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Cold Spray Process Development for the Reclamation of the Apache Helicopter Mast Support

by P. F. Leyman and V. K. Champagne

ARL-TR-4922 August 2009

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Cold Spray Process Development for the Reclamation of the Apache Helicopter Mast Support

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14. ABSTRACT

The U.S. Army Research Laboratory at Aberdeen Proving Ground, MD, has developed a novel process for repairing and rebuilding damaged aluminum components using Supersonic Particle Deposition, commonly referred to as cold spray. A Centerline Model No. SSM-P3300 Portable Cold Spray Deposition System was used to deposit a highly adherent, dense aluminum composite material to repair corrosion damage pits and rebuild the snap ring groove and gear teeth on the mast support on an Army helicopter. ARL performed microstructural analysis as well as adhesion, fatigue, and corrosion tests to evaluate the characteristics of the cold spray aluminum composite coatings. The cold spray deposited material was subsequently machined using conventional machining tools to dimensionally restore the component to its original condition. Final testing and approval for implementation of this repair procedure is in progress.

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We wish to thank Joshua Morales and Raymond Boland of Fort Hood, TX, for coordinating the cold spray demonstration at Ft. Hood and for the acquisition of actual helicopter parts to validate the repair process. Appreciation is also extended to Steve Howell and Courtney Guasti of the Aviation and Missile Research, Development and Engineering Center (AMRDEC) as well as Michael Kane and George Liu of the Aviation and Missile Command (AMCOM) for their continued support of cold spray technology.

1. Objective

The principal objective of this applied research effort was to demonstrate the ability of the cold spray process to repair damaged aluminum mast supports with the use of a commercial, field portable, cold spray system capable of restoring the dimensions of corroded or badly worn components, resulting in a repair that would be considered flight worthy.

2. Introduction

Corrosion and mechanical damage has rendered a number of 7075-T73 aluminum mast supports non-serviceable for continued use on Army helicopters. The U.S. Army Research Laboratory (ARL) Center for Cold Spray at Aberdeen Proving Ground, MD, developed a Supersonic Particle Deposition (SPD) process, more commonly called cold spray, to reclaim aluminum and magnesium components that shows significant improvement over existing methods and is in the process of qualification for use on rotorcraft.[1] The cold spray repair has shown superior performance in the tests conducted to date, is inexpensive, can be incorporated into production, and has been modified for field repair, making it a feasible alternative over competing technologies. The goal of this effort was to repair both the corrosion and mechanical damage by blending and machining damaged areas, rebuilding lost material using cold spray with aluminum-based powder, and final blending and machining to the original dimensions. Protective finishes, such as a conversion coating, primer, and topcoat, may be applied to the repaired areas of the cold spray coating. While it is possible to perform a remediation without rebuilding lost material, the number of times this type of repair could be performed would be limited. By using cold spray to rebuild lost material, the component could be remediated as many times as necessary until its safe-life has been reached. The predominant risks associated with this repair would be foreign object damage should cold spray material de-bond to generate debris.

[1]Champagne, V. K. The Repair of Magnesium Rotorcraft Components. *61st Meeting of the Society for Machinery Failure Prevention Technology, Cold Spray*, April 2007.

3. Components Needing Repair

The purpose of this program is to demonstrate and validate the cold spray deposition of aluminum-based material using a Centerline Model SSG-3800 GDS Cold Spray System as a cost effective, environmentally acceptable technology to repair corrosion damage pits and rebuild the snap ring groove and gear teeth on the mast supports used on Army helicopters.

Currently, there are 50 helicopter mast supports that are unserviceable with no viable means to repair the component for service. ARL was requested to perform spray trials on a test section of an Army mast support and then provide technical support to the Aviation and Missile Research, Development and Engineering Center (AMRDEC) to perform the cold spray demonstration on an actual component at Dyn-Corp in Killeen, TX, to assess the feasibility of restoring an unserviceable component to service. This repair effort focused on three types of damage—corrosion pits along the lower lip of the snap ring groove, mechanical damage on the upper lip of the snap ring groove, and mechanical damage to the gear tooth. A helicopter mast support is shown in figure 1.

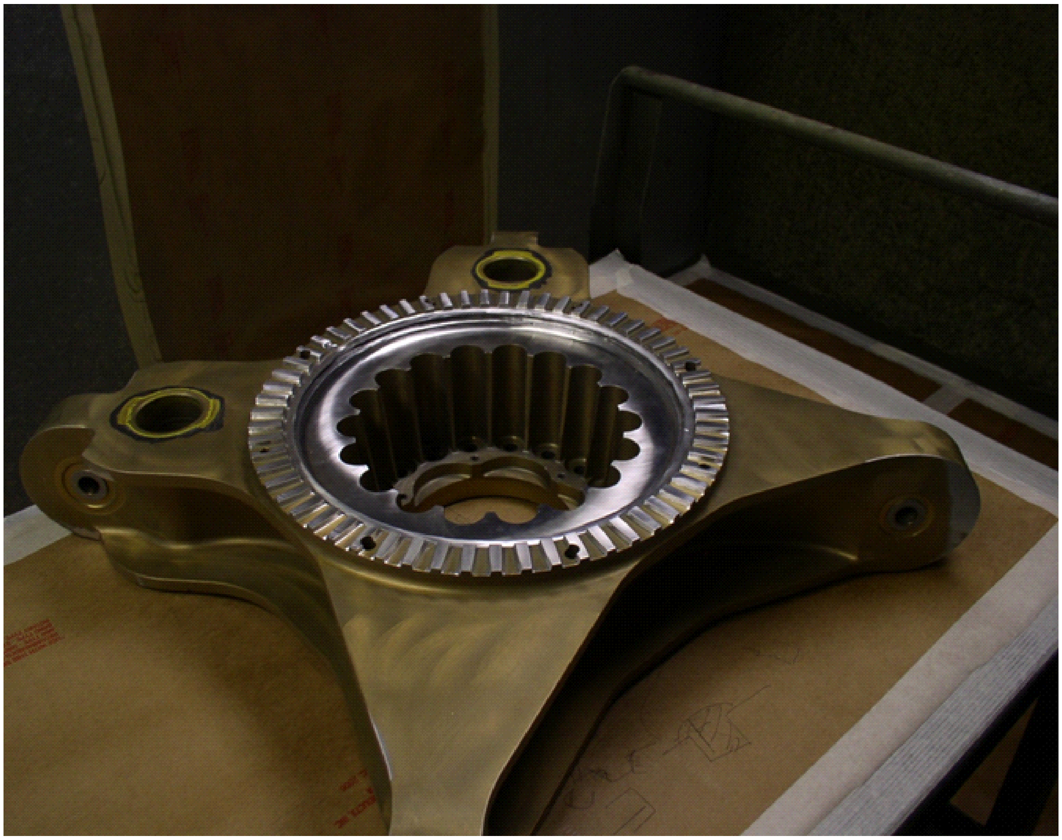

Figure 1. Aluminum helicopter mast support.

3.1 Corrosion Damage Pits

The first type of repair was performed on typical corrosion pitting damage shown near the lower lip of the snap ring groove on the Army helicopter mast support, as seen in figure 2. The pits, shown as a cross section in figure 3, were blended out as shown in figure 4, thereby reducing stress concentrators, and an aluminum coating was applied via cold spray to rebuild to original dimensions, as schematically shown in figure 5. A final machining and blending restored the original surface, as shown in figure 6.

