Corrosion Repair Using Cold Spray Technology

Matthew Chu, Luc Doan, Stonet Middleton and Conrad Macy
Fleet Readiness Center SouthWest (FRCSW)
Naval Air Station (NAS) North Island, Materials Engineering Laboratory
Door 1, BLDG. 469 North Utgoff Ave., San Diego, CA 92135
UNITED STATES

matthew.d.chu2.civ@us.navy.mil, luc.q.doan.civ@us.navy.mil, stoney.a.middleton.civ@us.navy.mil, conrad.a.macy.civ@us.navy.mil

Frederick Lancaster
NAWCAD Air Vehicle Engr/Materials Engr Div AB23000
48066 Shaw Road, Bldg 2188, Unit 5, 203C, Patuxent River, MD 20670
UNITED STATES

frederick.a.lancaster4.civ@us.navy.mil

ABSTRACT

Due to naval aircraft's operational environment, many airframes, components, and subsystem components corrode over time causing supply shortages and a decrease in readiness for aircraft. Many corrosion repair areas are considered dimensional damage for sealing/mating surfaces, visual appearance, and/or loss of factor of safety. Cold Spray is a deposition repair process that accelerates metallic powder in a high-velocity gas stream which the metallic powder kinetically impacts a substrate forming metallurgical and mechanical interlocking bonds and is an ideal repair technology for restoring metallic material. The Cold Spray process can be done by hand or a robot may perform the spraying operation. Due to the nature of corrosion being sporadic and random, the handheld feature is convenient for applying the proper amount of Cold Spray for the amount of corrosion damage that is seen in an area. For the same components, different amount and severity of corrosion can occur in different areas. The data required for approval depends on the subsystem engineer and the damage on the component. The component engineer receives a standard test data set which can included, but is not limited to, adhesion testing, porosity testing, hardness testing, and corrosion testing. Using Cold Spray Technology has saved the US Navy's Naval Air Systems Command (NAVAIR) millions of dollars in cost avoidance and, more importantly, increased operational readiness by having components repaired that were not able to be repaired before. NAVAIR has repaired 500+ components and has 45+ approved repairs.

Keywords: Corrosion Repair Technologies

1.0 INTRODUCTION

Due to naval aircraft's operational environment, many airframes, components, and subsystem components corrode over time causing supply shortages and a decrease in readiness for aircraft. Many corrosion repair areas are considered dimensional damage for sealing/mating surfaces, visual appearance, and/or loss of factor of safety. Of these components, it commonly cost tens of thousands of dollars to buy replacement parts and, to compound the problem, the supply system is in short supply because of the high replacement rate. Aerospace aluminium is the most commonly corroded materials as it is often bonded to composites and/or fasteners made of dissimilar metals. Therefore, an economical metallic repair technology was researched to dimensionally restore aluminium and steel surfaces allowing for improved material condition and extend the life of the components. Cold Spray technology has filled this Naval Aviation operational need.

Naval Air Systems Command (NAVAIR) has been working with Cold Spray since 2005 with the involvement in the US Army led Environmental Security Technology Certification Program (ESCTP) project. The project was aviation focused to use cold spray metallization to repair corrosion damage found on magnesium helicopter gearboxes. The Army ESTCP project built the foundation of the subsequent research and efforts to follow that focused on specific aircraft part repair for corrosion or wear damage.

1.1 Cold Spray Technology

Cold Spray is an ideal repair technology for restoring metallic material lost due to corrosion and mechanical wear. Cold Spray is a deposition repair process that accelerates metallic powder in a high-velocity gas stream which the metallic powder kinetically impacts a substrate forming metallurgical and mechanical interlocking bonds. In addition, Cold Spray is a solid-state process, meaning there is no phase change. Therefore, the coatings are great under compressive forces but weaker against tensile forces. Cold Spray is a part of the thermal spray process but has low temperature applications with the high particle velocity. This allows this process to have low heat affected zones on the substrate. Figure 1 shows a diagram of a standard Cold Spray System. The carrier gas gets heated by a heater and into the mixing chamber while some of the gas carries powder from the feeder into the mixing chamber.

