SOUTH DAKOTA
SCHOOL OF MINES
& TECHNOLOGY

Cold Spray

A guide to best practice

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Table of Contents

1.0 Introduction

The Arbegast Materials Processing and Joining Laboratory (AMP) is a research center at the South Dakota School of Mines & Technology created to examine advances in new technologies related to materials such as the friction stir welding processes and cold spray deposition. It provides fundamental and applied research and development opportunities in state-of-the-art materials joining and parts fabrication technology to students. AMP is the administrative lead of the National Science Foundation's (NSF) Industry/University Cooperative Research Center (I/UCRC) for Friction Stir Welding and works along with other universities, US Government/Military, and industrial sponsors from around the world in advancing this new technological application. It was built by congressional funding provided through the Army Research Lab. The Lab also receives funding from its association with the state funded Repair, Refurbish & Return to Service Center (R3S).

2.0 About this Guide

The purpose of this best practice guide is to develop the manufacturing process controls for a cold spray operation utilizing a high-velocity jet of solid-phase particles. The jet temperatures are below the melting thresholds of many engineering materials. This allows the process to be used to apply deposits on a wide variety of substrates, such as, alloys, ceramics, and plastics. Moreover, the deleterious effects of deposit oxidation, evaporation, and residual stresses are avoided.

3.0 Cold Spray

This standard describes the process requirements for surfacing by means of cold spray deposition. The term "cold spray" has been used to describe this process because both the temperature of the powder-laden gas jet and the temperature of the powder material are low enough to prevent a phase change or stress in the deposit or substrate. Cold spray is a process whereby metal powder particles are utilized to form a deposit by means of ballistic impingement upon a substrate. The metal powders range in particle size from 5 to 100 micrometers (µm) and are accelerated by injection into a high-velocity stream of gas. The high velocity gas stream is generated through the expansion of a pressurized, preheated, gas through a nozzle. The pressurized gas is expanded in order to achieve high velocity, with an accompanying decrease in pressure and temperature. The powder particles, initially carried by a separate gas stream, are injected into the nozzle either at the nozzle entrance or at a lower pressure point downstream of the entrance. The particles are then accelerated by the main nozzle gas flow and are impacted onto a substrate after exiting the nozzle. The solid particles that impact the substrate above a threshold (critical) velocity for the powder and substrate combination will deform and bond in a dense layer. As the process continues, particles continue to impact the substrate and form bonds with the previously deposited material resulting in a uniform deposition with very little porosity and high bond strength

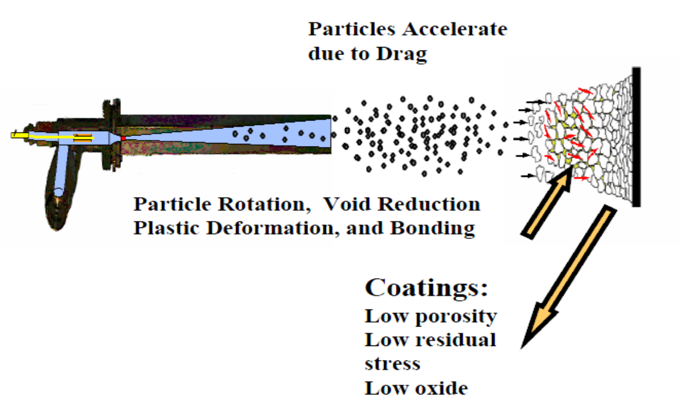

Figure 1 Kinetic Spray Process

3.1 Process Types

Cold Spray system configurations fall into two categories depicted by figure 2 and 3: high-pressure and low-pressure systems

- **High Pressure.** Figure 2 shows a high-pressure system in which the main gas stream and the powder stream are both introduced into the inlet chamber of the nozzle. This configuration requires that the powder feeder be capable of high gas pressure and is most often used in stationary cold spray systems. High-pressure systems utilize higher pressure gases and often have a dedicated gas compressor. A low molecular weight gas, such as helium, is sometimes used as the accelerating gas when particles must be brought to very high velocity.

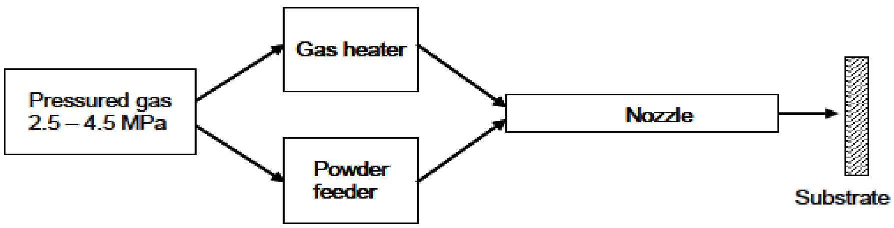

Figure 2 High Pressure System

- **Low Pressure.** Figure 3 shows a system in which the powder stream is injected into the nozzle at a point where the gas has expanded to low pressure. Atmospheric pressure air, drawn by the lower pressure nozzle injection point, is used for powder transport from the feeder. Since this system does not require a pressurized feeder, it is often used in portable cold spray systems. The low-pressure system generally utilizes readily available compressed air, but can utilize nitrogen as well.

