REPAIR OF SIMULATED BATTLE DAMAGED ALUMINUM USING COLD SPRAY TECHNOLOGY

Carl Paxton
Dennis Miller
Bowhead Science and Technology

Blake Barnett
Victor Champagne
Marc Pepi
US Army Research Laboratory
Weapons and Materials Research Directorate
Aberdeen Proving Ground, Maryland

Abstract
The US Army Research Laboratory was asked by the US Army Tank Automotive Research, Development and Engineering Center (TARDEC) to research the feasibility of cold-spray repairing aluminum armor panels that were shot at with 20-mm fragment simulating projectiles. The through-holes were filled using the CGT4000 cold-spray equipment. The repairs were deemed successful, since the objective was to provide protection against anticipated chemical, biological, radiological, and nuclear exposure, and to make the armor air and water tight. This result puts cold-spray technology on par with the current hull and metal component repair requirement which states, "Hull patches do not provide any additional ballistic protection; they are designed to maintain hull integrity (air/water tight)."

Introduction

Battle Damage Assessment and Repair (BDAR) is the process used to rapidly return disabled military equipment to operation by applying field expedient repairs to damaged components [1]. According to FM 4-30.31 [2], BDAR can be accomplished by bypassing components or safety devices, cannibalizing parts from like or lower priority equipment, fabricating repair parts, jury-rigging, taking shortcuts to standard maintenance, and using substitute fluids, materials, or components. References 1 and 2 do not provide remedial guidelines for ballistic repair and only list the following "fixes" with respect to repairing metal component repair:

- Metal epoxy stick (applied to damaged components as a temporary means of controlling fluid loss)
- 1:1 ratio metal polymer
- 3:1 ratio metal polymer (the best choice of polymer for engine blocks and coolant system components exposed to higher temperatures and pressures)

Welding has also been used as a means of repairing battle-damaged components; however, caution must be exercised when exposing metal components to these thermal gradients, due to the propensity of altering the prior heat treatment of the part. The US Army Tank and Automotive Research, Development and Engineering Center (TARDEC) tasked the US Army Research Laboratory (ARL) to determine the feasibility of repairing aluminum armor plates, subjected to range ballistic testing with cold-spray technology.

Cold Spray Technology

Cold spray was chosen for this repair process, because no heating of the substrate is encountered that could deleteriously affect the prior heat treatment of the armor plate. Cold spray is a mature repair technology, and the spraying of aluminum generally leads to one of the most reliable depositions of all cold-spray materials.

Cold-spray systems operate through the aerodynamic acceleration of small particles, which subsequently form a deposit through impact with a surface or with previously deposited particles [3-6]. The cold-spray process imparts supersonic velocities to metal particles by placing them in a heated nitrogen or helium gas stream that is expanded through a DeLaval converging–diverging nozzle. The powder feed is inserted at the nozzle entrance or immediately after the nozzle throat. High pressures and temperatures yield high gas velocities and high particle acceleration within the gas stream. The particles, entrained within the gas, are directed toward a surface where they embed on impact, forming a strong bond with the surface and previously deposited particles. Subsequent spray passes increase the structure thickness. The adhesion of the metal powder to the substrate, and the cohesion of the deposited material, is accomplished in the solid state.

Figure 1 is the diagram often used to illustrate this process [6]. The term “cold spray” has been used to describe this process due to the relatively low temperatures (100–500°C) of the expanded gas stream that exits the nozzle. The relatively high gas pressures used for this geometry (10–60 bar) result in the name High-Pressure Cold Spray (HPCS). The rate of powder spray (hence the rate of deposit buildup) is typically 0.05–0.2 kg/min. As the nozzle is moved over a surface, the deposited line is 5–10 mm wide, with a surface roughness, Ra, of 10–20 µm [7,8].