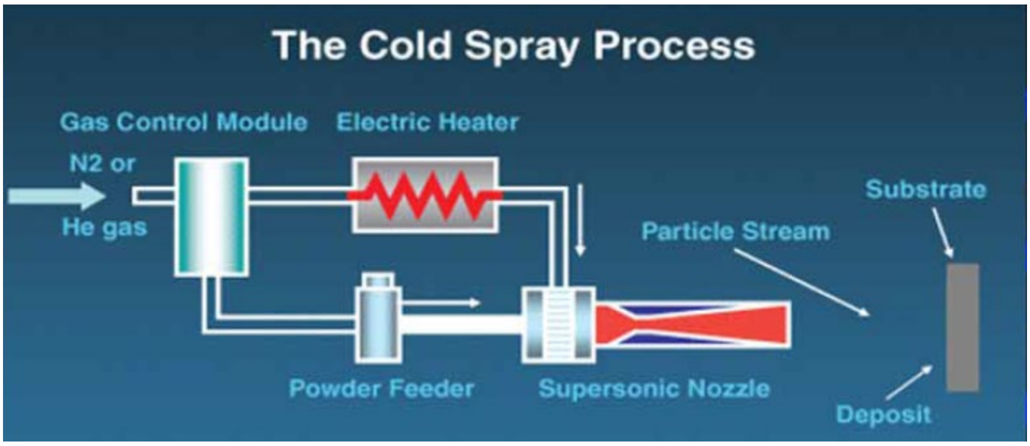

Figure 1: Cold Spray system process diagram.

Once in the mixing chamber, the particles go through a supersonic nozzle (convergent to divergent nozzle) to accelerate the particles onto the substrate. The Cold Spray coating adheres to the substrate and multiple layers can be applied to the Cold Spray coating to build up the optimal thickness required for dimensional restoration. Since this is a solid state process no oxidation or voids between Cold Spray coating layers. Therefore, there is no limit on deposition thickness when applying this coating. Since the metallic powder particles are building a compressed powder coating with less than 1% porosity, the Cold Spray coating can be machined without removing the entire Cold Spray coating. This allows for low risk of over application of the Cold Spray coating to refill the lost dimensional feature. In addition, the removal of the over application of Cold Spray coating does not require any special tooling. Traditional machining tools and techniques are commonly used such as, end-mills, lathes, grinders, and sanders because removing any overspray of the Cold Spray coating is like machining/reworking normal metal as seen in Figure 2.

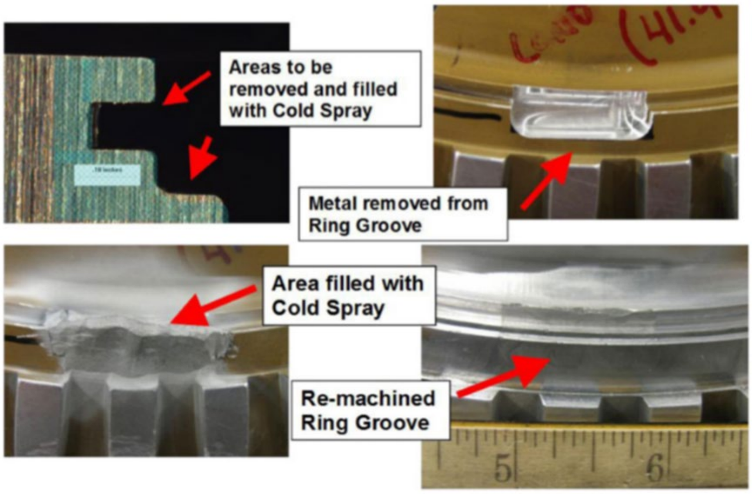

Figure 2: Cold Spray repair process.

2.0 NAVAIR COLD SPRAY CAPABILITIES

NAVAIR facilities have a mixture of high and low pressure cold spray systems. These systems are located at the depots and intermediate level aircraft maintenance facilities. The three Cold Spray system manufacturers that are in NAVAIR is Centerline, Inovati, and VRC. Each cold spray Original Equipment Manufacturer (OEM) offers different operational equipment packages that allow for various uses. Please see the Table below to see the different equipment owned by NAVAIR and their usage.

OEM	Centerline		Inovati	VRC Metal Systems
Equipment	SST PX	EPX	HDR 5.0	Gen III
Cold Spray Approach	Low Pressure	High Pressure	Low Pressure	High Pressure
Maximum Gas Pressure	250 psi	1000 psi	130 psi	1000 psi
Maximum Gas Temperature	550 C	800 C	1300 F	1200 C
Gas Types	Compressed Air, Helium, Nitrogen	Compressed Air, Helium, Nitrogen	Helium, Nitrogen	Helium, Nitrogen
Powders	Aluminium & Nickel Powders	Most Powders	Composite Powders	Most Powders

These systems each have their specific use case that is optimized for their use. The Centerline SST PX system is a mobile system that can easy to use and can easily spray Aluminium powders for repair. The Centerline EPX system is a high pressure system able to use compressed air to apply the heavy metal powders. The Inovati HDR 5.0 System is a low pressure system that is able to spray composite powders that simulate chrome plating. The VRC Gen III system is able to spray the heavy metal powders and has shown that structural repair is possible through test coupons.

