

This research used a quantitative optimization approach. The dataset used in this study was an existing secondary dataset obtained from a previous delivery-routing study on Shopee Express in Sawojajar, Malang. The initial dataset contained 178 customer delivery points recorded for one courier delivery cycle. Data cleaning was then conducted by removing incomplete and duplicate delivery locations, resulting in 155 valid delivery points. Each delivery point was treated as a TSP node, and the distance between every pair of nodes was converted into a deterministic 155 x 155 distance matrix, resulting in 24,025 pairwise distance values. The matrix was constructed using Google Maps distance information and was treated as fixed during the optimization process. The optimization process was conducted using MATLAB, and each parameter configuration was executed in ten replications to reduce the influence of stochastic variation.

For ACO, the adaptive parameters were pheromone evaporation rate (ρ), pheromone trail intensity (α), and visibility intensity (β), while the initial pheromone value (τ), number of ants, and maximum iteration were treated as structural or fixed experimental settings. For GA, crossover rate (Cr) and mutation rate (Mr) were controlled adaptively, while population size and maximum generation were treated as structural parameters. The adaptive mechanism followed a deterministic progressive formula in which each selected parameter changes from its minimum to maximum value, or inversely from maximum to minimum value, according to the iteration or generation number.

The performance indicators were the best route distance and computation time. ACO was tested using eight parameter configurations based on ant number, iteration, and adaptive direction, as listed in Table 1. GA was tested using twelve configurations based on population size, generation, and adaptive direction, as listed in Table 2. The best solution from each algorithm was then compared to identify the most effective method for the delivery routing case.

Table 1. ACO parameter configurations

Cfg.	ρ	α	τ	β	Ants	Iterations
1	0.2-1	0.1-1	0.01	0.3-1	50	500
2	0.2-1	0.1-1	0.01	0.3-1	50	1000
3	0.2-1	0.1-1	0.01	0.3-1	100	500
4	0.2-1	0.1-1	0.01	0.3-1	100	1000
5	1-0.2	1-0.1	0.01	1-0.3	50	500
6	1-0.2	1-0.1	0.01	1-0.3	50	1000
7	1-0.2	1-0.1	0.01	1-0.3	100	500
8	1-0.2	1-0.1	0.01	1-0.3	100	1000

Table 1 presents the complete ACO experimental configurations used in this study. Each configuration combines the adaptive direction of ρ , α , and β with the selected number of ants and maximum iterations, while the initial pheromone value (τ) was kept constant at 0.01. Table 2 presents the complete GA experimental configurations used in this study. The configurations were arranged by combining the adaptive direction of crossover rate and mutation rate with three population sizes and two generation settings.

Table 2. GA parameter configurations

Cfg.	Cr	Mr	Population	Generations	Adaptive direction
1	0.1-1	0.01-0.2	30	800	Increasing
2	0.1-1	0.01-0.2	30	1000	Increasing
3	0.1-1	0.01-0.2	60	800	Increasing
4	0.1-1	0.01-0.2	60	1000	Increasing
5	0.1-1	0.01-0.2	90	800	Increasing
6	0.1-1	0.01-0.2	90	1000	Increasing
7	1-0.1	0.2-0.01	30	800	Decreasing
8	1-0.1	0.2-0.01	30	1000	Decreasing
9	1-0.1	0.2-0.01	60	800	Decreasing
Cfg.	Cr	Mr	Population	Generations	Adaptive direction
10	1-0.1	0.2-0.01	60	1000	Decreasing
11	1-0.1	0.2-0.01	90	800	Decreasing
12	1-0.1	0.2-0.01	90	1000	Decreasing

Results and Discussion

The optimization results show a clear performance difference between adaptive ACO and adaptive GA. For ACO, the best result was obtained in the first configuration with $\rho = 0.2-1$, $\alpha = 0.1-1$, $\tau = 0.01$, $\beta = 0.3-1$, 50 ants, and 500 iterations, producing a route distance of 61,200 meters. However, the ACO results were relatively sensitive to the number of ants and the direction of adaptive parameter change. Inverted adaptive directions generally produced longer routes, indicating that the search process can be disrupted when the exploration-exploitation balance is not properly maintained.

For GA, the best result was obtained in the twelfth configuration with $Cr = 1-0.1$, $Mr = 0.2-0.01$, population size = 90, and 1000 generations. This configuration produced the shortest route of 34,915 meters. The result indicates that a larger population and longer search duration can preserve genetic diversity and improve the probability of finding better route sequences. The adaptive reduction of Cr and Mr also suggests that strong exploration at the early stage followed by stronger exploitation at the final stage is effective for this case.

Table 3. Best performance comparison of adaptive ACO and adaptive GA

Algorithm	Best route distance (m)	Computation time (s)	Best configuration
Adaptive ACO	61,200	172.51	50 ants, 500 iterations, increasing adaptive direction
Adaptive GA	34,915	5.44	90 population, 1000 generations, decreasing adaptive direction

As shown in Table 3, adaptive GA outperformed adaptive ACO in both route distance and computation time. The GA route was 26,285 m shorter than the ACO route, representing a reduction of approximately 42.95%. GA also required substantially less computation time. This advantage may be related to the ability of GA to maintain population diversity while refining route sequences through crossover and mutation. In contrast, ACO performance was more affected by pheromone dynamics and ant population settings. Therefore, adaptive GA is more suitable for the investigated e-commerce last-mile delivery route optimization case.

Conclusion

This study demonstrates that adaptive parameter control can be used to improve metaheuristic search for e-commerce last-mile delivery route optimization. Based on the investigated Shopee Express delivery case, adaptive GA produced a shorter route and faster computation time than adaptive ACO. The best adaptive GA configuration achieved a route

distance of 34,915 meters and computation time of 5.44 seconds, while adaptive ACO achieved 61,200 meters and 172.51 seconds. The practical implication is that adaptive GA can support courier route planning and data-driven logistics decision-making. Future studies may extend the model by considering delivery time windows, traffic conditions, vehicle capacity, dynamic orders, and real-time integration with geographic information systems.

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Progressive Evaluation of Quaternary Census Transform for Robust Industrial Stereo Matching

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Abstract— Accurate depth estimation is a critical challenge in computer vision for industrial robotic navigation. This paper presents a local stereo matching pipeline evaluated under three different experimental configurations using the Middlebury benchmark dataset. The proposed framework utilizes the Quaternary Census Transform (QCT) for robust matching cost computation. In the first experiment, a multi-scale window approach for Cost Computation and Winner-Take-All (WTA) selection is evaluated. The second experiment introduces Cost Aggregation using Joint Bilateral Filtering to analyze the impact of spatial and radiometric scale parameters (σ_s and σ_r). Finally, the third experiment implements a comprehensive refinement stage incorporating quadratic sub-pixel interpolation, left-right consistency check, hole filling, and weighted least squares (WLS) post-filtering. Experimental results on Middlebury datasets demonstrate that the fully refined pipeline (Experiment 3) produces qualitatively superior disparity maps with reduced noise, filled occlusion holes, and better-preserved edges compared to baseline configurations, proving its efficacy for robust depth sensing applications.

Introduction

Passive stereo vision has emerged as a vital technology for enabling AGVs and robotic manipulators to perceive 3D environments accurately [1]. This paper evaluates the progressive performance of a local stereo matching framework under different architectural complexities using the Middlebury benchmark dataset, which serves as a standard test bed for quantitative evaluation [1], [2], [3]. The primary challenge lies in high sensitivity to radiometric noise, illumination variations, and textureless regions, which can introduce matching ambiguities and degrade navigation safety [1], [2], [3]. Prior work has explored various modifications to address these issues, including support window size optimization and advanced matching cost functions such as the Quaternary Census Transform (QCT), which utilizes quaternary signature vector digits to represent pixel differences more robustly at depth discontinuities than standard binary Census transforms [1], [2], [3], [4]. While individual methods show promise, existing literature lacks granular evaluation of how each sequential stage contributes to error reduction. To fill this gap, we have structured a systematic ablation study with three progressive MATLAB configurations. The baseline (Experiment 1) suffers from salt-and-pepper noise and blurry edges. Experiment 2 introduces Joint Bilateral Filtering to smooth textureless regions while preserving boundaries. The fully refined pipeline (Experiment 3) delivers optimal performance, producing visually cleaner disparity maps with significantly fewer artifacts across Middlebury datasets.

Methodology

The proposed local stereo matching framework is designed to balance computational efficiency and depth boundary accuracy, which is highly critical for real-time robotic perception. The architecture follows a multistage local processing pipeline implemented entirely in MATLAB.

Feature Extraction via Quaternary Census Transform (QCT)

We implement QCT to achieve radiometric invariance. For each pixel, the QCT evaluates intensity differences between the central pixel and its neighbors within a support window. Using a threshold $T = 0.5$, gradients are classified into four states (highly negative, slightly negative, slightly positive, highly positive), mimicking human visual contrast perception. The matching cost volume is generated via bitwise XOR operations between the quaternary-encoded left and right image strings.

Experimental Framework and Ablation Setup

To systematically evaluate the performance improvements contributed by each algorithmic block, the methodology is divided into three progressive experimental phases, as illustrated in Fig. 1.

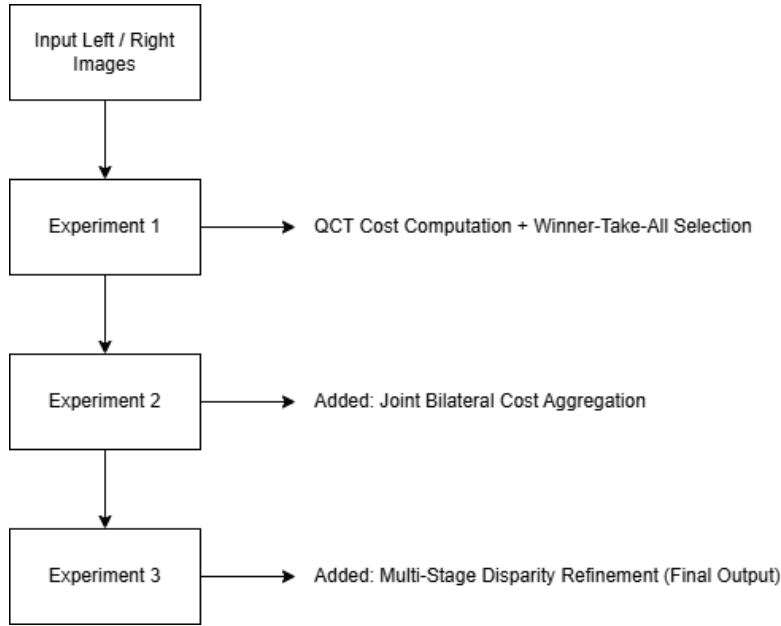


Fig. 1 Experimental phases

The baseline pipeline feeds the raw QCT cost volume directly into Winner-Take-All (WTA) optimization, which assigns disparity based on the minimum matching cost. This setup for Experiment 1 is evaluated across support window sizes of 3×3 , 5×5 , 7×7 , 9×9 , and 11×11 to analyze the trade-off between noise suppression and edge localization. To resolve matching ambiguities in textureless regions, Experiment 2 introduces a Joint Bilateral Filter that smooths the cost volume spatially while using the original color image as a structural guide. This ensures smoothing within uniform objects while stopping at object boundaries. The experiment evaluates the cooperative effect of spatial scale (σ_s) and radiometric scale (σ_r). Experiment 3 represents the complete, fully optimized pipeline. The coarse disparity map from the aggregation stage is passed through a sequential refinement pipeline:

- a. Sub-Pixel Interpolation: Quadratic curve fitting over discrete WTA costs to achieve fractional precision.
- b. Left-Right Consistency Check: Cross-checks left and right disparity maps; pixels with mismatch > 1 pixel are flagged as invalid occlusions.
- c. Hole Filling: Invalid pixels are filled by propagating the minimum valid disparity from the nearest background pixels.
- d. Weighted Least Squares (WLS) Filter: A final edge-preserving smoothing filter [3] realigns depth boundaries with the original guidance image. Fits a quadratic parabola curve over the discrete WTA costs to smooth out blocky quantization artifacts and achieve fractional depth precision.

A. Implementation Parameters

To ensure repeatability, the specific hyper-parameters embedded within the MATLAB code configuration are detailed in the table below:

Table 1: Algorithm Parameters

Algorithm Stage	Parameter Label	Variable Name	Default Value / Range
QCT Cost Computation	Threshold Tolerance	T	0.5
	Support Window Sizes	window_size	3 × 3 to 11 × 11 (Multi)
Joint Bilateral Filter	Radiometric Scale	σ_r	15
	Spatial Scale	σ_s	13
Post-Processing	Median Filter Radius	WMF_r	11
WLS Post-Filtering	Smoothing Smoothness	Lambda	12000
	Color Sensitivity	SigmaColor	1.2

Findings and Arguments

The empirical evaluation of the three progressive experimental configurations was conducted using the standardized Middlebury 'Teddy' benchmark dataset. This specific dataset presents a significant challenge for local stereo matching algorithms due to its extensive textureless regions (such as the flat background walls and uniform floor) and smoothly curved surfaces (such as the teddy bear body structure). All experiments were executed on an Intel Core i7-10700 CPU with 32 GB RAM at 640×480 resolution using a fixed 9×9 support window (mode='single'). Table 2 presents the runtime measurements for all three experimental configurations. The baseline pipeline (Experiment 1) completes in 8.66 seconds per frame. The introduction of Joint Bilateral Filtering (JBF) for cost aggregation, along with left-right consistency check and hole filling (Experiment 2), increases the runtime to 8.86 seconds. The fully refined pipeline (Experiment 3), which incorporates sub-pixel interpolation, guided filter denoising, and Weighted Least Squares (WLS) post-filtering, requires 8.94 seconds per frame, only 0.28 seconds slower than the baseline. These results demonstrate that the additional refinement stages add minimal computational overhead while contributing significant improvements to disparity quality, as evidenced in the qualitative analysis presented in the following subsection.

Table 2: Runtime Comparison Across Experimental Configuration

Configuration	Total Runtime (seconds per frame)
Experiment 1	8.66
Experiment 2	8.86
Experiment 3	8.94

While the full pipeline is not yet real-time on CPU, the runtime remains suitable for offline processing and industrial applications where depth accuracy is prioritized over frame rate. The Joint Bilateral Filtering component, which is executed per disparity level, is identified as the primary computational bottleneck and is a prime candidate for GPU acceleration in future implementations. Figure 2 presents the disparity maps generated by all three experimental configurations on the Middlebury Teddy dataset, alongside the ground truth for reference.

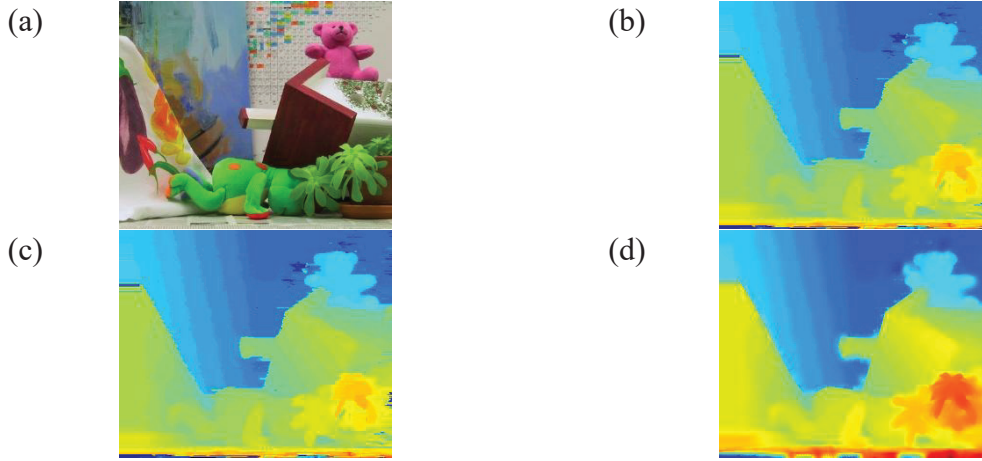


Fig. 2 Disparity maps on the Middlebury Teddy dataset: (a) Ground truth, (b) Experiment 1, (c) Experiment 2, and (d) Experiment 3

Brighter regions indicate larger disparity values (closer objects). The baseline (b) exhibits severe salt-and-pepper noise in textureless background regions and jagged object boundaries. Experiment 2 (c) shows reduced noise and smoother surfaces, though black holes remain at occlusion boundaries. The fully refined pipeline (d) produces the cleanest disparity map with virtually eliminated noise, filled occlusion holes, and sharply preserved object boundaries.

Experiment 1 (Figure 2b): The baseline pipeline produces a disparity map dominated by salt-and-pepper noise throughout the image. This noise is particularly severe in textureless regions such as the background walls and uniform floor areas. The teddy bear boundaries appear jagged and poorly defined, with stair-step artifacts on curved surfaces. These artifacts occur because the raw cost volume is used directly without any smoothing or refinement, making the algorithm highly sensitive to matching ambiguities in flat regions.

Experiment 2 (Figure 2c): The introduction of Joint Bilateral Filtering for cost aggregation significantly reduces noise in uniform regions. The background walls appear noticeably smoother, and the teddy bear structure becomes more recognizable. However, several limitations persist: black holes (invalid pixels) remain visible at occlusion boundaries, particularly around the teddy bear's arms and head where the left-right consistency check identifies mismatches. Additionally, stair-step quantization artifacts are still present on curved surfaces, indicating the need for sub-pixel precision.

Experiment 3 (Figure 2d): The fully refined pipeline produces the cleanest and most accurate disparity map among all configurations. Salt-and-pepper noise is virtually eliminated, occlusion holes are successfully filled using the background-priority filling strategy, and object boundaries are sharply preserved with clear delineation between foreground and background regions. Sub-pixel interpolation effectively removes stair-step artifacts, resulting in smooth depth transitions on the teddy bear's curved body surfaces. The WLS post-filtering further aligns depth boundaries with structural edges from the original guidance image, producing visually pleasing and physically plausible depth estimates.

These qualitative improvements from a noisy baseline to a clean, edge-preserved disparity map—confirm the efficacy of the proposed multi-stage refinement approach for robust depth estimation in challenging scenarios.

Results and Discussion

Support Window Size Selection (Experiment 1): While the multi-scale analysis (conducted separately) revealed that smaller windows (3×3 and 5×5) introduce excessive noise and larger windows (11×11) cause edge blurring, the fixed 9×9 window used in all three experiments provides a balanced trade-off between noise suppression and edge preservation. This window

size was empirically determined as optimal on the Teddy validation set. Benefits of Joint Bilateral Cost Aggregation (Experiment 2): The inclusion of JBF provides a substantial leap in visual quality compared to the raw baseline. By utilizing the original color image as a structural guide, the filter establishes cooperative smoothing between spatial scale ($\sigma_s = 13$) and radiometric scale ($\sigma_r = 15$). Cost data points are only aggregated if they share similar spatial proximity and color intensity, effectively preserving edges while smoothing uniform regions. Necessity of Multi-Stage Refinement (Experiment 3): While JBF cleans uniform surfaces, it still leaves discrete quantization steps and invalid black holes at occlusion boundaries. The multi-stage refinement successfully addresses these weaknesses:

1. Sub-pixel interpolation rounds off jagged stair-step artifacts on curved surfaces
2. Left-right consistency check and hole filling detect and reconstruct occlusion blind spots
3. WLS post-filtering performs final smoothing that realigns remaining pixels to object borders

Accuracy vs. Runtime Trade-off: The full pipeline requires only 0.28 seconds more than the baseline (8.94 s vs 8.66 s) while delivering substantially superior visual quality. This demonstrates that the refinement stages add minimal computational overhead while providing significant improvements in disparity quality. For real-time deployment, GPU acceleration of the Joint Bilateral Filtering component could reduce processing time to under 1 second per frame.

Conclusion

We systematically evaluated a QCT-based stereo pipeline across three configurations on the Middlebury dataset. Results show progressive visual improvements: from a noisy baseline to a clean, edge-preserved output via JBF and multi-stage refinement. The full pipeline achieves this at 8.94 seconds per frame, with minimal overhead over the baseline. Future work will focus on GPU acceleration of the JBF component to achieve real-time performance for industrial AGV deployment.

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Integration of Spatial and Temporal Data and Sentiment Analysis for Tourism Destination Management Optimization

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Abstract— This study aims to develop an integrated smart tourism platform named "dolanrek!" to support destination sustainability and cross-sector collaboration, particularly in addressing the challenges of overtourism in the Greater Malang and Probolinggo regions. As the initial phase of the mixed-methods approach employed, we have completed the collection and processing of spatial data and tourism information via Google Maps scraping. This process successfully extracted data on over 500 destinations, including names, categories, locations, ratings, and review counts, which were subsequently validated and deduplicated to ensure cross-source integration. To map tourist movement, visitor density data derived from the "popular times" feature was processed into hourly density metrics to create a more structured view of visitation patterns. Concurrently, over 16,000 tourist reviews were automatically collected. Following the preprocessing and destination matching stages, the reviews were analyzed using IndoBERT modeling. This text mining approach classifies tourist perceptions into positive, negative, and neutral sentiments, providing a comprehensive overview of satisfaction levels at each location. Currently, the entire database—encompassing tourism profiles, temporal density, popularity, and sentiment metrics, has been successfully integrated into a single master dataset. Future research will focus on advanced data processing and the development of the "dolanrek!" tourism UI/UX dashboard. This intelligent system is designed to display tourism recommendations, visualizations of visitor density patterns, and user experience insights, with the ultimate goal of sustainably alleviating congestion and optimizing destination management.

Introduction

The rapid growth of the tourism industry, particularly in emerging markets such as Indonesia, is frequently not counterbalanced by adequate infrastructural engineering readiness and destination governance capabilities. Malang Raya and Probolinggo are strategic regions in East Java that record massively fluctuating tourist visitations. Such dynamics trigger the risk of systemic imbalance, culminating in the threat of overtourism. This phenomenon has multidimensional implications, including mobility hindrances (traffic congestion), a decline in tourist comfort levels, and the escalation of ecological waste in destination hubs [1], [2].

To address these systemic disparities, a paradigm shift toward a smart tourism ecosystem has become an urgency. The practice of smart tourism emphasizes the integration of information systems architecture, big data analytics, the Internet of Things (IoT), and interface platforms to revolutionize the user experience [3]. At the technical level, the utilization of real-time data is considered essential for optimizing the efficiency of resource utilization and accurately monitoring the carrying capacity of tourist destinations [4], [5].

Despite the high urgency for digitalization, empirical evidence indicates that technology adoption at the regional level remains sluggish. A preliminary study in Blitar Regency in 2025 revealed that the adoption of tourism technology is limited to single-service instruments and static promotional media [6]. There is a notable absence of cross-sectoral frameworks or computational systems capable of processing tourist mobility data for destination density management. Addressing this gap, this study aims to develop an integrated platform prototype named "dolanrek!" as an end-to-end solution. By leveraging text mining algorithms, spatial extraction, and temporal analytics, the "dolanrek!" platform is projected to engineer visitation mobility and provide collaborative, cross-sectoral governance that supports sustainable tourism.

An integrated data architecture within the smart tourism concept is a crucial foundation for establishing sustainable smart tourism destinations. Accurate analytics can project mobility efficiency, control environmental anomalies, and provide a robust decision support system (DSS) for stakeholders [7], [8]. The processing of information from user-generated content (such as online reviews) is vital for designing superior services [3]. Natural Language Processing (NLP) algorithms, particularly those based on transformer architectures (e.g., IndoBERT), are implemented to classify tourism perceptions comprehensively, rapidly, and automatically by analyzing language specific to the Indonesian context.

Research Methodology

This study is based on a mixed-method approach modeled within a Research and Development (R&D) framework. The design process of the "dolanrek!" platform is divided into five operational system engineering phases as Fig. 1. This research only focuses up to stage 3.

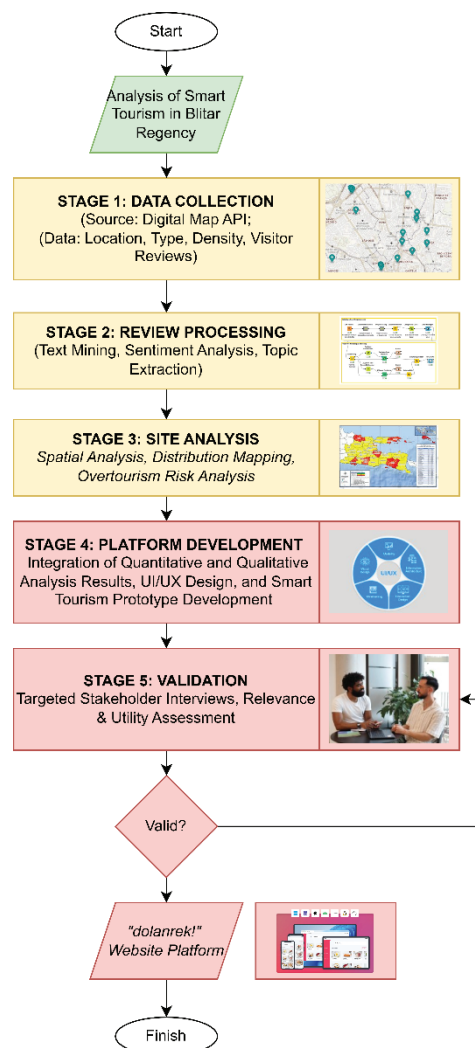


Fig. 2 Flowchart Research Methodology

1. Stage 1: Data Collection The first operational phase involves gathering empirical data utilizing a Digital Map API. The data collected encompasses the geographical locations of tourist sites, tourism typology, site density, and user-generated visitor reviews.
2. Stage 2: Review Processing Qualitative visitor data is then processed utilizing natural language processing (NLP) techniques. This stage applies text mining, sentiment analysis,

and topic extraction to derive meaningful insights regarding tourist perceptions and experiences.

3. Stage 3: Site Analysis In parallel with text analytics, physical site attributes are evaluated through spatial analysis and distribution mapping. A critical component of this stage is the overtourism risk analysis, which assesses the carrying capacity and sustainability of the identified destinations.

Results And Discussion

This section details the outcomes of the proposed smart tourism framework, highlighting its capabilities in spatio-temporal big data processing and IndoBERT-driven sentiment analysis. These integrated analytical results serve as the foundation for the "dolanrek!" platform, which is designed to mitigate overtourism and promote equitable economic empowerment across the region.

A. Spatio-Temporal Tourism Big Data Processing

Through massive-scale scraping techniques, the developed architecture has completed the identification and validation of a database comprising over 500 tourist destinations in the Malang Raya and Probolinggo corridors. The integration of density data based on popular times features was successfully modeled using hourly resolution time-series metrics. From an Industrial Engineering perspective, this modeling functions as an instrument for bottleneck mitigation and load-balancing. When the system detects peak hours at a specific tourism hub, the algorithm is prepared to recommend route engineering to destinations with under-utilized visitor capacities.

B. Sentiment Analytic Performance using IndoBERT

The application of text mining to 16,000 review data has been optimally calibrated. Summary of the datasets at Table 1. The IndoBERT model generates a holistic overview of customer satisfaction. This quantification maps not only the level of satisfaction with conventional services but also tourist sensitivity toward waste management (sustainability aspect) and socio-cultural interactions. This real-time measured sentiment supersedes the need for traditional physical surveys and accelerates the managerial response for local governments and local tourism operators.

Table 1: Statistic Descriptive of Datasets Variables

Variables	Count (N)	Mean	Standard Deviation	Minimum	Median (50%)	Maximum
density	4025	39.69	20.96	0	43.29	91.29
rating	4025	4.42	0.61	0	4.5	5
review_count	4025	44.2	6.06	0	45	50
popularity_score	4025	16.92	2.42	0	17.23	19.66
VDI	4025	0.41	0.14	0	0.43	0.74
Peak_Density	4025	93.72	14.96	0	100	100
Peak_Hour	4025	14.39	3.76	0	13	20
VDI_Available	4025	0.99	0.08	0	1	1
total_review	4025	36.58	18.7	0	49	50
negative	4025	0.09	0.12	0	0.06	1
neutral	4025	0.06	0.12	0	0.02	1
positive	4025	0.82	0.22	0	0.88	1
weighted_sentiment	4025	0.58	0.33	-0.04	0.72	1
Review_Available	4025	0.97	0.17	0	1	1

C. Integrated Architecture of "dolanrek!" and Cross-Sectoral Implications (Under Development)

The amalgamation of spatial variables, operational density, and satisfaction sentiments culminates in the development of the "dolanrek!" user interface (UI/UX) dashboard design. This smart platform is designed as a front-end that acts as a cross-sectoral collaboration support system. For end-users (tourists), the system provides precise insights regarding less-crowded tourism options to reduce massive carbon and waste production. Simultaneously, for supporting sectors (MSMEs and hospitality), the equitable distribution of tourists fosters economic empowerment (income smoothing) more evenly into areas that have not yet been reached by mainstream tourism.

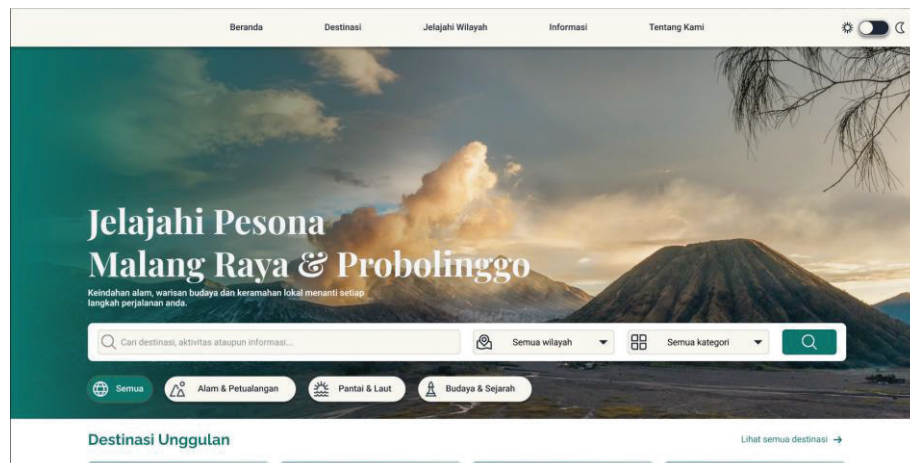


Fig. 2 Development of dolanrek! Platform

Fig. 2 displays the homepage interface of a web-based smart tourism platform designed to promote destinations across the Greater Malang and Probolinggo regions. The user interface features a visually engaging hero section with a high-quality landscape image and an inviting headline to attract prospective tourists. For intuitive navigation, the top bar includes standard menu links alongside a convenient toggle switch for light and dark viewing modes. A comprehensive search system is centrally located, allowing users to find specific destinations using text input, regional filters, and category dropdowns. Additionally, quick-access category buttons and a "Featured Destinations" section are provided below the search bar to further streamline the user's discovery process.

Conclusions

The adoption of the smart tourism paradigm in developing regions demands more than merely static service exhibition innovations. This concept requires the integration of large-scale analytics that orchestrate the mobility of logistical and human traffic. The "dolanrek!" integrated platform prototype has fundamentally succeeded in consolidating specific data from >500 spatial points, hourly temporal modeling, and 16,000 text mining classifications (IndoBERT). This interdisciplinary construction of Information Systems and Industrial efficiency management is capable of mitigating tourism operational congestion (overtourism), monitoring the impact of ecological waste, and mediating a tourism ecosystem that is pro-sustainability. The subsequent research phase will be directed toward optimizing live interface experiments on a larger user scale.

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Comparative Study of Classic RRT and RRT-Connect for Collision-Free Motion Planning of a UR10e Manipulator in Solar Cell Manufacturing

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Abstract— This study implements and compares the Classic Rapidly-exploring Random Tree (RRT) and RRT-Connect algorithms for collision-free motion planning of a Universal Robots UR10e manipulator across five simulated layouts representing solar cell manufacturing environments in MATLAB R2026a. Both algorithms were implemented using the manipulatorRRT planner from the Robotics System Toolbox, and a parameter analysis was performed by sweeping MaxConnectionDistance (step size) and ValidationDistance across 30 values each, with 10 repeated trials per value. Four performance metrics were evaluated: computation time, number of nodes explored, Cartesian path length, and planning success rate. Results show that RRT-Connect consistently outperformed Classic RRT across all five layouts, producing shorter path lengths, faster computation times, fewer nodes explored, and smoother trajectories, while both algorithms achieved a 100% planning success rate. Step size was found to be the more influential parameter, whereas ValidationDistance affected computation time only. These findings provide useful guidance for selecting efficient motion planning strategies for industrial robotic manipulators operating in constrained manufacturing environments.

Introduction

Automation is essential in the solar cell manufacturing industry, where robotic manipulators are widely used for wafer handling, stringing, soldering, and inspection due to the high precision and repeatability required when handling fragile silicon wafers [1]. As panel thicknesses continue to decrease, robots operate in increasingly dense and constrained production layouts, making collision-free motion planning a critical requirement prior to deployment. In Malaysia, growing investment in renewable energy, including initiatives such as the Solar for Rakyat Incentive Scheme (SolaRIS) [2], continues to drive demand for high-precision, automated solar cell production. Sampling-based motion planning algorithms, particularly the Rapidly-exploring Random Tree (RRT) and its variants, are widely used in industrial robotics because they can compute feasible paths in high-dimensional configuration spaces without requiring explicit obstacle modelling [3]. Among these, RRT-based planners remain the most widely adopted approach for industrial manipulators operating in cluttered, high-dimensional workspaces [4]. However, industrial robots still largely rely on predefined, static motion paths that lack the flexibility to adapt to layout changes, resulting in poor adaptability and increased reprogramming costs [5]. Testing new motion planning strategies directly on the factory floor is also costly and risky, as even small errors can damage fragile wafers. This study therefore develops a MATLAB-based simulation of a solar cell manufacturing environment, incorporating a UR10e manipulator and representative workspace obstacles, and implements Classic RRT and RRT-Connect to generate and compare collision-free trajectories under identical simulated conditions. Despite the widespread adoption of RRT-based planners, limited studies have systematically compared the influence of planner parameters on Classic RRT and RRT-Connect for industrial manipulators operating in solar manufacturing environments. The comparison aims to identify the more suitable planning strategy for collision-free robotic operation in constrained solar cell manufacturing environments.

Methodology

Five static-obstacle workspace layouts of increasing complexity were constructed in MATLAB R2026a using the Robotics System Toolbox, representing spatial constraints

commonly found in solar cell production, including a narrow passage, a ceiling constraint, two multi-height platform layouts, and an industrial multi-obstacle layout containing 25 collision objects (overhead pipes, a conveyor, wafer stacks, and tanks). A Universal Robots UR10e (Table 1) was selected as the manipulator model based on its payload, reach, repeatability, and native MATLAB support [6]. Classic RRT and RRT-Connect were both implemented through the manipulatorRRT planner, toggled using the EnableConnectHeuristic property, so that only the search heuristic differed between the two algorithms under otherwise identical conditions. Two planner parameters, MaxConnectionDistance (step size) and ValidationDistance, were each swept across 30 evenly spaced values from 0.01 to 0.30 rad, with 10 independent trials (distinct random seeds) per value, yielding 300 planning runs per algorithm per parameter sweep per layout. Four metrics were recorded for each run: computation time (tic/toc), number of nodes explored, Cartesian path length (from the tool-centre-point trajectory), and planning success. Mean and standard deviation were computed from successful trials, and results were exported and visualised as overlaid comparison plots for each layout.

Table 1 Simulation and algorithm configuration summary

Item	Specification
Robotic manipulator	Universal Robots UR10e (6-DOF, 1.3 m reach, 12.5 kg payload, ± 0.05 mm repeatability)
Algorithms compared	Classic RRT and RRT-Connect (manipulatorRRT planner)
Simulation layouts	5 layouts of increasing obstacle complexity
Parameter sweep	Step size & ValidationDistance: 0.01–0.30 rad, 30 values, 10 trials each
Performance metrics	Computation time, nodes explored, Cartesian path length, success rate

Results and Discussion

Qualitative inspection of the planned trajectories showed that Classic RRT produced visibly jagged, irregular paths in all five layouts, with the degree of jagging increasing with environment complexity, while RRT-Connect consistently produced smooth, direct trajectories regardless of obstacle density (Fig. 1). This is attributed to the bidirectional tree-growth strategy of RRT-Connect, which reduces unnecessary random expansions.

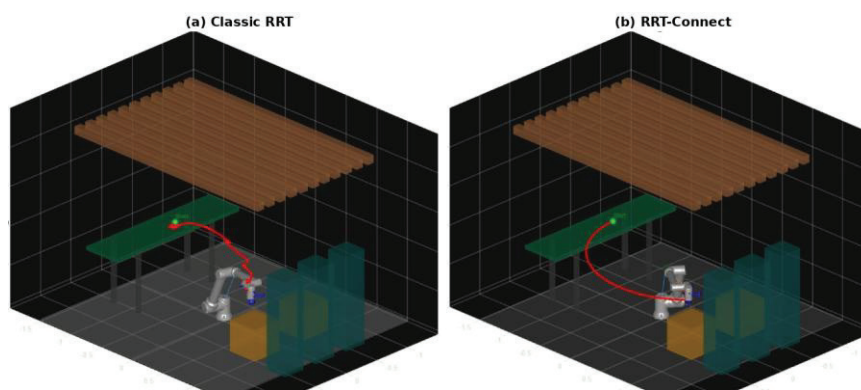


Fig. 1 Planned trajectories in the most complex layout (25 obstacles): (a) Classic RRT produces a jagged path; (b) RRT-Connect produces a smooth, direct path

The quantitative parameter sweep confirmed this advantage across all four metrics (Fig. 2). Across all layouts, RRT-Connect explored fewer than 20 nodes regardless of step size, whereas Classic RRT required up to ≈ 900 nodes at small step sizes, decreasing exponentially as step size increased (Fig. 2a). Computation time followed the same pattern: in the most complex layout, Classic RRT required up to ≈ 4.4 s at small step sizes, compared with under 1.0 s for

RRT-Connect throughout the sweep (Fig. 2b). Cartesian path length increased linearly with step size for both algorithms, but RRT-Connect consistently produced shorter, more repeatable paths, with markedly smaller standard deviation than Classic RRT (Fig. 2c). Both algorithms achieved a 100% planning success rate across all step size values (Fig. 2d). ValidationDistance had no measurable effect on nodes explored or path length for either algorithm, but produced an exponential decrease in computation time as its value increased, since fewer intermediate collision checks are performed per edge. Table 2 summarises the overall comparison for the most complex layout at the default operating parameters (step size = 0.15 rad, ValidationDistance = 0.03 rad).

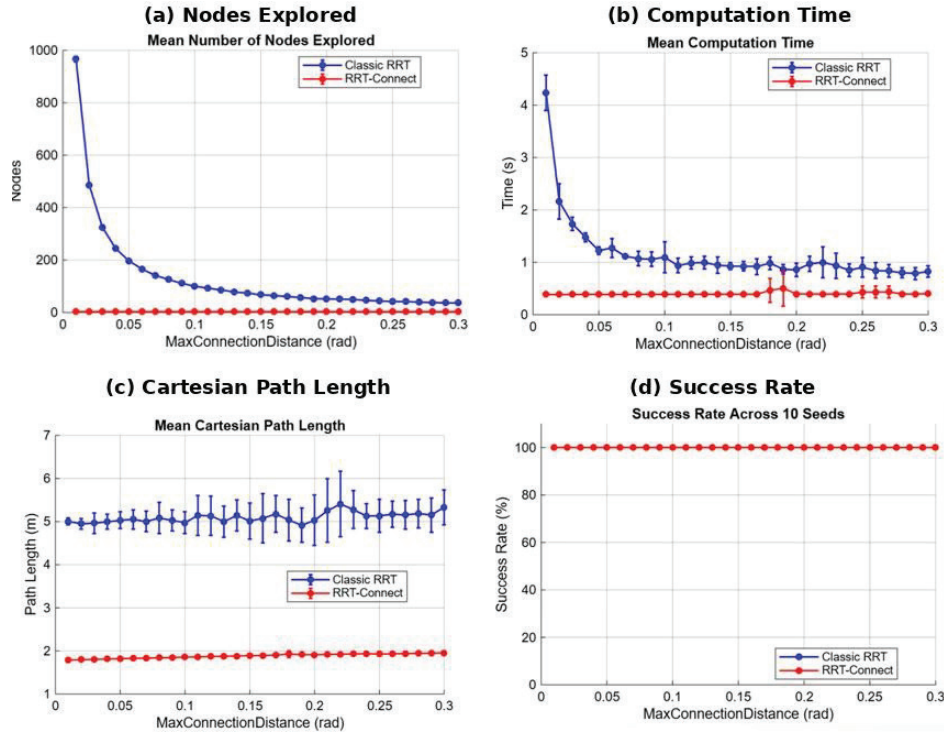


Fig. 2 Effect of step size (MaxConnectionDistance) on (a) nodes explored, (b) computation time, (c) Cartesian path length, and (d) planning success rate, in the most complex layout (blue: Classic RRT, red: RRT-Connect)

Table 2 Summary comparison of Classic RRT and RRT-Connect in the most complex simulated layout

Metric	Classic RRT	RRT-Connect
Nodes explored	Up to ≈ 900 (small step)	< 20
Computation time (s)	Up to ≈ 4.4	< 1.0
Path length	Longer, higher variability	Shorter, more consistent
Success rate	100%	100%

These findings are consistent with prior studies reporting RRT-Connect improvements for industrial manipulators, including reduced node counts and faster planning in fruit-pruning and emission-sampling arm applications [7], [8], and improved path planning performance in constrained industrial settings [9]. The pronounced sensitivity to step size observed for Classic RRT is also consistent with reported behaviour of other RRT variants in structured environments [10], while the overall performance gap between single-tree and bidirectional planners aligns with broader comparative reviews of sampling-based motion planning algorithms [11], [12].

Conclusion

This study demonstrated that RRT-Connect consistently outperformed Classic RRT for collision-free motion planning of a UR10e manipulator across five simulated solar cell manufacturing layouts, producing shorter paths, faster computation times, fewer explored nodes, and smoother trajectories, while both algorithms achieved a 100% planning success rate. Step size was identified as the more influential planner parameter, while ValidationDistance affected computation time only. RRT-Connect is therefore recommended as the preferred motion planning algorithm for collision-free robotic operation in solar cell manufacturing, where planning efficiency and trajectory smoothness are critical.

This study is limited to a simulation-based comparison of only two planners, without statistical significance testing beyond descriptive mean and standard deviation. Additionally, the five layouts, while inspired by solar cell manufacturing constraints, have not been validated against an actual production line. Future work will therefore (1) apply statistical significance testing (e.g., ANOVA or the Wilcoxon rank-sum test) to confirm that the observed performance differences are not due to chance, (2) benchmark against additional motion planners such as RRT*, Bi-RRT*, and PRM to position Classic RRT and RRT-Connect within the broader planning landscape, (3) verify the geometric and dynamic realism of the simulated layouts against actual production conditions, and (4) validate the findings through implementation on a physical UR10e platform, extending the framework to dynamic obstacles and multi-arm coordination to assess real-world applicability.

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INTEGRATED FRAMEWORK OF DISCRETE EVENT SIMULATION TECHNOLOGIES WITH DATA REPOSITORY FOR MATERIAL HANDLING SYSTEM

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Abstract— The integration of simulation technologies with data management has become increasingly important in supporting data-driven decision-making within material handling systems. This study proposes a Discrete Event Simulation (DES) model of a Material Handling System (MHS) that accurately represents the operational behaviour and interaction of system components. It implements data bridging mechanisms for real-time and structured data transfer to a centralized data repository, ensuring reproducibility of analyses performed on the obtained data. This study also evaluates the performance of data acquisition from MHS system components for decision-making and analysis.

Introduction

The integration of simulation technologies with centralized data management systems has become increasingly important in supporting data-driven decision-making within modern Material Handling Systems (MHS). However, many Discrete Event Simulation (DES) models operate independently from database platforms, limiting real-time data accessibility, traceability, and analytical capabilities. Integrating DES with a data repository enables simulation data to be stored, managed, and analysed efficiently, thereby improving system monitoring and supporting informed operational decisions. This study presents an integrated framework that combines DES with a centralized data repository for the MHS at the faculty laboratory. The research develops a simulation model of the laboratory system and establishes data connectivity between the simulation environment and a centralized data management platform. The integration enables systematic acquisition, storage, and management of operational data while supporting efficient data visualization and analysis. Furthermore, the integrated framework enhances data accessibility, traceability, and consistency, providing a foundation for performance evaluation and data-driven decision-making in material handling systems. The objectives of this study are to: (1) develop a DES model of a MHS that accurately represents the operational behaviour and interaction between system components; (2) integrate a data bridging mechanism between the DES environment and a centralized data repository, enabling real-time and structured data transfer; and (3) evaluate the performance of the Rail Guided Vehicle (RGV) and ABB robotic arm based on operational data acquired through the integrated data acquisition system. The scope of this study is limited to the Schmid Montrac Arena laboratory, involving three RGVs and one ABB robotic arm. The developed DES model represents the operational logic and material flow of the selected laboratory components.

Literature Review

The Fourth Industrial Revolution (IR4.0) represents a paradigm shift in manufacturing, integrating physical processes with cyber systems. However, practical implementation is often hindered by a gap between academic research and industrial application, with challenges arising from both managerial and technological perspectives [3]. Dobrzańska and Dobrzański [2] demonstrate the application of DES to create digital twins for intralogistics, enabling real-time monitoring and optimization of performance. This is crucial for complex systems, such as automated material handling, where high-fidelity simulation models are essential for effective

decision-making. Kang et al. [5] highlight a critical challenge: inherent uncertainty and potential bias in digital twin models can lead to inaccurate representations of physical systems, necessitating sophisticated calibration to ensure credible decision-making [5]. Complementing simulation, the Internet of Things (IoT) serves as a primary source of vast operational data. The integration of IoT with data analytics enables the extraction of valuable insights from connected devices, which is transformative for industries like manufacturing and logistics [1]. However, this integration faces significant hurdles, including issues related to data privacy, security, interoperability, and scalability [1].

To manage and preserve simulation and IoT-generated data effectively, structured data repositories are essential. Weise and Rauber [4] developed DBRepo, a system specifically designed to manage research data in databases, addressing the data lifecycle, versioning, and citation for long-term data reuse and reproducibility [4]. DBRepo supports automated versioning of relational data, temporal SQL, and query-based citation of arbitrary subsets of data, implementing the recommendations of the RDA Working Group on Dynamic Data Citation for the precise identification of arbitrary data subsets [7], recommendations that have since been adopted across a wide range of data infrastructures [8]. Compared with generic Database-as-a-Service or cloud-hosted database systems, DBRepo adds curation functionality on top of standard database storage, including semantic mapping of attributes to improve Findable, Accessible, Interoperable, and Reusable (FAIR) and export paths such as Software Independent Archiving of Relational Databases (SIARD) for long-term preservation.

Methodology

A Discrete Event Simulation (DES) model was developed using Siemens Tecnomatix Plant Simulation 2404 to replicate the Schmid Montrac Arena Material Handling System at the UTeM laboratory. The model includes three RGVs operating on predefined paths and an ABB robotic arm performing pick-and-place operations, as summarised in Table 1. Key operational parameters for this study working time, idle time, travel distance, and power consumption are collected using SimTalk commands executed at 10-second intervals. The model was validated before proceeding to data transfer.

Table 1: RGV and ABB robotic arm workflow at Schmid Montrac Arena Material Handling System

MHS item	Assigned Task	Route Sequence	Description
RGV 1	Transport material from aisle 2 to point C at aisle 3	Aisle 1 – Buffer in – Buffer out – C junction left – Aisle 3 – point C – Aisle 2	Handle material to point C
RGV 2	Transport material from point B at aisle 3 to aisle 2	Aisle 2 – Aisle 3 – point B – C junction right – Aisle 2	Handling material to aisle 2
RGV 3	Transport material at aisle 3 from point A to point D	Aisle 3 – point A – point D – point A	Handle material to point D
ABB robotic arm	Pick material at RGV 2 and place to RGV 1	RGV 2 – RGV 1	Pick and place the material between two RGVs

A data bridge was established using Python scripts embedded within the simulation environment. Simulation data is transferred to the DBRepo repository through automated CSV generation and HTTP requests, following the table schema shown in Table 2. A Generator object executes the Python script at one-minute intervals, enabling near real-time data synchronization. DBRepo additionally provides dataset versioning, query-based citability, and semantic mapping of attributes. Data from DBRepo storage systems is retrieved using Python

scripts within a Jupyter Notebook environment, loaded into Pandas DataFrames for analysis, and visualized using Matplotlib and Seaborn.

In the current implementation, data is exported to CSV before being imported into DBRepo. DBRepo also exposes an API that would allow writing directly from a Pandas DataFrame, and a REST-API / message-queue (RabbitMQ) based feed would offer lower latency and remove the intermediate export step; both are identified as improvements for a future iteration of the pipeline. To improve the FAIRness of the stored data, semantic mappings were considered for the DBRepo table definitions, linking the units of measurement in Table 2 (metres, seconds, kWh) to ontology terms from the SI Digital Framework, with the “Quantities and Units” ontology as a fallback where no SI Digital Framework term applies.

Table 2: Database table schema for the local MariaDB instance and DBRepo repository

Name	Data Type	Defaults	Extra
Data Time	Datetime	Timestamp	–
Id	Integer	–	Auto-increment
rgv_id	Variable Character	–	Size = 255
rgv_travel (m)	Decimal	–	Size = 30, decimal = 3
rgv_working (sec)	Integer	–	Size = 255
rgv_stop (sec)	Integer	–	Size = 255
abb_operational_time (sec)	Integer	–	Size = 255
Abb_working_power (kWh)	Decimal	–	Size = 30, decimal = 3
abb_operational_power (kWh)	Decimal	–	Size = 30, decimal = 3

Figure 1 illustrates the data integration framework implemented for the discrete event simulation (DES) system. The simulation model is developed in Siemens Tecnomatix Plant Simulation 2404, where operational data are generated and stored in a data table. A Python script is used as the data bridging mechanism to extract the simulation data, import live data set using AMQP and exporting the data in CSV format for uploading to DBRepo. Finally, Jupyter Notebook, executed through the Anaconda environment DBRepo for data visualization, analysis, and performance evaluation. This framework enables automated data acquisition, centralized data storage, and efficient processing of simulation data for decision-making and performance assessment.

