ESTCP
Cost and Performance Report

(WP-200620)

Cold Spray for Repair of Magnesium Components

November 2011

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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ACRONYMS AND ABBREVIATIONS

AL	aluminum
ARL	Army Research Laboratory
ASTM	American Society for Testing and Materials
CCAD	Corpus Christi Army Depot
Cd	cadmium
CGT	Cold Gas Technology GmbH
CP-Al	commercially pure aluminum
DoD	U.S. Department of Defense
DSTO	Defense Science and Technology Organization
%EL	elongation at failure
ESTCP	Environmental Security Technology Certification Program
FRC-E	Fleet Readiness Center East
GM	General Motors
He	helium
hex-Cr	hexavalent chromium
HP-Al	High Purity Aluminum
HVOF	High Velocity Oxygen Fuel
ID	inner diameter
JTP	Joint Test Protocol
ksi	kips per square inch
Mg	magnesium
N_2	nitrogen
NADEP	Naval Air Depot
NAVAIR	Naval Air Systems Command
NPV	net present value
NRL	Naval Research Laboratory
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PDM	Programmed Data Maintenance
PEL	permissible exposure limit
PSU	The Pennsylvania State University
PTMS	PTMS Exporters and Consultants Pvt. Ltd.

ACRONYMS AND ABBREVIATIONS (continued)

ROI	return on investment
S-N	stress to number of cycles to failure
SAC	Sikorsky Aircraft Corporation
SO_2	sodium dioxide
USMC	U.S. Marine Corps
UTRC	United Technologies Research Center
UTS	ultimate tensile strength
VHN	Vicker's Hardness Number
XRD	x-ray diffraction
YS	yield strength

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1.0 EXECUTIVE SUMMARY

The U.S. Army has experienced significant corrosion problems with magnesium (Mg) 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 technology that can restore them adequately for service. The U.S. Army Research Laboratory (ARL) has developed a Cold Spray process to reclaim Mg components that shows significant improvement over existing methods. Part of this program has demonstrated and validated a Cold Spray (supersonic particle deposition) process using aluminum (Al) and/or alloys as a cost-effective, environmentally acceptable technology to provide surface protection and a repair/rebuild methodology to a variety of Mg alloy components for use on Army and Navy helicopters and advanced fixed-wing aircraft.

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. A Cold Spray demonstration facility has been established at the Fleet Readiness Center East (FRC-E) North Carolina (formerly Naval Air Depot [NADEP] Cherry Point). The original equipment manufacturer (OEM), Sikorsky Aircraft Corporation (SAC), is in the final approval stage for implementation of the Cold Spray process developed by ARL for the H-60 family (Black Hawk, Seahawk, etc.) of helicopters.

The objectives of this program were: (1) to demonstrate and validate Cold Spray (supersonic particle deposition) of Al and/or Al alloys as a cost-effective, environmentally acceptable technology to provide surface protection and a repair/rebuild methodology to a variety of Mg alloy components on Army and Navy helicopters and advanced fixed-wing aircraft; (2) establish a Cold Spray demonstration facility, FRC-E; (3) validate the Cold Spray coatings through materials and component testing as defined by stakeholders; and (4) demonstrate that Cold Spray can be used as a repair/rebuild methodology that can reclaim currently unsalvageable parts.

The Cold Spray process involves the introduction of a heated high-pressure gas such as helium (He) or nitrogen (N_2) together with 1- to 50-µm particles of a metal or alloy into a gun onto which is attached a nozzle designed such that the gas exits at supersonic velocities. The powder particles entrained in the gas flow are accelerated to velocities in the range of 200 to 3000 meters-per-second, considerably higher than what is achieved in any thermal spray process, including High Velocity Oxygen Fuel (HVOF). Because the temperature of the gas generally ranges from 0 to 800 ºC, no melting of the particles takes place, plus there is no oxidation, decomposition, or other degradation of the powder material.

Other advantages of the Cold Spray process include:

- It provides extremely dense coatings with virtually no inclusions or cracks.
- It retains properties and microstructure of initial powder particles allowing the deposition of nanostructured materials.

- It has high deposition rates, up to 30 lb/hour, equivalent or superior to other thermal spray processes.
- It yields uniform microstructure and, for alloy coatings, powder phase structure is maintained.
- Extremely thick coatings can be deposited as well as bulk material and free-standing structures/parts can be fabricated (many mm thick).
- Functionally graded coatings/bulk materials can be produced.
- Unique and exotic coatings/materials can be formed that cannot be produced by conventional techniques, such as thermal spray or ingot metallurgy because consolidation is accomplished in the solid state.
- Impact of particles on surface acts like shot peening, imparting favorable residual compressive stress.
- Residual stress in coatings is neutral or slightly compressive.
- Low heat input allows for coating broad range of materials, such as composites, including components with thin walls.
- Process involves no toxic gases, radiation or chemical reactions.
- Very localized deposition is possible, thereby eliminating most requirements for masking.

Quantitative and qualitative objectives performance objects were established for this effort by the primary stakeholders who included representatives from the Tri-Services, academia, and industry. The quantitative performance objectives were approved by Naval Air Systems Command (NAVAIR), ARL and the OEM, which was SAC.

The quantitative performance objectives involved execution of various coatings testing and evaluation techniques, as well as comprehensive materials characterization and included (1) deposition rate, (2) coating thickness uniformity, (3) microstructure, (4) hardness, (5) fatigue, (6) stress/strain, (7) residual stress, (8) uni-axial adhesion, (9) shear adhesion (10) fretting fatigue, (11) salt fog, (12) cyclic corrosion, (13) powder particle size distribution, (14) powder chemical composition.

Test results from this program indicate that Cold Spray as a repair technology for the reclamation of Mg aerospace components offers improved performance and permits the reclamation of material properties as well as dimensional restoration and improved readiness since replacements would be less frequent. In conjunction, there is an anticipated reduction in logistics costs since fewer new gearboxes would be required in the field and fewer would have to be shipped back and forth between depots and operating bases for repair. A SAC study also shows a significant potential for cost reduction by reducing the number of condemnations, but in addition to reducing cost, reducing the number of condemnations will improve operational readiness.

SAC has invested over $1 million toward the development of Cold Spray in collaboration with ARL and is planning on introducing the process for repair of H-60 sumps because it produces a superior quality repair than the current HVOF Al-12Si, permitting the reclamation of otherwise unsalvageable components. The UH-60 Main Sump Gearbox is currently repaired by SAC using an HVOF Al-12Si coating together with a bond coat. This method is not satisfactory as the HVOF coating tends to crack on insertion of Rosan fitting and does not reclaim the mechanical properties of the Mg alloy. It is expected that the use of Cold Spray coating will allow these gearboxes to be reclaimed, largely eliminating condemnations.

One of the objectives for this ESTCP effort was to establish a fully functional Cold Spray facility at FRC-E capable of performing component repair of Mg aerospace components. A crucial step towards accomplishing this objective was achieved in January 2011 when the Cold Spray system at FRC-E was used to produce a batch of Al coatings. The test results from the demonstration confirmed that the system is functioning correctly and that the operators are following the ARL Cold Spray procedure correctly. Follow-on work has been continuous with the goal of flight testing repaired parts by the end of the calendar year.

A future research area should be the investigation of structural repair using the Cold Spray process. The mechanical test results of the 6061 He coating that ARL developed in particular suggest that there is potential beyond nonstructural or cosmetic repairs using Cold Spray technology. ARL has generated preliminary data, which shows that as-Cold Sprayed 6061 Al has a higher ultimate tensile strength, yield strength, and hardness than conventional wrought 6061 Al that has been heat-treated to the T-6 condition. Advancing the technology to the point where structural repair of gearboxes and other components is possible should be a priority of the U.S. Department of Defense (DoD) science and technology community. Structural repair capability would have a significant impact on DoD cost savings and war fighter capability.

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2.0 INTRODUCTION

2.1 BACKGROUND

Mg alloys are being increasingly used in the fabrication of components in advanced aircraft because of their good mechanical properties, low density, and high strength-to-weight characteristics. Examples include the large gearbox and transmission housing castings used in helicopters. Despite the obvious advantages of using these types of alloys on aircraft, Mg is a very active metal electrochemically and is anodic to all other structural metals. Therefore, Mg will corrode preferentially when coupled with virtually any other metal in the presence of an electrolyte or corrosive medium. Mg alloys are also very susceptible to surface damage due to impact such as during handling, assembly, or repair. The alloys must therefore be surface treated to prevent corrosion and oxidation and to increase surface hardness to resist impact damage.

For OEMs such as SAC the standard practice is to hard anodize the surface using a process designated Dow 17, followed by application of a phenolic resin (one version is designated "Rockhard"). For non-mating surfaces, multiple coats of chromate epoxy polyamide primer followed by multiple coats of epoxy paint are applied. For mating surfaces, no primer or paint is used, but other types of sealant compounds are applied. In repair/overhaul facilities, the standard practice is to use a chromate conversion coating, MIL-M-3171, followed by the Rockhard and the chromated primer and paint for non-mating surfaces and a sealant compound for mating surfaces. The intent of this demonstration is to investigate the Cold Spray coating in a typical operation with the standard finishing operation surface treatments and also investigate the potential of the Cold Spray coating to be used without these surface treatments.

Even with the multiple surface treatments involving anodization or conversion coating followed by application of resin, primer, and paint, the Mg alloy components are still subject to extensive corrosion and damage in service, resulting in significant unscheduled maintenance actions and high replacement costs. In 2001, NADEP Cherry Point, currently FRC-E, conducted an extensive review of the cost of corrosion on the H-60 main transmission. In 2000, 23 main modules were replaced and there were 23 unscheduled maintenance actions, at a total cost of \$8.5 million. In 1999, 30 main modules were replaced and there were 39 unscheduled maintenance actions, at a total cost of \$6.3 million. For the decade of 1991-2000, the total estimated cost for both unscheduled maintenance and module replacement was \$41 million. In addition to cost, readiness was greatly impacted because most unscheduled maintenance had to be performed by Depot Field Support Teams.

Repair of Army helicopter components, including those fabricated from Mg alloys, is performed by Corpus Christi Army Depot (CCAD) or by SAC. In 2003, the Army compiled data on repair and replacement of components. For example, the Army spent approximately \$763,000 to replace the H-60 Main Transmission and Tail Rotor Gearbox Housing Assemblies. These purchases represented only those aircraft that were overhauled and repaired by SAC. It is anticipated that a similar cost was incurred for repairs performed at CCAD. The total cost to the Army each year for replacement and repair of Mg helicopter components is approximately \$8 million.

Figure 1 is a schematic of the main transmission housing for the H-60 helicopter showing the areas most susceptible to corrosion. Because of the localized nature of the corrosion, surface treatments intended to mitigate the problem would have to be applied only in these specific areas. A combination of galvanic and crevice corrosion is the primary corrosion mechanism for Mg alloy gearboxes. Water and salt spray tend to accumulate in the recessed holes around the bolts, and galvanic corrosion occurs between the cadmium (Cd)-plated bolt head and the surrounding Mg alloy, as well as between the shank of the bolt and the inner diameter (ID) of the hole. In addition, gearboxes usually have Cd-plated steel studs and bushings press fitted into them, and galvanic corrosion occurs around these areas (see Figures 2 and 3). In particular, Rosan inserts are frequently used to hold bushings, fittings, and threaded fasteners into housings (see Figure 4). These fittings are designed to be press fitted into the housing, where their teeth bite into the Mg alloy and create a high degree of plastic deformation. Any coating or surface treatment that is applied to the Mg at repair facilities must be able to withstand the insertion. When corrosion becomes excessive, material is removed and an Al shim is glued in place of the missing Mg alloy. This can be done up to a thickness of 0.100 inches. Obviously, these shims cannot carry load and thus lead to weakening of the structure.

