

## **STRUCTURAL REPAIR FOR STRYKER HH STEEL BODY PANELS USING COLD SPRAY**

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### **ABSTRACT**

*Corrosion damage to military ground vehicles costs the U.S. Army around \$1.6B per year. A large part of that cost is related to keeping vehicles like the Stryker at their full fighting capability. Corrosion damage has been a common finding on Stryker vehicles and even light corrosion damage, which often reaches 10% of the body thickness or more, can degrade its armor protection rating and require replacement. Recently, cold spray deposition has been shown to be capable of restoring the full ballistic resistance of corrosion damaged high hard steel armor panels. These repairs can be done on-vehicle in depot facilities, using mobile high-pressure cold spray systems. This repair capability can reduce the number of entire side, roof, and floor panels that need to be cut out and re-welded in, which is the only currently approved repair operation for corrosion damage that exceeds allowable depths.*

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### **1. INTRODUCTION**

Corrosion damage to military ground vehicles cost the U.S. Army around \$1.2B in FY'16 [1]. A large part of that cost is related to keeping vehicles like the Stryker, shown in figure 1, at their full fighting capability. According to public sources [2], in order to provide simplicity of construction, as

well as armor protection, the vehicles body frame is made from high-hardness steel which offers a basic level of protection against 14.5 mm rounds on the frontal arc, and all-around protection against 7.62 mm ball ammunition. While its high hard steel body offers good ballistic protection against small arms fire, it is not particularly corrosion resistant, and corrosion damage has been a common finding on the more that 1000 Stryker vehicles that have been reset, since their inception in 2002 at Anniston Army Depot. Even light corrosion damage, which

often reaches 10% of the body thickness or more, can degrade its armor protection rating and require replacement.



**Figure 1:** U.S. Army Stryker wheeled vehicle

Cold Spray is solid-state powder deposition technology that can be used to restore structural strength to damaged materials and can even deposit materials that improve ballistic performance. Unlike low-pressure variants, high pressure cold spray has been showing increasing promise and application for structural repairs and coating applications where wrought like strengths are required. For example, numerous applications have been developed for repairing high cost and long lead time parts for the aerospace and defense market, such as aircraft skin panels, titanium hydraulic lines, aluminum valve actuator internal bores, hardened and chromed steel shafts, gas turbine engine parts, magnesium castings, and

many more [3-5]. These processes also have direct application in commercial markets like transportation and heavy industry. In particular, parts with long lead times, in excess of 12 months, have been successfully repaired and re-introduced into service. This saves not only the direct cost of the part, but also returns the system to service much sooner with a much lower labor cost due to a spot repair vs. total replacement approach. Additionally, many of these applications require spray applicator mobility, for either hand or robotic operation. VRC Metal Systems commercialized technology developed under partnership between the Army Research Laboratory and the South Dakota School of Mines and Technology which meets these mobility requirements.

### **1.1. Cold Spray Background**

The Cold Spray (CS) process is a low-cost, environmentally friendly, in-situ repair option that can add significantly more material to a surface than electroplating, without the thermal heat affected zone and distortion caused by welding. Cold Spray (CS) was developed accidentally in the mid 1980's at the Institute of Theoretical and Applied Mechanics, Novosibirsk, Russia, in the same way that many innovations have been discovered in this modern era, by trying to do something else and discovering a benefit from what was an otherwise failed experiment. What was discovered, was a method to deposit metallic powders, without melting them, onto a surface using relatively low temperature supersonic air or inert gas. Cold spray is a novel approach to applying powdered materials [6,7]. In the cold spray process small (5-50 $\mu$ m) metal particles are accelerated towards a substrate at high velocity (300-1400 m/s) by a supersonic jet of compressed gas. The particles form a coating on the substrate by means of ballistic impingement [8]. In the CS process a carrier gas (air, N<sub>2</sub>, or He), at pressures as high as 6.9 MPa (1000 psi) and temperatures as high as 800 °C (1470 °F), is expanded to supersonic

speeds through a converging diverging nozzle [9]. While gas supply temperatures may appear high, they are measured upstream of the diverging nozzle throat, after which they immediately cool as the gas expands, and the impinging gas heats the substrate to a lesser degree than other thermal spray processes, to the effect that substrate temperatures can be kept below 100°C for aluminum materials [4].

