Repairing casting defects by high pressure cold spraying method

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

The objective of this study was to investigate whether high pressure cold spray can be used to repair casting defects. The experiment conducted involved microstructural observations and mechanical property measurements of 316L stainless steel powder (20-44μ) cold sprayed coatings deposited onto a cast CA6NM martensitic stainless-steel substrate. The substrate was cold sprayed by hand using a VRC GEN III Cold Spray System with Nitrogen as the carrier gas. Substrate holes with different sizes and preparation techniques were created to mimic casting porosity. The backside of the plate was machined smooth and cold spray filled to perform ASTM C633 adhesion testing. Microstructural studies revealed cracks and improper bonding at the coating-substrate interface in many of the filled holes.

CHAPTER 1. INTRODUCTION

1.1 General Background

1.1.1 Casting and casting defects

Casting is usually a preferred method for making complex shapes that would otherwise be difficult or uneconomical to manufacture by other techniques. Thus, while castings may be used as a way to save money, the cost of castings can be relatively high depending upon the alloy type and the intricacy of the shape of the components. During a casting process, some casting defects can be difficult to avoid. A huge amount of waste is incurred if the component is cast incorrectly or otherwise damaged during fabrication. Hence, close control and supervision is required during the casting operations and procedures to avoid such situations. In spite of adopting suitable control measures, defects such as porosity, cracks, inclusions and shrinkage can and often do occur during a casting process [1].

Although the occurrence of defects can be associated with the skills of the workforce and observance of good casting practice, often their formation is associated with the physio-metallurgical properties of the mold and cast material. For example, Scabbing is an inclusion defect that looks as if there is slag inside of a metal casting. Scabbing is caused by a number of factors, such as low compactability of the molding sand, high pouring rate, long pouring time, etc. Castings with scabbing defects cannot be salvaged and must be re-cast.

Misrun occurs when the mold cavity is not filled by the liquid metal, resulting in an uncompleted casting. A similar problem occurs in multi-gated systems if two fronts of liquid metal do not fuse completely as the mold is filling, producing a cold shut and resulting in a weak spot. Both misruns and cold shuts are caused either because the liquid metal lacks fluidity or has a faulty gating system.

Perhaps the most common type of casting defect is porosity, and this can occur in a number of ways for various reasons. Unavailability of feed metal to compensate for shrinkage as the metal solidifies results in shrinkage defects. At the center of thick sections of a casting this shrinkage can end up as a distribution of small voids known as ‘shrinkage porosity’. Once present in the casting shrinkage porosity cannot be fixed and the entire casting must be re-cast, with parameters properly adjusted to ensure that liquid metal under pressure continues to flow into the mold as solidification occurs, preventing voids from forming. Micro-porosity can also result and appear as small holes scattered throughout the cast piece when dissolved gases in the liquid metal come out of solution and form gas bubbles. Porosity can also take the form of large, unfilled spaces or voids in the mold that result due to incomplete filling of the mold or shrinkage during solidification. The amount, size and distribution of pores is affected by a number of factors including the type of material being cast; the size, weight, and design of the casting; the mold material; the riser system; casting temperature, etc. [12]

1.1.2 Casting salvage

When defects do exist in castings it is often in the company’s best interest to salvage the casting if possible rather than scrap the piece entirely. The method of salvaging used, after identifying the area and extent of defects, depends on several factors such as composition of casting alloy, size and shape of casting, cost, difficulty of salvaging the defective casting, availability of repair equipment and quality requirements. [5] Many casting defects are only cosmetic in nature. Their repair is up to the discretion of the buyer and the seller as to whether it is cost effective to repair the defect or use the product as is. More serious are the defects that compromise the performance of the casting. In this case, casting salvage may or may not be possible depending on the nature of the defect, its location, and the stresses and / or environment the repaired area will see in service.

Several commonly used salvaging techniques exist [1] and are used in different situations. These are briefly described below:

(i) Mechanical removal of surface defects by grinding, cutting, milling, etc. These methods are used when extra material exists on the surface of the casting, such as mold over-run or flash between mold pieces. This is the easiest type of defect to correct as it simply involves removal of excess material.

(ii) Superficial filling of defects (e.g. modified resins) - Non-metallic compounds are used for improving surface finish and to fill pin holes, blow holes, etc. A high bond strength can be developed by using epoxy and acrylic resins which sturdily adhere to metals.

(iii) Impregnating is used to fill blowholes, porosity, cracks, etc. by impregnating resin under pressure while the casting is kept under vacuum. This process is particularly used to manufacture pressure tight castings especially for alloys prone to microporosity.

(iv) Metallization consists of blowing out small drops of molten metal using compressed air with the help of a spray gun on the surface to be repaired. A mechanical bond is formed with negligible diffusion. Small pores and shrinkage cavities on unimportant surfaces of the casting can be filled by this method.

(v) Brazing and soldering methods of salvaging are used when welding causes distortion and cracking of the components. Both these processes are carried out at a temperature below the melting point of the cast metal using a low melting alloy as a filler material.

(vi) Casting-on involves filling damaged places by a casting method and flooding with liquid metal.

