JTTEE5 25:193–201
DOI: 10.1007/s11666-015-0366-4
1059-9630/$19.00 © ASM International

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Application of High-Pressure Cold Spray for an Internal Bore Repair of a Navy Valve Actuator

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(Submitted May 30, 2015; in revised form October 12, 2015)

Cold spray is a reduced temperature, supersonic thermal spray process that is increasingly being used to perform repairs on high-value components. In this case, a valve actuator internal bore sealing surface was repaired on an aluminum 6061 hydraulic valve body using high-pressure cold spray. Corrosion damage to non-critical surfaces was also repaired, allowing the part to be returned to service. A high-pressure cold spray system was used to deposit gas-atomized 6061 aluminum powder using helium. The internal bore surfaces were approximately 100 mm in diameter with a depth of nearly 200 mm, and were sprayed using a 45° nozzle 65 mm in length. Modeling predictions validated the approach, and were used to identify a favorable nozzle geometry and process window combination. The minimum required adhesion strength on critical surfaces was 69 MPa. The average adhesion strength was 71.4 MPa, with glue failures on ASTM C633 bond test specimens. The actuator subsequently passed all bench top service related testing, was qualified as an approved repair, and is now in service. This was a first of its kind repair for cold spray, and demonstrates that it is a viable repair technology and is ready for broader implementation.

Keywords cold spray , corrosion, marine components, repair, tensile bond strength

1. Introduction

Corrosion-related maintenance and failures were estimated to cost the U.S. military over $20 billion in 2004 (Ref 1), and have been rising steadily since that time. Atmospheric and subsequent localized corrosion damage results in decreased safety and increased operating costs. Repair methods should restore the damaged material without adversely affecting the base material, and ideally should not overheat the underlying substrate material so as not to induce large residual stresses or cause unnecessary artificial aging or other microstructural changes. Cold spray technology has already been shown to have numerous industrial applications (Ref 2), as well as the potential to repair previously un-repairable corroded sealing surfaces for magnesium gearbox components for the U.S. Navy (Ref 3). In a more closely related application, aluminum mold surfaces were successfully repaired using cold spray technology, which subsequently allowed the original mold dimensions to be re-machined and the mold returned to service (Ref 4).

Cold spray (CS) was developed in the mid-1980s at the Institute of Theoretical and Applied Mechanics, Novosibirsk, Russia and was patented in 1990. CS is a low-cost and environmentally friendly process that presents a novel additive approach to applying powdered materials in a layer-by-layer fashion at relatively low temperatures, compared to other thermal spray processes (Ref 5). In the cold spray process, small (1-50 μm) metal particles are accelerated toward a substrate at high velocity (300-1200 m/s (Ref Mach 1-3.5)) by a supersonic jet of compressed gas. The particles form a coating on the substrate by means of ballistic impingement. The high-velocity impact can create a high degree of deformation at the interface of the particle and the substrate. The high deformation rates create locally high temperatures and very large strains and shear instabilities, which lead to dynamic recrystallization at the particle-interface and particle-particle boundaries (Ref 6). It can also create bonding through mechanical interlocking, but for high-strength cold spray coatings, this becomes much less of a contribution. In the CS process, a carrier gas (air, N_2, or He) is used at pressures as high as 6.9 MPa and temperatures as high as 1100 °C, and is expanded to supersonic speeds through a converging diverging nozzle.

The present work investigates the potential application for reclaiming previously un-repairable aluminum valve actuator bodies for the U.S. Navy. The actuators have internal bore features as small as 89 mm. This presents a

This article is an invited paper selected from presentations at the 2015 International Thermal Spray Conference, held on May 11-14, 2015, in Long Beach, California, USA, and has been expanded from the original presentation.

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particular challenge, since the cold spray process relies on nozzle length to allow time for particle acceleration. At less than optimum nozzle lengths, particle-gas interaction times are reduced, which reduces the particle velocity at the exit of the nozzle. Thus, it is important to adjust cold spray repair procedures to overcome these challenges. Helium has preferable thermal properties over nitrogen, i.e., a higher specific heat ratio and a higher specific gas constant, which allow it to increase to much higher velocities in a shorter nozzle with the same expansion ratio. Therefore, particles can be accelerated to velocities higher with helium in a shorter nozzle compared to nitrogen, allowing them to reach velocities that are higher than the bonding criteria, namely the critical velocity. Although cold spray operations become more expensive with the use of helium over nitrogen, the cost of the repair is minimal with respect to the cost of the part.

The repair application also had to fill both internal and external sharp corners. This presents a distinct challenge because the angle of incidence for the deposit is widely variable over the width of the spray pattern. Impact incidence angle can affect deposition efficiency (DE) (Ref 7), as well as other properties such a porosity and bond strength (Ref 8). Therefore, the success of an application like the part discussed here was not immediately obvious.