Cold spray has already been successfully applied to numerous parts within the Army, Navy, and the Air Force, with demonstrated cost savings on just 77 parts alone exceeding several million dollars as of June 2016 [10]. One of the first applications was for magnesium rotorcraft components with corrosion damage [3]. They developed a cold spray process to reclaim magnesium components that shows significant improvement over existing methods, with corrosion performance which exceeded that of the parent material across a wide range of corrosion tests [11]. The primary explanation for the increased corrosion resistance is because of the material substitution of aluminum for magnesium, thus replacing the more active magnesium with a material lower on the galvanic series. Additionally, aluminum forms a protective oxide layer, and magnesium does not. Another successful application of cold spray is for a valve actuator on Navy submarines, which has been approved for use under Uniform Industrial Process Instruction UIPI 6320-901 [12]. The repair was developed by a consortium under coordination with Puget Sound Naval Shipyard and the Army Research Laboratory where both significant corrosion and wear of the valve sealing surfaces had occurred [5].

## 1.2. A Green Technology

Cold spray has a tremendous opportunity to enhance the manufacturing sustainability of the U.S. military by repairing parts that previously could only be replaced and recycled. Cold spray

also has significant benefits for minimizing the impact of industrial processes on the environment [13,14]. It is a very “green” and environmentally-friendly process, as there are no toxic fumes or other harmful emissions from cold spray, and waste powder presents similar risks and is collected in the same way as grinding dust. The process uses inert gases like nitrogen and helium, and even high-pressure air. When nitrogen is used, it can be pulled from the surrounding environment using a nitrogen separator and then used and ventilated with fresh intake air. When helium is used, even though it is a non-renewable resource, it can be recycled indefinitely, using closed-loop helium recovery systems at efficiencies up to 95%, under idealized conditions. Furthermore, because parts are being repaired and refurbished rather than replaced, there is tremendous cost, energy, and overall environmental benefit, making cold spray a “green” technology and an excellent technology for enhancing the long-term sustainability of high value assets.

## 2. EXPERIMENTAL PROCEDURE

Because of the structural and ballistic requirements of the repair, high pressure cold spray equipment was selected for the development effort. High pressure cold spray increases the amount of kinetic energy transferred to the metallic particles in the gas stream. The consequence of this is that significantly higher particle velocities, typically increasing particle velocities by 100 m/s or more, are achievable with high gas pressures (greater than 500 psi) compared to low pressures (typically less than 300 psi). Recipes and powders were developed using a VRC Gen III™ high-pressure cold spray system (VRC Metal Systems, Rapid City, SD), which can be operated both robotically, shown in figure 2, or hand-held. VRC Metal systems has licensed a patent for the smallest and lightest cold spray gun of any cold spray system to date. The patent was developed under a joint ownership agreement between the Army Research Laboratory

and the South Dakota School of Mines and Technology.



Figure 2: VRC Gen III™ cold spray setup

### 2.1. Cold Spray of CrC-NiCr and CRC-Ni on HH Steel

**Powder:** 1) CrC-Ni and CrC-NiCr powder (VRC Metal Systems, Rapid City, SD), produced per Mil-DTL-32495, known commercially as, WIP-C1, and WIP-C2.

**Substrate:** ASTM grade HH Steel, supplied by Anniston Army Depot; 1" x 3 to 4" x 1/4" strips x 12,

**Cold Spray Process Parameters:** Nitrogen gas @ 650 psi, 700°C Applicator Temperature, 5 RPM powder federate with VRC nozzle part #NZZL0060.

**Additional Spray Parameters:** Bond Coat @ 60° spray angle with 20mm stand-off for 2 passes, with the remainder @ 90° spray angle with a 20 mm stand-off. A build thickness of 0.003-0.005" per pass for 10 passes was used to build up the test coupons.

### 2.2. Testing Procedures

**Metallography:** Samples were sectioned using a Buehler abrasive cut-off wheel, cleaned using an ultrasonic cleaner with isopropanol alcohol, and placed into individual disposable mounting cups in preparation for casting in Stycast 1266 epoxy. Once cured, the coupons were ground and polished started at 120 grit silicon carbide paper and progressed to 1200 grit silicon carbide paper. The coupons were given a final polish using 1µm alumina prior to micro-examination. Micro-examination was conducted using a Keyence VHX 6000 microscope. All photos were taken at 200x magnification. Porosity measurements were made using ImageJ image analysis software in accordance with MIL-STD-3021 and ASTM E2109.

