A PRELIMINARY STUDY OF COLD SPRAYED 6061 ALUMINUM PROPERTIES ON 7075-T6 SUBSTRATE FOR CRACK REPAIR

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ABSTRACT: The study explores the properties of cold-sprayed 6061 aluminum on 7075-T6 aluminum, focusing on microstructure and mechanical properties for crack repair. This research addresses the issue of persistent fuel leakage in military aircraft fuel tanks, which remains unresolved by traditional coating methods, prompting the investigation of innovative solutions. The study's objective is to assess the potential of high-pressure cold spray coatings using 6061 aluminum alloy on defective 7075-T6 aluminum samples, with a focus on analyzing the microstructural properties and adhesion mechanisms. The methodology includes sample preparation, defect simulation, material selection, and the application of Valimet Al-6061 powder. Tests such as SEM-EDX analysis, tensile strength testing, microhardness testing are performed to evaluate the coating's efficiency. This research aims to provide insights into the effectiveness of cold spray coatings for repairing critical components and improving their longevity, thereby contributing to future advancements in the field.

KEYWORDS: *High-Pressure Cold Spray; 6061 Al coating, Adhesion Bonding Mechanism; crack repair*

1.0 INTRODUCTION

In the mid-1980s, Professor Anatolii Papyrin and his team at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences (ITAM SB RAS) in Novosibirsk developed the cold spray technique. During their investigation of models subjected to high-speed two-phase flow (gas and solid particles) in a wind tunnel [1], they successfully applied a variety of pure metals, metal alloys, and composites to different substrate materials. Their work demonstrated the versatility and potential of cold spray technology for diverse applications.

As a recently emerged technology, the cold spray (CS) technique has garnered attention for its ability to fabricate samples through the solid-state deposition of feedstock powders without involving melting and solidification processes [2]. Unlike traditional thermal spray methods, which rely on high temperatures to melt particles before deposition, CS uses kinetic energy to achieve bonding [3]. This solid-state process allows the preservation of the original properties of the feedstock materials, making CS particularly suitable for sensitive materials that might degrade under high temperatures.

In the cold spray process, powders are accelerated to high velocities using a high-pressure gas stream [2]. When these high-velocity particles collide with the substrate or previously deposited layers, their kinetic energy is converted into plastic deformation and localized heating. This impact causes the particles to adhere strongly to the substrate, forming a dense and cohesive coating. The lack of melting prevents oxidation and other phase changes that could weaken the coating, resulting in superior mechanical and thermal properties compared to coatings produced by conventional methods.

At the oxide-free interface, where metal-to-metal contact occurs, a metallurgical bond is formed due to chemical reactions between the deposited particles and the substrate [2]. This bond is further strengthened by the adiabatic heating effect at the particle-substrate interface, which dominates over work hardening. The localized heating softens the metal, causing it to behave like a viscous material. This leads to the formation of an outward jet and extrusion of material at the point of impact, enhancing the mechanical interlocking and adhesion of the particles. The result is a robust, high-quality coating with minimal defects and excellent performance characteristics.

This project is conducted due to the primary structural components of military tanks often include fuel tanks constructed from high-strength aluminum alloys such as 7075-T6, chosen for their favorable strength-to-weight ratios. However, these fuel tanks frequently suffer from leakage issues due to various operational stresses and environmental factors. Despite numerous attempts to use different coating methods, persistent fuel leakage remains a critical problem. Traditional coatings have failed to provide a durable and effective seal, highlighting the need for innovative solutions. This study aims to explore the potential application of high-pressure cold spray coating using 6061 aluminum alloy on defective 7075-T6 aluminum samples to repair cracked fuel tanks. The objective is to assess its impact on the microstructural properties and adhesion bonding mechanisms. This approach aims to offer a more dependable and durable solution to fuel tank leakage, guaranteeing the structural integrity and operational readiness of military tanks.

2.0 METHODOLOGY

2.1 Preparation of Sample and Simulated Crack

The raw 7075-T6 aluminum samples, initially cylindrical, were precisely cut to a diameter of 25 mm and a thickness of 10 mm using a CNC 2+1 turning machine. This ensured accuracy in the machining process, with all samples undergoing thorough inspection to verify compliance with specified dimensions. To investigate the influence of flaws, controlled defects were introduced at the center of each specimen. The main simulated defect was a linear crack measuring 3 mm in width, 10 mm in length, and 3 mm in depth. These flaws were created using precise machining and cutting techniques, ensuring accuracy and consistency across all samples. This process is crucial for analyzing the mechanical characteristics and failure causes of the materials, providing valuable insights into their performance and reliability.