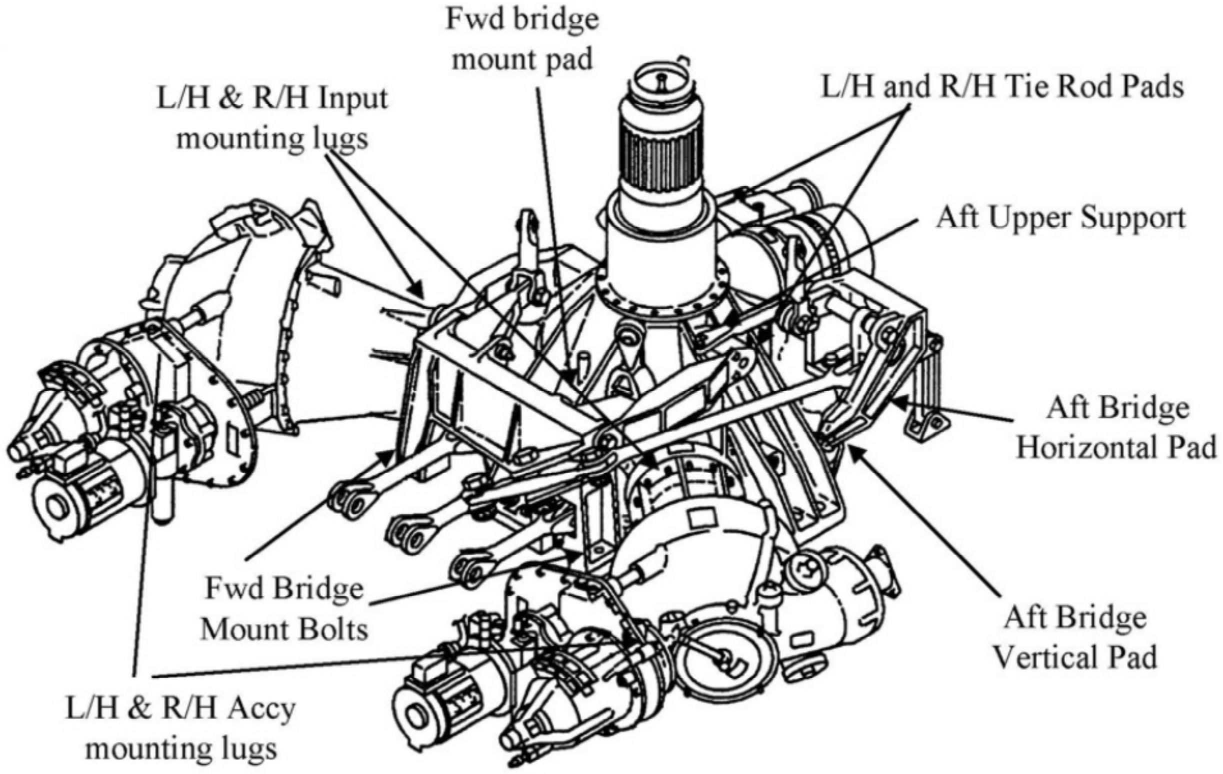

Figure 1. Schematic of an H-60 Main Transmission Housing showing areas most susceptible to corrosion.

Most of the corrosion occurs at attachment points where a dissimilar metal is in contact with the coated Mg component. This includes flanges, mounting pads, tie rods, lugs and mounting bolts.

Figure 2. Corrosion around a stud and hole on a helicopter Mg gearbox housing.
(Courtesy Robert Kestler, FRC-E)

Figure 3. Corrosion around an insert on a helicopter Mg gearbox housing.
(Courtesy Robert Kestler, FRC-E)

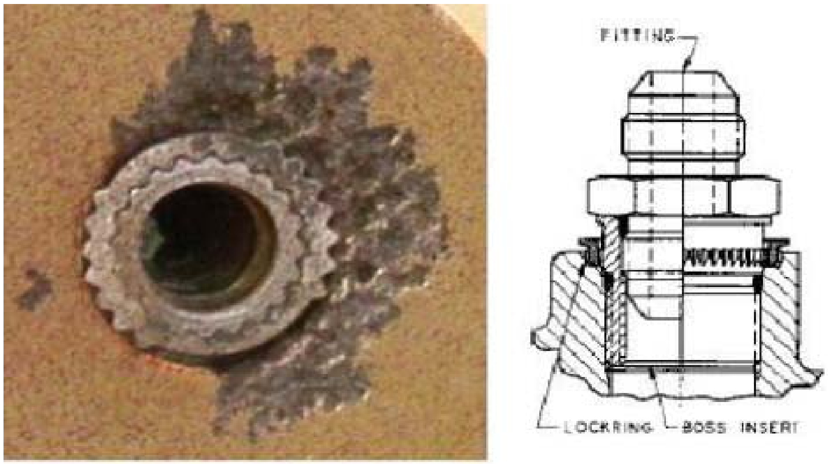

Figure 4. Rosan insert: corrosion around insert on a helicopter Mg gearbox housing (left) and cross section of insert with fitting (right).
(Courtesy Robert Kestler, FRC-E)

2.2 OBJECTIVES OF DEMONSTRATION

The objectives of the demonstration were to demonstrate and validate supersonic Cold Spray of Al and Al alloys as a cost-effective, environmentally acceptable technology to provide surface protection and a repair/rebuild methodology to a variety of Mg alloy components on Army and Navy helicopters and advanced fixed-wing aircraft; establish a Cold Spray demonstration facility at FRC-E (formerly NADEP Cherry Point) and validate the Cold Spray coatings through materials and component testing as defined by stakeholders; and demonstrate that Cold Spray can be used as a repair/rebuild methodology that can reclaim currently nonrepairable parts.

2.3 REGULATORY DRIVERS

By far the largest regulatory cost driver for finishing operations that involve the use of chromates such as the Dow 17 process is the hexavalent chromium (hex-Cr) permissible exposure limit (PEL) as established by the Occupational Safety and Health Administration (OSHA). For many years a lowering of the PEL was expected, but it was only in 2004 that the agency began the process to issue a new PEL as a result of a lawsuit filed in 2002 by a citizens group and union that petitioned OSHA to issue a lower PEL, and a subsequent ruling by a Federal District Court upholding the petition. The court ruling required OSHA to publish a new draft hex-Cr PEL in the Federal Register no later than October 2004. On October 4, OSHA proposed a new PEL of 1 $\mu g/m^3$ with a 0.5 $\mu g/m^3$ action level, which represented a significant reduction from the then PEL of 52 $\mu g/m^3$. In addition to the reduction in the hex-Cr PEL, the rule also included provisions for employee protection such as preferred methods for controlling exposure, respiratory protection, protective work clothing and equipment, hygiene areas and practices, medical surveillance, hazard communication, and record-keeping. The expected one-time compliance costs determined by OSHA in all industries, including electroplating, welding, painting, and chromate production, was $226 million, although the surface finishing industry expected that the costs would be substantially higher. There would also be increased annual recurring costs associated with health monitoring, record-keeping, etc. On February 28, 2006, the final rule was promulgated at 5 $\mu g/m^3$, with an action level of 2.5 $\mu g/m^3$. While this is a factor of five higher than the initial proposed PEL, it will effectively require that facilities maintain a level close to 1 $\mu g/m^3$ in order to stay below the action level. Therefore, the cost estimates at the originally proposed lower limits are still fairly accurate as ballpark figures. Using cost estimates performed by the Navy in 1995, it is clear that the additional annual costs to DoD will be at least several million dollars [1].

3.0 DEMONSTRATION TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

The technology associated with very-high-velocity, low-temperature spray deposition of coatings falls under the terminology of High Velocity Particle Consolidation, cold gas-dynamic spraying, or Cold Spray, as it is referred to in this demonstration plan. This technique was first demonstrated in the mid-1980s at the Institute of Theoretical and Applied Mechanics in Russia. They were able to produce coatings by injecting solid metal particles into a wind tunnel gas stream accelerated to high velocities. Research in the U.S. began in 1994 under a project sponsored by the National Center for Manufacturing Science. The principal organizations conducting research and development work on the technology in the initial years were the Applied Research Laboratory at The Pennsylvania State University (PSU) and Sandia National Laboratories. At the same time, several companies initiated the development of Cold Spray systems and these are now available commercially.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The Cold Spray process involves the introduction of a heated high-pressure gas such as He or N_2 together with 1 to 50 μm particles of a metal or alloy into a gun onto which is attached a nozzle designed such that the gas exits at supersonic velocities. The powder particles entrained in the gas flow are accelerated to velocities in the range of 200 to 3000 meters-per-second, considerably higher than what are achieved in any thermal spray process, including HVOF. Figure 5 is a schematic of the Cold Spray process. Because the temperature of the gas generally ranges from -10 to 1000 ºC, no melting of the particles takes place, plus there is no oxidation, decomposition, or other degradation of the powder material.

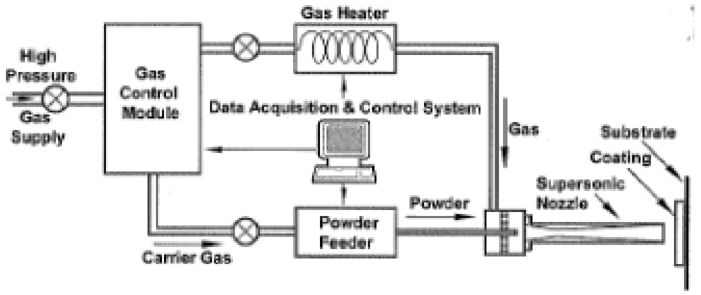

Figure 5. Schematic of the Cold Spray Process.

Other advantages of the Cold Spray process include:

- Extremely dense coatings with virtually no inclusions or cracks.
- Retains properties and microstructure of initial powder particles allowing the deposition of nanostructured materials.
- High deposition rates, up to 30 lb/hour, equivalent or superior to other thermal spray processes.

- Uniform microstructure and, for alloy coatings, powder phase structure is maintained.
- Extremely thick coatings can be deposited as well as bulk material and free-standing structures/parts can be fabricated (many mm thick).
- Functionally graded coatings/bulk materials can be produced.
- Unique and exotic coatings/materials can be formed that cannot be produced by conventional techniques, such as thermal spray or ingot metallurgy because consolidation is accomplished in the solid state.
- Impact of particles on surface acts like shot peening, imparting favorable residual compressive stress.
- Residual stress in coatings is neutral or slightly compressive.
- Low heat input allows for coating broad range of materials, such as composites, including components with thin walls.
- Process involves no toxic gases, radiation or chemical reactions.
- Very localized deposition possible, thereby eliminating most requirements for masking.

4.0 PERFORMANCE OBJECTIVES

The quantitative and qualitative objectives performance objects for this effort are provided in Tables 1 and 2, respectively. The quantitative performance objectives were set by NAVAIR and ARL after reviewing the past performance of the Cold Spray process. For example, the minimal adhesion requirement was based on results from ARL's collaboration with the Australian Defense Science and Technology Organization (DSTO) [2].