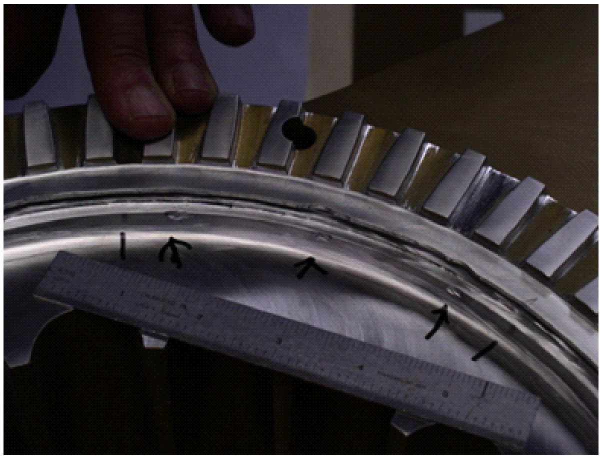

Figure 2. Corrosion pits in the lower lip of the snap ring groove.

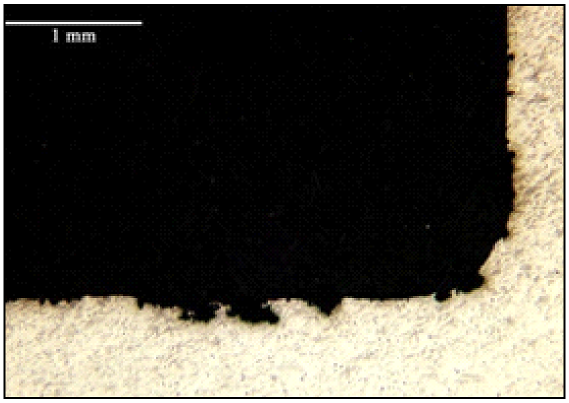

Figure 3. Cross section of the pitted surface.

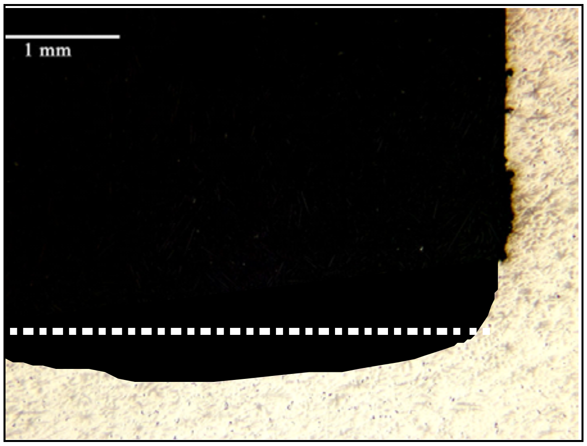

Figure 4. Blending out of the corrosion pits with a grinding tool.

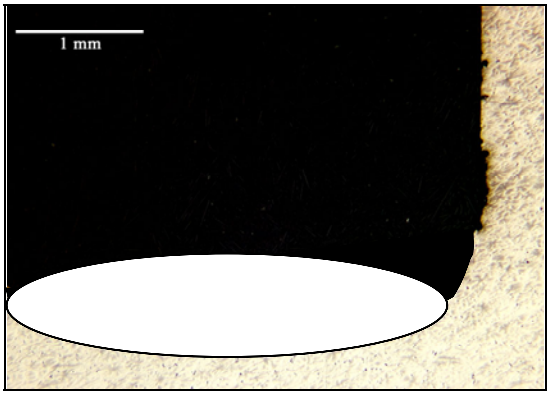

Figure 5. Area filled with cold spray material.

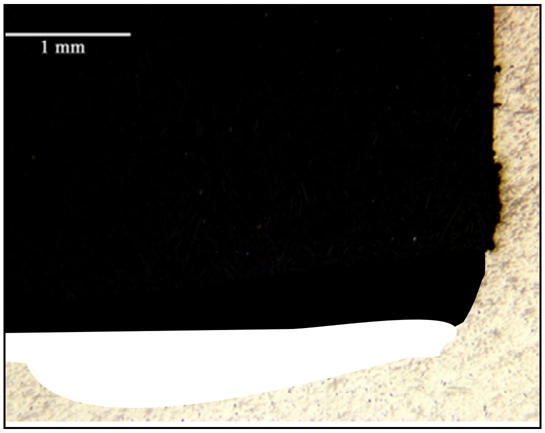

Figure 6. Surface ground or machined back to original surface.

The strategy for repairing the corrosion pits was to blend out the pit using either a grinding tool or machining to provide a clean surface. The surface was then grit blasted with 60-grit aluminum oxide to promote adhesion of the cold spray filler to the substrate surface. The top surface of the cold spray filler was then surface ground or machined back to the original surface as schematically illustrated in figures 3–6.

3.2 Mechanical Damage Repair of Snap Ring Groove

Figure 7 shows the second type of repair that would be performed on the mechanical damage. To demonstrate this repair, the entire snap ring groove area would be removed, as shown in figure 8. The damaged region cross section is completely removed (figure 8), the cold spray material is deposited on the entire area (figure 9), and then it is contoured by re-machining to the original shape and dimension (schematically depicted in figure 10).

Figure 7. Mechanical damage to the snap ring groove of the Army mast support.

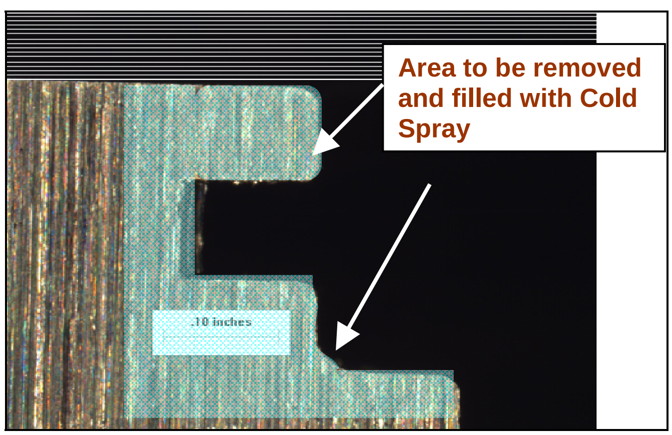

Figure 8. Complete removal of the snap ring groove.

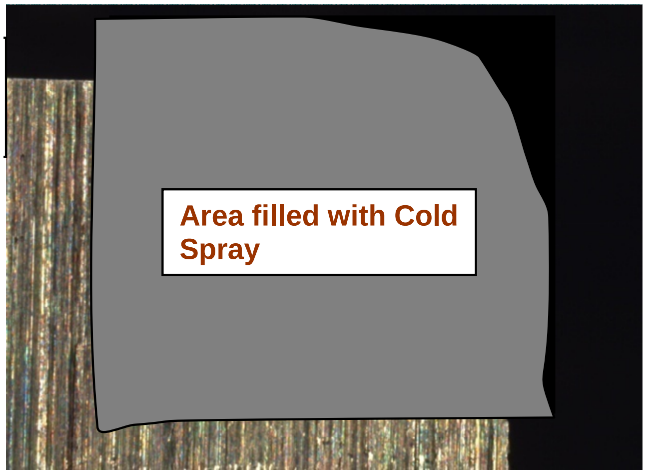

Figure 9. Area filled with cold spray material.