(vii) Welding is used to improve surface conditions or eliminate shrinkage voids, blowholes, etc., by partial melting of the casting material and blending it with a suitable filler material. It is a commonly used method to repair casting defects, however, some properties that make certain alloys ideal candidates for casting also makes them difficult to weld [5]. For example, alloys that tend to crack in the weld deposit or in the heat affected zone (HAZ) either during welding or during post-weld heat treatments may be categorized as not weldable, and are, therefore, often fabricated into the desired shape by casting [10]. Some alloys can only be welded under extreme conditions, such as temperatures more than 1600° F (871° C) (7).

Generally, mechanical removal, metallization, resin impregnation, brazing and soldering are used for cosmetic purposes since they do not provide adequate structural strength. Welding provides sufficient strength to withstand the working conditions for most applications; however, it depends on the alloy and nature of application. Extreme care must be taken with many alloy systems that the heat generated during a weld repair does not adversely affect either the mechanical or corrosion properties of the casting due to the formation of undesirable intermetallic phase in the heat affected zone (HAZ). For cases such as these, filling surface porosity by depositing coatings at a lower temperature than typically seen in a weld repair would avoid such problems. In this context there exists a tremendous potential for repairing steel castings by a solid-state deposition process such as cold spray [11].

1.2 Cold Spray

Cold Spray [9] is an additive manufacturing process wherein solid powder particles are accelerated over the sonic velocity onto (usually) a metal substrate by being carried in a stream of compressed gas. The melting point of the powder is higher than the temperature of the gas stream, hence the term cold spray. This qualifies the Cold Spray technique as a solid-state deposition process with quite unique characteristics.

The mechanism of powder deposition is based on local particle deformation, which occurs as a result of the accelerated particle impinging on the substrate [13]. Thus, the velocity of sprayed particles is critical and affects microstructure, physical, and mechanical properties of the coating [7]. A critical velocity has to be reached to achieve the desired bonding. In case of velocities lower than the critical velocity the particles will not adhere to the substrate [14]. The most commonly used cold spray processes are divided into low-pressure and high-pressure systems. Both these processes are briefly discussed below:

1.2.1 Low pressure cold spray

In low-pressure cold spray (LPCS) the accelerating gas, usually air or nitrogen, at relatively low pressure (5-10 bar) is preheated (up to 550°C) and forced through a 'DeLaval' nozzle. The heated gas is accelerated to a velocity in the range of 300 to 600 m/s. A powder feeder introduces solid powder particles into the throat section of the supersonic nozzle, the powders are entrained in the flowing gas, and are then accelerated toward the substrate. Advantages of a low-pressure system include that it is portable, flexible in automation, and has a lower cost than a high-pressure system. [10]. A schematic of this process is shown below in Figure 1.

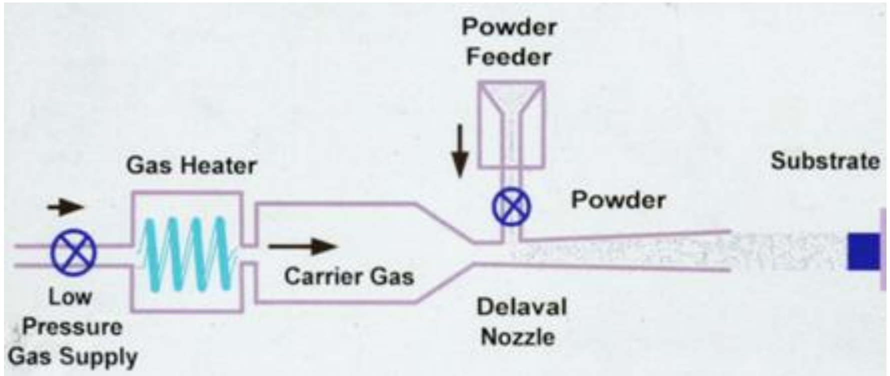

Figure 1: Operating principle of low-pressure cold spray. [15]

1.2.2 High pressure cold spray

In high-pressure cold spray (HPCS), the accelerating gas (helium or nitrogen) at high pressure (25-30 bar) is preheated (up to 1000 °C) and then forced through a converging-diverging 'DeLaval' nozzle. The solid powder particles are mixed with the propellant gas and are then axially fed into the converging section of the nozzle at a higher pressure than the accelerating gas. The accelerated solid particles (600 to 1200 m/s) impact the substrate with enough kinetic energy to induce mechanical and/or metallurgical bonding. HPCS has a higher spray efficiency reaching up to 90% as compared to 50 % in LPSC system. A schematic of this process is shown below in Figure 2.