**Mechanical:** Shear tests were conducted according to the requirements of MIL-J-24445A. The Triple Lug Shear Test method was used to as a second test to confirm coating adhesion. Triple Lug procedure methodology is prescribed in military specification, MIL-J-24445A. A coating with a thickness of greater than 0.125 inch is deposited onto the specimen. Three lugs are machined from the coating. The lugs are sheared from the test specimen using a compressive load frame. Only one lug is sheared from the specimen at a time. Failure stress is reported based on the load at failure and the surface area of the lug. Hardness testing was also conducted according to ASTM E 384.

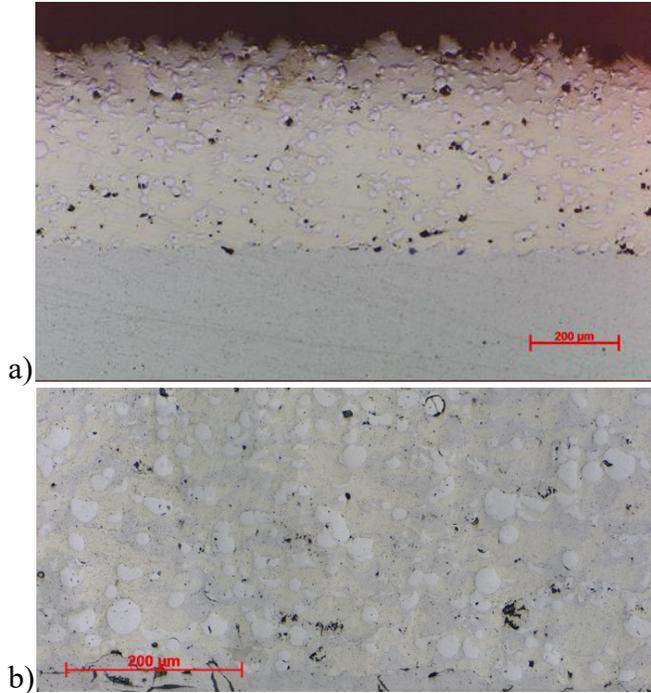
## 3. RESULTS & DISCUSSION

The results of the cold spray experiments performed are presented below. Testing included metallography, Vickers microhardness testing, three-lug shear testing, and ballistic evaluation to determine V50 performance against armor piercing threats compared to the base metal requirements.

### 3.1. Metallography

Micrographs of the deposits are shown in figure 2. Black spots in the micrographs represent voids,

but larger, particle size voids are generally carbide particle pull out rather than true pores in the coating. The actual porosity in all of the coatings tested was less than 1%.



**Figure 2:** Micrograph of NiCr + CrC (WIP-C2) cold sprayed onto HH steel using nitrogen at VRC Metal Systems a) 100x and b) 200x

### 3.2. Mechanical Results

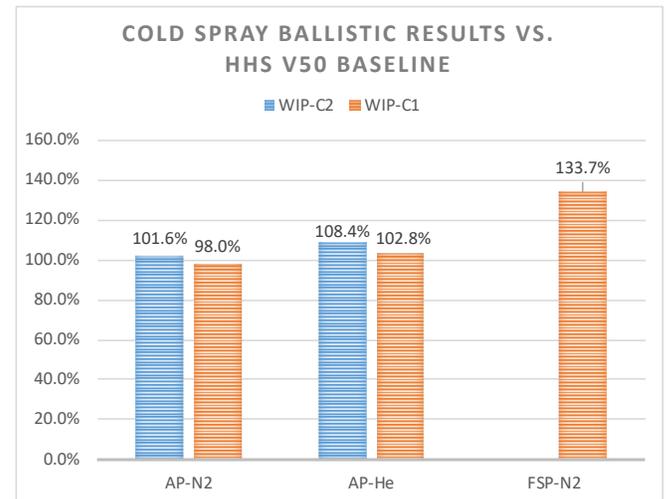
Both the CrC-Ni (WIP-C1) and CrC-NiCr (WIP-C2) cold spray deposits had three-lug shear values that exceeded 172 MPa (25ksi) when measured on the high hard steel substrate, based upon a set of 6 lugs each. The hardness of the cold spray deposits is shown in table 1 and are based on a minimum of 10 measurements.