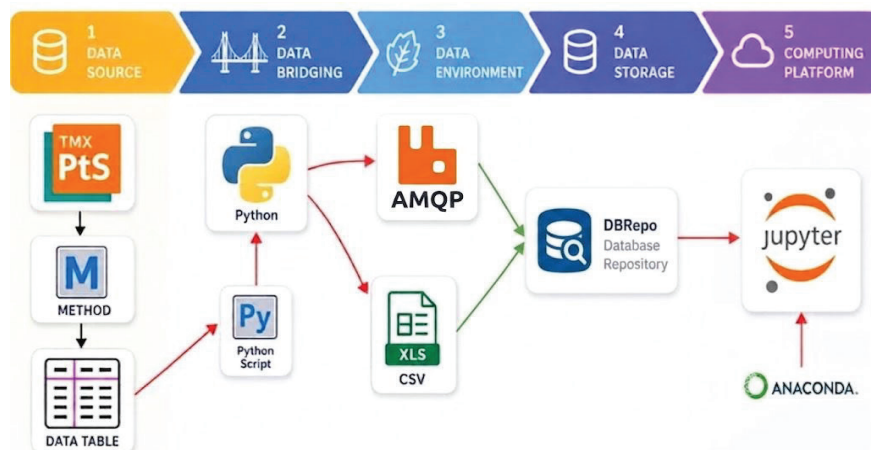


Fig. 1 Data Integration Framework for Connecting Tecnomatix Plant Simulation with Data Repository and Analytics Platform

Result and Discussion

The DES model was successfully developed using Siemens Tecnomatix Plant Simulation 2404, accurately replicating the operational behaviour of the Schmid Montrac Arena Material Handling System. The model comprises three RGVs operating on predefined rail paths governed by event-based, sensor-triggered logic, complemented by an ABB robotic arm performing automated pick-and-place operations. The simulation effectively captured critical operational parameters including working time, idle time, travel distance, and power consumption, validating its capability to represent system component interactions.

The data bridging mechanism was successfully implemented through Python scripts embedded within the DBRepo was achieved through automated CSV generation and HTTP requests, with the Generator object executing the script at one-minute intervals to facilitate near real-time synchronization. Data validation confirmed perfect consistency across all performance metrics with DBRepo. Value lies in confirming that the transfer pipeline introduces no data loss or corruption, which is a necessary precondition for treating DBRepo-hosted data as a trustworthy, citable copy of the simulation output.

The operational performance was evaluated through data acquired from the integrated system using Jupyter Notebook, presented in Figure 2, which illustrates the distribution of the working, stop, and travel states for the three RGVs in the Schmid Montrac Material Handling System. Notably, RGV 2 shows a slightly broader distribution in travel distance compared to RGV1 and RGV3, suggesting more frequent or longer-distance movements. This reflects its role in connecting the critical zone in the layout, while the stop-state densities remain consistently low across all RGVs, implying minimal idle time.

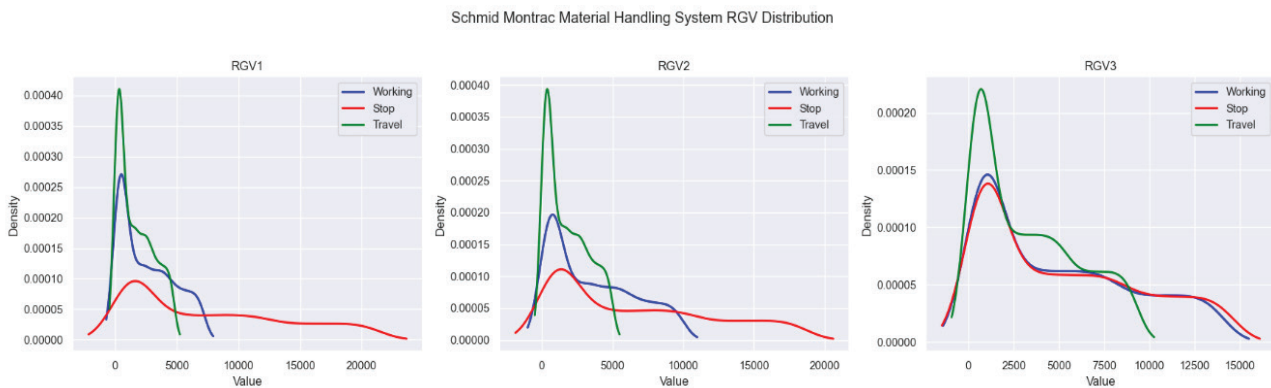


Fig. 2 Distribution of RGV Operational States for Three RGVs in the Schmid Montrac Material Handling System [D2]

Based on Figure 3, the distribution for the ABB robotic arm reveals two distinct operational regimes. The mean operational power of 5.84 kWh substantially exceeds the mean work power of 0.99 kWh, resulting in a work-to-operational power ratio of just 0.17. This indicates that approximately 83% of the energy input is dissipated as overhead rather than contributing to productive output.

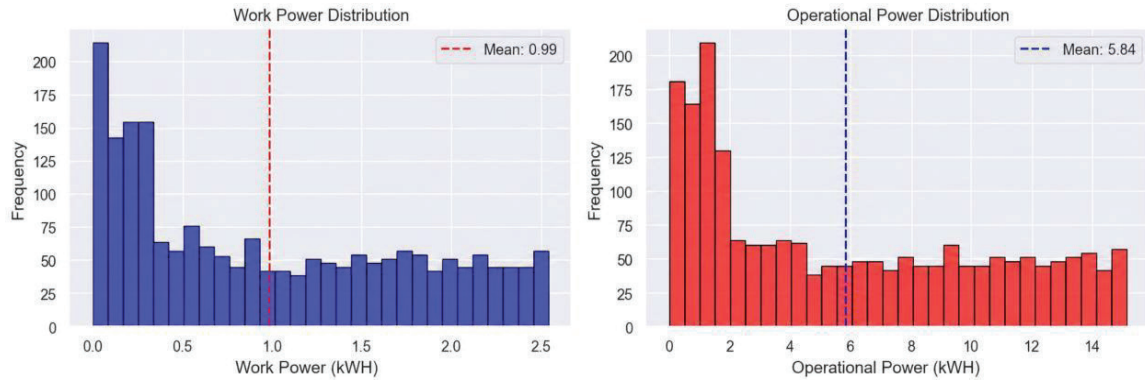


Fig. 3 Distribution of Work Power and Operational Power Consumption of the ABB Robotic Arm [D3]

Figures 2 and 3 are generated from a query over a subset of the accumulated simulation data rather than every simulation run ever performed. To preserve the citability and reproducibility benefits that motivate the use of a data repository, the underlying queries have been stored in DBRepo's query store and assigned persistent identifiers, listed under Supporting Material at the end of this paper (datasets D1–D3).

Conclusion

This study demonstrates an integrated framework combining Discrete Event Simulation with a centralized data repository through automated data bridging. All three objectives were achieved: the DES model was developed and validated, the data bridging mechanism was implemented, and the operational performance of the RGVs and ABB robotic arm was evaluated using data retrieved through the integrated pipeline.

The findings support three observations: (1) high-fidelity DES models can accurately replicate material handling operations; (2) Python-based data bridging enables reliable data synchronization across the local database and DBRepo, with the observed cross-database consistency confirming pipeline integrity; and (3) the ABB robotic arm's operational power consumption (mean: 5.84 kWh) substantially exceeds its working power (mean: 0.99 kWh), highlighting energy optimization opportunities through improved idle-state management.

Limitations include model simplification and reliance on simulation-derived rather than empirical data. Future work should also complete the semantic mapping of measurement units to SI Digital Framework ontology terms, extend the framework from a cyber-physical system to database applications in industrial settings, and develop web-based dashboards for real-time monitoring. The foundational framework provides a solid basis for advancing smart manufacturing and data-driven decision-making in material handling systems.

Acknowledgment

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Supporting Material: Datasets

Note: the persistent identifiers (PIDs) below are placeholders to be replaced once the corresponding queries are registered in DBRepo's query store.

- [D1] Event Simulation Database for the Schmid Montrac Handling System, UTeM, 2026. PID: <https://dbrepo.utem.edu.my/pid/cd0fcfa9-12ee-4b1a-bd50-8351b6578eaa>
- [D2] Distribution of RGV Operational States for event run / time period of x–y, extracted from [D1]. PID: <https://dbrepo.utem.edu.my/pid/1bce892a-4dc6-4334-baff-8fb2cd57d24d>
- [D3] Distribution of Work Power and Operational Power Consumption of the ABB Robotic Arm for event run / time period of x–y, extracted from [D1]. PID: <https://dbrepo.utem.edu.my/pid/e739e5b2-56f1-47ea-a17c-c4f80a417247>

Experimental State-of-Charge Determination of a 48 V Ternary Lithium-Ion Battery Using Discharge and Rested OCV Data

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Abstract— Reliable state-of-charge (SoC) estimation is important for battery-powered systems, yet commercial SoC indicators may offer limited flexibility for embedded applications. This study aimed to determine the usable capacity of a 48 V ternary lithium-ion battery and develop an experimental open-circuit-voltage–SoC (OCV–SoC) lookup table. The battery was discharged at 1.0 A in 0.3 Ah increments using a THINKCAR CE EVP902 analyzer. After each increment, the battery was rested for 20 minutes before OCV, and surface temperature was recorded. The experimentally measured usable capacity was 1.4 Ah, while the rested OCV decreased from 52.55 V at 100% SoC to 44.0 V at 0% SoC. The resulting lookup table provides a simple battery-specific method for approximating SoC and is suitable for implementation in embedded and microcontroller-based battery-monitoring systems.

Introduction

Lithium-ion batteries (LiBs) are widely used in electric and hybrid vehicles, stationary energy storage, and portable equipment because of their high energy density and favorable power-to-weight ratio. In 48 V vehicle architectures, reliable battery-state information is required for power management, range or runtime prediction, protection, and safe use of the available energy [1], [2]. State-of-charge (SoC) is therefore a key input to the battery management system (BMS), because an inaccurate estimate may lead to premature shutdown, underutilization, or excessive discharge [1], [3]. Common SoC-estimation approaches include Coulomb counting, open-circuit-voltage (OCV) mapping, equivalent-circuit models with Kalman-filter variants, and machine-learning methods [2]–[6]. Coulomb counting is simple but accumulates current-sensor and initial-SoC errors. Model-based filters can operate under dynamic load, but their accuracy depends on parameter identification and OCV-model quality. Machine-learning models can represent nonlinear behaviour but generally require larger datasets, memory, and processing capacity [2], [6]. For low-cost microcontrollers, a battery-specific OCV lookup table remains attractive because it requires only voltage measurement, stored calibration points, and simple interpolation.

The OCV–SoC relationship is affected by chemistry, temperature, ageing, hysteresis, and voltage relaxation [7]–[13], so a generic commercial indicator may not represent a particular pack. Rested measurements reduce the immediate ohmic drop and part of the slower polarization response, although short rest periods provide only quasi-equilibrium OCV [10]–[13]. Previous studies have proposed generalized curve fitting, temperature-dependent maps, reduced-time protocols, and advanced adaptive estimators [4]–[9]. However, limited battery-specific data are available for simple implementation on a low-cost 48 V pack using readily accessible discharge equipment. The contribution of this work is therefore not a new SoC algorithm, but an experimentally derived, microcontroller-ready OCV–SoC table for the tested 48 V ternary pack, together with a transparent assessment of its usable capacity and limitations. This work provides an experimentally calibrated OCV–SoC lookup table that can be implemented in resource-constrained battery-monitoring systems using voltage measurement and simple interpolation.

Methodology

The tested battery pack was constructed from 18650 ternary lithium-ion cells, each rated at 3.7 V and 1,800 mAh, arranged in a 13-series, 2-parallel (13S2P) configuration. This configuration provided a nominal pack voltage of 48.1 V, commonly designated as 48 V, and a nominal capacity of 3.6 Ah. The battery pack was tested using a THINKCAR CE EVP902 battery discharge analyser (model TKEP92). The battery was charged using its dedicated charger, rated at 54.6 V and 2.0 A, until the charger status indicator changed from red to green. The battery was then disconnected from the charger and allowed it to rest for 20 minutes before the initial OCV, and battery surface temperature were measured using an infrared thermometer. The Li-ion battery was subsequently discharged at a constant current of 1.0 A. Discharge was carried out in increments of 0.3 Ah. After each 0.3 Ah increment, the discharge current was stopped, and the battery was allowed to rest for 20 minutes before the OCV and temperature were again measured. The voltage was recorded at the end of the rest period rather than immediately after the current was interrupted.

The resting period was introduced to allow the terminal voltage to approach a quasi-equilibrium condition [10]-[12]. Immediately after the discharge current is interrupted, the terminal voltage changes rapidly due to the removal of the ohmic voltage drop, followed by a slower relaxation process associated with electrochemical polarization and lithium-ion diffusion [13]. To reduce the influence of these transient effects, the battery was rested for 20 minutes after each discharge interval before the voltage was recorded. Previous work has shown that longer relaxation periods can improve OCV characterization and battery-model parameter identification, but they also substantially increase the total experimental duration [14]. Therefore, the 20-minute interval was adopted as a practical compromise between voltage relaxation and testing time. Since complete electrochemical equilibrium was not independently verified, the measured voltages are referred to as rested or quasi-equilibrium OCV values, and the resulting OCV–SoC lookup table is specific to the adopted 20-minute rest protocol. The discharge-and-rest procedure was repeated until the battery could no longer continue discharging or the lower voltage protection limit was reached. The SoC at each measurement point was calculated from the removed charge relative to the experimentally measured usable capacity as shown in Eq (1):

$$SoC(\%) = \left(1 - \frac{Ah_{\text{removed}}}{C_{\text{usable}}}\right) \times 100 \quad (1)$$

where Ah_{removed} is the cumulative discharged capacity and C_{usable} is the total experimentally measured usable battery capacity. The measured OCV values were then correlated with the corresponding SoC values to develop an experimental OCV–SoC lookup table for the 48 V ternary lithium-ion battery. The experimental setup and battery-temperature measurement are shown in Fig. 1.

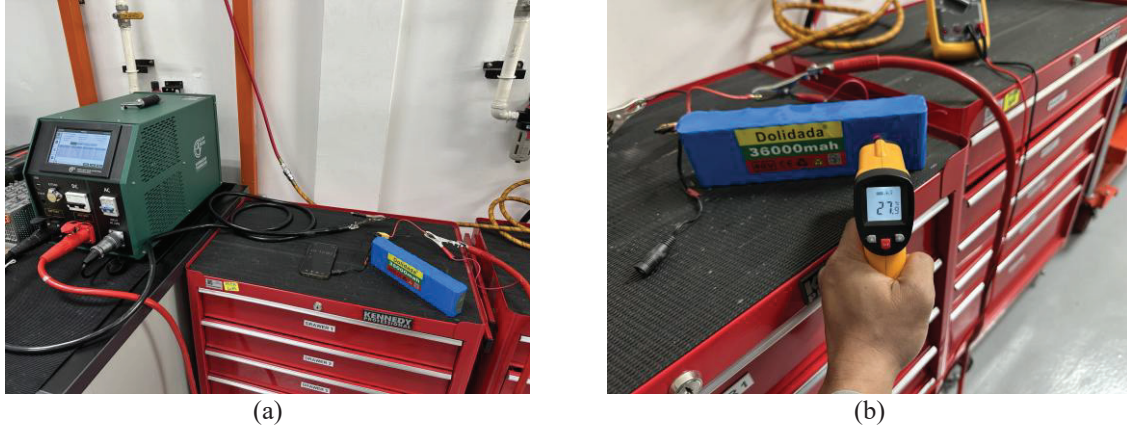


Fig. 1 Experimental setup for 48V battery discharge test (a) battery connected to the discharge analyser (b) battery surface temperature measurement

The experiment was repeated three times at a constant discharge current of 1.0 A. Repeatability was evaluated by comparing the measured usable capacity, rested OCV values, and overall discharge-curve trend between the repeated tests. The usable capacities obtained were 1.4 Ah, corresponding to a variation of 27%. The rested OCV measurements also showed a consistent decreasing trend with SoC. Preliminary tests at discharge currents above 1.0 A resulted in earlier activation of the string low-voltage limit. Consequently, 1.0 A was selected for the final characterisation.

Results and Discussion

The results demonstrate the typical discharge behavior of a Li-ion battery, in which the terminal voltage decreases gradually before dropping sharply near the end of the discharge (EOD) period [15]. The measured OCV and battery surface temperature at each discharge step are summarized in Table 1. The corresponding SoC was calculated using Eq. (1) based on the cumulative discharged capacity. For example, after 0.3 Ah had been removed, the SoC was calculated as:

$$\left(1 - \frac{0.3 \text{ Ah}}{1.4 \text{ Ah}}\right) \times 100 = 78.6\% \quad (2)$$

The measured usable capacity is important because it defines the practical 100–0% SoC operating range of the tested battery before the string low-voltage protection limit is activated. In this study, the measured usable battery capacity, C_{usable} of 1.4 Ah was used as the reference value for calculating SoC at each discharge step. The corresponding OCV–SoC relationship then provides a direct means of relating the rested terminal voltage to the remaining usable charge. Consequently, the developed lookup table represents the actual tested condition of the battery rather than relying solely on its nominal or labelled capacity.

Table 1: Experimental OCV–SoC lookup table

Step	Capacity Discharged (Ah)	Rest Interval (min)	Open Circuit Voltage (V_{oc})	SoC (%)	Battery Temperature ($^{\circ}\text{C}$)
0	0.00	20	52.55	100	27.2
1	0.3	20	52.00	78.6	25.5
2	0.6	20	51.00	57.1	25.0
3	0.9	20	50.21	35.7	23.7
4	1.2	20	49.13	14.3	24.3
5	1.4 (String Low Limit reached)	20	44.0	0	25.0

The measured battery surface temperature remained within a relatively narrow range of 23.7–27.2°C, with no progressive increase during the discharge test. This indicates that the 1.0 A discharge condition did not produce substantial observable surface heating. The experimental OCV–SoC lookup curve measured after a 20-minute rest at each capacity-removal step is shown in Fig. 2. The OCV decreases gradually with decreasing SoC before dropping sharply at the string low-voltage limit. This behavior represents the end-of-discharge knee, where the remaining usable capacity is minimal and the weakest cell in the series string approaches its lower protection threshold. Increased polarization, internal resistance, and possible cell imbalance contribute to the pronounced voltage reduction, triggering discharge termination to prevent over-discharge.

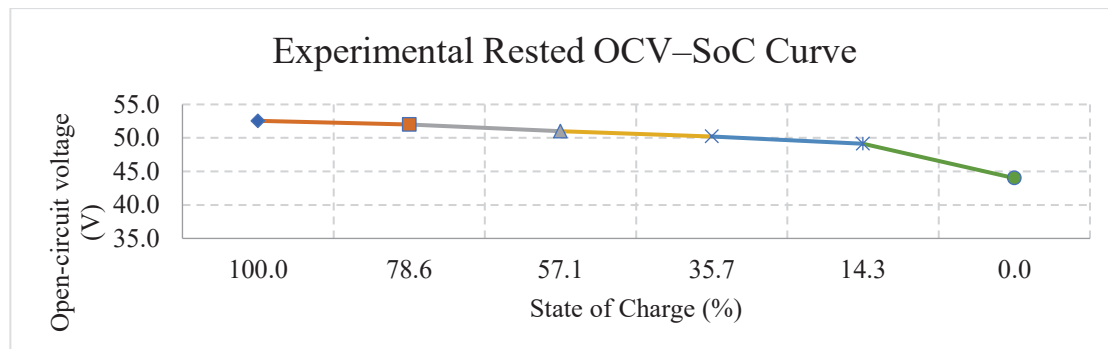


Fig.2 Experimental OCV–SoC lookup curve measured after a 20 min rest at each capacity-removal step

For embedded implementation, the measured OCV–SoC pairs can be stored as calibration points in microcontroller memory. The method has low computational and memory requirements because it uses voltage measurement, lookup operations, and simple interpolation

Conclusion

A rested OCV–SoC lookup table for a nominal 48 V ternary lithium-ion battery was successfully developed through controlled constant-current discharge testing. The experimentally measured usable capacity of the battery was found to be 1.4 Ah, and this value was used as the reference capacity for calculating SoC at each discharge step. The main practical contribution is a transparent, low-computation calibration that can be implemented with breakpoint comparison and linear interpolation. However, the lookup table is valid for the tested battery and experimental conditions, including the 20-minute rest period. Future work should repeat the test over multiple cycles and packs, log charging and cell voltages, compare 20 min OCV with longer rest periods, quantify interpolation error against a reference method, and develop temperature- and ageing-indexed lookup tables under different discharge currents.

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Scientific Machine Learning in Aerospace Engineering: A Bibliometric Analysis of Research Trends, Applications and Emerging Frontiers (2017–2026)

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Abstract— Scientific Machine Learning (SciML) combines machine learning techniques with the underlying physical laws to solve difficult scientific and engineering problems. SciML is getting more and more attention in aerospace engineering, for use in computational fluid dynamics, digital twins, predictive maintenance, and autonomous systems. However, although the field is growing fast, there is limited comprehensive understanding of its research landscape and emerging directions. This work presents a bibliometric analysis of the Scientific Machine Learning research in aerospace engineering based on the publications indexed in the Scopus database from 2017 to 2026. The first search yielded 98 478 records. After screening and eligibility, the final dataset comprised 961 publications. The field had an annual growth rate of 14.87%, indicating rapid research expansion. Bibliometric analysis was performed using Bibliometrix R package, Biblioshiny interface and VOSviewer. The results reveal the dominance of the research paradigm of Physics-Informed Neural Networks (PINNs), with strong ties to machine learning, deep learning, computational fluid dynamics and uncertainty quantification. The co-occurrence of keywords revealed five major thematic clusters, such as SciML core methods, aerospace physics applications, operator-learning methods, digital engineering technologies and intelligent aerospace systems. Developing topics like DeepONet, Fourier Neural Operators, digital twins, and satellite remote sensing indicate a move towards scalable operator-learning frameworks and autonomous aerospace ecosystems.

Introduction

Scientific Machine Learning (SciML) is a new paradigm that combines data-driven learning with governing physical laws to improve prediction accuracy, computational efficiency and generalizability in scientific and engineering applications [1], [2]. SciML has shown significant promise in aerospace engineering in the areas of computational fluid dynamics (CFD), structural analysis, digital twins, predictive maintenance, remote sensing, and autonomous systems [3], [4], [5]. Physics-Informed Neural Networks (PINNs) have emerged as a prominent SciML approach to solving forward and inverse problems described by PDEs, with the advantage of requiring less large labelled datasets [3].

Recent breakthroughs in operator-learning methods, such as DeepONet and Fourier Neural Operators (FNOs), have extended the scope of SciML to provide scalable approximations of complex physical systems [6], [7]. At the same time, the emergence of digital twin technologies and intelligent aerospace systems has motivated the integration of physics-based learning into real-time monitoring, optimization and decision-making applications [5]. Despite the rapid growth of the SciML field, a systematic understanding of the intellectual structure, prevailing research themes, and emerging directions of aerospace-oriented SciML is yet to be uncovered. Thus, this study aims to perform a bibliometric review of the Scientific Machine Learning research in the aerospace engineering domain to identify the main research trends, thematic clusters and future research opportunities.

Methodology

The present study employed a PRISMA-adapted bibliometric methodology to systematically identify, screen, and analyze the literature on Scientific Machine Learning (SciML) in Aerospace Engineering. The Scopus database was chosen for its extensive coverage of peer-reviewed engineering literature and compatibility with tools for bibliometric analysis. To

ensure the transparency and reproducibility of the study, a two-stage Boolean search strategy, a structured literature screening process, and bibliometric analysis were used.

Data Source and Search Strategy

Relevant publications were identified by a two-stage boolean search strategy. The first-stage search identified the broad research landscape of artificial intelligence and aerospace engineering, whereas the second-stage search refined the results using SciML-specific keywords to improve dataset relevance. The initial search used TITLE-ABS-KEY(("artificial intelligence" OR "machine learning" OR "deep learning" OR "artificial neural network*" OR "support vector machine*" OR "physics-informed neural network*" OR "physics informed neural network*" OR "scientific machine learning" OR DeepONet OR "deep operator network*" OR "neural operator*" OR "Fourier neural operator*" OR "graph neural network*") AND (aerospace OR aeronautic* OR aircraft OR aviation OR spacecraft OR satellite* OR UAV OR "unmanned aerial vehicle*")), yielding 98,478 records. The search was subsequently refined using TITLE-ABS-KEY(("physics-informed neural network*" OR "physics informed neural network*" OR "scientific machine learning" OR "physics-informed machine learning" OR DeepONet OR "deep operator network*" OR "neural operator*" OR "Fourier neural operator*" OR "physics-guided neural network*") AND (aerospace OR aircraft OR aviation OR aerodynamic* OR airfoil* OR aerofoil* OR UAV OR spacecraft OR satellite*)), resulting in the final dataset of 961 publications.

Literature Screening and Selection

The literature selection process followed the PRISMA- adapted flow [8] for bibliometric studies as shown in Fig. 1. The first search in Scopus yielded 98,478 records which were screened according to document type (Articles and Review papers), period of publication (2017-2026), Boolean search refinement, English language, and aerospace relevance. The final dataset comprised 961 publications.

Bibliometric Analysis

Bibliometrix and Biblioshiny [9],[10],[11] were used for bibliometric performance analysis, thematic evolution and conceptual structure analysis, and VOSviewer was used for keyword co-occurrence network visualization. The characteristics of the dataset are summarized in Table 1.

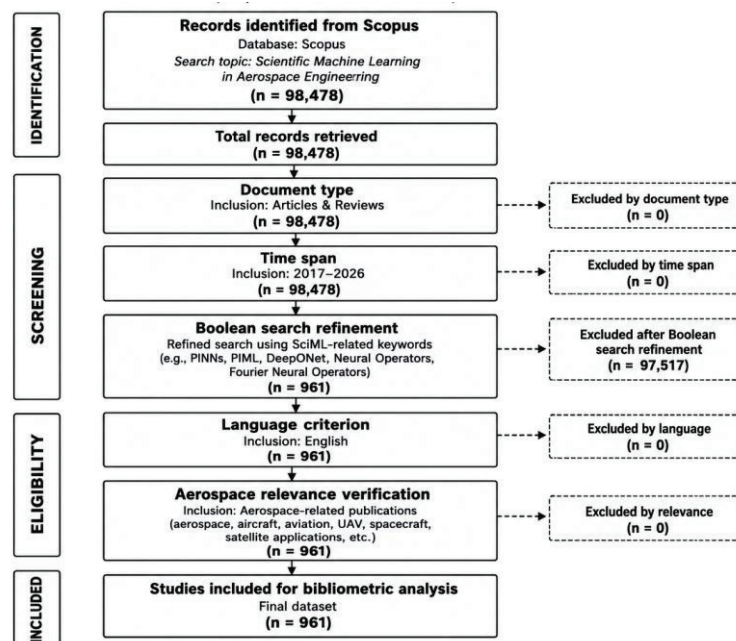


Fig. 1. PRISMA-adapted literature selection workflow for bibliometric analysis.

Table 1. Summary of Dataset Characteristics

Metrics	Results
Timespan	2017–2026
Documents	961
Sources	461
Authors	2,639
Author Keywords	2,455
References	23,394
Annual Growth Rate	14.87%
Average Citations per Document	9.34
International Co-authorship	18.63%

Results and Discussion

The bibliometric analysis of 961 publications indicates a rapid growth in Scientific Machine Learning (SciML) research in aerospace engineering. The annual scientific production has increased significantly after 2022, reflecting the accelerating adoption of physics-based modelling driven by data. The most frequent author keywords as summarized in Table 2 are Physics-Informed Neural Networks (PINNs) as the dominant research paradigm, machine learning, deep learning and physics-informed machine learning. This trend indicates a transition from pure data-driven approaches to hybrid frameworks integrating governing physical laws and machine-learning models. The most influential works are mainly related to computational fluid dynamics (CFD), fluid mechanics, heat transfer and other multi-physics problems governed by partial differential equations (PDEs) [2],[3],[4], [7].

The analysis further shows that the most mature application domains of SciML are still aerodynamics and fluid dynamics, but research has progressively expanded into thermodynamics, structural mechanics, structural health monitoring, additive manufacturing, flight systems and digital engineering, showing the growing adoption of SciML throughout the aerospace engineering lifecycle.

Table 2. Summary of Bibliometric Findings

Category	Key Findings
Research Growth	Number of publications has increased significantly after 2022, indicating a rapid growth of Scientific Machine Learning research.
Dominant Paradigm	Physics-Informed Neural Networks (PINNs) emerged as the most influential and frequently occurring research theme.
Core Technologies	Machine learning, deep learning, and physics-informed machine learning form the methodological foundation of the field.
Aerospace Applications	CFD, fluid dynamics, heat transfer, additive manufacturing, and satellite remote sensing are major application domains.
Emerging Methods	DeepONet, Fourier Neural Operators, graph neural networks, and neural operators represent emerging research directions.
Digital Engineering	Digital twins, predictive maintenance, anomaly detection, and remaining useful life prediction are gaining increasing attention.
Future Direction	Research is evolving toward operator learning, digital twins, and intelligent autonomous aerospace systems.

The keyword co-occurrence network generated with VOSviewer (Fig. 2) illustrates a well-connected knowledge structure of Physics-Informed Neural Networks, validating that this is the main research paradigm. The five major thematic clusters include: (i) core SciML methodologies such as PINNs, machine learning and deep learning; (ii) aerospace physics applications such as CFD, fluid dynamics, Navier-Stokes equations and heat transfer; (iii) emerging operator-learning methods such as DeepONet, Fourier Neural Operators and Graph Neural Networks; (iv) digital engineering technologies such as digital twins, uncertainty

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Toward Sustainable Road Safety: AI-Driven Safe Vehicles and Autonomous Mobility in Abu Dhabi

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Abstract: Artificial Intelligence (AI) and autonomous mobility are transforming road safety by shifting the focus from mitigating human error to preventing crashes through intelligent vehicle technologies. In line with this evolution, Abu Dhabi has adopted Vision Zero 2040, based on the Safe System Approach, to eliminate road fatalities and serious injuries. This paper presents Abu Dhabi's strategic transition from traditional road safety practices to an AI-enabled Safe System, highlighting the growing importance of the Safe Vehicle Pillar. Historical road fatality trends (2005–2025) demonstrate the effectiveness of previous interventions, while future action plans illustrate how the contribution of the Safe Vehicle Pillar is expected to increase from 5% in 2021–2025 to 25% by 2040, aligned with the target that 25% of personal trips will be completed by autonomous and driverless vehicles. The paper discusses the evolution of AI-enabled vehicle technologies, including Advanced Driver Assistance Systems (ADAS), connected and autonomous vehicles, and examines the complementary roles of industry, government, and research institutions in developing regulations, infrastructure, validation frameworks, and innovation ecosystems to support this transition. A strategic roadmap toward 2040 is proposed, demonstrating how AI-driven safe vehicles can become a cornerstone of sustainable road safety and offer insights for other cities pursuing Vision Zero and future smart mobility.

Introduction

Road traffic crashes remain one of the world's leading causes of death and serious injury despite continuous advances in infrastructure, legislation, and enforcement. While traditional road safety programs have significantly reduced fatalities over recent decades, future mobility requires a more integrated and technology-driven approach capable of addressing increasingly complex transportation systems. The rapid evolution of Artificial Intelligence (AI), connected vehicles, Advanced Driver Assistance Systems (ADAS), and autonomous driving technologies are fundamentally transforming vehicle safety. Modern vehicles are no longer passive modes of transportation but intelligent systems capable of continuously monitoring the driving environment, assisting drivers, communicating with surrounding infrastructure, and ultimately operating without human intervention. That pushes the government, industry, and innovative research to work together to make the roads safer.

Abu Dhabi's Vision Zero 2040 aims to eliminate road fatalities and serious injuries through the Safe System Approach. Central to this vision is the evolution of the Safe Vehicle Pillar into a key enabler of sustainable road safety through AI-enabled technologies and autonomous mobility. This paper outlines Abu Dhabi's strategic roadmap and the collaborative roles of industry, government, and academia in supporting this transformation.

Research Problem and Motivation

Despite significant improvements in road safety in Abu Dhabi, further reductions in fatalities and serious injuries are becoming increasingly challenging as conventional interventions approach their practical limits. Human factors remain a major contributor to crashes, while traditional measures cannot completely eliminate human error. At the same time, rapid advances in AI, ADAS, connected vehicles, and autonomous mobility provide new opportunities to prevent or mitigate crashes. However, realizing their safety potential requires more than vehicle technology alone; it depends on appropriate regulations, digital infrastructure, testing and validation, cybersecurity, data governance, human-machine interaction, and coordinated action among government, industry, and research institutions. This creates a need to define how AI-driven safe vehicles and autonomous mobility can be progressively integrated into Abu Dhabi's Safe System and contribute measurably to Vision Zero 2040. The research is therefore motivated by the opportunity to shift the Safe Vehicle

pillar from a predominantly protective role toward an active crash-prevention function and to establish a phased pathway for its increasing contribution to sustainable road safety.

Research Objectives

The research aims to assess the potential of AI, ADAS, connected vehicles, and autonomous mobility to enhance road safety in Abu Dhabi, evaluate the evolving role of the Safe Vehicle pillar in achieving Vision Zero 2040, identify the key requirements and challenges for their safe deployment, and propose a phased roadmap for integrating these technologies into Abu Dhabi's Safe System, supported by effective collaboration among government, industry, and research institutions.

Literature Review

Recent literature increasingly recognizes Artificial Intelligence (AI), Advanced Driver Assistance Systems (ADAS), connected vehicles, and Automated Vehicles (AVs) as important enablers of the Safe System approach. The World Health Organization (WHO) reported approximately 1.19 million road traffic deaths globally in 2021, highlighting the need for additional interventions beyond conventional road safety measures [1]. The increasing importance of vehicle-based safety technologies is particularly relevant because many crashes are associated with human error, which cannot be completely eliminated through education, enforcement, or infrastructure interventions alone.

Evidence from real-world studies demonstrates the safety potential of ADAS. Cicchino reported that Automatic Emergency Braking (AEB) reduced rear-end crashes by approximately 50%, while Forward Collision Warning (FCW) reduced them by 27%. Injury-related rear-end crashes were reduced by 56% with AEB and 20% with FCW [2]. Research on Lane Departure Warning (LDW) reported reductions of approximately 18% in relevant crashes overall and 24% in injury crashes [3]. A synthesis by the AAA Foundation estimated that large-scale deployment of selected ADAS technologies could potentially address approximately 40% of passenger-vehicle crashes, 37% of crash injuries, and 29% of crash fatalities. These figures represent theoretical potential rather than observed real-world reductions and should therefore be interpreted cautiously [4]. The literature on higher levels of vehicle automation also indicates considerable potential for improving road safety but emphasizes that the evidence base remains developing. A scoping review concluded that automated vehicles have the potential to improve overall road safety; however, much of the evidence was based on assumptions regarding vehicle capabilities and behavioural responses rather than extensive real-world deployment data [5]. Comparing Waymo's rider-only automated driving system with human-driver benchmarks over 7.1 million miles, Kusano et al. (2024) reported statistically significant reductions of 55% in police-reported crashes and 80% in crashes involving any injury [6]. Other research has identified crash-population analysis, traffic simulation, driving simulation, road-test data, system-failure risk assessment, and safety-effectiveness estimation as complementary approaches for evaluating automated-vehicle safety [7]. Recent evidence reinforces both the opportunity and the limitations of intelligent vehicle technologies. A 2025 review of ADAS technologies reported differing safety effects across systems, including Lane Keeping Assist, Driver Monitoring Systems, and AEB, while emphasizing that safety benefits vary by technology and operating conditions [8]. Research concerning automated vehicles and vulnerable road users has also identified human, environmental, and vehicle-related factors as important sources of challenging scenarios that automated systems must manage reliably [9].

From Traditional Road Safety to the Safe System Approach

Historically, road safety strategies focused on improving driver's behaviour through education, enforcement, and infrastructure measures. While these approaches achieved significant safety

improvements, they relied heavily on preventing human error. Recognizing that human error is inevitable, Abu Dhabi adopted the internationally recognized Safe System Approach in 2021, shifting the focus from preventing crashes to preventing fatalities and serious injuries when crashes occur. The approach is based on shared responsibility across government, industry, manufacturers, researchers, and road users, and is supported by Vision Zero 2040, targeting the elimination of road fatalities and serious injuries through four consecutive five-year action plans. During the first action plan (2021–2025), Abu Dhabi achieved approximately a 33% reduction in road fatalities, ranking eighth globally by fatalities per 100,000 population by 2025. Despite this progress, further reductions are becoming increasingly challenging as conventional measures approach their practical limits. Once fatality rates fall below approximately 5 fatalities per 100,000 population, diminishing returns become more evident, while human factors remain involved in approximately 95% of crashes and human error alone accounts for nearly 56% where road or vehicle factors are not significant. Errors such as misjudgment, limited visibility, distraction, fatigue, and drowsiness are difficult to eliminate through traditional interventions alone. Notably, while safer roads and improved road-user behaviour were the main contributors to progress during 2021–2025, the Safe Vehicle pillar made the smallest contribution, highlighting the need to increasingly leverage AI, advanced driver-assistance systems, connected vehicles, and autonomous mobility to move road safety from mitigating human error toward actively preventing crashes.

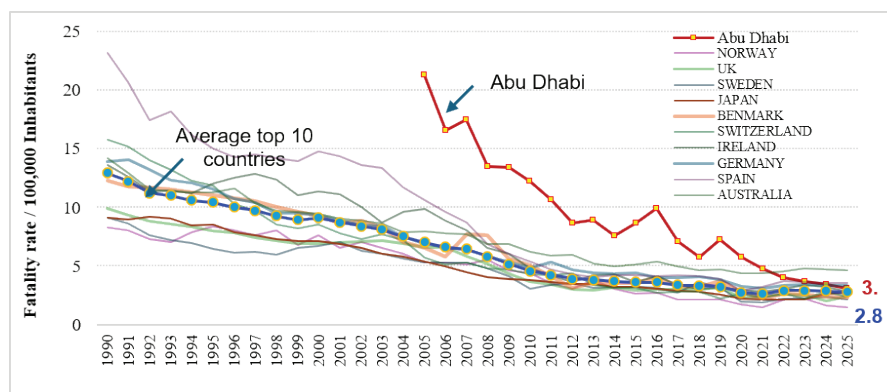


Figure 3: Road crashes fatality rates in Abu Dhabi and the best 10 countries

Consequently, the Safe Vehicle Pillar has emerged as a critical enabler of future road safety improvements. Rapid advances in Advanced Driver Assistance Systems (ADAS), connected vehicle technologies, and Artificial Intelligence (AI) are transforming vehicle safety from a passive protection mechanism into an active crash prevention system. These technologies have also become an important consideration for consumers when purchasing vehicles, with intelligent safety features increasingly complementing traditional factors such as price and design. This evolution represents the first step toward fully autonomous vehicles capable of substantially reducing the impact of human error.

Future Perspective: The Growing Role of the Safe Vehicle Pillar

As AI and vehicle automation continue to advance, the Safe Vehicle Pillar is expected to become a major driver of sustainable road safety which contributes very limited, about 2.0% in the action plan 2021-2025. Figure 2 illustrates the planned contribution of the five Safe System pillars across Abu Dhabi's five-year action plans from (2026–2040), showing that the contribution of the Safe Vehicle Pillar is projected to increase from 5% during the 2026–2030 plan to 25% during the 2036–2040 plan, supporting Abu Dhabi's Vision Zero 2040 strategy, coinciding with Abu Dhabi's target that 25% of personal trips will be completed using autonomous or driverless vehicles.

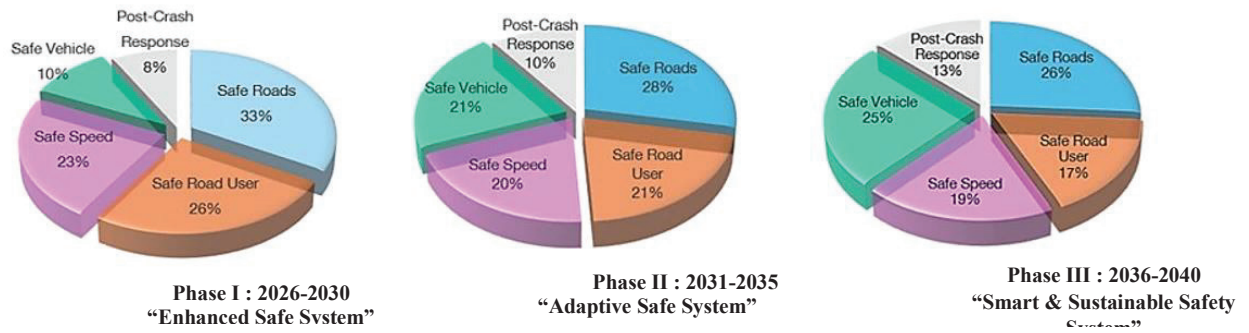


Figure 4: Evolution of Safe System Pillar Contributions

The progression of safety technologies including Automatic Emergency Braking (AEB), Lane Keeping Assistance, Adaptive Cruise Control, Driver Monitoring Systems, Blind Spot Detection, Intelligent Speed Assistance, Vehicle-to-Everything (V2X), Predictive collision avoidance, Digital twins for vehicle validation, AI perception systems, Edge computing, High-definition mapping. These technologies collectively reduce human error, improve situational awareness, and enable continuous learning from real-world traffic conditions.

Roadmap Toward 2040

The proposed roadmap consists of three strategic phases:

Phase I (2026–2030)	Phase II (2031–2035)	Phase III (2036–2040)
- Expansion of ADAS deployment - Regulatory development - Pilot autonomous vehicle operations - Connected infrastructure implementation	- Large-scale connected vehicle deployment - AI-supported traffic management - Commercial autonomous mobility services - Advanced digital infrastructure	- Mature autonomous mobility ecosystem - Fully integrated AI-enabled Safe System - Driverless public and private mobility - Achievement of the target that 25% of personal trips are autonomous

Building the Future Mobility Ecosystem

Achieving this transformation requires coordinated collaboration between manufacturers, government agencies, and research institutions:

Industry	Government	Research Institutions
Vehicle manufacturers are expected to: - integrate advanced AI safety systems - improve sensor reliability - enhance cybersecurity - validate autonomous driving algorithms - continuously update software - incorporate ethical AI principles - improve human-machine interfaces - ensure functional safety and redundancy	Government plays a central enabling role by: - developing legislation & regulations - creating testing and validation frameworks of AV - licensing autonomous vehicles - upgrading digital infrastructure - deploying V2X communications - establishing HD mapping standards - ensuring data governance - implementing public awareness programs & supporting public acceptance of autonomous mobility - preparing emergency response procedures	Research organizations contribute through: - AI algorithm development - safety evaluation methodologies - simulation environments - Human Factors Research - digital twins - autonomous vehicle validation - crash severity modelling - policy evaluation - lifecycle assessment - workforce development - interdisciplinary education - knowledge transfer to industry and government

Conclusions

Abu Dhabi's Vision Zero 2040 demonstrates that future road safety will increasingly depend on intelligent vehicles rather than solely on human behaviour. The Safe Vehicle Pillar is expected to evolve from a supporting component into a primary driver of sustainable road safety through AI, connected vehicle technologies, and autonomous mobility.

This transformation requires continuous cooperation between industry, government, and academia to develop safe, reliable, and socially accepted autonomous transportation systems. By combining technological innovation with evidence-based policy and scientific research, Abu Dhabi provides a scalable model for cities seeking to transition toward sustainable, AI-enabled mobility ecosystems.

Recommendations:

For industry	For government of Abu Dhabi	For research institutions
• Accelerate deployment of AI-enabled safety systems and higher-level automation. • Adopt safety-by-design, cybersecurity-by-design, and continuous over-the-air updates. • Collaborate with government and academia on real-world testing and standards.	• Continue strengthening regulatory frameworks for autonomous and connected vehicles. • Expand digital infrastructure (V2X, HD mapping, communications). • Develop certification, testing, and validation ecosystems. • Increase public awareness and workforce readiness to build trust in autonomous mobility.	• Advance AI-driven safety analytics, digital twins, and human factors research. • Establish living laboratories and simulation platforms for autonomous mobility. • Promote interdisciplinary collaboration with manufacturers and government agencies. • Develop education and training programs to prepare future mobility professionals.

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Design and Implementation of Super-Twisting Sliding Mode Control with Static Friction Feedforward Compensation for Precision Motion in Ball-Screw Driven Systems

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Abstract—In precision milling of components, friction-induced nonlinearities in the actuation system can significantly degrade the positioning accuracy of machined parts. If not properly compensated, these effects may lead to dimensional errors and rejections due to non-conformance with customer specifications. In particular, friction at low speeds, such as static and Coulomb friction, presents a major challenge in ball-screw driven systems. This paper presents the design and implementation of a Super-Twisting Sliding Mode Controller (ST-SMC) augmented with a static friction feedforward compensation scheme for an XY ball-screw driven milling table. The ST-SMC, with its tunable parameters L , W and λ , provides robust disturbance rejection and finite-time convergence, while the feedforward friction compensation enhances low-speed tracking by mitigating nonlinear stick-slip effects. Numerical simulations using MATLAB and Simulink were carried out to evaluate the controller's performance in terms of trajectory tracking accuracy and resilience to frictional disturbances. Tracking error metrics was applied to quantify performance. The proposed controller achieved high precision under varying load conditions, with tracking error improvements of 29.3% in the Y-axis, demonstrating its effectiveness in maintaining dimensional integrity during machining.

Introduction

Most machine tool servo systems are still controlled using the well-known Proportional-Integral-Derivative (PID) controller due to its simple structure and ease of implementation. However, PID controllers exhibit limited performance when dealing with nonlinear friction, external disturbances, and parameter uncertainties, particularly in high-precision CNC positioning systems operating at low feed rates [3], [7]. Friction phenomena such as static friction, Coulomb friction, and the Stribeck effect introduce stick-slip motion that degrades tracking accuracy and machining quality [3], [5].

Super-Twisting Sliding Mode Control (ST-SMC) has attracted considerable attention for precision motion control due to its finite-time convergence, strong robustness against disturbances, and reduced chattering compared with conventional Sliding Mode Control (SMC) [9]–[6]. Nevertheless, many existing ST-SMC approaches rely on adaptive algorithms, neural networks, or disturbance observers to compensate for friction and model uncertainties, resulting in increased computational complexity that may limit their implementation in real-time industrial CNC systems [3], [6]. Therefore, this work proposes a simple yet effective hybrid control strategy that combines Super-Twisting Sliding Mode Control (ST-SMC) with a Stribeck-based Static Friction Feedforward Compensation (SFFC) for a ball-screw-driven XY positioning system. Unlike adaptive or learning-based approaches, the proposed method does not require online parameter estimation or additional computational complexity, making it more suitable for real-time industrial CNC applications while maintaining high tracking accuracy under nonlinear friction conditions.

The main contributions of this work are threefold. First, a hybrid ST-SMCCFF controller is developed by integrating a static friction feedforward compensator with the ST-SMC to improve low-speed tracking performance. Second, a parameter sensitivity analysis is conducted to determine the optimal controller parameters (λ , W , and L) for robust operation under friction disturbances. Finally, the proposed controller is evaluated under three excitation frequencies (1 Hz, 1.5 Hz, and 2 Hz) and compared with conventional SMC and ST-SMC.

Simulation results demonstrate that the proposed method achieves lower tracking error and improved robustness against friction uncertainties, making it suitable for high-precision motion control applications [7], [6], [4].

ST-SMC Control

The ST-SMC utilizes a continuous control input to drive both $u(t)$ and its first derivative $\dot{s}(t)$ to zero in finite time, ensuring second-order sliding motion. The control input $u(t)$ is designed as:

$$u(t) = u_{eq}(t) + u_{st}(t) \quad (6)$$

Where:

$u_{eq}(t)$ is the equivalent control, handling a continuous state function (the nominal system dynamics), $u_{st}(t)$ is the discontinuous input with integrator, $u_1(t)$ responsible for robustness against disturbances,

$$u(t) = u_{eq}(t) - L|s(t)|^{0.5} \text{signs}(s(t)) + u_1(t); L = \frac{1}{A} \quad (7)$$

$$u_1(t) = -W \cdot \text{signs}(s(t)) \quad (8)$$

The control law includes two tunable positive gains, L and W , which shape the discontinuous portion of the super-twisting algorithm, while the sliding surface parameter λ governs the error convergence dynamics. Here, the signum function, denoted as $\text{sign}(\cdot)$, introduces directional control based on the sign of the sliding surface $u(t)$. When $\dot{s}(t) = 0$, while the super-twisting term guarantees finite-time convergences with reduced chattering [3] - [6].

To compensate for nonlinear friction effects that dominate during low speed operation, a static friction feedforward compensator is incorporated into the control loop. The feedforward term estimates the friction force using a Stribeck type friction model,

$$F_f(v) = F_c + (F_s - F_c) \exp \left[-\frac{|v|^2}{V_s} \right] \quad (9)$$

Where F_s , F_c and V_s represent the static friction, Coloumb friction, and Stribeck velocity, respectively. The estimated friction force is applied through a feedforward path to counteract the friction induced disturbance before it influences the plant dynamics, thereby reducing stick slip motion and improving tracking accuracy around zero velocity. The overall control input applied to the positioning table is obtained by combining the equivalent control, the super twisting control action, and the static friction feedforward compensation,

$$u = u_{eq} + u_{st} + u_{ff}, \quad (10)$$

$$\text{Where} \quad (11)$$

$$u_{eq} = \frac{\ddot{x}_r + \lambda e + B\dot{x} + Cx}{A}$$

Is the equivalent control derived from the identified plant model, u_{st} is the robust nonlinear feedback component, and u_{ff} is the friction feedforward compensation, the resulting controller simultaneously compensates for the nominal plant dynamics, rejects external disturbances and model uncertainties, and mitigated nonlinear friction effects, thereby enhancing the tracking performance of the ball screw driven positing system under low speed precision motion.