In this application, cold spray is used to repair both exfoliation and pitting corrosion damage to a part made from 6061 aluminum as seen in Fig. 1. It is generally believed that exfoliation corrosion is intergranular in nature and propagates due to a galvanic interaction between the precipitates and the matrix. When the precipitates are noble and concentrated at the grain boundaries, then the attack occurs at the solute depleted regions around the precipitates and propagates rapidly into the material along those boundaries (Ref 9). Pitting corrosion is another common form of attack observed in 6061 aluminum components, particularly in a seawater environment (Ref 10).

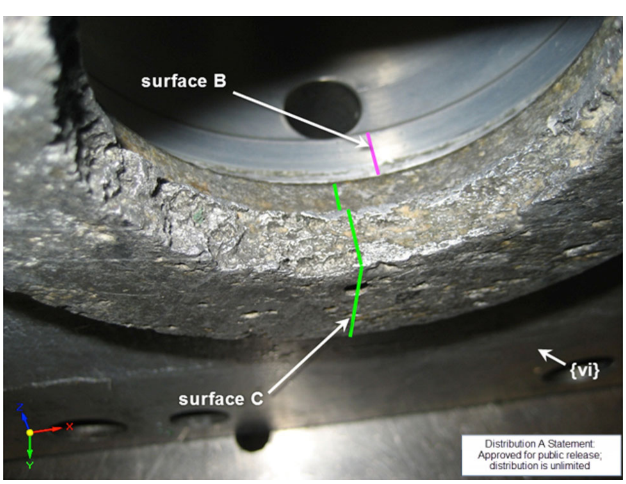

Fig. 1 Close-up photo of seawater corrosion damage on the outboard portion and sealing surfaces on the valve actuator's internal bore

2. Repair Background

Tungsten inert gas welding (TIG), metal inert gas welding (MIG), and laser cladding of aluminum are possible options for repair of the aluminum actuator. These methods are able to produce strengths and porosities that would meet or exceed the repair requirements for the aluminum actuator in coupon-type test samples. However, distortion of adjacent surfaces with limited space, tight tolerances, and numerous finished part features adjoining to the repair locations, as well as the knockdown in the heat affected zone of the substrate material, make those options unattractive. The internal bore with the critical mating surfaces has an internal diameter less than 102 mm. Laser cladding of internal bore surfaces is a new and growing technique. It has been proven to be effective at cladding the internal diameter of steel bores with nickel. However, at this time, all commercial processes are being run without an inert atmosphere, which would be required for optimal properties in aluminum cladding. The ideal candidate for any repair development effort for a new technology is a high-value but low-risk application. Low-risk applications are essential for a new technology implementation; however, parts that are overly mundane and which do not provide a return-on-investment (ROI) do not justify the higher development costs and perceived risks of a new technology. New technologies by definition are almost universally perceived to have higher risk because all of the data that we have on legacy processes is not available, and unknown risks are normally assumed to be high. One way to mitigate these risks is to choose non-critical features of valuable parts where failure of the repair would not result in a safety critical event. Furthermore, readily inspectable areas or parts which can be bench tested can also be used to mitigate the potential risks of using a new technology. The benefit of course of taking these managed risks are significant maintenance cost reductions as well as increases in system availability, since a part can often be repaired in much less time than a legacy part could be procured.

The Navy actuator in this program was chosen as an ideal candidate for repair for several reasons. The first was that this was a high-value component with at least some pressure on part availability, i.e., parts were not always available to support a return-to-service in the shortest timeframe desirable. Secondly, the risk was determined to be very low because the part, while important, has redundant backups and failure of the part would not be considered a critical safety issue.

3. Experimental Procedure

6061 aluminum coatings were produced via cold spray from commercially available gas-atomized 6061 Al powder (Valimet, Stockton, CA, USA), −325 mesh, shown in Fig. 2. The powder was heat treated for a minimum of 1 h at 250 °F to ensure the powder was dry and flowed well. The repairs were performed using a VRC Gen III high-pressure cold spray system (VRC Metal Systems, Rapid City, SD, USA) using a small 45° nozzle developed for internal bore cold spray applications. The nozzle has a throat diameter of 1 mm, an expansion length of 44.5 mm, and a 2 mm exit diameter.

