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# Structural repair using cold spray technology for enhanced sustainability of high value assets

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**Abstract**

Cold spray technology has been in significant development since the early 1990s, however, not until recently has it begun to approach near wrought like properties for metals and alloys of aluminum, copper, nickel, titanium, as well as steels, stainless steels, superalloys, and refractory metals like niobium and tantalum. These advancements have come through the use of high pressure cold spray equipment and a greater fundamental understanding of the process variables. As a result, numerous applications have been developed for repairing high cost and long lead time parts for the aerospace and defense market, as well as a broad range of commercial markets such as oil & gas, transportation, and heavy industry. In particular, parts with 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. Cold spray is an additive manufacturing technology that uses heated high-pressure inert gas to accelerate metal powders through a converging-diverging de Laval nozzle above the critical velocity for deposition onto a substrate. The process produces only mild heating of the substrate compared to most conventional metal deposition or welding technologies, hence the nomenclature of “cold” in cold spray, even though there is heating of the gas in almost all cases. There are also no toxic fumes or other harmful emissions from cold spray because the accelerant gases are: 1) inert (helium, nitrogen, or air), and 2) the heating source is electric and is controlled at temperatures below the melting temperature of the material being sprayed. Furthermore, because parts are being repaired and refurbished rather than replaced, there is tremendous cost, energy, and overall environmental benefit, making cold spray a very “green” technology and an excellent technology for enhancing the long-term sustainability of high value assets.


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## 1. Introduction

Cold spray technology (CS), also referred to as supersonic particle deposition (SPD) and cold gas dynamic spray (CGDS), is in the family of other thermal spray processes, but is unique because it is a completely solid-state deposition technology. Developed at the Russian Academy of Sciences in the 1980s and patented in the US in 1990 [1], cold spray has been around for a while, but it progressed slowly until the introduction of high pressure cold spray systems around 2007, which began yielding better properties [2-4]. Since 2013, major advancements have been occurring in the technology as additional equipment has become available and the fundamentals of the process are now much better understood [5-7]. Cold spray is an additive manufacturing technology that uses heated high-pressure inert gas to accelerate metal powders through a converging-diverging de Laval nozzle above the critical velocity for deposition onto a substrate. Upon impact particles deform, creating high strains and localized plasticization of the material so that a combination of both mechanical interlocking and metallurgical bonding can be achieved [7,8].

In this paper, current successfully repaired and qualified applications will be discussed, as well as the material properties achievable and their comparison to traditional wrought and cast materials that it is being applied to. Examples of successfully repaired parts include aluminum valve actuator internal bores [9], magnesium castings [10], aircraft skin panels [11], titanium hydraulic lines [11], as chrome replacement for steel shafts [12], gas turbine engine parts [13], aluminum molds [14], high strength steel parts [15], and many more. The paper will also discuss the development process for designing and qualifying a repair, as well as a basic understanding of the equipment and costs involved in implementing the repairs.

**Nomenclature**

| | |
|---|---|
| CS | cold spray |
| SPD | supersonic particle deposition |
| CGDS | cold gas dynamic spray |

### *1.1. Process Description*

Cold spray is a low temperature thermal spray process that uses primarily kinetic energy rather than thermal energy to form a coating or near net shape deposition on a wide range of substrates. The process can deposit metallic particles or combinations of metallic and non-metallic particles and consolidate them by means of ballistic impingement upon a suitable substrate. The particles utilized can be from commercially available powder sources and typically range in size from 5 to 50 μm. The powders are then accelerated to from 300 to 1,400 m/s when injected into a high pressure, pre-heated gas stream and accelerated through a converging-diverging De Laval nozzle, as shown in Fig. 1. The pressurized gas is expanded to supersonic velocities, approximately Mach 1-3 [16,17]. The particles, initially carried by a separate gas stream, are injected into the nozzle either prior to the throat of the nozzle or downstream of the throat. The particles are subsequently accelerated by the main nozzle gas flow and impacted onto a substrate after exiting the nozzle.