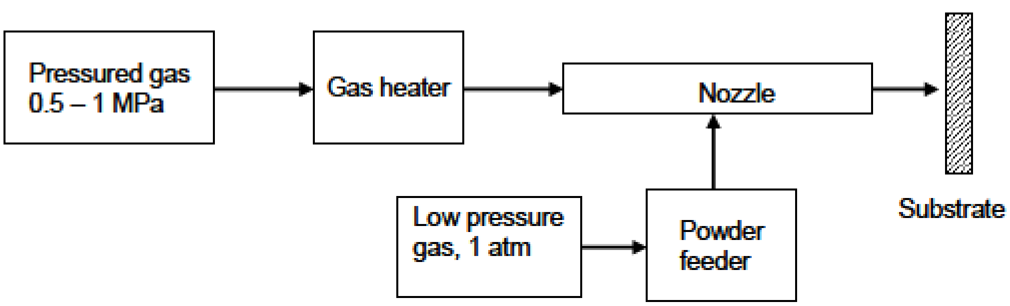

Figure 3: Low Pressure System

3.2 Range of Applications

The superior qualities of cold sprayed deposits are often required by the application. For example, the high heat transfer coefficient and electrical conductivity of cold sprayed deposits favor its use in electronic applications. Applications for cold spray technology often occur in situations where conventional thermal metal spray technology cannot be successfully used and where cold spray will result in an improved deposit. These situations often occur when high temperatures cannot be tolerated by the substrate. Good corrosion protection is achieved by dense, impermeable cold sprayed deposits. Wear resistant, hard surfaces, such as MCrAlYs, can be deposited by cold spray when operated at its high-temperature end.

3.3 Benefits of Cold Spray Over Other Thermal Spraying Processes

Compared with other coating processes, Supersonic Cold Spray offers many technical benefits, including:

- Has been used to produce dense, pure, thick and well bonded deposits of many metals and alloys, such as aluminum (Al), copper (Cu), nickel (Ni), tantalum (Ta), commercially pure titanium (Ti), silver (Ag), and zinc (Zn), as well as stainless steel, nickel-base alloys (Inconels, Hastalloys), and bondcoats, such as MCrAlYs.
- Cold spray can produce composites, such as metal-metal like copper-tungsten (Cu-W) or copper-chromium, metal-carbides like aluminum-silicon carbide (Al-SiC), and metal-oxides like aluminum-alumina.
- Cold spray has been used to produce protective coatings and performance enhancing layers, ultra thick coatings, freeform and near net shape substrates. Typical protective coatings produced by cold spray include MCrAlY coatings for high temperature protection and bond coats for thermal barriers, copper-chrome layers for oxidation protection, and corrosion resistant aluminum and zinc coatings for oil and auto industries and others.

3.4 Deposition and Bonding Process in Cold Spray

Cold spray is a solid-state particle deposition process that results in a combination of mechanical interlocking by deforming the substrate surface as well as true metallurgical bonding on the interfaces of each particle impact site. A schematic of the deposition and bonding process is shown in Figure 4. The mechanism is similar to explosion welding; however, the process occurs one particle at a time rather than one single sudden dramatic event. The depositions are characterized by significant increases in the percentage of cold work in the material from the large plastic strains that result from the impacts. The depositions also contain residual compressive stresses from those same impacts, similar to a shot peening phenomenon, except that the particles remain adhered to the surface of the material. There is also a degree of recrystallization that occurs at the actual particle interfaces which contributes to the metallurgical bonding that has been found to be present in the deposited layers.

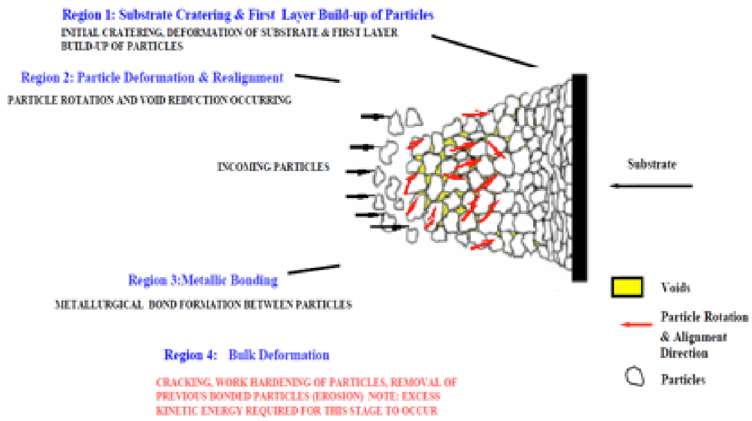

Figure 3: Bonding Stage

4.0 Process Technology and Applications

The term "cold spray" has been used to describe this process because both the temperature of the powder-laden gas jet and the temperature of the powder material are low enough to prevent a phase change or stress in the deposit or substrate. Cold spray is a process whereby metal powder particles are utilized to form a deposit by means of ballistic impingement upon a substrate. The metal powders range in particle size from 5 to 100 micrometers (μm) and are accelerated by injection into a high-velocity stream of gas. The high velocity gas stream is generated through the expansion of a pressurized, preheated, gas through a nozzle. The pressurized gas is expanded in order to achieve high velocity, with an accompanying decrease in pressure and temperature. The powder particles, initially carried by a separate gas stream, are injected into the nozzle either at the nozzle entrance or at a lower pressure point downstream of the entrance. The particles are then accelerated by the main nozzle gas flow and are impacted onto a substrate after exiting the nozzle. The solid particles that impact the substrate above a threshold (critical) velocity for the powder and substrate combination will deform and bond in a dense layer. As the process continues, particles continue to impact the substrate and form bonds with the previously deposited material resulting in a uniform deposition with very little porosity and high bond strength.

The two principal cold spray system configurations are depicted by Figures 1 and 2. The two configurations differ in the carrier gas, gas pressure, and powder injection location. Figure 1 shows a high-pressure system in which the main gas stream and the powder stream are both introduced into the inlet chamber of the nozzle. This configuration requires that the powder feeder be capable of high gas pressure and is most often used in stationary cold spray systems. High-pressure systems utilize higher pressure gases and often have a dedicated gas compressor. A low molecular weight gas, such as helium, is sometimes used as the accelerating gas when particles must be brought to very high velocity. Figure 2 shows a system in which the powder stream is injected into the nozzle at a point where the gas has expanded to low pressure. Atmospheric pressure air, drawn by the lower pressure nozzle injection point, is used for powder transport from the feeder. Since this system does not require a pressurized feeder, it is often used in portable cold spray systems. The low-pressure system generally utilizes readily available compressed air, but can utilize nitrogen as well.