2.2 6061 Al powder (Valimet USA)

As feedstock, 6061 Al powder (Valimet, USA) with a uniform grain size of 45 μm will be applied, as illustrated in Figure 1 below. 6061 Al powder is particularly notable for cold-spray deposition because it is widely used as a lightweight, high-strength structural material, and it has a relatively low critical impact velocity for this process. The material composition of the substrates to be used is presented in Table 1. Specimens measuring Ø 25 x 10 mm will be utilized to assess the coating adhesion strength.

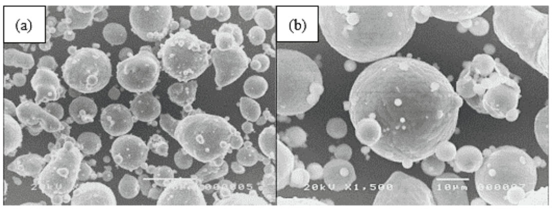

Figure 1: SEM images of the Al-6061 feedstock powder at (a) 50x and (b) 150x.

Table 1: Material chemical composition [wt%]

Element	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
7075-T6 Al	91.4	0.38	2.0	0.5	2.9	0.3	0.4	0.2	6.1

2.3 Deposit Pure Al and Al 6061

In this study, a high-pressure cold spray (HPCS) machine will be utilized as the coating technique for sample preparation. The process will involve accelerating nitrogen gas at a high pressure of approximately 500 psi. The primary goal will not be to increase the particle temperature but to enhance their aerodynamic properties as they are forced through a nozzle. At the nozzle, the gas will undergo an enthalpy conversion to kinetic energy through expansion, accelerating the gas flow to supersonic speeds while simultaneously reducing its temperature.

For this process, Valimet Al-6061 powder will be used. The gun temperature will be set at 500°C, while the powder heater will be maintained at 280°C. The powder feed rate will be adjusted based on the sample type: a 5% feed rate will be used for coating three cylindrical samples and two square samples fully, whereas a 2% feed rate will be employed for collecting particles on a single flat plate. This setup is designed to optimize the coating efficiency and ensure consistent application across different sample geometries. As shown in Table 2 below, all parameters are summarized as follows:

Table 2: Displays the conditions for conducting a coating test

Spray Parameters		
Cs System	Centreline EPX	
Test Substrate	(Al 7075-T6)	
Powder Type	Valimet Al-6061	
Gas Type	Nitrogen	
Gun Pressure	3.44738 MPa	
Gun Temperature	500ºC	
Powder Heater Temperature	280ºC	
Powder Feed Rate	3 cylindrical sample & 2 squares (full coating)	Single-splat particle collection
	5%	2%
Nozzle Transverse Speed	50 m/s	2000 m/s
Stand-off Distance	20mm	

2.4 Testing for the Coating Process

In accordance with ASTM C633, specimens of dimensions of Ø 25 mm x 10 mm without crack simulation as shown by Figure 2, assessed the adhesion strength of the coating given as the fracture load value as measured by the universal testing machine (Auto graph AGS-J 10kN Shimadzu) and subsequently divided by the cylindrical coating area. The FM 1000 adhesive glue film was used to bond the pin and coating. The strength test was performed after the glue was cured in oven 170 ± 6 °C for 90 min ± 10 min as per AMS2750. We measured the adhesion strength over an average of three specimens, as minimum requirement of ASTM C633 is 3 samples. On the fracture coating surface, EDX was used.

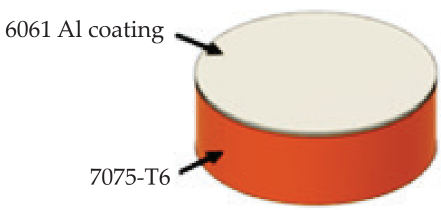

Figure 2: Cold sprayed 6061 coating

The cross-sectional microstructure of the 6061 Al coating on 7075-T6 substrate was analyzed using a scanning electron microscope (SEM, Jeol, Tokyo, Japan).

The hardness testing was 0.1 with a test force on the cross-section of 98.07mN at a dwell time of 10 s.

3.0 RESULT AND DISCUSSION

3.1 Cross-Sectional Microstructural of 6061-Al Coating

The cross-sectional microstructure of cold sprayed 6061 Al coating on a 7075-T6 Al substrate is shown in Figures 3 and 4 below. The coatings with a thickness in the range of 300 μm was showed and it indicated that critical velocity of the particles was reached during the coating process. On top of that, a good adhesion between coated area (6061 Al powder) and 7075-T6 substrate is showed in figures below.