Methodology

In this study, an XY Table Ball Screw Driven System composed of an XY feed table of a CNC milling machine (Googol Tech GXYZ 202010 series) is considered. The mathematical model

of the positioning system and its friction characteristics are adopted based on previous identification studies [9], [1].

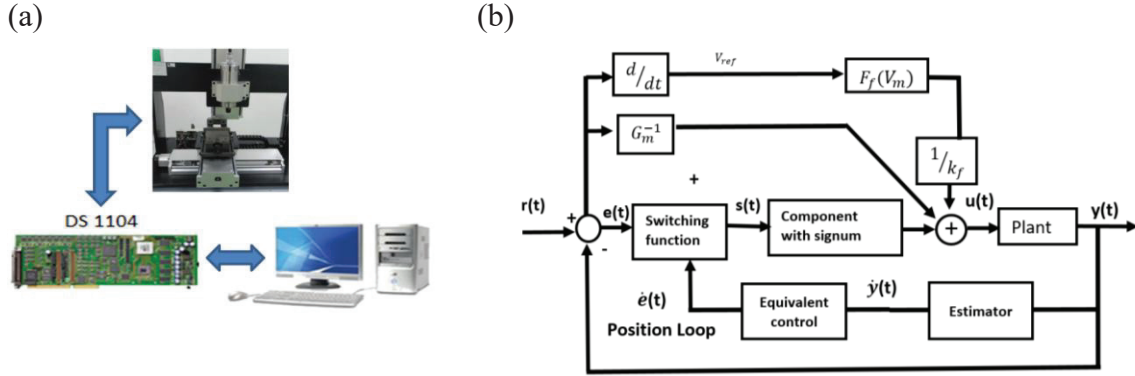


Fig 1 a. Experimental setup for XY Table Ball Screw Driven System feed table of milling machine
b) System in STSMC with frictions

Simulation Results

The proposed controller combines a Super-Twisting Sliding Mode Controller (ST-SMC) with a Static Friction Feedforward Compensation (SFFC) scheme to improve the tracking performance of the ball-screw-driven XY positioning system. The ST-SMC serves as the feedback controller to provide robust tracking performance under model uncertainties and external disturbances while reducing the chattering effect of conventional SMC [9], [1]. The SFFC estimates the nonlinear friction force using a static friction model incorporating Coulomb and Stribeck friction characteristics [3], [5]. The estimated friction is compensated through a feedforward path, thereby reducing stick-slip motion and improving low-speed positioning accuracy.

Table 1: STSMC with and without friction in 1.5Hz

Lamda, λ	W	L	Amplitude	mm		
				Without Friction	With Friction	Percentage Error%
3000	-0.6	-0.5	20	0.0117	0.03403	65.62
1000	-0.4	-0.4	20	0.02185	0.02599	-7.43
800	-0.2	-0.2	20	7.754	0.03043	-253.81
600	0.09	0.09	20	0.0118	0.03808	69.02
400	0.07	0.07	20	0.0178	0.05439	67.27

Table 1 presents the influence of the ST-SMC controller parameters (λ , W and L) on the tracking performance under friction-free and friction conditions. The results indicate that the controller performance is highly dependent on the selected gain values. Among the tested parameter sets, $\lambda=1000$, $W=-0.4$ and $L=-0.4$ exhibit the most balanced performance, with the maximum tracking error increasing only slightly from 0.02185 mm in the without friction to 0.02599 mm when friction is introduced. This demonstrates that the controller maintains its tracking capability despite the presence of nonlinear friction, indicating good robustness. In contrast, the parameter set with $\lambda=3000$ achieves the lowest tracking error under without friction (0.01171 mm), but its error increases to 0.05281 mm in the presence of friction, suggesting that the higher controller gain is more sensitive to friction disturbances. Lower gain settings, particularly $\lambda=600$ and $\lambda=400$, experience a significant degradation in tracking performance when friction is applied, with maximum errors increasing to 16.28 mm and 28.99 mm, respectively. This indicates that the controller gains are insufficient to overcome the nonlinear friction effects. Similar observations regarding gain sensitivity in Super-Twisting SlidingMode Control have also been reported in [9], [6].

Table 2 compares the maximum tracking error of the proposed STSMC with Static Friction Feedforward (STSMC-FF), conventional STSMC, and SMC using the selected

controller parameters ($\lambda=1000$) at excitation angular frequencies of 1Hz, 1.5Hz and 2Hz. The results indicate that the proposed controller consistently achieves superior tracking performance, particularly at medium and high operating frequencies. The improvement is attributed to the combination of the super-twisting control law and friction feedforward compensation, which effectively suppresses friction induced disturbance while maintaining finite time convergence. These findings are consistent with recent studies demonstrating the superior robustness and tracking performance servo system [9], [8].

Table 2: Comparison of Maximum Tracking Error of Different Controllers at $\lambda=1000$

Controller	Max error			Percentage Error%		
	1Hz	1.5Hz	2Hz	1Hz	1.5Hz	2Hz
STSMC						
FF	0.03616	0.02599	0.3016	0.1808	0.12995	0.0001508
STSMC	0.03537	0.03675	0.3537	0.17685	0.18375	0.0001769
SMC	39.01	31.53	39.01	195.05	157.65	0.019505

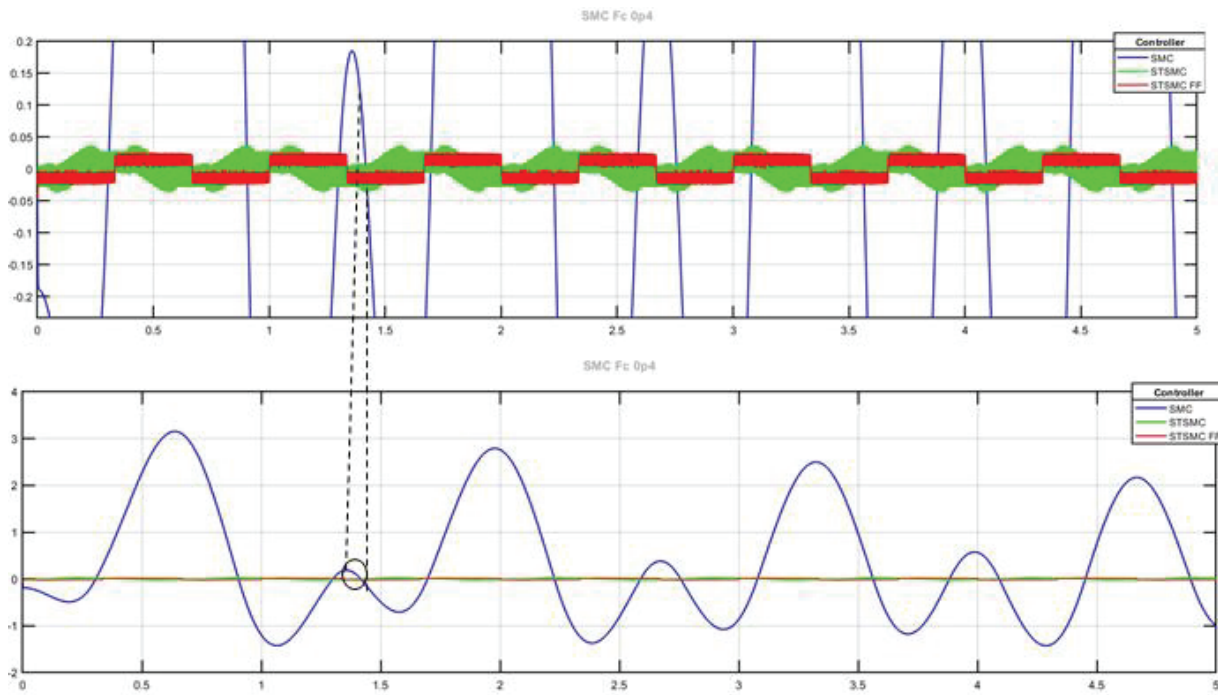


Fig. 3 Comparison of the performance based on tracking error for the system with different controllers

Figure 2 presents a comparison of the tracking error for the SMC, conventional STSMC, and the proposed STSMC with Static Friction Feedforward Compensation (STSMC-FF). The enlarged region around 1.4s clearly illustrates the difference in controller performance during the transition through zero velocity, where friction effects are dominant. The conventional SMC (blue) exhibits large oscillations and significant error peaks, indicating severe chattering and poor disturbance rejection. In contrast, both STSMC (green) and the proposed STSMC-FF (red) maintain substantially lower tracking errors with smoother responses due to the continuous control action of the super-twisting algorithm. Furthermore, the proposed STSMC-FF produces the narrowest error band around the zero-error line, demonstrating that the static friction feedforward compensation effectively mitigates stick-slip behaviour and reduces friction induced disturbances. As a result, the proposed controller achieves superior tracking accuracy and robustness compared with both the conventional STSMC and classical SMC, particularly during low-speed motion and velocity reversal.

Conclusions

The proposed ST-SMCFF consistently achieved lower tracking errors and improved robustness against friction induced disturbances, particularly under low speed operating conditions where static friction is dominant. The selected controller parameters ($\lambda=1000$, $W=-0.4$, and $L=-0.4$) provided the best balance between tracking accuracy and robustness. The obtained results agree with recent developments in super-twisting sliding mode control for precision motion systems and further demonstrate the effectiveness of integrating friction feedforward compensation into higher order sliding mode controllers [3] [6].

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3D Scan-Based Geometric Precision Assessment of the XOAR 3223 Propeller for CFD Model Refinement

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Abstract - A preliminary CFD study of the XOAR 3223 propeller reported roughly 16% deviation between simulated and experimental performance. Part of this gap was attributed to geometric uncertainty in the CAD model used for the simulation. To investigate, a physical XOAR 3223 propeller was 3D-scanned at 0.2 mm resolution using an industrial-grade structured-light laser scanner (EinScan HX), and the resulting point cloud was compared against the existing CAD reference model. Four discrepancies emerged: a blade-length difference of about 4 mm per side, an overall diameter deviation of roughly 0.54% relative to the nominal 32-inch reference, a maximum local surface deviation of 3.27 mm, and a mounting-hole pattern tilted about 3° out of symmetry. Together, these findings pinpoint specific sources of geometric mismatch and will guide the reconstruction of a refined 3D model for the next CFD iteration.

Introduction

Accurate propeller geometry is essential for CFD-based aerodynamic performance prediction [1-2]. An initial CFD analysis of the XOAR 3223 propeller, reported in Aero Report 1 [3], found that simulated performance differed from experimental measurements by approximately 16%. CFD accuracy depends heavily on the fidelity of the input geometry. One plausible source of this discrepancy is a mismatch between the CAD model originally built for the project and the true, as-manufactured geometry of the physical propeller.

This work presents a precision 3D scan of a physical XOAR 3223 propeller and compares the resulting point-cloud geometry against the existing CAD reference model. The aim is to quantify the geometric discrepancy and inform a refined CAD reconstruction for the next round of CFD analysis.

Methodology

Scanning was carried out with an EinScan HX, an industrial-grade 3D scanner that combines blue-light structured-light and laser scanning modes [4], chosen for high-quality reverse-engineering work. Before scanning, the scanner was calibrated and the propeller surface prepared with a self-evaporating anti-reflection spray and reference markers, enabling precise, marker-based laser alignment. This precision mode was later compared against a marker-free “quick scan” mode, which needed no calibration or surface spray but produced visibly coarser surface capture. The propeller surface was set as reflective in the scanner settings, and the scan resolution was fixed at 0.2 mm (the scanner’s maximum resolution is 0.1 mm).

The propeller was scanned in four orientations, namely top, bottom, and two sides, and the resulting point clouds were registered and merged into a single composite model. Scanning took place in the Additive Manufacturing Laboratory, FTKIP, UTeM, with ambient room lighting switched off to minimize white-light interference. The merged point cloud was then overlaid on the existing CAD reference model (XOAR 3223 V2) for direct deviation analysis. The half-blade geometry was subsequently divided into at least 13 cross-sectional planes, and spline curves were re-fitted to each contour as the basis for reconstructing an updated STEP-format solid model. These 13 sectioning planes were not spaced uniformly along the span. Station density was increased near the root and, especially, the tip, where blade twist, chord, and thickness change fastest; a coarser, near-uniform spacing sufficed across the mid-span,

where the geometry varies more gently. This non-linear distribution was adopted to capture local curvature at the root fillet and tip contour more accurately, without requiring an excessive number of sections.

Results

Table 1 compares diameter estimates from the CAD reference model, the 3D scan, and the relevant nominal size classes. The CAD reference model gives a diameter of 809.24 mm. The 3D scan data, including tip-region correction on both blades, gives 817.2 mm, a difference of about 4.4 mm (0.54%) from the nominal 32-inch reference diameter of 812.8 mm selected for the G7 design. By comparison, the next nominal size up (33 inch, 838.2 mm) is off by about 21 mm (2.5%). The scanned propeller is therefore dimensionally closest to the intended 32-inch class, and this nominal diameter should be retained (acceptable range approximately 812.8–820 mm).

Table 1: Comparison of propeller diameter across the CAD reference model, 3D scan measurement, and nominal reference sizes.

Reference / Measurement	Diameter (mm)	Deviation from 3D Scan (mm, %)
CAD reference model (Ilman, G7)	809.24	—
3D scan measurement (this work)	817.2	—
Nominal 32-inch reference (G7 selected)	812.8	4.4 mm (0.54%)
Nominal 33-inch reference	838.2	21 mm (2.5%)

Point-by-point deviation analysis between the scan surface and the CAD model (Fig. 1) shows a green contour where the two surfaces overlap within tolerance. The maximum local deviation reaches 3.27 mm, concentrated mainly toward the blade tip and leading edge. A separate overlay of the left and right blades against the CAD model confirms an approximate 4 mm length difference on each blade relative to the reference geometry.

Qualitatively, both effects are expected to alter the aerodynamic loading of the blade, not just its outer dimensions. The scan diameter of 817.2 mm is larger than the CAD diameter of 809.24 mm, so the effective radius increases. Because local blade-element velocity scales with radius, the CAD model under-represents this velocity, particularly outboard. The CAD-based simulation would therefore be expected to under-predict thrust and torque from the outer blade stations relative to the physical propeller. The 3.27 mm surface deviation, concentrated at the tip and leading edge, corresponds to a local change in aerofoil camber, thickness, and effective pitch angle. Aerodynamic loading is disproportionately sensitive to tip-region geometry (tip losses, local angle of attack, induced velocity), so even this comparatively small deviation could shift the spanwise pitch distribution and produce a locally non-uniform loading pattern near the tip, one the original CAD geometry does not capture. Together, these effects offer a plausible, physically consistent explanation for part of the approximately 16% CFD-experiment discrepancy reported in Aero Report 1 [3], to be confirmed once the refined CAD model is re-analysed.

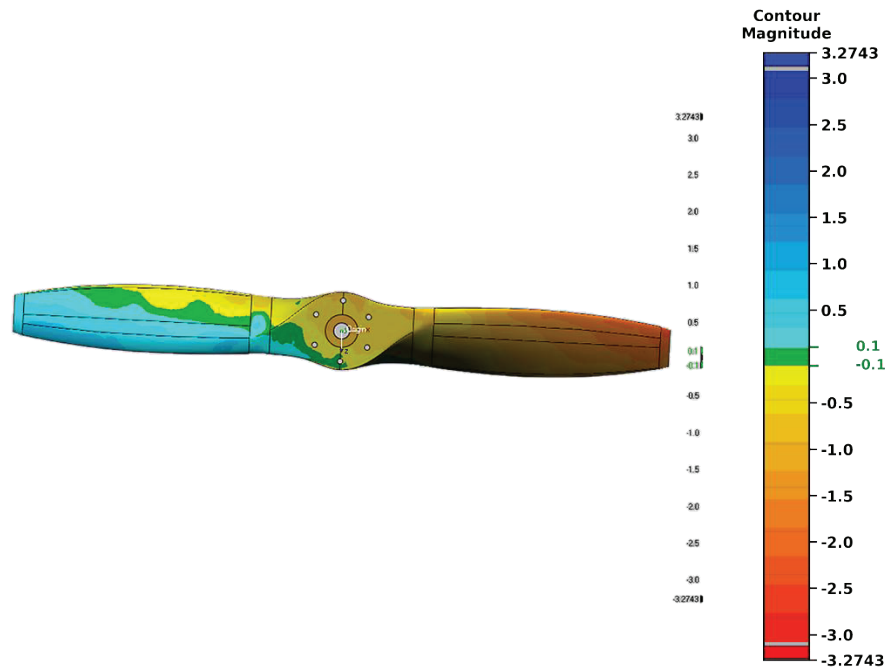


Fig. 1 Deviation contour between the 3D scan data and the CAD reference model (Initial Model, G7). Green indicates close overlap; the maximum deviation magnitude is 3.27 mm.

A further check of the centre positions of the six inline mounting holes (Fig. 2) shows the hole pattern tilted by approximately 3° relative to a symmetric axis. The six holes are not held perfectly symmetric about the hub centre. This has two implications: the physical propeller may be difficult to dynamically balance, and defining a consistent global coordinate system for the reconstructed CAD model becomes non-trivial, since the natural reference axis is itself skewed.

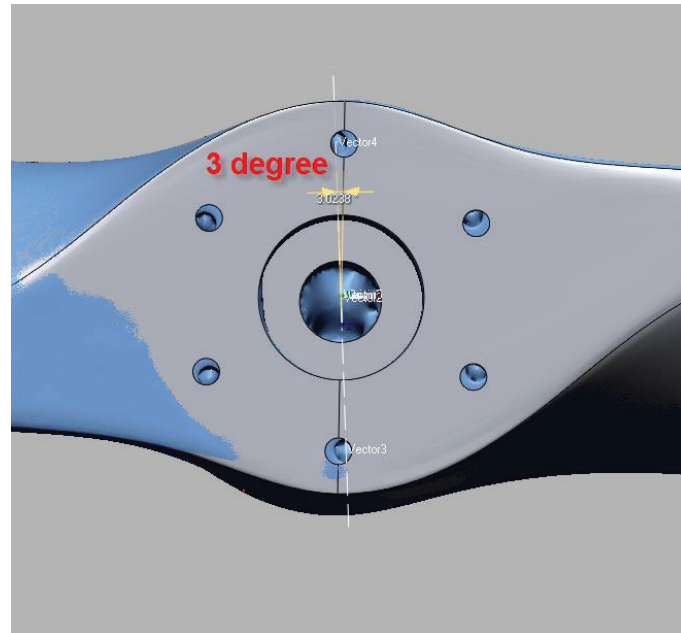


Fig. 2 Tilted-view comparison showing the centre positions of the six inline mounting holes, indicating an approximate 3° tilt relative to a symmetric axis.

The marker-based (laser) scan and the marker-free quick-scan mode differed substantially in captured surface fidelity. Marker-and-spray-assisted scanning is required to resolve the sub-millimeter surface detail needed for CFD-grade geometry reconstruction.

Conclusions

The 3D-scanned geometry of the XOAR 3223 propeller was compared against the existing CAD reference model. It revealed a blade-length difference of about 4 mm per side and a diameter deviation of 0.54% from the nominal 32-inch target, confirming the 32-inch class as the correct reference size going forward. The maximum local surface deviation between the scan and CAD models reached 3.27 mm, concentrated near the blade tip, a specific, previously unmeasured source of geometric uncertainty in the CFD input model. The six mounting holes were tilted by approximately 3° from a symmetric axis. This complicates the definition of a consistent global coordinate system for CAD reconstruction and suggests the physical propeller may not be inherently well balanced. These findings, including the 3° mounting-hole tilt, the 3.27 mm maximum local surface deviation, and the blade-length difference, all come from a single physical specimen. They should be read as characteristics of this individual unit, which may reflect specimen-specific manufacturing tolerances or, if representative, broader batch-level characteristics of the XOAR 3223 production run. Scanning additional units would be needed to tell the two possibilities apart. Marker-assisted (laser) scanning, using calibration, reference markers, and anti-reflection spray, is necessary to achieve the surface fidelity CFD-grade reconstruction requires. Marker-free quick scanning is not sufficient. Future work will reconstruct a new CAD/STEP model from the scan-derived cross-sectional planes, recompare it against the scan point cloud, and re-run the CFD simulation to see whether the refined geometry narrows the approximately 16% CFD-experiment discrepancy reported in Aero Report 1. These results are intended for presentation at the next project meeting.

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A Practical AI Governance Guardrail Framework for University–Industry Collaboration in Smart Manufacturing Ecosystems

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Abstract - Artificial intelligence (AI) is increasingly embedded in smart manufacturing through predictive analytics, computer vision, automation and decision support. Alongside productivity gains, AI deployment introduces governance risks involving data privacy, model bias, explainability, accountability, unsafe automation and weak auditability. These risks are amplified in university–industry collaboration, where AI systems are developed and piloted across stakeholders with different expectations, data practices and operational responsibilities. This paper proposes a practical AI governance guardrail framework for responsible university–industry collaboration in smart manufacturing ecosystems. A conceptual framework development approach was applied, comprising a targeted literature review, mapping of recurring AI governance risks, synthesis of principles from established governance references, and translation of these principles into practical collaboration guardrails. The principal result is a five-layer conceptual framework covering data governance, AI model governance, operational control, ethical and legal readiness, and talent and collaboration. The framework argues that successful AI-driven smart manufacturing depends not only on model performance but also on operational guardrails that regulate data access, model accountability, human oversight, auditability and talent readiness. The framework has not yet undergone empirical validation; expert review and pilot application are recommended. It offers universities, industry and government agencies a structured reference for responsible AI implementation, curriculum alignment and collaborative project governance.

Introduction

Smart manufacturing is a key driver of Industry 4.0 transformation. Through the Industrial Internet of Things, big data analytics, machine learning, computer vision and automation, manufacturers can monitor production processes, predict equipment failure, optimise resources and accelerate decision-making [1]. These capabilities open substantial opportunities for university–industry collaboration in applied research, industrial innovation, talent development and technology transfer. AI adoption in manufacturing cannot be judged on technical performance alone. Deployed AI systems interact with operational data, production workflows, business rules, human expertise and organisational accountability structures. When governance is weak, AI can introduce privacy leakage [2], biased or inaccurate predictions, black-box decision-making, unsafe automation, unclear ownership and limited auditability—concerns that recur across global AI ethics guidance [3]. Such risks erode trust among partners and limit the real-world impact of university-led AI projects.

These challenges are sharpest in collaborative ecosystems. Universities emphasise research output, prototypes and student learning; industry partners require reliability, compliance and business continuity; government agencies expect policy alignment, responsible innovation and national talent readiness. Established governance standards are comprehensive but largely organisation-centric, offering limited operational guidance for multi-party research-to-deployment collaboration.

The objective of this paper is therefore to propose a practical five-layer AI governance guardrail framework for responsible AI implementation in university–industry smart manufacturing collaboration. The paper contends that success depends not only on model performance and automation capability, but also on operational guardrails that govern data access, model accountability, ethical decision-making and talent readiness. The following sections describe the conceptual method, present the framework as the principal result, and discuss its implications, limitations and validation pathway.

Methodology

This is a conceptual paper. The framework was developed through four steps. First, a targeted literature review was conducted using combinations of keywords including “AI in smart manufacturing,” “Industry 4.0,” “AI governance,” “responsible AI,” “trustworthy AI,” “explainable AI,” and “AI risk management.” Sources were prioritised when they addressed AI-related governance risks, controls, or implementation considerations relevant to manufacturing and university–industry collaboration. Second, recurring governance risks identified across the selected sources were mapped and grouped into common themes, including data quality and ownership, privacy, model bias and explainability, over-automation, unclear accountability, insufficient documentation, and talent readiness. Third, governance principles were synthesised from established references, namely the NIST AI Risk Management Framework [4], ISO/IEC 42001 on AI management systems [5], and the Ethics Guidelines for Trustworthy AI [6]. Fourth, the synthesised governance principles were translated into practical guardrails and organised into five interconnected layers—data governance, AI model governance, operational control, ethical and legal readiness, and talent and collaboration—to support responsible university–industry collaboration across the AI lifecycle in smart manufacturing. The framework is conceptual and has not yet undergone empirical validation; structured expert review and pilot application are identified as the next research phase.

Results and Discussion

The principal result of this conceptual study is a five-layer AI governance guardrail framework for university–industry collaboration in smart manufacturing ecosystems. The result is conceptual rather than empirical: it is a synthesised governance structure, not a measured implementation outcome. The five layers—data governance, AI model governance, operational control, ethical and legal readiness, and talent and collaboration—span the AI lifecycle from data preparation and model development to deployment, monitoring, accountability and capability building. Figure 1 illustrates the five-layer framework architecture and the interaction among university, industry and government stakeholders, while Table 1 summarises each layer, its key risk, core guardrails and primary stakeholders.

Ethical and Legal Readiness Layer

This layer establishes accountability, transparency, auditability and responsible AI policy. Without a clear accountability structure, ownership of data access, deployment approval and decisions become ambiguous once prototypes reach production. Core guardrails include an AI use policy, audit trail, decision log, risk register, compliance checklist and periodic governance review [5], [6], consistent with converging global ethics principles [3]. For collaboration, it makes answerability explicit across organisational boundaries and aligns projects with policy and responsible innovation goals.

Talent and Collaboration Layer

This layer develops graduate readiness, curriculum alignment and joint governance capability. Skill mismatch and a research-output focus are key risks that limit industrial impact. Core guardrails include AI governance modules in curricula, university–industry sandbox environments, industrial case studies, joint review panels and multidisciplinary supervision. Universities gain a pathway to produce industry-ready talent conversant in governance as well as modelling; industry gains graduates prepared for real-world data, operational constraints and accountability requirements.

Integrated Discussion and Limitations

The five layers are designed to operate as an interconnected lifecycle rather than a checklist. Data governance underpins model reliability; model governance supports explainability and validation; operational control manages deployment and human oversight; ethical and legal readiness establishes accountability; and the talent layer embeds governance capability across organisations so that guardrails persist beyond individual projects. Through this chain, the framework connects academic experimentation, industrial deployment, governance responsibility and curriculum-driven industry readiness within a single structure.

The framework has limitations. It is conceptual and has not yet been empirically validated. Its implementation will differ according to organisational maturity, manufacturing context, data sensitivity and regulatory requirements, so the guardrails should be treated as a reference to be adapted rather than a fixed prescription. Structured expert review involving academia, industry and the public sector, followed by pilot application in selected collaborative projects, is recommended to assess practicality, relevance and completeness.

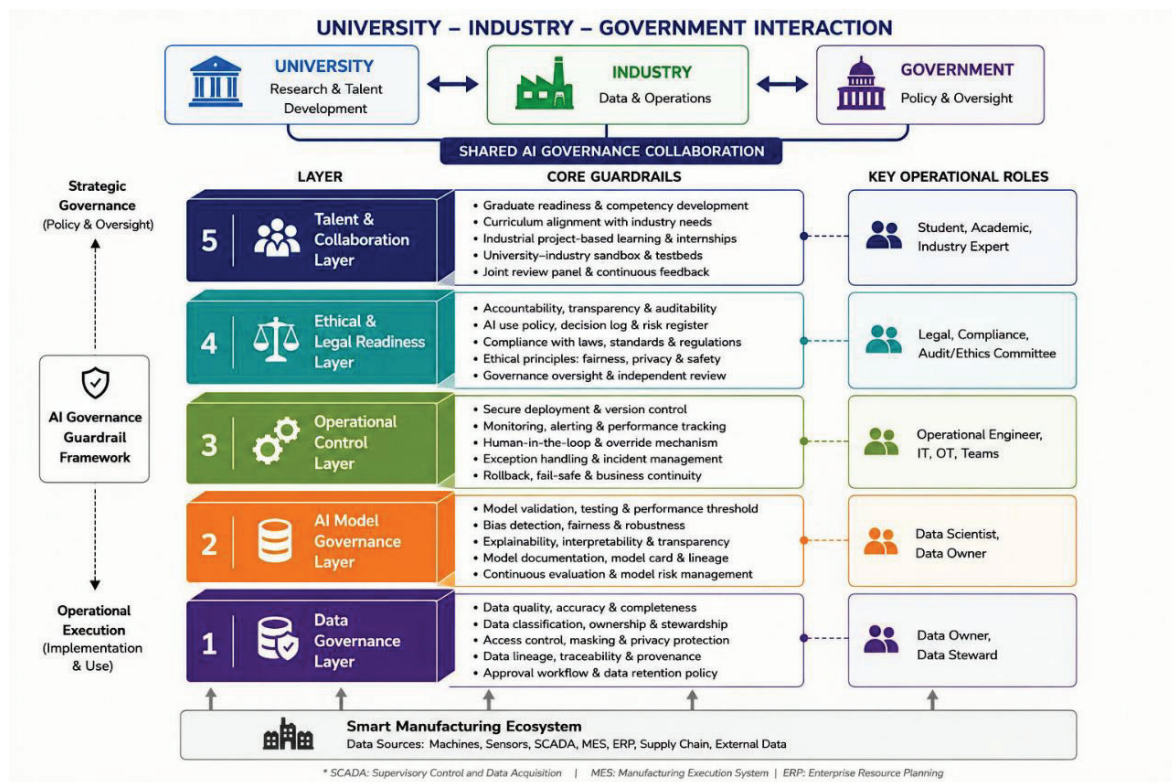


Fig. 5. Five-layer AI governance guardrail framework and university–industry–government interaction in smart

Table 1: Proposed AI governance guardrails across university–industry smart manufacturing collaboration

Layer	Governance Focus	Key Risk	Core Guardrails	Primary Stakeholders
Data Governance	Data quality, ownership, privacy, access	Data leakage; poor data quality; unclear ownership	Data classification, masking, role-based access control, data lineage	Industry data owner; university researcher; governance officer
AI Model Governance	Accuracy, bias, explainability, documentation	Black-box prediction; bias; weak validation	Model card, validation log, bias testing, explainable AI, performance threshold	AI developer; academic supervisor; industry technical team

Layer	Governance Focus	Key Risk	Core Guardrails	Primary Stakeholders
Operational Control	Deployment, monitoring, human oversight	Unsafe automation; model drift; disruption	Human-in-the-loop, monitoring dashboard, rollback, approval checkpoint	Operations team; AI system owner; production engineer
Ethical and Legal Readiness	Accountability, transparency, auditability	Weak accountability; non-compliance; poor traceability	AI use policy, audit trail, decision log, risk register, compliance checklist	Management; legal and compliance officer; government agency
Talent and Collaboration	Graduate readiness; joint governance	Skill mismatch; limited industrial impact	Curriculum governance modules, sandbox, industrial case studies, joint review panel	University; industry partner; government agency

Conclusion and Recommendations

This paper set out a five-layer AI governance guardrail framework as a practical governance structure for AI-driven university–industry collaboration in smart manufacturing. Its central position is that trustworthy industrial AI is achieved through lifecycle guardrails—spanning data, models, operations, accountability and people—rather than through model capability alone. The framework carries distinct implications for three stakeholder groups. Universities can use it to embed AI governance, ethics and risk management into curricula and industrial projects. Industry partners can apply it as a structured approach to deploying collaboratively developed AI with stronger accountability, monitoring and operational control. Government agencies can draw on it to inform policy on responsible AI adoption, talent development and trusted university–industry collaboration. As the framework has not yet been validated, two next steps are recommended: a structured expert review panel drawn from academia, manufacturing industry and the public sector to assess practicality and completeness, followed by pilot implementation in selected university–industry smart manufacturing projects to observe how the guardrails perform under real organisational, data and regulatory conditions.

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Design and Development of Meranti Wood Checking Fixture (CF) For Automotive Application Using CNC Routers

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Abstract— This project investigates the development of a checking fixture using CNC router technology with solid Meranti wood as an alternative to conventional metal-based fixture fabrication. Conventional checking fixture development is often associated with high cost, long manufacturing lead times, and limited flexibility for design modification. Therefore, this study aims to evaluate the effectiveness of CNC machining in improving production efficiency while maintaining acceptable dimensional accuracy for inspection applications. The checking fixture was designed using CAD software and fabricated using a Haas GR-510 CNC router through an integrated CAD/CAM process. Solid Meranti wood was selected as the primary material due to its machinability, cost efficiency, and suitability for prototype development. The fabricated fixture was evaluated through dimensional inspection at three critical points (707, 709, and 711), where each point was measured three times using a vernier caliper and ball gauge as part of the GR&R measurement approach. Results show that all measured values fall within the specified tolerance of 3.0 ± 0.5 mm, indicating that the fabricated fixture meets the required dimensional accuracy for inspection purposes. The findings confirm that CNC router machining with solid Meranti wood is capable of producing accurate and stable prototype checking fixtures while significantly reducing development time and cost compared to conventional methods. The study demonstrates that the integration of CAD/CAM and CNC machining provides a practical and efficient solution for checking fixture development in manufacturing industries.

Introduction

Checking fixtures (CF) are important inspection tools widely used in manufacturing industries, particularly in automotive production, to ensure that components meet required dimensional accuracy, geometric tolerances, and quality standards before assembly. These fixtures play a critical role in quality control by verifying part conformity and reducing production errors in high-volume manufacturing environments. Conventional checking fixture development typically uses metallic materials such as steel, aluminium or resin. Although these materials provide high strength and dimensional stability, the manufacturing process is often expensive, time-consuming, and less flexible when design changes are required. Traditional fabrication also involves multiple machining stages, which further increase production cost and lead time. To overcome these limitations, this study explores the use of CNC machining technology using a Haas GR-510 CNC router combined with solid Meranti wood as an alternative material. Figure 1 shows the existing checking fixture that is manufactured using resin material.

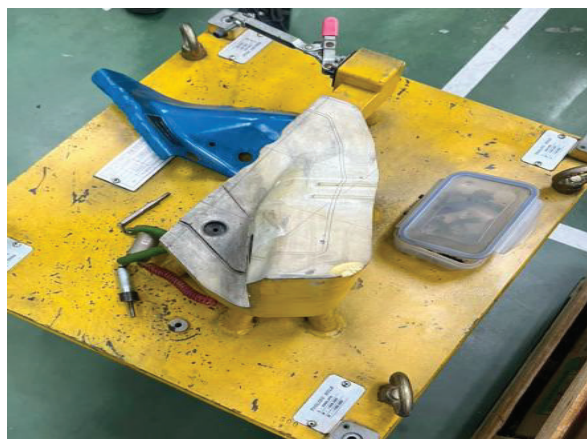


Fig.1: Existing Checking Fixture

Methodology

Checking fixtures (CF) are widely used in manufacturing industries as precision inspection tools to ensure that components meet required dimensional accuracy, geometric tolerances, and quality standards. In automotive manufacturing, CF plays an important role in quality assurance by verifying part conformity and reducing production errors during assembly processes [1], [2]. Previous studies highlight that checking fixtures help improve consistency, reduce rework, and enhance production efficiency in high-volume manufacturing environments [3]. Conventional checking fixture development mainly uses metallic materials such as steel and aluminium due to their high strength, rigidity, and durability. However, research shows that this approach is associated with high production cost, long lead time, and low flexibility when design modifications are required. The fabrication process typically involves multiple CNC machining stages such as roughing, finishing, drilling, and manual assembly, which increases manufacturing complexity and cost. Recent studies also explore alternative manufacturing methods such as CNC machining and additive manufacturing (3D printing) to improve fixture development efficiency. CNC machining offers high accuracy and repeatability but still requires significant machining time and skilled operators. On the other hand, additive manufacturing provides advantages such as design flexibility, rapid prototyping, and reduced material waste, making it suitable for low-volume fixture production. In addition, material selection plays an important role in fixture performance. Aluminium is commonly used for lightweight applications, while steel is preferred for high rigidity and durability. However, both materials contribute to higher cost and longer machining time. Therefore, recent research has begun to explore alternative materials such as wood-based materials for prototype fixture development due to their low cost and good machinability. Despite these developments, limited studies have investigated the use of solid Meranti wood combined with CNC router machining for checking fixture applications. This gap highlights the need for further research to evaluate its feasibility in terms of dimensional accuracy, cost reduction, and development time efficiency. Figure 2 illustrates the research methodology in developing a checking fixture for a automotive part.

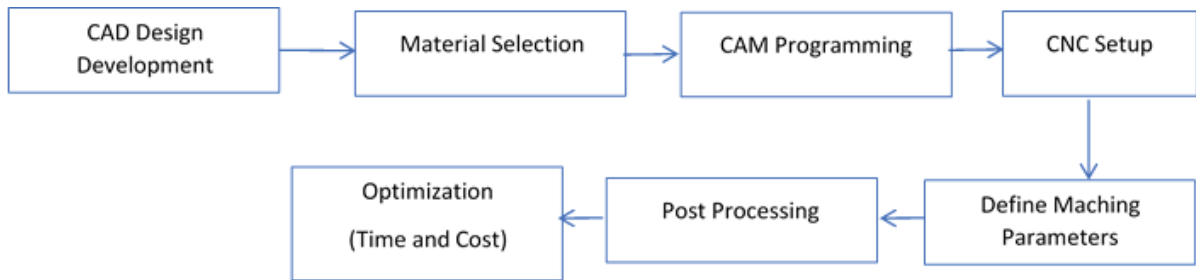


Fig.2: Research Methodology

Results and Discussion

The measurement process in this study was carried out to assess the dimensional accuracy of the CNC-machined checking fixture in a practical and reliable way. Three key inspection locations, Point 707, Point 709, and Point 711, were selected as the main reference points for evaluation as mentioned in Figure 3. Each point was measured three times using a vernier caliper and ball gauge to ensure consistency and to minimise human error through the application of one of the GR&R (Gage Repeatability and Reproducibility) methods. To further improve measurement reliability, a ball gauge was also used to check internal or less accessible features where direct caliper measurement was difficult. The fixture was designed with a nominal dimension of 3.0 mm and an acceptable tolerance range of ± 0.5 mm (2.5 mm to 3.5 mm), and all recorded data were analyzed to determine whether the fabricated part meets the

required dimensional specification for inspection use. Figure 4 shows the measurement process for a new checking fixture.

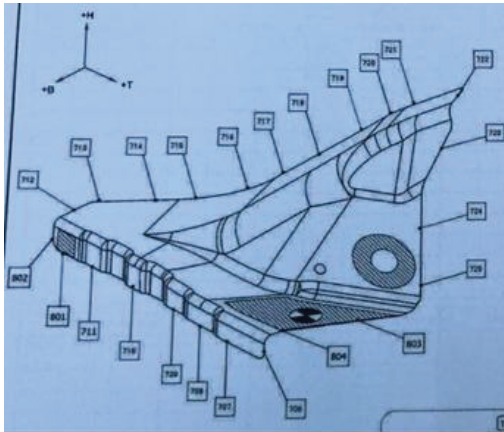


Fig.3: Inspection Points



Fig.4: Measurement Process

The dimensional inspection was conducted at three critical points, namely Point 707, Point 709, and Point 711, with each point measured three times using a vernier caliper as part of the GR&R evaluation. The nominal dimension for the checking fixture is set at 3.0 mm with an allowable tolerance of ± 0.5 mm, resulting in an acceptable range between 2.5 mm and 3.5 mm. The average measurement obtained for Point 707 is 2.80 mm, while Point 709 recorded an average of 3.03 mm, and Point 711 recorded 3.43 mm as mentioned in Table 1. All measured values fall within the specified tolerance range, indicating that the fabricated checking fixture meets the required dimensional accuracy for prototype application. Based on the inspection results, the part is classified as **ACCEPTED**, as all measured points comply with the tolerance requirement. Although minor variations are observed between readings, these differences are considered acceptable and are mainly influenced by machining surface condition and manual measurement. Figure 4 shows the developed checking fixture prototype manufactured using CNC Router with solid Meranti wood, demonstrating its dimensional accuracy, functional integration, and suitability for inspection applications in evaluating component conformity, measurement reliability and manufacturing efficiency.

Table 1: Measurement Results

Standard Nominal for Jig/CF = 3mm

Tolerance in between $0.5\pm = 2.50 - 3.50$

3 times measurement every single point (GR&R)

Point	Reading measurement (mm)	Average
707	2.70mm, 2.80mm, 2.80mm	2.70mm + 2.80mm + 2.80mm = 8.30mm / 3 = 2.80mm
709	3.00mm, 3.10mm, 3.00mm	3.00mm + 3.10mm + 3.00mm = 9.10mm / 3 = 3.03mm
711	3.50mm, 3.50mm, 3.30mm	3.50mm + 3.50mm + 3.30mm = 10.30mm / 3 = 3.43mm

Conclusion

This study focused on the design, fabrication, and evaluation of a checking fixture using CNC router technology with solid Meranti wood as an alternative material for conventional metal-based fixture development. The developed fixture was produced through an integrated CAD/CAM workflow, followed by CNC machining, post-processing, and dimensional inspection to evaluate its suitability for manufacturing inspection applications. The main objective of this study was to investigate the potential of CNC machining in reducing development time and cost while maintaining acceptable dimensional accuracy for prototype-level checking fixture applications. The results of the study demonstrated that the fabricated checking fixture achieved satisfactory dimensional performance, where all measured inspection points (707, 709, and 711) were within the specified tolerance of 3.0 ± 0.5 mm. The GR&R analysis conducted using a vernier caliper and ball gauge further confirmed that the measurement system is reliable and consistent for evaluating dimensional accuracy. The findings indicate that the CNC machining process using Haas GR-510 and solid Meranti wood is capable of producing stable and accurate prototype components suitable for inspection purposes. The comparison of manufacturing performance shows that the proposed approach significantly reduces production time and cost compared to conventional metal-based fixture fabrication methods. The use of solid Meranti wood also provides advantages such as better machinability, easier modification, and lower material cost, making it suitable for rapid prototype development. Although minor variations in measurement were observed, these are considered acceptable and mainly influenced by material properties and manual measurement techniques. The findings of this study demonstrate that CNC router machining combined with solid Meranti wood offers a viable and efficient solution for checking fixture development. The approach improves manufacturing efficiency while maintaining acceptable dimensional accuracy, and it has strong potential for application in prototype and industrial inspection environments.

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Feasibility Study of an Intelligent Temperature Monitoring Framework for Rubber Cutter Extrusion Applications

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Abstract— Stable temperature monitoring is essential for maintaining product quality and operational reliability in rubber manufacturing processes. However, conventional contact-based temperature monitoring systems often suffer from slow response, sensor degradation, and reliance on manual observation. This study proposes a feasibility framework that integrates a non-contact MLX90614 infrared sensor, Industrial Internet of Things (IIoT), Statistical Process Control (SPC), and a GPT4All-based artificial intelligence module for intelligent temperature monitoring. Temperature data are acquired by a Raspberry Pi Pico W, transmitted through the MQTT protocol, and processed using Node-RED for real-time visualization and SPC analysis. The AI module subsequently interprets temperature trends to classify operating conditions into NORMAL and CRITICAL levels while providing maintenance recommendations. Experimental results indicate that the MLX90614 sensor exhibits higher sensitivity to temperature variations than a conventional infrared thermometer. Furthermore, the proposed framework demonstrates the feasibility of integrating IIoT, SPC, and AI to provide context-aware operational assessment and intelligent decision support for potential rubber cutter extrusion applications.

Introduction

In the rubber manufacturing industry, stable and accurate temperature control is required to ensure consistent product quality, maintain machine reliability and safeguard operational safety. Temperature variation even in small amounts can affect rubber viscosity, cutting precision, and material uniformity. Conventional rubber manufacturing systems rely on traditional thermocouple-based sensors for monitoring which suffer from slow response rates, signal drift and sensitive to environmental conditions. These limitations can lead to inconsistent thermal readings, contribute to product defects, equipment fatigue and increased safety risks on the production floor. Besides that, current temperature monitoring in rubber extrusion processes generally lack intelligent capabilities such as real-time fault detection, autonomous decision making and integration with quality control tools. Many existing systems still rely on manual observation or operator intervention. This dependency on human judgment probably slows down the fault response time and limits the ability to predict potential failures. In addition, most available systems do not provide automated recommendations or incorporate statistical process control (SPC) which are essential for enabling manufacturers to transition from reactive maintenance toward preventive and prescriptive maintenance strategies.

Therefore, this study proposes an intelligent temperature monitoring system as a solution to address the limitations of conventional monitoring methods. By enabling real-time predictive control, the proposed system has the potential to improve operational consistency, reduce material waste, and enhance product quality across the manufacturing sector. This feasibility study aims to develop an accurate non-contact temperature measurement and monitoring system integrated with intelligent control logic to facilitate real-time fault detection for potential application in rubber cutter extrusion processes.

Literature Review

The advancement of the Internet of Things (IoT) has significantly enhanced temperature monitoring by enabling continuous data acquisition, wireless communication, cloud-based

storage, and real-time decision-making across various applications. Recent studies have integrated infrared sensors with IoT platforms using microcontrollers such as ESP8266, Raspberry Pi, and Arduino to provide real-time temperature monitoring, remote visualization, and automated notifications [1]-[4]. These systems have demonstrated improved operational efficiency through faster response times, enhanced monitoring accuracy, and reduced dependence on manual inspection.

Conventional contact-based sensors, including thermocouples and Resistance Temperature Detectors (RTDs), have been widely used due to their robustness, broad operating range, and high measurement accuracy [5]-[7]. However, these sensors require direct physical contact with the measured surface, making them susceptible to thermal lag, mechanical wear, signal degradation, and electromagnetic interference [5]. In contrast, non-contact infrared sensors such as the MLX90614 measure surface temperature by detecting emitted thermal radiation, providing rapid response, and minimal maintenance requirements [1][2]. Recent advances in Large Language Models (LLMs) enhanced intelligent decision-support systems in industrial applications. Google Gemini, GPT4All, OpenAI ChatGPT, Anthropic Claude, and DeepSeek are capable for industrial Internet of Things (IIoT) applications. Despite various LLMs, GPT4All has emerged as an open-source platform that enables to be executed locally without relying on cloud infrastructure [8]. GPT4All supports multiple open-source models while preserving sensitive operational data within the local computing environment [9][10], thus suitable for this study.

Methodology

Fig. 1 illustrates the proposed intelligent temperature monitoring framework, comprising four functional layers which are sensor node, communication, processing and visualization, and AI analysis. The MLX90614 infrared sensor acquires non-contact temperature measurements, while a Raspberry Pi Pico W collects the readings and publishes the data to an MQTT broker via a wireless network. A Raspberry Pi 4 running Node-RED subscribes to the MQTT data stream for real-time visualization, data logging, and SPC analysis. In parallel, the GPT4All AI module runs on a Windows workstation and subscribes to the same MQTT topic to analyse current and historical temperature trends. The Phi-3 Mini Instruct model was selected due to its lightweight architecture and relatively low computational requirements. The GPT4All AI module was hosted on an ASUS M409D laptop equipped with 8 GB of RAM and 512 GB of storage. During the feasibility evaluation, the GPT4All AI module exhibited a typical response latency of approximately 2 minutes 29 seconds per input. The AI output provides operational condition assessment and maintenance-related recommendations, demonstrating the feasibility of integrating IIoT, SPC, and local AI for intelligent temperature monitoring and decision support.

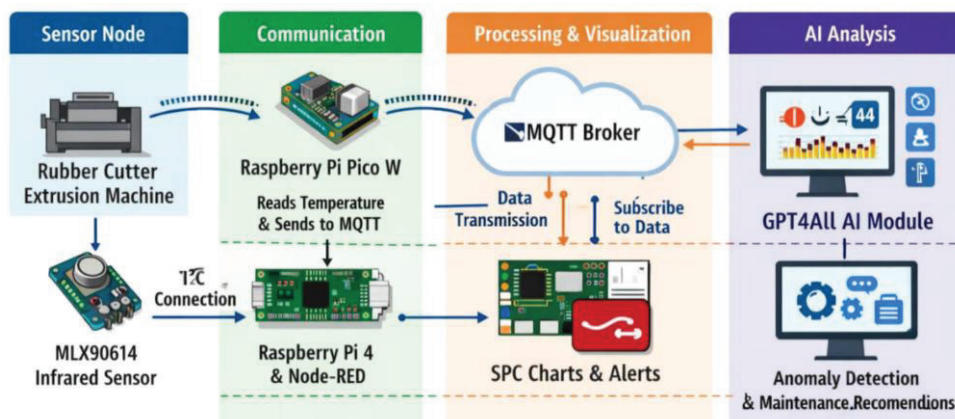


Fig. 1 Proposed system architecture

Results and Discussion

As an initial result, the MLX90614 sensor exhibits greater sensitivity to temperature variations than the infrared thermometer by capturing larger changes across successive measurements. This behaviour indicates its capability to detect dynamic temperature fluctuations more effectively, thus making it suitable for real-time monitoring applications. On the other hand, as a feasibility study, the proposed AI module classifies temperature conditions into two operational severity levels which are NORMAL and CRITICAL. The indicator for both levels is summarized in Table 1.

Table 1: Indication for operational severity level

Operational Classification	Indication
NORMAL	stable temperature behaviour under expected operating conditions
CRITICAL	abnormal or rapidly increasing temperature trends that may indicate potential process instability or equipment malfunction

Unlike conventional threshold-based monitoring systems, the proposed severity classification does not rely solely on predefined alarm limits. It employs contextual interpretation of temperature trends to support adaptive and intelligent decision-making. Using temperature data acquired from the MLX90614 infrared sensor, the AI module continuously analyzes temporal variations and provides context-aware operational assessments together with maintenance recommendations. Fig. 2 presents the dashboard visualization of temperature monitoring and AI feedback under two operating conditions. Fig. 2(a) shows both temperatures profiles remain stable with only minor fluctuations observed around their respective mean values. The SPC charts indicate the temperature measurements remain within the established upper (UCL) and lower control limits (LCL), suggesting a statistically stable operating condition. Based on these temperature trends, the AI module classifies the process as NORMAL and generates feedback indicating that the monitored conditions are operating within acceptable limits. In contrast, Fig. 2(b) illustrates a CRITICAL operating condition characterized by a sudden increase in object temperature, causing several measurements to exceed the SPC control limits. This abnormal trend indicates a potential thermal anomaly; thus, the AI module identifies the operating condition as CRITICAL. This demonstrates the feasibility of integrating SPC analysis with AI-based interpretation to provide context-aware operational assessments beyond conventional threshold-based monitoring.

