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Magnesium Repair by Cold Spray

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The U. S. Army and Navy have experienced significant corrosion problems with magnesium alloys that are used to fabricate aircraft components. The most severe of these are associated with large and expensive transmission and gearbox housings for rotorcraft, which have to be removed prematurely because of corrosion. Many of the parts cannot be reclaimed because there is not an existing technology that can restore them adequately for service. The U.S. Army Research Laboratory has developed a Cold Spray process to reclaim magnesium components that shows significant improvement over existing methods and is in the process of qualification for use on rotorcraft. The cold spray repair has been shown to have 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. Cold spray trials were performed using various aluminum powders at different deposition conditions with both helium and nitrogen carrier gas. Evaluations of the resultant cold spray aluminum coatings deposited on ZE-41A magnesium alloy substrates were conducted using microstructural analysis, hardness, bond strength and corrosion testing. The work presented here represents the first two years of a three-year effort, which will result in the establishment of a demonstration cold spray facility at the Naval Air Depot, where the overhaul and repair of Navy rotorcraft is accomplished.

Introduction

The Joint Strike Fighter aircraft employs several critical magnesium parts, which are susceptible to early rejection due to corrosion. The U.S. Army and Navy have experienced significant corrosion problems with magnesium alloys that are used to fabricate aircraft components. The most severe of these are associated with large and expensive transmission and gearbox housings for rotorcraft, which have to be removed prematurely because of corrosion, adversely affecting fleet readiness and safety. Many of the parts cannot be reclaimed because there is not an existing technology that can restore them adequately for service. The replacement of these parts is very expensive ranging in the millions of dollars every year. One common repair technique, used for some of those parts that can be salvaged, involves the use of aluminum shims, which are adhesively bonded over areas where the corrosion has been ground down and dimensional restoration is required. The U.S. Army Research Laboratory (ARL) Center for Cold Spray has developed a cold spray process to reclaim magnesium components that shows significant improvement over existing methods and is in the process of qualification for use on rotorcraft. The cold spray repair has been shown to have 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 work presented in this report represents the first two years of a three year effort, which will result in the establishment of a demonstration cold spray facility at a Naval Air Depot where the overhaul and repair of Navy rotorcraft is accomplished. The program involved the participation of all branches of the U. S. Department of Defense, major U.S. helicopter companies, academia and international groups.

Problem statement

The widespread use of magnesium in aircraft occurred during the Vietnam era to reduce weight and increase performance.[1] Magnesium is approximately 35% lighter than aluminum and has exceptional stiffness and damping capacity.[2] Therefore, magnesium alloys are used for the fabrication of many components on U.S. Department of Defense (DOD) aircraft, especially for complex components such as transmission and gearbox housings on helicopters and gearbox housings on fixed-wing aircraft, because of their high strength-to-weight characteristics.

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Magnesium is a very active metal electrochemically and is anodic to all other structural metals. Therefore, it must be protected against galvanic corrosion in mixed-metal systems because it will corrode preferentially when coupled with virtually any other metal in the presence of an electrolyte or corrosive medium.[3] Many of the corrosion problems associated with magnesium helicopter components occur at the contact points between inserts or mating parts, where ferrous metals are located, creating galvanic couples.[4] Much of the corrosion occurs at attachment points where a dissimilar metal is in contact with the coated magnesium component. This includes flanges, mounting pads, tie rods, lugs and mounting bolts. Figure 1 is a schematic of the main transmission housing for the H-60 helicopter showing the areas most susceptible to corrosion. Figure 2 shows the extent of corrosion damage on one of the mounting pads after one overhaul cycle.

Because of the localized nature of the corrosion, surface treatments intended to mitigate the problem would only have to be applied in these specific areas. In addition, magnesium alloys are also very susceptible to surface damage due to impact, which occurs frequently during manufacture and/or overhaul and repair. Scratches from improper handling or tool marks can result in preferential corrosion sites. The Department of Defense and the aerospace industry have expended much effort over the last two decades to develop specific surface treatments to prevent corrosion, to increase surface hardness, and to combat impact damage for magnesium alloys in order to prolong equipment service life.[5] However, the means to provide dimensional restoration to large areas on components where deep corrosion has occurred remains a challenge.

Proposed solution

The development and qualification of the cold spray process to deposit commercially pure aluminum (CP-Al) was recommended by the Center for Cold Spray Technology at ARL for providing dimensional restoration and protection to magnesium. The cold spray process was viewed as the best possible method for depositing the aluminum coatings and would be viewed as part of an overall strategy of replacement of the chromate processes currently in use today, eliminating environmental and worker safety issues, while significantly improving performance and reducing life-cycle costs.

Technical approach

The critical tasks associated with the qualification of the cold spray coatings on magnesium components were established in a document known as the Materials Joint Test Protocol (JTP) developed by representatives of the DOD, OEMs, industry and academia. The JTP is comprised of mechanical, physical and chemical tests designed specifically for this application. The most important qualification tests were identified as adhesion (uniaxial tension), salt fog exposure (ASTM-B117) and microstructural analysis, which will be the primary focus of this discussion. These screening tests would form the basis of the data required to recommend the use of cold spray to repair magnesium aircraft components. Additional tests would later be conducted to satisfy specific application requirements for structural repair.