4.1 Definitions

Cold spray. Cold spray is a materials deposition process in which relatively small particles (ranging in size from approximately 5 to 100 micrometers (μm) in diameter) in the solid state are accelerated to high velocities (typically 300 to 1200 meters/second), and subsequently develop a coating or deposit by impacting an appropriate substrate. Various terms—including "kinetic energy metallization," "kinetic metallization," "kinetic spraying," "high-velocity powder deposition," and "cold gas-dynamic spray method"—have been used to refer to this technique. In most instances, deformable powder particles in a gas carrier are brought to high velocity through introduction into a nozzle, designed to accelerate the gas. The subsequent high-velocity impact of the particles onto the substrate disrupts the oxide films on the particle and substrate surfaces, pressing their atomic structures into intimate contact with one another under momentarily high interfacial pressures and temperatures.

Increment. The distance between adjacent passes.

Layer. Multiple passes over the work piece that result in complete coverage.

Lot. A lot is all the parts of a similar configuration, coated sequentially on the same machine setup using the same batch of coating material and process parameters, within a shift or eight hours of operation, and presented for processor's inspection at one time.

Nozzle. A gas manifold designed to accelerate a gas to high velocity.

Pass. A single traverse by the nozzle over the work piece.

Powder lot. A powder lot is all the powder of a specified type manufactured at the same time.

Powder meter wheel. A perforated wheel which meters powder feed rate through rotation speed.

Simulated part. A simulated part is a test piece or section with a similar surface configuration to the part it represents. The simulated part will be approved by the acquisition authority.

Substrate. The material, work piece or substance on which a coating is deposited.

Thermal Spraying. A group of processes wherein metallic or nonmetallic materials are deposited in a molten or semi-molten condition to form a deposit. The feed material may initially be in the form of powder, ceramic rod, or wire.

4.2 General Requirements

The cold spray process has been used to produce dense, pure, thick and well bonded deposits of many metals and alloys, such as aluminum (Al), copper (Cu), nickel (Ni), tantalum (Ta), commercially pure titanium (Ti), silver (Ag), and zinc (Zn), as well as stainless steel, nickel-base alloys (Inconels, Hastalloys), and bondcoats, such as MCrAlYs. Cold spray can produce composites, such as metal-metal like copper-tungsten (Cu-W) or copper-chromium, metal-carbides like aluminum-silicon carbide (Al-SiC), and metal-oxides like aluminum-alumina. Cold spray has been used to produce protective coatings and performance enhancing layers, ultra thick coatings, freeform and near net shape substrates. Typical protective coatings produced by cold spray include MCrAlY coatings for high temperature protection and bond coats for thermal barriers, copper-chrome layers for oxidation protection, and corrosion resistant aluminum and zinc coatings for oil and auto industries and others.

Process. The process utilizes nitrogen, which has been compressed to propel metal powder onto the surface of a substrate. Alternatively, compressed air or helium may be used. The deposition thickness produced by a moving nozzle can vary from 0.01 to 1.0 millimeter (mm), depending on powder feed rate, nozzle traverse speed, and deposition efficiency. The cold spray nozzle is frequently handled by a robot. Multiple coating layers can result in deposits several centimeters thick. The width of a single pass can be between 2 and 12 mm, depending on nozzle design, and large surfaces can be coated through multiple, slightly overlapping, parallel passes. Large sizes and shapes can be spray fabricated and geometrical features can be easily incorporated during spray preparation and subsequent machine finishing. Moreover, by controlling the feedstock composition, one could vary the deposit microstructure and composition to produce functionally graded materials and other special structures.

Cold spray equipment. The process gas is introduced to a manifold system containing a gas heater and powder-metering device. The pressurized gas is heated to a preset temperature, often using a coil of an electrical resistance-heated tube. The gas is heated not to heat or soften spray particles, but instead to achieve higher flow velocities, which ultimately result in higher particle impact velocities. The high-pressure gas is introduced into the entrance of a nozzle (converging/diverging or converging only), where the gas accelerates to high velocity (Mach numbers ranging from 1 to 4) as it expands in the nozzle. The gas cools as it expands in the spray nozzle, sometimes exiting the spray gun at below ambient temperature. The powder to be deposited is introduced by a separate gas stream either at the nozzle entrance or at a lower pressure location on the nozzle, where the powder mixes with the main gas stream and is accelerated by the gas stream.

Materials. The process consists of two material types, the powder to be deposited and the carrier gas:

- **Coating powder.** The powder for coating shall be dry, free flowing, and thoroughly blended. Mixtures of powder stock with varying density and/or size particulates shall be kept from settling or stratifying in the feeder as long as that powder charge is utilized. The mass median particle size shall be between 5 and 100 micrometers in diameter. The user should be cautioned to the importance of paying attention to the manufacturer's instructions pertaining to the storage and handling of finely divided metal powders. If the powder to be used by the manufacturer requires that it is controlled by a specification, it shall be specified in the contract or purchase order.
- **Gas.** The gas may be (but not restricted by) any of the following:
    1. Nitrogen (N_2)
    2. Helium (He)
    3. Mixture Of Nitrogen and Helium (N_2 + He)
    4. Air
- **Gas specifications**. If used by the processor for procurement, shall be acceptable to the cognizant engineering organization.

4.3 Required Procedures and Operations

Checks. Process control procedures shall be checked during cold spraying to assure that the specified operating parameters on the control sheet are maintained. The nozzle shall be checked between runs for internal wear / deposition. The operator shall determine if the nozzle needs to be replaced and/or cleaned.

Table 1: Operating Parameters

	High-Pressure System	Low-Pressure System
Working gas	N_2, He, air	N_2, air
Gas pressure, MPa	2.5 – 4.5	0.5 – 1.0
Gas preheat, °C	20 - 800	20 - 550
Gas flow rate, m^3/hour	50 - 150	15 - 30
Maximum Gas Mach #	1 - 3	1 - 3
Powder flow rate, g/s	0.1 – 1.0	0.1 – 1.0
Particle size, µm	5 - 100	10 - 80

Gauges, meters, and sensors. If a minimum accuracy is required on these instruments, it shall be defined in the contract or purchase order.