Figure 10. Cold spray material machined back to the original dimensions.

3.3 Damage Repair of the Splines

An additional area where mechanical damage occurs is on the splines, as shown in figure 11. To demonstrate the effectiveness of the cold spray repair method, a section of the spline was mechanically removed using a milling machine, filled in using cold spray, then contoured via re-machining to the original dimensions.

Figure 11. Mechanical damage to the splines on the Army helicopter mast support.

4. Cold Spray Deposition Trials Conducted at ARL

The first phase of this effort was a laboratory demonstration conducted at ARL. ARL developed a material and cold spray process specification to deposit an aluminum-based material and demonstrated this capability on a test section of mast support. The mast support is fabricated from aluminum alloy 7075-T73; therefore, a cold spray coating of aluminum-based material would be compatible with regards to corrosion. Adequate adhesion is also necessary so that cold spray material does not de-bond and the ensuing foreign object damage can be avoided. The Centerline Model SSM-P3300 Portable Cold Spray System (figure 12) was used to deposit the cold spray aluminum coating on the test section of the Army helicopter mast support supplied to ARL. A schematic of the Centerline Cold Spray System is shown in figure 13.

4.1 Cold Spray Deposition System

Figure 12. Operator using a Centerline Portable Cold Spray System to repair a rotorcraft component.

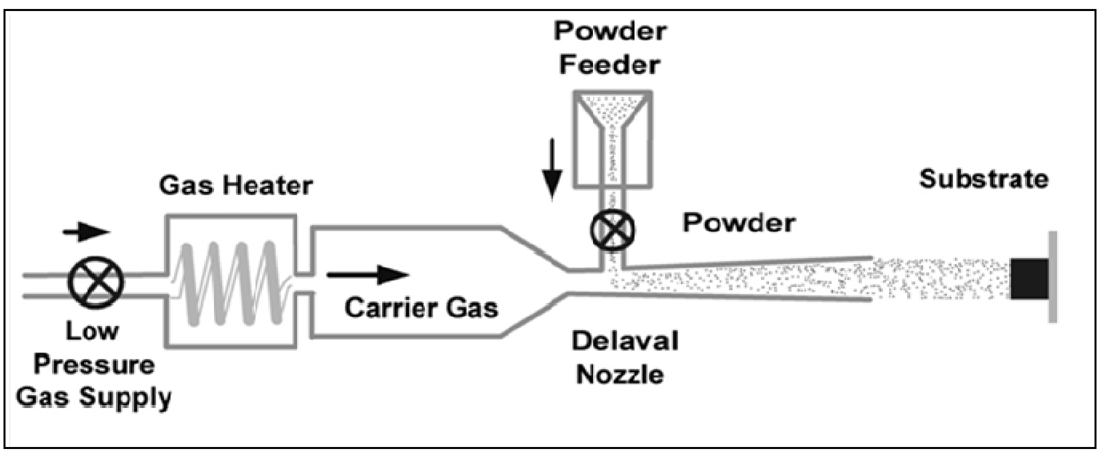

Figure 13. A schematic of the Centerline Portable Cold Spray System.

4.2 Powders

Three potential cold spray aluminum-based coating candidates were identified that can be used for repairing and rebuilding damaged aluminum components using the low pressure deposition process. The coatings were deposited using a feedstock powder composed of commercially pure aluminum (CP-Al), an aluminum/aluminum oxide mixture (A050), or an aluminum/zinc/aluminum oxide mixture (A027). The volume % composition of each feedstock powder is listed in table 1. The CP-Al powder is available from Valimet, Inc., while the A027 and A050 mixtures are available from Centerline (Windsor) Limited.

Table 1. Powder composition (volume %).

Powder	Aluminum	Zinc	Aluminum Oxide
CP aluminum	100	—	—
A050	70	—	30
A027	65	15	25

Scanning electron microscope (SEM) examination of the three feedstock powders was performed to analyze the structure and composition of each of the powders. The CP-Al powder has a spherical morphology with a particle size distribution range of 7–28 µm with an average particle size of 10.6 µm (figure 14). Since pure aluminum powder is softer than aluminum alloys such as 7075, two additional powder mixtures that contained aluminum oxide were evaluated. The aluminum oxide particles increase the hardness of the resultant coating and impart increased wear resistance. A050 powder contained 5–25 µm aluminum powder and 100–200 µm angular shaped aluminum oxide particles (figure 15). A027 powder is a mixture of the same aluminum powder and aluminum oxide particles as A050 but with the addition of 1–10 µm zinc powder (figure 16).

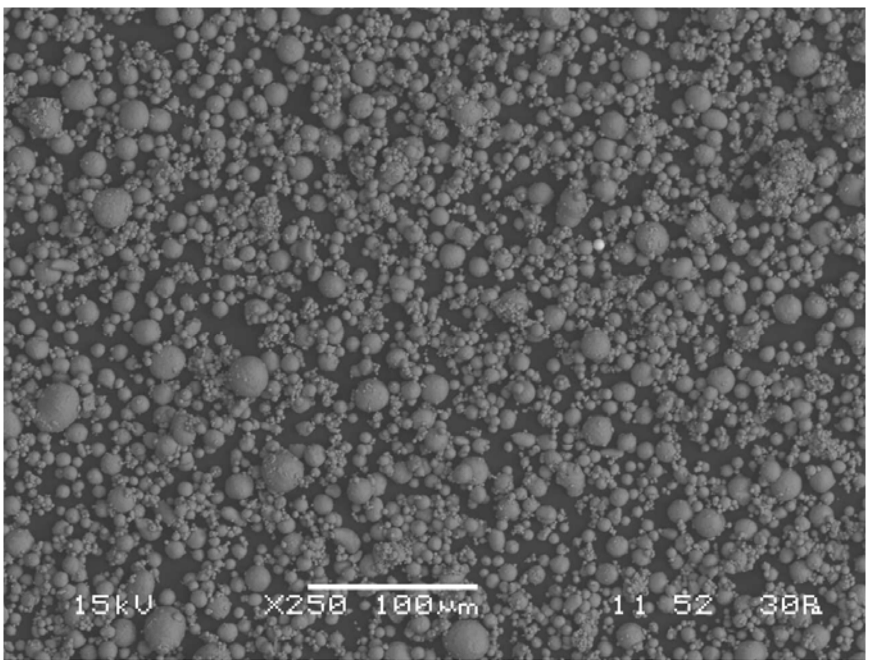

Figure 14. SEM photomicrograph of CP aluminum powder (Valimet H-12).