In addition, each of these systems have their limitations. Centerline SST PX system is unable to spray a chrome plating replacement. The Centerline EPX and VRC Gen IIII system are high pressure systems that drains the gas supply significantly faster than the low pressure. The Inovati HDR 5.0 System does not spray non-composite powder well.

3.0 NAVAIR COLD SPRAY REPAIRS

NAVAIR has over 40 authorized repair recipes and has many one-off repairs authorized to be performed. These authorizations has led to over 500 Cold Spray repaired components that have been returned to the fleet. Many of these repairs are brought to the Cold Spray process due to 3 major reasons:

1) Long Turn-Around-Time (TAT) of repairing the component with current repair method;
2) Shortage in Supply;
3) High component cost.

3.1 Cold Spray Application Process

The Cold Spray process can be done by hand or a robot may perform the spraying operation. Due to the nature of corrosion being sporadic and random, the handheld feature is convenient for applying the proper amount of Cold Spray for the amount of corrosion damage that is seen in an area. For the same components, different amount and severity of corrosion can occur in different areas. With handheld application, only the corroded areas will be sprayed for dimensional restoration without wasting powder, gas, and time by applying extra Cold Spray in areas that are not required (see Figure 3).

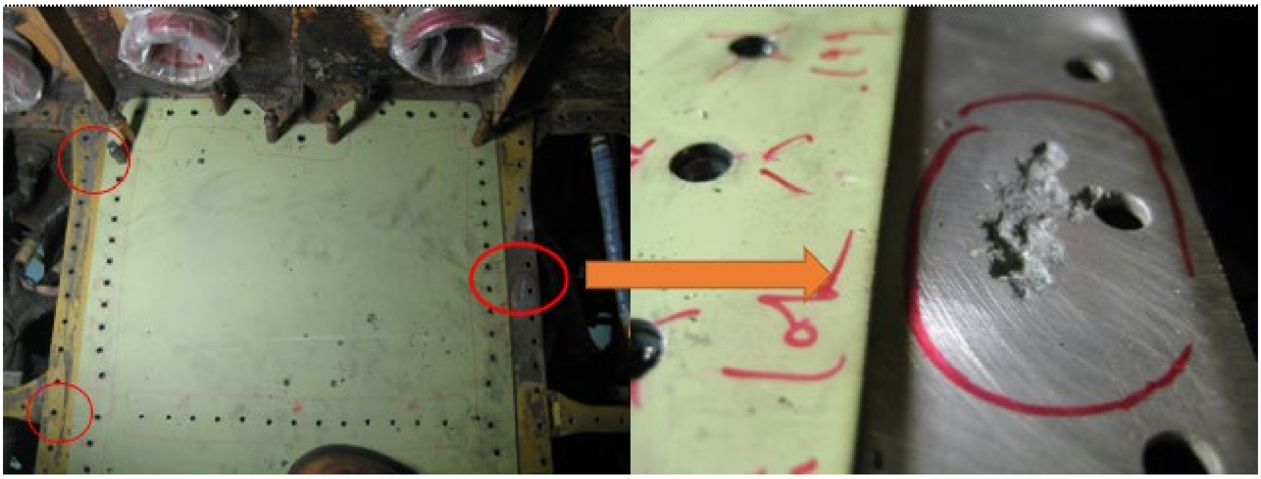

Figure 3: Inconsistent corrosion appearing on flange.

Robotic application is more appropriate and expedient when applying the same amount of Cold Spray on the same area of the component because there is a pre-machining step. This pre-machining step sets the dimensionally restoration needed to be the same every time. Therefore, a robotic program can reapply the Cold Spray coating the same every time without human error (see Figure 4).

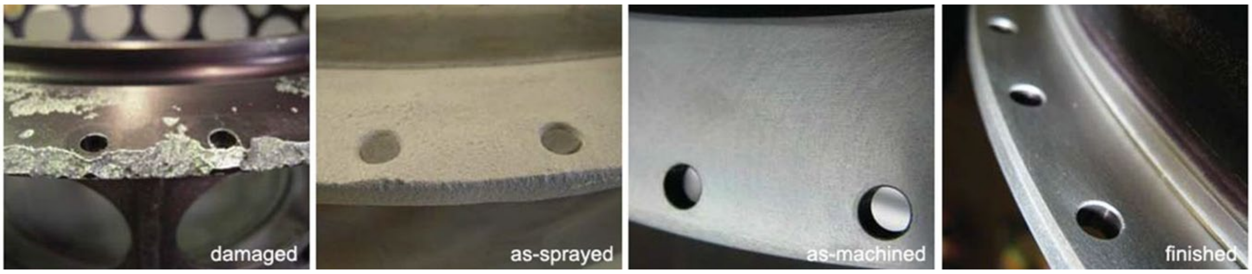

Figure 4. Consistent corrosion on the flange.