The quantitative performance objectives are based on the Joint Test Protocol (JTP). The JTP was designed to define the upper and lower technical capabilities of the Cold Spray repair process. The Cold Spray process is significantly different from other established Mg gearbox coating systems such as Rockhard and Dow 17. Both Rockhard and Dow 17 are thin corrosion protection coatings which can be considered to have negligible mechanical strength or thickness compared to the Mg gearbox. Cold Spray, on the other hand, will be applied to damaged areas of the gearboxes with thicknesses ranging from a few mils to approximately one-half of an inch. A thorough and quantitative evaluation of mechanical performance of the Cold Spray repair was therefore deemed necessary during the initial planning stages of the program. Corrosion performance was also a necessary benchmark to establish, so several quantitative and qualitative corrosion tests relevant to Mg gearbox castings were also included as performance objectives. Appearance and porosity are included as qualitative performance objectives. Both of these objectives fall under the regime of quality control since they can be evaluated in a production environment with relative ease.

Table 1. Quantitative performance objectives [3-9].

Performance Objective	Data Requirements	Success Criteria	Results
Deposition rate	Coating thickness measurement to an accuracy of ±0.0005 inch	Ability to deposit coatings at a rate of at least 0.005 inches per hour with coating quality such that they pass the acceptance criteria specified in the JTP	Passed
Coating thickness uniformity	Coating thickness measurement to an accuracy of ±0.0005 inch	Cold Spray coating thickness shall be uniform within ±20% for deposition onto various surfaces that simulate Mg alloy components.	Passed
Microstructure	Examined with optical microscopy	A uniform microstructure, especially for alloy coatings, must be achieved	Passed
Microhardness	American Society for Testing and Materials (ASTM) E384 - 10e2	Vicker’s Microhardness of as-deposited coatings shall be no less than 50 Vicker’s Hardness Number (VHN).	Passed
Fatigue	R.R. Moore High Speed Rotating Beam Rotating	No debit as compared to baseline noncoated specimens as specified in the JTP	Passed
Stress/strain testing; ductility	Microtensile testing as defined in Section 6.0	Monotonic stress/strain testing shall be conducted in a standard tensile tester. This will evaluate strain tolerance.	Passed
Residual stress	X-ray diffraction (XRD)	Applied coating must be in either a compressive or neutral stress state.	Passed
Adhesion in tension	ASTM C633	Adhesion must meet or exceed 8.0 ksi.	Passed
Shear adhesion	MIL-SPEC MIL-J-24445A	Adhesion must meet or exceed 8.0 ksi.	Passed
Fretting fatigue	As defined in Section 6.0	No debit as compared to baseline noncoated specimens as specified in the JTP	Passed- Coating system dependent- see Section 7.0
Salt spray corrosion	ASTM B117	Minimum of 336 hours exposure without penetration of salt spray through coating to the substrate as described in the JTP	Passed
Cyclic corrosion	General Motors (GM) 9540 Specification	Minimum of 500 hours exposure without penetration of salt spray through coating to the substrate as described in the JTP	Passed

ksi = kips per square inch

Table 2. Qualitative performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Appearance	Visual inspection	Coatings are continuous, smooth, adherent, uniform in appearance, free from blisters, pits, nodules and other apparent defects.	Passed
Impact testing	Visual inspection as per ASTM D5420-10	Coatings must not delaminate from the substrate.	Passed
Porosity	Examined with optical microscopy	Porosity of Cold Spray coatings should be less than 1%.	Passed
Beach corrosion	As specified in Section 6.0	No observable penetration or pitting through the coating and into the Mg	Ongoing
Galvanic corrosion	ASTM G71-81	No defined criteria. Used for comparison to High Velocity Oxygen Fuel (HVOF) Al-12 Si baseline specimen.	Passed
Crevice corrosion	ASTM G78	No observable corrosion product	Passed

5.0 SITE DESCRIPTION

5.1 TEST FACILITIES

The Navy's FRC-E was selected as the site for demonstration of the Cold Spray coating technology. One of the reasons for selecting a Navy site was that out of approximately 150 technology needs related to environment, safety, and occupational health issues, NAVAIR ranked requirements for new surface treatment technologies for Mg alloy components as number 12 (high priority). In addition, FRC-E management and H-60, H-53, and H-46 program offices expressed a high level of interest in reducing costs associated with degradation of Mg components, especially gearbox and transmission housings. FRC-E is the only Navy facility that overhauls these types of helicopter components.

FRC-E personnel are very familiar with the technology of thermal spray and the operation of various types of thermal spray systems in a production environment. They significantly participated in the ESTCP project related to replacement of hard chrome plating on helicopter dynamic components using HVOF thermal spray coatings.

FRC-E has a thermal spray booth complete with robot, exhaust hood, and particle filtration system available for Cold Spray system installation.

Finally, Cold Spray technology is being considered in the overall NAVAIR strategy to reduce or eliminate hex-Cr processes from Mg alloy components.

5.2 PRESENT OPERATIONS

The workload at FRC-E has expanded significantly since its early beginnings, but the aircraft program continues to be the backbone of the Center's production. When an aircraft is received at the Center for repair or overhaul, its condition is examined and evaluated to determine how much repair work must be done. Based on this evaluation, skilled artisans, mechanics, and technicians are able to disassemble the aircraft, fix the reported problems, and return the newly repaired airplane to action.

FRC-E has the capabilities to perform major airframe modifications and repair for a wide variety of aircraft including:

- **V/STOL:** AV-8B Harrier and V-22 Osprey
- **Rotary Wing:** AH-1 Cobra, UH-1 Huey, H-46 Sea Knight, H-53D Sea Stallion H-53E Super Stallion, MH-53J Pave Low
- **In-service repair:** EA-6B Prowler, H-2 Sea Sprite, H-3 Sea King, H-60 Seahawk, C-130 Hercules
- **Unmanned aerial vehicle/remotely piloted vehicle:** Assigned Depot Maintenance Manager for Logistics

The Center also repairs, overhauls, assembles and tests a wide range of aircraft gas turbine engines. As engines and parts are removed from the aircraft, they are routed to the various in-house shops for maintenance. In addition, various engines from the fleet supply system are also refurbished at the Center before they are returned to action.

Examples of the engines repaired at the Center include:

- T58 used in the H-46 Sea Knight and the SH-3 Sea King helicopters
- T400, which powers the UH-1 Huey and AH-1 Cobra attack helicopters
- F402 used in the AV-8 Harrier
- T64, which powers the CH-53 Sea Stallion helicopter.

The Center also is establishing capability for the T700 engine, which is used on several aircraft to include various models of the H-1, H-60, and H-64 helicopters.

It is expected that a Cold Spray repair procedure for Mg would not only benefit the platforms repaired at Cherry Point but could also be eventually implemented at depots all across DoD. Mg gearboxes are used in a large number of helicopter programs as well as some winged designs. Information on programs, types of applications for which Mg alloys are used, the alloy designation, and currently used protective coatings for Navy, Army, and Marine Corps is given in Tables 3 and 4. Similar information for fixed-wing programs that utilize Mg components is given in Table 5. These tables help shed light on the large-scale use of Mg gearboxes within DoD.

Table 3. U.S. Navy and Army helicopter programs.

Aircraft Program	Mg Applications	Mg Alloys	Coating Pretreatment	Protective Coatings (Internal & External)	Cure Schedule for Resin Coatings	Applicable Technical References
CH-53D CH-53E MH-53E (Navy & USMC)	Transmission Gearboxes	AZ91C & AZ91E	SAE AMS-M-3171 Type VIII (Iridite 15); SAE AMS-M-3171 Type VI used for touch-up only (Dow 19)	Low Temp Rockhard, P/N 985-111-002, on internal and external surfaces except machined bores. Dry film thickness 0.5-3.0 mils on cast and 0.5-1.2 mils on machined/mating surfaces (two-three coats). External surfaces are coated with one coat of MIL-PRF-85582 Type I Class C1 Epoxy Primer and two coats of MIL-PRF-85285 Type I Color 16081. External surfaces of Cd-plated steel bolts and external fasteners are cap-sealed with AMS-S-81733 Corrosion Inhibiting Sealant.	Pre-bake at 120-180° F. Low Temp Rockhard cured at 265 + 5° F. 30 minutes bake between coats and 4 hour final bake (after part reaches temperature).	Applicable technical gearbox manuals (ex. A1-866PA-260-950, Depot Maintenance Main Gearbox Assy)
SH-60 (Navy)	Transmission Gearboxes	ZE41A				
HH-1N (Navy – Search & Rescue)	Transmission Gearboxes	AZ91C				
UH-60 (Army)	Transmission Gearboxes	Mostly ZE41A, Some AZ91C	SAE AMS-M-3171 Type III (Dow 7)	Rockhard 961-450-002, internal and external surfaces. Dry film thickness 3.0 mils max (3 coats, ~0.5 mils/coat). 0.5-1.2 mils on machined surfaces. External, 2 coats MIL-PRF-23377 Type II Class C (0.3-0.6 mils/coat, 1 coat for machined areas); 3 coats MIL-C-46168 Type II (0.9-1.5 mils/coat). AMS-S-8802 Sealant.	Final bake 375° F max.	
AH-64 (Army)	Gearboxes	Mostly ZE41A, Some QE22A	SAE AMS-M-3171 Type III (Dow 7)	External, 2 coats MIL-PRF-23377 Type II Class C (1.2-1.8 mils, 1 coat for machined areas); 2 coats MIL-C-46168 Type II (1.		
CH-47 (Army)	Gearboxes	Mostly ZE41A, Some AZ91C 2 components – AZ80A/AZ31B	SAE AMS-M-3171 Type III (Dow 7)	MIL-R-3043, internal surfaces (0.6-1.0 mils). Brush resin, air dry. External, 2 coats MIL-PRF-23377 Type II Class C (1.2-1.8 mils, 1 coat for machined areas – 0.6-0.9 mils); 2 coats MIL-PRF-22750 (1.7-2.5 mils). Dry film thickness primer/topcoat min. 4 mils. Top of sump 2 coats MIL-PRF-23377 Type II Class C (0.6-0.9 mils), 2 coats MIL-PRF-22750 (1.5-2.0 mils total). AMS-S-8802 Sealant.	Bake at 325+5° F for 30 minutes.	
New CH-53	Gearboxes	Elektron 21 (EV31)		Not yet defined		

USMC = U.S. Marine Corps

Table 4. U.S. Marine Corps helicopter programs.

Aircraft Program	Mg Applications	Mg Alloys	Coating Pretreatment	Protective Coatings (Internal & External)	Cure Schedule for Resin Coatings	Applicable Technical References
CH-46E (USMC)	Transmission Gearboxes	AZ91C ZE41A	SAE AMS-M-3171 Type VIII; AMS-M-3171 Type VI used for touch-up only	MIL-R-3043 Permanent Resin Coating on internal surfaces except machined bores. External surfaces are coated with one coat of MIL-PRF-85582 Type I Class C1 Epoxy Primer and two coats of MIL-PRF-85285 Type I Color 16081. External surfaces of Cd-plated steel bolts and external fasteners are cap-sealed with AMS-S-81733 Corrosion Inhibiting Sealant.	MIL-R-3043 cured at 325+5° F for 30 minutes (after part reaches temperature)	MIL-C-5056
AH-1W (USMC)	Transmission Gearboxes	Mostly AZ91C; ZE41A (is used in some main transmission cases and combining gearboxes)		H-1 variants are Dow 7 conversion coated (AMS-M-3171 Type III) at Bell Helicopter. Protective coating is 2 coats of MIL-PRF-23377 Type I Class C2 epoxy primer and MIL-PRF-85285 topcoat. They are never anodized, even from OEM.		
UH-1Y (USMC) .	Transmission Gearboxes	Mostly ZE41A; Some internal AZ91E castings.				
AH-1Z (USMC)	Transmission Gearboxes	Mostly ZE41A. Reusing many of the ZE41A Combining Gearboxes from the AH-1W. Some internal AZ91E castings.				