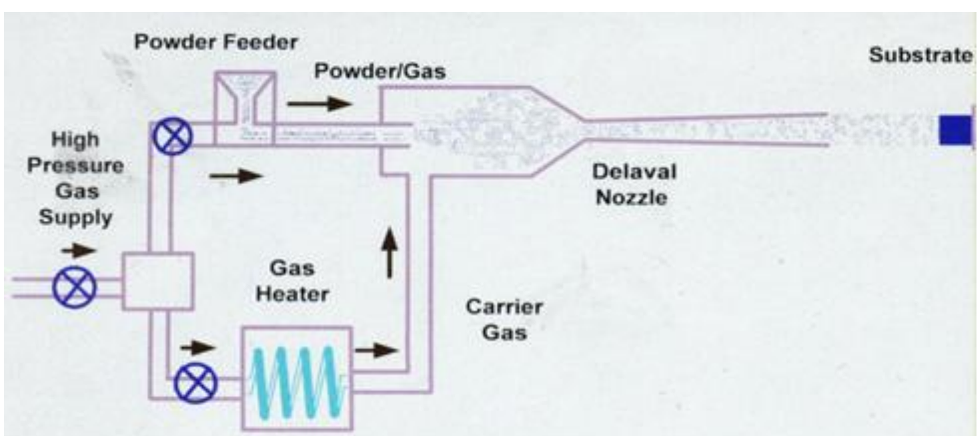

Figure 2: Operating principle of high-pressure cold spray. [15]

The unique advantage of cold spray due to the relatively low temperatures involved in either system, whether low or high pressure, is that any potential phase change (in either the matrix or the deposited powder) is minimized since both remain in the solid state. The kinetic energy imparted to the particles by the gas stream allows them to plastically deform, bond and form coatings. Many harmful deficiencies such as high-temperature oxidation, evaporation, melting, crystallization, residual stresses and gas release are eliminated. [15] If the deposition material is clean and free of oxides, potentially harmful inclusions are avoided. The low heat input involved makes the technique amenable to essentially any metal surface and the compressive stresses involved can give dense uniform deposits with a wrought-like microstructure.

R. Ganesan [8] conducted a preliminary study to investigate the use of cold-spray to repair minor porosity in steel castings. An alloy A487 Class A bar was drilled with differently sized drill bits to simulate casting porosity. The bar was cold sprayed using a high-pressure CGT Kinetiks 4000 Cold Spray System [8] by the US Army Research Laboratory (ARL), Aberdeen Proving Ground, Maryland. Microstructural studies and hardness measurements were conducted on the cold-sprayed samples. The microstructure revealed voids, homogeneously spread in the cold-sprayed region and the frequency of voids increased on the sides of the drilled holes. Cracks were seen in 2 mm and 1 mm divots; no cracks were seen in 0.5 mm or 1.5 mm divots. Further, some voids were seen on the interface at the side of the filled holes while the bottom of the holes were void-free. Higher hardness was found in the cold sprayed region (340HV to 420 HV) compared to the substrate (290 HV to 320 HV). Ganesan concluded that the penetration of the sprayed powder in small pores is excellent, while micro porosity is homogeneously distributed within the spray region.

Other previous studies [1, 8] on cold sprayed castings focused on bond strength and hardness, however, no research has been uncovered that focused on the effect of surface roughness, size, and shape of the porosity to be filled in determining the viability of the cold spray technique as a candidate for repairing steel castings.

1.3 Problem Statement

The purpose of this study is to investigate the effectiveness of using the cold spray technique in salvaging castings with surface porosity, primarily focusing on solving the cosmetic issue. However, preserving the structural integrity of the component may be possible with a cold sprayed part. While this might not be possible in a pure tensile force application cold sprayed material should have enough strength under compressive stresses in application to avoid leaks due to poor sealing. Also, the repair material used in the cold spray process can be chosen to be compatible with the parent casting material, hopefully avoiding selective corrosion of the deposited material. Thus, if successful, cold spray has the potential to result in significant savings by allowing castings to be salvaged that otherwise might have had to be scrapped.

In this thesis, the results of using the high pressure cold spraying method for filling casting defects are presented. The ability of cold spray to fill porosities of different size and surface preparation was investigated and the quality of the repaired regions was examined by conducting microstructural observations and hardness tests.

CHAPTER 2. EXPERIMENTAL PROCEDURE

2.1 Cold Spray Test Plan

The study was conducted on a CA6NM weld test plate provided by a member company of the Steel Founders Society of America. CA6NM is a martensitic stainless steel, an iron-chromium nickel-molybdenum alloy that is hardenable by heat treatment. CA6NM provides the optimum combination of toughness, hardness, ductility and strength and is used in chemical, marine petroleum refining, power plant because of its excellent corrosive properties. CA6NM is also used for manufacturing cast components such as Casings, compressor impellers, diffusers, hydraulic turbine parts, propellers, valve bodies, etc. A typical composition for CA6NM is given in Table 1.

Table 1. Typical composition of CA6NM. [27]

Cr	Fe	C Max	Mn	Other	Ni	Si
11.5 - 14.0	Bal	0.06 max	1.00 max	Mo 0.4 - 1.0	3.5 - 4.5	1.00 max

To mimic the surface porosity on a casting, differently sized holes were drilled per Figure 3 and cold sprayed after various surface preparation techniques with 316L stainless steel (SS) powder (20-44μ) provided by North American Hoganas.