Cold spray deposition equipment

The ARL Center for Cold Spray Technology currently maintains a high pressure stationary cold spray system manufactured by Ktech Corporation as well as four portable cold spray systems. Two of the portable cold spray systems were manufactured by Dymet Inc., one by Centerline and the remaining system was produced at ARL. All of the portable systems are considered low pressure with the exception of the ARL system which can operate at low or high pressures. The work performed under this program was conducted with the Ktech System and the portable ARL system.

Cold spray nozzle design

The conventional cold spray nozzle that is used with the Ktech System is normally fabricated from stainless steel or tungsten carbide. Various nozzle configurations have been designed and tested at ARL and it is not the intent of this work to repeat the research of others but to relate those aspects of nozzle design specific to this application. The primary concern was clogging of the nozzle while spraying CP-Al. Clogging can occur in the throat of the DeLaval-type nozzle, where higher temperatures are employed. Aluminum particles tend to stick to the sides of the nozzle, interfering with proper gas flow, which adversely affects coating deposition. To mitigate clogging, a thermoplastic nozzle was used with absolute success. ARL and others have conducted studies of various nozzle

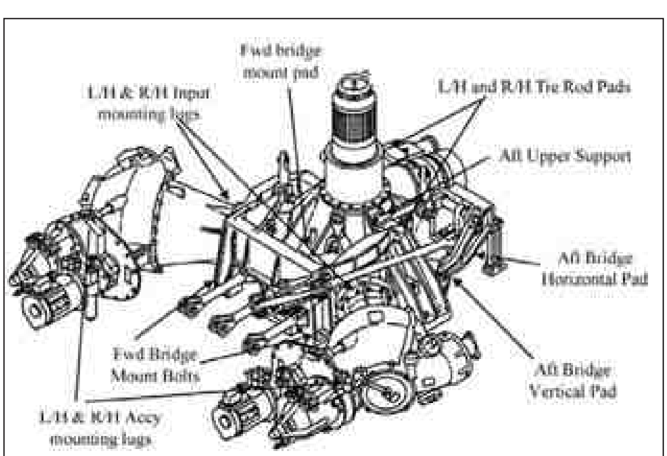

Figure 1—Schematic of H60 main transmission housing showing areas most susceptible to corrosion.

Figure 2—Corroded area on a magnesium transmission housing.

configurations and materials. Comparisons have been made of nozzles fabricated from ceramic, plastic, carbide and other metallic materials. A nozzle fabricated from a high temperature-resistant thermoplastic was operated at 400°C with satisfactory results without nozzle clogging. There are several thermoplastics on the commercial market that can be successfully machined and used as a nozzle material. Such thermoplastics can maintain their properties at high operating temperatures (400°C) and are adequately wear-resistant for use with CP-Al for extended periods of time. These plastics tend to be proprietary in nature but can be obtained from the cold spray equipment manufacturers.

Selection of gases

The decision to use helium versus nitrogen relies primarily on the added costs involved. However, from a technical standpoint, the velocities that can be achieved by helium and the resultant density of the coatings may well be worth the extra cost, especially for components that are valued at $400,000 each. During operation at ARL, the Ktech cold spray system uses 40 SCFM of nitrogen at a cost of $0.29/100 SCF for a gas operating cost of $0.116 per minute. With helium, it uses 70 SCFM at a cost of $11.50/100 SCF for a gas operating cost of $8.05 per minute. Therefore, the costs are substantially lower when using nitrogen. To put the gas costs into perspective, the labor rate for operating a cold spray system is about $1.00/minute and the powder costs are about $2.00/minute. Helium recycling systems have been designed and put into use that are able to recover approximately 90% of the helium, thereby greatly lowering the operating cost.[7] For an R&D cold spray facility that operates intermittently, the cost of the recycling system cannot be justified, but for a production cold spray facility, the payback time on the cost of the recycling system would be fairly short for these expensive components. Regardless, the results of this work demonstrated that nitrogen can be used as a carrier gas to produce satisfactory cold spray coatings of CP-Al.

Powders

Studies have shown that the difference in particle velocities is a function of particle size, with velocities approximately twice as much for helium gas versus nitrogen gas for 5-μm particles but only about 30% greater for helium for 25-μm particles. J. Vlcek, *et al*. has provided extensive information related to the physical processes that occur during the cold spray deposition of different materials and why some work better than others.[8] Impact heating, equations of state during impact, dynamic yielding of the particles and impact pressures were examined and it was concluded that the materials that are most amenable to cold spray are those with a face-centered cubic structure, which includes aluminum.

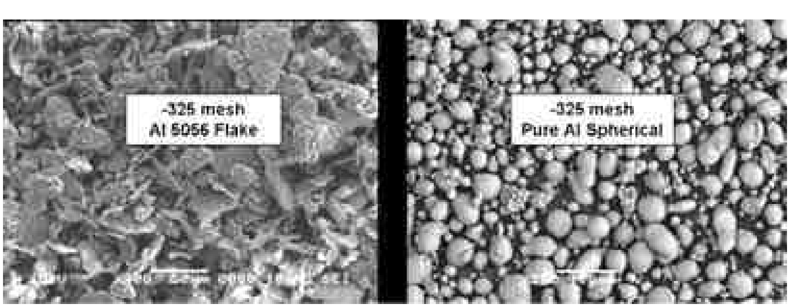

Figure 3—Particle shape effects on deposition.