USMC = U.S. Marine Corps

Table 5. Fixed wing programs.

Aircraft Program	Mg Applications	Mg Alloys	Coating Pretreatment	Protective Coatings (Internal & External)	Cure Schedule for Resin Coatings	Applicable Technical References
P-3 (Navy)	Prop Pump Housings	EZ33A	SAE AMS-M-3171 Type VIII (Iridite 15); SAE AMS-M-3171 Type VI used for touch-up only (Dow 19)	MIL-R-3043 Permanent Resin Coating on internal and external surfaces, except machined bores. In addition, one coat of MIL-PRF-85582 Type I Class C1 Epoxy Primer and two coats of MIL-PRF-85285 Type I Color 37038 are applied to external surfaces.	MIL-R-3043 cured at 325+5°F for 30 minutes (after part reaches temperature)	MIL-C-5056
F-35	PTMS generator	WE43B-T6	None	Prime and paint, some to use Tagnite		
TF33 GTE (USAF)	Gearboxes	AZ92-T6	Iridite	Varnish, epoxy primer, epoxy enamel		
F101 GTE (USAF)	Gearboxes	HC32A-T5	Iridite	Varnish, epoxy primer, epoxy enamel		
F118 GTE (USAF)	Gearboxes	QE22A-T6	Iridite	Varnish, epoxy primer, epoxy enamel		

PTMS = PTMS Exporters and Consultants Pvt. Ltd.

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6.0 TEST DESIGN

This chapter focuses on the JTP developed for this effort. There was a significant amount of laboratory and experimental work completed for this effort. This section is only an abbreviated summary of the test design presented in the ESTCP Final Report. Readers should reference the Final Report for more specific details on test methodology and the engineering origins of this effort.

The scale of this ESTCP effort is immense. There are two main end users for the technology (FRC-E and SAC) as well as a plethora of stakeholders, partners, and subcontractors (Army, Navy, PSU, UTRC, etc.). Therefore, an overall program plan (JTP) was necessary to structure the program. Additionally, all the stakeholders met at the beginning of the project and identified substrate materials of interest, coating compositions of interest, and the commercially available Cold Spray equipment to use for the actual implementation.

6.1 JTP DESIGN

As had been done previously with the hard chrome plating replacement projects managed by the Hard Chrome Action Team, a preliminary JTP was prepared and distributed to all potential stakeholders and then a meeting was held to identify and specify the exact materials tests required to qualify the Cold Spray Al alloy coatings. Under a contract from the Army, Concurrent Technologies Corporation developed a preliminary JTP titled “JTP for Validation of Corrosion Protection for Mg Alloys.” In addition to NAVAIR and ARL, the development of the JTP involved the input from a variety of individuals from the U.S. Army Aviation and Missile Command; U.S. Army Program Executive Office, Aviation; U.S. Army Corrosion Office; and SAC. The JTP was not directed towards qualification of Al alloy coatings but was meant to be generic for qualification of any type of corrosion protection scheme. This preliminary JTP formed the basis of the JTP that was prepared. A stakeholders meeting was held that involved these same organizations plus additional ones from the Navy, other OEMs, PSU, and the Australian organizations participating in the project. Contact information for the main stakeholders and principal investigators is provided in the Appendix. Materials test requirements were developed and these were inserted into the preliminary JTP to produce a final JTP for execution.

Table 6 provides some of the more common alloys used on DoD platforms. A single lot of each of these alloys was purchased to make test specimens for this JTP. AZ91C and ZE41A are the most widely used alloys in legacy systems. EV31 is used on some F-35 housings.

Table 6. Substrates and their heat treat conditions.

Material	Tensile Strength	Notes
AZ91C-T6	34 ksi	Legacy systems
ZE41A-T5	29 ksi	Legacy systems
EV31-T6	36 ksi	F-35

Candidate coating materials initially investigated include commercially pure Al (CP-Al), Al-12Si, 5056 Al alloy, 5356 Al alloy, 6061 Al alloy, and high purity Al (HP-Al). CP-Al and 6061 were down selected as final coating materials. These two compositions were selected based on compatibility with the process as well as commercial availability. CP-Al Cold Spray coatings provide good salt fog protection while also having hardness equal to or slightly lower than ZE41A-T5 [10]. The powder supplier used for the project is Valimet, Inc. of Stockton, CA. The specific powder is referred to as H-12 commercially pure Al. H-12 refers to a mean powder particle size on the order of 12 µm. This powder was previously used in the ARL-DSTO project.

The 6061 powder was also procured from Valimet, Inc. The specified particle size cut is -325 mesh, which corresponds to a maximum particle size of approximately 44 µm. The 6061 powder provides an advantage over pure Al in terms of hardness and strength. A downside of 6061 powder is a higher cost.

ARL purchased a Cold Gas technology, GmbH (CGT) Cold Spray system from Ampfing in Germany in order to execute the ESTCP demonstration. The specific model used is the Kinetiks 4000. A photo of the Cold Spray gun is shown in Figure 6.

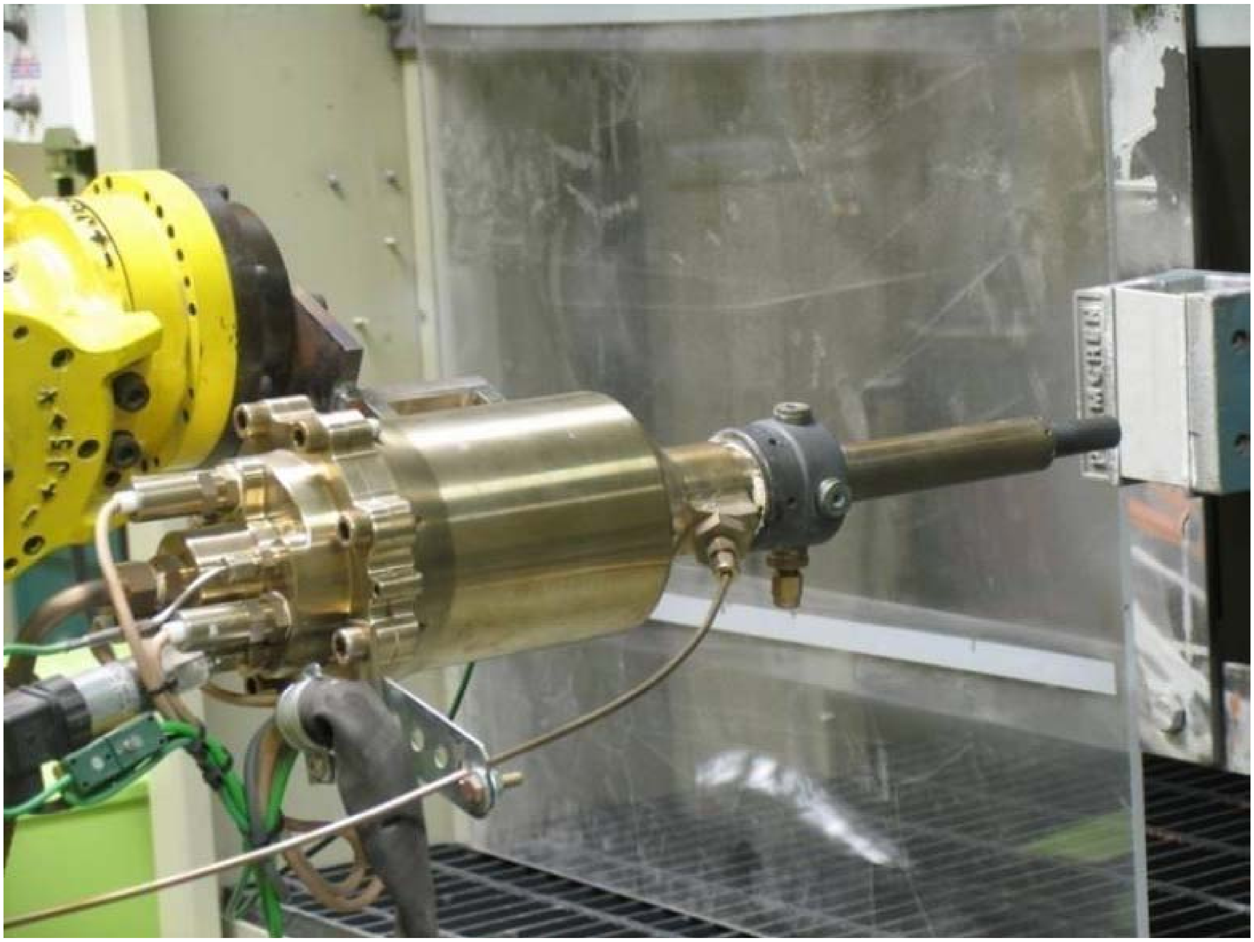

Figure 6. CGT Kinetiks 4000 gun heater.

The surface preparation for all samples was an abrasive blast followed by a solvent rinse. The abrasive blast equipment was a Port-A-Blast. This equipment does not recycle the abrasive. The use of virgin abrasive was necessary to minimize the embedding of corrosive materials such as iron into the Mg substrate. It has been proven that some of these containments are detrimental to corrosion resistance of the Mg substrate. The abrasive media used for the project was a 60 grit Al oxide from McMaster-Carr. This media was sprayed at 100 psi pressure at a 45° stand-off angles. The stand-off distance was between 4 to 6 inches away from the surface of the part. The solvent rinse was either methanol or ethanol.

6.2 EXPERIMENTS OUTLINED IN THE JTP

Mechanical integrity of the coatings was evaluated using the tests listed in Table 7. The mechanical tests were primarily conducted by the ARL at Aberdeen Proving Ground, MD, or through a contract with Westmoreland Mechanical Testing and Research, Inc. TEC, Inc. in Nashville, TN, performed the XRD residual stress analysis. SAC participated in evaluating the machining of the coatings. UTRC performed the fretting fatigue testing and tensile testing of the 6061 coatings. Specifics procedures for each test are provided in the Final Report.

Table 7. Tests for evaluating mechanical integrity of Cold Spray coatings.

Mechanical Test	Specification	Test Location
Adhesion or cohesion strength of thermal spray coatings	ASTM C633	ARL
Triple lug shear test	MIL-J-24445A	ARL
Vickers Micro-Hardness	ASTM E384	ARL
XRD residual stress	N/A	TEC
Machining evaluation rods	N/A	SAC
Impact	ASTM D5420	Westmoreland
R.R. Moore rotating beam fatigue	N/A	Westmoreland
Fretting fatigue	N/A	UTRC
Tensile testing	N/A	Westmoreland/UTRC

A significant number of laboratory and field corrosion tests were included in this study. Corrosion tests were included to help identify any potential issues such as galvanic corrosion or incompatibly with specific environments. For example, modified sodium dioxide (SO_2) testing was included because there was interest from the Joint Strike Fighter community to test these coatings in a salt water and jet exhaust environment. However, poor performance in the Modified SO_2 does not necessarily mean the same coating and substrate system would perform poorly in a different environment such as the interior of the H-60 main gearbox sump. The corrosion tests are therefore intended to provide qualitative engineering data to help in final decision making regarding implementing the coating systems in specific applications. These tests should not be considered a sole method to qualify of reject a particular coating and substrate system. Additionally, it is well known that correlating laboratory corrosion testing to real world performance is difficult. For reference, all coated test specimens were compared against uncoated Mg in order to establish a baseline. The corrosion tests included in this effort and the test location are provided in Table 8.