3.2 Cold Spray Powder Selection

The Cold Spray process can use a variety of powders. The powders can be the same as your substrate or different to improve on certain properties such as corrosion and wear resistance. Therefore, performing root cause analysis on the failure mechanism is critical for determining the powder selection. The two types of corrosion resistance coatings that can be applied is a noble coating or a sacrificial coating. The application of a noble coating, which is noble in the Galvanic Series to the substrate, can give the substrate longer term protection from corrosion due to the overall corrosion protection from the coating. Noble coatings are the cathode to the anode of the substrate, so any pore or break in the noble coating allows for galvanic corrosion corroding the substrate. Cold Spray limits the pores due to the coatings have <1% porosity and high adhesion to the substrate. Another type of coating is a sacrificial coating that allows the substrate to be cathode and the coating to be anodic. This allows the coating to be sacrificed to protect corrosion of the substrate material.

Lastly, applying the same material in powder form will not have the exact same properties of the substrate because Cold Spray has a unique microstructure. Therefore, applying the same material in powder form will bond and look visually different in the metallurgical as seen in the photo below. Therefore, the Cold Spray powder is selected base if it will reduce the risk of the same damage occurring on the component.

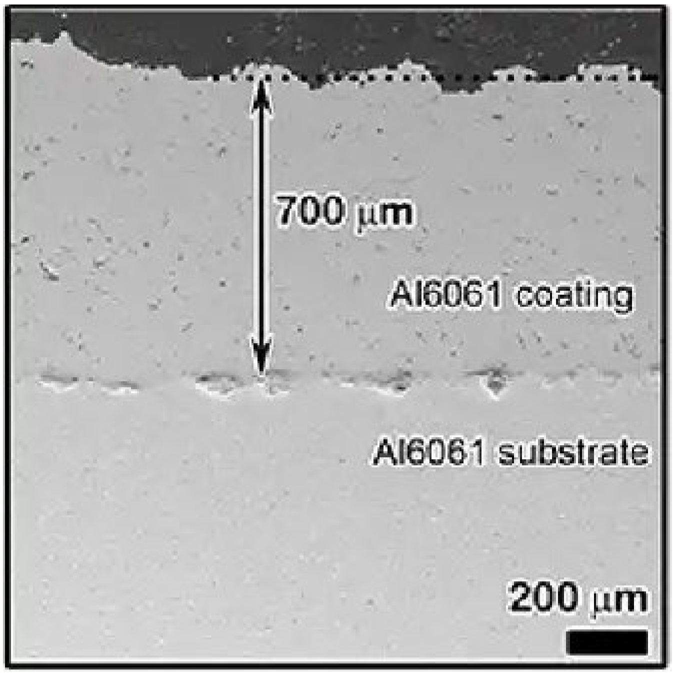

Figure 5: Cold Spray has a unique microstructure.

3.3 Cold Spray Repair Types

The main types of repair fall into two categories:

1) Blend and Fill:
    a) Corrosion Damage Dimensional Restoration.
    b) Wear Damage Dimensional Restoration.
2) Repair Process Replacement.

3.3.1 Blend and Fill

Blend and fill is a term used to describe the general method of repair for surface corrosion, physical damage or wear that is within structural limits. The process starts with the removal of the corrosion product and blending the damaged areas to remove corrosion such as glass bead, abrasive cloth paper, aluminium or stainless steel brushes, and abrasive disks. The blend and fill rework process is shown in Figure 6. After the corrosion has been removed and the area blended to at least a ratio of 10:1width to pit depth area.