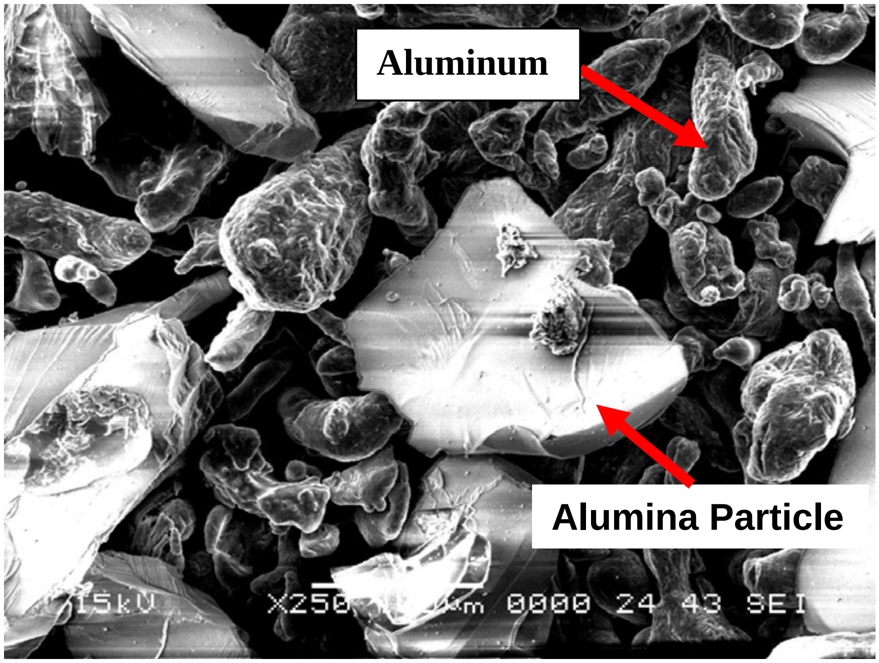

Figure 15. SEM photomicrograph of A050-aluminum/aluminum oxide powder.

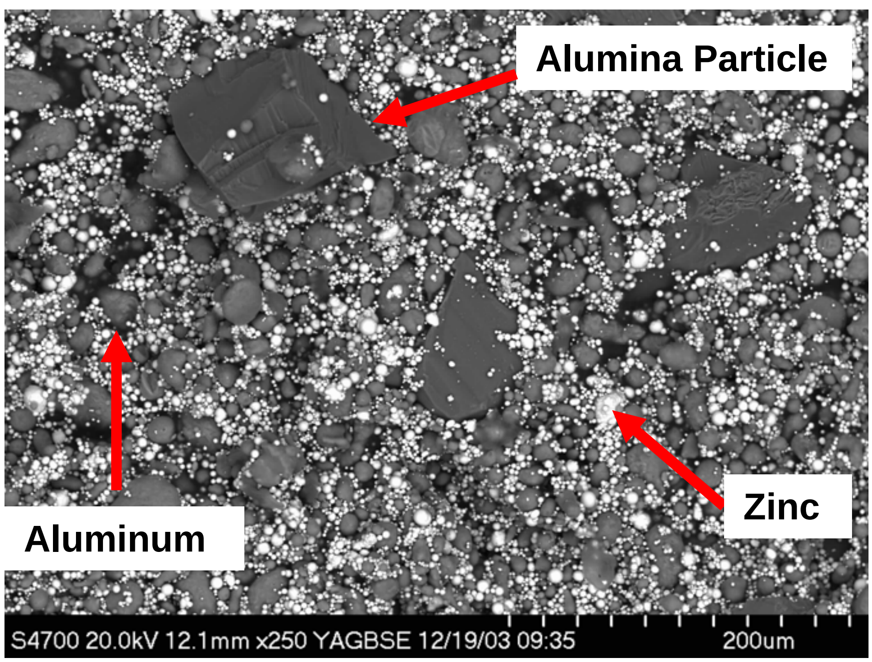

Figure 16. SEM micrograph of A027-aluminum/zinc/aluminum oxide powder.

4.3 Microstructural Analysis

Coatings deposited using all three powders were cross-sectioned and metallographically prepared. A representative scanning electron micrograph for each coating is shown in figures 17, 18, and 19. The coatings exhibit a fully dense structure with no visible voids and good bonding between the coating and the substrate. The bonding mechanism of cold spray is analogous to that of explosive cladding; whereas, the formation of a solid-state jet of metal occurs at the impact point between the particle and the substrate. The coating material is in intimate contact with the substrate forming a metallurgical bond as a result of the severe plastic deformation of the accelerated particle impact and is referred to as Super Plastic Agglomerate Mixing (SPAM).[2]

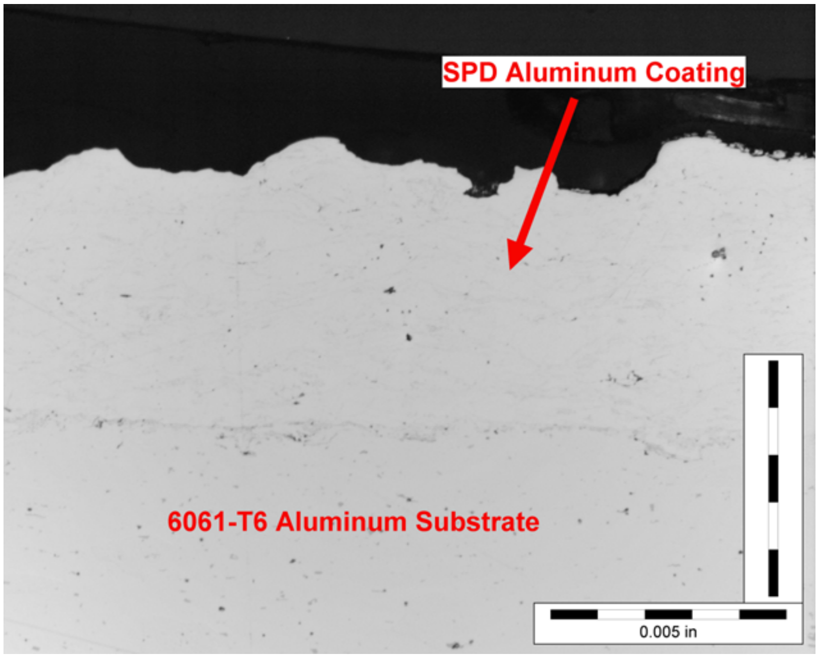

Figure 17. Microstructural analysis of CP-aluminum cold spray coating.

[2]Champagne, V. K.; Helfritch, D.; Leyman, P. F.; Grendahl, S.; Klotz, B. Interface Material Mixing Formed by the Deposition of Copper on Aluminum by Means of the Cold Spray Process. *J Thermal Spray Tech*. **2005**, *14* (3), 330–334.