Process control. The cold spray process is optimized through the adjustment of control parameters. These parameters include the gas preheat temperature, gas pressure, nozzle geometry, throat size, powder feed rate, and spray distance. A critical process parameter is the feedstock powder material itself—primarily particle size distribution and particle attributes such as oxide layer and mechanical properties, which influence the ability to form a compacted deposit. Operational parameters are typically selected to achieve the most suitable deposit for its intended application at the lowest operational temperatures. The distinguishing feature of the cold spray process compared with conventional thermal spray processes is its ability to produce deposits with preheated gas temperatures in the range of 0 to 800° C, a range that is generally lower than the melting temperature of the coating particle materials. The nozzle exit temperature is substantially lower than the gas pre-heat temperature, further lowering the temperature excursions experienced by the feedstock particles and substrate materials. The range of operation for the stationary and portable cold spray systems is provided in Table I. The values in the table are representative of values currently in use but are not necessarily limiting values for the systems.

4.4 Surface Preparation

Cleaning. Surfaces to receive deposits shall be thoroughly cleaned to remove oil, grease, dirt, paint and other foreign material. Final cleaning shall take place no more than four hours prior to coating. Cleaning procedures shall not embrittle, pit, or damage surfaces to be coated.

4.5 Handling and storage

Abrasive Blast. When required, all surfaces designated for cold spray coating shall be cleaned by abrasive blasting with the abrasive media specified in the qualified procedure.

Blast contamination. All blast media shall be free of contamination that will affect the base material, such as, utilizing a blasting cabinet that has been used for ferrous substrates in the past and is now being used for nonferrous substrates such as aluminum or magnesium.

Coating deposition. The coating material shall be deposited on the designated surfaces to a sufficient thickness to provide, after subsequent operations, a finished composition and thickness which will meet the engineering specifications.

Handling. All surfaces requiring cold spraying shall be handled with clean lint-free gloves, tongs, or other means that will avoid surface contamination.

Overspray protection. Areas adjacent to the area to be cold spray coated shall be suitably protected from overspray by masking or shielding.

Preheating. When required as specified in the contract or purchase order, surfaces shall be preheated by a suitable and controllable source. The following shall apply:

- Preheating is performed to remove moisture and minimize the thermal shock effect encountered during deposition. Preheating of the substrate is also known to improve deposition efficiency and bond strength as well.
- Temperature of the part, during the preheating and coating application, shall be controlled to prevent discoloration, oxidation, distortion and other conditions detrimental to the coating or substrate.
- Temperature of the part after preheat and prior to spraying shall be measured using the appropriate pyrometric devices in accordance with AMS 2750.

CAUTION: Special care must be taken to avoid overheating nonferrous alloys with low melting temperatures such as aluminum and magnesium.

Storage. If a delay in spraying occurs beyond 2 hours but less than 20 hours (except for magnesium which shall be limited to 8 hours), special measures shall be employed to protect the surface to be coated from dust, dirt, moisture, and other contaminants such as flash rust or excessive oxidation that would reduce adhesion of the cold-sprayed deposit. Protection shall be in the form of covering or inserting the parts in clean plastic bags. Alternative methods may be to store parts overnight in a moderate temperature oven maintained at approximately 95° ± 3° C or in a vacuum chamber under low pressure. Should the delay in spraying, after proper surface preparation, exceed 20 hours the parts shall be reprocessed.

5.0 Quality Assurance

5.1 NDT methods

Laser ultrasonic testing (LUT) combines the sensitivity of ultrasonic inspection with the flexibility of optical systems in dealing with complex inspection problems. It works well in the testing of metals, composite materials, ceramics, and liquids. Its remote nature allows the rapid inspection of curved surfaces on fixed or moving parts. It can measure parts in hostile environments or at temperatures well above those that can be tolerated using existing techniques. Its accuracy and flexibility have made it an attractive new option in the non-destructive testing market.

LUT systems operate by first generating ultrasonic waves in a component using a pulsed laser. When the laser pulse strikes the component, ultrasonic waves are generated through a thermoelastic process or by ablation. As shown in the figure below, the full complement of waves (longitudinal, shear, surface, and plate) can be generated with lasers. These waves interrogate a feature of interest in the interior or surface of the component and then propagate to the surface position of the detection laser. The resulting surface displacement is measured with the laser ultrasonic receiver. The measured signal is then processed to yield and display the required information. As with conventional UT, measurements can be performed in the pulse-echo, through-transmission and pitch-catch configuration.

It allows overhaul and repair shops to test manufactured components of equipment such as aircraft for structural defects and metallurgical properties while still in service. These types of measurements are crucial to manufacturing industries to improve the level of quality in products and to control the cost of parts. They permit industry to minimize the cost of stopping production lines to correct part defects that can be identified during real-time monitoring using laser ultrasonic technology.

Application Examples:	**Industries Served:**
Bond evaluation	Aerospace
Coating thickness measurement	Automotive
Composite flow detection	Electronic component

Crack sizing	Glass packaging
Grain size measurement	Oil and gas pipeline
Wall thickness measurement	Semiconductor packaging
Weld inspection	Shipbuilding
	Steel and cast iron manufacturing

Equipment Manufactures
Tecnatom (TECN iPLUS)
IOS Intelligent Optical Systems, INC. (LUKS-1550-TWM)

NDT methods for assessing general coating quality have limited success with sprayed deposits.

At present, current NDT techniques do not reliably measure coating features such as cracking, porosity, oxide levels, coating disbond or adhesion. Crack detection by dye-penetrate techniques often fails to detect isolated defects against the general presence of porosity. Radiography, eddy current and ultrasonic inspections are of little use because of the heterogeneous nature of sprayed coatings and the small dimensions of features and defects.