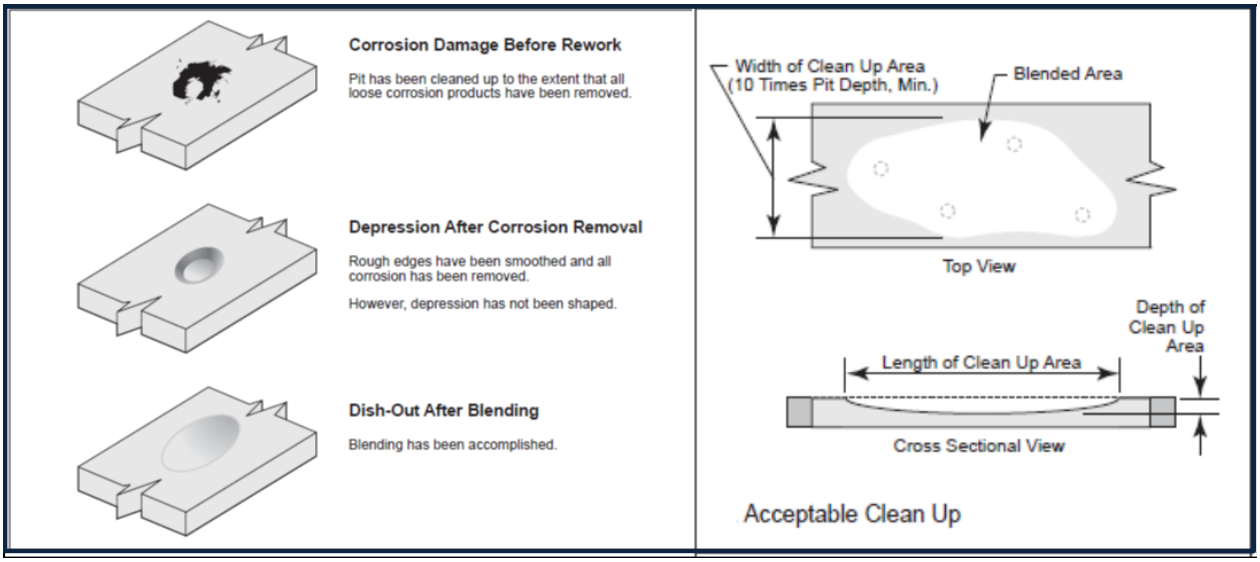

Figure 6: Blend and fill.

3.3.1.1 Corrosion Damage Dimensional Restoration

An example is the authorized repair on an AA 2024 fitting on a fuel bladder. The fitting is inside the bilge area rubbing against the walls allowing for the paint system to fail allowing for the substrate to be exposed to the chlorine in the marine environment. The allowable corrosion pitting depth is 0.030”. The damage is so extensive that they would be required to scrap the entire fuel bladder and did not have the ability remove and replace the bladder itself. This component is hand-made and only had a few in stock at a time. Applying a sacrificial cold spray coating for dimensional restoration was a major success allowing for a longer service life of these bladders. This sacrificial coating protected the substrate from corroding and not allow the substrate to be corroded any further, in addition, the Cold Spray coating is more abrasive resistant and did not wear as easily.

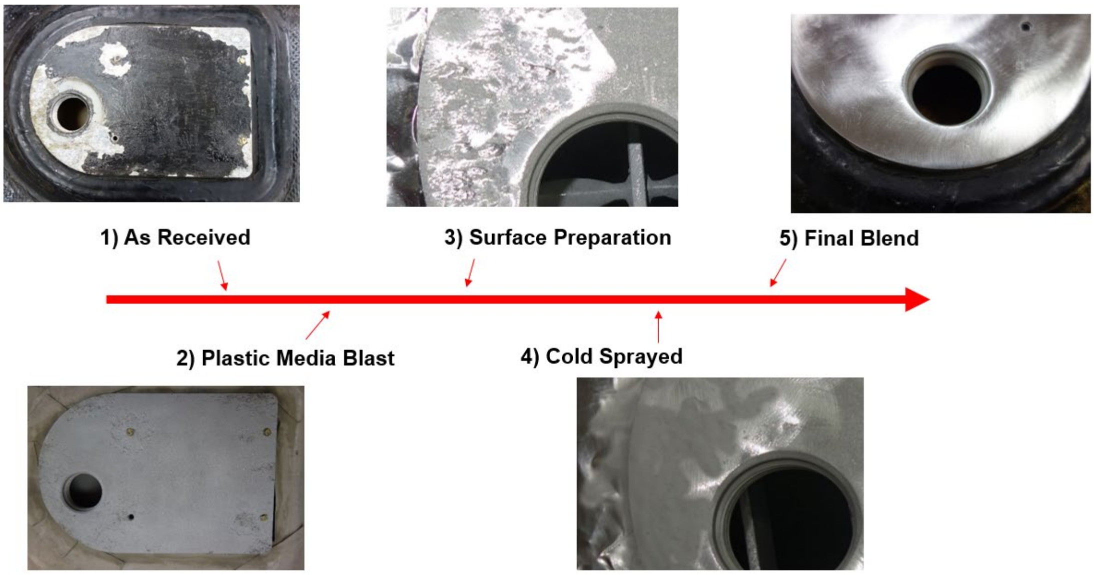

Figure 7: Authorized repair on an AA 2024 fitting on a fuel bladder.