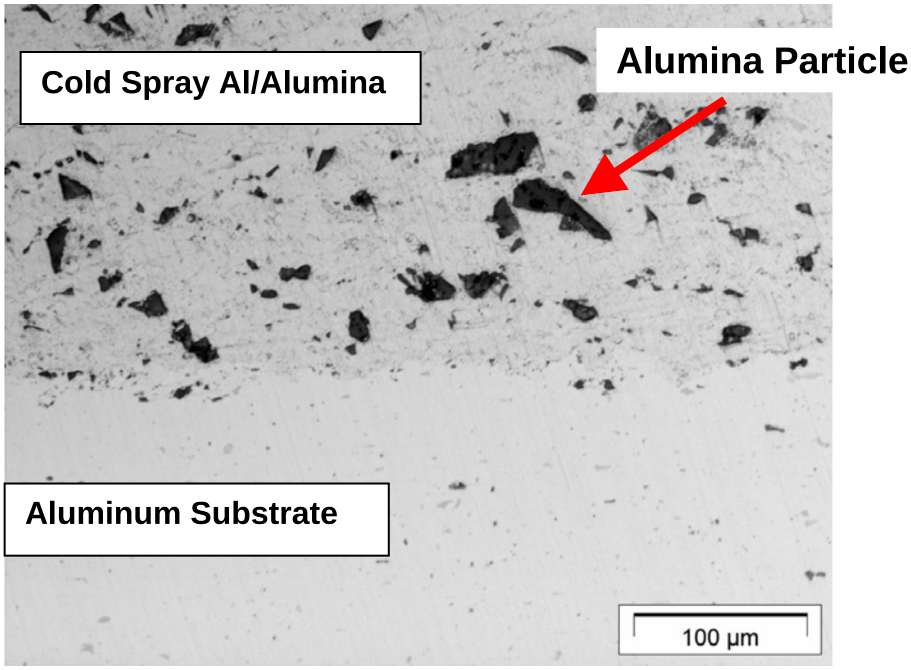

Figure 18. Microstructural analysis of aluminum/aluminum oxide cold spray coating.

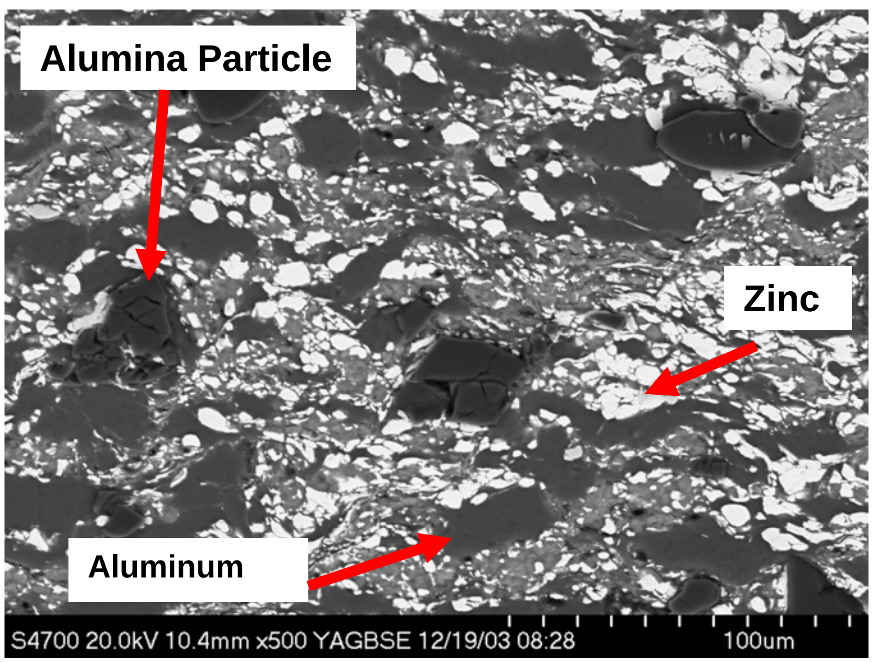

Figure 19. Microstructural analysis of the aluminum/zinc/aluminum oxide cold spray coating.

4.4 Hardness Measurements

The hardness of the cold spray coatings deposited using cp-aluminum, A050 and A027 powders measured from metallographic cross sections with a Wilson Tukon 240B Micro-Hardness Tester using a Vickers indenter at a load of 500 g. Table 2 shows a comparison between the hardness of all three powders. The tremendous plastic deformation of each particle as it impacts the surface of the substrate during the cold spray process results in microstructural changes that increase the hardness. It has been well established that cold spray is considered to be a powder shock compaction and consolidation process resulting in high localized strain and substantial grain refinement via fracturing or the formation of sub-grain structures.[3] Therefore, an increase in hardness, commensurate with the amount of plastic deformation of each particle during consolidation, was anticipated. Even though this consolidation theory has been associated with the deposition of powder mixtures, it is apparent that as a result of the high localized strain that occurs within each particle during impact the conditions were satisfied for significant grain refinement. The aluminum oxide particles in the A027 and A050 powders not only act as a hammer to aid in compaction of the coating, their entrapment in the coating results in an increased hardness of the resultant coatings as compared to the pure aluminum coating (table 2). The coating produced using the A027 powder yielded the hardest coating.

Table 2. Hardness and bond strength.

Powder	Hardness (Vickers)	Bond Strength (psi)
CP aluminum	46.2	3300
A050	60.1	8184
A027	66.9	4948

4.5 Bond Strength

Adhesion bond bar tensile tests, as per the American Society for Testing and Materials (ASTM) C633-01[4], were performed on 0.020-in thick coatings deposited on the 1-in diameter surface of the 2.5-in-long 6061-T6 aluminum alloy bond bars. FM 1000 adhesive film manufactured by Cytec Engineered Materials was used to glue the top surface of the coating to another 1 in × 2.5 in bond bar and cured for 3 h at 160 °C. The adhesively bonded bars were then threaded into the cross-heads of a tensile test machine and pulled apart. The loads were measured and converted to tensile strength. The results of the three different coatings are listed in table 2. Even though all three coatings failed cohesively within the coating, the coatings containing the aluminum oxide particles showed increased adhesion to the aluminum alloy substrate due to the hammer effect of the aluminum oxide as compared to the pure aluminum coating.

4.6 Fatigue Testing

Rotating cantilever beam (RCB) testing was performed on aluminum alloy 7075-T651 straight shank specimens, which had been grit blasted with 60-grit aluminum oxide particles at 30 psi pressure and then coated with a .010-in-thick coating of cold spray CP-aluminum. The RCB

[3]Stoltenhoff, T.; Kreye, H.; Krommer, W.; Richter, H. Cold Spraying-from Thermal Spraying to High Kinetic Energy Spraying. *HVOF Colloquium 2000*, Gemeinschaft Thermisches Spritzen e.V., 2000, 29–38.

[4]Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings, Annual Book or ASTM Standards, American Society for Testing and Materials, Vol. 3. 2001.

fatigue tests are performed at fully reversed (r = –1) loading at loading frequency of 100 Hz (6000 rpm), similar to the RR Moore fatigue testing. These were compared to specimens that were uncoated in addition to specimens that had been grit blasted using the same process as the coated specimens. The plot of the resultant data is shown in figure 20. The uncoated and grit blasted specimens had very similar cycles before failure, while the cold spray aluminum coated specimens had a consistently higher number of cycles before the specimens failed. The cold spray aluminum coating had an improved fatigue life and enhanced the fatigue performance of the 7075 aluminum alloy.