For potential implementation in rubber extrusion environments, environmental factors such as dust, fumes and surface contamination may affect the MLX90614 sensing and temperature measurement. Appropriate physical safeguards such as protective sensor housing, suitable optical window and periodic cleaning may help minimise such interference. As this study focuses on feasibility evaluation, these factors and safeguards were not experimentally validated and should be considered in future industrial implementation.

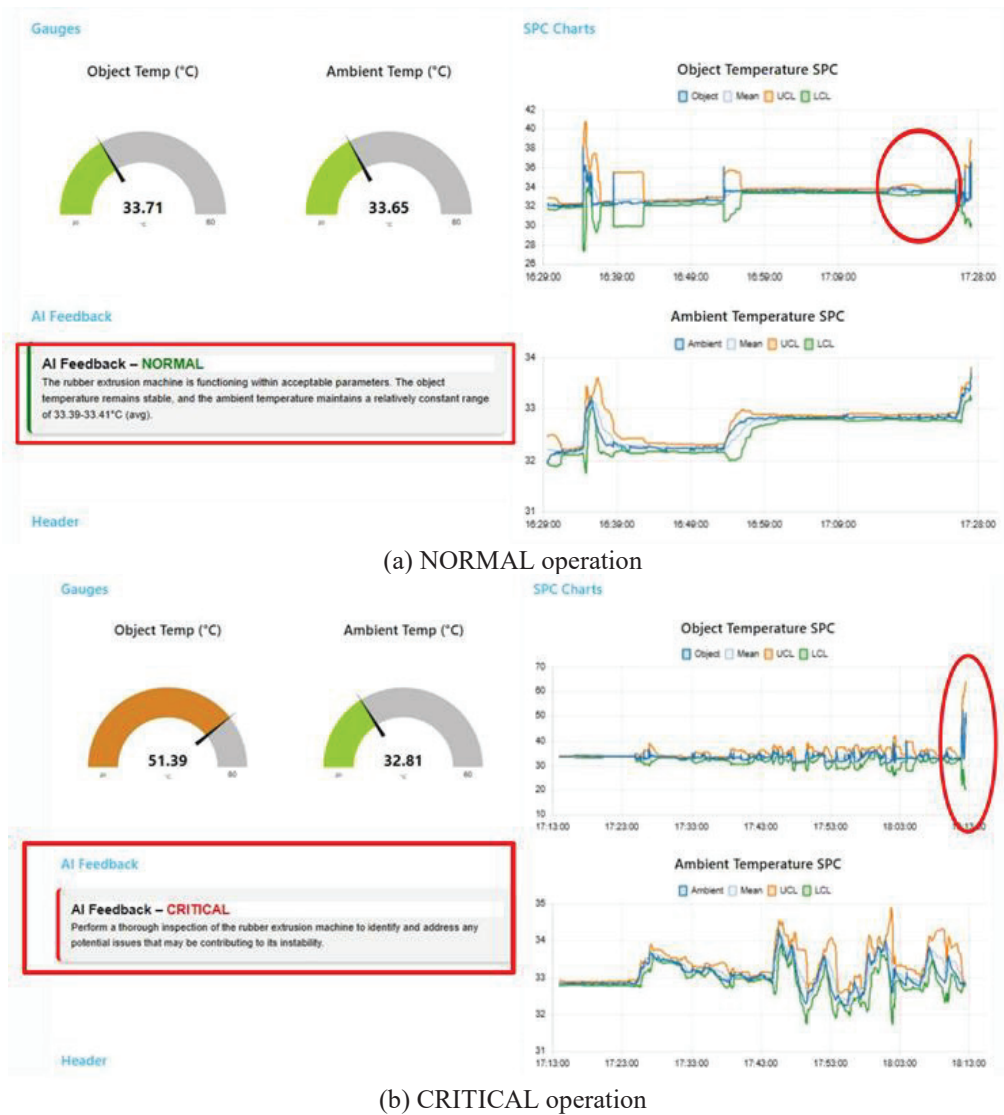


Fig. 2 Dashboard visualization of temperature monitoring and AI feedback

Conclusion

This study presented the feasibility of an intelligent temperature monitoring framework that integrates non-contact MLX90614 infrared sensor, IIoT, SPC charts and GPT4All for potential application in rubber cutter extrusion processes. The proposed framework demonstrated the capability of the MLX90614 infrared sensor to capture dynamic temperature variations more effectively than a conventional infrared thermometer, making it suitable for continuous monitoring. The integration of SPC with AI-based interpretation enabled contextual assessment of temperature behaviour through two operational severity levels, namely NORMAL and CRITICAL, accompanied by maintenance recommendations. Unlike conventional threshold-based monitoring, the proposed approach interprets temperature trends to support more adaptive operational decision-making. Although the framework has not yet been implemented in an actual industrial environment, the findings indicate the feasibility of combining IIoT, SPC, and AI technologies for intelligent temperature monitoring. Future work will focus on industrial validation, multi-level severity classification, and enhanced AI reasoning to improve predictive maintenance capabilities.

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PLANNING THE ACTUAL PRODUCTION CAPACITY OF SUBSIDIZED NPK FERTILIZER AT PT PUPUK SRIWIDJAJA PALEMBANG USING THE ROUGH-CUT CAPACITY PLANNING (RCCP) METHOD

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Abstract—Indonesia's agricultural sector plays a vital role in the economy and relies on the fertilizer industry to support that. PT Pupuk Sriwidjaja Palembang, under the PT Pupuk Indonesia (Persero), is responsible for producing subsidized Phonska NPK fertilizer. This quantitative study analyzes the alignment between actual production capacity and production planning using the RCCP-BOLA method in NPK Fusion-I Plant. This research includes production process analysis, MPS preparation and validation, MPS revision based on actual capacity. The results show that regular production regular production exceeded 16,000 tons per month, surpassing the target company of 10,000-11,000 tons. The revised MPS was developed using an effective plant capacity of 542.27 metric tons/day to better align the production plan with the available capacity and reduce the mismatch between the established target and actual plant capability.

Introduction

Indonesian agricultural sector relies on the fertilizer industry to support agricultural productivity. PT Pupuk Sriwidjaja Palembang (Pusri), the subsidiary of PT Pupuk Indonesia (Persero), produces subsidized Phonska NPK fertilizer (15-10-12) as part of the government's Public Service Obligation (PSO). However, after production capacity improvements at the NPK Fusion-I Plant Pusri the actual production consistently exceeded the Master Production Schedule (MPS) and company production target, indicating that the existing production plan no longer reflect the plant's actual manufacturing capability.

Rough-Cut Capacity Planning (RCCP) is widely used to evaluate the feasibility of a Master Production Schedule by matching required capacity with available capacity at critical work centers, thereby supporting medium-term production planning and capacity management [1-4]. This study applies the Bill of Labour Approach (BOLA), which is suitable because standard processing times are available for each work center.

The study aims to evaluate whether the actual production capacity of the NPK Fusion-I Plant is sufficient to accommodate the planned production load and to assess the suitability of the existing MPS. A quantitative approach was employed through production process analysis, MPS validation using RCCP-BOLA, MPS revision based on actual capacity. The results indicate that the plant has surplus production compared with company target, so MPS requires revision to better align production planning with actual manufacturing capability and reduce the risk of overproduction.

Following the capacity upgrade, the existing production target and Master Production Schedule (MPS) at the NPK Fusion-I Plant have not been fully adjusted to actual operating capacity. Previous planning was mainly based on the established target and did not explicitly validate the monthly production load against available work-center capacity. Therefore, this study applies Rough-Cut Capacity Planning using the Bill of Labour Approach (RCCP-BOLA) to validate the existing MPS and develop a capacity-based MPS. The study contributes a practical production-planning basis for aligning the annual production target with actual plant capability.

Methodology

This study employed a quantitative research approach to evaluate the alignment between production planning and actual production capacity at the NPK Fusion-I Plant of PT Pupuk Sriwidjaja Palembang. Primary data were collected through field observations and interviews, while secondary data included production realization, company target, master production schedule (MPS), work center information, processing times, machine capacity, and working days. The MPS was validated using the Rough-Cut Capacity Planning (RCCP) method with the Bill of Labour approach (BOLA), which evaluates production feasibility by comparing required and available capacity at each critical work center [2-4].

RCCP-BOLA was performed by converting the monthly MPS into required capacity at each work center using the standard processing time. Available capacity was determined from the effective operating time, considering the number of working days, operating hours, utilization, and efficiency. The monthly capacity balance was obtained from:

$$\text{Capacity Balance} = \text{Available Capacity} - \text{Required Capacity}.$$

The effective production capacity of 542.27 metric tons/day was calculated from the observed production realization and effective operating days during the study period. This value was subsequently used as the basis for revising the MPS.

The Finding and Arguments

Based on Figure 1, production data shows that actual production at the NPK Fusion-I Plant during 2022 until 2025 consistently exceeded the targets set in the company target. This increase occurred following a production capacity upgrade program, resulting in actual production capacity exceeding the capacity used to set the production targets. As a result, regular production often exceeded 16,000 metric tons per month, while the company target set in 2026 is only around 10,000 until 11,000 metric tons per month, so based on condition indicates that the company target used does not yet reflect actual production capacity.

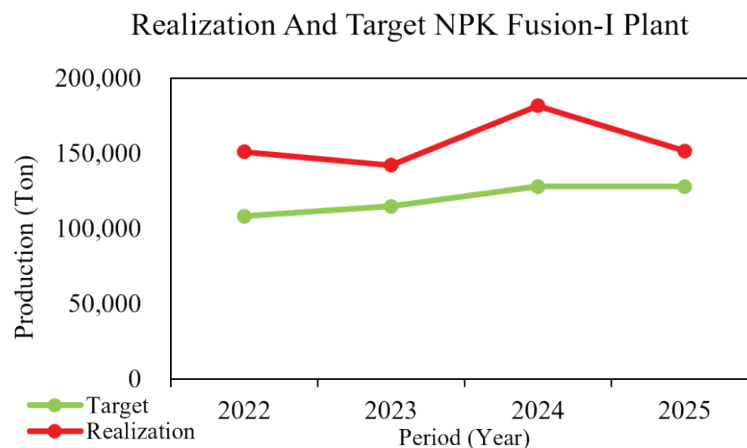


Fig.1 Difference about realization and target NPK Fusion-I Plant

RCCP-BOLA validation showed in Table 1, that available capacity consistently exceeded the required capacity throughout the planning horizon. Available capacity ranged from 26,907 to 33,314 minutes per month, while required capacity ranged from 24,102 to 30,482 minutes, resulting in capacity surpluses around 2,332-8,030 minutes. That available capacity was calculated by considering work center operating time adjusted for utilization (design capacity/actual output) and efficiency (effective capacity/actual output), providing a realistic representation of the plant's production capability. Figure 2 shows that all planning periods recorded capacity surpluses, ranging from 2,332 to 8,030 min/month. The largest surpluses occurred in January, while the smallest surpluses were observed in July and August. These

results confirm that the available production capacity consistently exceeded the required capacity, supporting the feasibility of the revised MPS.

Table 1: Monthly RCCP-BOLA Capacity Balance at the Critical Work Center of NPK Fusion-I Plant

Summary ¹	Jan	Feb	Mar	Apr	Mei	Jun
Available Capacity (min/month)	33314	29470	33314	32032	33314	32032
Needed Capacity (min/month)	25284	24102	30482	29301	30482	29301
Capacity Surplus (min/month)	8030	5368	2832	2732	2832	2732
Summary	Jul	Aug	Sep	Oct	Nov	Dec
Available Capacity (min/month)	26907	26907	32032	33314	32032	33314
Needed Capacity (min/month)	24575	24575	29301	30482	28355	30482
Capacity Surplus (min/month)	2332	2332	2732	2832	3677	2832

Monthly Capacity Surplus Based on RCCP-BOLA Validation

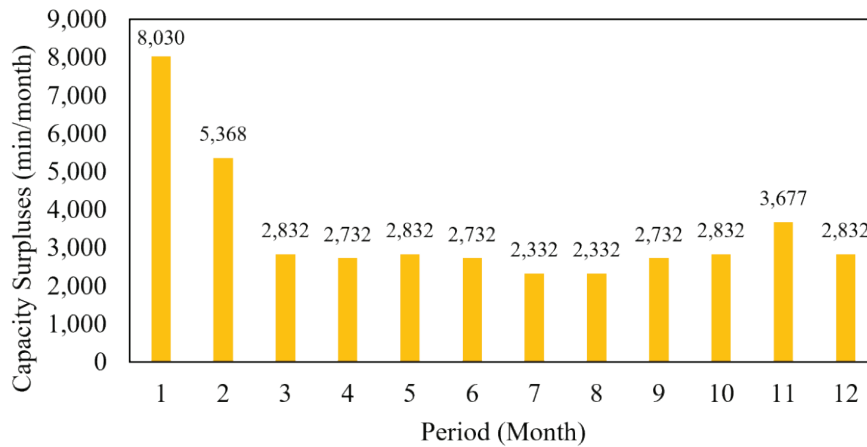


Fig 2. Monthly Capacity Surplus Based on RCCP-BOLA Validation

Table 2: Comparison metric ton quantity between actual capacity and Pusri target

Actual Capacity		PUSRI Production Target	
Period	Metric Ton	Period	Metric Ton
1	14,098	1	10,700
2	12,472	2	10,200
3	14,098	3	12,900
4	12,400	4	12,400
5	12,900	5	12,900
6	13,556	6	12,400
7	11,387	7	7,900
8	11,387	8	10,400
9	13,556	9	12,400
10	14,098	10	12,900
11	13,556	11	12,000
12	14,098	12	12,900
Total	157,607	Total	140,00

¹ Note: Capacity surplus = available capacity – required capacity. The values represent critical work center such as: Feeding Unit, Granulation, Dryer, Cooler, Screen on size, Oversize screen, Coater, Bagging

Based on Table 2, the calculated annual capacity was 157,607 metric tons, which was 17,607 metric tons (12.58%) higher than the annual company target of 140,000 metric tons. This finding indicates that the plant possesses surplus production capacity following the capacity upgrade. Therefore, the production target and MPS should be revised to better reflect the plant's actual manufacturing capability. This findings enabling more efficient capacity utilization and reducing the risk of production planning mismatches and avoid the damaging of production facility.

Conclusion

This study shows that actual production capacity of the NPK Fusion-I Plant reached 157,607 metric tons per year exceeding the Pusri and PT Pupuk Indonesia (Persero) production target 140,000 metric tons by 12.58%. RCCP-BOLA validation confirmed that the existing MPS no longer reflect the plant's actual manufacturing capability. The revised MPS based on a actual capacity of 542.27 metric tons per day provides a more balance production plan and minimize damaging of production facility. However, this study is limited to NPK Fusion-I Plant because from three NPK Plant in Pusri, the most production above the established target realization was handled by NPK Fusion-I plant and the method using the RCCP-BOLA because the limited data can provide. Therefore, PT Pupuk Sriwidjaja Palembang should periodically review production targets using actual operating data considering the on-stream days, utilization and efficiency, also for PT Pupuk Indonesia (Persero) should integrate the production planning with Advanced Planning and Scheduling to monitoring all of the changes from each subsidiary company.

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Integrating Lot Size Optimization and Workplace Layout Enhancement in Semiconductor Backend Operations

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Abstract— In today's highly competitive semiconductor industry, productivity enhancement is essential for achieving sustainable manufacturing performance and meeting growing customer demand. Conventional lot size optimization and scheduling approaches often overlook the influence of workplace layout on material flow, operator movement, and overall manufacturing efficiency. As a result, lot size decisions are frequently driven by equipment convenience rather than operational performance indicators. This study proposes an integrated framework that combines lot size optimization with workplace layout enhancement to improve operational efficiency. The methodology incorporates Value Stream Mapping (VSM), Overall Equipment Effectiveness (OEE), and discrete-event simulation to identify bottlenecks, quantify productivity losses, and evaluate improvement scenarios. The framework establishes lot size decision rules based on three critical operational indicators: Q staging limit, layout limit, and process cost. The Q staging limit controls Work-in-Progress (WIP) accumulation and queue delays, while the layout limit represents the physical workplace constraints for a smooth lot of movements throughout the production line. Process cost considerations are incorporated to balance operational efficiency and resource utilization. Lean manufacturing principles were subsequently applied to redesign the workplace layout and eliminate non-value-added activities. The framework was validated through an industrial case study in a semiconductor backend production environment. Empirical results demonstrated a 14% improvement in equipment utilization and approximately 40% reduction in cycle time, accompanied by reduced operator movement, 27% WIP reduction, 23% lower material handling requirements, and 5% throughput improvement with high OEE performance approximately 75% to 80%. Results from the case study indicates that productivity improvements are more sustainable when lot size decisions were evaluated together with physical workplace constraints rather than independently.

Introduction

Semiconductor industry plays a key role in enabling technological advancement across sectors such as consumer electronics, automotive, industrial automation, and artificial intelligence. Semiconductor backend operations are among the most operationally complex manufacturing environments because unlike frontend wafer fabrication that is dominated by linear and highly automated production processes, backend operations are distinguished by their batch-oriented workflows and frequent manual change overs [1]. The application of lean manufacturing that includes waste reduction, value-stream focus, pull-based flow, and standardization, can generate substantially greater productivity gains when combined with dynamic lot sizing and improved workplace layout design. Rather than small productivity improvement from separate initiatives, this integrated approach creates a stronger and more sustainable impact on operational performance [2]. The research is bounded along four dimensions to keep the inquiry tractable while retaining substantive relevance to Malaysian backend semiconductor manufacturing. First, the study focuses on backend operations within the Malaysian Semiconductor Manufacturing landscape. Secondly, the study covers full backend flow from pre-assembly through Front of Line operations and End of Line operations. These processes put particular emphasis on the stations that exhibit the strongest integration between lot sizing decisions and physical layout constraints [1]. The third boundary refers to system boundary which encloses the lot sizing decision layer, the workplace layout design layer, and the dispatch/scheduling layer within a single integrated analytical framework.

Finally, the boundaries of theoretical and methodological scope refer to the lean manufacturing as a connective framework rather than a standalone program [2].

Problem Statement and Objective of the Study

Malaysian backend semiconductor facilities continue to treat workplace layout design and lot size optimization as separate improvement programs. As a result, dynamic lot sizing decisions intended to reduce cycle time and minimize setup overhead are partially negated by layout which induced material travel, WIP accumulation at standby point, and excessive distance for tools and equipment. This integrated framework aims to represent realistic operational flow conditions, simultaneously reduce cycle time, optimize machine utilization, and improve OEE in the backend operation.

Methodology

This research adopted the Define, Measure, Analyze, Improve and Control DMAIC methodology in developing and validating the integrated framework for lot size optimization and workplace layout enhancement in semiconductor backend operations. A case study approach is conducted in a semiconductor backend manufacturing environment to systematically identify productivity losses and implement sustainable improvements as shown in Fig.1.

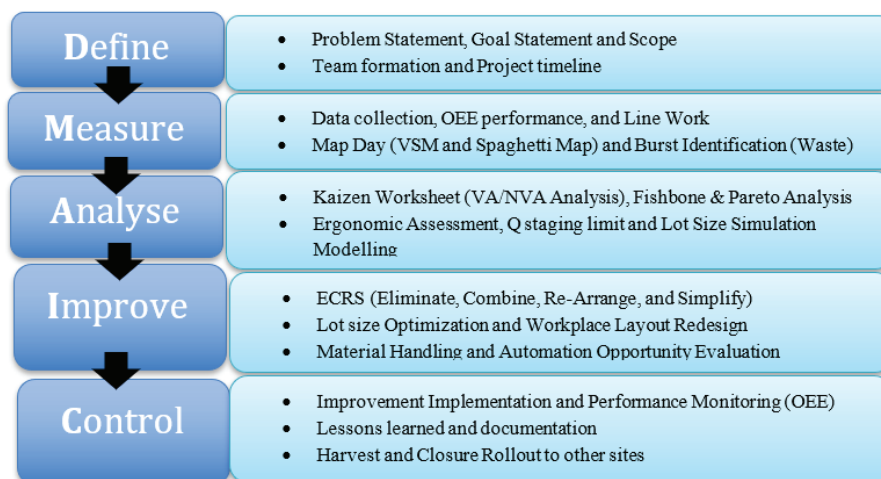


Fig. 1 D-M-A-I-C systematic approach

Results and Discussion

During preliminary observations of the production line, lot size decisions were largely determined by machine loading preferences and historical practices. This frequently resulted in material accumulation at intermediate staging areas. Similarly, lot sizes that are compatible with machine throughput may exceed the physical carrying capacity of the workplace or increase setup related inefficiencies [3]. To address these limitations, an integrated framework was developed incorporating 3 main elements; Q staging limit, layout limit, and process cost. Each indicator is linked to a discrete optimization variable within the discrete-event simulation model, enabling systematic evaluation of operational performance under different lot size scenarios [5], as illustrated in Fig. 2. The Q staging limit was used as the primary control parameter for lot size determination. Excessive queue time may increase quality risk and prolong cycle time. Therefore, a staging-time threshold was established based on product quality requirements. The control limit balances the trade-off between delay costs associated with excessive waiting time and capacity losses caused by underutilized equipment. In this study, the Q staging control was established at 24 hours, representing the maximum allowable staging duration. Simulation results showed that the optimized lot size maintained the actual Q

staging time at approximately 6 hours, well below the defined control threshold. This result demonstrates that the proposed lot size is still maintaining sufficient margin against quality risks such as adhesive leaking and material oxidation. Several threshold values were evaluated during simulation.

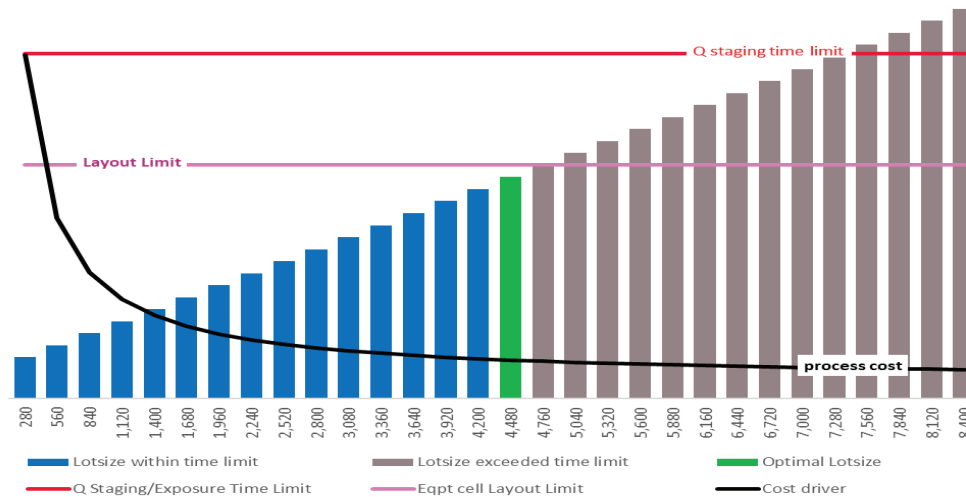


Fig.2 Simulation Modeling for Lot Size Optimization

The layout limit represents the physical constraint imposed by workplace design. It defines the maximum number of units that can flow through the production line without exceeding staging buffer capacity. Unlike conventional queueing analysis, which assumes unlimited staging capacity, the layout limit incorporates the spatial realities of semiconductor backend operations [4]. In the production line studied, the layout limit was primarily governed by the storage capacity of standby racks and material handling trolleys, which could accommodate to a maximum of 12 carrier at a given workstation. This constraint is particularly important in Malaysia's OSAT facilities, where multiple product families with different package densities and carrier configurations compete for the same production resources. Without explicitly considering these physical capacity limitations, optimization models may generate theoretically optimal lot sizes that cannot be practically accommodated on the production floor [2].

By increasing the lot size from 2,240 units to 4,480 units, process cost improvement can then be simulated through a few quantifiable parameters. Machine utilization increased by 14% and WIP was reduced by 27%, indicating improved production flow and reduced queue congestion. In addition, OEE improved 5% from 75% to 80% which was primarily attributed from the reduction in setup frequency. The bigger the lot size, the longer productive operating time, the lower setup required within the same period of time. By ensuring the new proposed lot size is within Q staging limit and layout limit, these results confirmed that productivity gains were achieved without compromising quality requirements or workplace capacity limitations.

Furthermore, the results indicate physical layout constraints are not merely supporting factors but critical decision variables in lot-size optimization which can be further extended by adopting Automated Material Handling Systems (AMHS) and Automated Guided Vehicles (AGVs) enabling greater flexibility in optimizing lot sizes and material flow [6].

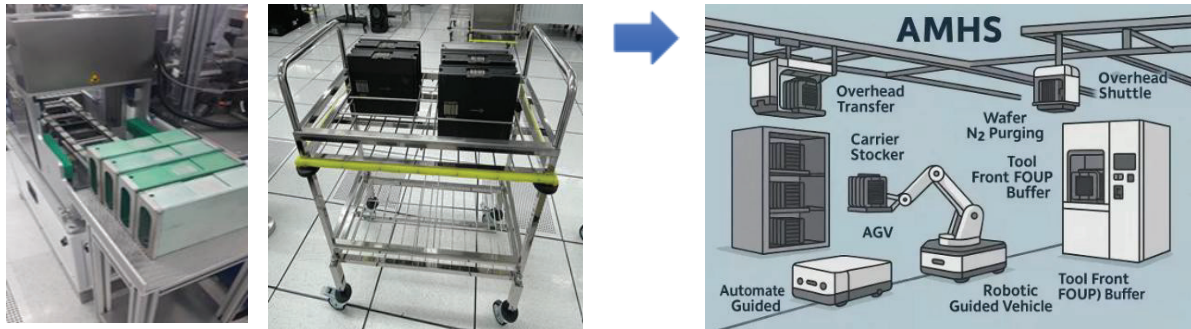


Fig. 3 Traditional Handling vs Workplace Enhancement with Automated Handling

Conclusion

The integrated framework simultaneously improves machine utilization (+14%), WIP (-27%), material travel (-23%), and AMHS delivery variance (-62%), with no domain showing a clear trade-off effect against the others. The improvement phase demonstrated that the integrated framework resulting dynamic lot sizing under the Q staging, layout or process cost indicator hierarchy, cellular layout grouping, AMHS reconfiguration and hierarchical dispatch rules produced a cumulative cycle time reduction of 41-44% without additional capital, matching the canonical Siemens backend study's 41% reduction [1]. Standard operating procedures, performance monitoring, and periodic review of lot sizing parameters were introduced to sustain productivity gains over time. Future recommendations to consider traceability aspect in dynamic lot size applied across processes in backend operation.

Acknowledgement

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A Systematic Literature Review on Modelling Process–Property Interactions and Microstructural Evolution in Wire Arc Additive Manufacturing of Aluminium Alloys with Interlayer Friction Stir Processing

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Abstract— Wire Arc Additive Manufacturing (WAAM) offers high deposition rates for large aluminium alloy components, yet as-built structures exhibit coarse columnar grains (200–600 μm), hydrogen porosity (up to 2.4%), and longitudinal residual tensile stresses of 80–200 MPa. Interlayer Friction Stir Processing (FSP) is a solid-state interlayer treatment that closes pores and refines grains to 2–15 μm via continuous dynamic recrystallisation (cDRX). Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) modelling provide the mechanistic basis for predicting melt pool thermal fields, residual stress, and fatigue life. No study has addressed ER5356 (Al–5Mg) processed by coldArc GMAW-AM with interlayer FSP, and no validated CFD–FEA model exists for this combination. This paper presents a Systematic Literature Review (SLR) following PRISMA 2020, screening 172 records from Scopus and Web of Science (January 2021–June 2026) and including 15 studies. Five critical research gaps for ER5356 with coldArc are identified, providing the evidence-based justification for this research.

Introduction

WAAM Process and Industrial Context

Wire Arc Additive Manufacturing (WAAM) deposits metal layer-by-layer using an electric arc and consumable wire feedstock, offering deposition rates of 1–10 kg/h with material utilisation exceeding 90% at substantially lower cost than powder-based additive processes for medium-to-large structural components. This study employs the coldArc process variant (EWM Alpha Q 352, KUKA KR 5 robot) with ER5356 wire ($\varnothing 1.2$ mm, Al–5Mg) on an AA6061-T6 substrate [1]. The coldArc process operates approximately 30–40% below conventional pulsed GMAW heat inputs at equivalent deposition rates, producing narrower beads (≈ 5 mm width) with reduced spatter and thermal distortion [1].

Defects in As-Built WAAM Aluminium Structures

As-built WAAM aluminium structures systematically exhibit three defect classes that limit structural performance [2], [3]. First, coarse columnar grains (200–600 μm) arise from epitaxial solidification along the build direction under steep thermal gradients (10^4 – 10^6 K/m), producing crystallographic texture and mechanical anisotropy [2]. Second, hydrogen solubility drops from ~ 0.65 cm³/100g in liquid to ~ 0.036 cm³/100g upon solidification, driving nucleation of spherical gas pores up to 2.4% by area fraction that act as fatigue crack initiation sites [2], [4]. Third, non-uniform thermal contraction generates longitudinal residual tensile stresses of 80–200 MPa at bead boundaries and interlayer interfaces [3]. These defects collectively reduce tensile strength, elongation, and fatigue life up to 15–40% below wrought equivalents [2], [3].

Interlayer FSP as a Hybrid Manufacturing Solution

Interlayer FSP eliminates all three defects simultaneously: the rotating tool plasticises material without remelting, closes pores hydrostatically, and accumulates severe plastic strain that

activates cDRX, transforming columnar grains into fine equiaxed grains [5], [6]. When applied independently to each deposited layer prior to the next deposition pass, interlayer FSP ensures uniform through-thickness microstructural treatment regardless of total build height—a fundamental advantage over post-process FSP, which is constrained by tool pin penetration depth ($\approx 2\text{--}3\text{ mm}$) and leaves sub-surface layers unaffected [6], [7]. Published studies on Al–Cu (2xxx) and Al–Mg (5xxx) WAAM systems confirm grain refinement to $2\text{--}15\text{ }\mu\text{m}$, porosity reduction exceeding 80%, and tensile strength improvements of 20–78% [4], [5], [6], [8], [9], [10].

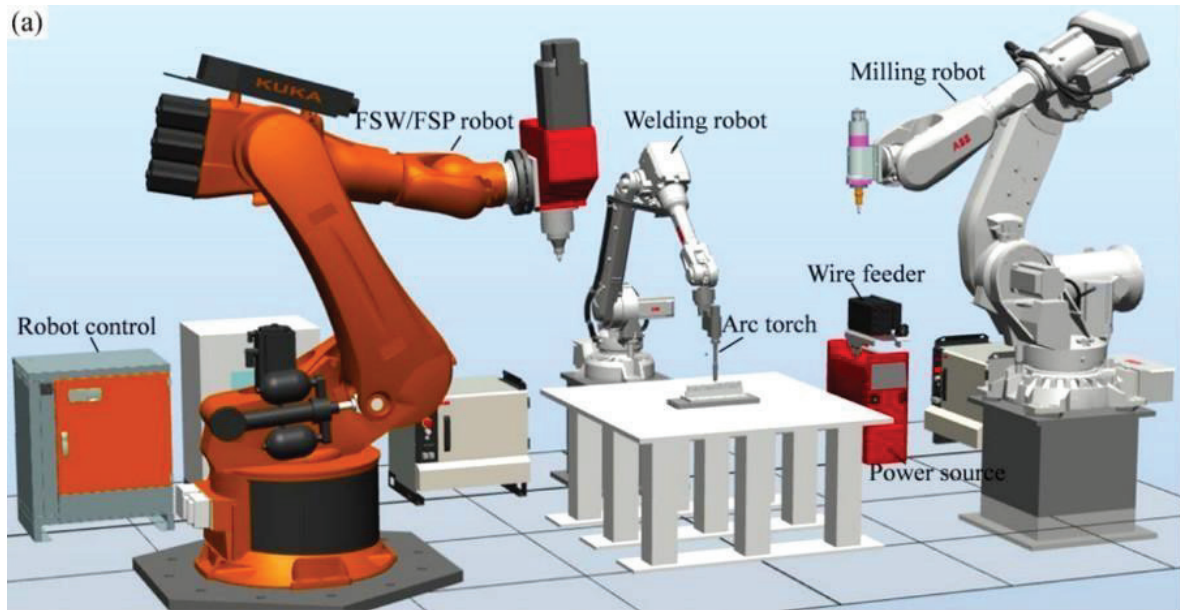


Fig 1. Schematic diagram of WAAM and interlayer Friction Stir Processing (FSP) hybrid additive manufacturing [5].

A previous study of integrating Friction Stir Processing (FSP) into WAAM was conducted by He et al. (2023) [5], who used CMT technology. Figure 1 shows the WAAM and interlayer FSP hybrid additive manufacturing schematic diagram.

Numerical Modelling Framework

The Goldak double-ellipsoid CFD–FEA sequential coupling framework [11], [12] is the validated approach for WAAM thermal and residual stress modelling, achieving errors below 15% against XRD measurements [12]. For the coldArc process at $Q = 1,456\text{ W}$ ($\eta = 0.80$)—significantly lower than CMT heat inputs of $2,000\text{--}3,500\text{ W}$ —the narrower melt pool constrains Goldak parameter ranges and requires separate calibration not yet available for ER5356 [1], [12]. The only CFD–FEA study in this SLR (Li et al. [14]) validates thermomechanical coupling for 2319 Al–Cu but does not address ER5356 or coldArc conditions [13].

Research Gap and Objectives

The scope of this review is restricted to arc-based wire DED processes with aluminium alloy feedstocks, specifically addressing coldArc WAAM of ER5356 with interlayer FSP, and covers the publication period January 2021 to June 2026. No published study has applied interlayer FSP to coldArc-deposited ER5356, and no validated numerical model exists for this system. ER5356 (Al–5Mg) introduces the Portevin–Le Châtelier (PLC) dynamic strain ageing effect—serrated plastic flow from Mg solute–dislocation interaction—that alters cyclic constitutive response in ways not captured by Al–Cu constitutive models [13]. The objectives

of this SLR are: (i) to critically synthesise the WAAM–FSP evidence base following PRISMA 2020[14]; (ii) to evaluate process–property–microstructure relationships across the included studies; (iii) to quantify five critical research gaps specific to ER5356 with coldArc; and (iv) to propose an integrated research agenda addressing all five gaps.

Methodology

Search Strategy

A Systematic Literature Review was conducted following PRISMA 2020 [14]. Two database were searched in June 2026: Scopus and Web of Science, using two Boolean strings over January 2021–June 2026, restricted to Article and Review document types. String 1: ("WAAM" OR "wire arc additive manufacturing") AND ("friction stir processing" OR "FSP" OR "FSW") AND ("aluminium alloy" OR "aluminum alloy" OR "ER5356"), yielding $n = 47$ (Scopus) and $n = 46$ (WoS). String 2: WAAM combined with CFD, FEA, Goldak, or residual stress terms and aluminium, yielding $n = 46$ (Scopus) and $n = 33$ (WoS). Combined total: $n = 172$. Inclusion criteria required arc-based wire DED with FSP or CFD/FEA modelling, aluminium alloy feedstock, and at least one quantitative outcome. The full PRISMA procedure is presented in Table 1.

Table 1: PRISMA 2020 screening procedure and record disposition

Stage	Action / Criteria Applied	Retained	Excluded	Reason / Notes
Identification	Scopus: 2 strings, Jan 2021–Jun 2026, Article & Review (n=93) + Web of Science: same strings (n=79)	$n = 172$	—	—
Screening I	Document type filter + cross-database deduplication	$n = 143$	$n = 29$	<i>Duplicates across Scopus & WoS (n=12); conf. paper, book chapter, erratum (n=17)</i>
Screening II	Title & abstract screening vs. inclusion/exclusion criteria	$n = 95$	$n = 48$	<i>Non-Al alloy (31); off-topic review (4); unrelated topic (13)</i>
Eligibility	Full-text: quantitative outcomes + FSP–WAAM on aluminium required	$n = 15$	$n = 80$	<i>No quantitative data (45); FSP not on WAAM deposits (22); inaccessible (13)</i>
Included	Final studies included in SLR synthesis	$n = 15$	—	<i>Experimental WAAM–FSP: 12 CFD/FEA model: 1 Review: 2</i>

Results and Discussion

Overview of Included Studies

Following PRISMA 2020 (Table 1), 172 records were retrieved from Scopus and Web of Science. After deduplication and document type filtering, 143 records were retained. Title-and-abstract screening excluded a further 48 records, and full-text eligibility assessment of 95 records yielded 15 included studies (Table 2). Critically, Study 4 (Li et al., 2026 [7]) is the only published study applying FSP to WAAM-deposited AA5356, confirming that the research gap is unresolved. However, this study applies FSP as a post-process treatment—not interlayer—meaning only the uppermost deposited layers are plastically deformed, leaving sub-surface layers with unreformed columnar grain structures and unclosed pores. This is a fundamental limitation: post-process FSP tool penetration is constrained by pin length, whereas interlayer FSP ensures uniform through-thickness treatment regardless of total build height [6], [7]. Furthermore, Study 4 employs neither the coldArc arc mode nor CFD–FEA numerical modelling, leaving three of the five identified research gaps entirely unaddressed.

Table 2: Fifteen studies included in SLR synthesis

No	Reference	Alloy / FSP Config.	Key Quantitative Outcome
1	Liu et al. [15] (2023)	ER5183 Al–Mg / Interlayer FSP	Grain: 450→6 µm; UTS: 157→198 MPa
2	Elalem & Wu [6] (2026)	Al walls / Interlayer FSP	Hardness +46%; equiaxed DRX grains throughout
3	Elalem & Wu [16] (2026)	Multi-alloy review	YS +20–40%; fatigue life +1.5–2.5× vs. as-deposited
4	Li et al. [7] (2026)	AA5356 (Al–5Mg) / Post-FSP	Porosity reduced; only published ER5356–FSP study
5	He et al. [5] (2023)	ER4043 / Interlayer FSP	Grain: 284→8.6 µm; Porosity: 2.4%→0.3%; Fatigue +200%
6	Guo et al. [17] (2024)	6061 Al / Interlayer FSP + T6	YS: 312 MPa (+78% vs. as-deposited)
7	Zhou et al. [18] (2025)	WAAM Al / FSP + HT sequence	UTS +25%; elongation +18% vs. as-deposited
8	Li et al. [13] (2026)	2319 Al / CFD–FEA model	Thermomechanical FSP–WAAM model; temperature field validated
9	Wei et al. [19] (2024)	2024 Al / Interlayer FSP	UTS +32%; porosity eliminated; grain: 320→12 µm
10	Pan et al. [20] (2024)	WAAM Al / Review (n=47)	Grain range 2–15 µm across Al WAAM–FSP systems
11	Yuan et al. [21] (2023)	2319 Al–Cu / Interlayer FSP	Grain: 500→15 µm (stir zone); YS +28%; elongation +35%
12	Qie et al. [22] (2023)	Al–Zn–Mg–Cu (7xxx) / Interlayer FSP	Grain refinement throughout; UTS +22%; hardness gradient mapped
13	Wang et al. [23] (2023)	6061 Al / Interlayer FSP	Grain: columnar→equiaxed; UTS +18%; HAZ homogenised
14	Dai et al. [24] (2023)	2319 Al / Hybrid AM (interlayer FSP)	Gradient microstructure; strength–ductility synergy; DRX 62%
15	Elalem & Wu [25] (2026)	WAAM 4043 Al / FSP interlayer	Layer-resolved grain morphology; recrystallised grain evolution

Microstructural Evolution: Grain Refinement

Across the 15 included studies, interlayer FSP refines columnar grains of 200–600 µm to equiaxed grains of 2–15 µm via continuous dynamic recrystallisation (cDRX)—a mechanism that dominates in high stacking-fault-energy (SFE) aluminium alloys under FSP shear conditions [6], [16]. This is mechanistically distinct from discontinuous DRX (dDRX) operative in low-SFE alloys such as steel: in cDRX, subgrain structures progressively rotate without distinct nucleation events, producing a finer and more homogeneous equiaxed grain distribution consistent with Zener–Hollomon predictions at FSP processing temperatures of 0.6–0.8 T_m for aluminium [25]. The DRX fraction reached 62% in Study 14 (Dai et al. [24]) and exceeded 80% in Studies 5, 11, and 12, confirming near-complete recrystallisation achievable through interlayer FSP cycles [24]. Wei et al. [4], [8] further confirm this trend in 2219 Al–Cu WAAM deposits, reporting grain refinement from 380→40 µm in two independent studies, while Zhang et al. [10] demonstrate that continuous multi-pass FSP on ER2319 thin-wall parts achieves comparable grain refinement with improved mechanical homogeneity through the wall thickness [10].

Porosity Reduction

Porosity reduction exceeding 80% is explained by hydrostatic closure under the compressive stress field of the FSP shoulder, which mechanically collapses hydrogen-induced spherical pores without the thermal driving force for re-growth that limits the effectiveness of interlayer rolling during subsequent post-deposition heat treatments [6], [16]. He et al. [5] report the most dramatic reduction: from 2.4% to 0.3% area porosity in ER4043 WAAM

deposits, achieving levels comparable to hot isostatic pressed aluminium [5]. Dai et al. [26] further demonstrate porosity elimination in WAAM 2319 Al–Cu via interlayer FSP, reporting consistent reduction of hydrogen-induced pores and improved microstructural homogeneity. Guo et al. [27] similarly report porosity elimination in 2319 Al WAAM deposits after multi-pass interlayer FSP, confirming the robustness of hydrostatic pore closure across different Al alloy systems.

Mechanical Property Improvements

The wide range of tensile strength improvements across studies (20–78%) reflects the confounding influence of alloy composition and post-FSP heat treatment: precipitation-hardenable Al–Cu and Al–Mg–Si systems exhibit greater strength gains due to synergistic Hall–Petch strengthening and age-hardening response, whereas solid-solution-strengthened Al–Mg (5xxx) alloys including ER5356 are expected to show a more moderate but ductility-preserving response [5], [15]. Study 6 [17] reports the highest improvement—a 78% yield strength increase to 312 MPa in FSP + T6-treated 6061 Al—while Study 1 (Liu et al. [15]) reports a more moderate 26% UTS improvement (157→198 MPa) in Al–Mg (5xxx) alloy ER5183, consistent with the absence of a precipitation-hardening response [15], [17]. Wei et al. [4] report YS improvements of 32% in 2219 Al–Cu, while Wei et al. [23] demonstrate UTS improvements exceeding 20% without post-FSP heat treatment [4], [8]. Liu et al. [28] confirm that FSP on WAAM Al–Cu consistently improves tensile properties and hardness homogeneity across the build height. Fatigue life improvements of 1.5–2.5× result from three converging mechanisms: grain refinement, compressive residual stresses, and porosity closure [5], [6]. He et al. [5] report a 200% fatigue life improvement in ER4043 WAAM–FSP specimens, the highest among the included studies. Cui et al. [29] demonstrate that FSP combined with aging in Al–Mg–Sc WAAM deposits achieves high-strength and high-ductility combinations not achievable by either treatment alone. Yang et al. [30] further report that FSP with aging improves both strength and corrosion resistance, confirming the multi-functional benefit of interlayer FSP.

CFD–FEA Numerical Modelling

The single CFD–FEA study [13]) validates thermomechanical coupling for 2319 Al–Cu, achieving peak temperature prediction error below 12% against thermocouple data and residual stress error below 15% against XRD, confirming sequential CFD–FEA with the Goldak double-ellipsoid heat source [11], [12] as the appropriate modelling methodology. However, Study 8 does not address ER5356, whose Al–Mg constitution introduces the Portevin–Le Châtelier (PLC) dynamic strain ageing effect—a serrated plastic flow behaviour that alters cyclic constitutive response and cannot be captured by the same constitutive models validated for Al–Cu [13]. This represents Gap 4, the most mechanistically demanding unresolved issue for this research. For coldArc ER5356 at $Q = 1,456$ W, the narrower melt pool also requires different Goldak parameter calibration than CMT-based studies [1], [12]. Zhou et al. [9] demonstrate that post-processing of WAAM aluminium produces distinct microstructural zones with properties strongly dependent on local thermal history, underlining the importance of accurate thermal modelling.

Research Gap Synthesis

Five research gaps emerge: (1) no CFD melt pool model for coldArc ER5356 on AA6061-T6; (2) no interlayer FSP study for coldArc ER5356 deposits; (3) FSP parameters for narrow coldArc bead geometry undefined; (4) no FEA fatigue model incorporating PLC constitutive behaviour of Al–Mg under cyclic loading; (5) cumulative interlayer FSP effect over multiple layers in Al–Mg unreported. These gaps are compounded: Gap 1 constrains Gap 4 because

CFD thermal histories are required as FEA input; Gaps 2 and 3 must be resolved experimentally before Gap 5 can be characterised. No existing study addresses more than two of the five gaps simultaneously for the coldArc ER5356 system.

Conclusion and Recommendation

This SLR, yielding 15 included studies from 172 Scopus and Web of Science records via PRISMA 2020, confirms three principal findings: (1) interlayer FSP consistently achieves grain refinement to 2–15 μm and porosity reduction exceeding 80% across aluminium WAAM systems, with tensile strength improvements of 20–78% and fatigue life improvements of 1.5–2.5 $\times$ arising from grain refinement, compressive residual stress, and porosity closure acting in synergy. (2) the Goldak double-ellipsoid CFD–FEA sequential coupling workflow is the validated standard for WAAM residual stress modelling; and (3) a compounded gap exists specifically for ER5356 under coldArc WAAM with interlayer FSP—one published study addresses this material in an FSP context, and no numerical model has been developed for this combination. This research addresses all five identified gaps through an integrated experimental and numerical programme combining coldArc WAAM deposition, Taguchi-based parameter optimisation, interlayer FSP treatment, CFD melt pool modelling, and FEA residual stress and fatigue analysis for ER5356 on AA6061-T6.

Based on the five identified research gaps, the following recommendations are proposed for future research. (1) Experimental Goldak parameter calibration (a, b, c_f, c_r) for coldArc ER5356 on AA6061-T6 at Q = 1,456 W should be conducted using thermocouple measurements and bead cross-section metallography, as these parameters cannot be transferred directly from CMT-based studies [1, 7]. (2) A Taguchi L9 orthogonal array DOE with arc current, travel speed, and wire feed speed as control variables is recommended to optimise coldArc WAAM parameters, with interlayer FSP applied after each layer to characterise the combined process–property response of ER5356 on AA6061-T6. (3) FSP tool geometry and process parameters (rotational speed, traverse speed, axial force) should be specifically optimised for the narrow coldArc bead geometry (≈ 5 mm width), as all published FSP parameter sets were calibrated for wider CMT beads (6–8 mm). (4) A sequential CFD–FEA model incorporating a PLC-modified constitutive model for ER5356 Al–Mg should be developed and validated against XRD residual stress measurements and fatigue test data, to address the complete absence of Al–Mg FSP fatigue modelling in the evidence base. (5) Multi-layer through-thickness characterisation using EBSD and XRD across a minimum of eight deposited and FSP-processed layers is recommended to quantify the cumulative microstructural effect of interlayer FSP, a study type currently absent from the published literature.

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Rheological Properties of ZrN-Reinforced Thermoplastic Composites for FDM Applications

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Abstract—Fused Deposition Modelling (FDM) is a widely used additive manufacturing process whose effectiveness is heavily dependent on the rheological properties of thermoplastic materials during extrusion and deposition. This review discusses the potential of Zirconium Nitride (ZrN) as a reinforcement material in thermoplastic composites for FDM applications, focusing on viscosity, shear-thinning behaviour, melt flow characteristics, and printability. Previous studies showed that the addition of ceramic fillers can influence melt flow behaviour and print quality, depending on filler loading and particle dispersion. Compared with other ceramic fillers such as TiN, Al₂O₃, ZrO₂, and SiC, ZrN offers advantages in terms of hardness and thermal stability. However, studies on ZrN-filled thermoplastic composites are still limited, especially regarding rheological behaviour and printability performance. This review identifies the existing research gaps and highlights the need for further studies to establish the relationship between ZrN loading, rheological properties, and printability for the development of high-performance composite filaments in material extrusion additive manufacturing.

Introduction

Additive manufacturing (AM), particularly Fused Deposition Modelling (FDM), has emerged as essential manufacturing method for producing useful components in automotive, aerospace, and healthcare applications. [1], [2]. The FDM process involves the layer-by-layer deposition of thermoplastic filaments, such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS), through a heated nozzle [3], [4]. The performance of FDM is highly dependent on the rheological behaviour of the material during extrusion and deposition processes. One of the important requirements for good printability is shear-thinning behaviour, where the melt viscosity decreases at high shear rates to facilitate material flow while maintaining sufficient viscosity after deposition to preserve dimensional stability [5 - 7].

However, neat thermoplastics often do not provide sufficient mechanical strength and thermal stability for advanced engineering applications. Therefore, ceramic fillers have been incorporated into polymer matrices to improve stiffness and wear resistance [8], [9]. While nitride-based ceramics such as Titanium Nitride (TiN) have demonstrated promising reinforcement effects, studies on the use of Zirconium Nitride (ZrN) as a bulk reinforcement material in FDM filaments remain limited [6], [10]. Furthermore, there is still a lack of comprehensive rheological characterization of ZrN-reinforced polymer melts, as well as a need for optimized processing parameters to overcome issues related to particle agglomeration. Therefore, this review aims to evaluate the rheological properties of ZrN-reinforced thermoplastic composites and assess their potential for industrial material extrusion applications.