Upon impact, the solid particles deform and create a bond with the substrate [17,18]. The bonds are comprised of both mechanical interlocking, as well as metallurgical bonding by dynamic recrystallization at high shear strain boundaries. As the process continues, particles continue to impact the substrate and form bonds with the consolidated material resulting in a uniform deposit with very little porosity and high bond strength. The term ‘cold spray' has been used to describe this process due to the relatively low temperatures (100 to 400 °C) of the expanded gas stream that exits the nozzle, but more importantly because of low rate of heating caused in the material substrate. The temperature of the gas stream is set below the melting point of the particulate material during cold spray, and the resultant consolidated material is formed in the solid state, which yields some unique material properties. The low temperatures associated with the cold spray process are desirable, especially when it comes to joining dissimilar metals that have low melting points, such as aluminum to magnesium, materials which are sensitive to heating and oxygen uptake such as titanium, or when nanostructured powders are used as feedstock. Because the process is occurring at low temperatures and very short durations, the risk of grain growth and phase transformation is minimal or nonexistent, as is the formation of a heat affected zone. Additionally, particle oxidation is avoided as are high tensile stresses that occur during thermal contraction from the liquid to solid phase, most often associated with welding techniques. The stresses which do occur are generally low by comparison to traditional welding and are compressive rather than tensile, but nevertheless may not be negligible for very thin substrates or complex stress states. Because of these advantages, cold spray has been successfully developed for a broad range of applications [19].

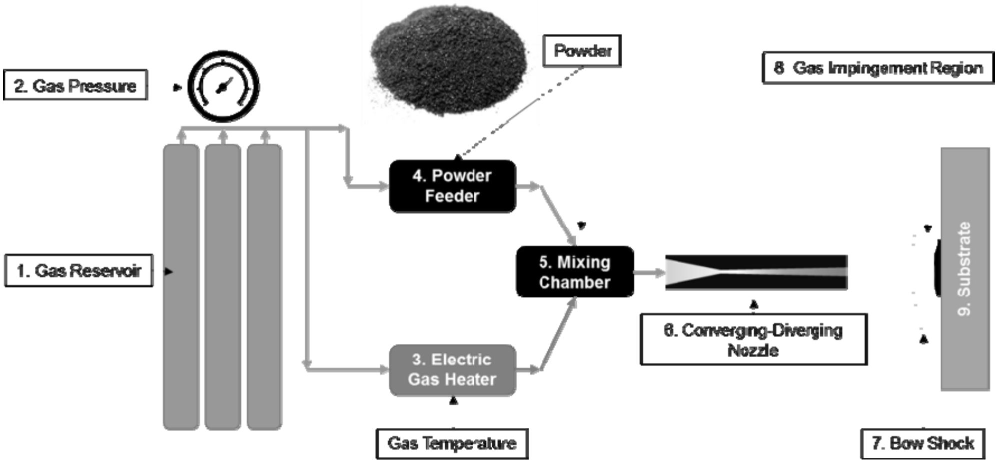


Fig. 1. cold spray process diagram

## *1.2. Benefits*

The primary benefits of this technology over other thermal spray options (e.g. plasma spray) are low operating temperatures (<800 °C), ease of implementation, and low manufacturing and operating costs. The simplicity of the cold spray process makes it an attractive alternative to high temperature thermal spray processes such as: in-flame spraying, high velocity oxy-fuel flame spraying and plasma spraying, where a combustion chamber or electric arc have to be used [17,20]. In cold spray, inert and light compressible gasses are used for particle acceleration. The lack of oxygen in the process reduces the chance of oxide generation and retention, and superior mechanical properties can be achieved in comparison to thermal spray processes [21]. Furthermore, cold spray operating temperatures are far below the melting temperatures of both the substrate and the powder, and thermal stresses on sensitive parts can be greatly reduced [22].

Restoration of worn and corroded parts is a common application of the current high pressure cold spray technology development. Throughout the cold spray process, particles and the substrate are in the solid state and are well below their melting temperatures, where the mechanism of bonding is mainly caused by extreme plastic deformation. This makes cold spray deposition a good fit for coating of heat and oxidation sensitive materials such as copper and titanium. Also, the structural integrity of the target substrate remains unaffected by the cold spray process due to the low working temperatures of the process. Thus, cold spray repair has the potential to improve part life without adversely affecting strength, especially in nonstructural, wear and corrosion repairs.