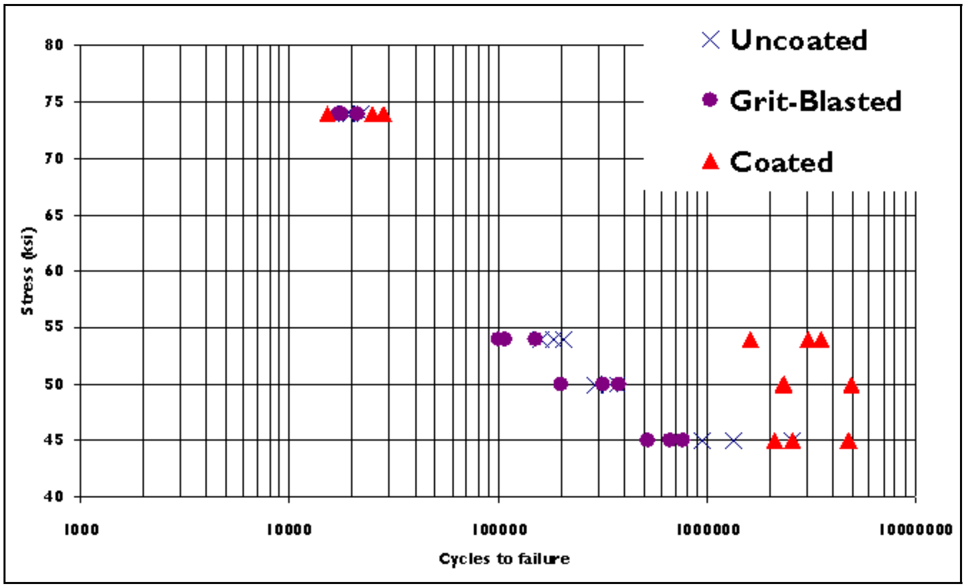

Figure 20. Plot of RCB fatigue test results for cold spray aluminum on 7075 aluminum RCB fatigue specimens. (*Australian Defence Science and Technology Organization)*

4.7 Corrosion Test Results

Corrosion testing was performed on aluminum alloy 7075-T651 panels that had been coated with 0.015 in of cold spray CP-aluminum. The coated panels underwent neutral salt spray testing (NSS), as per ASTM B117-85.[5] After 7000 h in the salt spray chamber, there was no visible evidence of corrosion of the AA7075-T651 substrates. The tests were conducted at the Australian Defence Science and Technology Organization.

4.8 Cold Spray Demonstration

Cold spray trials were conducted on a test section of the Army helicopter mast support to demonstrate that the aluminum based coating could be used to fill in both the corrosion pits and the mechanical damage areas and be ground and/or machined back to the original specifications without delaminating from the substrate material. The A027 feedstock powder, which

[5]Standard Test Method for Salt Spray (Fog) Testing; ASTM-B-117-85; *Annu. Book ASTM Stand.* **2001**.

had yielded good microstructure, hardness, and adhesion performance, was deposited on the test section of the mast support employing a circular nozzle at the process parameters listed in table 3.

Table 3. Process parameters.

Nozzle temperature	350 °C
Gun air pressure	85–90 psi
Standoff distance	5–10 mm
Powder feed setting	20%

The results of the initial demonstration for the corrosion damage are shown in figures 21–23.

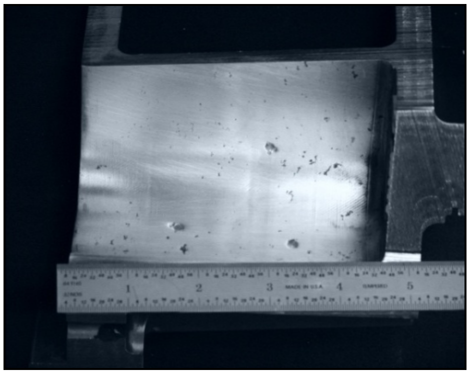

Figure 21. Mast support test section as received.

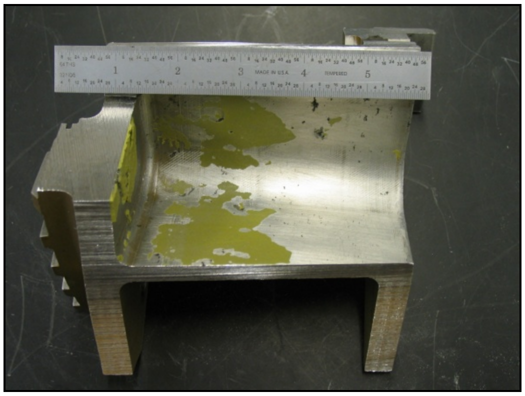

Figure 22. Test section after cleaning and grinding out the pits.

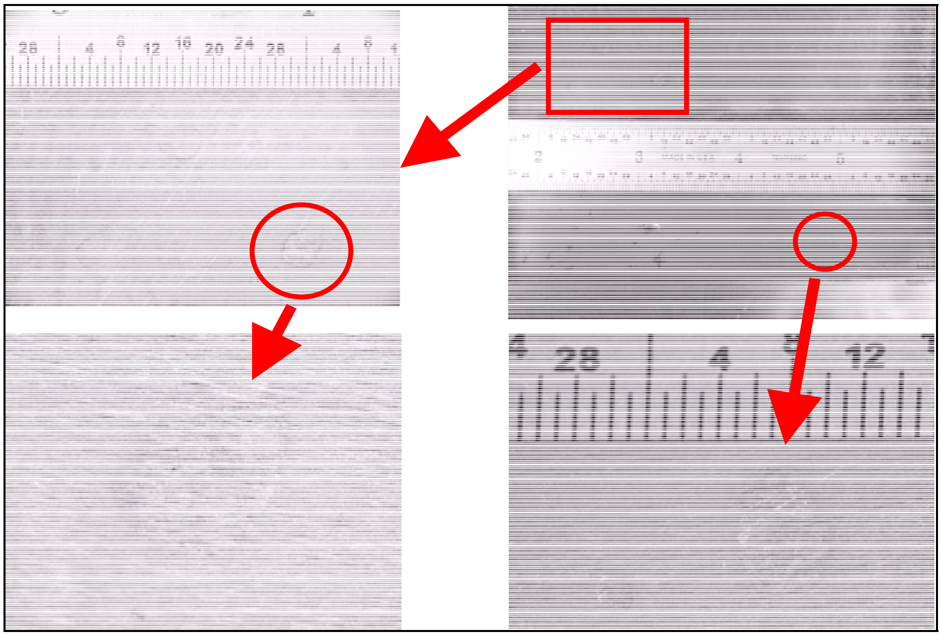

Figure 23. High magnification of cold spray repair to corrosion damage conducted at ARL.

Cold spray trials were also performed on the snap ring groove by removing a section of the snap ring groove to about 0.50 in deep and 1.0 in long into the snap ring groove (figure 19) and then filling it with cold spray aluminum above the surface of the snap ring grove. The excess material was machined back to the original surface contour of the component, as seen in figure 24.