The powders under consideration for the cold spray repair of magnesium transmission housings are commercially pure aluminum (CP-Al), aluminum-12% silicon alloy (Al-12Si) and aluminum alloy 5056. The criteria are based on the requirements associated with this application where galvanic corrosion and corrosion pitting are the primary causes for removing the components from service. In addition, the repair was confined to nonstructural areas of the transmission and gearbox housings. There are advantages and disadvantages associated with each material.

The 5056 aluminum alloy (composition Al-5Mg-0.1Mn-0.1Cr) was considered because it is compatible with magnesium and has better tensile, yield, elongation and fatigue strength than any magnesium alloy. The corrosion resistance of 5056 is also among the best of any aluminum alloy. The presence of the manganese is important because it serves to tie up any residual iron contamination which has been shown to degrade corrosion performance. The Al-12Si Alloy was chosen as a candidate based upon its excellent mechanical properties and resistance to wear and corrosion. It is also used extensively with thermal spray and the powders are commercially available.

Initially, concern was expressed over CP-Al as the material of choice for the cold spray repair of magnesium ZE-41A because it was lower in hardness and strength than other aluminum alloys that were also being considered for this application. It was later selected since the primary reason that the magnesium components were removed from service was due to corrosion and not wear, and the cold spray repair was to be performed on nonstructural areas of the component, making the strength requirement less an issue. Additionally, the CP-Al powder could be doped with a certain percentage of hardened particles to impart wear resistance if required. The cost of CP-Al is attractive at approximately $11.00/lb and is commercially available, while many other alternative alloys originally considered were much more expensive and/or had to be produced as a specialty item. The Al 5056 is an example of a powder that is not commercially available. The stock material used in the melt of the Al 5056 powder was also not available forcing the powder manufacturer to purchase and subsequently mix the raw materials to produce the alloy prior to atomization.

Finally, the spherical particle shape of the CP powder was preferred over that of the Al 5056 flake. Spherical particles form a more densely packed structure when deposited by the cold spray process resulting in better protection for the magnesium substrate. Figure 3 shows micrographs of the two powder types.

Predictive modeling for process optimization

The nature of the bond created during particle consolidation and the properties of the material produced by the cold spray process have been modeled at ARL. These predictive models are used to establish and optimize cold spray process parameters. Modeling efforts predict the amount of mixing at the interface between the particles and the substrate with concomitant high coating adhesion when the particle velocity reaches a certain minimum value. Compressible, isokinetic flow equations are used to model gas flow within the nozzle. Modified drag and heat transfer coefficients are then used to calculate iteratively the resulting particle velocities and temperatures. An example of this calculation for the aluminum/helium nozzle acceleration is shown in Fig. 4. The particle size for this calculation is 20 μm, and the initial gas pressure and temperature are 2.75 MPa and 20°C. Calculated particle velocities are verified experimentally by means of a dual-slit, laser velocimeter.

An empirical relationship of the penetration of micrometeorites into spacecraft skin is used to model the interface between the deposit and the substrate, and an empirical relationship between particle characteristics and critical velocity is used to model deposition efficiency. The cold spray material is evaluated for shear strength at the interface and for hardness. Magnified cross sections are examined for density and interface locking.

The demonstrated prediction accuracy of these results allows the ability to define operating parameter values and expected coating characteristics prior to cold spray operation. This prediction algorithm was subsequently used on multiple coating/substrate combinations with favorable results.

Cold spray trials

A series of cold spray trials were performed to optimize coverage, adhesion and coating integrity. Each trial run required the specification of the powder, powder feed rate, gas, gas pressure and gas temperature. Gas pressure and temperature were specified by model calculations to produce sufficient particle velocity for good deposition. Subsequent coating evaluation prescribed changes to the operating conditions if coating characteristics needed improvement.

A stationary and a portable cold spray system were used in these tests. A schematic of each system is shown in Fig. 5. The stationary system, supplied by Ktech allows for the range of operation parameters given by Table 1. Because the portable system does not have a gas heater, nitrogen gas cannot be used, as unheated nitrogen gas cannot achieve the required particle acceleration. The operating limits for the portable system are also given in Table 1.

Besides the limitations imposed by maximum allowable temperature and pressure, two operational restrictions narrowed the available parameter range - nozzle fouling and ambient temperature gas (for the portable unit). Low melting point powders can stick to nozzle walls, eventually plugging the nozzle. This is especially true for aluminum powders. Limiting gas heating to lower temperatures can prevent nozzle fouling.