As a consequence, greater emphasis must be given to destructive techniques such as adhesion tests and metallography. Destructive testing on a small percentage of components is acceptable where large numbers of similar articles are being processed. However, many thermal spraying jobs involve coating small numbers of components, and in reclamation work, it is typical for only one part to be repaired. In these circumstances it is necessary to coat a test coupon. It is essential to ensure that the coating on the test coupon is similar to that on the component. This requires not only consistency in spraying conditions but also an appreciation of the effects of, for example, differences in component section thickness and cooling rate on deposit structure and properties.

5.2 Metallographic examination

Using metallographic examination of the cold spray deposit can quantify the quality of the deposition. Examination can reveal cracks, porosity, oxides and entrapped grit, particle density if using mixed powders, and also reveals any problems at the interface of the bulk substrate and the powder deposition such as delamination. Care must be taken when preparing metallographic samples, as poor preparation can lead to incorrect assumptions when looking at the sample under magnification. Samples should be prepared according to ASTM E3, and etching should follow the procedures laid out in ASTM E407. Care should be taken in cutting the sample, as cracks and delamination can occur at this stage of the preparation. Polishing the sample can create edge rounding leading to uneven polishing, and brittle particles can pull out of the surface, leading to higher porosity measurements than the true value.

Porosity measurements are usually performed by visual inspection of the sample prepared for the metallographic examination at low magnifications. Specialized image analysis software can be used to measure porosity. According to MIL-STD-3021, porosity is not excessive if less than five percent of the total area when viewed at 200x after etching. In depositions that include both brittle and ductile materials, such as spraying aluminum and ceramics mixed together, the ductile material can smear into the pores if not prepared correctly, covering up the true porosity of the deposition. Examining the spray for oxides should be performed at 100x, and is excessive at three percent or greater for coatings that do not incorporate oxygen as an integral part of the material.

Hardness of the coating can also be used as an indication of the quality of the deposition. If the deposit is very porous, hardness measurements may indicate an apparently low measurement compared to a non-porous sample. Cold sprayed deposits are usually very hard compared to the material the powder was made from due to the substantial plastic deformation of the particle during spraying.

5.3 Adhesion testing

Adhesion of the cold spray deposit is an essential part of quality assurance. There are several ways of quantifying the adhesion of a cold spray deposit to a substrate, including both qualitative and quantitative tests. “Perfect” adhesion, as described by ASTM B571 is when the bonding between the deposit and the base substrate is greater than the cohesive strength of either material.

Qualitative adhesion tests have the objective of determining less than perfect adhesion, and can be any test that attempts to separate the coating from the substrate. ASTM B571 lays out many different qualitative tests that allow for easy testing to determine if the coating is sufficient. A common qualitative test is the bend test, which bends the specimen around a mandrel with a diameter four times the thickness of the sample. Any peeling or flaking of the coating are indications of a possible adhesion problem. Other tests may be as simple as dropping the sample or hitting it with a hammer to determine the quality of the coating.

For more in-depth testing for both qualification of deposits and parameter development, quantitative testing must be performed. Both ASTM C633 and ASTM D4541 outline procedures to test the adhesion of cold sprayed deposits.

The most common test is outlined in ASTM Standard C 633-01. This test uses a tensile testing machine that is able to pull rods in a uniaxial tension method, to eliminate any forces from bending. The basic setup is shown below in Figure 5.

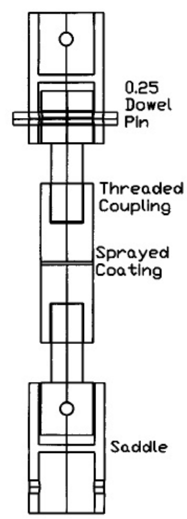

Figure 4 ASTM C633 Adhesion Test Fixture

Round bond bars are prepared and sprayed with the powder that is being tested. The bars must be made of the same material as the substrate for the coating: ie if the bond being tested is a copper powder sprayed on aluminum, the bond bar must be made of the same grade aluminum as the part. Since surface preparation is critical to bond strength of the deposition, the bars are usually prepared using a grit blast method. This removes any oxides or contaminates on the bar that could cause adhesion of the deposition to be compromised. The grit must be new, as any contaminates such as iron or other metals could become embedded in the surface and also cause adhesion problems. The powder is then deposited in a manner similar to the procedure used to coat the product. On the other bar, a suitable adhesive bonding agent is applied and stuck to the coating and left to cure, as recommended by the manufacturer. Once cured, the specimen is pulled in tension to failure. The adhesion or cohesion strength of the coating is the maximum load divided by the cross-sectional area of the round bar. If the coating pulls from the substrate, the failure is adhesive. If the coating pulls away from itself, the failure is cohesive. If the adhesive pulls away from the coating, then it can be assumed that the adhesive strength of the coating is greater than that of the adhesive, which is determined from a similar test without the cold spray layer. Due to the penetration of the adhesive into the deposition, the coating must have a thickness greater than 0.38 mm (0.015 in).

Other tensile methods to test the adhesive strength of coatings exist, such as portable adhesion testers. These methods are outlined in ASTM standard D4541-02. Portable testers use a dolly or stud that is adhered normal to the surface of the deposition. The dolly is then loaded into the tester and pulled until failure of either the coating or adhesive occurs. This method can yield different results than the test described earlier since the dolly is not ensured to be pulled in a completely uniaxial direction. Also, if not careful with adhesive application, excess adhesive can build up at the edge of the dolly, increasing the cross-sectional area of the test, altering the results.

Adhesion can also be measure using shear tests. A triple lug shear test is explained in MIL-J-24445A. This test calls for coatings to be sheared off the substrate by moving strips of the coating past a sharp corner. This setup is shown in Figure 6.