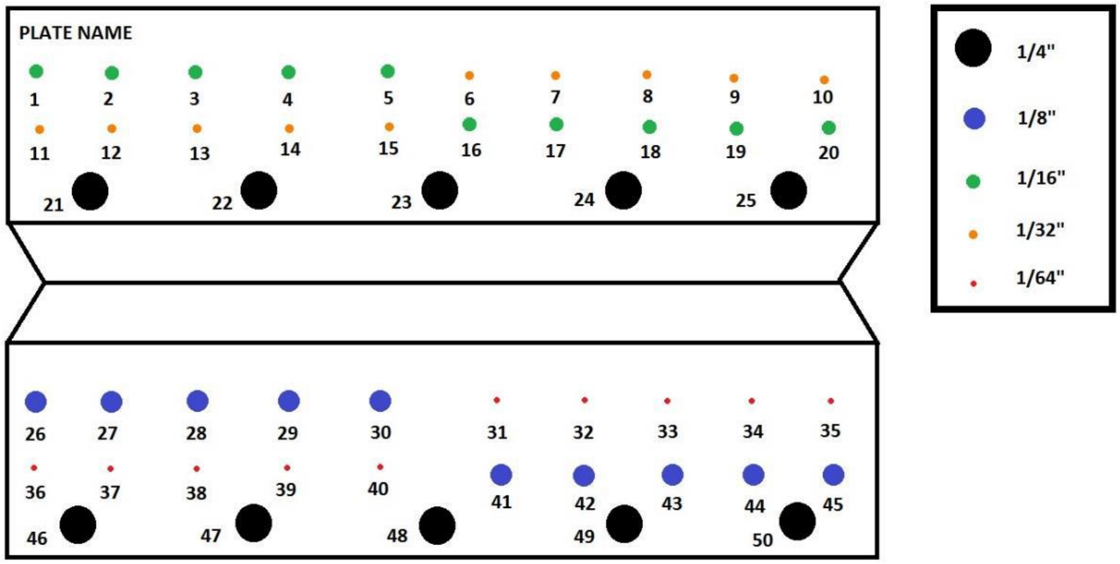

Figure 3: Test plan for the provided CA6NM plate. [5]

Cold spraying was done manually at VRC Metal Systems LLC, Rapid City, SD using nitrogen carrier gas with the VRC GEN III Cold Spray System. The CA6NM plate was prepared and sprayed per the initial cold spray plan formulated in conjunction with SFSA and described below. The plan involved roughening the surface of the substrate slightly, changing the shape of the initial drilled hole by grinding or chamfering, and also substituting a mixed powder at times for the selected 316L stainless steel fill powder. The headings given to the various samples were: [5]

- None: No surface preparation was conducted, and the substrate was sprayed “as is”.
- Grind out Flat: The sharp angles were eliminated by grinding the substrate hole smooth.
- Chamfer Edges: The leading edges of the substrate hole were tapered smooth by grinding slightly.
- Scotch-Brite™ Only: Scotch-Brite™ abrasion pad was used to scuff the substrate hole

- Chamfer Edges with 75/25 Powder Mix: The substrate hole was prepared in the same manner as stated above in "Chamfer Edges", however the powder had a 25% by volume hard Chrome Carbide (20-44μm) powder added to aid bonding.

All spraying of this initial attempt was made at an angle 90˚ with respect to the sample surface. Upon initial spraying and investigation VRC found out that many holes did not fill at all and that the deposition could be removed with minimal effort (Figure 4) from essentially every hole. This demonstrated that the deposit was unable to penetrate the substrate effectively in the current condition of the drilled holes.

Figure 4: Failed deposition from the initial attempt. [5]

In subsequent discussions with VRC engineers they stated they suspected this would happen since in their experience the initial parameters suggested were inadequate. Thus, the initial cold spray plan was modified and several suggestions were provided as to what might be done to improve adherence of the powder to the substrate. These included using the mixture of 75 volume% 316L and 25 volume % chrome carbide powder for all attempts to roughen the surface; changing the angle of the sizes of the hole to be filled from 90˚ to a mixture of 90˚ and 45˚; and roughening the surface in different ways, by ball end milling, grit blasting or by using a scratch pad. The 45˚ spray was made from one side and then after rotating the sample 180˚ from the opposite side. Based on those suggestions an extensive matrix of varying surface conditions was devised for the drilled holes. The various combinations of preparation techniques used are listed below under the designations assigned for further reference. This modified cold spray plan consisted of the following sets of conditions: [5]

- None: The substrate was sprayed "as is" with no preparation.
- Minor Chamfer: The sharp angles of the substrate hole were removed by grinding with a ½" ball end mill.
- Medium Chamfer: 1" ball end mill was used to grind the substrate hole and the leading edges were tapered by a grinding stone.
- Scotch-Brite™ Only: The substrate hole was scuffed up with a Scotch-Brite™ abrasion pad.
- Grit Blast: The sample was grit blasted with 60 grit alumina powder to roughen the surface.

A complete listing of all the combinations as identified for each of the drilled holes is included in Table 2 below.