3.3.1.2 Wear Damage Dimensional Restoration

3.4.2 Repair Process Replacement

3.4.2.1 Magnesium Gearbox Housing

Several cold spray repairs have been developed for magnesium gearbox housings. The first repair involved repair of chafing damage that also leads to pitting where a carbon fiber bleed air duct was wearing a groove into a ZE-41A magnesium gearbox housing shown in Figure 8 marked in red. The previous repair involved blending the damage smooth to a depth 0.090" and filling with epoxy. The epoxy repair was then covered with a protective tape to provide a visual indication of continued wear. A project was undertaken to validate a cold spray repair in this application. Worked in conjunction with the Army Research Lab, a series of repair materials were evaluated and tested. Tests included metallographic evaluation, hardness, adhesion, triple lug shear, residual stress, corrosion, as well as tensile and fatigue testing that were used in a finite element analysis model. The testing was thorough as this was the first application of cold spray for NAVAIR.

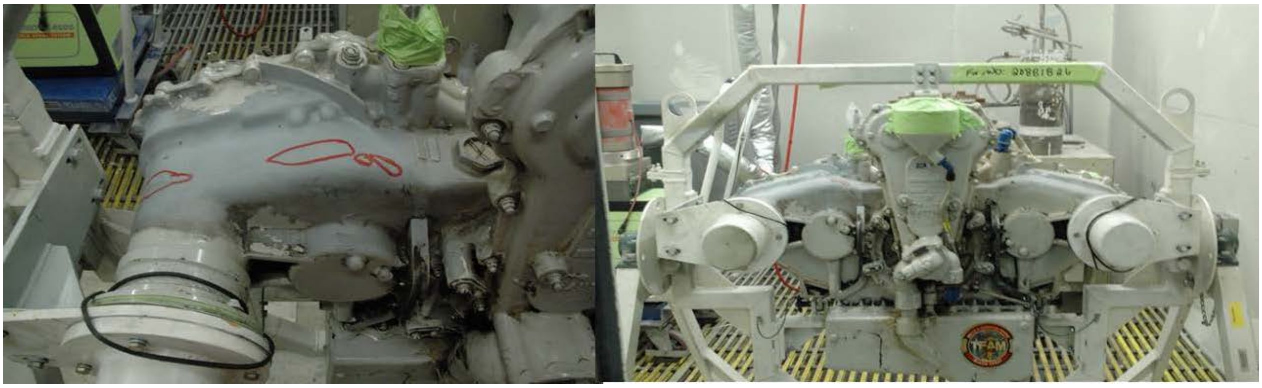

Figure 8: AZ41 magnesium gearbox.

The testing was thorough as this was the first application of cold spray for NAVAIR aluminum. Test panels were coated and place in ASTM B117 neutral salt fog, ASTM G85 method 4 acidified salt fog, and beach exposure at the Kennedy Space Center corrosion site. Figure 9 shows a panel coated with 6061 aluminum that underwent acidified salt fog testing. All of the panels were from the same lot of AZ41 cast magnesium and were cut to 3 inches' x 4 inches' x 0.25 inches thick, then half of the panel was left bare and the other half coated with 6061 CS aluminum to a thickness of 0.012-.0.015 inches (0.30mm-0.39mm). The entire panel was then pretreated, Rockhard® coating applied, primed and topcoated and scribed.

Figure 9: Corrosion panel after 500hrs acidified salt fog, (left) magnesium prime/paint only, (right) magnesium 6061 CS, prime/paint.

The resulting 6061 CS aluminum test panel side after 500 hours shows the beginning of undercutting. As compared to the current coating system which showed total failure at the scribe line with extreme exfoliation of the substrate. The modified coating stack-up in contrast performed extremely well and subsequent fleet trials also affirmed this anodic protection.

3.4.2.2 Aluminum Avionics Rack

Wrought aluminium avionics racks exhibit a lot of corrosion damage in service due to presence of chlorine in the marine environment and exacerbated by gun gasses. The corrosion was heavy pitting corrosion as shown in Figure 10 below. The damage was so extensive that the racks were no longer serviceable and since they also come in paired sets if one of the two racks was bad, both were scrapped. A repair was desperately needed to avoid aircraft down situation due to spare non availability of spare parts. The cold spray process was used to deposit Al-Trans 10-20-50 Chrome® aluminum blend onto the 7075-T7351 aluminium rack.

Figure 10: Corrosion damage (left) lower rack, (right) upper part of rack.