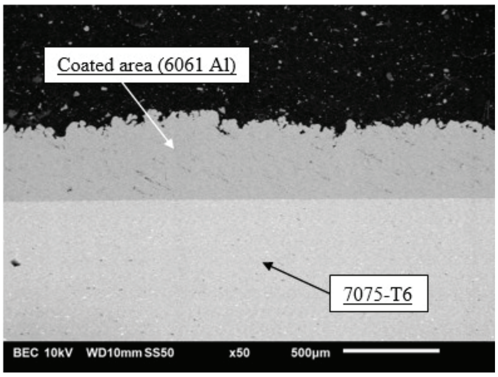

Figure 3: Cross-sectional microstructure of 6061 Al coatings.

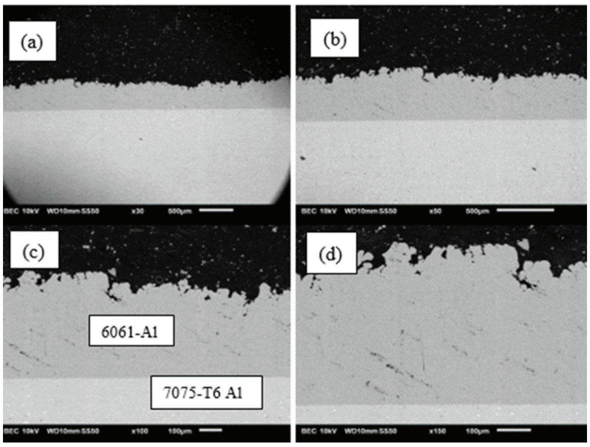

Figure 4: Cross sectional microstructure of 6061 Al coatings (a) 30x, (b) 50x, (c) 100x, (d) 150x.

A high-density cold spray coating of 304L austenitic stainless steel powder with a porosity level of about 0.3% was applied to a through-crack on 304L substrate, as shown in Figure 5a below, resulting in a coating thickness of approximately 620 μm. Interestingly, the crack width decreased near the coating/substrate interface, disappearing about 90 μm above it. Severely distorted powder particles were observed inside the crack (Figure 5b). This crack repair mechanism likely involves the substrate's deformation near the crack opening, followed by the compressive stresses from the cold spray deposition process and the overlay of stainless steel. The impact of powder particles causes the substrate to deform, reducing the crack opening size. Subsequent particle impacts achieve full coating coverage once the crack opening is smaller than the powder particle size (< 44 μm). Unlike friction-surfaced coatings, cold spray coatings do not induce martensite formation and preserve the original phase of the material, demonstrating the method's effectiveness in repairing cracks with minimal substrate modification [4].

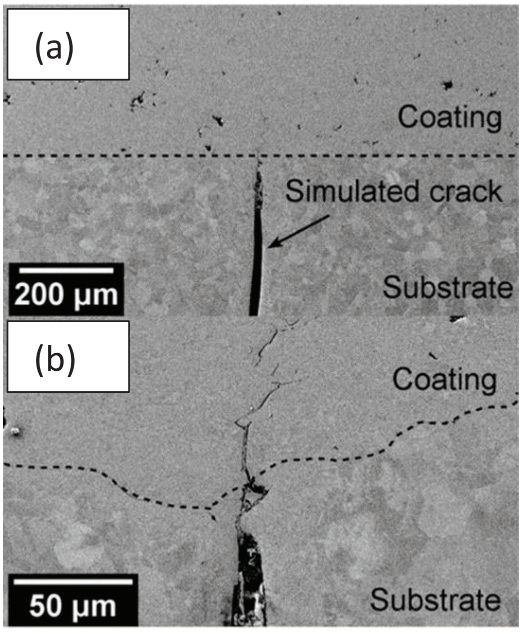

Figure 5: Cold spray deposition for surface crack repair in 304L stainless steel [4].

The adhesion strength of the cold sprayed 6061-Al on 7075-T6 Al substrate without any crack is shown in the figure 6 below. The mean value of the coating adhesion strength is 10 MPa.