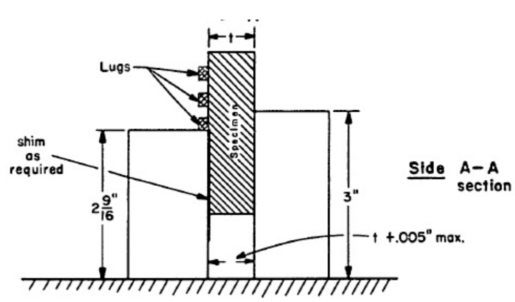

Figure 5 Lug Shear Test Setup

To prepare a sample for this test, powder is deposited on the substrate to an appropriate thickness. The deposition is them machined down to create three 3/16” wide lugs spaced ¼” apart. The edges of the lugs closest to the substrate must be sharp 90 degree corners. The test specimen is then loaded into the test fixture and stresses to shear failure. The shear strength is the force required to shear the lugs divided by the area of the lug bonded to the substrate.

6.0 Safety

6.1 Air Flow Design Considerations

The factors that follow include considerations for the coating quality, personnel safety, and overall cleanliness.

1. ***Airflow Distribution***. The airflow within the spray booth should be uniformly distributed through careful placement of the air intake and exhaust plenums. Laminar flow can best be achieved using an inlet plenum with many small evenly-distributed inlet air openings. Exhaust plenum placement on opposite ends of the spray booth from the air intake is **recommended** as part of an overall design to enhance smooth flow. Positioning of the exhaust plenum is typically on the wall or floor just beyond the process.
2. ***Air Flow Velocity***. To remove airborne particles from a cold spray booth, typical airflow velocities in the range of 75 to 200 feet per minute (23 to 61 m/min.) are recommended.
    a. Air velocities in the vicinity of 300 feet per minute (91 m/min.) may adversely affect the cold spray process.
3. ***Dual-Speed Exhaust systems.* –** Dual speed exhaust fans are recommended to allow the system to maintain a low-level ventilation mode at all times when the booth door is open and when the booth may be occupied for maintenance or setup, and revert to a high-level or normal operation when the booth is closed for process operation.
4. ***Heat Dissipation*.** The total air flow to a spray booth is required to be sufficient to prevent exhaust air temperatures from exceeding the design temperature specification of the filter media and ductwork.
5. ***Inlet Air Flow.*** The inlet air flow for the cold spray process can be from inside the facility in which a booth is installed, or from outside the building.
6. ***Negative Booth Pressure*.** There should be a negative pressure relationship between the spray booth and the rest of the building. If the ventilation system intake air is from outside the building, the negative pressure range may be from 0.1 to 0.5 Inches of water (0.25 to 1.24 mBar)
7. ***Sound Control*.** It is recommended that air intakes to the spray booth located inside the building provide sound control in the form of acoustic insulation, duct silencers, etc. to attenuate noise emitted by the process within the spray booth.

8. ***Total Air Flow***. The total recommended air flow for the spray booth should provide for a minimum of 5 air changes of the entire spray booth volume per minute.

The following layout guidelines are recommended:

1. Process control equipment that must be placed inside the spray booth such as powder feeders, flow meters, etc., should be placed in the spray booth near the air inlet and away from the actual spray process. Process equipment requiring maintenance operations, such as adding powder, etc. is recommended to be positioned in the ventilation stream so as to minimize operator exposure to additional dust or fume hazards during the maintenance operation.
2. Robots, gun manipulators, and spray operators should be placed near the center of the spray booth facing the exhaust plenum/spray hood with the part to be sprayed between the exhaust plenum and the robot/manipulator.
3. The work piece to be sprayed and any work piece manipulation equipment such as turntables or spindles should be placed in front of the exhaust plenum.
4. A combination of floor/cross-flow ventilation is sometimes used to minimize accumulation of heavier particles on the floor nearest the cold spray process.

Due to the nature of entrained particulates in the exhaust air stream, consideration must be given to the design of the overall ductwork. For specific details on duct layout and design consult SMACNA (Sheet Metal and Air Conditioning Contractors National Association). It is highly recommended that a competent local contractor be used to fabricate and install the ductwork in compliance with federal, state and local codes. The following are a few safety-related concerns:

- ***Back-draft Damper*.** The back-draft damper serves to prevent the reverse flow of air from outside the building back into the spray booth when the exhaust system is off, and also serves to prevent smoke from any potential fire in the dust collector from backfilling into the building.
- ***Duct Class/Shape*.** Ventilation ductwork used primarily for air conditioning systems is not normally considered adequate for this task.

- ***Duct Velocity***. The recommended air velocity inside the ductwork between the spray booth and the dust collector should be a minimum of 3,500 feet per minute (fpm) (17.78 m/s) to a maximum of 4,000 fpm (20.32 m/s).
- ***Intrusion*.** Protection against animal and weather intrusion into the ductwork is required at the point where the ductwork ends.

6.2 Booth Roof

If gas reclamation systems, storage tanks, or other systems/equipment are going to be placed on the roof of the spray booth due consideration should be given to the design load capacity of the roof. Consideration should also be given to provide:

- Adequate walk area to facilitate safe servicing of equipment.
- Fall-protection devices to ensure that the top of the booth is a safe place to work.
- Ladders or stairs to provide easy access to the booth roof area.

6.3 Booth Structure

Cold spray booths work with other sub-systems (interlocks, controls, ventilation/filtration, etc.) to provide protection from excessive sound levels and powder/dust. To provide protection from these hazards doors must be provided with positive latches, and hinges and seals must ensure continued protection of personnel. All opening must be sealed to minimize sound leakage and maintain an adequate seal against powder/dust leakage.

6.4 Cold Spray Booth Design

This document does not provide all the information required for cold spray booth design, and should only be used as a guide. To ensure that a safe spray booth is designed, professionals in the areas of ventilation, sound suppression, piping, etc. should be consulted.