Table 2: test plan for the provided CA6NM plate. [5]

HOLE #	**PREPARATION**	**SPRAY ANGLE**
1	None	90°
2	None	~45°
3	Minor Chamfer	90°

Table 2 continued

4	Minor Chamfer	~45°
5	Minor Chamfer	90°
6	None	90°
7	None	~45°
8	Minor Chamfer	90°
9	Minor Chamfer	~45°
10	Minor Chamfer	90°
11	Minor Chamfer, Grit Blast (60 Grit Alumina)	~45°
12	Scotch-Brite™ Only	90°
13	Scotch-Brite™ Only	~45°
14	Minor Chamfer	90°
15	Minor Chamfer	~45°
16	Minor Chamfer	~45°
17	Scotch-Brite™ Only	90°
18	Scotch-Brite™ Only	~45°
19	Minor Chamfer	90°
20	Minor Chamfer	~45°
21	None Grit Blast (60 Grit Alumina)	90°
22	None	~45°
23	Minor Chamfer	90°
24	Minor Chamfer	~45°
25	Minor Chamfer	90°

Table 2 continued

26	None Grit Blast (60 Grit Alumina)	90°
27	None Grit Blast (60 Grit Alumina)	~45°
28	Medium Chamfer, Grit Blast (60 Grit Alumina)	90°
29	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°
30	Medium Chamfer, Grit Blast (60 Grit Alumina)	90°
31	None, Grit Blast (60 Grit Alumina)	90°
32	None, Grit Blast (60 Grit Alumina)	~45°
33	Medium Chamfer, Grit Blast (60 Grit Alumina)	90°
34	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°
35	Medium Chamfer, Grit Blast (60 Grit Alumina)	90°
36	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°
37	None, Grit Blast (60 Grit Alumina)	90°
38	None, Grit Blast (60 Grit Alumina)	~45°
39	Medium Chamfer, Grit Blast (60 Grit Alumina)	90°
40	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°
41	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°
42	Medium Chamfer, Grit Blast (60 Grit Alumina)	90°
43	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°
44	None, Grit Blast (60 Grit Alumina)	90°
45	None, Grit Blast (60 Grit Alumina)	~45°
46	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°
47	None, Grit Blast (60 Grit Alumina)	90°
48	None, Grit Blast (60 Grit Alumina)	~45°

Table 2 continued

49	Medium Chamfer, Grit Blast (60 Grit Alumina)	90°
50	Medium Chamfer, Grit Blast (60 Grit Alumina)	~45°

Spray parameters were as follows:

Spray gas	Nitrogen
Pressure set point	720 PSI
Temperature set point	400 °C
Powder feed rate	2 RPM
Powder	75% 316L / 25% CrC
Pressure set point	700 PSI
Feeder pressure	700 PSI
Main gas flow	1097 SLM
Gun temperature	365 °C

Since in the initial attempt none of the holes had any significant deposit in them the existing drilled plate was merely cleaned and reused for the second spray attempt. Figure 5 shows the CA6NM substrate before cold spraying.

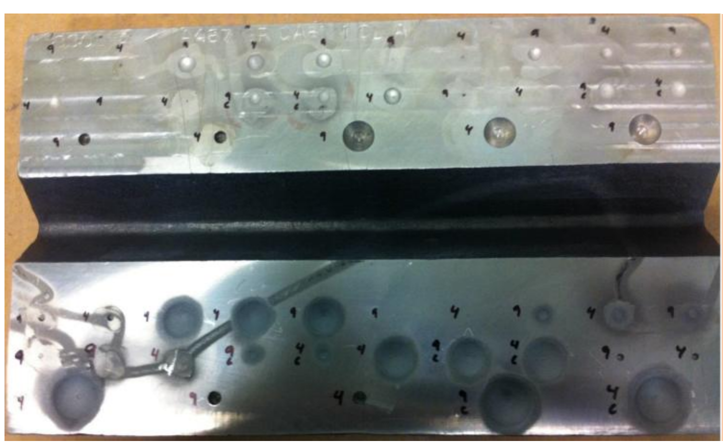

Figure 5: Prepared CA6NM substrate before cold spray. [5]

The as-cold-sprayed CA6NM substrate is shown in Figure 6.

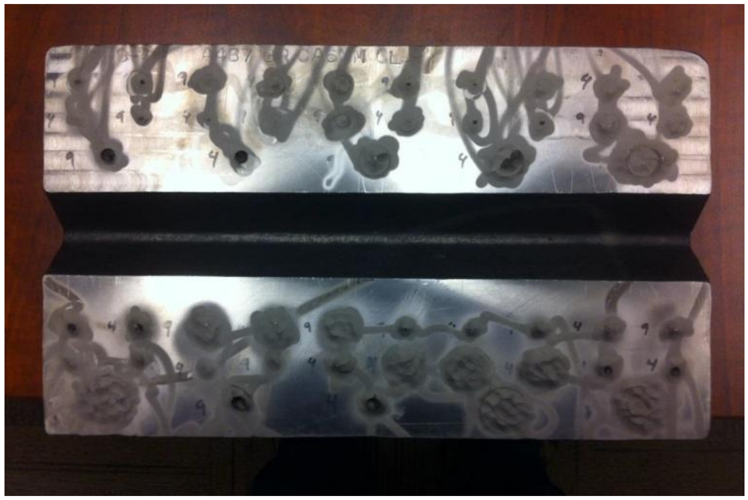

Figure 6: Cold sprayed CA6NM substrate. [5]

2.2 Bond Strength Test (ASTM C633)

To determine the adhesion test of a coating, ASTM C633 test method is used. The test is performed by subjecting the coating to tension perpendicular to the surface. To perform ASTM C633 adhesion testing, the backside of the plate was machined smooth, next two grooves were machined into it followed by machining two holes for adhesion tests, and then cold sprayed as shown in the Figure 7.