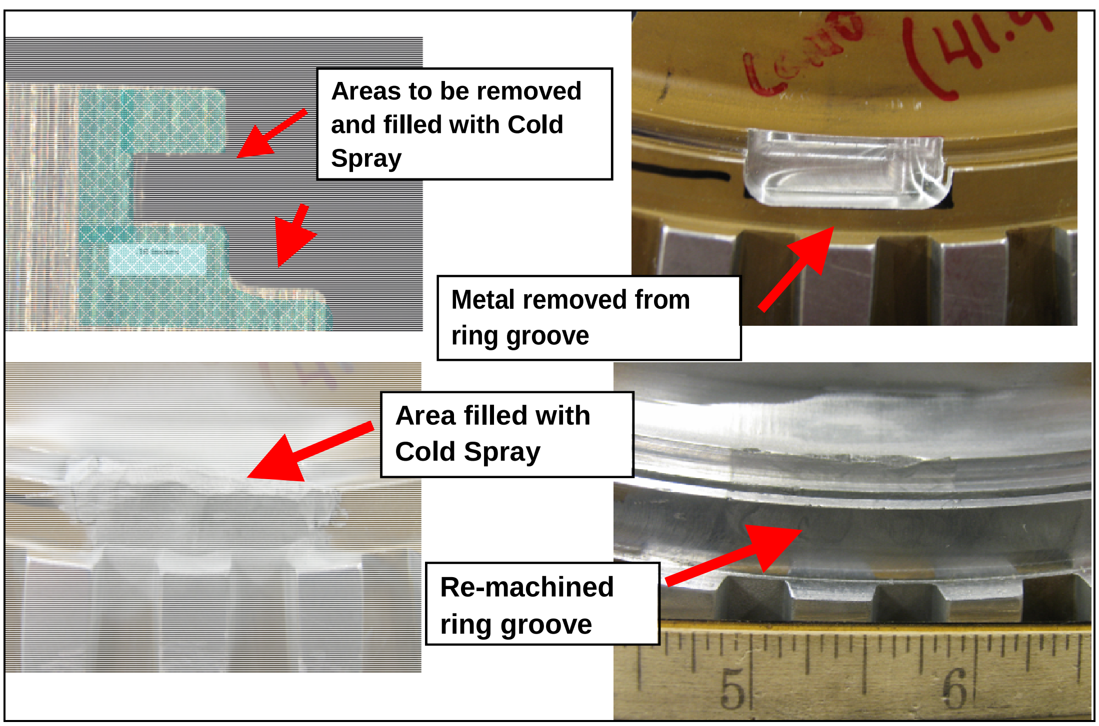

Figure 24. Cold spray repair on mechanical damage to a snap ring groove conducted at ARL.

5. Demonstration Conducted at Fort Hood, TX

After the successful completion of the first phase, the second phase of the demonstration was initiated, which consisted of remediation at Ft. Hood, TX, on otherwise non-serviceable, Category D hardware. All process feasible cold spray repairs similar to those developed at ARL on scrap components, but at other locations on actual hardware, were also evaluated. The Centerline Portable Cold Spray System was transported to the test site to perform a demonstration of the process on both corrosion pits (figures 25–27) and mechanical damage (figures 28–30) on a full-size scrap Army mast support component. The final machining was done by the machine shop on site, as shown in figure 31.

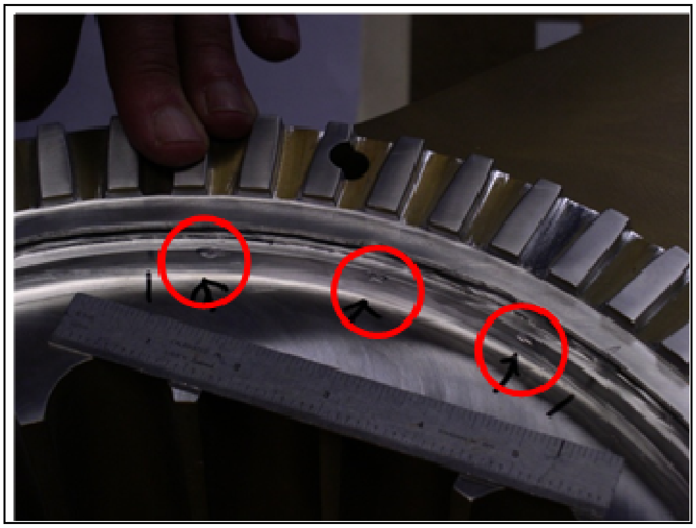

Figure 25. Corrosion pits in lower lip of snap ring groove before cold spray.

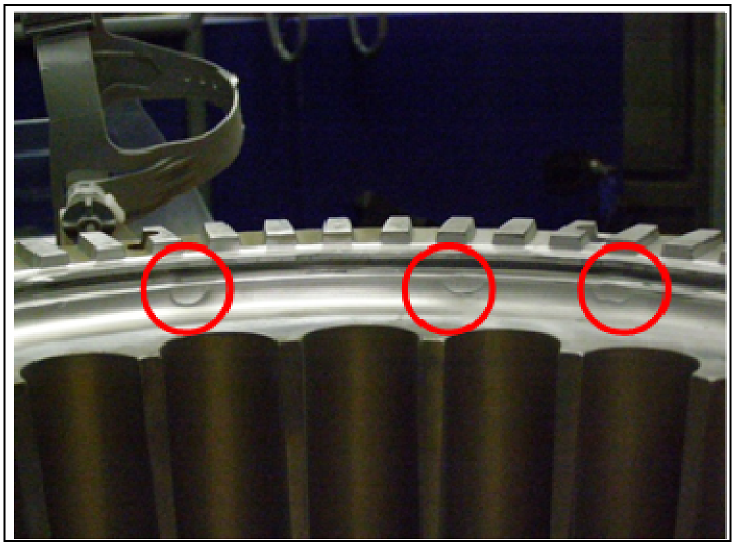

Figure 26. Corrosion pits after cold spray fill and restoring back to original dimensions.

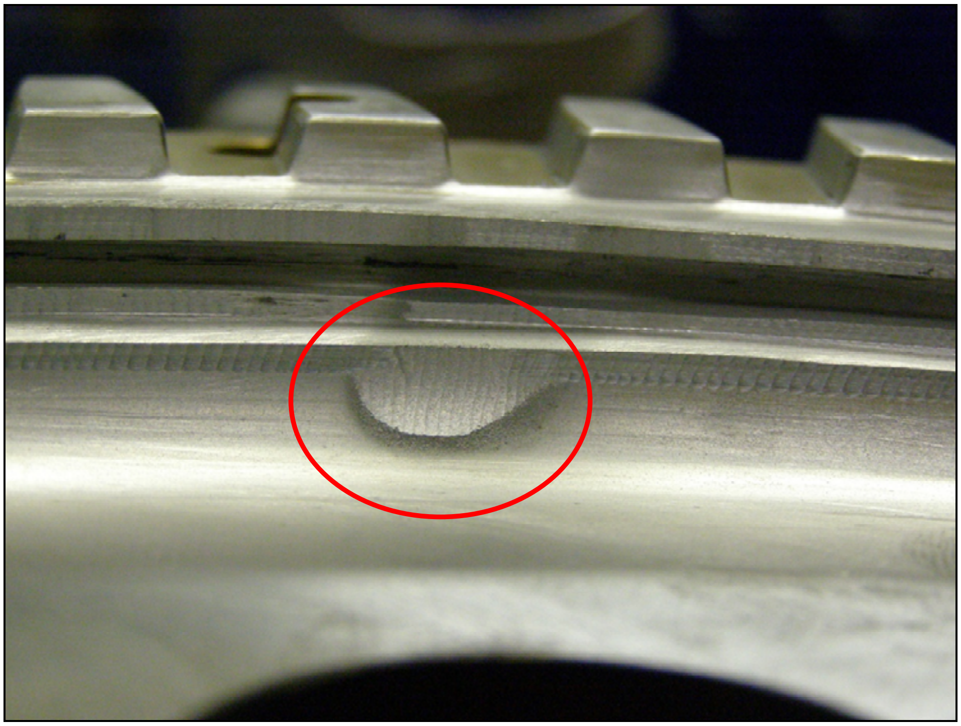

Figure 27. Close up of a corrosion pit filled with cold spray aluminum, machined back to the original dimensions.