Table 1

Cold spray operating parameters

Parameter	Stationary system	Portable system
Gas	Nitrogen, Helium	Helium
Gas pressure	1 - 2.74 MPa	1 - 2.74 MPa
Gas temperature	20 - 500°C	20°C
Powder feed rate	1 - 50 g/min	1 - 5 g/min

Cold spray trials were carried out within the parameter limits listed in Table 1, in order to determine optimum spray conditions for the two systems. As expected, maximum pressure and temperature produced the best coatings, where the coatings were evaluated by the methods described. In addition, it was found that helium gas produced superior coatings as compared to nitrogen when using a conventional nozzle fabricated from stainless steel or tungsten carbide. However, fouling occurred when temperatures in excess of 250°C were used with conventional nozzles. It was therefore necessary to conduct similar studies incorporating a plastic nozzle. Higher gas temperatures could be attained without nozzle fouling through the use of thermoplastic nozzles, and denser deposits with significantly increased bond strength were achieved. Optimum conditions determined by these tests are given in Table 2.

Coating characterization

The mechanical properties, corrosion resistance and microstructural features of the CP-aluminum cold spray coatings were analyzed. The results obtained are provided in this section, as well as a discussion of the test methods employed, when determined to be of significant importance to the data obtained or are necessary in order that test results may be duplicated by other researchers. Special surface preparation techniques, test fixtures, specimen geometry

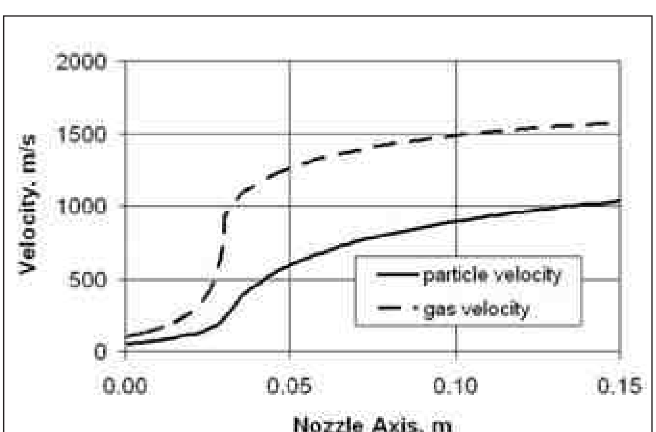

Figure 4—20 µm aluminum particles accelerated through a 150-mm nozzle by helium.

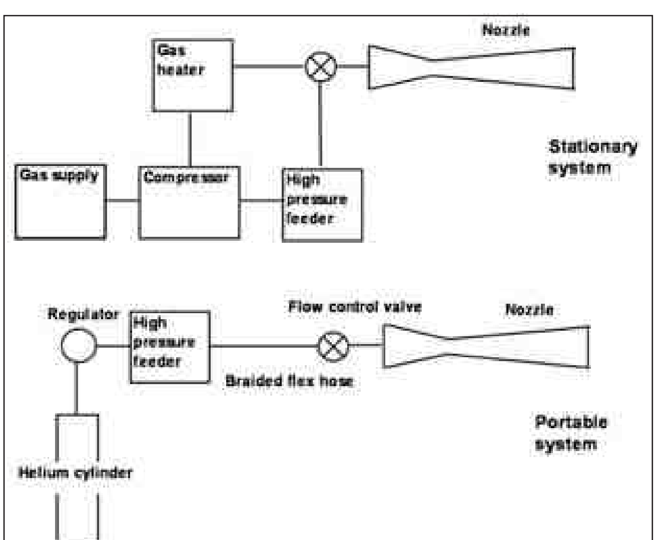

Figure 5— Stationary and portable cold spray system schematics.

Table 2
Optimum conditions

Parameter	Stationary system (standard nozzle)	Portable System (standard nozzle)	Stationary system (thermoplastic nozzle)
Gas	Helium	Helium	Nitrogen
Pressure	2.74 MPa	2.74 MPa	2.74 MPa
Temperature	250°C	20°C	400°C
Gas flow rate	122 m^3/hr	41 m^3/hr	39 m^3/hr
Powder feed rate	3 g/min	1 g/min	3 g/min
Stand-off distance	25 mm	10 mm	25 mm
Particle MMD	20 μm	20 μm	15 μm

or other procedures that affect test results are worthy of discussion and will provide valuable insight to those wishing to gain a better understanding of the evaluation of cold spray coatings. Bond strength and corrosion resistance were used as the primary screening tests to qualify the use of cold spray for this application.

Bond strength

The adhesive strength (strength of the bond between the coating and the substrate) and cohesive strength (strength of the bond between particles) of the cold spray coatings was determined to be an important factor in the qualification of the cold spray process for use on magnesium by the aerospace community. A major problem associated with the application of thermal spray coatings onto magnesium is the formation of oxides on the surface of the substrate, which adversely affects adhesion. Conventional thermal spray processes involve preheating the powders to a semi-molten state prior to being deposited onto the substrate. Magnesium is a highly reactive material and is very susceptible to oxidation. An advantage of the cold spray process for this application is that the powders are not heated sufficiently to cause the formation of a deleterious oxide layer.

Adhesion of the cold spray coatings was measured according to ASTM Standard C 633-79. Since bond bars made of ZE41A magnesium were not available, a 2.5 cm diameter plug was cut out of the 0.65 cm thick aluminum-coated ZE41A magnesium coupons and bonded to the 2.5 cm diameter 6061-T6 aluminum bond bars. Each of the bond bars was threaded on one end, in order that they could be inserted into the test fixture of a tensile test machine. The bond bar assembly is shown in Fig. 6. In the first step of this test, a cold spray coating was deposited onto the ZE41A magnesium coupon that had been lightly abraded with 60 grit aluminum oxide. It is essential that virgin, uncontaminated grit be used, which is not contaminated with extraneous particulate matter, such as iron which could become imbedded into the substrate and affect adhesion or corrosion test results. The main purpose of the surface cleaning operation is to remove the magnesium oxide layer and expose the fresh metal beneath in order to facilitate the bonding mechanism. The cold spray coating was applied immediately afterward.