Figure 7: Provided substrate sprayed according to test plan
with adhesion witness coupons. [5]

While performing ASTM C633 test, tensile stresses are applied to the coated sample glued to another cylindrical sample. Tensile strength test was conducted on the test specimen using a Positest AT-A automation adhesion tester. [5]

The ASTM C633 testing was performed using a loading rate of 200 psi/s in the Positest AT-A automatic adhesion tester as shown in figure 8.

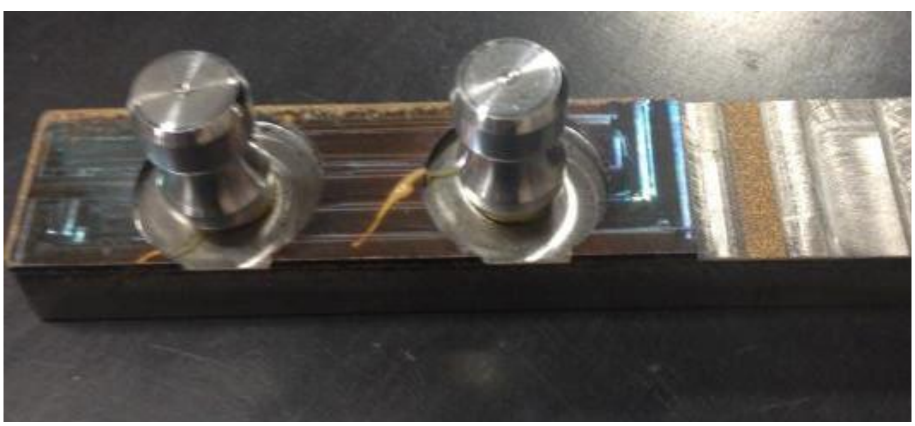

Figure 8: Image of a typical sample as prepared for ASTM C633 testing. [5]

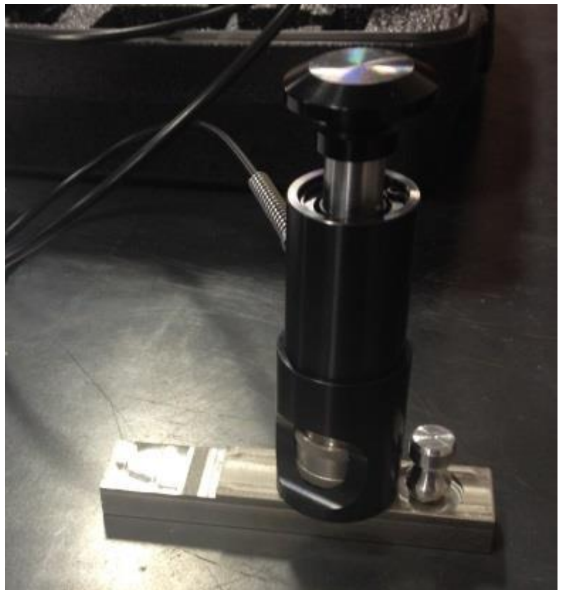

Figure 9: Image of a sample setup with the positest AT-A automatic adhesion tester. [5]

The following results are from the performed ASTMC633 testing.

Table 3: ASTM C633 adhesion test results. [5]

Sample	Adhesion (Ksi)
Straight Line	1.6,5.8
Circular motion	4.8,4.8

2.3 Metallographic and Hardness Study

After being cold sprayed the test bar was cut into smaller pieces to facilitate sample polishing. Microstructural studies were conducted at the coating-substrate interface by polishing the samples both in plan view as well as cross section. The samples were observed in the as-polished and etched conditions. Samples for optical microscopy were prepared using standard metallographic procedure. Final polishing was done using 1 µm diamond polish. An Olympus GX51 was used for recording photographs of the microstructure.

Hardness was measured for all the 20 samples which were completely filled after cold spray and did not pop out during the polishing step. Hardness readings were taken from different spots across the specimen. Hardness was recorded at a distance of 100, 200 and 300 microns from the interface on both the substrate and cold sprayed regions to identify any trends across the sample. A LECO LM- 247AT Vickers micro hardness testers with load of 300 g was used to record the hardness.

CHAPTER 3. RESULTS

3.1 Visual Observations

The lower part of the sectioned as-sprayed plate shown in Figure 8 reveals that even with the modified spray plan several holes were not completely filled, such as holes #47 and #48 (circled). Such holes were considered as defective and further hardness measurements and metallographic studies were not conducted on these holes. In total, 18 holes fell into this category. These are designated in Table 2 by having crosses through them.