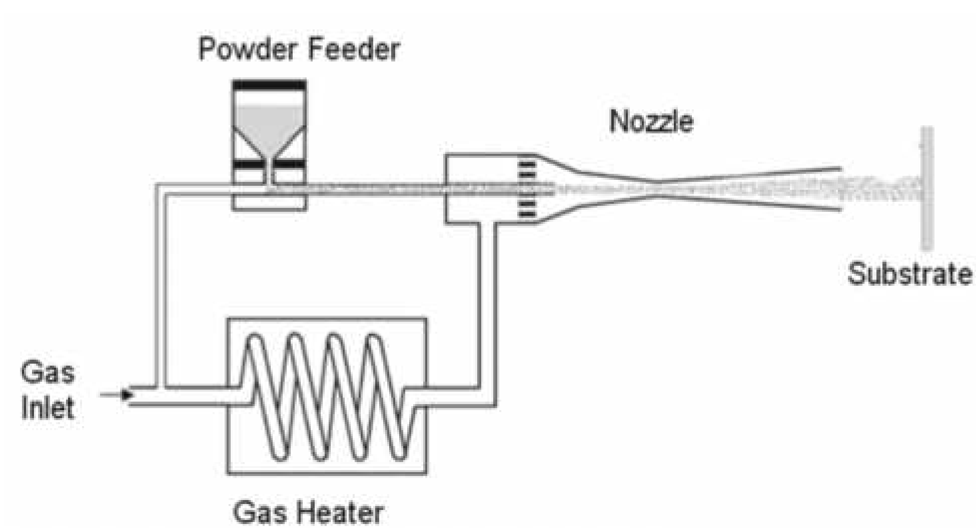

Figure 1 Schematic of a typical cold-spray assembly

Experimental

TARDEC shipped an aluminum alloy (AA) 5083 armor plate to ARL that was 24-inch × 24-inch × 0.75-inch thick (Fig. 2). It had been shot at with 20-mm fragment simulating projectiles (FSP) resulting in complete penetration through the armor. These holes were to be repaired by ARL using the cold-spray process.

Figure 2 As-received damaged AA5083 plate prior to cold spray repairs.

ARL was tasked to identify a surface preparation protocol for repairing these through-holes, as well as a suitable aluminum alloy for cold spray. ARL began with coupon-level simulated repairs, which were subjected to microstructural evaluation to get a visual of surface adhesion and fill integrity. The test coupon is shown in Fig. 3. This simulated a chamfered hole, with a backplate, which turned out to be the process used to repair the holes in the armor plate. Figure 4 shows a cross section of the coupon after it was filled with cold spray using 80% AA6061 and 20% aluminum oxide (Al_2O_3) powder; Fig. 5 shows the cross section after metallographic preparation.

Figure 1 Test coupon utilized to determine feasibility of cold spray repair of the armor plate.

Figure 2 Cross section of test coupon showing cold spray fill (region above arrows).

Figure 3 Metallographically prepared cross section shown in Figure 4.

The CGT4000 system was used for these repairs, and the parameters used are listed in Table 1.

Table 1 Cold spray parameters used for repair

Cold Spray Parameters	Robot Programming
N_2 gas at 30 Bar Gun temperature at 500°C Powder feeder at 1 rpm	Spiral program at 2000; circle program as hole is filled; back to spiral program

There appeared to be excellent adhesion between the cold-spray fill and the substrate, and the coating showed little to no porosity/cavities.

Once it was determined that the process was adequate on coupons, an actual damaged plate was repaired via cold spray. A typical projectile through-hole is shown in Fig. 6. These holes were chamfered, as shown in Fig. 7, to allow better adherence of the cold-sprayed powder, using a countersink HS 4-3-120 tool (Fig. 8). Once the chamfering was complete, the Motoman robot that holds the cold-spray nozzle, was programmed to spray the powder perpendicular to the angled sides of the chamfer. Once robot programming was accomplished, a backplate was affixed to the aluminum armor to allow for the cold-sprayed powder to build up from the bottom. As the hole was being filled, the robot would need to be reprogrammed to accommodate the new contour of the hole. Figure 9 shows an example of a completed cold-spray filled hole. After ensuring that the fill was above the surface of the plate, the cold spray was ground down to the level of the plate (Figs. 10 and 11) using a 1-inch to 3-inch fly cutter tool, followed by a 1/2-inch end mill and surface sanded using an air Dymet sander and Scotch Brite pads. Figure 12 shows a plate in various stages of repair.

Figure 4 Typical ballistic damage noted on the as-received aluminum armor plate.

Figure 5 Chamfering of hole to allow for better cold spray adherence.

Figure 6 Tool utilized to chamfer projectile holes in preparation of cold spray fill.