Repair capabilities of CGDS have also been evaluated and compared with traditional repair methods for high strength steel materials in general, by Faccoli et al. [15]. In their work, two identical martensitic steel substrates were repaired with TIG welding and cold spray deposition, and the repairs were compared using optical metallography, corrosion, residual stress, and micro-hardness analyses. Post-deposition observations showed that the base material was not altered in any physical form except a very thin adhesion layer (up to 50 μm) upon the impact of powder particles. The bombardment of particles was found to add compressive residual stress with peening effect, which would in general improve the fatigue properties of the material. Hardness of the cold spray repair is reported to be higher than that of the welding repair. It was also noted that the high hardness of the coating does not have adverse effects to the base material with high toughness. Welding repairs generally induce high thermal stress concentration regions and distortions in the crystal structure. Preheating and/or post-weld heat treatment procedures are thus required to relieve the negative effects of welding, consequently adding cost and time to the repair process. Unlike welding repairs, cold spray repairs do not often require post-spray heat treatments. Since negligible alterations to the base material are introduced during cold spray deposition, this allows the base material to be repaired multiple times.

Bonding of dissimilar materials is another advantage of cold spray [23]. Like explosive bonding, the mechanical and metallurgical adhesion of the particles to the substrate allows for dissimilar material coatings, which is important for benefitting from the corrosion resistant properties of a dissimilar material coating. Dissimilar metal coatings with low porosity can also be used for corrosion prevention applications with either anodic or cathodic passive protection [24].

## 2. Sustainability Considerations

While cold spray has been shown to be viable metal deposition coating technology with numerous benefits, one aspect of cold spray that has not gained as much appreciation, is what it can contribute in terms of sustainability. Cold spray is a very “green” technology. It creates no harmful emissions, has no appreciable environmental impact, and is a powerful tool for sustainability across a wide range of industries by repairing rather than replacing components. The process can also be used to replace less environmentally friendly processes like chrome plating, which produces hexavalent chrome emissions. Cold spray can even perform “spot” repairs on components coating with other plating and thermal spray processes which would normally have to be completely stripped and recoated to repair a damaged area.

Thus, the benefits of cold spray for sustainable manufacturing can be divided into four main areas:

1. Low environmental impact of the process
2. Repair rather than replacement
3. Advanced performance enhancing the useful life of components
4. Displacement of more polluting or less sustainable alternatives

### *2.1. Environmental Concerns*

Overall, cold spray technology has a low environmental impact as an industrial process. There are no toxic fumes or harmful emissions from the process, metal powders and inert gases such as helium are recyclable, and the powders can be deposited with very high efficiencies. However, there are features of its use that without context or other related experience, may at first appear to be more dangerous and difficult to manage than they are. The primary risks are related to the handling of metal powders, oxygen displacement from the carrier gas, hearing protection from the spray nozzle, breakage of high-pressure heated hoses, and the use of a pressure vessel which feeds powder to the process. These risks can be mitigated and controlled, and are generally much less than risks associated with other common industrial processes, however, as with any new process, there is a need to educate the work force about the associated risks, so that they can be managed accordingly.

For instance, cold spray uses metal powders that must be handled and transported properly or they can pose a risk of flammability and explosion. It is important to note that the explosion risk is in a similar manner to flour, sugar, and gasoline. Cold spray powders are explosive when: (1) there is a cloud of powder of sufficient concentration, (2) the presence of oxygen (or similarly reducing gas) and (3) there is a significant ignition source. There are also industrial specifications for the handling and use of metal powders which both aid in the design of facilities and the development of standard operating procedures for working with them [25,26], as well as applicable sections from OSHA General Industry safety standards (29 CFR 1910). Common mitigation solutions include having special Class D fire extinguishers present for metal powders and avoiding flammable quantities in the work area with dust collection equipment and regular housekeeping so that appreciable amounts of powder do not accumulate.