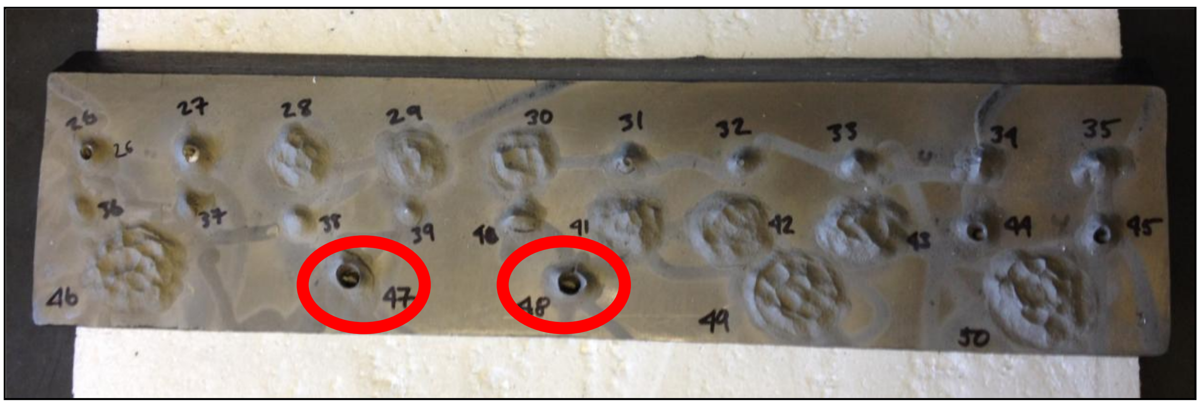

Figure 10: Cold sprayed weld plate with filled and unfilled holes.

It was discovered during polishing of the samples for subsequent metallographic study that the deposited material in many of the holes popped out as the sample was polished. A total of 12 samples popped out during the polishing step (see Table 2) out of which 10 belonged to the 1/64-inch size hole category, an example of which is shown in Figure 9. Thus, these samples were also excluded from further examination. Hence, a sample is considered to have failed if either the hole was not completely filled or the coating popped out during the polishing step.

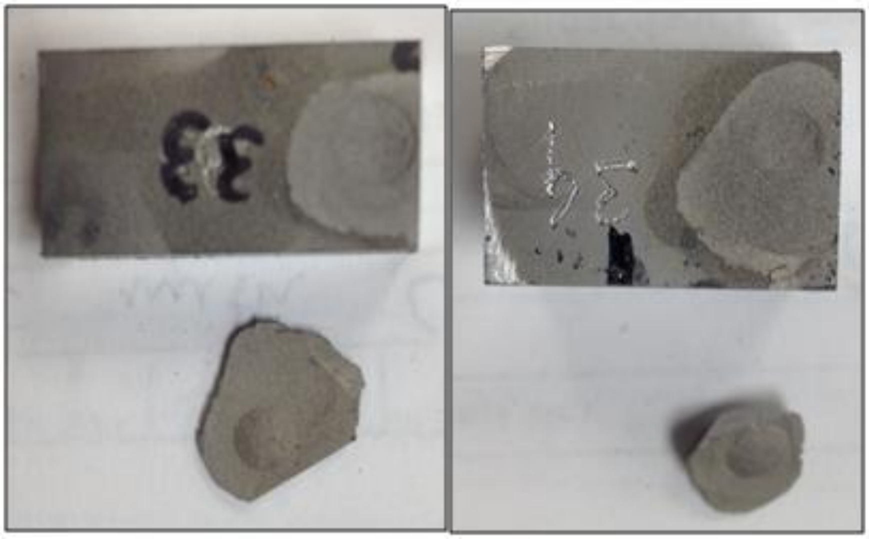

Figure 11: For samples with 1/64” sized hole cold spray popped out during polishing.

In total, 30 of the 50 samples failed before they were ever examined. A complete listing of all samples which survived sectioning and those that failed is given in Table 4. The hole size after medium chamfering changed to 1” since 1” ball end mill was used to grind the substrate hole. Similarly, the hole size after minor chamfering changed to ½” since the hole was ground by a ½” ball end mill. Thus the planned hole size is not relevant and the new hole size should be taken into consideration for the new analysis. All the samples for 1/4”, 1/8”, 1/16”, 1/32” and 1/64” size hole failed. 53% of the 1” size hole failed and 13% of the 1/2” size hole failed.

Chamfering the holes introduces a new variable of hole geometry which seems to play a major role in affecting the deposition characteristics. Grinding with the ball end mill eliminates the sharp edges and creates a flat contour with reduced depth.

Table 4: Different sized holes: filled and unfilled.
(Crossed samples are unfilled/defective)

None	None Grit blast	Minor Chamfer	Medium Chamfer	Scotch-Brite™ Only

	1"	1/2"	1/4"	1/8"	1/16"	1/32"	1/64"
	~~28~~	3	~~21~~	~~26~~	~~1~~	~~6~~	~~31~~
	29	4	~~22~~	~~27~~	~~2~~	~~7~~	~~32~~
	~~30~~	5	~~47~~	~~44~~	~~17~~	~~12~~	~~37~~
	~~33~~	8	~~48~~	~~45~~	~~18~~	~~13~~	~~38~~
	~~34~~	9					
	~~35~~	~~10~~					
	~~36~~	11					
	~~39~~	14					
	~~40~~	15					
	41	16					
	42	19					
	43	20					
	46	23					
	49	~~24~~					
	50	25					
Defected	8	2	4	4	4	4	4
Total	15	15	4	4	4	4	4

The effect of using various preparation techniques prior to cold spraying the weld plate is summarized in Table 5. Minor Chamfering seems to be the most effective followed by the medium chamfering technique since only 13 % of the minor chamfer samples were defective i.e. either they were not completely filled or popped out during polishing. In comparison, 53% of the medium chamfered samples were defective and 100 % of all the substrate holes sprayed without any chamfering (e.g. both grit blasted and substrate holes scuffed with Scotch-Brite™ abrasion pads) failed.