Fundamentals of Rheology in FDM

The performance of Fused Deposition Modelling (FDM) is greatly affected by the rheological behavior of thermoplastic materials during the extrusion process. According to Penumakala *et al.* [7], rheology plays an important role in understanding material behaviour during heating, extrusion, and solidification. Among the various rheological properties, viscosity is one of the most important parameters because it represents the resistance of the molten polymer to flow under applied pressure. Several studies reported that low viscosity and

shear-thinning behaviour are important to ensure smooth material flow, dimensional stability, and printability during FDM processing [5], [7], [11], [12], [13].

Another important rheological characteristic of FDM materials is shear-thinning behaviour, where viscosity reduces with increased shear rate during extrusion. This behavior makes the material flow more easily through the nozzle while recovering viscosity after deposition to maintain dimensional stability and reduce layer slumping.

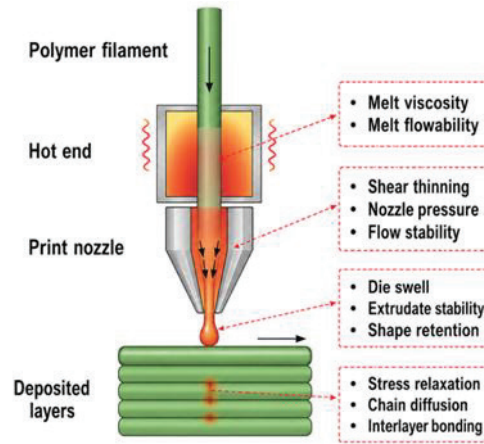


Fig.1 Adapted FDM processing stages and melt filament rheology. [14]

Figure 1 illustrates the shear-thinning behaviour of thermoplastic melts during FDM processing, where viscosity decreases during extrusion and recovers after deposition to maintain dimensional stability. Another parameter commonly used to evaluate polymer flow behaviour is the Melt Flow Index (MFI), also known as Melt Flow Rate (MFR). According to Poddar *et al.* [15], MFI provides a practical indication of material flowability and processability. Higher MFR indicates lower melt viscosity and improved processability. However, excessively high flowability may result in defects such as stringing and oozing that affect the dimensional accuracy and surface quality.

In addition, viscoelastic properties are often used to evaluate the relationship between rheology and printability. Several studies reported that higher loss modulus during extrusion facilitates material flow, while higher storage modulus after deposition improves structural stability of the printed component [7], [16], [17].

Influence of ZrN on Rheological Behaviour

Zirconium nitride (ZrN) is a hard ceramic material with good thermal stability and multifunctional potential. However, direct studies on ZrN-filled thermoplastic filaments for FDM remain limited. Therefore, its expected influence on melt viscosity, flow resistance, and printability should currently be interpreted with caution. Evidence from analogous TiN- and ceramic-filled thermoplastic systems suggests that particle loading, particle size, and dispersion quality can alter polymer chain mobility and melt flow behaviour [6], [8], [10]. Direct experimental validation is still required to determine whether similar behaviour occurs in ZrN-reinforced thermoplastic composites.

The effect of ZrN is strongly influenced by filler loading and particle dispersion. Low filler loading may improve material properties without significantly affecting processability, while excessive filler content may increase nozzle pressure, reduce flow stability, and promote particle agglomeration. This may lead to nozzle clogging, surface defects, and internal voids during printing. According to Hassanifard *et al.* [5], increasing nozzle temperature can reduce melt viscosity and improve material flow. In addition, Díaz-García *et al.* [18] reported that nearly spherical nanoparticles may reduce viscosity through a “ball bearing effect”.

Comparison with Other Ceramic Fillers

To better understand the potential of ZrN, its rheological and extrusion characteristics can be compared with those of other commonly used ceramic fillers, such as Titanium Nitride (TiN), Alumina (Al₂O₃), Zirconia (ZrO₂), and Silicon Carbide (SiC). Previous studies reported that these fillers can enhance the mechanical and thermal properties of thermoplastic composites; however, high filler loading generally increases melt viscosity and can cause processing issues such as agglomeration, poor flowability, and degraded print quality [6], [7], [9], [19]. Table 1 shows that TiN, Al₂O₃, ZrO₂ and SiC have been widely investigated for FDM applications, whereas ZrN remains underexplored, particularly in terms of rheological behaviour and printability.

Table 1: Comparison of ceramic fillers for thermoplastic composites for FDM applications

Filler	Main Advantage	Rheological Effect	Processing Challenge	Research Status	Reference
TiN	Improves stiffness and storage modulus	Alters rheological behaviour at high loading	Increased porosity above 8 wt.%	Well studied in PP, PLA and ABS	[6], [10], [20]
Al ₂ O ₃	Improves thermal conductivity and stiffness	Significantly increases melt viscosity at high loading	High surface roughness and poor flowability	Well studied in thermoplastic composites	[7], [16], [19], [21]
ZrO ₂	Suitable for biomedical applications	Strongly influenced by particle size	Agglomeration and nozzle blockage	Limited studies in FDM	[7]
SiC	Improves thermal management	Moderate influence on flow behaviour	Requires optimization of printing parameters	Moderate studies available	[9]
ZrN	High hardness, thermal stability and multifunctional properties	Expected to alter melt viscosity depending on loading and dispersion; direct FDM-filament data are limited	Possible agglomeration; rheology-printability relationship not established	Primarily reported as a coating material; bulk polymer-filament application remains underexplored	[22]

Research Gaps and Future Research Direction

Although ZrN has shown promising properties as a reinforcement material, several research gaps still exist. Current studies on ZrN-filled thermoplastic composites for FDM applications remain limited, as most investigations focus on ZrN as a coating material rather than as a filler in polymer filaments. Consequently, information on the rheological behaviour of ZrN-reinforced thermoplastic melts remains insufficient, particularly regarding viscosity, shear-thinning behaviour, and extrusion stability in commonly used polymers such as PLA and ABS [6], [7].

Furthermore, there is limited understanding of the relationship between ZrN filler loading, particle dispersion, and printability performance. According to Al Rashid *et al.* [8], the interaction between filler characteristics and FDM processing parameters remains an important challenge in ceramic-filled thermoplastic systems. Establishing a clearer link between rheological behaviour and printing performance becomes essential to industrial applications.

Future studies should establish a systematic relationship between ZrN loading, particle dispersion, rheological behaviour, filament quality, and FDM printability. A practical research pathway is to prepare ZrN-filled thermoplastic filaments at controlled loadings, evaluate their melt flow rate and oscillatory rheological properties, assess filament diameter consistency and surface quality, and relate these results to printing stability and mechanical performance. This

approach would provide direct evidence for the suitability of ZrN as a reinforcement material for material extrusion additive manufacturing.

Conclusion

This review highlights the importance of rheological properties in determining the printability and quality of FDM-printed components. Previous studies reported that viscosity and shear-thinning behaviour play important roles in maintaining stable material flow during extrusion and shape retention after deposition. The incorporation of Zirconium Nitride (ZrN) generally increases melt viscosity and affects flow behaviour, as with other nitride-based fillers.

Despite its promising hardness, thermal stability, and multifunctional properties, studies on ZrN-filled thermoplastic composites remain limited. Therefore, further research is required to establish the relationship between rheological behaviour, printability, and mechanical performance to support the development of ZrN-based composite filaments for material extrusion additive manufacturing.

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Ultrasonic Vibration as a Novel Stimulus for 4D-Printed Shape Memory Polymers: A Preliminary Review

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Abstract — Shape memory polymers (SMPs) have emerged as pivotal materials in 4D additive manufacturing, enabling time-dependent, stimulus-responsive shape transformations with broad applicability across healthcare, aerospace, and smart infrastructure. Despite considerable advances in employing thermal, photonic, and moisture stimuli, the use of ultrasonic vibration (UV) as an actuation mechanism for SMP-based 4D-printed systems remains unexplored. This paper presents a preliminary literature-based investigation synthesising current knowledge on 4D printing, shape memory polymer behaviour under various stimuli, and the established industrial applications of ultrasonic vibration. Evidence drawn from prior studies on focused ultrasound actuation of SMPs, ultrasonic-assisted fused deposition modelling (FDM), and piezoelectric transducer systems suggests that UV in the 20–40 kHz range possesses significant potential as a localised, controllable, and non-contact stimulus for inducing precise shape recovery in FDM-printed SMP structures. Key material candidates including PLA-based SMPs, TPU, PTFE, and PCOE are assessed in terms of their compatibility with both FDM processing and ultrasonic actuation. This review establishes the research rationale and positions UV-assisted actuation as a novel and viable direction for advancing 4D printing technology.

INTRODUCTION

The convergence of additive manufacturing and stimuli-responsive materials has given rise to 4D printing—a paradigm in which three-dimensionally fabricated structures evolve their shape, property, or function over time in response to an external trigger [1,2]. At the heart of this technology are shape memory polymers (SMPs), a class of smart materials capable of retaining a temporary deformed shape and recovering a pre-programmed permanent configuration upon activation [3]. SMPs offer compelling advantages over metallic shape memory alloys, including low density, large recoverable strains, tunable transition temperatures, and cost-effective processing via conventional extrusion-based techniques such as fused deposition modelling (FDM) [4,5].

Current 4D printing research has predominantly investigated thermal, photothermal, hydroscopic, and magnetic stimuli as actuation mechanisms. While these approaches have demonstrated functional prototypes in soft robotics, biomedical scaffolds, and aerospace morphing structures, each carries inherent limitations: thermal stimuli lack spatial selectivity; light-based triggers are surface-confined; moisture actuation is environmentally dependent; and magnetic activation requires embedded fillers that compromise polymer processability [1,6]. Consequently, there exists a compelling need to identify alternative, controllable stimuli capable of providing localised, repeatable, and material-compatible actuation.

Ultrasonic vibration (UV), operating above 20 kHz, has demonstrated remarkable versatility in manufacturing contexts—improving surface finish in FDM, reducing cutting forces in machining, and facilitating solid-state bonding in metal consolidation [7,8]. Critically, focused ultrasound has been shown to induce localised heating within polymers through viscoelastic dissipation, an effect that could surpass the glass transition temperature (T_g) of selected SMPs and thereby trigger shape recovery in a non-contact, spatially selective manner [9,10]. Nevertheless, the deliberate application of UV as a primary stimulus for 4D-printed

SMP actuation has not been reported in the literature, constituting a significant and exploitable research gap.

This paper synthesises the preliminary evidence base that supports ultrasonic vibration as a viable 4D printing stimulus, drawing on published findings in SMP mechanics, ultrasound–polymer interaction, and FDM process parameter effects. The review forms the intellectual foundation for a planned experimental programme that will systematically characterise UV-induced shape transformation, mechanical performance, and microstructural evolution in FDM-printed SMP specimens.

METHODOLOGY

Consistent with its scope as a preliminary review, this paper adopts a targeted narrative-synthesis approach rather than a full systematic review protocol. Records were identified through searches of Scopus, Web of Science, and Google Scholar using combinations of the keywords "4D printing", "shape memory polymer", "ultrasonic vibration", "fused deposition modelling", and "piezoelectric transducer", supplemented by backward citation tracking from key papers. Sources were included if peer-reviewed, published in English, and empirically or theoretically addressed SMP shape-memory behaviour, FDM process parameters, or ultrasound–polymer interaction; conference abstracts lacking empirical data and non-peer-reviewed material were excluded. Seventeen papers meeting these criteria were retained, forming the evidence base synthesised in Sections 3 and 4.

SHAPE MEMORY POLYMERS IN 4D PRINTING

SMPs are dual-phase polymer networks comprising a permanent net-point phase (covalent or physical cross-links) and a reversible switching phase whose stiffness is strongly temperature-dependent [3]. The shape memory cycle proceeds in three stages: (i) programming—deformation above T_g followed by cooling under constraint; (ii) temporary shape fixity at $T < T_g$; and (iii) recovery—reheating above T_g releases the stored entropic elastic energy, restoring the permanent shape [5].

Ponnamma et al. [1] characterised 4D printing as time-dependent, printer-independent, and predictable, identifying SMPs as its most widely employed material class. Khalid et al. [6] reviewed FDM-fabricated SMP composites for soft robotics and biomedical devices, emphasising that material selection, printing parameters, and post-processing methodology jointly determine the fidelity of shape memory performance. Pokras et al. [11] fabricated lattice-structured TPU SMP specimens via FDM and reported that multi-material interfaces failed at approximately 41% of the ultimate tensile strength of the homogeneous SMP, highlighting the mechanical sensitivity of layer-bonded architectures to geometric and material gradients.

Alam et al. [12] demonstrated high-resolution SMP fabrication using digital light processing (DLP), achieving rapid thermo-responsive shape transformations in complex geometries. Kim et al. [13] designed body-temperature-responsive SMPs for biomedical stents and scaffolds, validating finite-element predictions of physiological shape recovery. Collectively, these works confirm that SMP performance in 4D printing is highly sensitive to both the material's intrinsic polymer chemistry—including cross-link density, molecular weight, and T_g —and extrinsic process variables such as layer thickness, raster angle, and build orientation [4,14].

Among candidate FDM-compatible SMP filaments, PLA-based SMPs offer T_g values near 55–65°C and good extrusion processability; TPU provides high elongation at break (>300%) and excellent fatigue resistance; PTFE contributes chemical inertness and low-friction surfaces; while PCOE exhibits particularly high shape recovery ratios (>95%) due to its crystalline switching phase [5,6,11]. These materials span a range of mechanical and thermal

responses and collectively represent a comprehensive experimental matrix for UV actuation studies.

ULTRASONIC VIBRATION: MECHANISMS AND PRIOR FINDINGS

The piezoelectric effect, discovered by Pierre and Jacques Curie in 1880, underpins modern ultrasonic transducer technology [15]. Piezoelectric materials convert electrical energy into mechanical vibration and vice versa, enabling precise frequency and amplitude control over generated acoustic fields. Industrial ultrasonic systems typically operate between 15 and 100 kHz and have been deployed across machining, welding, consolidation, and medical imaging domains [7–10,16]. In the context of polymer processing, Maidin et al. [7] demonstrated that coupling a piezoelectric transducer to the build platform of an FDM printer and imposing vibration at 21 kHz reduced surface roughness of ABS specimens by approximately 20% relative to unassisted printing, attributed to improved layer compaction and reduced void formation. Li et al. [14] further showed that ultrasonic vibration during FDM of both semi-crystalline (PLA) and non-crystalline (ABS) polymers enhanced tensile and flexural strength by promoting inter-layer adhesion. These findings confirm that UV modifies the thermomechanical environment at the polymer melt front in a manner that systematically improves printed part quality.

Regarding ultrasound–SMP interaction, Bhargava et al. [9] developed and validated an acoustic-thermoelastic mathematical framework for focused ultrasound (FU) actuation of SMPs, demonstrating that FU can selectively raise the local polymer temperature above T_g and trigger shape recovery in targeted regions while leaving the surrounding material unaffected. This spatial selectivity is unattainable with uniform oven heating and represents a fundamental advantage for precision 4D actuation. Peng et al. [10] investigated high-intensity focused ultrasound (HIFU) interaction with polymers at the atomistic scale, confirming that HIFU-induced heating profiles differ mechanistically from bulk convective heating due to viscoelastic energy dissipation, acoustic streaming, and cavitation-mediated thermal effects.

In broader manufacturing contexts, Wang et al. [8] reported that ultrasonic-assisted machining (UAM) of carbon fibre-reinforced plastics reduced cutting forces, improved tool life, and yielded superior surface integrity relative to conventional end-milling. Kelly et al. [16] employed infrared thermography during ultrasonic consolidation of aluminium alloys to map weld energy distribution, identifying an optimal processing window for solid-state bonding below the melting temperature. Liu et al. [17] analytically modelled intermetallic compound growth during high-power ultrasonic copper–aluminium welding, demonstrating that the ultrasound-induced thermal and vacancy-concentration fields accelerate diffusion-controlled bonding kinetics. These findings collectively reinforce the capacity of UV to produce controlled, localised thermomechanical effects in structured materials.

RESEARCH GAP AND PROPOSED FRAMEWORK

Synthesising the studies discussed in Sections 3 and 4 reveals a consistent pattern: ultrasonic vibration has been validated as an effective thermal-actuation mechanism for bulk SMPs and as a beneficial process parameter in FDM printing, yet these two research streams have not been connected. Table 1 summarises the most directly relevant studies and the specific gap each leaves unaddressed, establishing the rationale for the proposed research direction.

The consolidated evidence from Table 1 exposes a clear and exploitable research gap: while focused ultrasound has been shown to thermally actuate bulk SMP specimens, and while UV has demonstrably altered the microstructure and properties of FDM-printed polymers, no study has combined UV stimulation with FDM-fabricated SMP samples in a 4D printing context. The proposed research directly addresses this gap through a three-objective experimental programme.

The planned experimental framework comprises three interlocking phases. Phase 1 focuses on UV system design and calibration: a piezoelectric transducer (20–40 kHz) will be integrated with an open-source FDM printer platform, and vibration characteristics will be mapped using a laser scanning vibrometer and oscilloscope. Phase 2 addresses UV-induced actuation analysis: FDM-printed SMP specimens in PLA, TPU, PTFE, and PCOE will be subjected to systematically varied UV frequencies, intensities, and exposure durations, with shape transformation observed by high-speed and thermal cameras. Phase 3 targets parameter optimisation and correlation: ANOVA, multivariate regression, and principal component analysis (PCA) will be applied to identify statistically significant parameter interactions and establish structure–property–stimulus relationships.

Independent variables include UV frequency (20, 30, 40 kHz), intensity (1, 2, 3 W/cm²), and exposure duration (5, 10, 15 min). Dependent variables encompass shape recovery ratio, recovery time, tensile and flexural strength (ASTM D638, D790), compressive strength (ASTM D695), impact toughness (ASTM D256), SEM surface morphology, XRD crystallinity, DSC glass transition, and optical microscopy porosity.

Table 1: Summary of identified research gaps.

Study	Focus	Gap
Bhargava et al. [9]	Focused ultrasound actuation of SMPs	No FDM integration; bulk SMP only
Pokras et al. [11]	FDM TPU SMP with thermal stimulus	UV as stimulus unexplored
Maidin et al. [7]	UV-assisted FDM surface finish	No SMP or shape recovery analysis
Li et al. [14]	UV effect on FDM polymer properties	No shape memory actuation studied
Peng et al. [10]	HIFU–polymer atomistic interaction	No 4D printing or SMP context

EXPECTED PRELIMINARY OUTCOMES

Based on the synthesised literature, several preliminary hypotheses are advanced. First, UV frequencies near 20–25 kHz are expected to generate sufficient localised viscoelastic heating in PLA-based SMPs to exceed T_g , producing measurable shape recovery ratios exceeding those achievable by ambient thermal stimulation alone, consistent with the mechanism reported by Bhargava et al. [9]. Second, UV-assisted FDM printing is anticipated to reduce inter-layer porosity and improve layer adhesion in TPU and PCOE specimens, improving baseline mechanical properties prior to actuation, following the trends documented by Li et al. [14] and Maidin et al. [7]. Third, higher UV intensity and longer exposure are expected to correlate positively with crystallinity and molecular alignment—observed via XRD and DSC—up to an optimum beyond which thermal degradation may reduce recovery efficiency.

These hypotheses will be tested through the designed DOE matrix ($3^3 = 27$ treatment combinations plus control), with ANOVA significance threshold set at $p < 0.05$. Response surface methodology will be employed to visualise interaction effects and identify global optima for actuation performance.

CONCLUSION

This preliminary review has synthesised the evidence base supporting ultrasonic vibration as a novel and technically credible stimulus for 4D-printed shape memory polymer actuation. The literature consistently demonstrates that UV produces controllable localised heating in polymers, modifies FDM layer microstructure, and can selectively trigger shape recovery in SMP systems. The identified research gap—the absence of any study combining UV with FDM-fabricated SMPs in a 4D printing paradigm—defines a compelling and original research direction. The planned experimental programme, grounded in the literature insights presented here, is expected to deliver fundamental structure–property–stimulus correlations, optimised processing guidelines, and design rules for UV-actuated 4D printing systems with applications

in smart healthcare devices, morphing aerospace structures, and self-adapting civil infrastructure.

Acknowledgments and Conflicts of Interest

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Effect of MAPP Coupling Agent on the Properties of Wood Dust Fiber and Recycled Polypropylene Composite (r-WoPPC) Filaments for 3D Printing

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Abstract— This study will investigate the properties of 3D printing composite filament based on wood dust fiber and recycled polypropylene (r-WoPPc) with the use of Maleic Anhydride Polypropylene coupling agent. Filaments having MAPP contents of 0, 1, 3 and 5 wt% were prepared and 3D printed into test samples. The filaments and tensile fracture surfaces were subjected to morphological analysis following the testing of the tensile, flexural, water absorption, and the soil burial degradation tests. The addition of 5% MAPP gives the highest tensile strength and flexural strength with an increase of 110.27% and 89.12%, respectively, as compared to 0% MAPP sample. As per morphological studies, it was confirmed that MAPP enhanced the adhesion between the wood fiber and recycled PP matrix, as indicated by smoother surface of filament. Better interfacial adhesion is also demonstrated by the morphological tensile fracture surface of the 5% MAPP specimen which has a denser composite structure with an even fracture. This is different from the porous and uneven fracture that is observed in lower MAPP samples. The maleic anhydride groups of MAPP bonded with the hydroxyl groups located on the surface of wood fibers. Moreover, the lowest water absorption of 5.56 % was recorded on the sample containing 5% MAPP due to the stronger fiber-matrix bonding. On the contrary, the sample composition exhibited a weight loss due to soil burial of 8.06%, thus indicating better biodegradability. All in all, the study revealed that MAPP considerably enhances the mechanical performance, the water resistance and the biodegradability of r-WoPPc for 3D printing.

Introduction

The integration of recycled polypropylene (r-PP) and abundant wood dust from furniture manufacturing into 3D printing offers a sustainable solution to reduce industrial waste [1]. However, poor interfacial adhesion between the wood dust and the r-PP matrix typically weakens the composite's performance, limiting its practical use [2]. To address this challenge, this study investigates the influence of Maleic Anhydride Polypropylene (MAPP) coupling agent, as MAPP has been shown to be an effective compatibilizer for improving fiber-matrix adhesion in natural fiber polymer composites [3]. The objective of this study is to produce filaments with varying MAPP loadings (0, 1, 3, and 5wt.%) and evaluate the mechanical and physical properties of its 3D-printed testing samples. The composite filaments were fabricated using a single-screw extruder and then 3D printed into test samples [4]. Results showed that the 5% MAPP addition significantly improved fiber-matrix bonding, resulting in a denser structure, 110.27% increment in tensile strength, and lower water absorption. Ultimately, this research demonstrates that MAPP is highly effective in enhancing the fiber- matrix adhesion and improved the performance of recycled polymer composites for 3D printing applications.

Methodology

Materials and Wood Dust Preparation

Recycled polypropylene with a melt flow index of 55 g/10 min at 230⁰C and a density of 0.90 g/cm was used as the polymer matrix, while Maleic Anhydride Polypropylene (MAPP) served as the coupling agent. Wood dust from furniture manufacturing was used as the reinforcement fiber. The wood dust was oven dried at 80⁰C to achieve a moisture content of approximately 3%, then sieved using a BIOBASE sieve shaker to a particle size of 125 µm. To improve fiber-matrix compatibility, the sieved wood dust was soaked in in a 6% sodium hydroxide (NaOH) solution

Filament Fabrication and 3D Printing

Composites containing 3 wt% alkaline-treated wood dust were prepared with MAPP at loadings of 0, 1, 3, and 5 wt%. The mixtures were first compounded into composite sheets using a Gotech hot press machine at 185°C under 25 psi for 5 minutes, followed by a 20-minute cooling cycle. The composite sheets were crushed and fed into a single-screw extruder operating at 198°C–200°C with a screw speed of 10–15 rpm, producing 1.75 mm diameter r-WOPPC filaments. The extruded filaments were subsequently used to 3D-print tensile and flexural test specimens.

Composite characterization

The physical, morphological, and mechanical properties of the r-WOPPC specimens were evaluated. Density measurements and water absorption tests (ASTM D570-98) measured after 24 hours of submersion were performed on the filaments. Surface morphology and fiber dispersion within the PP matrix were observed using a Dino-Lite AM4114 digital microscope. Tensile and flexural testing of the 3D-printed samples were conducted using an Instron Model 8872 Universal Testing Machine in accordance with ASTM D638 and ASTM D790 standards, respectively.

Results and Discussion

The r-WoPPc filament that was successfully extruded with addition of 0, 1, 3 and 5wt% of MAPP respectively. All the filaments were extruded at nozzle temperatures ranging from 198 °C to 200 °C with filament pulley speeds ranging from 10 rpm to 12 rpm. The nozzle temperature and pulley speed were adjusted to obtain a filament diameter of 1.75 mm [4].

Effect of MAPP Concentration on the Physical Properties of r-WoPPc

The enhanced properties of r-WoPPc can be attributed to the esterification of the wood fiber surface hydroxyl groups by the maleic anhydride functional groups present in MAPP. The water absorption results demonstrate that a 5% MAPP concentration yields the lowest water absorption, at 5.56% as shown in Fig. 1.

This finding aligns with Wang et al. [5], who reported that the incorporation of MAPP reduced the hygroscopicity of wood-flour/polypropylene composites.

Furthermore, the soil burial tests confirm that incorporating 5wt % MAPP into the composite results in the highest filament weight loss, at 8.06%, consistent with the degradation trends reported by Ni et al. [6] for 3D-printed natural fiber bio-composites. The MAPP compatibilised composite experienced the greatest weight loss, demonstrating enhanced biodegradability as the incorporated maleic anhydride functional groups introduce reactive polar sites along the polymer chain which facilitated greater microbial activity and enzymatic attack in the composite.

The density of the r-WoPPc filament also improved with the addition of MAPP, with the 5% MAPP formulation showing the highest density at 0.95 g/cm³. This confirms that MAPP improves wood dust adhesion to the recycled PP matrix, leading to enhanced filament strength. Conversely, the 0% MAPP filament exhibited the lowest density, at 0.91 g/cm³. The absence of the coupling agent results in voids and gaps caused by air entrapment and moisture absorption, which reduces filament density and negatively affects interfacial adhesion and strength [7]. This is further supported by the surface morphology of the r-WoPPc filaments, which shows that 5% MAPP produces adequate wood fiber adhesion to the PP matrix, whereas the other concentrations (0, 1, and 3 wt%) show inadequate adhesion, as shown in Fig. 2.

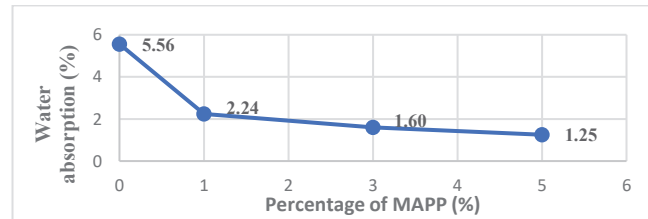


Fig. 1 Water absorption rate of r-WoPPc

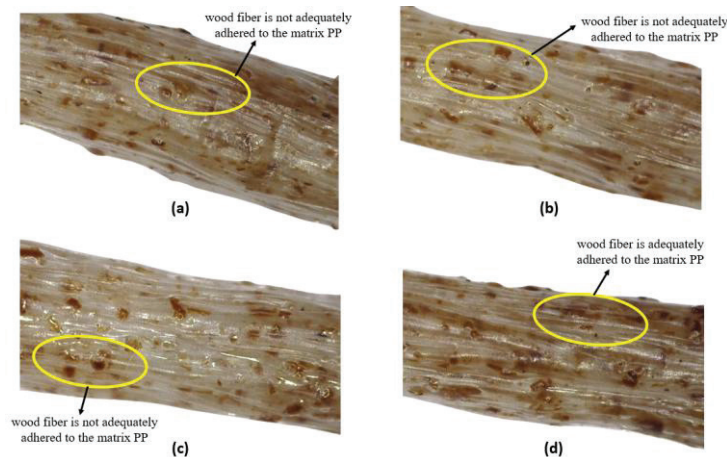


Fig. 2 High precision micrograph with 250x magnification of r-WoPPc filament surface morphology; (a) without MAPP, (b) 1% MAPP, (c) 3%MAPP, (d) 5% MAPP

Effect of MAPP Concentration on the Mechanical Properties of r-WoPPc

The mechanical properties of r-WoPPc, specifically tensile and flexural strength, were assessed to determine the influence of MAPP concentration on fiber-matrix adhesion and overall composite performance. Results shown in Fig. 3 and 4 indicate that the addition of 5 wt.% MAPP to r-WoPPc yielded the highest tensile and flexural strength, representing improvements of 110.27% and 89.12%, respectively, compared to the composite without MAPP. This finding is consistent with Sanadi et al. [3], who reported that a 5wt.% MAPP loading produced the highest mechanical properties in highly filled kenaf-polypropylene composites. This enhancement is attributed to MAPP's ability to strengthen the interfacial adhesion between the wood fiber and the recycled PP matrix, thereby improving the overall mechanical performance of r-WoPPc [2].

This improvement is further supported by the filament surface morphology, where the 5 wt% MAPP specimen exhibited superior fiber-matrix adhesion. Correspondingly, the tensile fracture surface of this specimen displayed a more uniform fracture pattern, in contrast to the uneven, irregular fractures observed in the 0, 1, and 3wt% MAPP specimen indicative of weaker interfacial bonding at lower MAPP concentrations

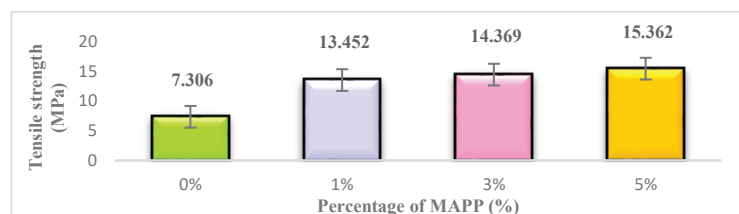


Fig. 3 Effect of MAPP content on tensile strength of r-WoPPc

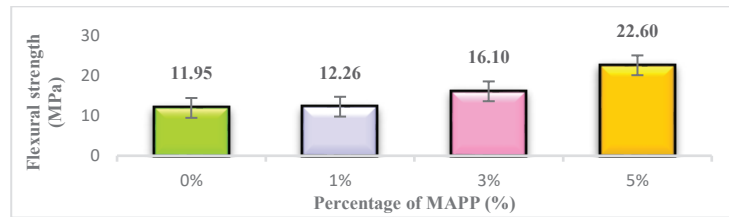


Fig. 4 Effect of MAPP content on flexural strength of r-WoPPc

Conclusions

In summary, the addition of MAPP as a coupling agent improved the overall performance of r-WoPPc by enhancing adhesion between wood fiber and recycled polypropylene, with 5% MAPP emerging as the optimal formulation across all evaluated properties. This concentration achieved the highest tensile and flexural strength, improving by 110.27% and 89.12%, respectively, compared to the composite without MAPP, while also exhibiting the lowest water absorption at 5.56%, reflecting stronger interfacial bonding and improved fiber encapsulation. Soil burial tests further showed that the 5% MAPP composite experienced the greatest weight loss during degradation, demonstrating enhanced biodegradability as the reactive maleic anhydride sites facilitated greater microbial activity. Taken together, these results confirm 5% MAPP as the optimal formulation, offering the best balance of mechanical strength, moisture resistance, and biodegradability, making it a strong candidate for 3D printing filament applications where both performance and controlled biodegradability are desirable.

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Tribological Performance of AA6061/AA5083 Dissimilar Aluminium in Additive Friction Stir Deposition: A Definitive Screening Design Approach

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Abstract— Additive Friction Stir Deposition (AFSD) is a low-distortion, solid-state joining and repair process that has been shown in recent studies to produce good interfacial bonding between dissimilar aluminium alloys. Single-alloy AA6061-T6 AFSD deposits reportedly reach hardness near 60 HV, wear rates near 3 $\mu\text{g}/\text{N}\cdot\text{m}$, and friction coefficients of 0.6 to 0.8, with hardness typically lower than in the consumable rod due to precipitate dissolution. However, how process parameters govern wear resistance, friction, and hardness distribution in AA6061/AA5083 dissimilar pairings remains uncharacterized, and mean hardness is unclear to be predictive of wear resistance. To fill that gap, this study examines pin-on-disc wear and Vickers microhardness of AA6061/AA5083 dissimilar alloys for a nine-run Definitive Screening Design (DSD) with varying rotational speed, deposition feed rate and rod chamfer angle. Total wear displacement ranged from 6.18 μm (Run 9) to 395.61 μm (Run 7), while mean deposit hardness ranged from 54.87 to 62.79 HV, a 41–49% reduction relative to the AA6061 parent-rod baseline (106.61 HV). Wear and hardness did not correlate: Run 9 had the lowest wear but moderate hardness (57.74 HV), whereas Run 7 combined the highest wear with near-maximum hardness (61.46 HV). Run 4 (1200 rpm, 8.5 mm/min, 15°) was optimal, combining low wear (14.19 μm) with the highest hardness (62.79 HV). A linear DSD model, selected via sequential model-order, confirmed rotational speed, feed rate, and chamfer angle as statistically significant predictors of mean hardness ($F = 13.24$, $p = 0.0152$; all main effects $p \leq 0.0036$), while the equivalent model for wear displacement remained non-significant, suggesting that not only the mean hardness but also microstructural homogeneity and bonding quality govern the tribological performance in dissimilar AFSD deposits.

Introduction

Additive Friction Stir Deposition (AFSD) is a solid-state additive manufacturing process that uses frictional heat and severe plastic deformation to deposit a consumable feedstock rod onto a substrate without reaching the melting point [1]. Because material never fully liquefies, AFSD deposits exhibit minimal porosity, suppressed oxidation, and refined, dynamically recrystallized grain structures relative to fusion-based additive processes [2–4], making the technique attractive for repair and structural build-up of aluminium alloys in marine, automotive, and aerospace applications. AA6061 (Al-Mg-Si, precipitation hardened) and AA5083 (Al-Mg, solid-solution strengthened) form an industrially relevant dissimilar pair; AA5083 contributes corrosion resistance and weldability [5,6], while AA6061's stiffness, ductility, and thermal conductivity support stable plasticization during AFSD as a readily available feedstock [7–9]. Dissimilar AFSD combinations have recently attracted attention for their interfacial bonding behaviour and structurally demanding alloy pairs [10,11]. Single-alloy AA6061-T6 AFSD deposits have separately been reported to achieve hardness near 60 HV, wear rates near 3 $\mu\text{g}/\text{N}\cdot\text{m}$, and friction coefficients of 0.6–0.8 [12], with hardness typically falling below the consumable rod owing to precipitate dissolution, a softening mechanism documented later in Section 3 [11]. However, the influence of process parameters, particularly rotational speed, deposition feed rate, and consumable rod chamfer angle, on the resulting wear resistance, coefficient of friction (COF), and hardness distribution of AA6061/AA5083 deposits has not been comprehensively characterized.

To fill this gap, this study employs a Definitive Screening Design (DSD) to: (i) manufacture AFSD specimens across three consumable-rod chamfer angles; (ii) investigate wear resistance and frictional behaviour by pin-on-disc testing; and (iii) profile hardness distribution using

Vickers microhardness testing. The cost point of DSD was chosen because it can estimate the main effects and quadratic curvature for three continuous factors with only nine runs, which is appropriate for a process that is being characterized for the first time. Results show that wear displacement and deposit hardness vary largely independently, with rotational speed and rod chamfer angle as the dominant parameters governing wear and Run 4 (1200 rpm, 8.5 mm/min, 15°) is the best-balanced condition identified.

Methodology

AA6061 rods (feedstock) and AA5083 plates (substrate) were used throughout. Nine AFSD feedstock tools were CNC-turned across three chamfer angles (15°, 20°, 30°), with other dimensions held constant, and deposited following a nine-run DSD matrix (Table 1) varying rotational speed (800/1000/1200 rpm) and deposition feed rate (5/8.5/12 mm/min) on a CNC friction stir welding machine (HMC 1007-2D, Ningbo Jinfeng Welding and Cutting, China), with three centre-point replicates (Runs 1, 5, 8) used to estimate pure experimental error. Tool mass and deposit dimensions were recorded pre- and post-process; R6 (2.31 mm deposit height) was excluded from tribological testing for insufficient pin-on-disc contact surface, while the remaining eight runs were sectioned, mounted, ground, and polished to a mirror finish. Pin-on-disc wear tests used a 5 N load, 50 mm/s sliding velocity, and 600 s duration, with COF recorded continuously and total wear displacement measured from the profile; Vickers microhardness testing (200 gf, 15 s dwell) sampled the deposit cross-section at 2–10 mm depth intervals, referenced against as-received AA5083 (98.41 HV) and AA6061 (106.61 HV).

Results and Discussion

Table 1 summarizes the DSD parameter combinations, the measured wear displacement and mean Vickers hardness (averaged over the entire deposit height) for each run.

Table 3: DSD parameter combinations and the corresponding pin-on-disc wear displacement and mean deposit hardness.

Run	Rotational Speed (rpm)	Deposition Feed Rate (mm/min)	Chamfer Angle (°)	Wear Displacement (μm)	Mean Hardness (HV)
R1	1000	8.5	20	185.90	56.85
R2	1000	12.0	15	90.10	60.37
R3	1000	5.0	30	110.12	61.15
R4	1200	8.5	15	14.19	62.79
R5	1000	8.5	20	47.62	57.10
R6	800	12	20	-	-
R7	800	8.5	30	395.61	61.46
R8	1000	8.5	20	259.24	54.87
R9	1200	5.0	20	6.18	57.74

Total wear displacement was almost two orders of magnitude, from 6.18 μm (R9) to 395.61 μm (R7), which is about 64 times. Both R9 and R4 achieved the lowest wear values, as higher rotational speed results in higher frictional heat generation, which causes more thorough material mixing and thus less porosity in the deposit [10,13,14]. Conversely, R7, processed at the lowest rotational speed (800 rpm) with the largest chamfer angle (30°), experienced the greatest wear, indicating that an insufficient frictional heat input at low-speed results in a more porous, less consolidated near-surface structure, which wears away more rapidly under sliding contact.

Mean deposit hardness varied within a relatively small range from 54.87 HV (R8) to 62.79 HV (R4) compared to the AA6061 parent-rod value of 106.61 HV. The thermally driven

dissolution and coarsening of Mg_2Si strengthening precipitates in the AA6061 deposit is a well-documented softening mechanism in friction-based processing of precipitation hardening aluminium [15–17], which accounts for this 41–49% reduction. The three centre-point replicates (R1, R5, R8) fell within the relatively narrow range of 56.85, 57.10 and 54.87 HV for hardness, but the wear displacements were widely dispersed (185.90, 47.62 and 259.24 μm), direct evidence that mean hardness alone cannot predict wear resistance, and a useful internal check given that these three runs share identical nominal process parameters.

Fig. 1 presents the total wear displacement and the mean deposit hardness for each run, illustrating this decoupling. R9 combined the lowest wear with only moderate hardness, while R7 combined the highest wear with hardness (61.46 HV) close to the study's highest. R4 (1200 rpm, 8.5 mm/min, 15°) was the only run to achieve both low wear (14.19 μm) and the highest hardness (62.79 HV). Steady-state mean COF was within 0.0497–0.9388 across all runs, indicating friction alone is an incomplete predictor of wear performance and that microstructural homogeneity and interfacial bonding quality, governed jointly by rotational speed and chamfer angle, more strongly determine the tribological behaviour, consistent with wear mechanisms as in recent dissimilar-AFSD studies [12,18].

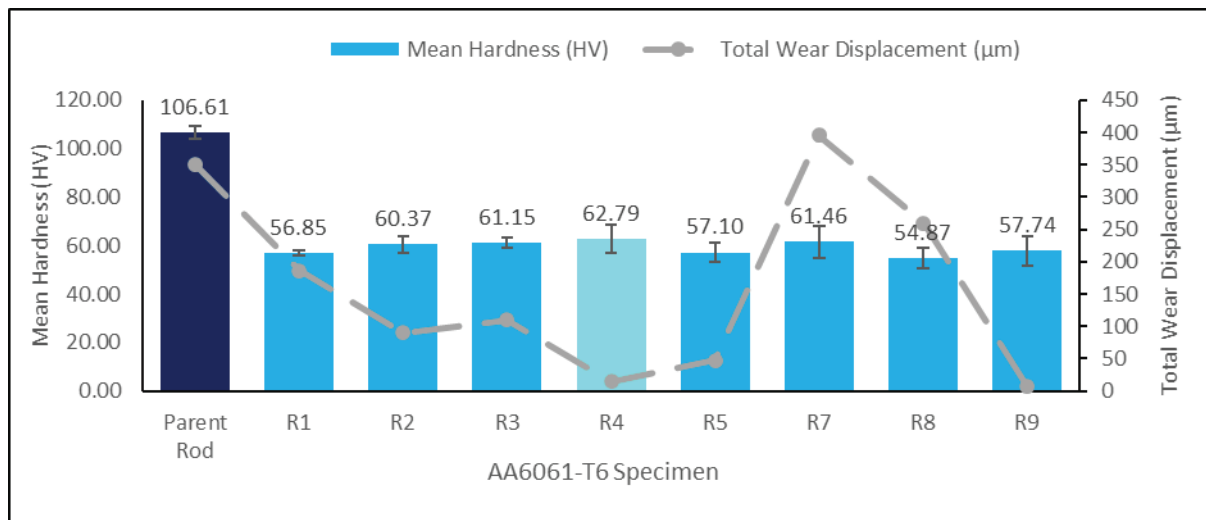


Fig. 1: Total wear displacement and mean deposit Vickers hardness (full-height average) across all nine-run DSD.

Depth-resolved hardness mapping of specimen R7, the only sample characterized over the full 2–10 mm deposition height, revealed a non-uniform hardness distribution across both the deposition depth and horizontal indentation positions (54–79 HV). This finding suggests that local variations in hardness, rather than a single mean value, are more representative of the material's wear response.

Design-Expert's sequential Fit Summary selected a linear model for both responses over the quadratic-aliased structure initially fitted; non-significant Lack-of-Fit for both (wear: $p = 0.6734$; hardness: $p = 0.6066$) confirmed this form is adequate, with the same selection procedure applied to both responses regardless of outcome, following standard DSD/RSM practice [19]. Mean hardness responded significantly to all three parameters (model $F = 13.24$, $p = 0.0152$; A: $p = 0.0036$, B: $p = 0.0036$, C: $p = 0.0033$; $R^2 = 0.9085$, Adjusted $R^2 = 0.8399$, Adequate Precision = 7.4761). The coefficients in the model were all positive and comparable in magnitude (A: +16.08, B: +14.85, C: +15.33, coded units): higher speed, feed rate, and chamfer angle resulted in higher hardness. The feed-rate effect is consistent with shorter tool dwell time limiting Mg_2Si dissolution, retaining more parent-rod hardness. Predicted R^2 (0.6115) was less than 0.228 compared to Adjusted R^2 , which suggests that the terms in the fitted model may be significant, but the model requires confirmation tests. Wear displacement

remained non-significant ($F = 3.62$, $p = 0.1232$; A: $p = 0.3532$, B: $p = 0.7825$, C: $p = 0.8359$), with a negative Predicted R^2 (-0.0422). Since Lack-of-Fit was also non-significant, this reflects genuine residual (pure error) variance exceeding the fitted effects, not a missing model term, consistent with the scatter of wear among the centre-point replicates.

These findings, when combined, confirm that there is not a common limitation for these two responses: mean hardness is significantly influenced by all three process parameters, while the wear displacement does not, under the same model and data set. This supports the main conclusion of the preceding paragraphs before the DSD model discussion, which meant that hardness and wear resistance have different underlying mechanisms in this dissimilar AFSD system, and moves it up to a semi-formal statistically supported conclusion.

Conclusion and Recommendations

A nine-run DSD characterized the tribological performance of AA6061 deposited onto AA5083 via AFSD. Wear displacement ranged from 6.18 to 395.61 μm and mean deposit hardness from 54.87 to 62.79 HV, a 41–49% decrease compared to the AA6061 parent rod. A linear DSD model, selected via Design-Expert's sequential model-order procedure and validated by a non-significant Lack-of-Fit test for both responses, showed that mean hardness responds significantly to rotational speed, deposition feed rate, and chamfer angle ($F = 13.24$, $p = 0.0152$; all main effects $p \leq 0.0036$), while wear displacement does not ($F = 3.62$, $p = 0.1232$; Predicted R^2 of -0.0422). Rotational speed and rod chamfer angle were the most important parameters, with 1200 rpm (R4, R9) consistently giving the least wear, and R4 (1200 rpm, 8.5 mm/min, 15°) offering the best overall outcome, though this ranking is not yet statistically confirmed. Wear resistance and hardness did not correlate consistently, indicating that microstructural homogeneity and bonding quality, not mean hardness alone, govern wear behaviour; AFSD parameter selection for this alloy pairing therefore should be based on direct wear measurement and control of rotational speed and chamfer angle, not hardness inspection alone. Future work should extend the DSD with additional runs to improve power for wear-specific effects, profile hardness across the full deposition depth for all runs, extend the rotational speed range beyond 1200 rpm, incorporate multi-pass deposition for thicker layers, and apply complementary SEM/EBSD characterization to establish the mechanistic basis for the observed wear–hardness decoupling.

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AI-Assisted Post-Processing Software for Continuous Functionally Graded Material in Fused Filament Fabrication

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Abstract— Functionally Graded Materials (FGM) fabricated using Fused Filament Fabrication technology offer tailored mechanical properties within a single 3D printed part. Nevertheless, no existing software supports continuous gradient generation, and the material transition zone remains poorly controlled and unpredictable, with current methods relying on non-traditional 3D printing workflow and manual G-code editing that is impractical for most users. This paper proposes a desktop post-processing tool that converts standard slicer generated G-code files into continuous FGM print files, enabling gradient boundary definition via interactive 3D planes. The effect of print speed, nozzle temperature, and retraction distance on transition length is investigated through experimental study, feeding a data-driven polynomial linear regression AI model. Two integrated Artificial Intelligence models provide decision support: a local model trained with 270 print runs predicts transition compensation length, while a cloud-based AI generates contextual quality guidance. The validation experiment confirmed that printed samples fell within the defined error ratio acceptance threshold, validating the framework's capacity to produce accurate FGM parts within an existing slicer workflow, without requiring G-code knowledge or FGM design expertise.

Introduction

Functionally Graded Materials (FGMs) are engineered composites in which composition varies continuously across the volume, eliminating abrupt interfaces and enabling spatial tailoring of mechanical and thermal performance [1]. Multi-material Fused Filament Fabrication (FFF) has emerged as a cost-effective platform for FGM fabrication, offering path-level material control without complex tooling [2]. In dual-material FFF systems, material transitions are governed by tool change commands. However, following a tool change, the nozzle continues to extrude a blend of both materials over a finite mixing zone before the new material fully dominates. This transition length is poorly controlled and is affected by hardware configuration, material properties, and process parameters, introducing unintended material contamination and reducing gradient spatial accuracy.

Current commercial slicers offer limited support for gradient fabrication, forcing practitioners and researchers to rely on manual G-code editing and iterative calibration. Prior research has pursued different routes such as developing an active-mixing hotends [3] or use bicontinuous mesostructural geometries [4], design a tool path specific for material gradient [5], as well as G-code post-processing approaches [6]. Brackett et al. [7], [8] characterised transition variability in large-scale multi-material deposition. Despite recent advances, FFF remains constrained by a lack of dedicated software able to translate a desired property gradient into executable machine or an automated workflow for continuous gradient generation with predictive transition compensation on standard desktop machines.

To address this gap, the current work presents a post-processing software that integrates directly into an existing 3D printing workflow. The software reads standard slicer G-code files and visualizes the tool path, allowing users to define gradient boundaries by positioning interactive planes over a live 3D model preview. Through 270 print runs using two material

combinations (PLA and TPU), important process parameters were investigated, including print speed, nozzle temperature, and retraction distance. The resulting data fed into a data-driven polynomial linear regression AI model built with TensorFlow integrated within the software, allowing automated transition delay compensation. A cloud-based AI module offers additional print quality guidance. Validation results confirmed that printed samples met the acceptance criteria defined during the experimental study, demonstrating that the framework effectively enables continuous FGM fabrication while requiring no G-code expertise or specialised FGM design knowledge.

Methodology

Machine Setup.

A custom FFF machine is assembled as the experimental platform and fitted with a Geeetech A30M 2-in-1-out passive mixing hotend. The extrusion system combines two independent filament feeds through a shared heating block and a single 0.6 mm nozzle orifice. Klipper firmware is installed and modified to support mixing materials, real-time configuration and improved process control. To reduce the common clogging issue for mixing hotends and vary the internal melt path size, a continuous PTFE liner was installed, together with nested PTFE inserts inside the nozzle that produced three nozzle bore configurations: 4 mm, 2 mm, and 1 mm.

Experiment.

An experiment was designed to measure transition delay; the distance from which a material change command is issued to complete material change at the nozzle. A Box-Behnken response surface design is used and covered four material transitions (PLA-PLA, TPU-TPU, PLA-TPU, TPU-PLA) across three parameters (temperature, retraction, print speed) at three levels (15 runs per transition) with three replicates, see Table1. Nozzle bore diameter (4, 2, 1 mm) was additionally varied for PLA-PLA yielding 270 total runs. Data were analysed via response surface regression (ANOVA, quadratic model fitting, effect size (η^2), lack-of-fit testing) in Minitab to identify significant effects and generate contour and response surface plots for process optimization.

Table1: Factor levels for material change latency Experiment.

Factor	Levels
Material pair	PLA-PLA, TPU-TPU, PLA-TPU, TPU-PLA
Nozzle internal (bore) diameter	4, 2, 1 mm (PLA-PLA only)
Nozzle temperature	190 / 210 / 230 °C
Retraction distance	0 / 2 / 4 mm
Print speed/Feed rate	1000 / 2500 / 4000 mm·min ⁻¹
Replicates / total runs	3 per combination; 270 runs

Software Development. The software program building followed Design Science Research (DSR) framework [9]. Within this framework, the program's requirements are identified, analysed, and categorized into functional requirements (defining what the program must accomplish) and nonfunctional requirements (describing how the program should operate). Electron (HTML, JS, CSS) was selected as the development framework because of its performance and cross-platform compatibility.