Table 8. Corrosion tests included in JTP.

Corrosion Tests	Specification	Test Location
Unscribed salt spray (fog)	ASTM B117	PSU and ARL
Scribed salt spray (fog)	ASTM B117	PSU
Modified SO_2 salt spray (fog)	ASTM G85 Annex 4	NAVAIR
Crevice corrosion	ASTM G78-01	PSU
Galvanic corrosion	ASTM G71	PSU
Cyclic corrosion	GM9540	PSU
Beach corrosion	N/A	NAVAIR

7.0 PERFORMANCE ASSESSMENT

7.1 RESULTS FROM JTP LABORATORY TESTS

All JTP laboratory tests were completed with the optimized coating parameters. All the coating systems exceed adhesion strength of 8000 PSI. The Triple Lug Shear test results are graphed in Figure 7. All the coating and substrate combinations tested achieved the 8.0 ksi minimum adhesion except for the CP-Al N_2 coating on ZE41A-T5 (Table 10). This coating had an average adhesion of 7.4 ksi. It is suggested that component specific adhesion requirements first be identified before implementing a repair of ZE41A-T5 with CP-Al N_2. It should be noted, however, that a shear adhesion value of 7.4 ksi represents a fairly robust coating-substrate bond.

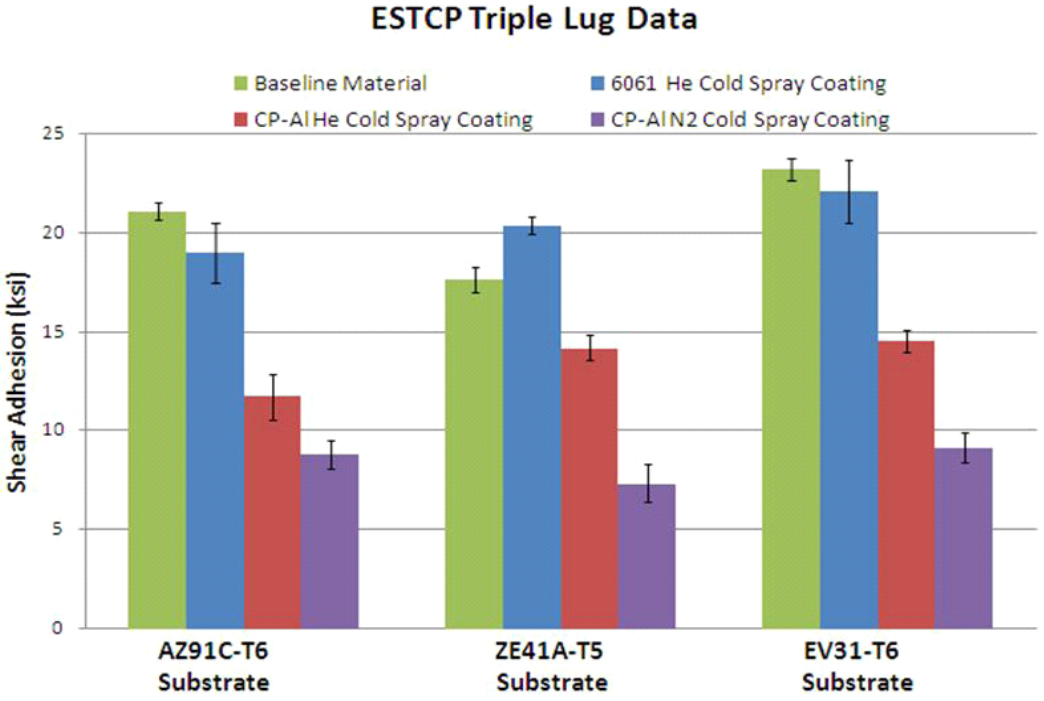

Figure 7. Triple lug shear adhesion data.

All the 6061 He coatings showed very high adhesion on the Mg alloys. The average adhesive strength of the 6061 He coating on ZE41A-T5 actually exceeded the average strength of the base line ZE41A-T5 samples. Correspondingly, seven of the 12 6061 lugs on the ZE41A-T5 broke off by fracturing material well beneath the coating-substrate interface. This is a positive indication that structural repair could be possible with the 6061 He coating since the weakest point is no longer at the coating interface. All other coating lugs failed by shearing cleanly off at the substrate interface.

The microhardess results for all three coatings exceeded the minimum hardness requirement of 50 VHN (Table 9). Additionally, the difference in the hardness of the CP-Al N_2 and CP-Al He is attributed to the greater degree of work hardening in the CP-Al He coating caused by higher particle impact velocities. A model relating particle velocity to work hardening was developed (Figure 8). The model correlated well with the measured VHN. The results are published in Modeling and Simulation in Materials Science and Engineering [12].

Table 9. Microhardness of the three coating systems.

Coating System	Vickers Microhardness (VHN)	Standard Deviation (VHN)	95% Confidence Interval (VHN)	Pass/Fail for Non-Structural Applications
CP-Al N_2	61	1	0.9	Yes
CP-Al He	68	1	1	Yes
6061 He	105	2	2	Yes

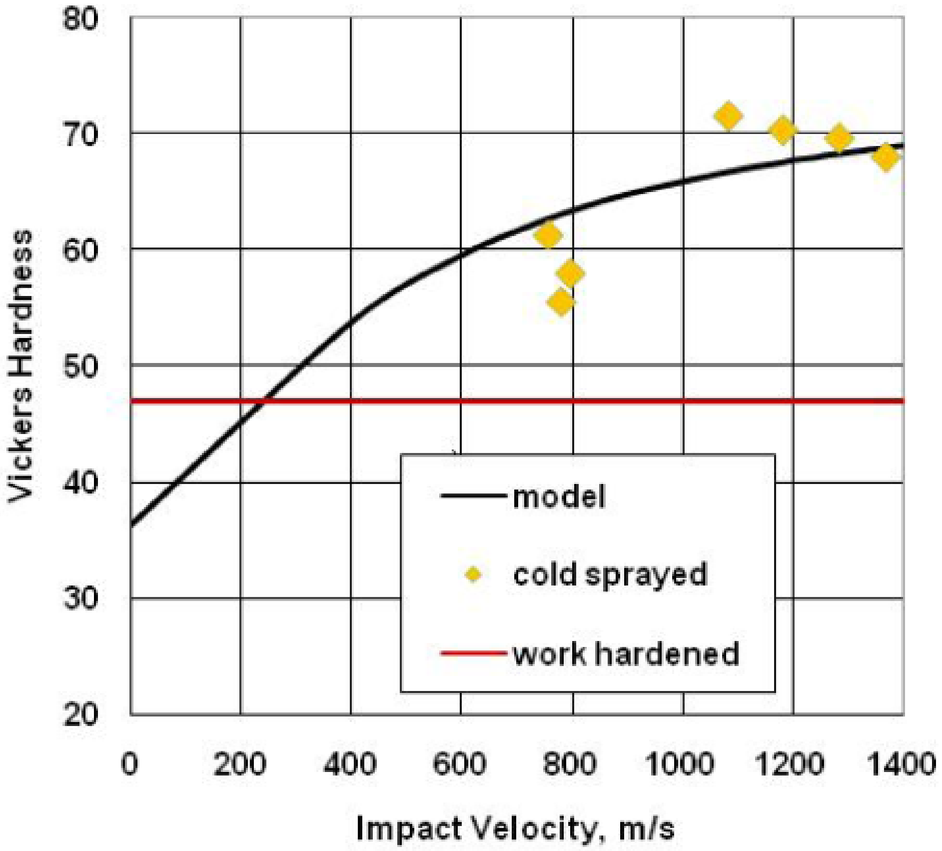

Figure 8. Model of VHN versus impact velocity for CP-Al Cold Spray coatings [12].

All the XRD residual stress measurements showed that the coating was in a compressive stress state and that the substrate was also in a compressive state just below the surface. This is an ideal scenario for these repair coatings since compressive stress impede crack growth. Additionally, the compressive stress beneath the surface is ideal since the corresponding tensile stresses are not located near the coating interface.

The results from the machining evaluation rod study are qualitative. Feedback from SAC as well as ARL's own machinist indicated the 6061 coating was much easier to machine than either CP-Al or HP-Al. This is attributed primarily to the hardness of the coatings. The micrograph in Figure 9 shows a 6061 He coating on a ZE41A-T5 rod.

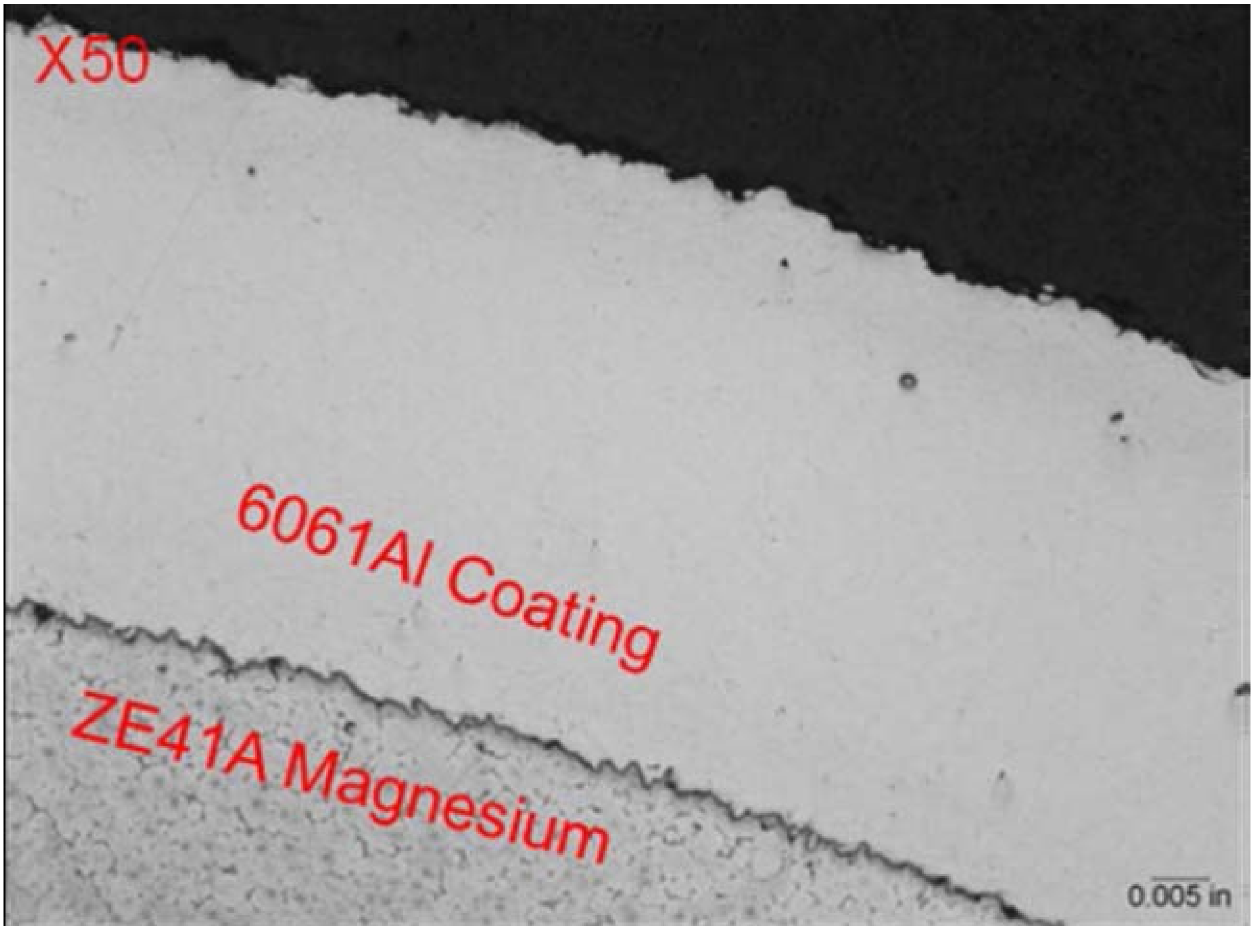

Figure 9. Optical micrograph showing a 6061 He coating on a ZE41A-T5 rod.
(Micrograph courtesy of SAC)

The tensile tests for the CP-Al N_2 coating and the 6061 He coating both passed the requirements for the nonstructural repair (Table 10). The ultimate tensile strength (UTS) of the coated specimens slightly exceeded the performance of all three uncoated alloys. This indicates that the coatings could be bearing a small amount of load during testing. Follow-up testing to evaluate elastic modulus, and yield strength (YS) of CP-Al N_2 is suggested.