The cold spray system and the actuator repair setup with internal bore nozzle are shown in Fig. 3 and 4, respectively. Helium was used as the process gas to achieve high impact velocities between incident particles for deposition on a 6061 aluminum alloy substrate. Helium has a higher specific heat ratio and a higher specific gas constant than nitrogen. This allows helium to reach higher velocities than nitrogen for any given nozzle that is maintained at supersonic conditions. Much higher velocities achieved by helium helps accelerate particles to higher velocities faster, and this is critical for cold spray operations that require short nozzle lengths. The pressure and temperature of helium were maintained at 3.5 MPa and 500 °C at the heater exit, respectively. These conditions correlate to a pressure of approximately 3.0 MPa and a temperature of 375 °C at the nozzle inlet. The nozzle used for the experiments is made from polybenzimidazole and has an area expansion ratio of 4 and an expansion length of 44.5 mm. At these conditions, the impact pressure and temperature conditions are calculated numerically for helium. Knowing the impact conditions, bonding conditions can be calculated similar to the procedures presented in Schmidt et al. (Ref 11). A critical velocity and an erosion velocity are calculated. Particles that achieve a velocity higher than the critical velocity and remain below the erosion velocity are expected to bond successfully. The ideal condition for bonding is when the ratio of the impact velocity to the critical velocity (η) is approximately 1.5 according to Assadi et al. (Ref 12). If the ratio of the impact velocity to the erosion velocity ($\eta_{erosion}$) is above 1.0, the impact of the particles causes erosion behavior on the substrate (Ref 12). The mass distribution of particles is shown in Fig. 5.

The numerical determination of the bonding criteria of the particle range between 4 μm and 100 μm helps us determine the expected amount of the bonding particles versus the amount of particles impacting the surface, namely the DE (Ref 13). Figure 6 shows the particle impact conditions, and critical and erosion velocities for the spray conditions of the experiment presented here.

The majority of the particles between 5 and 68 μm (Fig. 5) hold the bonding criteria, which correlates to DE