AI Model Development. TensorFlow.js is selected for developing the core AI engine for both prediction inference and incremental model, which enables lightweight predictions of transition compensation length in the selected Electron framework. Polynomial linear regression is used as the core predictive model to be trained on 270 experimental runs across

material transitions and process parameters (temperature, retraction, speed). Stochastic Gradient Descent (SGD) optimization is selected to facilitate the process of learning from user calibration data. Model weights saved locally as JSON files, allowing continuous adaptation to individual hardware while maintaining baseline experimental findings.

Validation Study. To empirically verify that gradients generated by the developed software are realized on hardware as designed, and that results are repeatable for multiple prints, a $180 \times 150 \times 10.2$ mm rectangular frame specimen was designed. A hypotheses is set to evaluate, (Accuracy): the measured printed gradient transition length, L_m , should equal the target length, L_t , within a tolerance which is derived from the hardware-induced error ratio calculated from the experimental study.

Results and Discussion

Experimental Result. Nozzle bore diameter was the dominant driver of absolute latency: PLA-PLA measured 385.8, 103.0, and 51.4 mm for 4, 2, and 1 mm bores respectively; a 73-87% reduction from baseline, consistent with volumetric melt-zone scaling. Retraction was the most predictable compensation factor, with latency falling linearly at -10.65 mm per mm retraction ($\eta^2 = 0.985$), closely matching the retracted filament length. Temperature and speed impacts were substantially material-dependent: PLA-PLA delay increased with both, whereas TPU-TPU remained temperature-independent, and TPU-PLA displayed a reversal speed trend due to elastic recovery. The results are summarised in Table 2.

To distinguish between hardware-limited deviation caused by melting chamber internal pressure variation (due to the lack of an active mixer) and process error, the error ratio $er = |l_m - l_t|$ was defined, where l_m represents the measured transition delay and l_t represents the target (designed) delay. The acceptance threshold was calculated as mean + 1 SD. The overall threshold was 4.402 millimetres. Compliance rates of 91.8% suggest that most conditions are within the predicted range. This threshold provides a data-driven, hardware-aware acceptance criterion for evaluating the software's generated gradient accuracy.

Table 1. Transition compensation model parameters by material pair (relative to default: 2500 mm/min, 210°C, 0 mm retraction).

Material Pair	Base L (mm)	Temp. Effect (mm)	Retr. Effect (mm)	Speed Effect (mm)
PLA-PLA	385.8	-26.2 to +47.4	0 to -42.6	-23.0 to +61.8
TPU-TPU	379.4	~0 (flat)	0 to -15.0	-37.2 to +70.0
PLA-TPU	370.2	-7.2 to +5.4	0 to -32.0	-15.6 to +98.2
TPU-PLA	420.0	-30.8 to -2.6	0 to -34.0	-20.4 to -38.2

Developed Software. The software is built with Electron framework (HTML, JS, CSS, approximately 12,000 lines across nine modules) and accepts standard G-code files as input. The software renders 3D printer's tool paths in a 3D WebGL viewer with material and temperature gradient colour mapping, layer animation, and G-code synchronisation. The core feature allows users to place up to four interactive planes in the 3D scene and their intersections with print paths determine where material transitions are applied. A ghost plane, offset by the AI-predicted compensation distance, gives real-time visual feedback of the actual material boundary location.

AI Model. Two AI systems are developed and integrated into the software. The local model, a polynomial linear regression model (formulated as Eq.1) used to serve as the core predictive engine trained with the 270 experimental runs and stored in a JSON file.

$$E_{Delay} = \beta_0 + \beta_1 T + \beta_2 S + \beta_3 R + \beta_4 (TxS) + \beta_5 (TxR) + \beta_6 (SxR) + \beta_7 T^2 + \beta_8 S^2 + \beta_9 R^2 \quad (1)$$

Where T is current printing temperature, S is current printing speed, and β is constant. The formulation follows the Box-Behnken experimental design. For each transition matrix (block), the 15 experimental data points are fitted to this regression structure, yielding 10 numerical weights for each of the four material transitions. These weights account for linear, interaction, and curvature effects. Using the uploaded G-code and slicer-defined print settings, the model predicts the transition length when a plane is placed. If the user shortens or lengthens the transition zone, the software modifies the G-code file automatically so that the material transition occurs at the specified zone. The model runs completely offline, and a calibration module in the user interface allows to record new measurements to refine the AI predictions for a specific hardware over time. Stochastic Gradient Descent (SGD) optimization (formulated as Eq.2) is used to facilitate the model refinement as new calibration data are entered.

$$\beta_{t+1} = \beta_t - \alpha \nabla L(\beta) \quad (2)$$

where α is the learning rate and $\nabla L(\beta)$ is the gradient of mean squared error loss. The trained weights are stored locally as JSON files using Node.js file system access, allowing the model to continuously adapt to a specific machine extrusion system's behaviour while maintaining the baseline experimental findings as initialization parameters. A second AI model is included which connects the software to Google's Gemini Application Programming Interface (API), and analyses printed output across six modes: general print analysis, gradient analysis, material blend recommendation, purge optimization, application recommendation, providing contextual guidance for 3D printing.

Validation Result. A $180 \times 150 \times 10.2$ mm rectangular validation specimen was designed and sliced in OrcaSlicer (0.3 mm layer height, 0.9 mm layer width), then processed through the FGM software by placing two planes to define the gradient zone and adjusting the target transition length to match the rectangle dimensions (see Fig1).

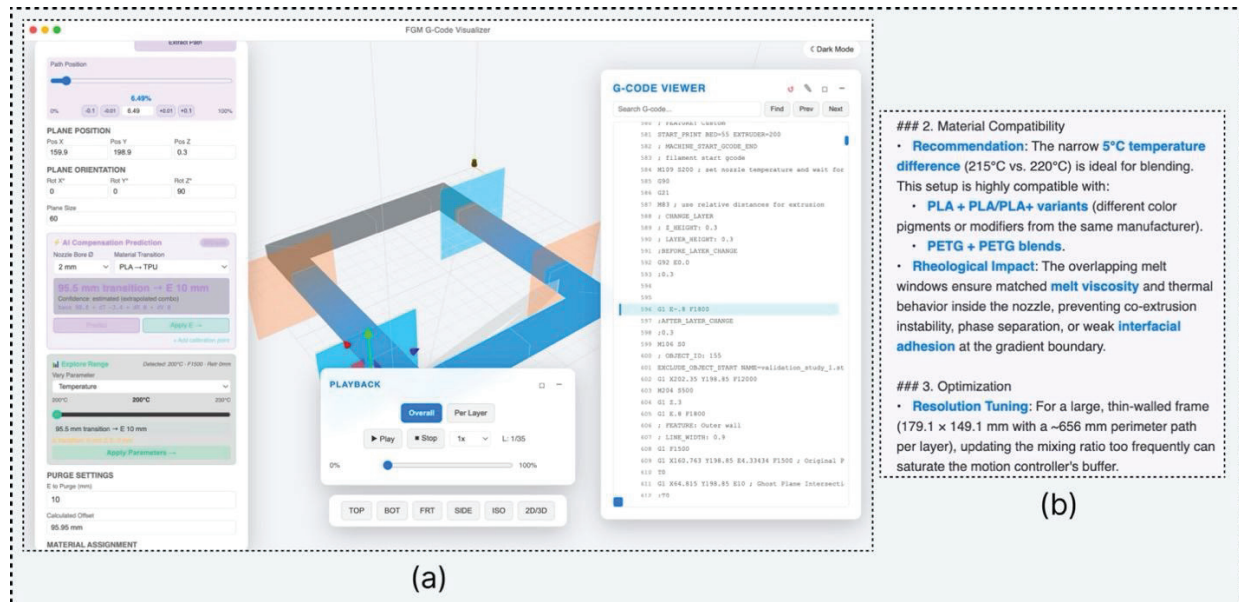


Fig. 4 Software interface showing (a) plane placement with AI-predicted transition compensation, and (b) A sample of the AI material compatibility and optimization analysis.

The software modified the G-code accordingly and the part was printed successfully across five replicates to assess repeatability (see Fig2). For testing the accuracy of the 5 printed

samples, the printed gradient transition length L_m needed to be equal the G-code target L_t within a tolerance derived from the error-ratio analysis of previous experiment: $|\Delta L| \leq \max(AT, 5\% \times L_t)$. the standard deviation $\sigma = 0.542$ mm, equivalent to 0.45% of L_t and well below the 2% criterion; $C_{pk} = 3.187$, consistent with Six-Sigma-class capability; and both TOST p-values were below the threshold. Confirming that the printed gradient was consistent with the intended result within the error-ratio caused by hardware limitation defined during experimental stage.

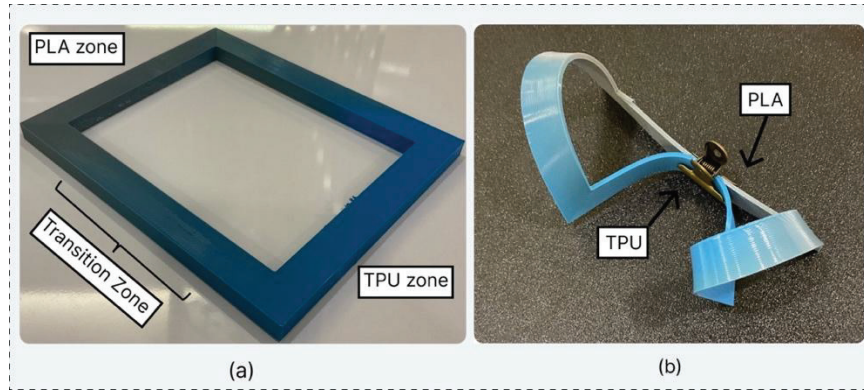


Fig. 5 Printed continuous-gradient PLA-TPU specimen: (a) showing PLA zone, transition zone, and TPU zone; (b) specimen bent to demonstrate dual mechanical behavior, rigid PLA and flexible TPU within a single part.

Conclusions

This paper presented an AI-assisted desktop post-processing software for continuous FGM fabrication using dual-material FFF. The software enables spatial gradient boundary definition via interactive planes over a live 3D model preview, and generates compensated G-code that accounts for the material transition mixing zone. Two AI systems are integrated: a local Polynomial linear regression model trained on 270 experimental print runs across two material combinations TPU and PLA, and four material transitions (PLA-PLA, TPU-TPU, PLA-TPU, TPU-PLA), which predicts transition compensation length as a function of print speed, temperature, and retraction; and a cloud based AI that provides qualitative print guidance through contextual analysis. The developed software makes predictions transparent and hardware-adaptable. The overall framework aligns with smart manufacturing goals by delivering AI-driven, automated G-code adaptation within an existing slicer workflow, without requiring specialised operator knowledge. Future work will focus on expanding the material database, incorporating other parameters effects into the prediction model, and investigating real-time closed-loop feedback for in-process transition monitoring.

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Experimental Evaluation of Airflow Performance in an Automotive Rubber Post Cure Oven Using Full Factorial Design

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Abstract— Uniform airflow inside a post cure oven is essential to ensure consistent curing quality of automotive rubber products. In industrial practice, exhaust duct openings and inlet dampers are commonly adjusted based on operator experience without quantitative optimization. Although previous studies have investigated airflow behavior using Computational Fluid Dynamics (CFD), experimental evaluations of exhaust ducting configurations in automotive rubber post cure ovens remain limited. Therefore, this study experimentally evaluates the effects of exhaust duct opening, damper configuration, and blower speed on airflow performance using a Full Factorial Design ($2 \times 4 \times 10$). Three operating factors were investigated: ducting configuration (Half Open and Full Open), damper configuration (Open, Ø50 mm, Ø30 mm, and Ø10 mm), and blower speed (10–100 RPM). Air velocity was measured using a hot-wire anemometer and converted into airflow rate. The experimental data were analyzed using the General Linear Model (GLM) and Analysis of Variance (ANOVA). The results showed that blower speed ($F = 141.10, p < 0.001$) and damper configuration ($F = 37.78, p < 0.001$) significantly affected airflow rate, whereas ducting configuration had no statistically significant effect ($F = 0.11, p = 0.739$). The developed model explained 95.45% of the variation in airflow rate ($R^2 = 95.45\%$), indicating good predictive capability. The findings provide a data-driven basis for optimizing airflow operating conditions in automotive rubber post cure ovens without requiring modifications to the existing exhaust duct system.

Introduction

Automotive rubber products such as engine mountings, seals, grommets, and bushings require a post-curing process to complete vulcanization and stabilize their mechanical properties. Uniform hot-air circulation inside the post cure oven is essential to ensure homogeneous heat transfer, minimize temperature variation, and achieve consistent product quality. Insufficient airflow distribution may result in uneven curing, dimensional instability, and reduced mechanical performance [6].

The airflow performance of a post cure oven is governed by the interaction between the circulation blower, inlet damper, and exhaust ducting. In industrial practice, these operating parameters are commonly adjusted based on operator experience without quantitative evaluation, leading to uncertainty in identifying the optimum operating condition. Consequently, airflow optimization remains an important issue for improving process consistency and energy efficiency. Previous studies have demonstrated that airflow distribution significantly affects temperature uniformity and thermal performance in forced-convection ovens [14]. Numerical and experimental investigations have shown that airflow optimization can enhance heat transfer efficiency [12], while CFD simulations confirmed that duct geometry influences airflow characteristics in industrial convection ovens [11]. Similar findings have also been reported in ventilation systems, where airflow uniformity strongly affects system performance and energy consumption [4]. However, most existing studies rely primarily on Computational Fluid Dynamics (CFD) or focus on temperature distribution, whereas experimental investigations evaluating exhaust ducting configurations using Design of Experiments (DOE) in automotive rubber post cure ovens remain scarce.

Unlike previous studies that mainly emphasize CFD-based airflow analysis, this study experimentally evaluates the combined effects of exhaust duct opening, inlet damper configuration, and blower speed using a Full Factorial Design ($2 \times 4 \times 10$). The proposed approach provides a statistically validated, data-driven methodology for identifying the dominant operating parameters affecting airflow performance in an automotive rubber post cure oven, thereby supporting evidence-based process optimization in rubber manufacturing.

Methodology

Experimental Design

A Full Factorial Design ($2 \times 4 \times 10$) was employed to experimentally evaluate the effects of exhaust ducting configuration, inlet damper configuration, and blower speed on airflow performance in an automotive rubber post cure oven. DOE is a well-established statistical approach for simultaneously investigating multiple process parameters and identifying their significant effects on process responses (Montgomery, 2019). Three experimental factors were investigated: ducting configuration (Half Open and Full Open), damper configuration (Open, Ø50 mm, Ø30 mm, and Ø10 mm), and blower speed from 10–100 RPM at 10 RPM intervals. The experimental design consisted of 80 treatment combinations, with airflow rate selected as the response variable. The investigated factors and levels are summarized in Table 1.

Table 1. Experimental Factors and Levels

Factor	Levels
Ducting Configuration	Half Open, Full Open
Damper Configuration	Open, Ø50 mm, Ø30 mm, Ø10 mm
Blower Speed	10–100 RPM
Number of Experiments	80

Experimental Setup and Procedure

Experiments were conducted using an automotive rubber post cure oven equipped with a centrifugal circulation blower, an adjustable inlet damper (Ø110 mm; cross-sectional area of 0.010 m²), and an exhaust duct. The oven was operated under steady-state conditions at an internal temperature of 50 °C with an oven chamber volume of 0.24 m³. Air velocity was measured at the exhaust outlet using a hot-wire anemometer and converted into airflow rate using the continuity equation:

$$Q = A \times V$$

where Q is the airflow rate (m³/s), A is the duct cross-sectional area (m²), and V is the measured air velocity (m/s). The overall experimental procedure is illustrated in Figure 1.

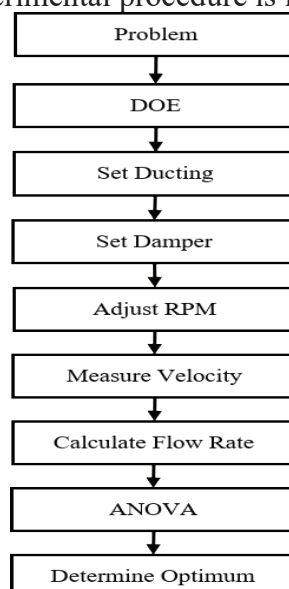


Fig 1. Experimental Procedure

Statistical Analysis

The Experimental data were analyzed using the General Linear Model (GLM) and Analysis of Variance (ANOVA) in Minitab 18. Airflow rate was treated as the response variable, whereas ducting configuration, damper configuration, and blower speed were considered fixed factors.

Statistical significance was evaluated at a 95% confidence level ($\alpha = 0.05$). Main effects and interaction effects were further examined to identify the dominant operating parameters affecting airflow performance.

Result and Discussion

The effects of ducting configuration, damper configuration, and blower speed on airflow rate were evaluated using the General Linear Model (GLM). The Main Effect Plot (Figure 2) shows that blower speed had the strongest influence on airflow performance, followed by damper configuration, whereas ducting configuration exhibited only a minor effect. Increasing blower speed from 10 to 100 RPM produced an almost linear increase in airflow rate because higher rotational speed generated greater volumetric airflow through the centrifugal blower. In contrast, the Ø10 mm damper produced the lowest airflow due to increased inlet flow resistance, while the larger damper openings resulted in higher airflow rates.

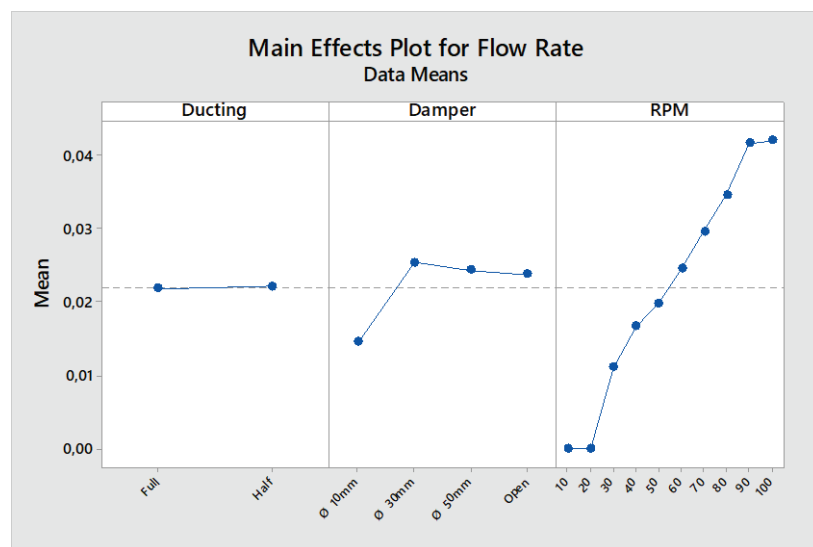


Fig 2. Illustrates the Main Effect Plot

Figure 2 shows the ANOVA results. Blower speed was identified as the dominant factor affecting airflow rate ($F = 141.10$, $p < 0.001$), followed by damper configuration ($F = 37.78$, $p < 0.001$). Conversely, ducting configuration showed no statistically significant effect ($F = 0.11$, $p = 0.739$). The developed GLM explained 95.45% of the variation in airflow rate ($R^2 = 95.45\%$), indicating good predictive capability.

Table 2. The ANOVA Result

Source	DF	F	P
Ducting	1	0.11	0.739
Damper	3	37.78	<0.001
RPM	9	141.10	<0.001

The insignificant effect of the exhaust duct opening suggests that the investigated duct opening contributed only a small pressure loss relative to the pressure generated by the circulation blower. Consequently, enlarging the exhaust opening from Half Open to Full Open did not significantly increase airflow rate. These findings are consistent with previous studies reporting that airflow performance in forced-convection ovens is primarily governed by blower characteristics and flow resistance rather than exhaust opening alone [11]. Similarly, [12] demonstrated that optimizing airflow requires simultaneous consideration of multiple

operating parameters rather than individual geometric modifications. Unlike previous studies that primarily employed CFD analysis, the present work experimentally demonstrates through DOE that blower speed is the dominant operating parameter, providing statistically validated guidance for airflow optimization in automotive rubber post cure ovens.

The dominant effect of blower speed can be explained by the fan affinity law, where airflow is approximately proportional to rotational speed. Increasing blower speed increases the pressure rise generated by the centrifugal blower, resulting in a higher volumetric airflow throughout the oven chamber [2].

Conclusion and Recommendation

A Full Factorial Design ($2 \times 4 \times 10$) successfully evaluated the effects of ducting configuration, damper configuration, and blower speed on airflow performance in an automotive rubber post cure oven. Blower speed was identified as the dominant factor influencing airflow rate, followed by damper configuration, whereas the investigated exhaust duct opening had no statistically significant effect. The developed GLM achieved an R^2 of 95.45%, indicating that the selected operating parameters adequately represented the airflow characteristics of the system. This study demonstrates that DOE provides a practical and statistically validated approach for identifying optimum airflow operating conditions without modifying the existing exhaust duct. These findings provide practical guidance for selecting blower operating conditions in industrial post cure ovens while avoiding unnecessary modification of the exhaust duct. Future work should integrate Computational Fluid Dynamics (CFD) with experimental measurements to visualize airflow distribution and evaluate the relationship between airflow uniformity, temperature distribution, and rubber curing quality. Unlike previous CFD-based investigations, the present study provides experimental evidence that blower speed rather than exhaust duct opening is the dominant operating parameter governing airflow performance in automotive rubber post cure ovens.

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Investigation of Local Solidification Characteristics of AlSi7Mg0.3 Alloy Using Virtual Cooling Curve Analysis

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Abstract— Solidification behavior plays a critical role in determining the microstructure and mechanical properties of aluminum castings. This study investigates the cooling curve characteristics and local solidification behavior of AlSi7Mg0.3 alloy during the gravity die casting process using AnyCasting simulation software. A three-dimensional mould model was developed in SolidWorks and analyzed under a pouring temperature of 720°C and a filling velocity of 10 cm/s. Six virtual sensors were positioned at different locations within the mould cavity to monitor thermal behavior throughout the casting process. The simulation data were subsequently processed using FlexPro 9 software to obtain cooling curves, first derivative curves, minimum eutectic temperature (T_{min}), eutectic growth temperature (T_g), and local solidification time (LST). The results revealed significant variations in thermal behavior among sensor locations. The longest filling time of 0.3087 s was recorded at the thin-wall section of the cavity, whereas the shortest filling time of 0.0488 s occurred near the downsprue. Analysis of local solidification time showed that Sensor 5 exhibited the fastest solidification rate with an LST of 9.75 s, indicating the formation of a finer grain microstructure and superior mechanical properties. In contrast, Sensor 4 recorded the longest solidification time of 27.89 s, suggesting slower heat extraction and the development of a coarser grain structure. The findings demonstrate that cooling curve analysis is an effective approach for evaluating solidification behavior and predicting microstructure development and mechanical performance in AlSi7Mg0.3 gravity die castings.

Introduction

Nonferrous metals and alloys, particularly aluminum, magnesium and copper, are widely used in engineering applications due to their excellent corrosion resistance, high thermal and electrical conductivity, low density, and good manufacturability [1]. These properties make them suitable for components that require lightweight structures, efficient heat transfer, and enhanced performance under various operating conditions. Al-Si alloys have been developed due to their good cast ability properties like excellent fluidity and easy feed –ability, suitable specific mechanical properties and formability, and high corrosion resistance. Among these alloys, they are really suitable where good corrosion resistance combined with thermal properties is required and strength is attained by heat treatment [2]. The quality and properties of the cast products are affected by microstructural changes during the solidification process of the melt alloy [3]. Understanding the stage development during the casting process is valuable to get ideal material properties after resulting heat treatment as far as the required mechanical properties [4]. Mechanical properties and microstructure of AlSi7Mg0.3 castings are strongly influenced by the solidification behaviour during the gravity die casting process. However, variations in cooling rate and local solidification time at different regions of the mould cavity may lead to non-uniform microstructure formation and inconsistent mechanical properties. Therefore, an analysis of the cooling curve and solidification characteristics is required to predict the quality of the casting and understand the relationship between solidification behaviour, microstructure development in gravity diecasting process.

Methodology

Casting component was selected based on several design and manufacturing criteria, with a particular focus on parts produced using the gravity die casting process. The three-dimensional (3D) model of the selected component was developed using SolidWorks CAD software.

Subsequently, the mould design for the gravity die casting process was generated based on the developed 3D geometry. All the 3D modelling was converted into STL file and insert in Anypre (Anycasting Software). During this stage, all relevant simulation parameters were established, including the entity configuration, meshing settings, heat transfer model, material properties, and processing conditions. 6 virtual sensor (thermocouple) were located as Fig. 1a, to capture the cooling curve during solidification process. Each sensor located mainly at the down sprue, cavity, runner and riser. The simulation data obtained from AnyCasting were subsequently analyzed using FlexPro 9 software. The software was employed to process the thermal data such as T_{min} (eutectic transformation) and T_g (maximum temperature in the eutectic area) and extract solidification characteristics, as well as the first derivative curves required for detailed cooling curve analysis [5]. The simulation was performed at a pouring temperature of 720°C and a filling velocity of 10 cm/s .

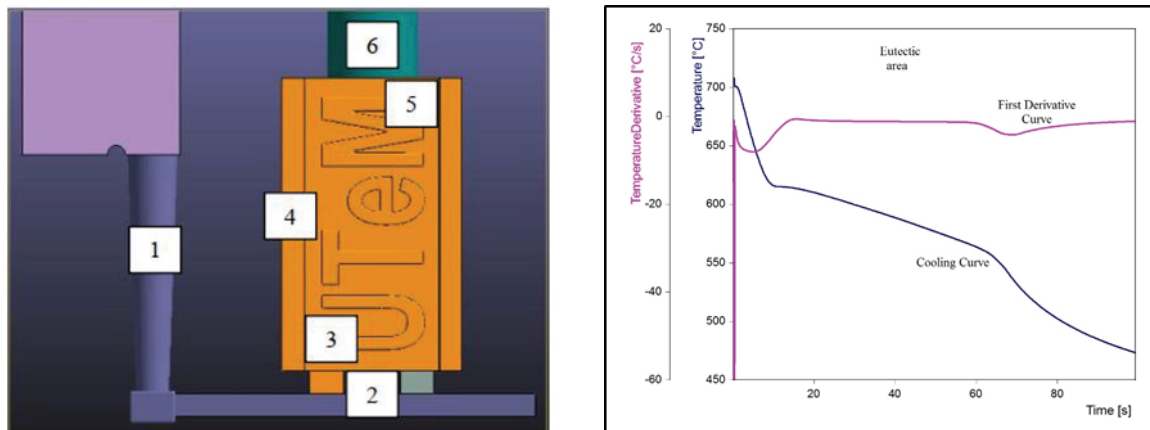


Fig. 1: (a) The position of each of the sensor, (b) Cooling curve with its corresponding first derivative curve for sensor 6

Result and Discussion

The results show that the sensor located in the thin-wall section at the center of the cavity exhibited the longest filling time of 0.3087 s , corresponding to a 70% filling fraction. Conversely, the sensor positioned near the downsprue recorded the shortest filling time of 0.0488 s at a filling fraction of 10%. This variation indicates the influence of mould geometry and sensor location on the filling behavior of the molten metal. Fig. 1b, show the example of the cooling curve graph and 1st derivative curve at sensor 6 (riser). Fig. 2 show, the T_{min} increasing from Sensor 1 to Sensor 6 which explained that aluminium alloy AlSi7Mg0.3 has solidifies in the eutectic area where for the increasing start from sensor 1 that rapidly increase from pouring the molten metal going down to choke through downsprue that require 21.97 second of 589.70°C as for the sensor 2, the increasing of T_{min} also with the increasing of T_g shows that at the inlet gating system the molten metal of AlSi7Mg0.3 solidified with the growing of the nucleation with T_g equals to 599.44°C . Next, starting from sensor 3, it can be seen that T_g decreasing from sensor 2 to 597.7°C with increasing of T_{min} of 616.76°C at 19.67 seconds . There, in the graph could be seen that, the graph increase again to 603.6°C for sensor 4 at 27.89 second for T_g and T_{min} 615.75°C . in the cavity, the sensor 5 detect the molten metal at 9.75 seconds only, which quite fast with the T_{min} 616.45°C but with slow growing of AlSi7Mg0.3 which the growing temperature is 576.48°C . as for the sensor at riser which detect very fast when the temperature growing increase to 613.55°C and minimum temperature is 617.23°C at 19.67 seconds .

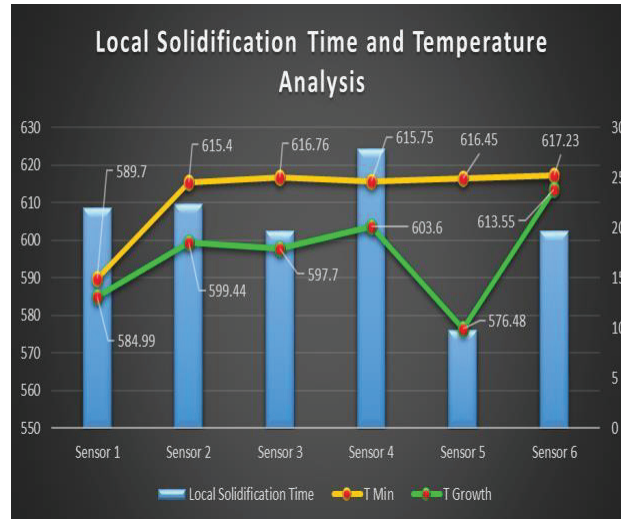


Fig. 2: Analysis of local solidification time, Tmin, Tg

Table 1 summarizes the eutectic transformation characteristics obtained from each sensor location. The analysis was performed based on the minimum eutectic temperature (Tmin) and eutectic growth temperature (Tg), where Tmin denotes the lowest temperature reached during eutectic transformation and Tg represents the peak temperature within the eutectic region [6]. Among all sensors, Sensor 1 recorded the shortest eutectic transformation time, indicating a faster transition from the liquid to solid state. The remaining sensors showed relatively uniform behaviour, suggesting consistent solidification characteristics throughout the casting. The results indicate that the casting volume, which represents the heat content of the molten metal, and the cooling surface area of the mould significantly influence the heat transfer rate during solidification. These factors directly affect the time required for dendrite growth to occur. Sensor 1 was located in a region with a relatively larger casting volume and cooling surface area compared to the other sensor locations. As a result, this region possessed a higher thermal modulus, allowing it to retain heat for a longer period and delaying its cooling process. Consequently, Sensor 1 required more time to reach the solidification temperature compared to the other sensors. Local solidification time analysis revealed significant variations among the sensor locations. Shortest solidification time was recorded at Sensor 5, requiring only 9.75 s for the molten metal to completely transform into the solid phase. In contrast, Sensor 4 exhibited the longest local solidification time of 27.89 s. These differences in solidification behaviour can be used to predict the resulting microstructure and mechanical properties of the casting. Sensor 5 is expected to produce a finer grain microstructure due to its rapid solidification rate. Faster cooling promotes grain refinement, which is generally associated with improved mechanical properties such as higher strength and hardness. Therefore, the region represented by Sensor 5 is predicted to possess the most favourable mechanical characteristics. Conversely, Sensor 4 experienced the longest solidification time, indicating slower heat extraction and prolonged dendrite growth. This condition promotes the formation of a coarser grain microstructure, which is commonly associated with reduced mechanical performance. Sensor was located near the central region of the mould cavity, where heat dissipation was relatively slower compared to other locations. Variation in solidification behaviour may be attributed to differences in molten metal flow, local pressure distribution, and thermal conditions within the mould cavity. These factors influence the cooling rate and ultimately affect the final microstructure and quality of the casting.

Table 1: Data collected from each of the sensor located on the mould

	Local solidification Time [s]	T _{min} [°C]	T _g [°C]	Time Range for T _{min} – T _g [s]
Sensor 1	21.97	589.70	584.99	3.11
Sensor 2	22.33	615.40	599.44	6.08
Sensor 3	19.67	616.76	597.70	6.12
Sensor 4	27.89	615.75	603.60	6.17
Sensor 5	9.75	313.45	576.48	6.05
Sensor 6	19.67	617.23	613.55	6.03

Conclusion

From all the result and discussion, the conclusion can be made: Filling time for the molten metal to arrive at the sensor does not affect to much in the solidification of that particular part. Time range for the sensor 1 to meet the dendrite growth which is the fastest because it only needs 3.11 seconds while the other need the range of 5 seconds because of the heat transfer for that particular design of the part including the area and its volume as the analysis was made up to find the first derivative of the temperature to find out the T_{min} and T_g of each of the sensor. Mechanical properties and microstructure can be measured by consuming the time taken for each of the sensor to solidified which is the best mechanical properties and fine microstructure grain for the Al-Si7 Mg0.3 was at the sensor 5 which located at the top of the mould cavity as the analysis made up by using the FlexPro 9 because the data that fetch out were more accurate.

Acknowledgement

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Enhancing Manufacturing Process Efficiency through Heuristic Line Balancing: A Case Study of Food Packaging Operations

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Abstract— Manufacturing industries continuously seek to improve production efficiency by optimizing workstation utilization and reducing operational inefficiencies. This study aims to improve the manufacturing process of a packaged snack production line in an Indonesian food manufacturing company using heuristic line balancing techniques. A quantitative case study was conducted through work measurement, precedence analysis, cycle time determination, and the application of Ranked Positional Weight (RPW), Region Approach (RA), and Largest Candidate Rule (LCR). The proposed workstation configurations were evaluated based on line efficiency, balance delay, smoothness index, and production productivity. The results show that all heuristic methods improved the existing production line, with the Region Approach achieving the best performance by increasing line efficiency to 99.72%, reducing balance delay to 0.28%, lowering the smoothness index to 0.80, and improving productivity from 168 g/s to 192 g/s while maintaining the same number of workstations. These findings demonstrate that heuristic line balancing provides a practical and cost-effective approach to improving workstation utilization, reducing production bottlenecks, and enhancing manufacturing process performance in high-volume food packaging operations.

Introduction

Manufacturing industries continuously strive to improve production efficiency to remain competitive in an increasingly dynamic market. In high-volume food manufacturing, packaging operations play a critical role because they directly influence production throughput, resource utilization, and customer demand fulfillment. However, production lines frequently experience workstation imbalances, in which uneven task allocation leads to bottlenecks, excessive idle time, and reduced productivity. Assembly line balancing (ALB) has therefore become one of the fundamental approaches for improving manufacturing performance by distributing tasks among workstations while satisfying precedence constraints and cycle time requirements [1]. Recent reviews indicate that ALB remains an active research area in the Industry 4.0 era because of its significant contribution to enhancing operational efficiency, reducing production costs, and supporting smart manufacturing initiatives [2].

The Assembly Line Balancing Problem (ALBP) has evolved considerably over the past two decades, extending from conventional single-model production lines to more complex manufacturing systems involving multiple optimization objectives, human–robot collaboration, and intelligent optimization techniques [3-4]. Despite these developments, heuristic approaches remain widely adopted in industrial practice because they provide near-optimal solutions with relatively low computational effort and are suitable for real-world production environments [5]. Among these approaches, Ranked Positional Weight (RPW), Region Approach (RA), and Largest Candidate Rule (LCR) continue to be applied because of their simplicity, ease of implementation, and effectiveness in improving workstation utilization while minimizing idle time. Previous comparative and review studies have shown that the effectiveness of assembly line balancing methods depends on production characteristics, task precedence relationships, optimization objectives, and operational constraints [6]. Consequently, selecting an appropriate balancing strategy is essential to achieving optimal manufacturing performance in different production environments [7].

This study aims to improve the manufacturing process of a packaged snack production line in an Indonesian food manufacturing company by optimizing workstation allocation using heuristic line balancing techniques. A quantitative case study was conducted using work

measurement, precedence analysis, and cycle time determination, followed by the application of Ranked Positional Weight (RPW), Region Approach (RA), and Largest Candidate Rule (LCR). The proposed line configurations were evaluated using line efficiency, balance delay, smoothness index, workstation requirements, and production productivity to identify the most effective manufacturing process improvement strategy.

Methodology

This study employed a quantitative case study approach to improve the manufacturing process of a packaged snack production line in an Indonesian food manufacturing company. The research began with problem identification and a literature review on assembly line balancing and work measurement. Primary data were collected through direct observation and time studies of each production task. The collected data were subsequently tested for sufficiency and uniformity to ensure their validity and reliability before further analysis. Standard times were then determined by incorporating performance rating and allowance factors, followed by the construction of a precedence diagram and the calculation of the production cycle time. These procedures are commonly adopted in assembly line balancing studies to establish reliable input data for workstation assignment [8]. The validated data were analyzed using three heuristic line balancing methods: Ranked Positional Weight (RPW), Region Approach (RA), and Largest Candidate Rule (LCR). Each method generated an alternative workstation configuration while satisfying task precedence relationships and cycle time constraints. The resulting configurations were evaluated and compared using the number of workstations, line efficiency, balance delay, smoothness index, and production productivity to determine the most effective manufacturing process improvement strategy. The comparative evaluation enables the selection of the heuristic method that best balances workload distribution and enhances operational performance under the existing production conditions [9].

Result and Discussion

The data collected for this case study are operation times measured directly during the production process using a stopwatch, with 40 repeated measurements collected for each of the six operations. Then, a data sufficiency test was conducted at a 95% confidence level and 5% precision level. The results presented in Table 1 show that the required sample size (N') for all operations was lower than the number of observations collected ($N = 40$), indicating that the collected data were sufficient for further analysis. In addition, a data uniformity test was performed by determining the upper control limit (UCL) and lower control limit (LCL). As summarized in Table 2, all observations for the six operations fell within the specified limits, indicating that the collected operation-time data were uniform and suitable for subsequent work measurement and line balancing analysis.

Table 1 Summary of overall operation data sufficiency test

Data Sufficiency Test								
Operation No.	K	S	$\sum x_i$	$\sum x_i^2$	$(\sum x_i)^2$	N	N'	Remark
1	1	2	0.05	187.3	898.8	35080.83	6.3	Sufficient
2	2	2	0.05	154.14	609.72	23759.38	6.51	Sufficient
3	3	2	0.05	165.53	693.42	27400	4.44	Sufficient
4	4	2	0.05	137.55	482.05	18920.02	5.533	Sufficient
5	5	2	0.05	150.43	573.48	22627.82	4.69	Sufficient
6	6	2	0.05	144.95	547.99	21011.68	8.32	Sufficient

Table 2 Summary of operation data uniformity test

Data Uniformity Test						
Operation No.	Mean	Std. Dev.	K	UCL	LCL	Remark
1	4.682469	0.747353	2	6.177175	3.187763	Uniform
2	3.853519	0.635215	2	5.123949	2.583089	Uniform
3	4.138236	0.46468	2	5.067596	3.208876	Uniform
4	3.438751	0.48171	2	4.402171	2.475332	Uniform
5	3.760636	0.446812	2	4.65426	2.867013	Uniform
6	3.623851	0.762971	2	5.149793	2.09791	Uniform

The validated data were then analyzed using three heuristic line balancing methods: Ranked Positional Weight (RPW), Region Approach (RA), and Largest Candidate Rule (LCR). The implementation of heuristic line balancing methods significantly improved the performance of the existing packaging production line. The initial production system exhibited an uneven distribution of work elements among workstations, resulting in bottlenecks, excessive idle time, and underutilized resources. The performance of each heuristic method was evaluated using line efficiency, balance delay, smoothness index, number of workstations, and production productivity as shown in Figure 1.

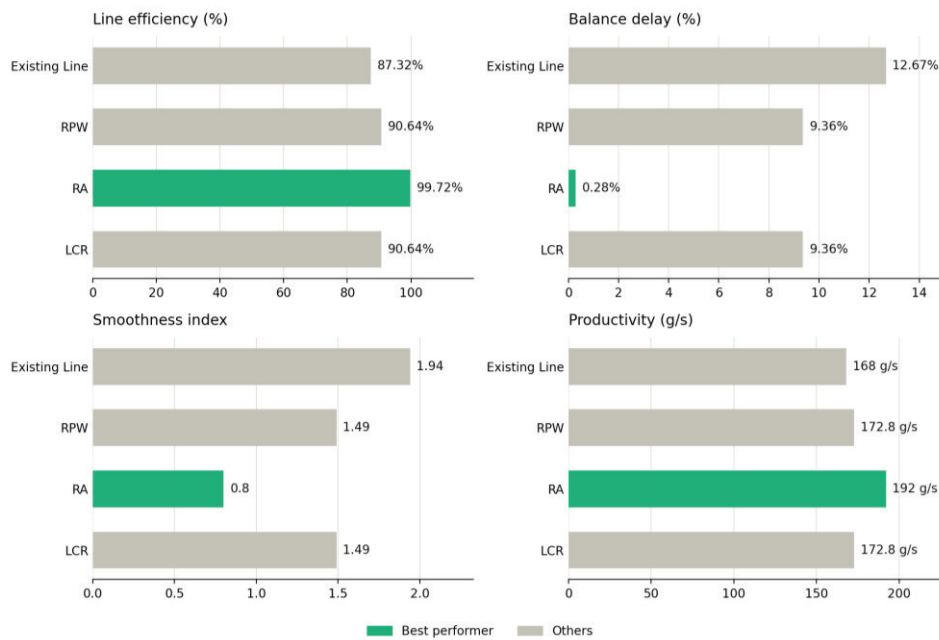


Fig. 1 Performance comparison of existing and proposed line balancing configuration

Among the evaluated methods, the Region Approach (RA) produced the best manufacturing performance. This method generated the most balanced workload distribution across the six workstations, resulting in the highest line efficiency of 99.72% and the lowest balance delay of 0.28%. The smoothness index of 0.80 indicates a nearly uniform distribution of processing time among workstations, which minimizes idle time and reduces production bottlenecks. Compared with the existing production line, productivity increased from 168 g/s to 192 g/s, representing an improvement of approximately 14.3%. These results suggest that Region Approach is better to allocate work elements more evenly while satisfying precedence and cycle-time constraints for this case. Improved workload distribution minimizes bottlenecks, enhances workstation utilization, and supports smoother production flow without requiring additional equipment or workforce.

The results are consistent with previous studies reporting that heuristic line balancing methods effectively enhance workstation utilization and reduce operational inefficiencies in

manufacturing systems [5]. However, unlike studies that focus primarily on comparing heuristic algorithms, this research highlights the practical contribution of line balancing as a manufacturing process improvement strategy for food packaging operations. By improving workload distribution, the proposed production line redesign supports smoother material flow, higher resource utilization, and increased production capacity.

Conclusion and Recommendations

This study confirms that heuristic line balancing is an effective approach for improving manufacturing process performance in high-volume food packaging operations. Among the evaluated methods, the Region Approach provided the most effective workstation configuration by achieving the best overall balance between workload distribution and production efficiency. The improved line configuration reduced operational inefficiencies and increased productivity without requiring additional production resources, demonstrating that manufacturing performance can be enhanced through better workstation allocation rather than capital-intensive investments. These findings highlight the practical value of heuristic line balancing as a continuous improvement tool for manufacturing industries seeking higher operational efficiency and resource utilization.

Although the proposed approach successfully improved manufacturing performance, several limitations should be acknowledged. The study was conducted on a single packaging line and considered only deterministic processing times under stable production conditions. Variations caused by machine failures, operator performance, material shortages, or fluctuating production demand were not incorporated into the analysis. Therefore, while the results demonstrate the effectiveness of heuristic line balancing under normal operating conditions, their applicability may vary in more dynamic manufacturing environments. Future research should integrate stochastic production factors, simulation-based validation, or artificial intelligence-based optimization methods to evaluate production systems under real-time operating conditions and support the development of smart manufacturing systems. From a practical perspective, the proposed workstation configuration can serve as a reference for production managers seeking continuous improvement initiatives to enhance productivity, optimize resource utilization, and strengthen manufacturing competitiveness in the food industry.

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Debinding and Sintering in Metal Additive Manufacturing: A Material Extrusion-Focused Review.

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Abstract — Debinding and sintering transform a printed green part into a dense metal component in sinter-based metal additive manufacturing (AM). Although these post-processing stages are critical, they are also among the least standardised and contribute to many of the problems affecting final part quality. This review aims to compile the latest research on debinding and sintering for the most common sinter-based metal AM processes, with a special focus on material extrusion (MEX), which is also referred to as metal fused filament fabrication (FFF) or metal FDM and heavily relies on both stages. The review includes an account of the different techniques used for debinding, such as solvent, thermal, and catalytic debinding, as well as the mechanisms involved in sintering densification. It contrasts the shrinkage behaviour, densification, and final density of MEX, binder jetting, and metal injection moulding (MIM) technologies, as well as those of fusion-based technologies, which do not require post-build debinding or sintering. The debinding and sintering atmosphere, combined with the thermal profile, is consistently identified across the published studies as one of the most influential factors affecting final density and dimensional stability. Although the benefits of vibration-assisted MEX are widely anticipated to enhance green-part density prior to debinding and improve the quality of the sintered part, little research has been conducted in this area, as revealed by the existing literature.

Introduction

Metal additive manufacturing has a number of different process families, which vary greatly in terms of how the component is built. Fusion processes, such as powder bed fusion (PBF) and directed energy deposition (DED), involve selectively melting and solidifying metal powder layer by layer to create a near-fully dense part. In contrast, sinter-based processes, such as metal injection moulding (MIM), binder jetting (BJT), and material extrusion (MEX), also known as metal fused filament fabrication (FFF) or metal FDM, first produce a green part by shaping a metal powder/binder mixture at relatively low temperatures. Debinding is then followed by densification of the remaining powder structure during sintering through solid- or liquid-phase diffusion [8].

Among these processes, MEX has received considerable attention due to its relatively low cost and ease of implementation. It can be performed using modified desktop-scale polymer 3D printers with highly filled metal filaments, without the need for loose powder handling, inert gas protection, or high-energy sources during printing [1]. However, these practical benefits place a significant burden on the post-processing stage. The debinding and sintering processes are as important as the printing process, since a typical green part consists of approximately 40–65 vol% polymer binder, and the final density, dimensional accuracy, and mechanical properties are highly dependent on the effectiveness of the debinding and sintering processes. If debinding is incomplete, it can result in microscopic pores or even the formation of carbon residues, while insufficient sintering can cause blisters in the printed parts during the sintering process and leave pores inside the parts, even when the printed geometric features are well defined. Therefore, success in MEX processing is as much dependent on post-processing as it is on the printing process. One of the most significant contributors to density and dimensional stability is the atmosphere, which consistently plays an important role in conjunction with the thermal profile. The literature also shows that, although vibration-assisted MEX remains an area of limited research, it could enhance the density of the green component before debinding and potentially improve the quality of the sintered part. There are two types

of existing reviews of metal additive manufacturing: general reviews of the debinding and sintering processes as a small sub-step within the broader framework of AM processes [8,16], and narrow, process-specific reviews of either binder jetting [9,10] or metal injection moulding (MIM) [8] separately. Very few reviews have focused on debinding and sintering as the central and controlling processes for MEX, or compared and contrasted the MEX literature on debinding and sintering behaviour with the more established literature on MIM and binder jetting. This represents a significant gap, as MEX is a rapidly growing AM technology that provides a relatively accessible entry point, yet its post-processing remains less standardised compared with other sinter-based technologies [1,2,3].

This review addresses this gap by summarising the existing knowledge on debinding and sintering in metal AM, with particular emphasis on MEX, as mentioned above. Binder jetting, MIM, and fusion-based routes are discussed comparatively, while findings from these technologies are presented primarily to provide context for MEX-specific results rather than to provide exhaustive reviews of each individual technology. The results from binder jetting, MIM, and fusion-based technologies are considered where they provide useful context or reveal similarities and differences in processing behaviour, rather than as detailed reviews of the individual technologies.

Methodology

This review follows the style of a scoping review and does not present new experimental data. The literature was gathered from peer-reviewed journal articles available through ScienceDirect, MDPI, Springer, and PubMed-connected repositories, covering publications from 2017 to 2026. The keywords used in the search included metal fused filament fabrication, debinding, sintering, binder jetting, 17-4PH, and 316L stainless steel. The following criteria were used to select studies: studies that reported debinding methods, sintering conditions, shrinkage, density, or mechanical properties of a sinter-based metal AM process, or studies that included comparisons with fusion-based AM processes. The selected literature was organised into four main themes of the paper: feedstock and green-part formation, debinding mechanisms, sintering densification, and the effects of processing on shrinkage and material properties. Instead of conducting a formalised meta-analysis, the results were qualitatively synthesised to identify common trends, differences in manufacturing processes, and areas requiring further research, as appropriate for this extended review.

Findings and Discussion

Feedstock and Green Part Formation

The metal component of MEX feedstocks is usually composed of fine metal powders, typically 15-4PH, 17-4PH, or 316L stainless steel, with a median particle size (D50) in the tens of micrometres, combined with a polymer binder system at metal loadings of around 55–65 vol%. The mixture is then extruded to produce filament for printing [2]. For most commercial materials, the binder formulation is similar to that used in metal injection moulding (MIM). It typically consists of a primary binder, which is removed during the first stage of debinding, and a secondary polymer, usually a polyolefin, which maintains the integrity of the powder structure until the sintering process is completed [8]. The printed green part itself is extremely fragile due to the high-volume fraction of binder. At this stage, the component has limited mechanical strength and does not yet possess the required structural integrity. The final geometry and structural integrity are achieved only after the binder has been removed and the metal particles have been consolidated during sintering.

Debinding Mechanisms

Three debinding mechanisms are commonly employed in sinter-based metal additive manufacturing and are summarised in Table 1. Among these, solvent debinding is the method most frequently reported for MEX using 17-4PH and 316L stainless steel filaments. In this process, the primary binder is dissolved, creating an interconnected pore network that allows the remaining binder to escape more readily during the subsequent thermal debinding stage. Acetone and heptane are the solvents most commonly used before a combined thermal debinding and sintering cycle [1,2,3]. Mechanistically, solvent debinding proceeds through Fickian diffusion: the solvent penetrates the part surface, dissolves the soluble binder phase, and the dissolved binder diffuses outward along the resulting concentration gradient. Therefore, the removal rate depends on factors such as immersion temperature, part wall thickness, and solvent diffusivity rather than on time alone [8].