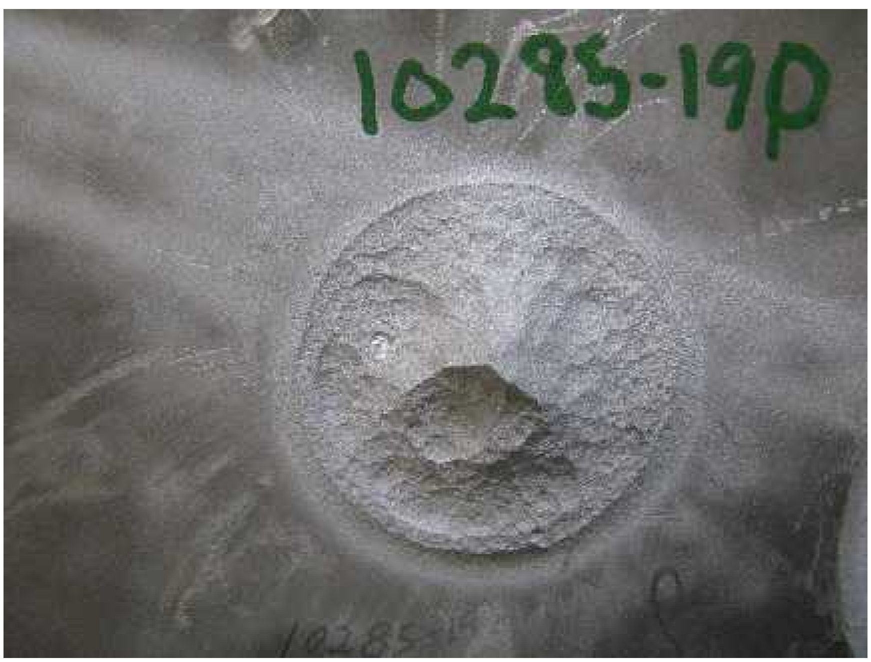

Figure 7 Typical hole filled with cold sprayed aluminum powder.

Figure 8 Typical filled hole ground smooth with a fly cutter tool, followed by a ½-inch end mill, and surface sanded using an air Dymet® sander and Scotch Brite® pads.

Figure 9 Similar to Figure 10, a filled hole ground smooth with a fly cutter tool, followed by a ½-inch end mill and surface sanded using an air Dymet® sander and Scotch Brite® pads.

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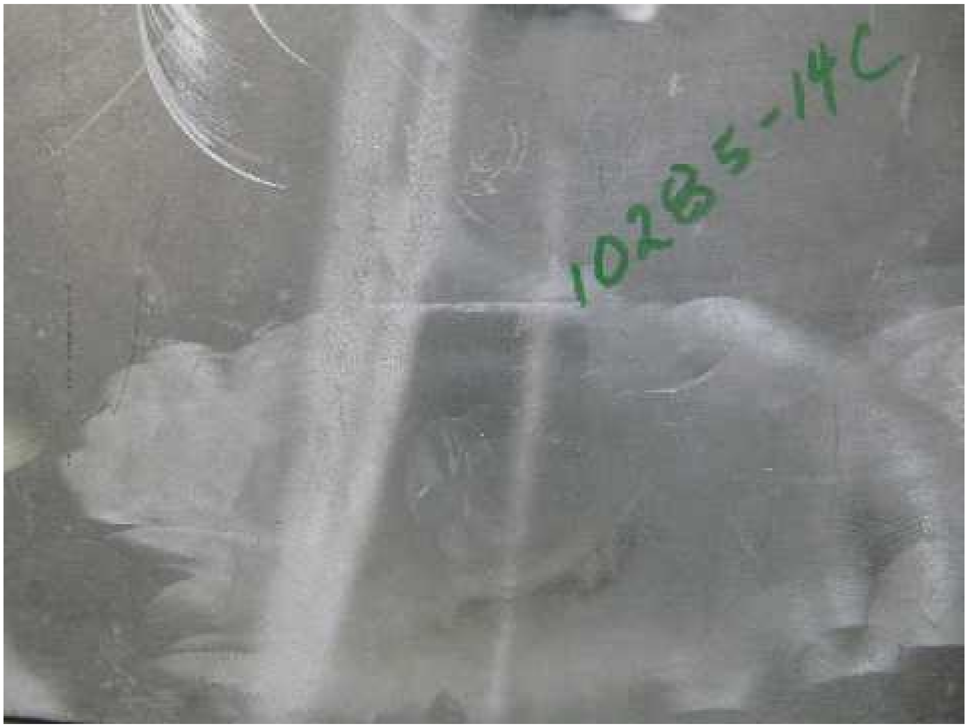

Figure 10 Aluminum armor plate showing varying degrees of repair.

Conclusions and Future Research

As far as being able to patch holes created by projectiles in aluminum armor, cold spray performed admirably. This could be deemed successful, if the object was to provide protection against anticipated chemical, biological, radiological and nuclear exposure. This result puts cold-spray technology on par with hull and metal component repair as outlined in FM 4-30.31,2 which states, "Hull patches do not provide any additional ballistic protection; they are designed to maintain hull integrity (air/water tight)."

This process could possibly be improved by first grinding off the damaged area smooth to the plate. Then, a slightly tapered cylindrical "plug" could be created from a solid rod of aluminum or of the same material as the damaged plate. The plug would need to have the larger diameter end just slightly larger than the hole in the plate. The plug would need to be driven or pounded into the hole, so that the larger end is approximately 1/8-inch below the surface of the plate. The edge of the hole would then need to be tapered, beveling the wall of the hole to 30°. This will greatly reduce the void needing to be filled with cold-sprayed powder at the inlet section of the wall and plug surface. The remaining area would simply be filled with cold spray on the plug and taper so that the coating is above the surface of the plate. The deposit could then be machined smooth with the surface of the plate as described previously, or left as coated. This would result in a much quicker repair process and be less expensive, as less powder and cold-spray operation time would be needed.

Acknowledgments

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