Figure 11: Avionics rack repair.

3.4.2.3 Aluminum Gearbox Housing

Internal features and mounting flange faces of airframe mounted accessory drive gearbox housings made of cast A357 or A356 aluminum have been repaired. The flange faces experience fretting damage beyond current repair limits. This leads to loosening of the mating components and creates leaks in the system. Previously, the only repair was a limited machining of the flange face to attempt to remove the damage or machine the face. In some cases, the amount of machining required was so extensive as to make the flange too thin to mate properly with the opposing flange. An alternate method was to use plasma spray to apply aluminum or welding which would create a heat affected zone requiring subsequent heat treatment. The alternate methods were not ideal and rarely used.

The aluminum gearboxes were good candidates to evaluate a cold spray repair as the affected area was only dimensional and the item was high in cost and in demand. Cold Spray was tried using both high pressure and low pressure machines. It was proven that a cold spray with an aluminum-nickel blend (Al-Trans® 7075 with nickel) or commercially pure 1100 series aluminum (SST A5001®) sprayed with low pressure machines or 4047 aluminum powder sprayed with a high pressure machine, were all effective and restoring the flange height after completely removing the damage. The aluminum alloy containing nickel provided additional resistance to future fretting damage and created a more robust joint. It was also easily machinable which facilitated the repair.

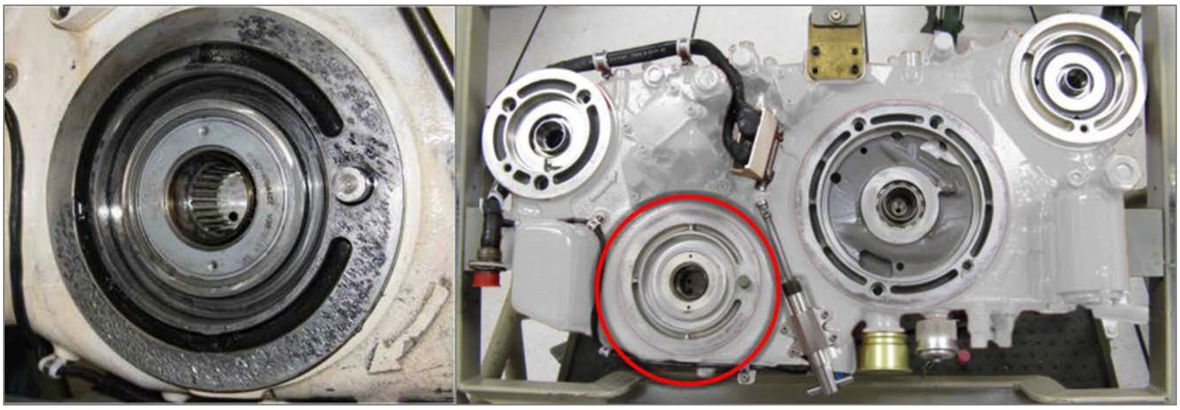

Figure 12: Cast aluminum gearbox housing (right) fretting, (left) repaired.

Figure 13: Aluminum housing inspection after 1,748 flight hours.

3.4.2.4 Wing Leading Edge Cover

This repair was developed to for a leading edge cover that also has a deicing boot attached to it. The panel is curved and constructed of 7075 aluminum with a honeycomb sandwiched core in the middle of the panel, where the edges are flat. Corrosion was found on the lower nine fastener holes where moisture collects at the lowest point. The configuration of this leading edge did not have a corrosion inhibited primer coating in the coating stack-up and only consisted of a pre-treatment bonded boot and then a topcoat. This created the conditions for pitting corrosion around the fastener heads, in an area susceptible to corrosion.

Figure 14: Corroded areas on leading edge around lower fasteners.

Figure 15 shows the same mode of corrosion as found on all of the panels, pitting attack, exacerbated by being entrapped under the deicer boot and the lack of a corrosion inhibitive primer. The corrosion is identified by visual inspection where the rubber deicer boot lifts due to the corrosion product. Remaining adhesive for the deicer boot can be seen in the figure as brown material.