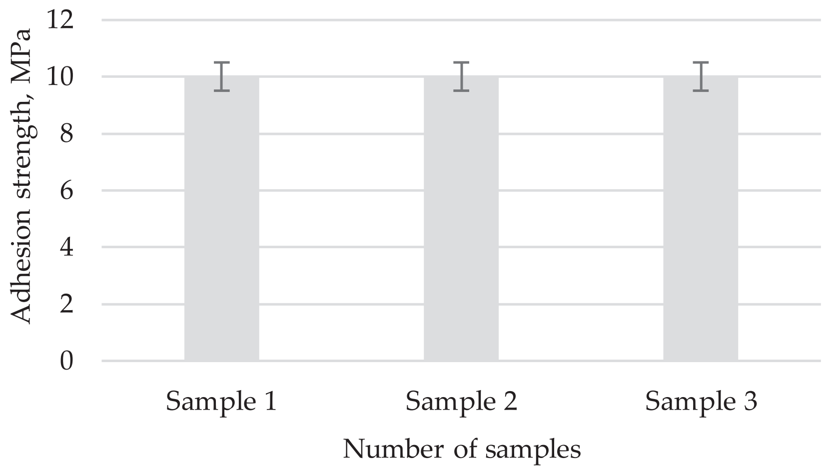

Figure 6: Adhesion strength of the 6061 Al coating on 7075-T6 substrate.

The coating thickness play an important role in adhesion strength, as the coating thickness increase from 1.2 mm to 2.9 mm, it led to reduction in tensile bond strength from 10 MPa to 5.1 MPa for cold sprayed 7075 Al coatings on 7075-T7351 Al alloy [5]. We expected the adhesion strength of cold sprayed 6061-Al on 7075-T6 substrate for crack repair is approximately 10 MPa because tensile strength of cold sprayed 6061 Al alloy on magnesium plate for crack repair, showed 350 MPa compared to 280 MPa for wrough 6061 alloys [6]. Such properties allow cold spray repairs to closely surpass in strength the material that is repaired.

According to figure 7 and table 3, SEM-EDX image of fracture coating of 6061 Al on 7075-T6 Al substrate. The SEM image showed 6061-Al particle uniformly dispersed within the coatings. EDX elemental mappings are magnesium (Mg), and aluminum (Al).

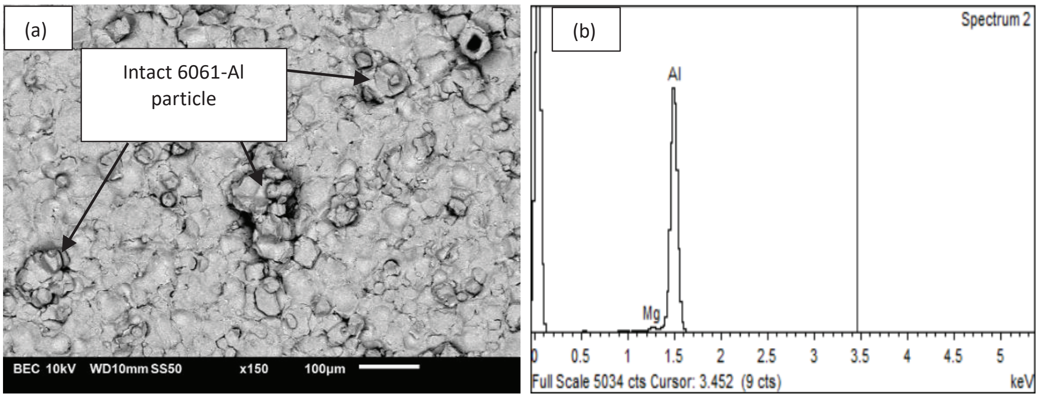

Figure 7: EDX elemental mapping of fracture coating of cold sprayed 6061 coating: (a) SEM (b) map sum spectrum

Table 3: Composition of 7075-T6 substrate

Element	Weight %	Atomic %
Mg	1.32	1.46
Al	98.68	98.54

3.3 Microhardness Test

Microhardness measurements of the coated substrate indicate sufficient adhesion strength for the 6061 Al powder coating, with hardness values showing 24.27 HRB for the coating compared to 89.4 HRB for the 7075-T6 Al substrate. The study emphasizes the importance of interfacial adhesion for coating performance and notes that each layer of the coating acts as a diffusion barrier, enhancing overall effectiveness and mechanical stress tolerance [7].

4.0 CONCLUSION

This study investigated the potential of the cold spray coating method in repairing cracks and enhancing the mechanical properties of the 7075-T6 aluminum substrate. SEM images reveled thick cold sprayed coating on 7075-T6 substrate with uniformly dispersed 6061-Al particle by SEM-EDX image. It shows that, cold spray is one of the few possibilities for crack repair.

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