Electrical Guidelines

- ***Documentation Recommendations*.** Adequate documentation for each installation should be provided such as to permit and encourage safe operation, maintenance and service of the cold spray cell and associated components.
- ***Dust protection*.** Electrical components within the cold spray booth require the type or design characteristics that afford protection from powder and dust.
- ***Emergency Stops (E-Stop)*.** Emergency stop buttons are required at appropriate locations around the cold spray cell. Actuating an E-Stop button will remove power in an emergency, except for functions that are required for personnel safety such as the ventilation system,

fire suppression, hazard alarms, etc. E-Stop button locations must be selected to afford operator and maintenance people quick access in case of an emergency.

- ***Gas interlocking Requirement.*** Process gas flow into the cold spray booth must be electrically interlocked through suitably rated solenoids or other automatic shutoff devices such that gases are allowed to flow only when sufficient ventilation airflow through the booth is confirmed.
- ***Grounding/bonding requirements.*** Grounding of electrical cabinets, booth walls and other metallic structures must be provided. Grounding to metallic building structures or metallic plumbing is typically sufficient. Check local codes.
- ***Lock-out/Tag-out.*** System shutoff means are required to allow all energy sources to be disconnected and isolated from the cold spray system or cell. Such shutoff devices must be equipped to accept a lockout device and associated tag to prevent accidental re-energizing of the equipment and subsequent exposure to hazards.

6.4 Ergonomics

This section on ergonomics is intended to provide information to increase safety awareness and use of safe practices in designing the human-machine interface to prevent musculoskeletal disorder injury/illness. This should be included in the design of both the cold spray booth, tooling/fixture to be utilized in the booth, coating materials and actual work steps.

- ***Consideration:*** should be given to the movement of material into the workplace, in the workplace and out of the workplace. Consideration to include the handling of material so that the operator is not over extending himself/herself, frequency of motions, as in loading/unloading parts is minimized and lifting/bending and twisting is controlled to an acceptable practice.
- ***Consideration:*** for the weight, size and shape of the work piece must be factored into the ergonomic analysis. Many companies now have weight limits placed on individuals to reduce the injury potential.
- ***Consideration:*** the posture of the individual performing the work. Correct posture is also defined as the ears, shoulders and hips being in vertical alignment. The work needs to be close at hand, this is true whether the operator is standing or sitting. Less force is required when the work is within reach (12 to 18 inches (305 to 457 mm) of the body and at an

acceptable elevation). Beyond that the work becomes awkward and injury potential increases.

- ***Consideration:*** must include the frequency and force of the task. Performing a minor task over and over or performing a task with excessive force may lead to a cumulative trauma ergonomic injury/illness. Consider periodic breaks or job rotation as a means to reduce the stress from these tasks.

6.5 Exhaust Equipment and Facility Layout

The design of the overall exhaust system is dictated by the physical layout and size of the spray booth enclosure and the exhaust equipment locations. The following steps are recommended:

- The dry dust collection components and exhaust blower should be located outside the building, preferably near the spray booth. Depending on the process and materials to be sprayed, consideration should be given to incorporating explosion relief panels in the filter housing and using flame-resistant filter media.
- Larger spray booths typically require a higher air velocity to capture and carry particles to the collection system. Spray booths should be sized just large enough to allow for safe processing, where practicable, including spray equipment clearances, without additional space.

6.6 Interlocks & Labels

The cold spray booth design should incorporate safety interlocks. Interlocks provide protection by removing power, preventing entry, limiting equipment travel, starting a fan, and the like. Warning labeling are required on all cold spray equipment to ensure that employees are aware of the associated hazards and the steps and/or equipment required to allow them to perform their job in a safe manner.

6.7 Piping Guidelines

Nitrogen, Helium and Compressed air are typically piped using black iron, carbon steel, or stainless steel with welded or threaded fittings.

A *Station Outlet* valve is **recommended** at the end of branch lines supplying each individual cold spray cell. These should be conveniently located and clearly identified so as to provide emergency shut-off capability and a place for support of lockout tag-out maintenance activities.

Pressure Relief valves are **required** to protect downstream plumbing and devices from over-pressure such as from the failure of a regulating device. When used, pressure relief devices must release at a pressure no higher than the maximum design pressure of the system. Pressure relief devices must be designed to handle the full flow of the supply piping.

It is recommended that relief ports for pressure-relief devices used with gases other than air be piped to the building exterior. This is to prevent the creation of a toxic or asphyxiating atmosphere.

6.8 Powder & Dust Control

Specific ventilation areas impacted by booth layout are:

- ***Entry Timer.*** A timer should be considered to prevent entry into the booth until a preset time has elapsed after the shutdown of the process. This allows the ventilation system to clear the air of hazardous dust.
- ***Negative Pressure.*** A slight negative pressure should be maintained it the spray booth so that if there are small leaks dust particles are drawn inward to the dust collection unit and not into the shop area.

- ***Total air flow and local velocities.*** It is important that local air velocities are high enough to carry dust particles into the duct work rather than having them settle and accumulate in the booth. Laminar flow is preferred as turbulent flow creates low pressure regions that allow dust particles to fall out of the air stream.

The use of air flow in the cold spray process is required to meet world-wide operator safety and environmental regulations. The reasons for having an exhaust system are as follows:

- Prevent personnel from inhaling fumes or dust and prevent contamination of the environment.
- Improper ventilation can have detrimental effects on coating quality.

Of the many types of dust collection components available, the combination of equipment utilized must be based upon the application, applicable codes, and installation requirements.

Water wash units used primarily before the 1980s, are a wet method of dust collection. In most locations around the world these units no longer meet environmental requirements as this type of equipment is not very efficient at removing particles, and proper disposal of the wet waste has become increasingly expensive.

Dry dust collection units used primarily since the 1980s, use highly efficient dry filters to capture the particulates. Current designs use replaceable cartridges (typically 99% efficient), or bags that achieve efficiencies in excess of 95% in order to meet EPA, state, and local regulations on industrial plant emissions. This type of unit is generally recommended for cold spray installations. High efficiency particulate air (HEPA) filters can be used as secondary filters to enhance the efficiency of dry dust collectors to 99.97% for particles as small as 0.3 microns. Cyclones can be used before these dust collection devices to enhance cleaning efficiency and prevent damage to the fragile dust collection cartridges.