The front and back surface of the cold spray-coated plug was grit blasted in addition to both surfaces of the aluminum bond bars. A 2.5-cm diameter disk of FM-1000 adhesive was placed between both of the bond bar/plug contact areas and subsequently placed in a fixture to hold them together while the adhesive cured for 3 hr at 150°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. This test is preferred over the conventional "dolly" or the "Patti" test where 2.5-cm diameter plugs are bonded to a coated test panel, because the bond bar test conducted with the use of a tensile test machine best insures that uniaxial tension is maintained throughout the duration of the test and also that it eliminates the risk of excess adhesive seeping out from around the edges of the plugs, which in turn can bias the test results by increasing the cross-sectional area being tested, thus yielding erroneously higher adhesion values. The FM-1000 adhesive is also recommended because it does not easily migrate through open porosity down to the substrate, which can also result in invalid adhesion values.

The averaged test results shown in Table 3 revealed that in all instances where helium was used as the accelerating gas the glue failed before the coating. Therefore, the reported adhesive strengths represent that of the glue and those of the coating are higher. In the test trial where nitrogen was used with a WC nozzle inlet section, the values were significantly lower as a result of the lower particle velocities achieved at low gas temperatures needed to prevent nozzle clogging. In order to achieve higher gas temperatures without clogging the nozzle, a thermoplastic nozzle was

Figure 6—Bond bar adhesion test configuration.

Table 3
Adhesion values of CP-Al deposited by the cold spray process

Program	Conditions	Adhesion (MPa)	Failure mode	Microns/Pass
ARL-DSTO	N_2, 2.74 MPa, 300°C	19.1	Adhesive	508
ARL-DSTO	He, 2.74 MPa, 20°C	>45.0	Glue failure	64
ARL-NCMS	He, 2.74 MPa, 20°C	>58.6	Glue failure	177
ARL	N_2, 2.74 MPa, 400°C	> 59.8	Glue failure	64

incorporated with satisfactory results for the ARL samples done at 400°C as Table 3 indicates. The results show that increased adhesion values were achieved with nitrogen at 400°C and by applying a thinner coating per pass.

Hardness

The hardness of the cold spray coatings of CP-Al were measured from metallographic cross-sections with a Wilson Tukon Micro-Hardness Tester utilizing a load of 500 g and a diamond indenter. The values obtained were converted to Brinell for comparative purposes. Figure 7 shows a comparison between annealed and fully worked wrought aluminum to that of a CP-Al cold spray coating.[9] It is important to note that the values of the cold spray coating were significantly higher than what was achieved by conventional materials processing. The cold spray coatings had an average value of 57 Brinell while that of fully hardened wrought aluminum was 45 Brinell. 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.[10-12] 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.

Microstructural examination

The microstructural features of the CP-aluminum cold spray coatings were examined utilizing optical and electron microscopy. Cold spray coatings were produced with the high pressure Ktech system and the high pressure ARL system using both helium and nitrogen for comparative purposes. Figure 8 shows a representative micrograph of the CP-Al coating produced using helium gas at room temperature and at a gas pressure of 2.75 MPa with the ARL portable system. The coating is very dense and shows no evidence of significant inherent material defects. The coating/substrate interface is free from voids, entrapped grit or areas of delamination. 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.[13]

Figure 9 shows a higher magnification of Figure 8 but subsequent to etching with Keller's reagent. There was evidence of plastic deformation of the consolidated particles and significant grain refinement that was the result of the shock compression which occurs during particle impact causing grain size reduction.[14]

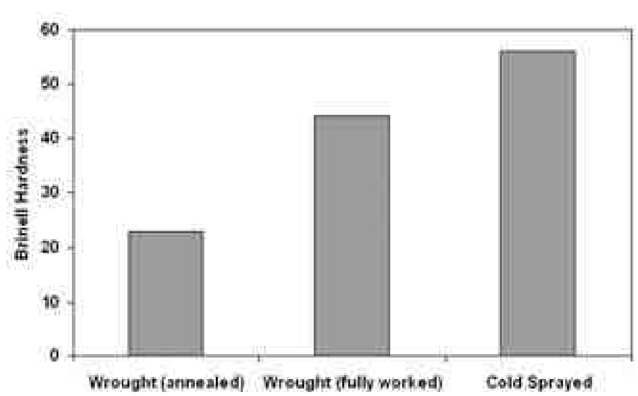

Figure 7—Hardness of CP-Al cold spray coatings compared to fully worked and annealed wrought material.