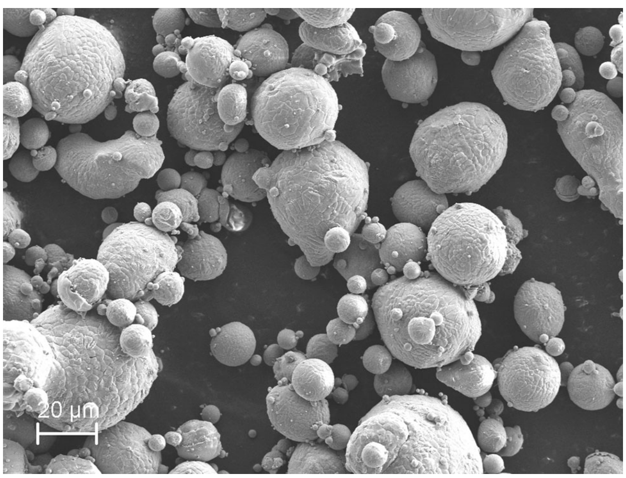

Fig. 2 SEM micrograph of the as-received 6061 powder

Fig. 3 VRC Gen III cold spray system

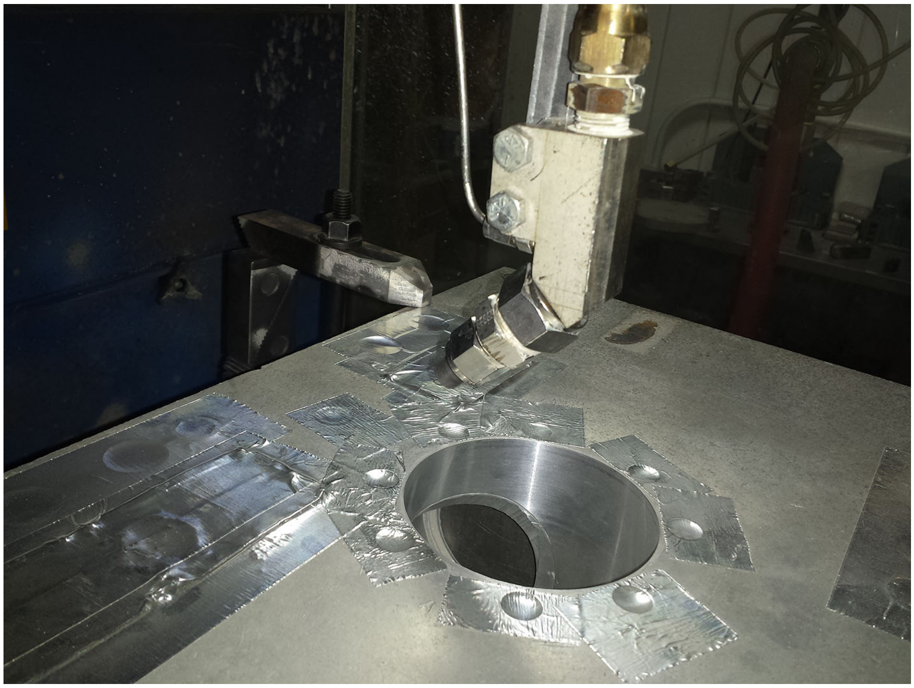

Fig. 4 Experimental setup to repair the valve actuator with internal bore nozzle

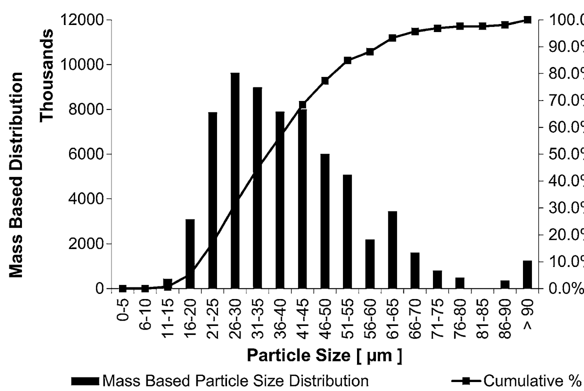

Fig. 5 Al 6061 powder particle mass distribution plot

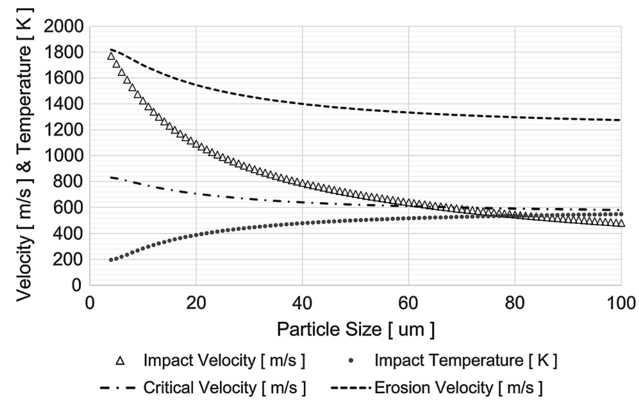

Fig. 6 Impact velocity and temperature, critical and erosion velocities for the short nozzle

of 87%. In order to further justify the use of helium versus nitrogen, numerical calculations are made for the same nozzle (‘‘short nozzle’’) with a pressure of 5.77 MPa and a temperature of 375 °C at the gun. Also, numerical calculations are made with a nozzle with the same expansion ratio and an expansion length of approximately 112 mm (‘‘long nozzle’’). The spray conditions at the gun are kept at the conditions used for the experiment. Figure 7 shows the η and $\eta_{erosion}$ plotted against the particle size range to observe the comparison between these three spray conditions numerically.

The DE of the particles is calculated as 46% for the calculation with nitrogen, where particles ranging between 5 and 43 μm are estimated to be bonding. The nitrogen gas provides a lower DE, although a higher pressure setting was used for the simulation. Figure 7 shows that with nitrogen, the η value is barely above 1.0, whereas the helium keeps an average particle (40 μm) at an η value of approximately 1.25. It is expected that values closer to 1.5 provide a better bonding condition. Figure 7 also shows that a shorter nozzle returns lower η values than the longer nozzle. On the other hand, the losses with the shorter nozzle can be compensated through the use of helium over nitrogen and adjusting the spray parameters through predictive numerical methods. Erosion was not found to be an issue for the vast majority of particle sizes that were tested among the three spray conditions (Fig. 7).

Deposition took place using a nozzle stand-off distance of 20 mm, 45° deposition angle, medium powder feed rate of approximately 10 g/min., and a nozzle traveling speed of 250 mm/s. Finally, total deposition thicknesses ranged from 2 to 8 mm.

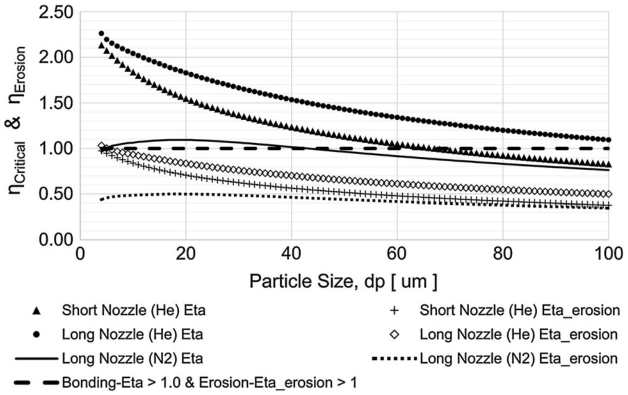

Fig. 7 Plot of η and $\eta_{erosion}$ plotted against the particle size range

4. Results

The performance requirements for this repair were porosity values below 5% on critical surfaces, adhesion strengths in excess of 68.9 MPa, machinability to drawing specifications, and satisfactory performance in bench testing of the final repaired component. Prior to repair of the aluminum actuator, proof of concept testing was required to ensure that cold spray could achieve the level of properties needed for the repair. A mockup, which had the same internal bore geometry as the actuator, was repaired first. Tensile, ASTM C633 bond adhesion, and porosity testing results from the mockup were reviewed and approved prior to the repair of the aluminum actuator. Due to the stringent performance requirements, it had to be demonstrated that minimum coating properties were achieved through these tests before the repair of the aluminum actuator would be authorized.