Another risk is the displacement of oxygen by the inert gases used as the propellant for the metal powders. This risk is very low, and is completely non-polluting and non-toxic. Furthermore, the risk can be managed using system controls and commercial oxygen sensors and alarms that can alert personnel if oxygen limits fall below a safe limit in a working space. Sound decibel levels created by the process are another important concern and must be controlled per applicable standards [27]. Cold spray nozzles can produce between 110-120 dB in the immediate vicinity of the nozzle (<1m). Therefore, cold spray is generally performed in a sound damping enclosure, and any person working within the enclosure or working in an area with sustained noise above 85 dB should be wearing hearing protection. For a person operating a hand-held cold spray system, it is generally recommended that they use both in-ear (ear plugs) and over-ear (ear muffs) hearing protection for the best overall protection.

Finally, the process uses a high-pressure heated gas source and therefore there are risks associated with the high temperatures and pressurized regions of the system, due to mechanical failures. Personnel can receive burns from heated lines or sudden failure of press, either from contact with an un-insulated portion of the line or from hot gas exiting the line either at the nozzle end or from a rupture or leak in the line. Also, in the unlikely event that the pressure vessel of the heater or powder feeder failed, or were opened under pressure, there is a risk of injury as well. The cold spray applicator nozzle must also never be placed up against a person's skin or body, as severe injury or death could result when the system is pressurized or still hot.

### *2.2. Repair vs. Replacement*

Probably the most obvious way that cold spray technology can enhance the sustainability of manufacturing and manufactured systems is through repairing rather than replacing components [28]. The decision to repair or replace is also highly driven by both the repair cost and the repair frequency [29]. With cold spray, there is the opportunity to both maintain reasonable repair costs and reduce the frequency of repair. This can be accomplished in two ways:

1. The repair can be performed with the same or similar material. Many repairs are recurring repairs due to failures of the repair materials, as in composite and epoxy patches, which may need to be routinely replaced in maintenance and overall activities because of interfacial stresses from differential thermal expansion or accelerated corrosion at failed faying surface interfaces.
2. The application is generally only needed on the repair zone. Unlike welding solutions, which often require multiple locations to be repaired because of distortions in the part, cold spray can be applied solely to the affected area and then re-machined or ground to the proper dimension.

### *2.3. Increased service life through advanced coatings*

Another significant opportunity for cold spray repairs to increase the sustainability of systems is by substituting an even higher performing material where corrosion or wear are the dominant failure mechanisms. For instance, ceramics and carbides can be easily incorporated into cold spray deposits, providing significant wear benefits in percentages as low as 20%. Furthermore, materials with different electrochemical corrosion potentials can be deposited, such that the cold spray zone corrodes preferentially (anodic), at a similar rate to the substrate (matching), or is protected from corrosion (cathodic), or because it generally resists chemical corrosion in that environment.

### *2.4. Replacement of more polluting or less sustainable options*

The strengths and weaknesses of a technology must always be considered against existing alternatives, particularly in the evaluation of its potential benefits. If a given technology, while not perfect, can replace a technology that is less so, then it may be worth considering. In particular, chrome plating, which releases hexavalent chrome, Cr(VI), and is a genotoxic carcinogen, has been targeted for replacement, due to its low exposure limits set by governing bodies such as OSHA, the Occupational Safety and Health Agency in the United States. Cold spray offers an attractive alternative, as no hexavalent chrome or metal fumes are produced during the process. Cold spray also boasts very high deposition efficiencies under optimum conditions [30], efficiencies which compared to typical values typically observed in thermal spray, can be from 2-3 times better. This increased efficiency can lower costs and reduce waste compared to other processes.

## 3. Cold Spray Properties

As mentioned in section 1, many applications have already been successfully implemented using cold spray. For industrial application, those success stories are often not available due to their proprietary nature, however, some of the growing number of cases were referenced in this introduction. Additionally, since the introduction of pressures over 250 psi (17 MPa), cold spray properties have been increasing, opening the door for structural repairs with the introduction of systems which were capable of pressures greater than 500 psi (35 MPa). The VRC Gen III cold spray system (VRC Metal Systems, Rapid City, SD), provides a system with pressures up to 1000 psi (69 MPa), and was used to produce the data in this study.