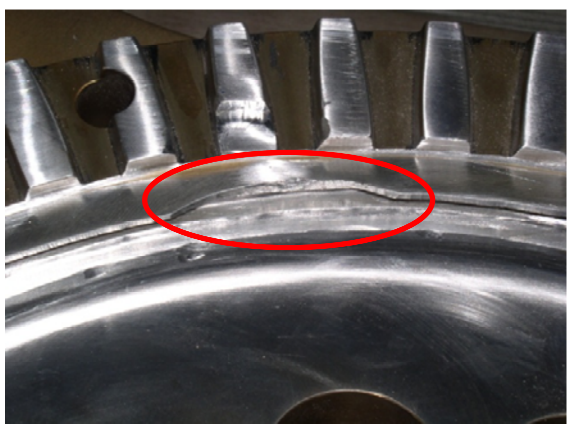

Figure 28. Mechanical damage on a snap ring groove.

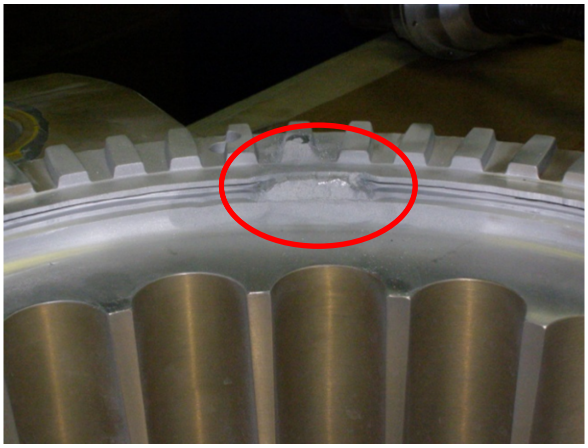

Figure 29. Areas on a snap ring groove and spline requiring repair.

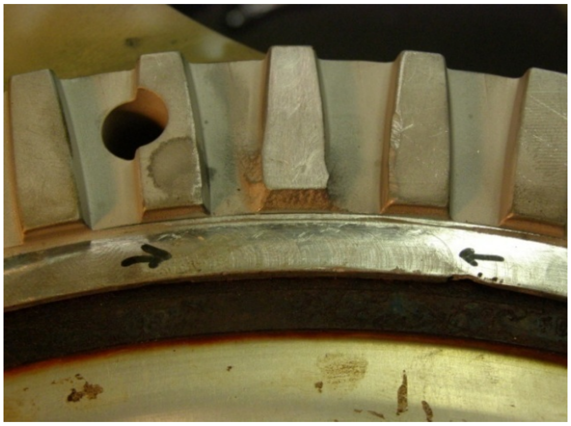

Figure 30. Cold spray aluminum fill machined back to the original dimensions.

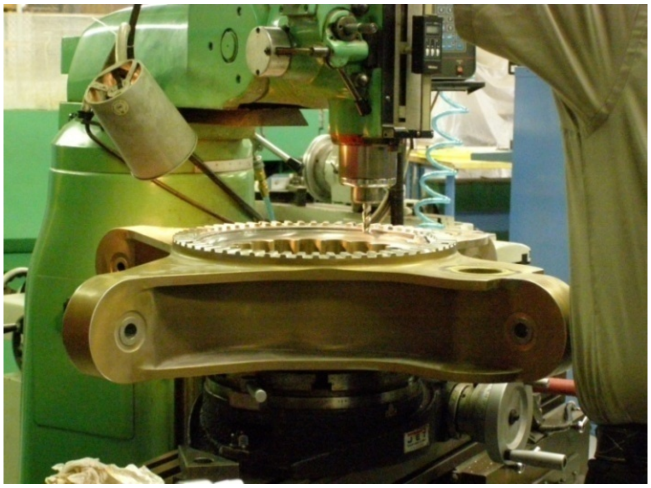

Figure 31. Machinist performing re-contouring of the cold spray aluminum repair to the original dimensions.

6. Discussion

The microstructural analysis, adhesion, fatigue, and corrosion testing results obtained from this study indicated that there are three cold spray aluminum composite materials that are viable candidates for remediation repair of 7075-T6 aluminum components using the portable Centerline Cold Spray System. An aluminum composite material using the cold spray process was applied to all three types of repair during the on-site demonstration. The corrosion pits and the mechanical damage on the three targeted sections of the Army helicopter mast support were successfully repaired. The machinability and structural integrity of the cold spray material was determined to be acceptable and the method was demonstrated to be capable of repairing both corrosion pits and mechanical damage on both the snap ring groove and the splines.

Therefore, cold spray has proven to be a viable and cost-effective repair process for the remediation of an otherwise unserviceable component critical to the operation of the Army helicopter.[6] Final testing and approval to implement this repair procedure is currently in progress. Further process development using alternative powder formulations, including cp-Al are being evaluated in an effort to improve the bond strength and structural properties of the resultant cold spray coating.

The focus of this effort was to demonstrate the feasibility of using the Centerline Cold Spray System to repair worn and/or corroded regions on the 7075-T6 aluminum mast support, but it should be noted that these areas were considered to be non-structural and did not require the stringent qualification testing of structural repairs. For repairs that require higher impact velocity and/or alternative coating materials, such as cp-aluminum, 6061 aluminum, or other alloys, it is recommended that a stationary cold spray system be used to achieve higher particle velocities. The stationary cold spray systems operate with higher gas temperatures and pressures, and also have the capability to pre-heat the powder stock, which assists in the consolidation of the coating. Higher values of adhesion and a wider variety of coating materials are capable of being sprayed with these types of cold spray systems. Additionally, greater deposit efficiencies can also be realized.

[6]Celloto, S. et al. "The Economics of the Cold Spray Process" In *The Cold Spray Materials Deposition Process*; Champagne, V. K., ed.; Woodhead Publishing Limited: Cambridge, 2007.

7. Conclusions

- It is recommended that the Centerline Cold Spray System be considered as a viable means to produce aluminum composite coatings to reclaim 7075-T6 aluminum Apache Mast Supports in non-structural areas.
- For repairs that require higher impact velocity and/or alternative coating materials, such as 6061 aluminum or other alloys, it is recommended that a stationary cold spray system be used.

List of Symbols, Abbreviations, and Acronyms

AMCOM	Aviation and Missile Command
AMRDEC	Aviation and Missile Research, Development and Engineering Center
CP-Al	commercially pure aluminum
ARL	U.S. Army Research Laboratory
ASTM	American Society for Testing and Materials
NSS	neutral salt spray testing
RCB	Rotating cantilever beam
SEM	scanning electron microscope
SPAM	Super Plastic Agglomerate Mixing
SPD	Supersonic Particle Deposition

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