A mockup of the actuator is shown in Fig. 8. The purpose of the mockup was to determine the feasibility of repairing the critical surfaces of the aluminum actuator using cold spray. Figure 9 is an image of the final mockup after cold spray showing the most critical surfaces for parameter development. Dark spots in the micrograph represent porosity. The maximum allowable porosity in this zone is 5%. Applying a coating on this area proved to be challenging due to the sharp interface at the corner. The porosity in the initial mockup was as high as 16%. In order to achieve a more consistent coating, it was necessary to experiment with parameters, such as approach angle and speed, to minimize porosity and defects in the inside bottom corner of the internal bore. Optical porosity measurements performed on the final mockup cold spray repair are shown in Table 1. Measurements were made using an area fraction analysis with Buehler Omnimet software. From the results, it can be seen that the cold spray coating was able to achieve an average of 3% porosity based on a total of 14 measurements from two locations. This result compares well with previously reported results, which produced cold spray coatings of 6061 aluminum using high pressure in the range of 2-3% porosity (Ref 14).

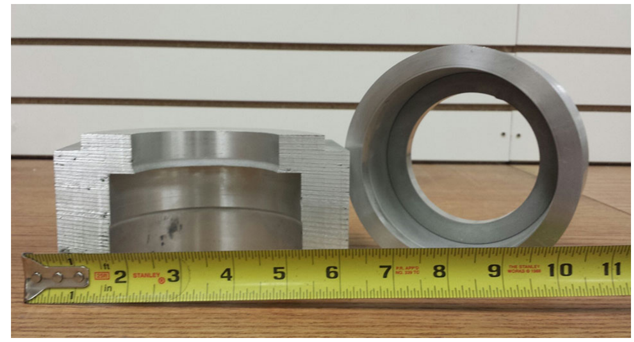

Fig. 8 A photo of the mockup used as a proof of concept for the aluminum actuator

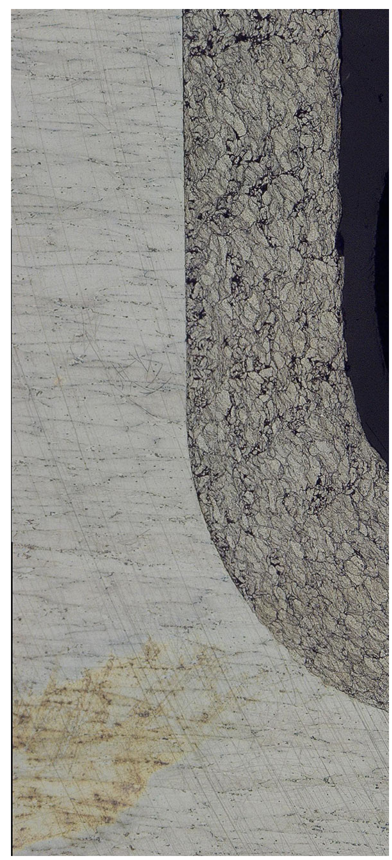

Fig. 9 Micrograph showing the quality of the cold spray deposition in the bottom corner of the internal bore critical surface of the aluminum actuator mockup

Tensile testing was the second requirement for approval to repair the aluminum actuator. A solid block of Al-6061 was produced using the same incident angle between the cold spray gun and the substrate as would be used during deposition on the critical surfaces. From the deposited block of Al-6061, a set of four reduced size ASTM E8 type tensile specimens were removed using wire EDM. Two of the test specimens were tested internally and two were sent to the Navy for testing. Table 2

Table 1 Shows the results of the optical porosity testing performed on the mockup sample

Field #	% Porosity	Field #	% Porosity
1.1	0.93	1.8	1.79
1.2	1.25	1.9	1.86
1.3	1.40	2.1	7.9
1.4	1.48	2.2	5.4
1.5	1.85	2.3	3.1
1.6	1.58	2.4	3.7
1.7	1.66	2.5	4.9
Total		2.9 ± 2.10	

Table 2 Shows the results of the ASTM E8 type ultimate tensile testing that was performed during the initial qualification effort