Table 10. Results for tensile testing.

Substrate	Coating System	Pass/Fail for Non-Structural Applications	Potential for Structural Repair Applications
ZE41A-T5	CP-Al N_2	Pass	No
AZ91C-T6	CP-Al N_2	Pass	No
EV31-T6	CP-Al N_2	Pass	No
N/A	6061 He	Pass	Yes
N/A	6061 He post in-process anneal	Pass	Yes

The 6061 He micro-tensile testing showed that this coating system has very high strength in the as-Cold Sprayed condition (Figure 10). The YS and the UTS of the Cold Spray deposit actually exceed the properties of wrought 6061-T6 [11]. The primary strengthening mechanism is most likely work hardening since the elongation at failure (%EL) is only 3%. However, 3%EL is in line with cast Mg alloys [10-11]. The %EL increased to approximately 17% after the in process annealing. The YS and UTS dropped to values typical of wrought 6061 with T4 tempering. Both the as-deposited and in-process annealed data indicate that there is potential for structurally repairing these Mg alloys with this Cold Spray coating.

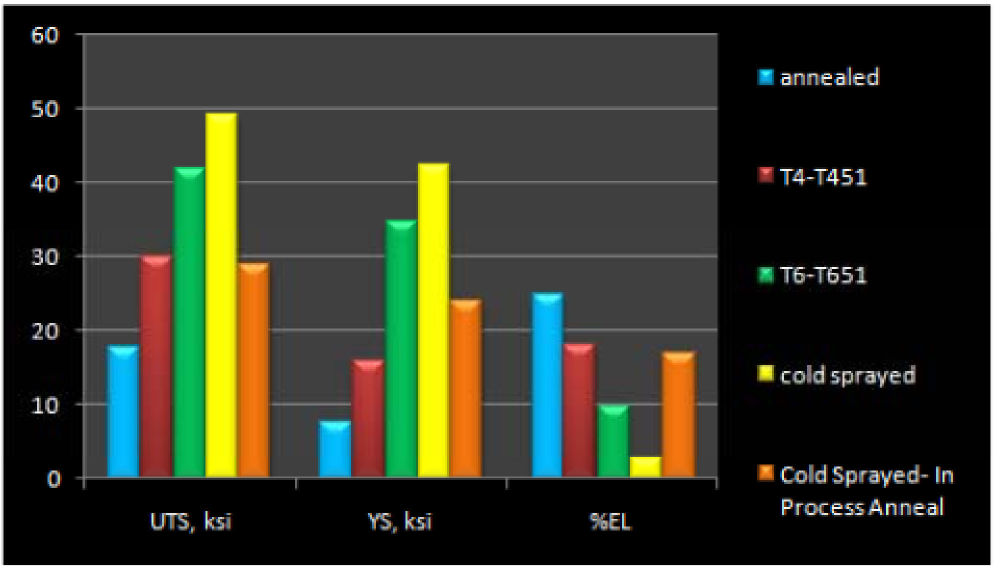

Figure 10. UTS, YS, and percent elongation at failure for as deposited 6061 He Cold Spray (yellow), in-process annealed 6061 He Cold Spray (orange) versus wrought 6061.

There was a significant difference in the rotating beam fatigue performance for samples coated with CP-Al N_2 versus the 6061 He. The stress to number of cycles to failure (S-N) plot for the coatings on ZE41A-T5 is provided in Figure 11. It should be noted that not all specimens failed exactly in the gage. Failure location as well as the cycles, stresses, and gage thickness for all data points for all alloy and substrate combination are provided in the Final Report.

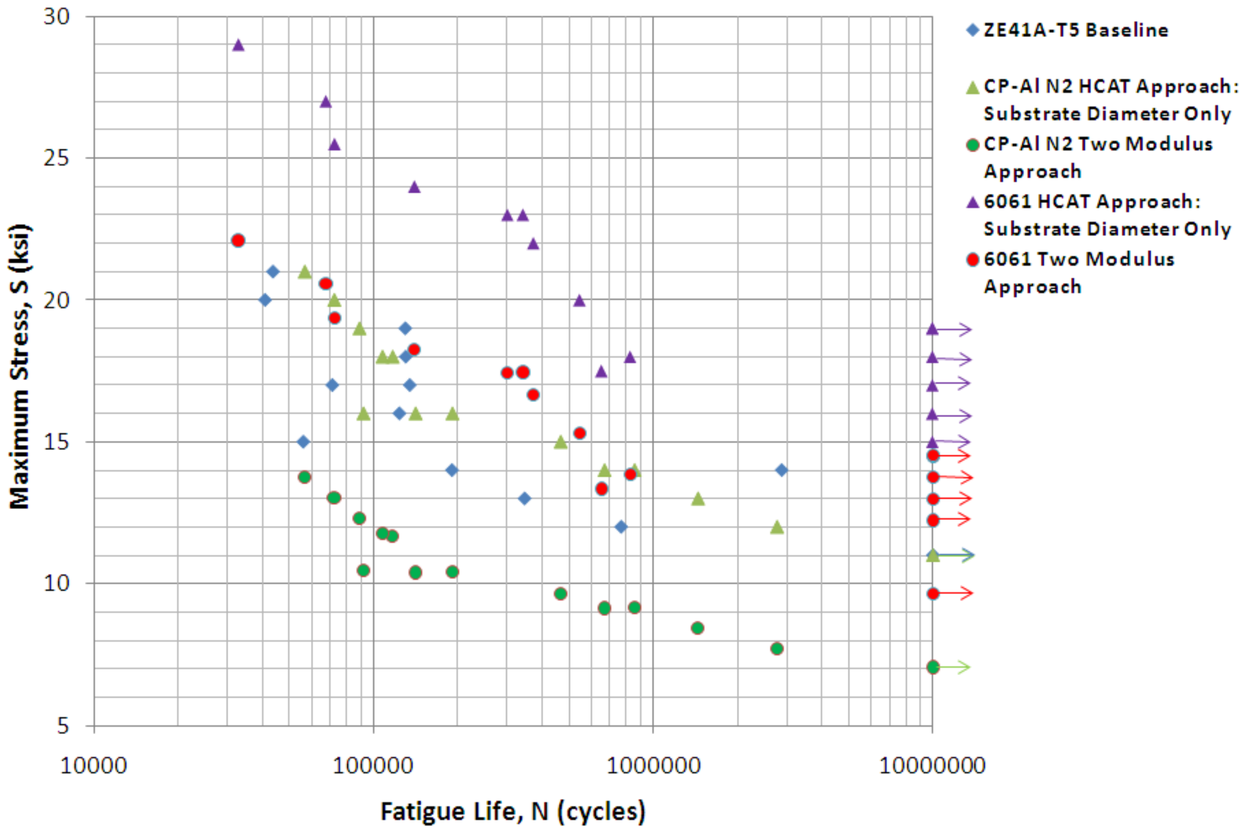

Figure 11. S-N plots for 6061 He and CP-Al N_2 Cold Spray Coatings on ZE41A-T5.

A plot of the fretting fatigue results are provided as Figure 12. The 6061 He coating on the ZE41A-T5 caused a very slight debit. The CP-Al He coating caused no noticeable debit in performance. The CP-Al N_2 sample, on the other hand, caused a significant debit to the fretting resistance. A curve for the CP-Al N_2 is shown in black on Figure 12. UTRC cited low ductility of the CP-Al N_2 system as one of the primary reasons for poor fretting performance. Therefore, CP-Al N_2 coatings should not be used in contact scenarios where fretting could be an issue. The slight debit observed for the 6061 coating is also attributed to the low ductility of the coatings.

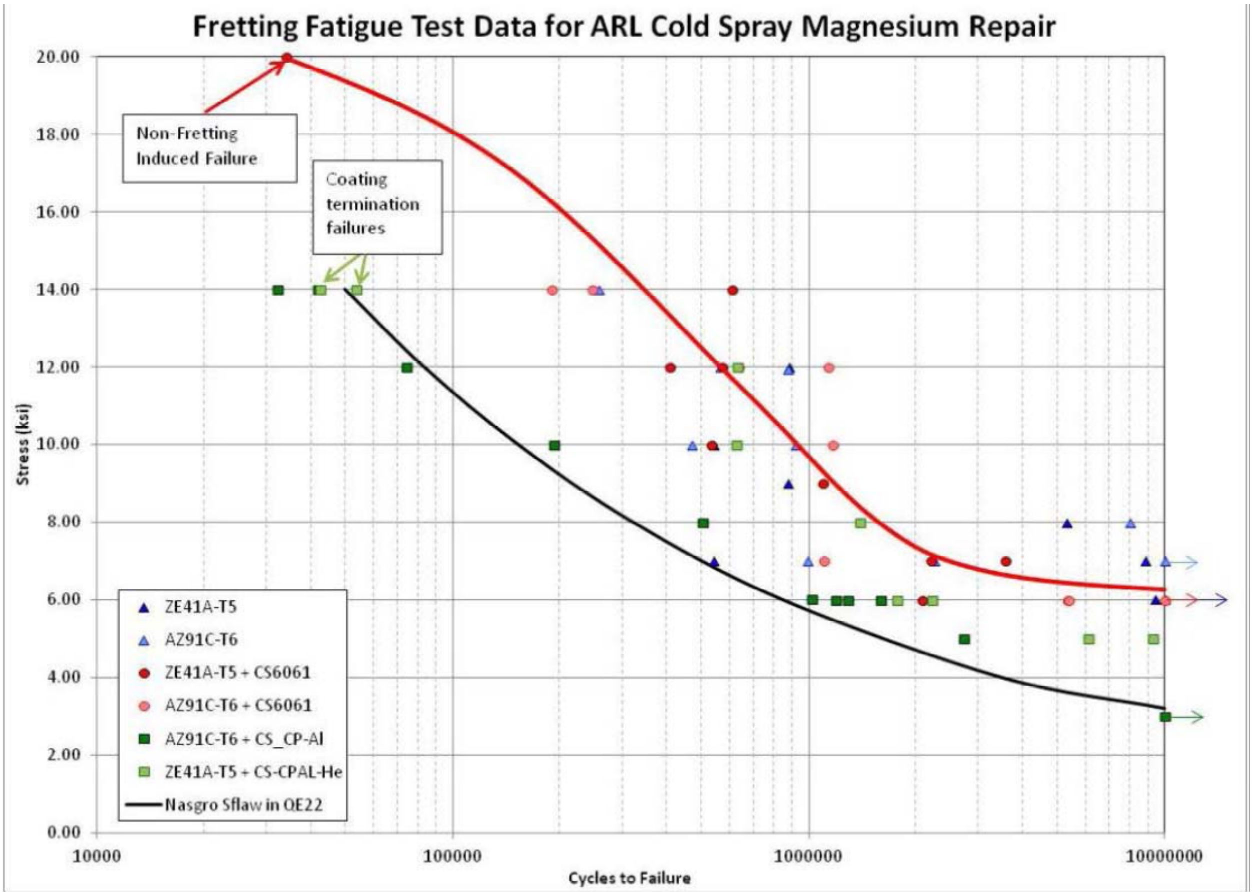

Figure 12. S-N plot for fretting fatigue.