When designing a dust collection system considers the following:

- *The types and forms of materials* - The following information is needed at a minimum:

1. The toxicity and flammability of the materials being sprayed, available in the MSDS sheets.
2. The allowable exposure levels (TLV, PEL, REL, etc.), to allow system design to control these levels.
3. Annual consumption of each material based upon spray rates and hours of operation.
4. Expected inflow of each material (overspray) into the dust collector for a given unit of operating time.
5. Calculated emission of each material into the atmosphere on an annual basis given the information above and the efficiency of the dust collection system.
6. Calculated air-to-media ratio in the exhaust stream along with the manufacturers recommended ratio for the filters.

6.9 PPE Equipment

- ***Air Purifying Respirators.*** Air-purifying respirators are typically negative pressure units in which the user’s inhalation draws contaminated air in through a filtration medium and exhalation pushes air out through one-way valves back into the atmosphere.

- Cloth or paper nuisance dust masks are tempting to use, but they do not provide adequate protection for cold spray operations and should not be used.

To provide optimal protection it is important that the mask fits properly and is well maintained. It is also important that the correct cartridges are chosen and that they are replaced as needed.

- ***Air Supplied Respirators.*** In an air-supplied respirator the worker typically wears a half- or full-face mask and breathable air is supplied via a pressurized airline.
- ***Eye Protection.*** All persons in eye hazard areas, including visitors, need to wear protective eyewear.
- ***Foot Protection.*** In area where heavy materials could fall or roll on the feet or where puncture protection is required safety footwear complying with ANSI Z41-1991 and ASTM F2413 shall be worn.
- ***Hand Protection.*** Suitable gloves need be worn when hazards from chemicals, cuts, lacerations, abrasions, punctures, burns, biological agents, and harmful temperature extremes are present. Glove selection shall be based on performance characteristics of the gloves, conditions, duration of use, and hazards present. Any one type of glove will not work in all situations.

  To protect hands from injury due to contact with moving parts, it is important to:

  1. Ensure that guards are always in place and used.
  2. Always lockout machines or tools and disconnect the power before making repairs.
  3. Treat a machine without a guard as inoperative; and
  4. Do not wear gloves around moving machinery, such as drill presses, mills, lathes, and grinders.
- ***Head Protection.*** Helemets are required when spraying the interior surfaces of a large space, applying coatings overhead, or working with cranes, and forklifts.

  Head protection should be stored away from direct sunlight in a cool dry place. Visually inspect gear for signs of damage or deterioration. Head protection should be replaced at intervals recommended by the manufacturer.
- ***Hearing Protection.*** In accordance with OSHA 1910.95, it is required that employees are protected from noise levels above 85 dBA, time weighted average, during a normal eight hour workday.

Every employee, who is required to wear hearing protection, in the performance of his or her duties, must participate in a hearing conservation program that includes yearly auditory testing to insure the effectiveness of the Hearing Protection Program.

Ear plugs and earmuffs with the highest Noise Reduction Rating (NRR) should be provided by the employer to all who require them at no cost. The employer should also bear the cost of the annual auditory testing.

- ***High Noise Areas.*** In areas were noise levels exceed 125 dBA both earplugs and earmuffs are required. The effectiveness of either plugs or muffs should be calculated using the following formula, using earplugs as an example.

(NRR-7) / 2 = effective NRR

6.10 Sound Suppression

The table below shows typically accepted tolerable noise limits for various exposure times: the louder the noise level present, the shorter the permissible exposure time. The cold spray process generates noise levels in excess of 110 dBA, requiring the use of hearing protection. In most situations, it is the employer that has the ultimate responsibility for protecting employees from excessive noise. Engineering controls, such as spray booths, which focus on reducing or containing the noise hazard are the best approach for protecting employees. For operations that use cold spray equipment on an infrequent basis administrative controls that reduce employee exposure time offer an acceptable alternative.

Tolerable Noise Limits of Various Exposure Times (Source NIOSH – ACGIH)	
Exposure Duration (Per Day)	**Sound Level (dBA)**
Hours	
16	82
8	85*
4	88
2	91
1	94
Minutes	
30	97
15	100
7.5	103
2	109

* OSHA Requirements state that any exposure over this level **requires** hearing protection.

Appendix I Cold Spray Powder Table

Powder	Typical Applications	Typical Substrates
Aluminum-Based Powders	• Corrosion Protection • Component Repair • Dimensional Restoration	• Aluminum and Aluminum Alloys • Magnesium and Magnesium Alloys • Steels • Stainless Steels
Copper-Based Powders	• Component Repair • Electrical and Thermal Conductivity	• Copper and Copper Alloys • Stainless Steels • Aluminum and Aluminum Alloys • Ceramics
Nickel and Iron-Based Powders	• Cast Iron Repair • Magnetic Properties • Substitute for Electrolytic Nickel Plating	• Cast Iron • Copper and Copper Alloys • Nickel and Nickel Alloys • Permalloy • Gold
Zinc-Based Powders	• Corrosion Protection • Thermal Conductivity • Intermediate Weld Layer	• Stainless Steels • Magnesium and Magnesium Alloys • Steels
Tin-Based Powders	• Corrosion Protection • Electrical Conductivity • Improved Solderability	• Aluminum and Aluminum Alloys • Circuits
Blasting Media	• Surface Preparation	• All Cold Spray Substrates
Titanium-Based Coating	• Corrosion Protection • Biomedical Prosthetic	• Aluminum and Aluminum Alloys • Copper and Copper Alloys • Steels • Stainless Steels • Ceramics
Brittle Component Coatings • Oxides • Ceramics • Carbides	• Wear Protection	• Most Ductile Substrates