Sample Id	UTS, MPa	% Elongation
1	199	1.92
2	203	2.01

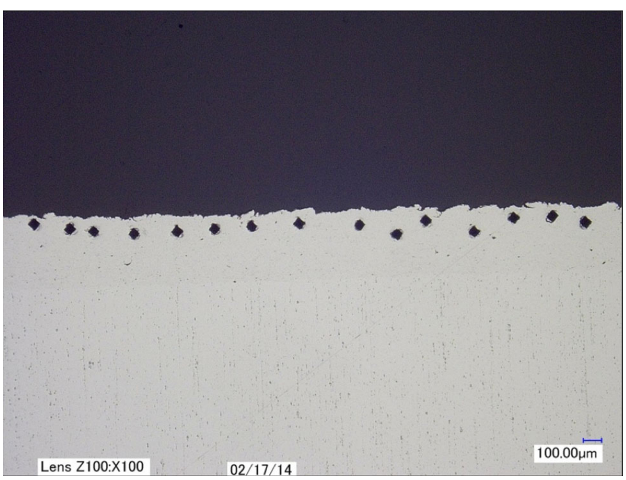

Fig. 10 Hardness profile measured on the cold spray deposition on the mockup sample

shows the results from the internal testing. The results showed that the strength of the cold spray material far exceeded the minimum requirement of 68.9 MPa for ASTM C633 bond strength; however, there were no minimum tensile values as a part of the qualification requirements. Hardness testing was also performed on the mockup of the actuator bore, as shown in Fig. 10. Using a 100 g load, the average hardness was 87 ± 3.3 HV.

ASTM C633 bond testing was the final cold spray development requirement for approval to repair the aluminum actuator. The incident angle between the cold spray gun and the substrate had to be the same as the incident angle during deposition on the critical surfaces. Table 3 shows the results from the ASTM C633 bond testing. Figure 11 is an image of the cold spray depositions made for testing. The actual bond strength of the Al-6061 coating was higher than the reported average as all of the

Table 3 Shows the results of the ASTM C633 bond testing for initial qualification testing

Bond strength	S1: 69.7 MPa—glue failure S2: 66.9 MPa—glue failure S3: 73.2 MPa—glue failure S4: 76.0 MPa—glue failure Average: 71.4 MPa

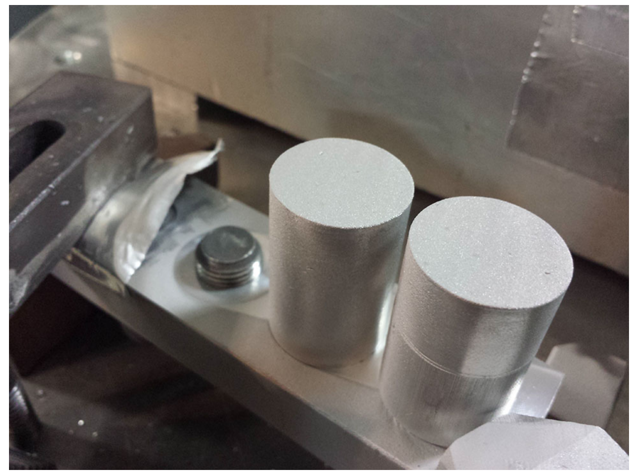

Fig. 11 Photo of the ASTM C633 bond test specimens deposited for proof of concept testing to support approval to proceed with actuator repair

failures occurred as glue failures, as opposed to adhesive or cohesive failures of the coating, i.e., the CS layer exceeded the strength of the epoxy. From the results, it can be seen that the cold spray depositions were able to meet the requirements for approval to repair the aluminum actuator.

To provide additional confidence that the cold spray process was achieving the same properties in the mockup as seen for the bond coupons, a series of bond tests were performed on the deposited mockup. Figure 12 shows the setup used to perform bond testing of the deposited mockup. From the image, it can be seen that the mockup was sectioned and areas of the cold spray deposit were prepared for ASTM C633 type bond button testing using a reduced size bond button and a Positest® AT-M adhesion tester (DeFelsko Corp., Ogdensburg, NY, USA). Table 4 shows the results of the bond button testing, which all reached the test system maximum load of 68.9 MPa without failure. The results show that the cold spray depositions were able to meet the requirements for approval to repair the aluminum actuator.

Once the proof of concept testing was completed, approval was received to repair the aluminum actuator. Figure 13 shows a picture of the corroded outlet ring of the actuator body after machining to prepare the surface for cold spray. In this case, it was not possible to remove all of the corrosion damage. Because this was a low-stress non-critical feature of the valve actuator body, it was approved to spray over and fill the remaining corrosion pits in the outlet ring. This was done successfully, and Fig. 14

Fig. 12 Photo of the modified C633 bond testing which was performed on flat portion the mockup internal bore bottom lip

Table 4 Shows the results of the modified ASTM C633 bond testing performed on the mockup

Bond strength	Sample 1: >68.9 MPa Sample 2: >68.9 MPa Sample 3: >68.9 MPa Average: >68.9 MPa