Developing a CS repair requires an understanding of the stresses and conditions present that led to failure in the first place and an understanding of the mechanical properties and microstructure of the cold spray deposit that would be subjected to the same conditions at the failure location. With these two pieces of information, the likelihood of repair success or failure can be determined. Along with some cost estimates, the feasibility of a cold spray repair can then be decided.

### *3.1. Mechanical Properties*

A selection of cold spray properties that can be achieved using cold spray are shown in Tbl. 1 below. All materials showed that greater than 10 ksi (6.9 MPa) bond strengths were achievable, with maximum as-sprayed tensile strengths as high as 78.5 ksi (541 MPa). As seen, the best properties are still achieved with helium, however, high pressure has made it possible to reach very high deposition strengths with nitrogen, and even air.

Table 1. Examples of cold spray properties achieved for select materials

| Cold spray material | UTS (*MPa*) | Elongation (%EL) | Adhesion (MPa) | Hardness |
|---|---|---|---|---|
| 316L SS (He) | 40.1 (276) | 1.5 | >10 (69) | 30 HRC |
| 90Cu-10Sn [DT31] (He) | 56.1 (387) | 1 | >10 (69) | 125 HV |
| 4340 + 20%CrC (He) | ---- | -- | >10 (69) | 50 HRC |
| CP-Ti (He) | 78.5 (541) | 2.8 | >10 (69) | 230 HV |
| NiCr + 25%CrC ($N_2$) | ---- | -- | >10 (69) | 40 HRC |
| Al 2024 (He) | 60.1 (414) | 4.1 | >10 (69) | 167 HV |
| Al 7075 (He) | 53.4 (368) | 2.8 | >10 (69) | 132 HV |
| Al 7075 ($N_2$) | 37.9 (261) | <1 | >10, (69) | 109 HV |
| Al 6061 (He) | 46.7 (322) | 5.2 | >10 (69) | 90 HV |
| Al 6061 ($N_2$) | 29.8 (205) | <1 | >10 (69) | 105 HV |
| Al 6061 (Air) | 19.7 (136) | <1 | 9.2 (63) | 105 HV |

### *3.2. Microstructure*

As discussed in section 1, and shown in Fig. 2, cold spray produces a low porosity, highly cold-worked, wrought microstructure using high pressure cold spray. Porosities are generally below 1%, and even under poorer deposition conditions, or when depositing difficult to spray materials, can be kept below 5%. The other question, particularly with regards to corrosion, is whether there is interconnected porosity. One way to test for this is using a vacuum test and checking for helium leakage into the vacuum area. The Al 6061 CS coating made using helium has been found to be leak tight to $10^{-9}$ torr, but a similar coating using nitrogen as the process gas was not, indicating that the level of consolidation is most likely related to its mechanical strength and/or ductility.