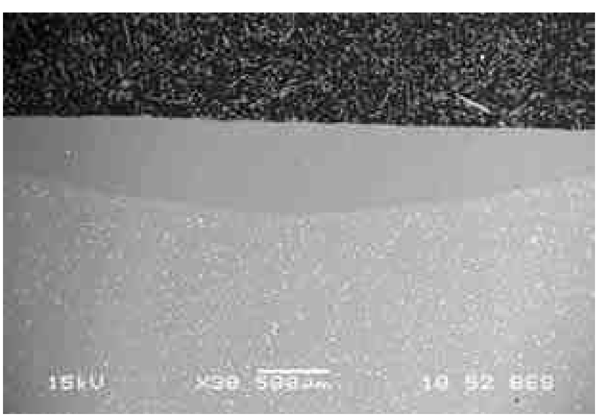

Figure 8—CP-Al deposited by the ARL portable cold spray system on ZE-41A magnesium interface.

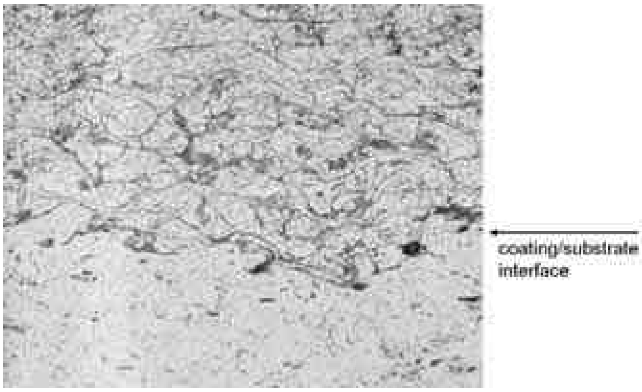

Figure 9—Etched sample using Keller's reagent showing grain refinement and plastic deformation.

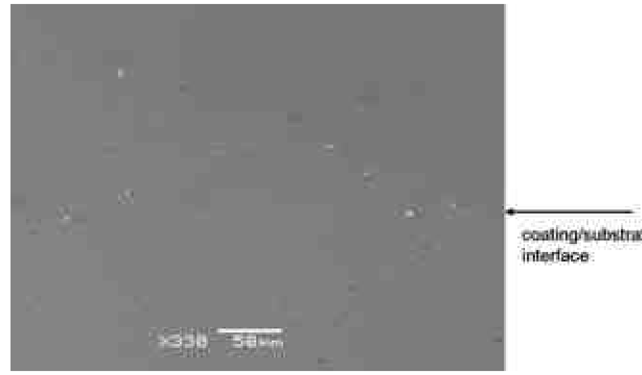

Figure 10—Al 5056 deposited by the stationary Ktech system using helium as the carrier gas. Note the high level of density.

Figure 10 is an example of a coating of Al 5056 produced with the Ktech high pressure stationary system also using helium gas at a temperature of 400°C and a pressure of 2.74 MPa. It was necessary to incorporate the use of helium at high gas temperatures in order to attain a dense deposit. The figure clearly illustrates the potential of cold spray to produce an adherent and dense coating. The microstructure is free from voids and porosity and the interface between the coating and the substrate is barely discernable.

Figure 11 shows a representative example of a cold spray CP-Al coating deposited with the use of nitrogen as the carrier gas at a temperature of 250°C and at a gas pressure of 2.74 MPa. The resultant coating was porous and had low bond strength because the gas temperature could not be increased until the incorporation of a plastic nozzle that prevented nozzle fouling. Figures 12 and 13 show significant improvement of the coating when the gas temperature was increased to 400°C. The density had improved as a result of the higher particle velocity as is the interface between the coating and the substrate.

Corrosion testing

The requirement for salt fog exposure established by the Corpus Christi Army Depot (CCAD) and the Naval Air Depot (NADEP), Cherry Point, is 336 hr, according to the requirements of ASTM B117, "Standard Practice for Operating Salt Spray (Fog) Apparatus." A total of three test panels of ZE-41A magnesium (7.62 cm × 10.16 cm × 0.64 cm) were machined from a plate, degreased and then grit blasted lightly with 60 grit Al_2O_3 that was free of any contamination. This is important as any iron contamination can adversely affect corrosion test results. The panels were subsequently coated with 0.30 - 0.375 mm (0.012" -.015") of commercially pure aluminum via cold spray. The carrier gas was helium, the pressure was 2.74 MPa, the traverse rate was 100 mm/sec, the feed rate was 2 g/min and the standoff distance was 25 mm**.** The uncoated edges of the panels were coated with a lacquer to prevent the salt from contacting the bare magnesium areas of the panels.

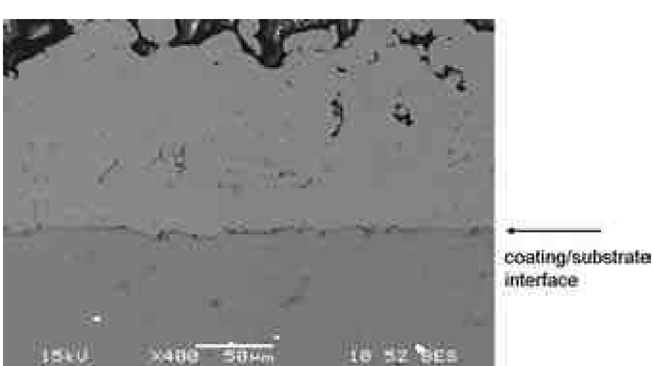

Figure 11—CP-Al deposited by the stationary Ktech system using nitrogen as the carrier gas at 250°C. Note the high level of porosity.