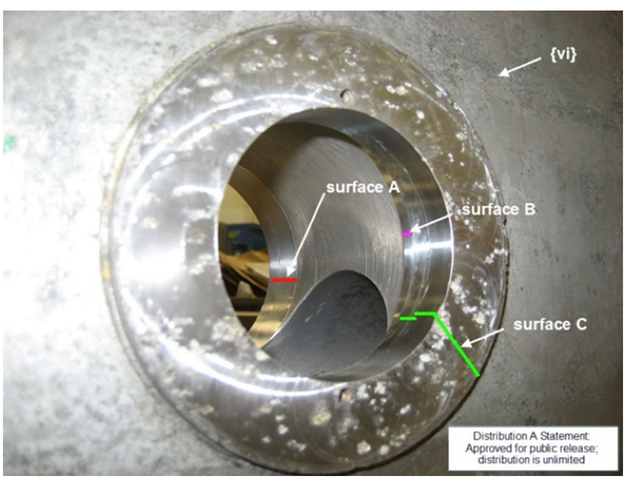

Fig. 13 Machined corrosion damaged surface of the actuator shown in Fig. 1

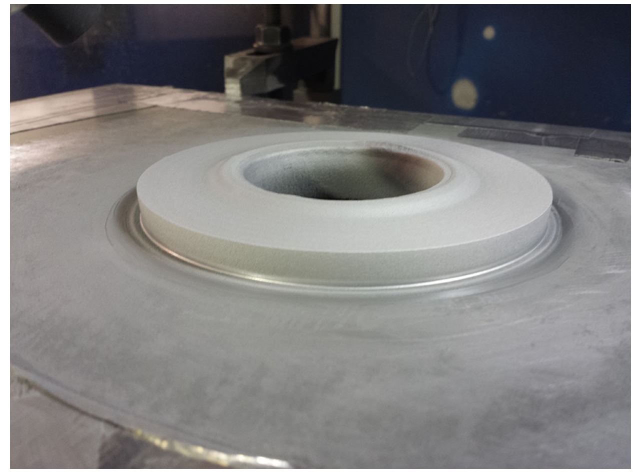

Fig. 14 Repaired external corrosion surfaces of the aluminum actuator post deposition

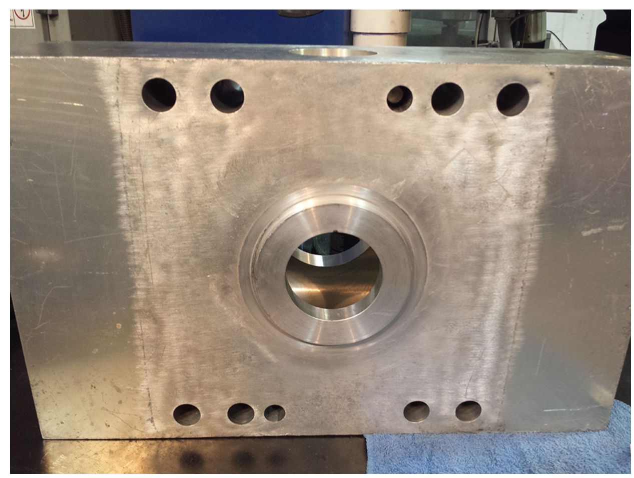

Fig. 15 Photo of the pre-machined aluminum actuator before preparation for cold spray

shows an image of the aluminum actuator post deposition, showing the repair of the corroded surfaces with a large build up of cold spray material.

Unfortunately, the first actuator repair attempt failed due to poor bonding in the inside corner region near the bottom of the internal bore (i.e., in the general area shown in Fig. 8). The cold spray material was then machined off, and based on the lessons learned during the first failed repair attempt, a stringent process control document was prepared and followed during the next deposition process, which led to a successful repair on the second attempt. During the repair operation, it was noted that the sharp corner had the propensity to build up first on both sides of the corner before the corner itself could be build up to join the sides. This is a natural geometric challenge, as the point of the corner does not present an ideal surface for deposition. We learned, however, that if we sprayed the equivalent of a fillet joint into the bottom corner first, followed by deposition on the walls and bottom shelf of the bore, that we achieved reliable deposition on all surfaces. An image of the as-received aluminum actuator after re-machining in preparation for the repair is shown in Fig. 15.

In order to ensure the quality of the cold spray deposit, witness coupons were sprayed just after completing the repair operation. The testing of these sample coupons sprayed during the repair of the aluminum actuator was required to ensure that the cold spray coating applied to the repaired actuator had achieved the level of properties needed for the repair. Tensile testing, ASTM C633 bond testing, and porosity testing were performed. As with the proof of concept testing, the incident angle between the cold spray gun and the substrate for the witness coupons had to be the same as would be seen during the deposition

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Table 5 Shows the results of the tensile testing of bulk cold spray deposit material that was performed for the final process repair qualification