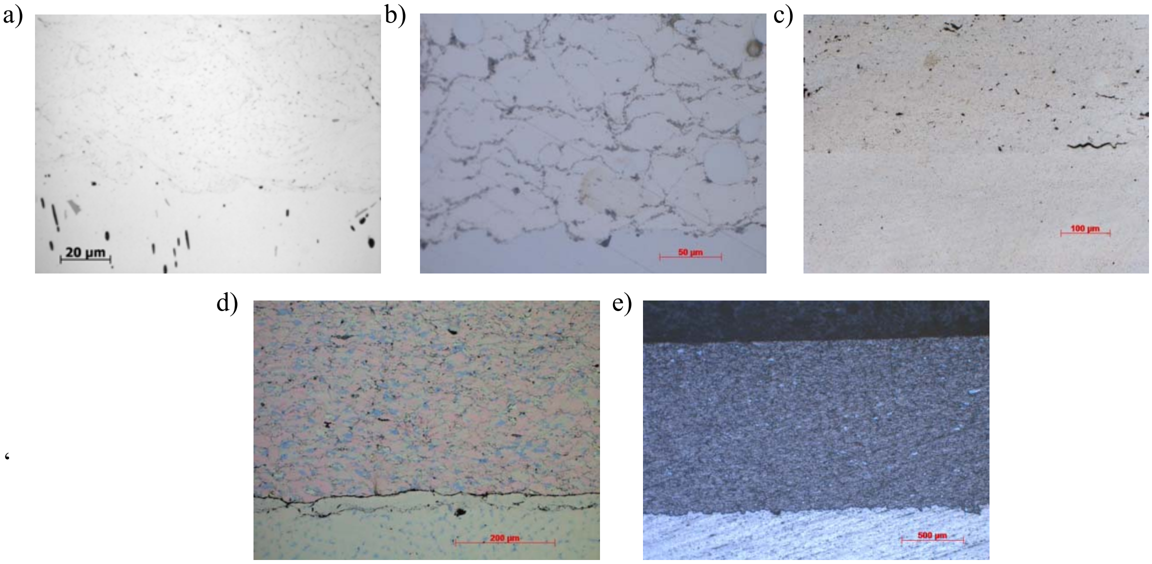


Fig. 2. a) 2024 aluminum on 2024 b) NiCr + 25%CrC on mild steel c) 316L stainless steel on 316L d) 90Cu-10Sn (DT31) on bronze alloy e) commercially pure Titanium on Ti-6-4.

### *3.3. Estimating Cold Spray Costs*

When considering costs of CS, there exists some notion that higher pressures also equate with higher costs, however, this is not necessarily true. The increase of pressure in a cold spray system increases the velocity of the powder particles by increasing the gas density, drag, and subsequent acceleration forces on a particle. This leads to higher deposition efficiencies, so more of the powder being sprayed ends up in the coating. Cold spray costs include: 1) gas (He, $N_2$, or Air), 2) powder usage, 3) labor costs, 4) equipment capital related costs, and 5) facilities costs. The primary cost driver for all of those, except 2) powder usage, is the cold spray deposition rate. High pressure increases the maximum possible deposition rate by increasing the carrying capability of the gas stream. Thus, when one considers the cost per deposited lb or kg of material, the faster it can be deposited per unit time, at acceptable quality properties, the lower the unit cost. This is because labor rates, overhead, shop floor space, equipment, etc. are fixed costs per hour, but they can be spread over a greater number of parts if the deposition rate is higher and cycle times are shorter, irrespective of the gas usage over a given hour. Powder costs are a fixed cost per part, so it is the only variable which is irrespective of time. With a high-pressure system using 30-100 cfm (800-2800 slm), cold spray deposition rates can range from 2-15 lb/hr (1-7 kg/hr), while maintaining high strength performance targets. Using less gas flow or lower pressure would also mean less powder flow, and hence higher fixed costs per deposited lb/kg. Cold spray can use commercially available powders, which depending on the supplier and material type can range from $20-$100 USD/kg for engineering alloys, or even more for specialty and precious metal powders. The powders may also require additional sieving or heat treating which can add additional processing costs. Electrical costs are relatively low, \$1.50 - \$6 USD/hour. The gas used is largest variable cost ranging from \$0.03-\$0.07 / $ft^3$ (\$1.76 / $m^3$) for nitrogen to \$0.30 - \$0.50/ $ft^3$ (\$10.59 / $m^3$) for helium. With helium recovery, however, 90-95% can be captured and recycled, making it the cheapest gas for high rate production. Finally, deposition efficiencies are typically 60-90%.

## 4. Summary and Conclusions

This work represents an attempt to demonstrate the viability of cold spray technology as a sustainable manufacturing process, with broad reaching benefits, particularly for structural repair. Cold spray can be a powerful tool for maintaining and refurbishing high cost items, which not only controls cost, but can help maintain productivity of a system, factory, or facility. This is accomplished through environmentally friendly means, and provides a method to deposit metals onto components with very high adhesion and strength, with minimal impact on the substrate. As with any new industrial process, there can be risks associated with its operation, and it is important to both design a facility installation correctly to accommodate the new process, and to properly educate and train the workforce engaged in adopting the new technology.

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