**Table 1:** Cold spray hardness results

Sample Name	Hardness (HV)
WIP-C1 (He)	425
WIP-C1 (N2)	385
WIP-C2 (He)	475
WIP-C2 (N2)	400

### 3.3. Ballistic Results

WIP-C1 and WIP-C2 were applied at the Army Research Laboratory using a VRC Gen III™ cold spray system using process parameters similar to those developed by VRC Metal Systems for the baseline metallography and coupon level mechanical testing for deposition onto 12" x 12" high hard steel armor test panels to evaluate performance against armor piercing threats. These panels were prepared by first removing 1mm of steel from the surface, then replacing that material with the Cold Sprayed material. The original panel thickness was 7.3 mm. The depth of 1 mm was chosen because experience at the Anniston Army Depot has found that the majority of corrosion pits identified during inspections were 1 mm or less in depth, which reduces the ballistic resistance of the plate by approximately 14% and its V50 velocity by nearly 7%. V50 testing was then performed for both armor piercing (AP) and a fragment simulating projectile (FSP) on sheets repaired back to full thickness using cold spray to provide a quantitative method of comparison back to the V50 baseline for HH steel in pristine full thickness, as shown in figure 3. The results are shown as percentages of baseline.



**Figure 3:** Ballistic results for cold spray repaired panels as a percentage of baseline for AP and FSP projectiles, using helium (He) or nitrogen (N2) gas.

This testing showed that both WIP-C1 and WIP-C2 repaired panels produced using helium as an accelerating gas outperformed the baseline steel panels. WIP-C1 and WIP-C2 panels produced with nitrogen performed comparably to the baseline steel panels, and all repaired and baseline panels outperformed the specification requirements for high hard armor, with the exception of WIP-C1 with nitrogen, which was still reasonably close at 98% of baseline. It was also evident from the number of shots possible per panel (limited by the damage circumference around each shot location) that WIP-C2 outperformed WIP-C2 likely due to a slightly higher toughness in the matrix material. Limited testing performed with WIP-C1 coating sprayed with nitrogen and tested against fragmentation threats showed a significant increase in V50 performance over baseline steel. Although there is no specification requirement for high hard steel armor with respect to fragmentation threats, this result also showed great promise for increased soldier protection.

#### 4. CONCLUSIONS

Cold spray deposition of WIP-C1 and WIP-C2 powders have been shown to be capable of restoring and increasing the full ballistic resistance of corrosion damaged high hard steel armor panel when they have lost up to 1 mm (or 14% of their original thickness). The ballistic performance of the repaired panels can be increased by as much as 8% for AP rounds and 33% for FSP rounds over the original baseline HH steel, attaining multi-hit capability and defeating fragmentation threats. This means that the protection on even new vehicles could be enhanced using this technology. It also means that it is likely that even greater depths of damage than those explored in this study could be performed successfully as well, but it would require additional testing and qualification to validate that assumption. These repairs can be performed on-vehicle in depot facilities or out in the field, using mobile high-pressure cold spray systems available

from VRC Metal Systems with nitrogen and/or possibly air as the accelerating gas. Future studies could also evaluate the effectiveness of using air as the accelerant gas for cold spray deposition of WIP-C2. This repair capability will reduce the need to cut out and weld-in entire side, roof, and floor panels, which is the current repair operation when corrosion damage is found that exceeds allowable depths. It is estimated that the cold spray repair to cover the typical corrosion damage that would normally require full replacement would take about 30 man hours and \$2500 in expendables to repair, for a total estimated repair cost of less than \$15,000 per panel when equipment costs and required documentation and quality control measures are also included. This would provide a substantial savings in both repair time and direct cost when compared to full panel replacement. The ROI for this type of repair is expected to easily exceed 5:1. This new repair capability can not only save thousands of welding man-hours per year, relieving strain on the demand for qualified welders, but it also provides a dramatic cost savings. By lowering the repair costs on Stryker vehicles, we can not only reduce maintenance costs, but we could save numerous Stryker vehicles every year that have been determined to be too expensive to be repaired and instead are scrapped. At approximately \$4-5M per Stryker, cold spray is poised to save the U.S. Army hundreds of millions of dollars every year.

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