Sample Id	UTS, MPa	% Elongation
1	272	2.91
2	251	3.02

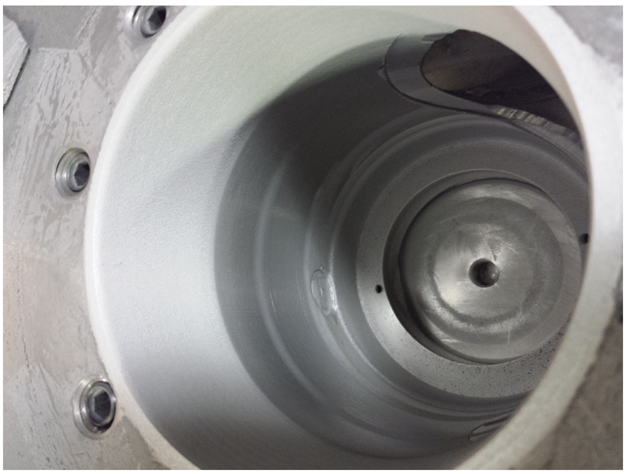

Fig. 16 Photo of the aluminum actuator internal bore repair with solid masking in place

of the critical surfaces. From a deposited block of cold spray material, a set of four tensile specimens was excised. Two of the test specimens were tested internally and two were sent to the Navy for testing. Table 5 shows the results from the internal testing that was performed. After further process development, the results of the internal testing show that the strength of the cold spray-deposited material exceeded the requirement set forth to get approval to repair the aluminum actuator. The results of the Navy testing were reported to NAVSEA and were accepted. Figure 16 shows the solid masking used to protect surfaces from over spray after cold spraying. It was necessary to machine out the overspray in order to remove the masks; otherwise, forceful removal of the masking could damage the cold spray deposition. Masking materials made from PEEK high-temperature plastic and aluminum were used to protect surfaces from over spray which were directly in the spray path of the deposition. Another challenge that was discovered during the development effort was the possibility of void formation on inside corners, as shown in Fig. 17. In order to avoid this condition and ensure adequate fill in the corner, a 1 mm or larger radius was recommended in the corner during pre-machining and the corner was sprayed as a separate operation to fill the corner area prior to spraying the sealing surfaces of the internal bore.

ASTM C633 bond testing and porosity testing were the final requirements for approval to repair the aluminum actuator. As with the proof of concept testing, the incident angle between the cold spray gun and the substrate was the same as used on the critical surfaces. Optical porosity

Fig. 17 Photo of bottom inside corner of the internal bore showing the lack of fill in the bottom corner during the initial deposition trials

Table 6 Shows the results of the optical porosity testing performed for repair qualification on the final mockup sample

Field #	Field area, µm	Pore area, µm	% Porosity
1	689,035	4537	0.66
2	696,284	2805	0.40
3	691,296	7213	1.04
4	734,710	4298	0.59
5	702,271	8620	1.23
6	743,023	11,371	1.53
7	761,011	6050	0.80
8	774,172	9026	1.17
9	827,792	6719	0.81

measurements were also performed on one of the ASTM C633 witness samples, which were provided with the repaired actuator (Table 6). The cold spray witness sample measured far less than the required 5% porosity on the critical surfaces; however, flat surfaces are expected to be lower than the complex internal corner surfaces, etc. Table 7 shows the results from the ASTM C633 bond testing. Again, the cold spray depositions were able to meet the requirements for approval to repair the aluminum actuator, which was a minimum of 68.9 MPa.

After final deposition and measurements were completed, the aluminum actuator was crated and sent out for post-machining by the Navy, where post-repair certification testing and final machining were performed. The following operational testing was accomplished on the assembled actuator: internal hydrostatic testing to 1.5×

Table 7 Shows the results of the ASTM C633 bond testing for repair qualification on the witness coupons of the repaired actuator

Bond strength	Sample 1: 73 MPa glue failure Sample 4: 78 MPa glue failure Average: 75.7 MPa

operating pressure, joint tightness testing to operating pressure, and operational testing. All testing was per the applicable maintenance standards, and the actuator passed all testing. After functional testing, the repaired actuator was cleared for installation.

5. Conclusions

For the first time, an internal sealing bore was repaired for a Navy Al-6061 hydraulic valve actuator using high-pressure cold spray deposition. The repair demonstrated the ability of cold spray to successfully deposit Al-6061 on internal surfaces of relatively small diameter, deep bores. The repair process development has shown the potential for even more challenging future applications, since the strength of the cold spray-deposited material was found to be in excess of 200 MPa as deposited. The potential for achieving the necessary critical particle velocities with a reduced nozzle section was also demonstrated via modeling, and was found to be a valuable tool for predicting the necessary nozzle conditions, geometries, and gas type needed for a successful deposition. This repair is now being offered commercially by MOOG, which demonstrates a full technology transition pathway from a university R&D laboratory in partnership with an equipment supplier to design and provide the necessary hardware for the repair, and an industrial service provider to fulfill future repair needs. This repair is expected to both provide a generous ROI as a repair process, as well as to increase system availability by providing an alternative to the long lead times of new purchased parts.

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