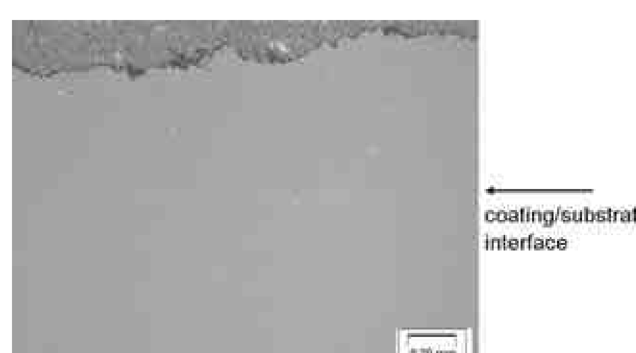

Figure 12—CP-Al deposited by the stationary Ktech system using nitrogen as the carrier gas at 400°C. Slight evidence of porosity (50×).

The test panels were placed into a salt fog chamber operating at 35°C with a 5% salt solution and periodically examined every 4 hr. The lacquer applied to the magnesium test panels failed prematurely, allowing corrosion to take place from a few areas on the edges of the panels. When this occurred, the magnesium test panels were removed from the salt fog chamber and the edges were cleaned, recoated with lacquer and corrosion testing was resumed. The magnesium panels had to be repaired in this manner several times during corrosion testing and after 504 hr, the repair procedure could not be attempted again, since too much of the magnesium substrate had corroded away from the edges and the back side of the test panels. However, the minimum requirement of 336 hr had been achieved. Figure 14 shows the aluminum cold sprayed magnesium panels after 336 hr in the salt spray chamber. For comparison, test panels of aluminum and steel had been exposed for 7,000 hr before some visual evidence of rust spots appeared on the steel panels. The aluminum test panels never experienced any substrate corrosion after 7,000 hr, but the test was stopped at that point.

Another set of five CP-aluminum magnesium panels were deposited using nitrogen gas at 250°C and a pressure of 2.74 MPa. This was the highest nitrogen gas temperature that could be employed using a metal nozzle without nozzle clogging. These panels were subjected to the same salt fog spray conditions, but due to the porous nature of the coating, as shown in Fig. 11, the aluminum coating failed after only 8 hr. The failed panels are shown in Fig. 15. A close-up of the resultant protrusion from a pinhole in the aluminum coating is shown in Fig. 16.

A third set of four corrosion test panels was prepared, but the test panels were machined to round off sharp edges and all of the exposed coupon surfaces (front, back and edges) were coated with cold spray CP-Al. In addition, a proprietary thermoplastic nozzle was used for these deposition runs, which would allow a higher nitrogen gas temperature to be used. A nitrogen carrier gas temperature of 400°C and a pressure of 2.74 MPa were used. A line-to-line index of 1 mm was used for one of the panels and a 0.5 mm index was used for the other panel. The edges of the panels were sealed with epoxy so only the front and back surfaces were exposed to the salt spray. The panels shown in Fig. 18 with epoxy sealed edges had been exposed for 804 hr (0.5 mm coupon) and 1,000 hr (1 mm coupon). Except for some discoloration of the aluminum, no corrosion is evident on the aluminum or the magnesium. However, upon inspection, a pinhole in the epoxy coating was found in each of the epoxy coated coupons. The pinholes in the epoxy coating have been repaired and the panels have been returned to the salt spray chamber for further exposure. Figures 17 and 18 show these panels before and after salt spray exposure.

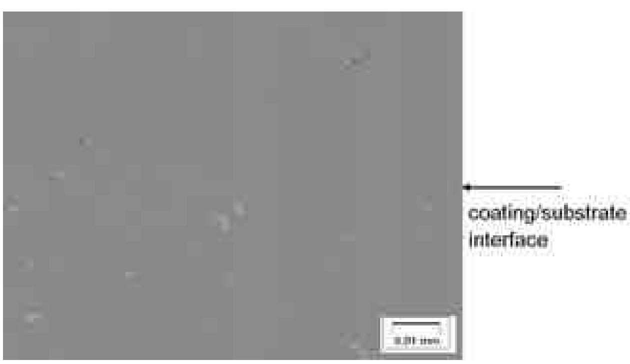

Figure 13—High magnification SEM of CP-Al deposited by the stationary Ktech system using nitrogen as the carrier gas at 400°C (1000×).

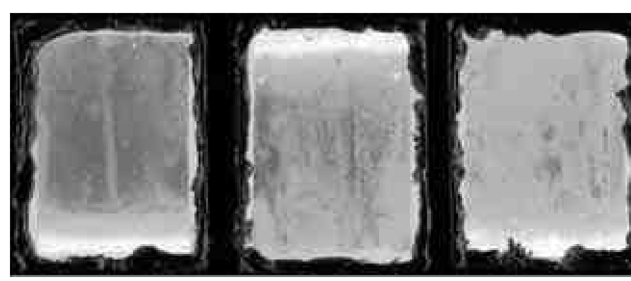

Figure 14—Cold spray CP-Al coated magnesium panels using helium gas after 336 hr of exposure in the salt fog chamber.