Thermal debinding can also be carried out without a preceding solvent treatment, although the process is considerably slower and more susceptible to defects. Thermal debinding removes the binder through pyrolytic decomposition, a process governed by Arrhenius-type reaction kinetics in which the decomposition rate increases exponentially with temperature. Because the pore structure remains largely closed during the early stages of thermal debinding, the gaseous decomposition products have limited pathways for escape. Consequently, an aggressive heating rate can generate internal gas pressure faster than it can be released, resulting in blistering or cracking, particularly in highly filled feedstocks [8].

Catalytic debinding, which is widely adopted in industrial metal injection moulding (MIM), offers a much faster alternative. By exposing a polyacetal-based binder to an acid catalyst atmosphere, the primary binder decomposes progressively from the surface inward, reducing debinding time by approximately an order of magnitude compared with conventional thermal debinding [8]. This speed advantage arises because catalytic debinding is primarily a surface-erosion process rather than a bulk-diffusion process. The acid catalyst depolymerises the polyacetal chains into gaseous formaldehyde monomers at the exposed surface, continuously revealing fresh binder beneath. As a result, the removal rate remains relatively constant over time rather than slowing as diffusion distances progressively increase through the already-debound outer layer [8]. Despite the similarities between MIM and commercial MEX binder formulations, catalytic debinding has received limited attention in MEX and ultrasonic vibration-assisted FDM (UV-FDM) systems, highlighting a clear opportunity for future process development. This represents a specific process gap, as MEX has largely inherited MIM-based binder chemistry without yet adopting its more efficient catalytic debinding route.

Table 1: Debinding methods used in sinter-based metal additive manufacturing.

Method	Mechanism	Typical conditions	Notes / primary use
Solvent	Primary binder fraction dissolved in a liquid medium (organic solvent or water), leaving an open-pore network.	Immersion, hours to ~1-2 days, near room temperature.	Gentle, low-distortion risk; dominant route reported for metal-filled MEX filaments such as 17-4PH and 316L [1,2,3].
Thermal	Binder decomposed or evaporated by controlled heating below the sintering temperature.	Slow ramp rates, dwell steps up to several hundred degrees Celsius.	Simplest equipment; slow and prone to defects (blistering, cracking) if used alone on high-loading feedstocks [7].
Catalytic	Acid-catalysed surface decomposition of a polyacetal backbone binder into volatile species.	Gaseous acid atmosphere, ~110-120°C.	Fastest and most scalable; standard in industrial MIM, not yet common in MEX/UV-FDM feedstocks [8].

Recent work suggests that this gap is beginning to close. A combined fused deposition modeling and sintering (FDMS) route for 316L stainless steel has demonstrated the use of catalytic debinding directly on a metal-filled FDM feedstock, rather than the solvent/thermal route typically used in MEX, resulting in dense sintered parts [14]. This finding suggests that the faster debinding chemistry established in MIM is beginning to be adopted in MEX, although it remains an exception rather than the norm.

Sintering Densification

Sintering is a process in which the “brown” part undergoes densification through diffusion and pore elimination between the powder particles, thereby increasing the density of the debound “brown” part. It is thermodynamically driven by the reduction of surface energy as free particle surfaces are converted into grain boundaries [8]. The densification process generally proceeds through three stages: the first involves the initial formation of necks between adjacent particles, the second involves the shrinkage and closure of interconnected pores, and the third involves the elimination of isolated pores. The progression through these stages depends on the combined effects of peak temperature, holding time, heating rate, and process atmosphere. The atmosphere during sintering is particularly important. Under a vacuum or reducing atmosphere, oxide layers can be removed or prevented from forming on the surfaces of the metal powders, which is an important precondition for diffusion bonding between particles. However, if the atmosphere remains oxidative and does not favour densification, an oxide film may remain on the particle surfaces even after reaching the same peak temperature and holding time, thereby inhibiting densification [8]. Since material extrusion (MEX) and metal injection moulding (MIM) share the same fundamental powder metallurgy principles, the sintering windows established for MIM 17-4PH and 316L feedstocks provide useful starting points for MEX. However, the residual carbon content originating from the binder, which is highly dependent on the degree of debinding, can directly alter the sintering processing window and therefore needs to be revalidated for each specific feedstock [2,3].

Comparative Shrinkage and Dimensional Behaviour Across Routes

Shrinkage during sintering is substantial and highly route-dependent, introducing distinct design constraints that are summarized in Table 2. Because material extrusion (MEX) and metal injection moulding (MIM) parts originate from relatively uniform, isotopically packed green bodies, they typically experience 15% to 20% linear shrinkage. This contraction is largely isotropic, meaning designers can easily compensate for it by applying a fixed scale factor to the CAD model before printing. [2,3,17]. In contrast, binder jetting parts begin with a much lower green density of roughly 40% to 55% because the powder is loosely bound layer by layer without compaction. Consequently, these components undergo larger, distinctly anisotropic shrinkage that is usually most pronounced along the build direction. This variation makes simple scale-factor compensation highly complex, driving recent research toward specialized finite-element modeling and dilatometry-based shrinkage predictions [9,10,11]. Meanwhile, fusion-based additive manufacturing routes avoid this densification challenge entirely since they do not require a separate post-build sintering step. However, this advantage comes at the cost of significantly higher machine and material expenses, alongside a shift from shrinkage-driven defects to melt-pool-driven defect mechanisms [5].

Table 2: Comparative shrinkage and density outcomes across metal AM routes.

Process route	Debind + sinter required?	Reported linear shrinkage	Reported relative density
MEX / metal FFF (17-4PH, 316L)	Yes - solvent/thermal debind then sinter	~15-20%, compensated by scaling the CAD model before printing	>99% achievable after optimised sintering and post-treatment [1,2,3]
Binder jetting	Yes - binder burnout then sinter	~15-25%, markedly anisotropic (largest along the build/Z direction)	Up to ~99.9% at high sintering temperature, but with pronounced shape distortion [9,10,11]
MIM (reference baseline)	Yes - the process debind/sinter route was derived from	~15-20%, isotropic due to uniform green compaction	>95%, the industrial benchmark MEX and BJ are measured against [8]
PBF / DED (laser or EB melting)	No - parts consolidate by melting during the build	Negligible; dimensional error is a build-process, not a post-process, issue	>99% as-built, at markedly higher machine and powder-handling cost [5]

Mechanical Property Outcomes

Material extrusion (MEX) parts can achieve mechanical properties that are comparable to those of powder bed fusion (PBF) parts produced from the same material, although they are often slightly inferior when optimized debinding and sintering cycles are used. For example, MEX 17-4PH can be fully sintered and heat treated to achieve a yield strength of approximately 1000 MPa, an ultimate tensile strength (UTS) of more than 1200 MPa, and a relative density of more than 99% [1]. Although direct comparisons between fused deposition modeling (FDM) and selective laser melting (SLM) have shown that SLM produces denser as-built parts with fewer defects [5,15], the mechanical performance of optimized MEX parts is within the general range reported for PBF 316L. However, poor debinding or sintering performance can significantly compromise the final properties. If the binder is not completely removed or the sintering atmosphere is not properly controlled, the density of a part can be reduced to less than 50% of that of an optimized component, resulting in a substantial loss of strength. Residual porosity resulting from incomplete debinding or inadequate sintering has also been shown to reduce the wear and corrosion resistance of fused filament fabrication (FFF) 17-4PH parts, in addition to affecting their bulk mechanical properties [6,7]. This sensitivity is consistent with the well-established relationship between porosity and strength in powder metallurgy, where strength decreases significantly with relatively small increases in pore fraction. Pores act as stress concentrators and reduce the effective load-bearing cross-section, meaning that even a slight increase in residual porosity caused by incomplete debinding can result in a disproportionately large reduction in tensile strength [8]. In addition, residual carbon from incomplete pyrolysis of the binder can segregate to grain boundaries during sintering and promote the formation of brittle carbides, further reducing the toughness and mechanical performance of the part independently of its overall density [8]. Therefore, debinding and sintering should not be regarded merely as finishing operations; rather, they are critical processes that strongly influence the mechanical properties and their variability in sinter-based MEX components.

Vibration-Assisted MEX: An Emerging Lever

The effect of vibration during the printing stage on green-part density has not been well investigated in the literature on metal MEX debinding and sintering. In conventional polymer FFF, it has been found that interlayer bonding and intra-layer porosity can be improved when ultrasonic vibration is applied either to the nozzle or to the substrate. In particular, the tensile and bending strengths of FDM parts were enhanced by 13.2% and 12.6%, respectively, when

ultrasonic vibration was applied during the printing process with an amplitude of 12 μm [12]. Likewise, in FFF-printed ABS, interlayer adhesion was found to increase by up to 10% when ultrasonic vibration was introduced at the print joints [13]. This improvement was hypothesised to result from polymer chain relaxation at the print joints due to the application of ultrasonic vibration. Although neither study used metal-filled feedstocks, the reported mechanisms, including void reduction and improved interlayer contact during deposition, may also be applicable to metal-filled MEX green parts. These initial physical improvements are important because they determine the initial density and internal structure of the green part that subsequently undergoes debinding and sintering. However, the effects of vibration-assisted printing on green-part density, debinding kinetics, and debinding and sintering shrinkage in metal-filled feedstocks such as 17-4PH have not been reported in the literature. This represents a specific research niche for investigating the relationship between vibration-assisted printing and the subsequent debinding, sintering, and densification behaviour of metal MEX components.

Conclusions

In sinter-based metal AM processes, debinding and sintering are critical stages that strongly influence the final density, dimensional accuracy, and mechanical performance of the produced components, rather than the shaping process alone. The literature reviewed in this study leads to four main conclusions. First, MEX has adopted binder chemistries similar to those used in traditional MIM but has not yet widely adopted MIM's faster catalytic debinding route. Consequently, solvent and thermal debinding remain the most commonly used approaches in MEX, although both can require relatively long processing times. Second, although MEX sintering schedules can be guided by the established schedules and parameters used for MIM, the sintering atmosphere and thermal profile remain among the most important factors determining densification behaviour and therefore require careful control for each feedstock and process. Third, sintering shrinkage can be substantial and varies according to the processing route. Binder jetting typically exhibits approximately 15–25% shrinkage, which can be highly anisotropic, whereas MEX and MIM parts generally exhibit approximately 15–20% shrinkage that is more largely isotropic. Therefore, dimensional changes in sinter-based AM components need to be calibrated empirically rather than being based solely on assumptions about the process. Fourth, while vibration-assisted printing has been shown to reduce porosity and improve interlayer bonding in polymer FFF, the effects of vibration on green-part density and the subsequent debinding and sintering behaviour of metal-filled feedstocks remain largely unexplored. This represents an important research opportunity for future experimental investigations into vibration-assisted metal MEX and its potential to improve the quality of sintered components.

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Optimisation of Stir-Casted A356/MWCNT/Al₂O₃ Hybrid Composites for Motor Pump Applications

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Abstract—Industrial motor pumps require high-performance materials to withstand the severe mechanical stress during operation. Hence, this study systematically quantifies the weight percentage (wt. %) of aluminium oxide (Al₂O₃), weight percentage (wt.%) multi-walled carbon nanotubes (MWCNTs) and stirring time influence the outcomes of the stir casting parameters on the hardness properties of developed A356/MWCNTs/Al₂O₃ hybrid composites. Taguchi L8 orthogonal array were employed for single-objective optimization, with the aim to maximizing the hardness properties. Through the systematic evaluation of Taguchi L8, the optimal processing for stir casting parameters was achieved at 1.0 wt.% MWCNTs, 6 wt.% Al₂O₃, combined with a 5 min of stirring time. These insights demonstrate that incorporation MWCNTs and Al₂O₃ is a highly effective strategy for optimising A356-based hybrid composites with superior mechanical properties. Ultimately, this research provides a viable material processing route for achieving superior hardness properties, extending the operational lifespan of industrial motor pumps.

Introduction

Aluminium matrix composites (AMCs) have emerged as a critical category of metal matrix composites (MMCs) owing to their low weight and high strength. Their unique performance profile is further characterised by a superior wear characteristic, a controllable thermal expansion coefficient, improved fatigue life and reliable thermal stability at high temperatures [1]. These tailored attributes enable the strategic design of numerous advanced components, specifically within the domain of motor pump technologies. The reinforcement material such as silicon carbide (SiC), aluminium oxide (Al₂O₃) and titanium boride (TiB₂) serves to increase the mechanical and physical properties of AMCs, specifically yielding higher hardness, wear resistance, and density [2–4]. In recent years, the use of carbon nanotubes (CNTs) and Al₂O₃ as reinforcements in composites has been widely recognized for their role in enhancing material strength. The primary method used to produce aluminium metal matrix composites is powder metallurgy and stir casting processes. Although powder metallurgy enables precise control over composition and near-net-shape fabrication, it remains a time-consuming and multi-step process involving powder production, compaction, and sintering. Despite its effectiveness in achieving homogeneous dispersion at elevated weight percentage, the process is still highly susceptible to the localised agglomeration of nano-reinforcements [5]. Hence, the optimisation efforts dictate either the refinement of current operations or the creation of strategic designs to maximise the operational feasibility, directly aligning with modern industrial mandates to balancing the cost efficiency, product quality and waste minimisation [6]. The optimisation of stir casting parameters is extensively reported, where the Taguchi technique has frequently served for maximising process efficiency. Thus, this investigation primarily focuses on the fabrication of A356/MWCNTs/Al₂O₃ hybrid composites, utilising the Taguchi method with an L8 orthogonal array. The effects of MWCNTs content, Al₂O₃ content and stirring time on hardness strength were analysed through signal-to-noise (SN) ratios. Finally, the optimised parameters were then verified through a confirmation experiment.

Methods

The ingot of A356 alloy was melted until 700 °C and remained for 5 min for fully melted. The MWCNTs and Al₂O₃ as reinforcement and the magnesium (Mg) powder with 1 wt.% as a

wettability agent were wrapped in aluminium foil and placed in the molten metal of alloy at 650 °C. The stirrer immediately placed in the molten metal and stirred at 500 rpm. The molten metal poured in the steel mould and solidified. The Vickers hardness testing was conducted in accordance with ASTM E92 with load of 1 kgf with a 15 s dwell time. Each hardness testing was performed three times, with data subsequently expressed as mean values accompanied by standard deviations. To achieve Taguchi's high efficiency, an orthogonal array is necessary [7]. In this study, a Taguchi L8 orthogonal array was selected to optimise the process parameters. Three independent control factors (MWCNTs content (wt.%) (A), Al₂O₃ content (wt.%) (B) and stirring time (min) (C)) were evaluated at two discrete levels each. The overall study involves seven degrees of freedom (DOF), given that each two-level parameter contributes a single DOF. The DOF of the selected orthogonal array must be greater than or equal to total DOF of the experiment. However, selecting an excessively large array leads to unnecessary experimental effort and inflated the cost. Therefore, an L8 orthogonal array with seven degrees of freedom was selected to evaluate the three experimental parameters. Table 4 outlines the Taguchi experimental layout designed to systematically investigate the process parameters affect the resulting composites response.

Table 4: Stir casting parameters and their values at a different level

Process Parameter	Level	
	1	2
MWCNTs Content (wt.%) (A)	0.5	1.0
Al ₂ O ₃ Content (wt.%) (B)	4.0	6.0
Stirring Time (min) (C)	5	10

Results and discussion

Table 2 presents the Vickers hardness value of the composites at the different runs of the Taguchi L8, indicate that the hardness of most composites exceeded that of the base alloy (63 ± 3.19 HV). The influenced of the selected variables on composite hardness was investigated via the signal-to-ratio (S/N) approach, leveraging the “larger-the-better” characteristic to maximise resulting material characteristics. Fig. 6 presents the main effects plot for S/N ratios, illustrating the individual contribution of each parameter to the hardness of the composites. The experimental results identify stirring times as the dominant operating variable, while the weight percentage of both MWCNTs and Al₂O₃ exerted a secondary, sequential impact on the composites. The optimum S/N ratio configuration was identified at a stirring time of 5 min, with the reinforcement levels set at 1.0 wt.% MWCNTs and 6 wt.% Al₂O₃ (A2B2C1). The optimum operating conditions optimise the equilibrium between the hydrodynamic force and mixing efficiency, effectively preventing agglomeration and promoting uniform distribution of the hybrid reinforcements. This suggests that an optimal stirring time is essential for maximising the hardness of AMCs. Exceeding the optimal stirring limit triggers a notable decline in the S/N ratio, revealing that the composite microstructure is highly evolve to vortex instability and gas entrapment induced by excessive agitation.

Table 5: Results of Vickers hardness for Taguchi L8 orthogonal array

Experiment	MWCNTs Content (wt.%)	Al ₂ O ₃ Content (wt.%)	Stirring Time (min)	Vickers Hardness value (HV)
1	0.5	4	5	71.85 ± 1.71
2	0.5	4	10	69.24 ± 2.08
3	0.5	6	5	74.50 ± 0.74
4	0.5	6	10	66.80 ± 1.07
5	1.0	4	5	73.53 ± 2.34
6	1.0	4	10	69.10 ± 2.41
7	1.0	6	5	75.21 ± 1.76
8	1.0	6	10	75.66 ± 2.17

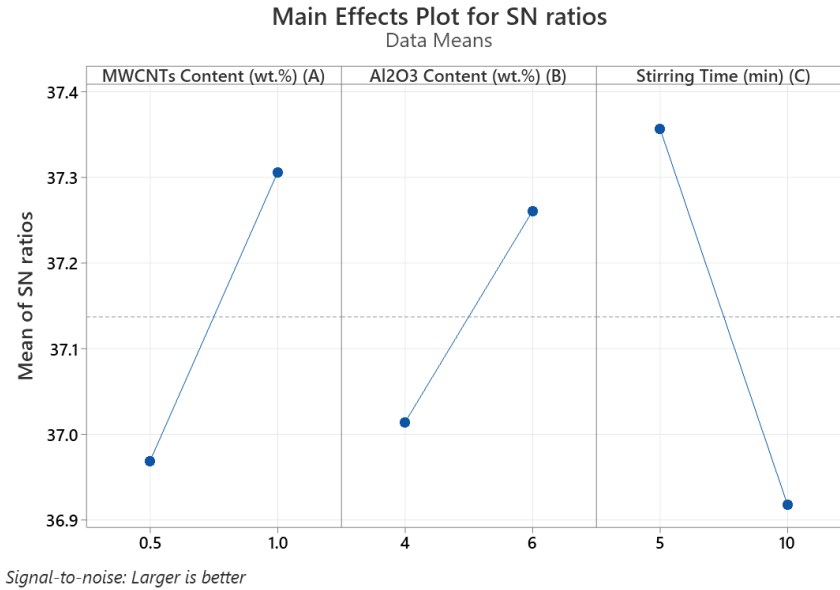


Fig. 6: Main Effect Plot for Signal to Noise (S/N) ratios

Similarly, the significant enhancement in hardness at the higher reinforcement content is directly attributed to the intrinsic high mechanical strength of the MWCNTs and their effective integration within the matrix. The addition of 1.0 wt.% MWCNTs provides greater resistance to localised plastic deformation during indentation. Meanwhile, the main effects plot for the S/N ratios demonstrates that the Al₂O₃ content also exerts a strong positive influence on the hardness of the composite. The substantial enhancement in hardness achieved at these maximum reinforcement levels is directly attributed to the intrinsic mechanical properties of the hybrid reinforcement and their effective integration within the matrix. The primary strengthening mechanisms involve efficient load transfer across the interfacial boundary and dislocation pinning, where uniformly dispersed MWCNTs act as physical barriers that restrict dislocation movement via Orowan looping [8]. Furthermore, the presence of MWCNTs at the grain boundaries restricts grain growth during processing, leading to grain refinement that inherently increases hardness. Concurrently, the hard ceramic Al₂O₃ particles contribute to dispersion strengthening and load-bearing effects, where the matrix effectively transfers stress to the rigid ceramic phase. In summary, the optimised process parameters for achieving superior hardness in A356/MWCNTs/Al₂O₃ hybrid composites were MWCNTs content of 1.0 wt.% (A2), Al₂O₃ content of 6.0 wt.% (B2) and stirring time of 5 min (C1) and it was carried out for the confirmation experiments.

The confirmation test was carried out for the response parameters to predict and verify the improvement of the quality characteristic using the optimal level of design parameters as shown in Fig. 7. From Fig. 7, it is clear that the optimal data obtained from the confirmation test, which was conducted with the level settings parameters of MWCNTs content (1.0 wt.%), Al₂O₃ content (6.0 wt.%) and stirring time (5 min) had good agreement with the predicted optimum parameter (A2B2C1). In addition, the experimentally measured Vickers hardness (HV) values also showed a good agreement with predicted values, with prediction errors below 1.0 %, confirming the reliability of the optimised parameters.

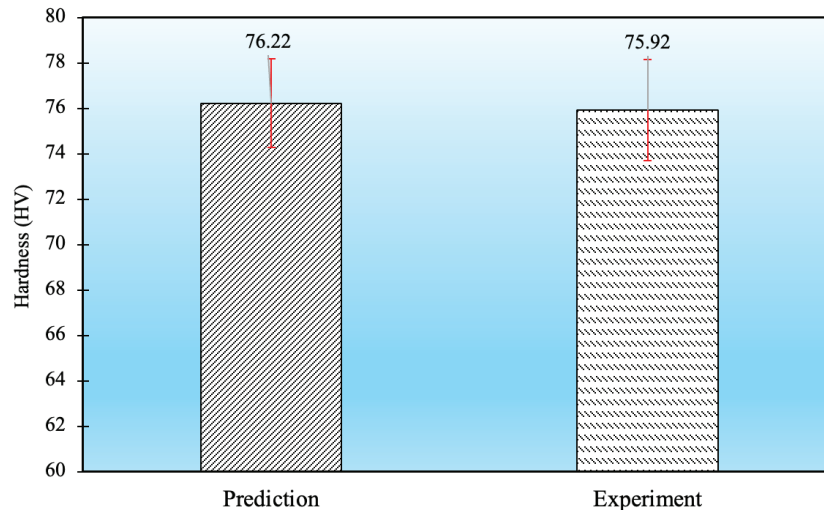


Fig. 7: Comparison of hardness value between prediction and experiment for the optimum parameter (A2B2C1).

Conclusions

A356/MWCNTs/ Al_2O_3 hybrid composites were successfully produced, and process parameters were optimised in accordance with L8 orthogonal array. The optimal processing conditions determined were 1.0 wt. % MWCNTs (A2), 6.0 wt. % Al_2O_3 (B2), and stirring time of 5 min (C1), yielding 75.21 ± 2.14 HV. The findings of the optimum were validated by confirmation experiments and compared with prediction optimise parameters. Thus, optimisation approach developed provides a strategy enhancing the performance of A356-based composites for motor pump applications.

Acknowledgement

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Wear Performance of T6 heat-treated A356 Composites Reinforced with Graphene Nanoplatelets for Motor Pump Applications

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Abstract—The demand for lightweight materials in motor pump applications has increased considerably. In this study, graphene nanoplatelets (GNPs) were used to reinforce A356 aluminium alloy through stir-casting, followed by T6 heat treatment. Vickers hardness and dry sliding wear tests were conducted under a constant normal load of 10 N. Among the investigated compositions, the composite containing 0.3 wt.% GNPs exhibited the highest hardness and the lowest specific wear rate. Further increases in GNPs content reduced the hardness and wear resistance, which may be associated with GNPs agglomeration and non-uniform dispersion. The results indicate the existence of an optimum GNPs content and provide insight into the relationship between processing, composition and tribological performance of A356/GNPs composites for motor pump applications.

Introduction

Current research on lightweight materials focuses on developing affordable cost-effective processing methods for aluminium-graphene composites while simultaneously improving their mechanical and tribological properties [1]. Driven by the need for enhanced mechanical strength, high modulus, superior thermal performance, carbon nanotubes and graphene have emerged as a potential reinforcement for aluminium matrix [2]. Graphene is extensively investigated as a reinforcement phase owing to its exceptional thermal, physical and tribological properties [3]. In addition, numerous recent studies demonstrate that incorporating graphene as a reinforcement phase significantly enhances the wear resistance of aluminium composites [4–7]. In addition, graphene nanoplatelets (GNPs) can be serve as an effective reinforcement in aluminium matrix, substantially lowering the friction and wear rates through the formation of a self-lubricating layer during sliding [8]. However, the processing route and reinforcement content must be carefully controlled to minimise GNPs agglomeration and the associated deterioration in the material properties. Thus, this study evaluates the influence of GNPs addition (0 wt.%, 0.3 wt.%, 0.5 wt.%, and 1.0 wt.%) on the hardness and wear behaviour of A356 matrix composites fabricated stir casting and subsequently subjected to T6 heat treatment.

Materials and Methods

In this study, A356 aluminium alloy exhibited the following composition by wt.%: 7.37% Si, 0.27% Mg, 0.04% Cu, 0.011% Ni, 0.006% Zn, 0.17% Mn, 0.26% Fe, and 91.87% Al. GNPs (Sigma-Aldrich) with purity with more than 95%, particle size less than 2 nm, and average thickness of a few nm were used as reinforcement material. The ingot of A356 alloy was melted until 700 °C and held for 5 mins to ensure complete melting. GNPs at 0, 0.3, 0.5 and 1.0 wt.% and the magnesium (Mg) powder of 1 wt.% as a wettability agent were wrapped in aluminium foil and introduced into the melt at 650 °C. The melt was stirred at 500 rpm for 10 min, poured into the steel mould and allowed to solidify. The cast specimens were solution-treated at 540 °C for 8 h, quenched in warm water and artificially aged at 160 °C for 6 h. Table 6 presents the material compositions, processing conditions, and the sample nomenclature.

Table 6: Composites samples and their nomenclature.

Material	Process	Nomenclature
A356	As-received	A
A356	As-cast + T6 heat treatment	A-T
A356 + 0.3 wt.% GNPs	As-cast + T6 heat treatment	B-T
A356 + 0.5 wt.% GNPs	As-cast + T6 heat treatment	C-T
A356 + 1.0 wt.% GNPs	As-cast + T6 heat treatment	D-T

Vickers hardness testing was conducted in accordance with ASTM E92 using a load of 1 kgf and dwell time of 15 s. Each sample was tested with 15 indentations to ensure the reliability, and the average value was recorded as the final hardness value. Dry sliding wear behaviour was evaluated using a ball-on-disc tribometer in accordance with ASTM G99 under a constant normal load of 10 N, a sliding speed of 1.45 m/s, and a total sliding distance of 2000 m. In this test, a GCR15C steel ball with a diameter of 6 mm and a hardness of 60 HRC was used on the specimen disc with 15 mm wear track diameter. Each sample in this experiment was conducted at least three times under the same parameters to confirm the consistency of the results. The disc samples were weighed before and after each run to compute the wear volume (mm^3) by dividing the weight of the disc samples (g) to the density of the disc samples (g/mm^3). The specific wear rate was defined using calculation by wear volume (mm^3) per load (N) and per sliding distance (mm).

Results and Discussions

Fig. 1 illustrates the Vickers hardness of the base alloy, T6-treated alloy, and GNPs-reinforced composites. T6 heat treatment increased the hardness of A356 from 63.00 ± 3.68 HV (A) to 71.13 ± 3.07 HV (A-T). The highest hardness, 111.95 ± 1.95 HV, was obtained for B-T containing 0.3 wt.% GNPs. This value represents a 57.4% increase relative to A-T and a 77.7% increase relative to as-received A356. However, increasing the GNP content beyond 0.3 wt.% reduced the hardness to 95.41 ± 2.57 HV for C-T and 90.09 ± 3.11 HV for D-T but it still high than sample A and sample A-T. This result shows that the addition of GNPs providing the enhancement in hardness strength. Furthermore, the employed fabrication process in this study reveals the effective technique to promotes a homogeneous distribution of the graphene reinforcement within aluminium matrix, effectively mitigating the common challenge of particle agglomeration. Nevertheless, increasing the reinforcement concentration beyond 0.3 wt.% GNPs induces particle agglomeration within the matrix, a phenomenon driven by the high specific surface area and resultant surface energy, compounded by its poor interfacial wettability with molten aluminium alloys. Consequently, exceeding the 0.3 wt.% GNPs induces agglomeration of the particle dispersion within the matrix, thereby degrading the overall hardness of the composites.

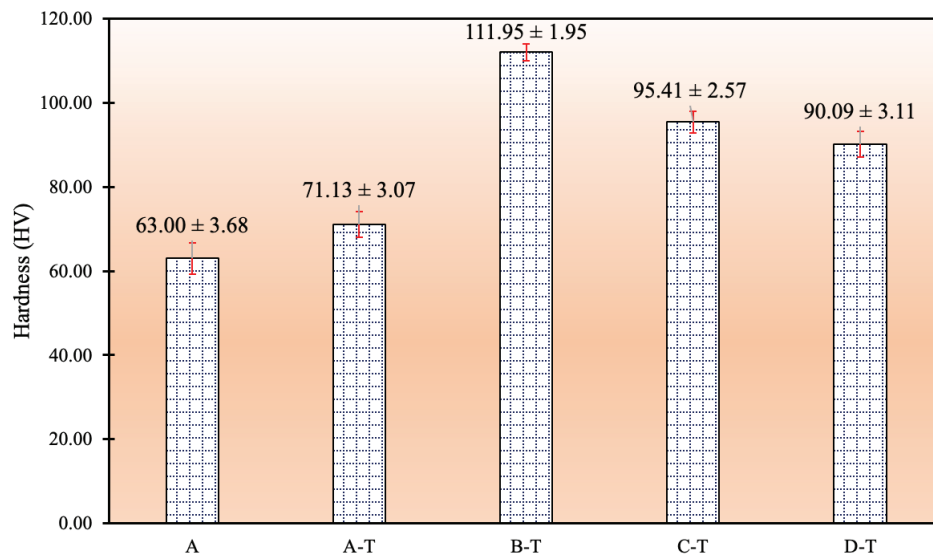


Fig. 1 The comparison of hardness properties for the base alloy, T6-treated alloy and T6-treated composites.

Fig. 2 presents the specific wear rate of the investigated samples under normal load of 10 N at a speed of 1.45 m/s with sliding distance of 2000 m. Sample A exhibited the highest specific wear rate of $2.712 \pm 0.3 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$. T6 heat treatment reduced the value to $1.868 \pm 0.22 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$ for A-T. Sample B-T exhibited the lowest specific wear rate of $1.067 \pm 0.03 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$, corresponding to a 60.7% reduction relative to sample A. The specific wear rate subsequently increased

to $1.575 \pm 0.07 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$ for C-T and $1.712 \pm 0.09 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$ for D-T. The improved wear resistance of B-T may be associated with its higher hardness.

The friction force serves as a quantitative measure of the shear resistance opposing relative sliding at the contact interface between the counterface ball and the specimen disc. Fig. 2 also shows the coefficient of friction of the investigated samples. According to the coefficient of friction data shown in Fig. 2, the unreinforced A356 alloy (sample A) exhibited the highest coefficient of friction of 1.82 ± 0.21 , whereas B-T exhibited the lowest value of 0.31 ± 0.05 . The corresponding values for C-T and D-T were 0.62 ± 0.07 and 0.95 ± 0.08 , respectively. The coefficient of friction of B-T was approximately 83.0 % lower than that of sample A. The trend generally corresponded with the specific wear-rate results. The higher hardness and possible solid-lubricating effect of the GNPs may have contributed to the improved tribological performance. The hardness evaluation showed the sample B-T possessed the highest hardness among the investigated samples, thereby exhibiting enhanced wear resistance and better resistance to surface degradation.

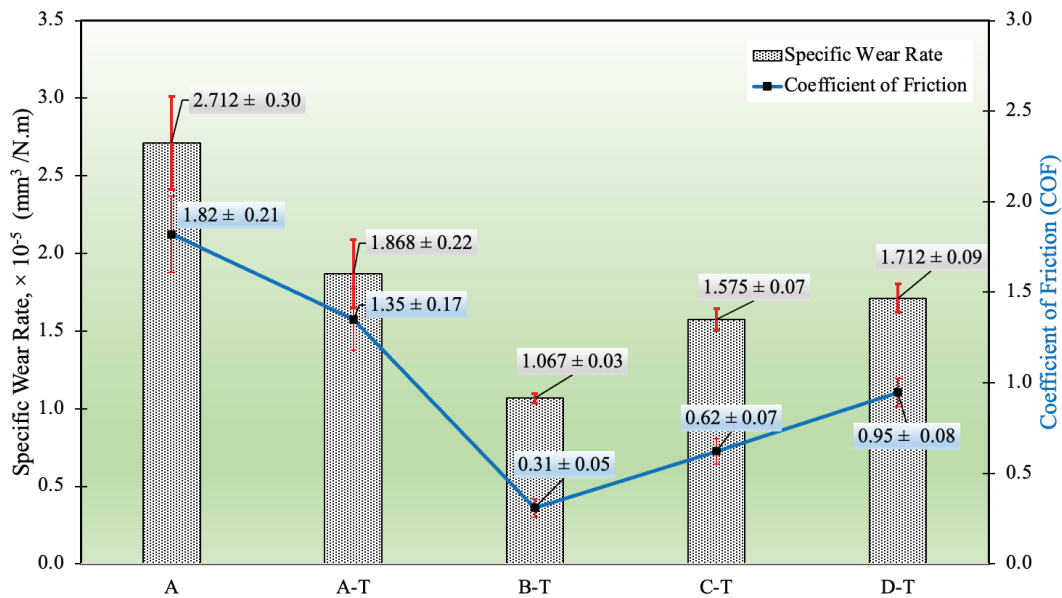


Fig. 2 Comparison of specific wear rate and coefficient of friction for the investigated samples.

Conclusions

The A356/GNPs composites were successfully fabricated by stir casting and subsequently subjected to T6 heat treatment process. The composite containing 0.3 wt.% GNPs achieved the highest hardness of $111.95 \pm 1.95 \text{ HV}$, representing an increase of 57.4 % relative to T6-treated A356 (A-T) and 77.7 % relative to as-received A356 (A). The same composite exhibited the lowest specific wear rate of $1.067 \pm 0.03 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$, corresponding to a 60.7 % reduction relative to as-received A356. Its coefficient of friction decreased from 1.82 ± 0.21 for sample A to 0.31 ± 0.05 for B-T, equivalent to a reduction of approximately 83.0 %. Increasing the GNP content beyond 0.3 wt.% reduced both hardness and wear resistance. This behaviour may be associated with GNP agglomeration.

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Finite Element Analysis of TPMS-Based SS316L Porous Structures

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Abstract

Additive manufacturing enables the layer-by-layer fabrication of AISI 316L stainless steel components with precisely engineered internal porosity, opening a new design space for lightweight, energy-absorbing, and bio-interfacing structures. This study employed finite element analysis to characterize the mechanical behavior of SS316 porous structures under three loading modes: compression, three-point bending, and axial tension [2]. Three macro-geometries (cube, bar, dog-bone) were combined with three volume porosities (20%, 50%, 80%) and three triply periodic minimal surface architectures in a 27-run full-factorial matrix, plus three solid control baselines. Absolute mechanical parameters peak load capacity and maximum Von Mises stress decreased monotonically with increasing porosity in all three families. In contrast, the equivalent structural stiffness displayed a distinctive non-linear trend: it attained a maximum at 50% porosity in compression and tension, and at 80% porosity in flexural bending, because the allowable displacement before yielding contracts more rapidly than the load capacity. A structural optimization matrix distilled these findings into design rules: 50% porosity is optimal for lightweight bone implants that must match the flexibility of human bone, whereas 20% porosity is recommended for high-stress aerospace components under tensile or bending forces.

Keywords: Finite Element Analysis; AISI 316L Stainless Steel; Porous Structures; Triply Periodic Minimal Surfaces; Porosity; Equivalent Stiffness

Introduction

Metal additive manufacturing enables complex metallic components and internal architectures that are difficult or impossible to achieve with conventional processes [1]. Among metallic materials, AISI 316L stainless steel is one of the most frequently used in additive manufacturing owing to its favorable strength–ductility synergy and corrosion resistance, and laser powder bed fusion is the most commonly applied AM method for processing it [2]. The systematic fabrication of engineered porous metallic structures has become one of the most scientifically relevant applications of this technology, since three-dimensional lattices open applications in structural lightweighting, impact absorption, and biomedicine.

Fully dense metallic implants possess an elastic modulus of about 200 GPa, whereas cortical bone ranges from 10 to 30 GPa and cancellous bone from 1 to 15 GPa [3]; when an implant is far stiffer than the host bone, it takes up physical stresses rather than the bone, causing bone shrinkage, implant loosening, and even failure the destructive stress-shielding phenomenon [4]. Introducing controlled interconnected porosity reduces the bulk modulus of the implant toward the bone range, mitigating stress shielding while simultaneously enabling osseointegration the ingrowth of bone into the implant [5]. This porosity-based design strategy, validated analytically through Gibson–Ashby cellular solids models, is now central to modern porous orthopedic implant development. Despite this potential, a significant gap persists in the literature. The bulk compressive behaviors of simple cubic blocks are studied almost solely in most numerical and experimental research, leaving a severe lack of comparative data for the response of identical porous architectures to uniform axial tension and complex flexural bending. It also remains unclear at exactly which porosity thresholds failure mechanisms switch from near-solid material yielding in the lower porosity domain to local buckling and global lattice collapse at the upper porosity domain. Finally, no central, multi-variable optimization matrix exists that scores these architectures across multiple loading conditions for

engineering use. Accordingly, this study systematically investigates the structural response of porous SS316 architectures by integrating three specimen geometries cubic, bar, and dog-bone configurations with prescribed volume porosities of 20%, 50%, and 80%. Particular emphasis is placed on quantifying the effects of geometry and porosity on localized stress concentration, structural stiffness, and total deformation, thereby establishing the relationship between architectural design and mechanical response. The resulting performance trends are subsequently synthesized into a structural optimization framework to identify configuration–porosity combinations suited to different load-bearing requirements. This approach provides a quantitative basis for tailoring porous SS316 structures toward engineering and biomedical applications where controlled stiffness, deformation, and stress distribution are critical design considerations.

Methodology

All simulations employed AISI 316L stainless steel represented by an isotropic bilinear elasto-plastic constitutive model: elastic modulus $E = 193$ GPa, Poisson's ratio $\nu = 0.27$, yield strength $\sigma_y = 290$ MPa, and tangent modulus $E_T = 1.5$ GPa, consistent with published AM literature values. Grain anisotropy, surface roughness, and manufacturing-induced chemical heterogeneities were intentionally excluded to isolate the effects of geometry and porosity on mechanical response. Three macro-specimen geometries were designed in Fusion 360 to replicate standard destructive mechanical test configurations:

Table 1: Specimen geometry specifications

No	Shape	Dimension (mm)
1	Cube	15x15x15
2	Bar	100x20x5
3	Dog-bone	100 × 6 × 10 (ASTM E8 sub-size)

The internal architectures comprised three continuous-curvature TPMS topologies — Gyroid, Schwarz D, and Schwarz P which were generated with implicit modeling methods so that the internal cell walls integrated smoothly with the external solid skin; such smooth, self-supporting TPMS geometry avoids the sharp nodal intersections of strut-based lattices and is extensively used for porous scaffold design in bone tissue engineering [6], [7]. The internal unit cell pattern was kept identical across every model, ensuring that any differences in mechanical behavior could be traced to geometry and porosity alone.

A three-factor, three-level full-factorial Design of Experiments (DoE) matrix was constructed, crossing specimen geometry (cube, bar, dog-bone), porosity (20%, 50%, 80%), and topology (gyroid, Schwarz D, Schwarz P), yielding 27 unique simulation profiles plus three solid-material reference specimens. A representative subset is presented in Table 2. All simulations were run under quasi-static, displacement-driven loading with fixed constraints using implicit finite element solvers. Because of the highly curved TPMS surfaces, high-order ten-node quadratic tetrahedral elements were employed to capture the severe local bending and thin-walled stretching of the minimal surfaces. Post-processing extracted Von Mises stress contours, reaction forces, and force–displacement curves, from which peak load capacity, maximum localized stress, displacement limits, minimum factors of safety, and equivalent structural stiffness were derived for every run.

Results and Discussion

Across compression, three-point bending, and axial tension, increasing porosity produced a clear reduction in the absolute load-bearing capacity of the SS316 structures. The solid specimens sustained the highest loads, reaching 46,125 N in compression, 5,500 N in bending, and 50,000 N in tension. As shown in Fig. 1 (a), the normalized peak load decreased

progressively with increasing porosity, with approximately 20% of the solid load capacity retained at 80% porosity under compression and tension, compared with approximately 5% under bending. This reduction is primarily attributed to the loss of effective load-bearing area with increasing porosity, consistent with the relative-density dependence described by cellular-solid theory [8]. In contrast to the monotonic reduction in peak load, equivalent structural stiffness exhibited a non-linear and loading-dependent response (Fig. 1 (b)). Compression showed the most pronounced variation, reaching approximately 106.9% of the solid-reference stiffness at 50% porosity before decreasing to approximately 97.6% at 80% porosity.

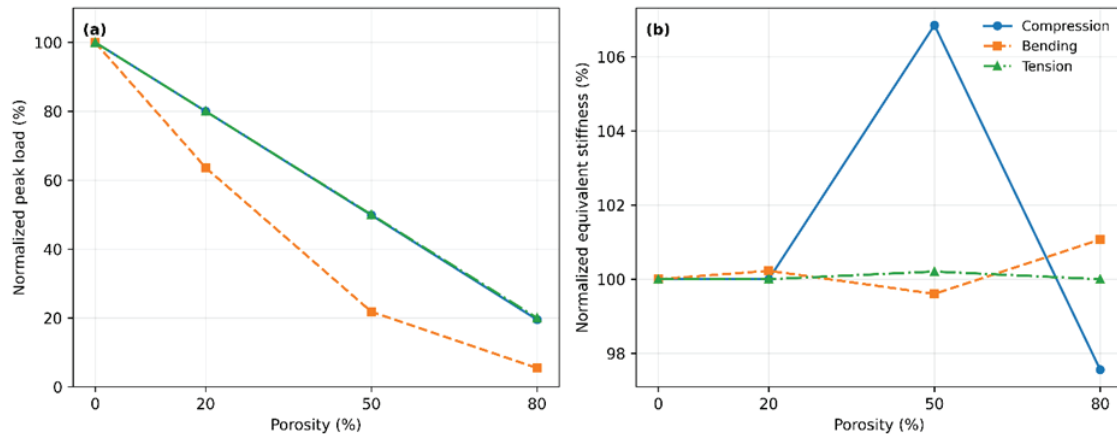


Fig 1. Effect of porosity on the normalized mechanical response of SS316 porous structures under different loading conditions: (a) peak load and (b) equivalent structural stiffness. Values are normalized with respect to the corresponding solid reference specimen (0% porosity).

Topology became increasingly influential as porosity increased. At 20% porosity, the Gyroid, Schwarz P, and Schwarz D structures exhibited relatively distributed von Mises stress fields. At 50% and 80%, stress localization became more pronounced as loads were transferred through thinner cellular walls. The Schwarz P topology exhibited greater stress concentration near geometrical junctions, whereas the Gyroid maintained a comparatively uniform stress distribution because of its smooth and continuously curved surface. Correspondingly, the Gyroid showed the most favourable stiffness retention relative to material utilization, followed by Schwarz D and Schwarz P. These results indicate that porosity primarily governs the available load-bearing material, while topology controls how efficiently that material redistributes stress. The influence of porosity also depended strongly on loading mode. Under compression, highly porous cube specimens were increasingly susceptible to localized cell-wall deformation and structural instability. Under tension, deformation became concentrated within the thin TPMS walls of the dog-bone specimens, particularly beyond 50% porosity. Bending was especially sensitive to material removal because increasing porosity reduced the effective second moment of area of the bar specimens. Consequently, highly porous configurations cannot be evaluated solely on the basis of mass reduction; their suitability depends on the interaction between topology, relative density, and the imposed loading condition. The combined performance assessment therefore identifies distinct design windows rather than a universally superior configuration. Gyroid structures with 20–50% porosity provide a favourable balance between mechanical compliance and load-bearing capability, making them promising for biomedical applications where reduced stiffness may help mitigate stress shielding. For bending-dominated lightweight structures, the Schwarz D bar at 20% porosity provided the most favourable flexural response within the investigated design space. Overall, the results demonstrate that effective design of porous SS316 requires simultaneous consideration of porosity, topology, and loading mode, providing a rational basis for selecting application-specific TPMS architectures prior to experimental fabrication and validation.

Conclusions

Based on the findings, the following conclusions can be drawn:

1. The Gyroid topology consistently demonstrated the highest stiffness-to-density ratio under compression, bending, and tensile loading. Its continuous and smooth geometry promotes a more uniform stress distribution, resulting in lower stress concentrations than the Schwarz D and Schwarz P topologies.
2. The results revealed a clear transition in the dominant failure mechanism as porosity increased. Specimens with 20% and 50% porosity were primarily governed by material yielding, whereas those with 80% porosity exhibited lattice buckling as the dominant mode of failure. This behaviour highlights the increasing influence of structural instability at high porosity levels and the limitations of relying solely on linear elastic FEA for highly porous designs.
3. The optimization study identified Gyroid structures with 20–50% porosity as the most suitable configurations for biomedical implants because they provide a balanced combination of mechanical compliance and load-bearing capability, helping to reduce stress shielding. For lightweight structural components subjected to bending, the Schwarz D bar with 20% porosity offered the best flexural performance.
4. The FEA framework provides an efficient alternative to extensive physical prototyping by enabling rapid evaluation and comparison of different lattice configurations. It also establishes a reliable foundation for future studies involving more advanced TPMS geometries, dynamic loading conditions, and multi-material lattice structures.

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A Systematic Review of Load-Aware Toolpath Generation in FDM: Algorithmic Advancements and Manufacturing Limitations

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Abstract—Fused Deposition Modeling (FDM) of Polylactic Acid (PLA) inherently suffers from severe mechanical anisotropy and weak inter-filament bonding. These issues are exacerbated by conventional, homogenous infill patterns that fail to efficiently distribute complex and non-uniform stresses. To address this fundamental limitation, this study presents a systematic literature review of 34 high-quality articles, conducted in accordance with PRISMA guidelines using Scopus and Web of Science databases, to critically evaluate the algorithmic methodologies used to map Principal Stress Lines (PSLs) into continuous, load-aware FDM toolpaths. A thematic analysis of computational strategies reveals a prominent shift from traditional, iterative Finite Element Analysis (FEA) toward advanced machine learning frameworks, such as Graph Neural Networks (GNNs), which significantly accelerate trajectory generation while actively mitigating stress field singularities. Mechanically, aligning material deposition with PSLs increases ultimate tensile load capacities by up to 38% for pure PLA matrices. This alignment fundamentally shifts structural failure modes from premature, shear-induced inter-layer delamination to progressive localized yielding. However, translating these theoretically optimized vectors into physical components remains critically constrained by hardware kinematic limitations and the thermo-rheological anomalies of PLA. Moreover, a complex and high-curvature toolpaths frequently induce micro-voids, under-extrusion, and severe thermal warping. In conclusion, while stress-trajectory algorithms transformatively enhance the strength-to-weight ratio and load-bearing efficiency of FDM components, their ultimate viability is bottlenecked by physical manufacturing defects. Consequently, future research must urgently prioritize evaluating these highly aligned architectures under dynamic, multi-axis cyclic fatigue scenarios while developing automated commercial software integrations to realize accessible, strength-aware industrial manufacturing.

Introduction

Fused Deposition Modeling (FDM) of Polylactic Acid (PLA) inherently suffers from mechanical anisotropy driven by the layer-by-layer material extrusion process and weak inter-filament bonding [1]. Standard infill patterns such as grid, honeycomb and gyroid distribute material homogeneously throughout the internal volume of a printed component. This structural uniformity represents a critical mechanical limitation, as these homogeneous patterns cannot efficiently distribute non-uniform stress or optimize material usage under complex load-bearing scenarios [2]. While conventional topology optimization successfully reduces component weight, a significant knowledge gap persists regarding the computational and manufacturing challenges of translating theoretical Principal Stress Lines (PSLs) from Finite Element Analysis (FEA) into continuous and printable toolpaths [3],[4]. Principal stress vector fields are frequently non-integrable, and existing algorithms often fail to incorporate physical manufacturing constraints directly into the optimization loop [3]. Therefore, this systematic literature review aims to evaluate current algorithmic methodologies for mapping stress trajectories into viable FDM toolpaths. Additionally, it assesses their direct impact on the mechanical performance of FDM-printed PLA which serves as the primary benchmark thermoplastic in the literature due to its well-characterized thermo-rheological behavior and high sensitivity to process-induced anisotropy. Ultimately, by overcoming inherent structural anisotropy and actively minimizing process-induced defects, advanced infill algorithms can ensure that filament deposition is precisely aligned with maximal principal stresses.

Methodology

A comprehensive systematic literature search was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines across the

Scopus (609 records) and Web of Science (647 records) databases up to June 2026. To ensure complete transparency and reproducibility, the precise Boolean search query executed was: TITLE-ABS-KEY(("Fused Deposition Modeling" OR "FDM" OR "FFF") AND ("PLA" OR "Polylactic Acid") AND ("infill*" OR "toolpath*") AND ("stress-driven" OR "load-aware" OR "principal stress line*")). Following duplicate removal, 868 unique records were screened against strict eligibility metrics to maintain critical analytical rigor. Included studies were restricted to peer-reviewed English journal articles focusing on FDM of PLA thermoplastic matrices including short-fiber and continuous fiber-reinforced variants that implemented continuous stress-driven or PSLs toolpath generation algorithms backed by experimental, quantitative mechanical testing such as tensile, flexural, or yield failure analysis. Conversely, editorials, conference abstracts, non-English publications, studies focusing strictly on global macro-topology optimization without toolpath generation and papers lacking experimental toolpath validation were systematically excluded, yielding a final cohort of 34 high-quality articles.