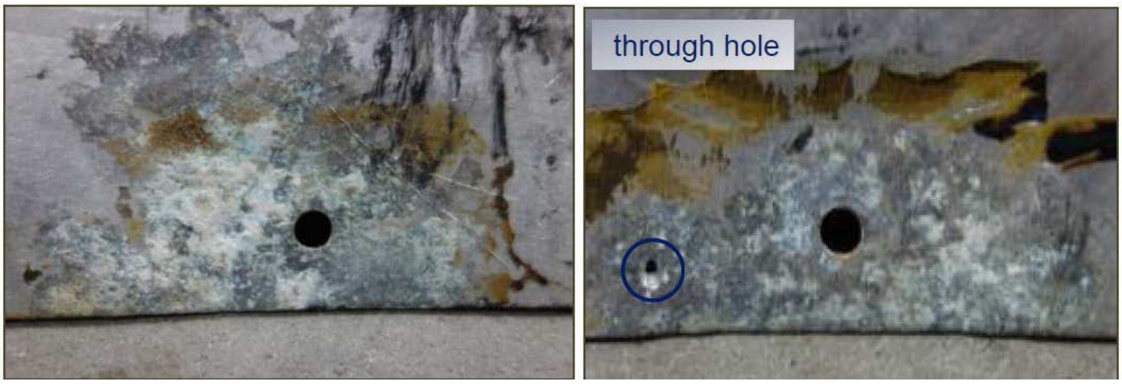

Figure 15: Expanded view of corrosion around fastener holes.

A cold spray repair using an aluminum blend of powder, Al-Trans Chrome® was used to elicit the repair. The repair process is shown in Figure 6 where the corrosion product is removed, the panel thickness and fastener hole measured, then if within acceptable tolerances proceeded to be blended out, filled with the cold spray material, ground down to the original dimension, primed and then apply the deicer boot. This cold spray repair allows for the quick repair of an asset that is in demand by performing the repair and returning the asset back to the squadron in less than a week for a fraction of the cost of a new leading edge. The repair and modification to the coating stack-up is in line with other aircraft that use a primer and do not exhibit corrosion on the leading edge that incorporates a deicer boot.

4.0 APPROACH TO FURTHER REPAIRS

Finally, we will discuss NAVAIR's methodology in assessing corrosion damaged parts as candidates for cold spray repairs. For currently approved deposit-substrate combinations, no additional analysis is required beyond what was necessary to determine the limits of the blend repair. Our approved cold spray deposit-substrate combinations have been proven through testing to have no detriment on the remaining base material. Current focus is on expanding our repair capability to other deposit-substrate combinations. For those parts where current blend limits are insufficient to repair the damage, a database has been created to focus development efforts in testing for potential structural repairs to those deposit-substrate combinations that have the best return on investment.

For those parts where current blend limits are insufficient to repair the damage, a database has been created to focus development efforts in testing for potential structural repairs to those deposit-substrate combinations that have the best return on investment.

4.1 Repair Database

A pilot effort is underway to develop a materials engineering database to house all cold spray related repair data. The database will catalog materials data from coupon manufacturing to post-test analysis. It will house property curves once enough test data is generated. The database will be searchable by substrate, powder, repair type, and other inputs. It will allow for sharing of data across the NAVAIR enterprise. This will speed up the background work that goes into selecting a repair process for a given part function-substrate material-damage type combination.

NAVAIR is also working to develop a database that can be used to catalog each cold spray blend and fill repair. This will enable engineers to monitor repaired areas of components and track the corrosion performance of the repaired areas through subsequent inspections. As the same areas of components repeatedly need repair, this may provide justification for upgrading paints or other protective coatings in these areas, as well as enabling the capture in the increase in component life made possible by blend and fill repair.

4.2 Structural Repairs

The long range vision for cold spray repair technology is to perform structural repairs, whereby we are taking credit for the strength of the deposited material. This will require extensive testing and characterization of numerous cold spray material and process combinations followed by the development of appropriate standards to ensure process consistency and deposit quality and performance. NAVAIR Materials Engineering has worked with Structures Engineering to develop test coupons that will provide the mechanical property data necessary to analyse and validate structural repairs.

5.0 PATH FORWARD

The path forward for NAVAIR in the next five to eight years is to fully integrate cold spray metallization technology this across the Naval Aviation Enterprise as a standard corrosion prevention method. With this NAVAIR needs to encourage the development easy tools for the maintainers such as vacuum recovery, containment/capture, quality assurance, and powder packaging. NAVAIR also needs to fully integrate all of the materials and supplies into the logistics system as well as to develop and maintain a robust training program for maintainers. Simultaneously engineering needs to explore the potential to mitigate corrosion in new designs by including cold spray in the manufacturing process through building functionally graded materials, manipulation of the powders to achieve desired properties, as well as to pursue potential structural applications.

One of the original gearboxes was removed for a general inspection after 1,748 flight hours and no fretting damage to the repaired hydraulic pad was observed as show in Figure 13. This gearbox was sprayed with 4047 aluminum using a high pressure system and showed that the new alloy applied was not susceptible to the fretting condition.