Overall, the ASTM B117 salt fog test specimens performed as predicted. The unscribed CP-Al He samples achieved over 3000 hours of exposure with only one of the four samples developing a pin hole through the coating into the substrate. Figure 13 shows the CP-Al He samples on ZE41A-T5. At approximately 500 hours of exposure, no pin holes were detected and the samples showed only slight discoloration caused by Al corrosion.

The scribing of the Stack-Up samples was conducted in two steps. Samples were first scribed through the Stack-Up to the Cold Spray surface. The specimens were then tested to 1000 hours of exposure in order evaluate the Cold Spray coating compatibility with the Stack-Up. All samples reached the 1000 hours of exposure with no blistering or peeling of the Stack-Up. A second scribe was then made through the Stack-Up and the Cold Spray into the substrate. The samples were then retested in the chamber. This result showed that the galvanic corrosion is definitely a concern since all these specimens tested worse than Mg coated with just the Stack-Up. Figure 13 shows an EV31-T6 panel coated with CP-Al N_2 after testing the top coat and Cold Spray compatibility (a) and after testing with a the scribing through to the substrate (b). The roughness around the scribing in (a) is attributed to initial poor curing of one of the Stack-Up layers. Subsequent low temperature bake-out improved the scribing. Frequent inspection intervals are suggested for the first sets of coatings implemented since the correlation between this laboratory test and real world performance is difficult to predict.

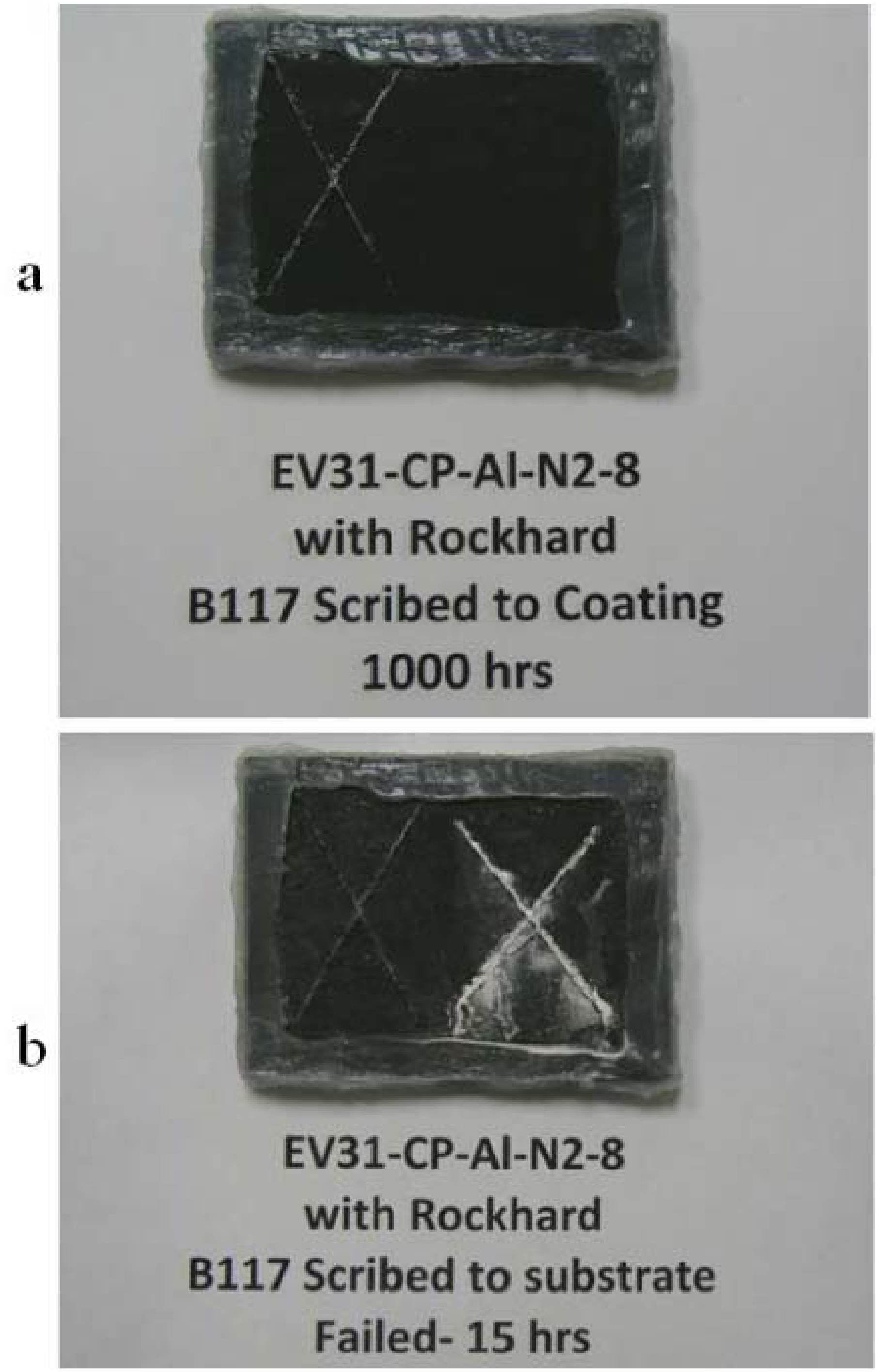

Figure 13. An EV31-T6 panel coated with CP-Al N_2 after (a) testing the top coat-Cold Spray compatibility and (b) after testing with the scribing through to the substrate.

The ASTM G85 SO_2-Annex 4 test is a very aggressive environment to test Al and Mg samples. Unfortunately, most of the test data was invalidated due to rapid failure at the edges and corners. This resulted in undercutting coating adhesion and delamination.

The overall crevice corrosion resistance of the coatings can be considered excellent. Only one of the 16 Cold Spray coated samples did not reach the 500-hour goal. Sample ZE41A-6061Al-He-4 was removed from the test chamber at 350 hours due to pitting corrosion issues or a pinhole failure to the substrate. The crevice corrosion results for the coatings with the Stack-Up and Cold Spray condition are provided in the Final Report.

Overall, the GM9540 scribed test panels survived much longer in this test than the scribed ASTM B117 salt spray test. This is attributed to the fact that the cyclic test does not continuously expose the specimens to the electrolyte (salt water solution). The majority of the corrosion damage occurred during the first 48 hours of testing. After 48 hours, the coatings continued to corrode until all panels either failed before 500 hours or reached the 500 hour with significant corrosion present. The main corrosion issue appears to be galvanic in nature since the baseline specimens without Cold Spray performed significantly better during the test. It is recommended that the coatings be inspected often during initial flight testing trials to ensure there are no major corrosion issues.

Current measurements from the galvanic corrosion test confirmed that galvanic corrosion is a concern for these coating systems. Therefore, protective coatings such as the Stack-Up used in this study should always be applied to Cold Spray repaired areas which might be exposed to salt water. Additionally, coatings should be applied in such a manner that the transition between the Mg alloy and the Cold Spray repair coating does not happen in corrosion prone area.

The first Cold Spray application that SAC is considering implementing is the repair of corroded areas on the H-60 sump. Currently, SAC uses an HVOF Al-12Si repair technique, but this coating is limited in use due to both thickness and performance limitations. Figure 14 shows an H-60 sump and the corresponding repair area of interest. At SAC's request, ARL then transferred the coating process parameters to a potential Cold Spray subcontractor, ASB Industries in Akron OH, in order to start the full-scale repair qualification process required to implement this repair.

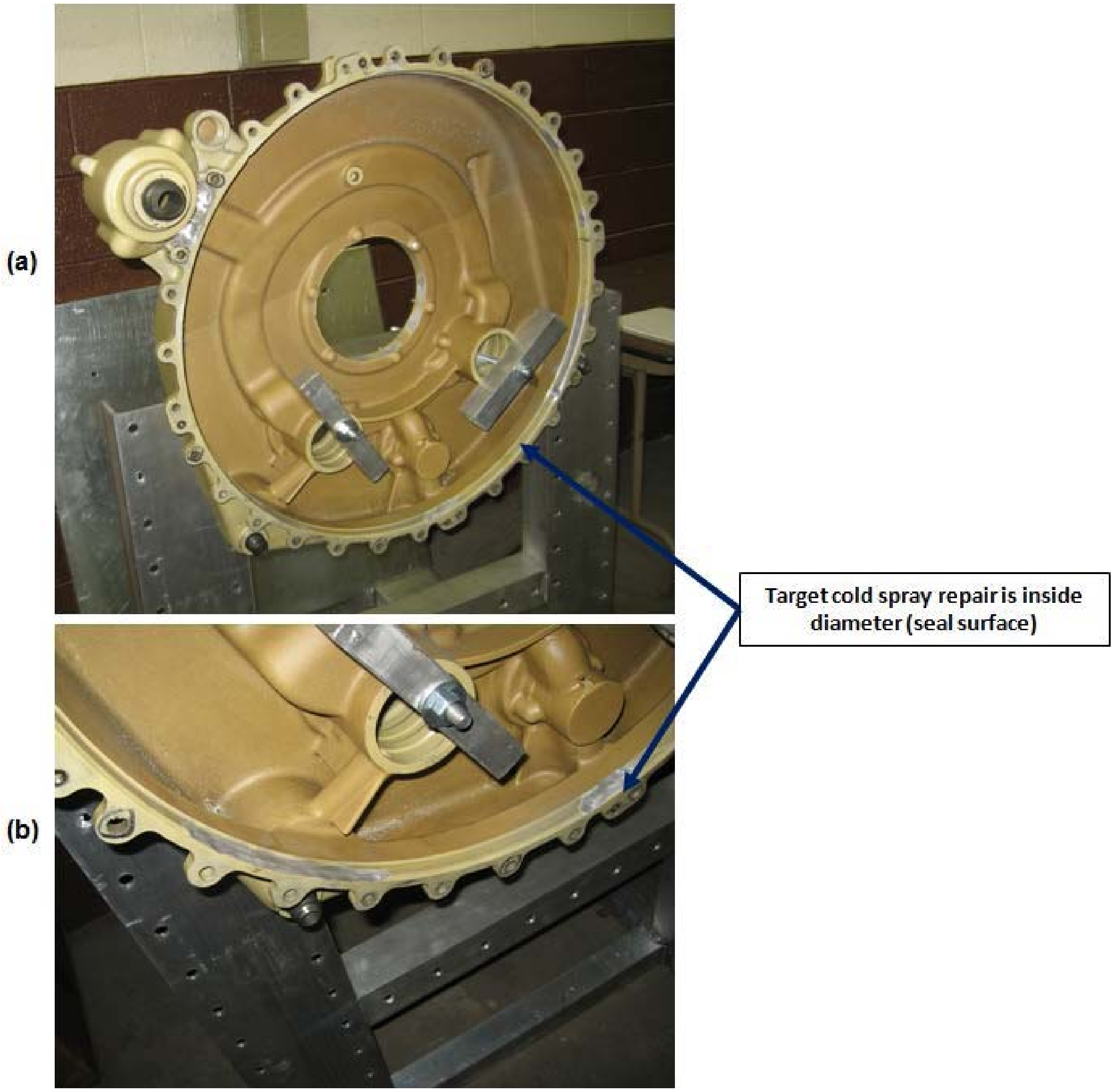

Figure 14. SAC H-60 Sump (a) and detail of inside diameter showing simulated corrosion damage (b).