Figure 15—The panels sprayed using nitrogen gas after 8 hr of exposure.

Figure 16—A close-up of the growth resulting from a pinhole in the aluminum coating.

Oxide Analysis

Inert gas fusion according to ASTM E1019 was used to analyze the oxygen content of a CP-Al deposit produced by cold spray. These results were subsequently compared to the oxygen content of the starting powder. In this test, the starting powder consisted of CP-Al, -325 mesh (Fig. 19). The results revealed that the cold spray deposit did contain less oxygen (0.25%) as compared to the powder (0.34%). The reason for this decrease is that the brittle oxide layer on each particulate fractures during deposition as a result of the extreme amount of plastic deformation, and a portion of it falls away, never being incorporated into the deposit. The oxygen content of the CP-Al cold spray coating is largely determined by the oxygen content of the original powder, not the process.

Discussion

In recent years, experimental and computational studies at universities such as Helmut Schmidt University in Hamburg, Germany, have led to a better understanding of the cold spray process.[15] Modeling of the particle impact and bonding mechanisms has been performed as well as measurements of the effect of process variables on particle temperatures and velocities. For the former, a number of researchers have likened the bonding mechanisms in cold spray with those identified in explosive welding, where bond formation relies on deformation under high pressures.[16] With respect to process variables, helium or nitrogen are the most commonly used gases with cold spray, with higher particle velocities obtained with helium. However, nitrogen is generally preferred because it is much less expensive. The results of this study have shown this to be the case, but that adequate adhesion, density and corrosion resistance can be achieved with the use of nitrogen for CP-Al.

The feasibility of using the cold spray process to repair non-structural magnesium aircraft components has been demonstrated by the satisfactory results obtained from adhesion, corrosion testing and microstructural analysis. The cold spray process yielded adhesion values in excess of 58.6 MPa when helium was used as the carrier gas and 71.3 MPa when nitrogen was employed. These values represent the strength of the adhesive used, as all failures occurred at the interface between the adhesive and the coating. The cold spray coating was not pulled off of the substrate and the coating did not fail cohesively.

The cold spray coating was required to withstand a minimum of 336 hr of salt fog exposure according to the requirements of ASTM B117. The CP-Al coating applied by cold spray on ZE-41A magnesium test panels to a thickness of 0.305 - 0.381 mm (0.012” - 0.015” using helium as the carrier gas lasted at least 500 hr before the lacquer used to seal the edges and back face of the test panel failed. The coating was intact and did not fail from the front face of the test panel. Corrosion test panels fabricated from aluminum and steel that had also been coated with CP-Al by cold spray at the same time as the ZE-41A magnesium panels using the identical process parameters, lasted 7,000 hr in the salt fog chamber. These results serve as testimony that adherent and dense coatings can be achieved by the cold spray process for this application. An additional set of ZE-41A magnesium alloy panels coated with CP-Al using nitrogen gas were in the B117 salt fog spray chamber at the time of this writing and had exceeded 1000 hr (Fig. 18).

Conclusions

The cold spray process has matured from an emerging technology to a viable alternative to thermal spray for selected applications.[17] This study has shown it to be a promising cost-effective and environmentally acceptable technology to impart surface protection and restore dimensional tolerances to magnesium alloy components on helicopters and fixed-wing aircraft.

Acknowledgements

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Figure 17—Magnesium panels before exposure.

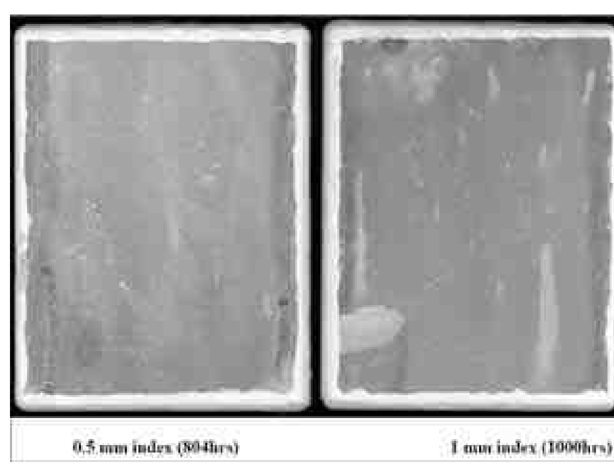

Figure 18—Aluminum-coated ZE41A magnesium panels with epoxy coated edges after salt spray exposure.

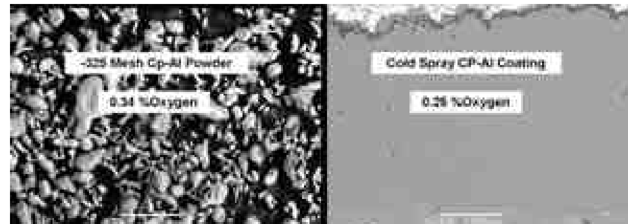

Figure 19—Oxygen content measured by inert gas fusion.

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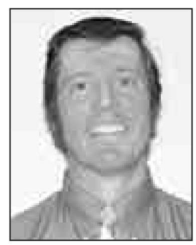
About the Author



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