To rigorously synthesize the final cohort, a standardized data extraction framework was deployed across three primary domains: (1) algorithmic parameters, (2) computational and Finite Element Analysis (FEA) solver environments and (3) mechanical and physical manufacturing assessments. Data were systematically extracted into a comprehensive matrix capturing critical operational parameters, including specific FEA solvers, machine learning surrogate frameworks, hardware configurations and printing speeds. Furthermore, the framework captured key performance metrics and physical outcomes, specifically tensile and flexural strength increments, structural load capacities and process-induced failure modes enabling a robust critical synthesis of computational advancements and physical manufacturing limitations. The Fig. 1 shows the systematic literature review using the PRISMA.

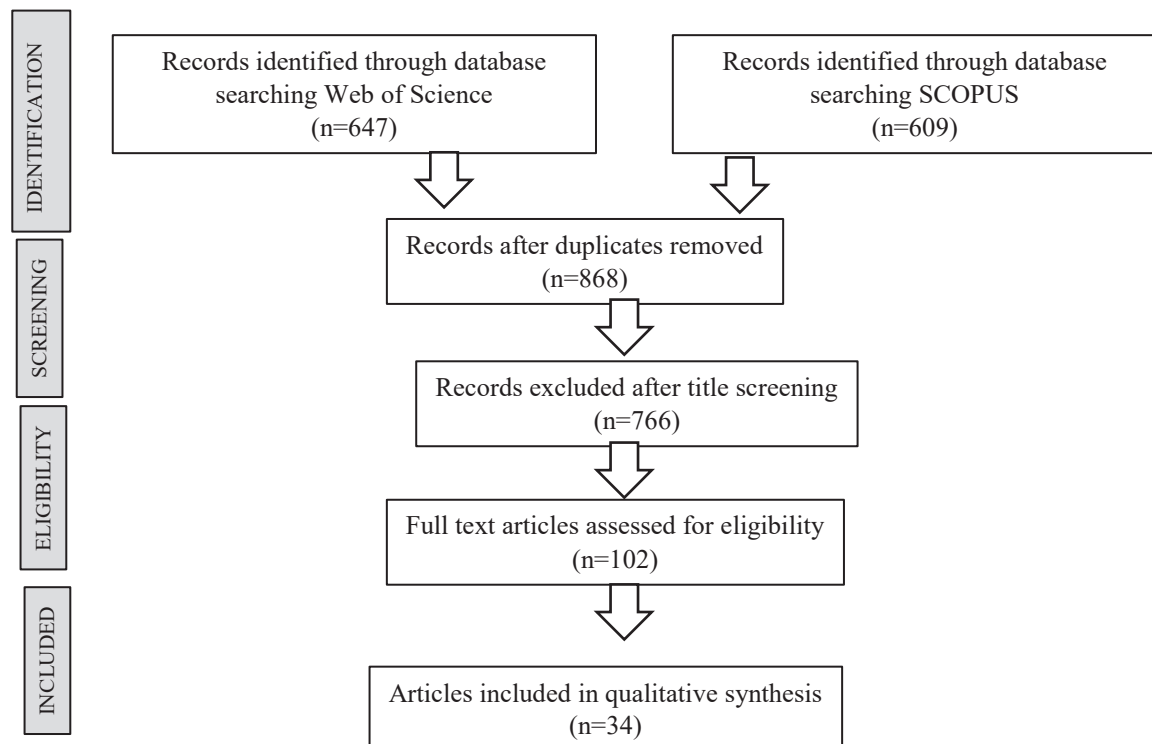


Fig. 8 The PRISMA flow chart

Findings and Arguments

In general, the findings are categorized into three assessments. First, the algorithmic & computational strategies. The toolpath generation pipeline typically begins with FEA to map

solid CAD model stress distributions, commonly utilizing solvers like Abaqus, ANSYS, or Nastran [3],[5]-[10]. A prominent shift is occurring from traditional and computationally expensive iterative FEA operations toward advanced machine learning frameworks, such as Graph Neural Networks (GNNs), which can predict principal stress vectors on unstructured meshes in roughly 10 milliseconds [11]. To handle toolpath convergence at high-stress constraint nodes and prevent localized material over-accumulation and overlapping, dynamic spatial compensation algorithms adaptively scale down the extrusion rates or dynamically adjust physical toolpath widths in proportion to the severity of line overlap [9],[12].

The second assessment was the mechanical performance. Aligning toolpaths with PSLs fundamentally shifts mechanical optimization from generic geometric filling to localized, stress-responsive material deposition. Generating FDM toolpaths that strictly align with PSLs ensures that the deposited polymer directly opposes the applied load vectors. Across the reviewed cohort, stress-aligned toolpaths consistently yield significant mechanical improvements, with benchmark studies reporting ultimate tensile load capacity increases of up to 38% for pure PLA matrices compared to traditional contour-parallel and grid toolpaths [13]. Furthermore, by minimizing interfacial shear stress across weak filament boundaries, failure mechanisms shift from premature, shear-induced inter-layer delamination to progressive localized material yielding [11],[13].

The third assessment was the manufacturing limitations. Despite theoretical structural improvements, practical application is heavily constrained by printer hardware limits. Abrupt direction changes forced by high-curvature toolpaths require rapid printhead acceleration and deceleration, inducing machine vibrations and mismatched system dynamics that lead to under-extrusion and overfills [14]. Additionally, executing highly fragmented trajectories forces frequent non-printing travel moves and repeated extruder retraction, introducing nodal instability of micro-voids and gaps between parallel print lines that act as severe stress concentrators [13],[15]-[16]. Furthermore, PLA's thermo-rheological behavior under these irregular deposition paths causes highly uneven cooling rates and severe thermal gradients. This restricts polymer chain reptation across deposited strands, yielding weak inter-strand bonding, differential thermal contraction, and macroscopic part warping [17].

A synthesis of the 34-paper cohort reveals a fundamental mathematical-physical gap in load-aware manufacturing: while machine learning models like Graph Neural Networks (GNNs) achieve extreme computational speed, 10 ms and bypass heavy iterative FEA cycles, they do not inherently incorporate the physical constraints of FDM kinematics [6],[9],[11]. This mismatch forces a trade-off between algorithmic complexity and physical printability. Field-based continuous approaches minimize interfacial shear but trigger severe material misalignment or path folding at sharp turning angles exceeding 120° [6]. Conversely, explicit stream tracing using Euler integration produces well-defined physical trajectories but leads to toolpath fragmentation, requiring rigorous post-processing regularization such as Laplace operators, Douglas-Peucker algorithms, or strict $\pm 30^\circ$ path smoothing to suppress internal micro-voids and warping [11]-[13]. Ultimately, the mechanical benefits of stress-alignment in a range of 36%-38% load capacity, increase can be entirely negated if these process-induced defects are not controlled [13]. Thus, highlighting that future designs must co-optimize algorithmic trajectories with real-time kinematic extrusion feedback.

Conclusions

Stress-trajectory based infill optimization algorithms possess transformative potential in mitigating the inherent mechanical anisotropy of FDM-printed PLA by maximizing both the strength-to-weight ratio and load-bearing efficiency. However, highly continuous, stretch-dominated structures engineered for optimal axial load transfer introduce a "design paradox," as they become inherently susceptible to nodal instability and catastrophic cascade failures.

Furthermore, the kinematic limitations of FDM hardware and the thermo-rheological anomalies of PLA prevent the accurate, gap-free deposition of theoretical stress trajectories. To bridge the gap between academic theory and practical manufacturing, future research must transition from evaluating isolated 2D planar static stresses toward dynamic, multi-axis cyclic fatigue scenarios. Concurrently, the development of automated, machine learning-assisted commercial software integrations is essential to bypass computational bottlenecks and realize accessible, strength-aware industrial manufacturing.

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Optimization of Surface Roughness in WEDM of SKD11 Tool Steel Using Taguchi Method

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Abstract— Wire Electrical Discharge Machining (WEDM) has been widely used for machining hardened tool steels owing to its capability to produce complex geometries with high precision. However, achieving consistently low surface roughness (Ra) for SKD11 tool steel has remained challenging because the optimum machining parameters have varied across different WEDM systems. This study aimed to optimize the WEDM parameters for minimizing the surface roughness of SKD11 tool steel using the Taguchi method. Four machining parameters, namely pulse duration (ON), pulse interval (OFF), peak current (IP), and servo voltage (SV), were investigated using a Taguchi L9 orthogonal array, while signal-to-noise (S/N) ratio analysis and Analysis of Variance (ANOVA) were employed to determine the optimum parameter combination and factor significance. The optimum condition was identified as ON = 3 μ s, OFF = 10 μ s, IP = 8 A, and SV = 10 V, producing the lowest surface roughness of 1.148 μ m. Pulse duration was found to be the dominant factor, contributing 96.30% to surface roughness variation. These findings provide a practical guideline for improving the surface quality of SKD11 during WEDM.

Introduction

Wire Electrical Discharge Machining (WEDM) has become one of the most widely adopted non-conventional machining processes for producing components with complex geometries and high dimensional accuracy, particularly for electrically conductive materials with high hardness [2]. Among hardened tool steels, SKD11 has been extensively used in die, mold, and precision engineering applications because of its excellent hardness, wear resistance, and dimensional stability [1]. However, these properties have also made SKD11 difficult to machine using conventional cutting methods, making WEDM a preferred manufacturing process. Surface roughness (Ra) is one of the most critical quality characteristics in WEDM, as it directly affects the functional performance, wear resistance, and service life of machined components. Previous studies have reported that machining parameters, particularly pulse duration (ON), pulse interval (OFF), peak current (IP), and servo voltage (SV), significantly influence the surface quality achieved during WEDM [2,3,6-11].

Various optimization techniques, including the Taguchi method, Response Surface Methodology (RSM), and statistical analysis, have been employed to improve WEDM performance [2-7]. Similar investigations have been conducted on SKD11, D2 tool steel, stainless steel 304, magnesium alloys, and hybrid metal matrix composites [6-11]. Nevertheless, the optimum machining parameters reported in the literature have varied considerably due to differences in workpiece materials, machine configurations, dielectric systems, and machining conditions. Consequently, the optimum parameter settings established for one WEDM system cannot be directly applied to another machine, highlighting the need for machine-specific optimization.

Therefore, this study aimed to optimize the WEDM parameters for minimizing the surface roughness of SKD11 tool steel using a Sodick VZ500L five-axis WEDM machine. The machining parameters were optimized using the Taguchi L9 orthogonal array, while the signal-to-noise (S/N) ratio and Analysis of Variance (ANOVA) were employed to determine the optimum parameter combination and evaluate the significance of each machining parameter. The findings provide a practical machining guideline for improving the surface quality of SKD11 and contribute to more efficient parameter selection for die and mold manufacturing.

Methodology

Experimental Design

The experiments were conducted using a Sodick VZ500L five-axis Wire Electrical Discharge Machining (WEDM) machine. SKD11 (DIN 1.2379) tool steel specimens (20 mm × 22 mm × 5 mm) were machined using a 0.25 mm diameter brass wire electrode. Four machining parameters, namely pulse duration (ON), pulse interval (OFF), peak current (IP), and servo voltage (SV), were investigated using a Taguchi L9 orthogonal array. The experimental design and statistical analyses were performed using Minitab. The machining parameters and their corresponding levels are presented in Table 1. Machining voltage, wire tension, and dielectric injection pressure were maintained constant throughout the experiments.

Table 1: WEDM machining parameters and levels

Parameter	Level 1 (Low)	Level 2 (Med)	Level 3 (High)
Pulse Duration, ON (μs)	3	7	12
Pulse Interval, OFF (μs)	10	15	20
Servo Voltage, SV (V)	10	15	20
Peak Current, IP (A)	8	12	16

Surface Roughness Measurement

Surface roughness (Ra) was measured using a Mitutoyo SURFPAK SV-614 surface profilometer in accordance with the JIS 2001 (R JIS) standard. Six measurements were taken from each machined specimen, and the average value was used for subsequent analysis.

Statistical Analysis

The measured surface roughness values were analyzed using the Taguchi signal-to-noise (S/N) ratio based on the smaller-the-better criterion:

$$\frac{S}{N} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad (1)$$

where y_i is the measured surface roughness, and n is the number of observations. The measured surface roughness values were analyzed using the Taguchi signal-to-noise (S/N) ratio based on the smaller-the-better criterion to determine the optimum machining parameters. A one-way Analysis of Variance (ANOVA) was then performed on the measured surface roughness values to evaluate the significance and percentage contribution of each machining parameter.

Results and Discussion

Experimental Results

The experimental results obtained from the Taguchi L9 orthogonal array are summarized in Table 2. The measured surface roughness (Ra) varied with the selected machining parameters, ranging from 1.148 μm to XX μm. The lowest Ra (1.148 μm) was obtained in Run 1 (ON = 3 μs, OFF = 10 μs, IP = 8 A, and SV = 10 V), whereas the highest Ra was recorded in Run 7. These results indicate that the selected WEDM parameters have a significant influence on the surface quality of SKD11 tool steel.

Table 2: Experimental results of the Taguchi L9 orthogonal array

Exp. No.	ON (μs)	OFF (μs)	IP (A)	SV (V)	Ra (μm)	S/N (dB)
1	3	10	8	10	1.148	-1.199
2	3	15	12	15	1.226	-1.770
3	3	20	16	20	1.336	-2.516
4	7	10	12	20	1.836	-5.277
5	7	15	16	10	1.875	-5.460
6	7	20	8	15	1.731	-4.766
7	12	10	16	15	2.128	-6.559
8	12	15	8	20	1.977	-5.920
9	12	20	12	10	2.046	-6.218

Taguchi Optimization

The response analysis based on the signal-to-noise (S/N) ratio is presented in Figure 1. Using the smaller-the-better criterion, the optimum machining parameters for minimising surface roughness were identified as ON = 3 μ s, OFF = 10 μ s, IP = 8 A, and SV = 10 V, corresponding to Level 1 for all factors. Among the investigated parameters, pulse duration (ON) showed the largest variation in S/N ratio, indicating the greatest influence on surface roughness. Increasing the pulse duration generally increased the surface roughness because the higher discharge energy produced larger discharge craters on the machined surface. In comparison, pulse interval, peak current, and servo voltage exhibited relatively smaller effects within the investigated range. In comparison, pulse interval, peak current, and servo voltage exhibited relatively smaller effects within the investigated range. This is because pulse duration directly governs the discharge energy per spark, producing deeper craters and greater Ra, whereas the other parameters mainly influence gap flushing and discharge stability rather than crater depth. The comparatively wider range tested for pulse duration may have further amplified its dominant contribution in the ANOVA.

ANOVA and Surface Morphology

One-way ANOVA of the measured surface roughness (Ra) values was performed to determine the contribution of each WEDM parameter. As shown in Table 3, pulse duration (ON) was the dominant factor, contributing 96.30% to the total variation in surface roughness, followed by peak current (IP) (3.56%), while servo voltage (SV) and pulse interval (OFF) had negligible effects. These results indicate that pulse duration plays the most important role in controlling the surface finish of SKD11.

The three-dimensional surface topography in Figure 2 supports the statistical findings. Sample 1, machined under the optimum parameter combination, exhibited a smoother surface with shallower discharge craters and the lowest surface roughness (1.148 μ m), whereas Sample 7 showed a rougher surface with deeper and more irregular craters.

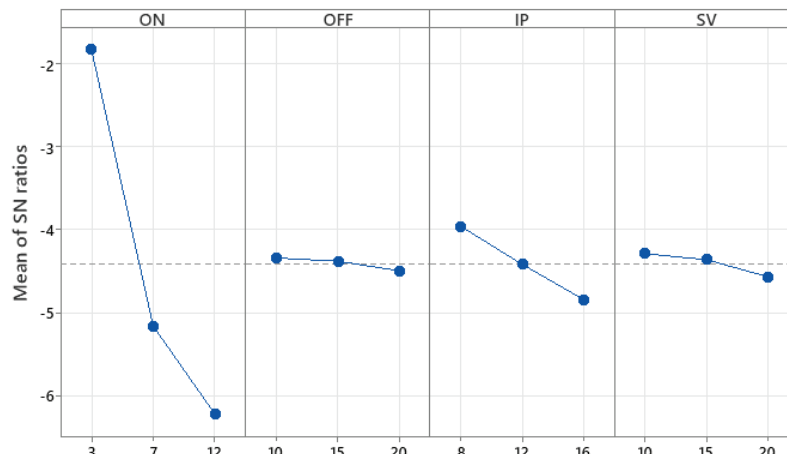


Fig. 9 Main effects plot for S/N ratios of surface roughness (Ra)

Table 3: ANOVA results for surface roughness (Ra)

Parameter	Contribution (%)
Pulse Duration (ON)	96.30
Peak Current (IP)	3.56
Servo Voltage (SV)	0.11
Pulse Interval (OFF)	0.02

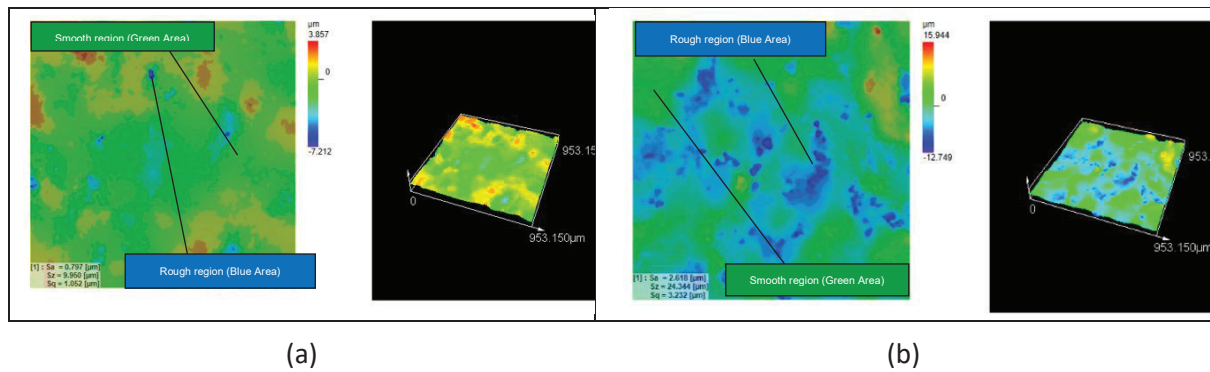


Fig. 2 Three-dimensional surface topography of (a) Sample 1 (lowest Ra) and (b) Sample 7 (highest Ra)

Conclusion

This study successfully optimized the WEDM parameters for minimizing the surface roughness of SKD11 tool steel using the Taguchi method. The optimum machining parameters were ON = 3 μ s, OFF = 10 μ s, IP = 8 A, and SV = 10 V, producing the lowest surface roughness of 1.148 μ m. ANOVA showed that pulse duration was the most influential parameter, contributing 96.30% to the variation in surface roughness. These findings provide a practical reference for selecting suitable WEDM parameters to improve the surface quality of SKD11 tool steel.

Acknowledgement

The authors gratefully acknowledge the support provided by the Japan-Malaysia Technical Institute (JMTI) and Universiti Teknikal Malaysia Melaka (UTeM) for the facilities and technical assistance that made this research possible.

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Performance Assessment of Reinforced Plaster of Paris Molds for Burnout of 3D-Printed PLA Patterns in Investment Casting

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Abstract- The use of 3D-printed polylactic acid (PLA) patterns in investment casting offers significant advantages in terms of design flexibility and reduced tooling costs. However, PLA undergoes thermal expansion and decomposition during burnout, which can induce internal pressure and cracking in Plaster of Paris (POP) molds. This study evaluates the performance of reinforced POP mold compositions subjected to a controlled five-stage burnout cycle for investment casting applications. Five mold formulations (T1-T5) incorporating silica sand, bentonite, and fiberglass reinforcement were prepared and compared with an unreinforced POP control mold. PLA propeller blade patterns were fabricated using fused deposition modelling (FDM) and embedded in POP-based molds. Following a 48-hour pre-drying stage, molds were subjected to a burnout schedule consisting of heating stages up to 500°C. Mold performance was assessed through mass loss behaviour, Crack Severity Index (CSI), and dimensional stability measurements. Dimensional measurements were obtained using digital vernier calipers, while visual inspection was used to evaluate crack formation. Results showed that reinforced mold compositions demonstrated improved thermal stability and reduced cracking compared with the control specimen. The fully reinforced composition (T5), consisting of POP, silica sand, bentonite and fiberglass, produced the smallest dimensional reduction of 0.97 mm (2.26%) and achieved a CSI score of 0, indicating no visible cracks. The findings suggest that the combined use of silica sand, bentonite and fiberglass enhances mold integrity and dimensional stability during the burnout of 3D-printed PLA patterns.

Introduction

Investment casting is widely used for manufacturing components requiring high dimensional accuracy and complex geometries. Recent developments in additive manufacturing have enabled the replacement of conventional wax patterns with 3D-printed PLA patterns, reducing tooling costs and production time while increasing design flexibility (Kristiawan et al., 2021; Taib et al., 2023).

Despite these advantages, PLA patterns present challenges during burnout because they thermally soften and decompose rather than melt and flow out like traditional wax patterns. The decomposition process generates gases that may create internal pressure and thermal stresses within the mold, leading to cracking and dimensional distortion, particularly when low-cost mold materials such as POP are used (Scheinberg et al., 2024).

Previous studies have reported that mold reinforcement materials such as silica sand, bentonite and fiberglass can improve thermal stability and crack resistance of casting molds (Mapossa et al., 2023). However, limited studies have investigated their combined effect on POP molds used with 3D-printed PLA patterns.

Therefore, this work evaluates the performance of five reinforced POP mold formulations under a selected five-stage burnout cycle. The study aims to compare mold compositions in terms of mass loss behaviour, crack formation, and dimensional stability. The outcome provides practical guidance for developing low-cost investment casting molds suitable for prototype and low-volume manufacturing applications.

Methodology

PLA propeller blade patterns were fabricated using an Ultimaker FDM printer with a layer height of 0.15 mm, 10% triangular infill density, and printing speed of 60 mm/s.

Five mold formulations were prepared using POP, silica sand, bentonite, fiberglass and water. The compositions are summarized in Table 1. All percentages are presented on a mass basis.

Table 1. Mold compositions investigated

Specimen	POP (%)	Silica Sand (%)	Bentonite (%)	Fiberglass (%)	Water (%)
T1	60	0	0	0	40
T2	50	10	0	0	40
T3	48	10	0	2	40
T4	48	10	2	0	40
T5	46	10	2	2	40

After casting around the PLA patterns, molds were pre-dried at room temperature for 48 h before burnout. The burnout cycle consisted of five stages: 50°C for 5 h, 100°C for 3 h, 300°C for 3 h, and 500°C for 2 h with heating rates of 0.5-1°C/min.

Mold performance was evaluated using:

- Mass loss analysis
- Crack Severity Index (CSI)
- Dimensional stability measurements

The CSI scale used was:

- CSI = 0 : No visible cracks
- CSI = 1 : Hairline cracks
- CSI = 3 : Visible surface cracks
- CSI = 5 : Through-thickness cracks

Dimensional reduction was determined by comparing the original pattern diameter (43 mm) with the post-burnout cavity diameter measured using a digital vernier caliper.

Results and Discussion

The mass loss results demonstrated progressive decomposition of PLA during heating, with the most significant reduction occurring between 300°C and 500°C. All specimens experienced substantial mass loss within this temperature range, indicating effective pattern removal.

The addition of silica sand, bentonite and fiberglass improved resistance to thermal degradation effects by reducing crack formation and improving dimensional stability. Bentonite-containing specimens (T4 and T5) exhibited superior cohesion and lower crack formation than molds without bentonite.

Table 2. Dimensional stability and crack severity results

Specimen	Mass Loss Percentage (%)	Average Diameter (mm)	Shrinkage (%)	CSI
T1	71.14	41.87 ± 0.15	2.63	1
T2	41.55	41.93 ± 0.44	2.48	1
T3	42.11	41.96 ± 0.17	2.42	1
T4	42.28	42.01 ± 0.37	2.30	0
T5	44.36	42.03 ± 0.24	2.25	0

The results indicate a gradual reduction in dimensional shrinkage with increasing reinforcement content. The control specimen T1 recorded the highest shrinkage (2.63%), while T5 achieved the lowest value (2.25%) indicating improved dimensional stability.

The CSI assessment further demonstrated the effectiveness of reinforcement. Hairline cracks were observed in T1, T2 and T3 (CSI = 1), whereas T4 and T5 (Figure 1) showed no visible cracks (CSI = 0). The improved performance is attributed to the combined effects of

silica sand in improving thermal stability, bentonite in enhancing bonding, and fiberglass in restraining crack propagation.



Figure 1. Visual Inspection- Crack Severity Index (CSI)

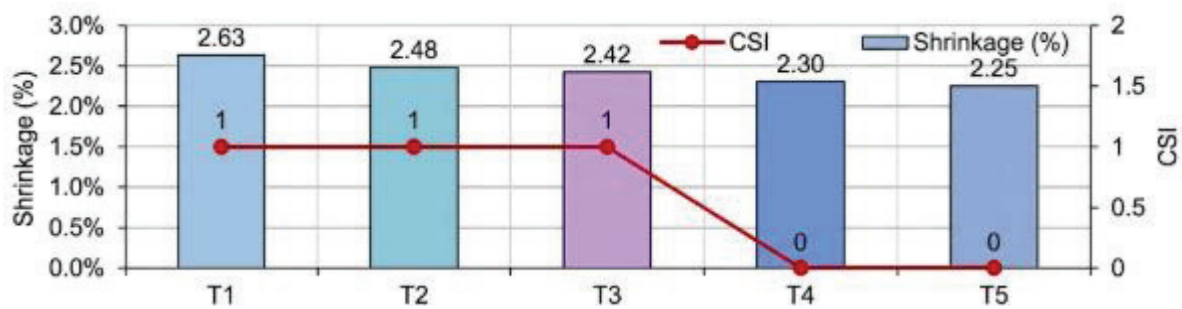


Figure 2. Comparison of Shrinkage (%) and CSI for T1-T5

Overall in Figure 2, T5 demonstrated the best performance among all compositions, providing the lowest dimensional reduction and eliminating visible cracks after burnout.

Conclusion and Recommendations

This study evaluated the performance of reinforced POP molds during the burnout of 3D-printed PLA patterns under a controlled five-stage burnout cycle.

The findings show that reinforcement significantly improved mold performance compared with unreinforced POP molds. The incorporation of silica sand, bentonite and fiberglass reduced dimensional shrinkage and improved crack resistance. Among the formulations investigated, T5 exhibited the highest dimensional stability, with a dimensional reduction of only 0.97 mm (2.26%) and a CSI value of zero.

The results support the use of reinforced POP molds as a practical and low-cost alternative for prototype and low-volume investment casting applications employing 3D-printed PLA patterns. However, conclusions should be limited to the measured parameters of mass loss, dimensional stability and visible crack formation.

Future work should include repeated experimental trials, variability analysis, additional burnout schedules, mechanical strength testing and actual metal casting validation to establish a more comprehensive assessment of mold performance.

Acknowledgement

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Effect of Cutting Parameters on Surface Integrity and Machining Performance of T-Shaped CFRP Components during Slotting Using a T-Slot Cutter

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Abstract— Carbon Fiber Reinforced Polymers (CFRP) are widely used in aerospace due to their high strength-to-weight ratio. However, machining CFRP, especially T-shaped components, presents challenges such as delamination and fiber pull-out. This study optimizes spindle speed and feed rate for slotting T-shaped CFRP components using a newly fabricated T-slot cutter on a Haas VOP-C CNC machine. The research employed the Taguchi method to evaluate the trimmed surface quality. Results showed optimized machining parameters improved surface quality and minimized defects, contributing to aerospace component manufacturing.

Introduction

Carbon fiber reinforced polymers (CFRPs) are utilized in a variety of high-performance applications such as those in the aerospace industry, owing to their high strength to weight ratio, stiffness and resistance to corrosion. Due to their heterogeneous and anisotropic properties, however, they are hard to machine and can lead to various manufacturing defects, including fibre pull-out, fibre breakage, matrix cracking, delamination and poor surface quality (Kiliçkap et al., 2015; Davim & Reis, 2005; Karataş & Gökkaya, 2018). The cutting parameters, especially cutting speed and feed rate, have a great influence on the surface quality and damages of CFRP parts, as well as the tool geometry on the machining performance (Voß et al., 2017; Geier et al., 2023). However, the previous research has been mostly on flat CFRP laminates by conventional milling or trimming, while only a few works are conducted on slotting of T-shaped CFRP parts by a special T-slot cutter. Hence, the present study aims to understand the influence of cutting speed and feed rate on surface quality and machining induced damage of T-shaped CFRP component parts using a specially designed T-slot cutter to determine optimum machining parameters for good surface integrity.

Methodology

CFRP laminates with a thickness of 3.5 mm and the specified stacking sequence were first prepared using an Abrasive Water Jet (AWJ) machine to ensure accurate dimensions while minimizing thermal and mechanical damage during specimen preparation, as illustrated in Fig. 1. A custom-designed T-slot cutter, fabricated from tungsten carbide alloy, was then developed specifically for the slotting operation of the T-shaped CFRP specimens (Fig. 2). The cutting tool geometry was tailored to accommodate the complex profile of the workpiece while enhancing machining stability and surface quality. Subsequently, all machining experiments were performed on a Haas VOP-C vertical machining centre under predetermined spindle speed and feed rate conditions (Fig. 3). The experimental setup was designed to evaluate the influence of machining parameters on cutting performance, with particular emphasis on surface roughness, cutting force, and machining-induced damage of the T-shaped CFRP components.

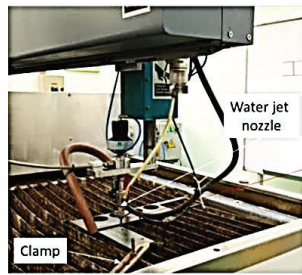


Fig. 1 Abrasive Water Jet Machine

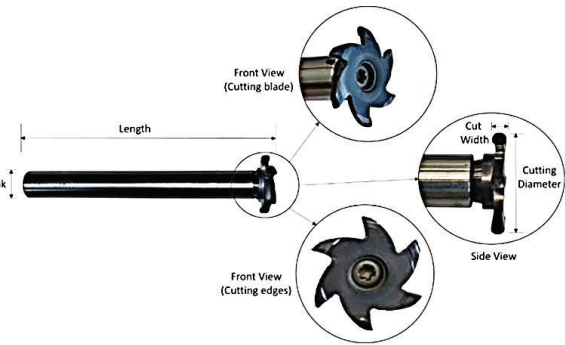
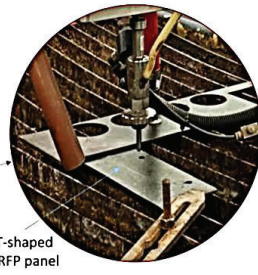


Fig.2 T-Slot Cutter

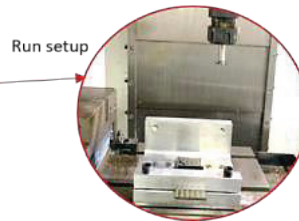
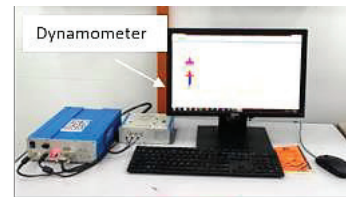
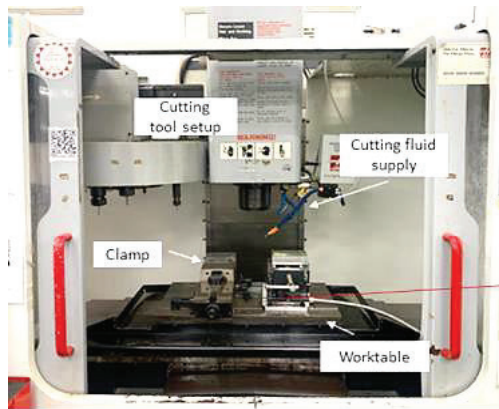


Fig.3 The 3-Axis CNC Milling Machine, Haas VOP-C

The machining parameters were designed using the Taguchi L4 orthogonal array to systematically evaluate the effects of spindle speed and feed rate on machining performance. Two levels of spindle speed (3660–4933 RPM) and feed rate (600–900 mm/min) were selected based on the Design of Experiments (DoE) approach. The experimental matrix is presented in Table 1 and was used to determine the optimal cutting conditions for minimizing surface roughness, cutting force, and delamination.

Table 1: Cutting Parameters

Run	Cutting Speed, V_c	Feed rate, V_f	Spindle Speed, RPM
1	155	900	4933.16
2	115	900	3660.09
3	155	600	4933.16
4	115	600	3660.09

Surface roughness measurements were performed using a Mitutoyo Surftest SJ-410 profilometer (Fig. 4-left). The arithmetic average roughness (R_a) was selected as the evaluation parameter, with measurements conducted along the longitudinal cutting direction. Three measurements were obtained from each specimen, and the average value was used for subsequent analysis. A constant stylus travel length of 5 mm was maintained to ensure measurement consistency and repeatability.

The machined surface morphology and damage characteristics were examined using a Leica DVM6 digital microscope with magnification up to 3000 $\times$ (Fig. 4-right). Microscopic observations were focused on critical regions, particularly the trimmed edges and machined surfaces, to evaluate machining-induced defects such as fibre pull-out, matrix damage, and

delamination. The captured micrographs were directly analyzed using the integrated Leica software for surface damage assessment.

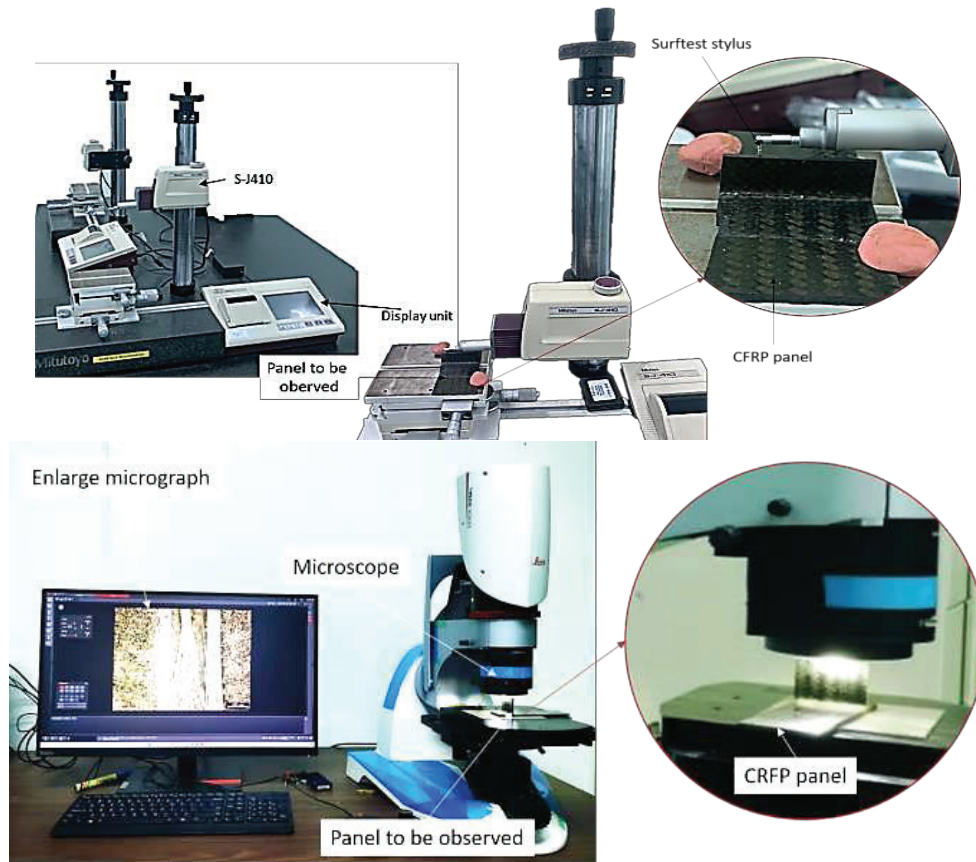


Fig. 4 Surftest SJ-410 for measuring surface roughness (left) and Leica DVM6 Microscope for delamination evaluation (right)

Results and Discussion

Fig. 5 presents the mean signal-to-noise (S/N) ratio for the *smaller-the-better* characteristic of surface roughness obtained using the Taguchi method in Minitab 21. The results indicate that both cutting speed and feed rate influence surface roughness, with cutting speed exhibiting the greater effect as evidenced by its steeper S/N ratio slope. A lower cutting speed (115 m/min) and a higher feed rate (900 mm/min) produced the highest S/N ratio, indicating the optimal parameter combination for minimizing surface roughness.

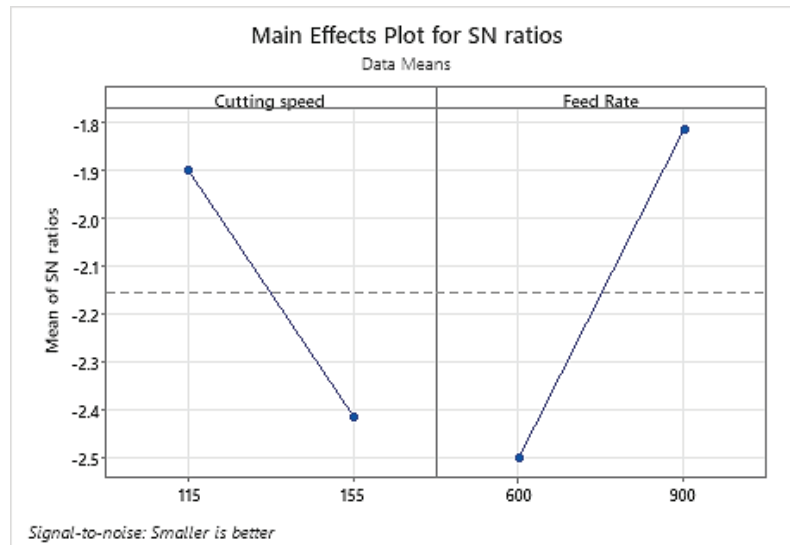


Fig.5 Mean of S/N ratio for smaller the better characteristics of Surface Roughness

Fig.6 illustrates the influence of machining parameters on the surface damage of the CFRP workpiece. The results show that damage severity varies considerably with cutting speed and feed rate. The combination of a higher cutting speed (155 m/min) and higher feed rate (900 mm/min) produced the least damage, characterized by minimal fiber pull-out and matrix cracking. In contrast, lower cutting speed (115 m/min) and lower feed rate (600 mm/min) resulted in the most severe damage, including extensive fiber breakage and matrix degradation. Intermediate parameter combinations exhibited moderate levels of damage, indicating that both machining parameters contribute to the integrity of the machined surface.

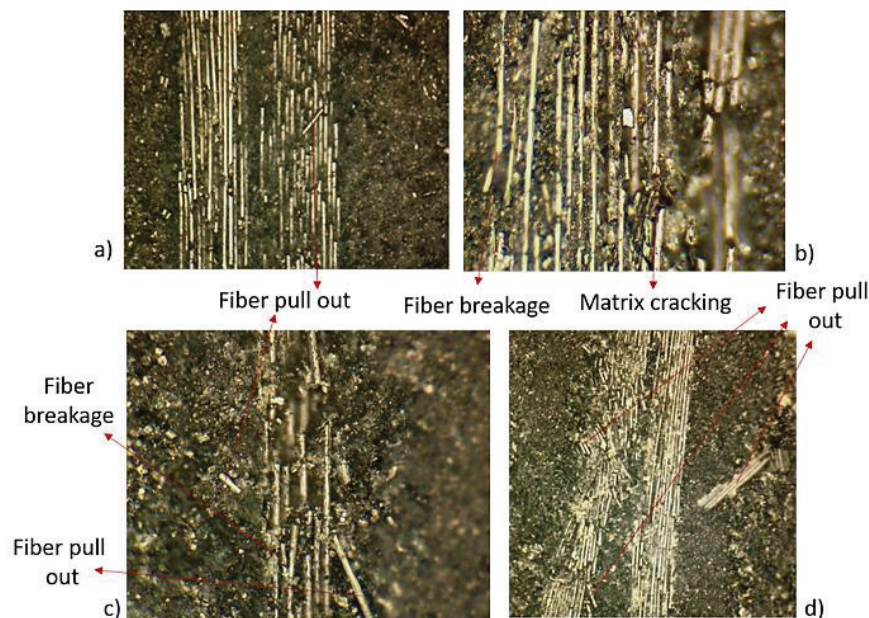


Fig.6 Micrograph image in scale bar of 50 μ m for various machining parameters a) Run 1 b) Run 2 c) Run 3 d) Run 4

The observed damage can be attributed to the variation in cutting mechanics under different machining conditions. Higher cutting speeds promote a cleaner shearing action and reduce cutting forces, while higher feed rates shorten the tool–workpiece interaction time, thereby limiting fiber debonding and matrix fracture. Conversely, lower cutting speeds and

feed rates increase friction, prolong tool–material contact, and generate higher mechanical stresses, leading to more pronounced fiber pull-out, fiber breakage, and matrix damage. These findings indicate that employing higher cutting speed and feed rate is beneficial for improving the machined surface integrity of CFRP.

Conclusion

This study successfully optimized the machining parameters for slotting T-shaped CFRP components using a custom-fabricated T-slot cutter. The findings revealed that the optimal surface quality was achieved at a spindle speed of 3660 RPM and a feed rate of 900 mm/min, resulting in reduced fiber pull-out and improved machined surface integrity.

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A review of anisotropic behavior in Wire Arc Additive Manufacturing (WAAM)

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Abstract— Wire Arc Additive Manufacturing (WAAM) is a promising metal additive manufacturing technology due to its high material utilization, low production cost, high deposition efficiency, and reduced environmental impact. However, widespread adoption is hindered by anisotropic mechanical properties caused by the layer-by-layer deposition process, which promotes columnar grain growth along the build direction. The resulting variations in strength, ductility, and toughness can compromise component reliability and performance. This review critically examines current approaches for reducing anisotropy in WAAM thin-wall structures, including heat treatment, rolling-assisted processing, inoculation, and deposition strategy optimization. Although heat treatment, rolling, and inoculation can refine grain structures, reduce residual stresses, and improve mechanical properties, they often increase manufacturing cost, processing time, and system complexity. In contrast, deposition strategy optimization, particularly a 45° build orientation, promotes equiaxed grain formation and improves mechanical isotropy without additional equipment or post-processing. Based on the reviewed literature, deposition strategy optimization offers the most practical and cost-effective solution for reducing anisotropy while preserving the advantages of WAAM. Further research is required to better understand microstructure evolution and texture development for the production of high-performance and structurally reliable WAAM components.

Introduction

Wire Arc Additive Manufacturing (WAAM) has emerged as a promising metal additive manufacturing technology due to its high material utilization efficiency, cost-effectiveness, and relatively low environmental impact. Compared with conventional manufacturing methods and powder-based additive manufacturing processes, WAAM offers significant advantages, particularly for the production of large-scale metallic structures. Previous studies have reported that WAAM can reduce fabrication time by up to 60% and decrease post-machining requirements by approximately 15-20%, depending on component geometry and size [1]. In addition, WAAM consumes nearly 85% less energy than powder-based additive manufacturing techniques, highlighting its potential as a sustainable manufacturing solution [2].

Despite these benefits, material anisotropy remains a major challenge that limits the broader industrial adoption of WAAM. The layer-by-layer deposition process generates directional variations in mechanical properties between the build direction (Z-axis) and the deposition plane (XY-plane). Such anisotropic behavior is mainly attributed to the formation of columnar grains that preferentially grow along the build direction during solidification. As a result, WAAM-fabricated components often exhibit higher strength and hardness in the horizontal direction but lower ductility and toughness in the vertical direction [3]. This microstructural characteristic is strongly influenced by steep thermal gradients and relatively slow cooling rates, which promote epitaxial grain growth throughout the deposition process [4].

To overcome this limitation, various approaches have been developed to control microstructure evolution and reduce anisotropy in additively manufactured components. Accordingly, this review provides a comprehensive assessment of current strategies for mitigating anisotropy in WAAM and related additive manufacturing processes. The effectiveness, limitations, and future potential of each approach are critically discussed. By synthesizing existing findings, this review aims to identify practical solutions for enhancing the structural performance, reliability, and industrial applicability of WAAM-fabricated components.

Microstructural properties and influence of process

Columnar grains in WAAM grow epitaxially from previously deposited layers and align with the dominant thermal gradient, which generally follows the build direction [5]. This growth behavior produces a strong grain orientation that contributes to anisotropic mechanical properties, as illustrated in Figure 1(a) [6]. Consequently, WAAM components often exhibit direction-dependent tensile strength and ductility [7].

The alignment of elongated columnar grains along the build direction is a major factor affecting tensile performance. Horizontal loads are primarily resisted by grain boundaries, whereas vertical loads are mainly supported by grain interiors and interlayer bonding regions, resulting in different tensile responses for each loading orientation [8]. In addition, lack-of-fusion defects generate higher local stresses under vertical loading, further increasing anisotropy and reducing damage tolerance, as shown in Figure 1(b) [9][10].

Kumar et al. [11] reported that tensile properties in the 0° (horizontal) and 90° (vertical) orientations differed by more than 30%, highlighting the importance of anisotropy in load-bearing applications. Therefore, mitigating anisotropy is essential for improving the structural reliability and industrial adoption of WAAM components. Table 1 summarizes the main strategies used to reduce anisotropic mechanical behavior.

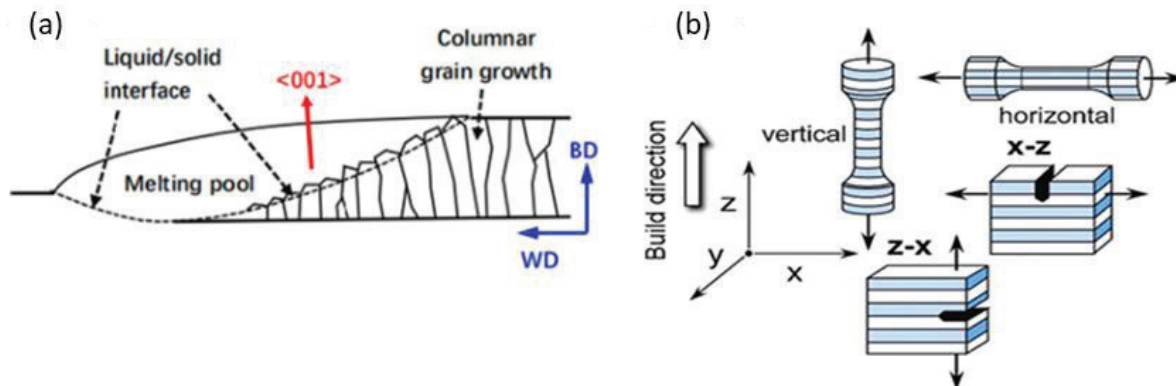


Fig. 1 (a) Formation of columnar and (b) building direction of tensile testing

Table 1: Summary of strategies to reduce anisotropic techniques in the deposition of thin wall structures.

No	Material	Mitigation Technique	Specific Process Details	Key Findings	Ref
1	SS 316L	Heat Treatment	Heat treatment conducted at 400°C, 600°C, and 800°C for 1 h, followed by furnace cooling at approximately 2.5°C/min.	WAAM SS 316L showed a temperature-dependent response. UTS increased with increasing treatment temperature up to 600°C, reaching approximately 1560 MPa.	[12]
2	SS 316L	Heat Treatment	Heat treatment performed at 650°C, 800°C, 1000°C, 1100°C, and 1200°C for 1 h using furnace cooling (650°C) and water quenching after homogenization (800°C, 1000°C) and solution annealing (1100°C, 1200°C).	Heat treatments $\leq 1000^{\circ}\text{C}$ were insufficient to eliminate microstructural heterogeneity, and anisotropic tensile behaviour remained evident.	[13]
3	SS 316L	Rolling	Cold rolling applied to the as-built sample using a unidirectional roll mill operating at 34 rpm. Rolling direction was aligned with the build direction.	Cold rolling increased grain anisotropy along the build direction. Rolling reductions above 50% were associated with residual stress issues in the as-built structure.	[14]
4	316LSi	Inoculation	Tensile and microhardness evaluation of WAAM SS 316LSi thin walls with and without <i>TiC</i> nanoparticle inoculation.	<i>TiC</i> inoculation increased vertical UTS (706.4 ± 4.7 MPa) and horizontal UTS (679.7 ± 14.3 MPa), reducing anisotropy to 3.8%.	[15]
5	E6013	Deposition Strategy	Layers deposited at alternating inclination angles of 0° , $\pm 15^{\circ}$, $\pm 30^{\circ}$, and $\pm 45^{\circ}$ relative to the substrate.	Specimens built at 0° and 15° exhibited pronounced anisotropy and lower longitudinal tensile strength and toughness due to weak interlayer bonding.	[16]
6	308LSi	Deposition Strategy	Comparison of WAAM deposition strategies at 0° and 45° . The 45° strategy employed a double-sided substrate to enhance heat dissipation.	The 45° strategy promoted refined equiaxed grain formation, whereas the 0° strategy produced coarse columnar grains due to epitaxial growth.	[17]

Conclusion and further research suggestions

Post-processing techniques, including heat treatment, rolling, and in-situ inoculation, can improve WAAM microstructures and mechanical properties, but often at the expense of higher cost, longer processing times, and increased complexity. In contrast, deposition strategy optimization, particularly a 45° build orientation, provides a practical and economical approach to reducing anisotropy. By modifying heat flow and thermal gradients during deposition, the 45° orientation promotes more uniform grain growth and a higher fraction of equiaxed grains, resulting in improved mechanical isotropy. Based on the reviewed literature, this approach offers the most effective balance between performance enhancement and manufacturing efficiency. Further studies on heat transfer, microstructure evolution, and texture development are needed to support the design of high-performance and structurally reliable WAAM components.

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