The Cold Spray system at FRC-E was demonstrated to deposit CP-Al N_2 coatings. The metallography results from the demonstration confirmed that the system is functioning correctly. At the very least, specific objectives need to be accomplished before fully implementing this Cold Spray repairs at the depot.

- FRC-E staff needs to increase familiarity with the equipment.
- Coating quality in regards to adhesion and microstructure needs to be confirmed.
- Limited flight testing needs to occur.
- Depot maintenance manuals will have to be produced.

ARL will continue to work closely with FRC-E as well as NAVAIR to implement this critical technology.

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8.0 COST ASSESSMENT

8.1 COST MODEL

Because Cold Spray can be used at both the OEM and depot repair level in different areas, analysis has been done for several situations:

- Depot repair of gearbox feet by Cold Spray in place of glue shims
- Gearbox reclamation by repair of flanges or other types of damage
- Repair of flanges by Cold Spray in place of current HVOF Al-12Si repair.

Each of these assessments is provided in the Final Report. Only a simple cost savings based on parts reclamation will be presented in the present report.

8.2 COST ANALYSIS AND COMPARISON

As shown in Table 11, the primary direct cost of Cold Spray is labor, of which the primary labor cost is setup (robot programming, surface preparation, etc.) and final machining (inspection, grinding, etc.) rather than the deposition itself. The most significant contribution to labor cost is the cost of setting up the deposition rather than the time involved in the deposition itself. This is especially true when the deposition is in a complex and difficult-to-reach area such as the gearbox foot.

Table 11. Direct cost/sq ft of Cold Spray Al with N_2 and He gas.

Item	Cost/sq ft Breakdown	Total Cost/sq ft
N_2 gas		
Burdened labor		$131.93
Consumables	Powder-$8.91	$9.42
	Gas-$0.45	
	Electricity-$0.07	
Total		**$141.35**
He gas		
Burdened labor		$131.93
Consumables	Powder-$8.91	$120.34
	Gas-$111.38	
	Electricity-$0.05	
Total	**$252.27**	**$252.27**

The H-60 Main Sump Gearbox (Figure 15) is currently repaired by SAC using an HVOF Al-12Si coating together with a bond coat. This method is not satisfactory as the HVOF coating tends to crack on insertion of Rosan fitting and does not reclaim the mechanical properties of the Mg alloy. It is expected that the use of Cold Spray coating will allow these gearboxes to be reclaimed, largely eliminating condemnations.

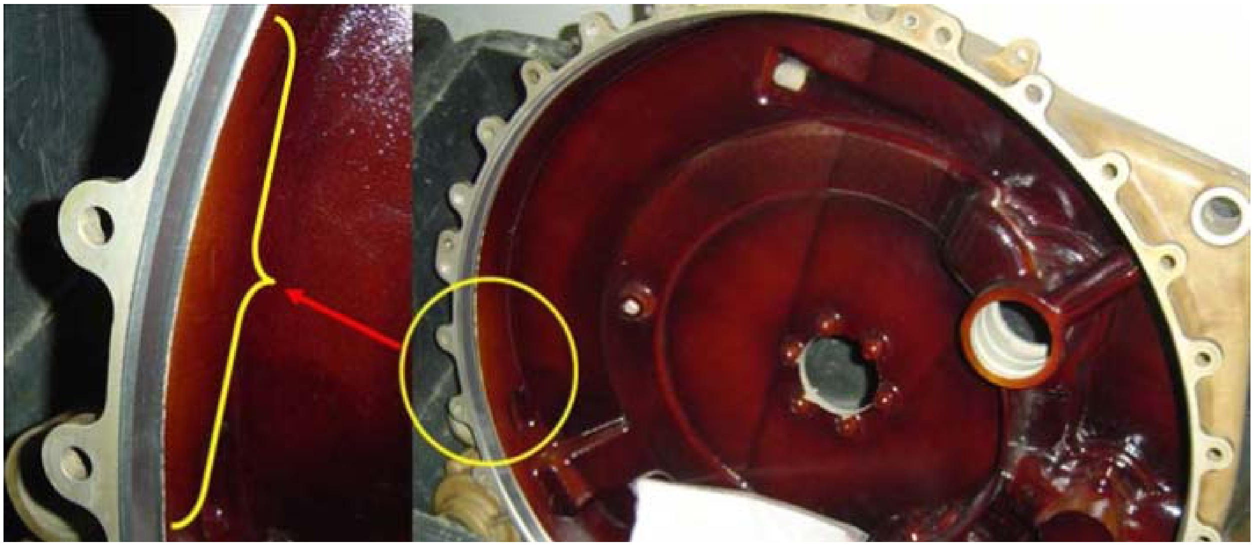

Figure 15. Flange repair area of H-60 Main Sump Gearbox.

For this application, the cost of the process is almost immaterial compared with the value of the components that would otherwise be condemned since the primary cost is removing assisting corrosion, setup for spraying, and finishing the spray component. The efficiency with which these operations can be done is the primary determinant of process cost.

In this analysis we have assumed that each of the components that would otherwise have been condemned annually is repaired by Cold Spray, thus implicitly assuming that the Cold Spray repair will reclaim the component, but will need to be renewed every Programmed Data Maintenance (PDM) cycle. If, as we expect, the Cold Spray repair provides much better corrosion resistance, then the annual repair cost will drop. Since this is an application in which the repaired area, because it is a flange surface, cannot be Rockhard coated and top coated, it is highly likely that the Cold Spray prepare will provide corrosion protection for longer than a normal PDM cycle.

The results of the cost-benefit to evaluation are shown in Table 12 and Figure 16. This is a simple financial scenario since we are merely repairing gearboxes and putting them back into service rather than condemning them as nonrepairable. As a result, there is a small cost in the first 1 to 2 years followed by a steady rise in savings over subsequent years. The capital and adoption cost of putting Cold Spray into production is completely outweighed by the saving within the first 2 years. The predominant cost saving is the purchase price of the gearboxes.

Table 12. Fifteen-year value parameters and 2σ values for H-60 Main Sump Gearbox cold spray repair.

	-2 Sigma	Value	+2 Sigma
NPV	$9,061,887	$9,677,638	$10,293,390
Internal rate of return	120%	72%	51%
Annualized ROI	42%	72%	101%
Total ROI	881%	922%	963%
Payback period	2.1	1.5	0.0

NPV – net present value
ROI – return on investment

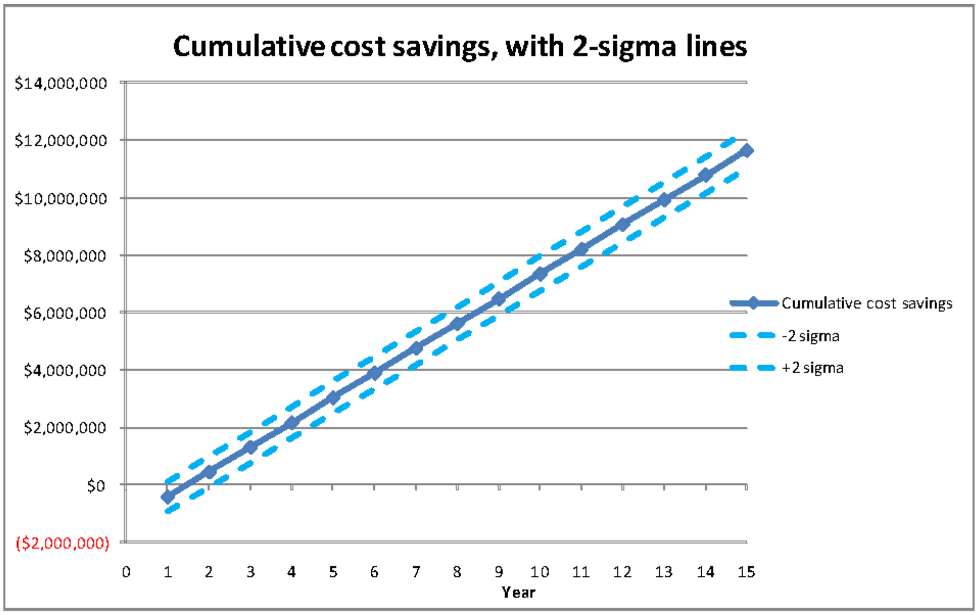

Figure 16. Cumulative cost savings for H-60 Main Sump Gearbox Cold Spray repair.

As shown in Table 12, the 15-year NPV is $9.6 million with a high internal rate of return and high ROI. The payback period is expected to be less than 2 years.

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9.0 IMPLEMENTATION ISSUES

The galvanic corrosion performance of these coatings in the field still needs to be assessed. To date, a Cold Spray repair in a salt water corrosion prone area has yet to be fielded. It is recommended that flight testing be conducted under tight monitoring conditions with regular inspection intervals in order to evaluate issues with corrosion.

A definite future research area should be structural repair using Cold Spray. The mechanical test results of the 6061 He coating in particular suggest there is potential beyond nonstructural or cosmetic repairs using Cold Spray technology. Advancing the technology to a point where structural repair of gearboxes and other components is possible should be a priority of the DoD science and technology community. Structural repair capability would have a significant impact on DoD cost savings and war fighter capability.

The high pressure Cold Spray community is plagued by two significant procurement issues.

1. Very few acceptable off-the-shelf Cold Spray powders
2. Limited number of Cold Spray subcontractors in the United States.

The Cold Spray particle velocity and temperature models presented in Chapter 6 highlight how small variations in particle sizes can significantly alter the Cold Spray process. This phenomenon creates a significant issue for quality control since there is currently no Al powder specification for this repair. As a follow up-to this ESTCP effort, ARL will take the lead on developing an MIL Specification for Cold Spray Al Powders. This is an essential step towards insuring that these coatings will consistently meet performance requirements.

ARL is also assisting private companies in establishing Cold Spray facilities or job shops in the United States. These vendors will be able to support DoD and OEMs such as SAC. The lack of SAC approved subcontractors is currently delaying the implementation of the H-60 sump repair.

ARL will continue to assist FRC-E as they begin implementing the Cold Spray repair on a component-by-component basis. An example of this continuing effort is the current Office of Naval Research Funded Technical Insertion Program for Savings project to repair AH-1 gearboxes. This effort focuses on ARL developing a low pressure repair for wear damage on the combining gearboxes. FRC-E has purchased two handheld Cold Spray systems to implement the repair process at the beginning of the 2012 calendar year.

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APPENDIX A
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