Table 5: Holes associated with different preparation techniques.

	None	None Grit blast	Minor Chamfer	Medium Chamfer	Scotch-Brite™ Only	Total
Defected	5	11	2	8	4	30
Total	5	11	15	15	4	50

The effect of spraying at different angles is not clear. For example, 56 % of the samples sprayed at 45 failed while 64 % of the samples sprayed at 90 failed. Hence, a conclusive statement regarding the effect of spray angle cannot be made.

3.2 Microstructure

There is a distinct gap between the cold sprayed material and the substrate for a majority of the samples and the width of the gap seems to vary along the interface. An example representative of cold-sprayed samples showing this microstructure is shown in Figure 12 (a) & (b), which are the top surface and cross section of sample #41, 1/8-inch sized hole with the preparation condition of medium chamfer, Grit Blast (60 Grit Alumina) and cold sprayed at ~45°, respectively.

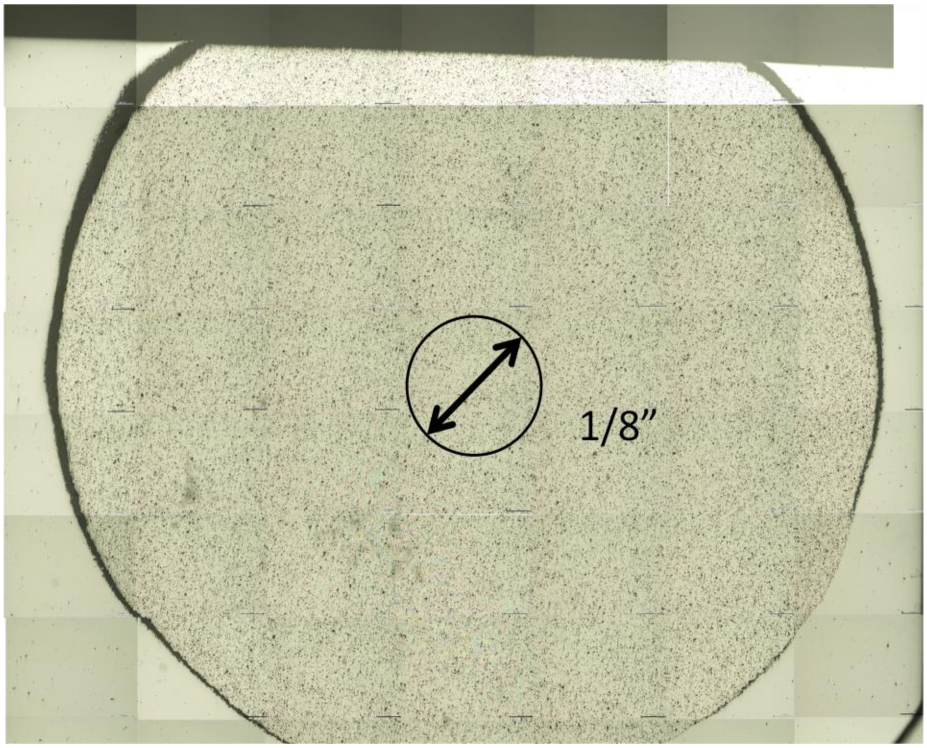

Figure 12(a): Top surface of sample #41 (1/8-inch sized hole)

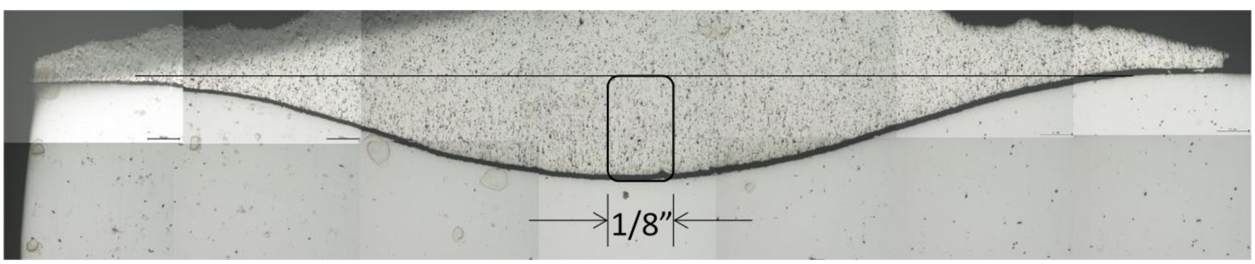

Figure 12(b): Cross section of sample #41 (1/8-inch sized hole)

Similarly, Figure 13 shows sample # 42 (1/8-inch sized hole, prepared by Medium Chamfer, Grit Blast (60 Grit Alumina) and cold sprayed at 90°. Again, there is a distinct gap on the right side of the image while the left side seems to have better adhesion. Partial adhesion as shown in Figure 13 was seen in 14 % of the samples (7 out of 50).

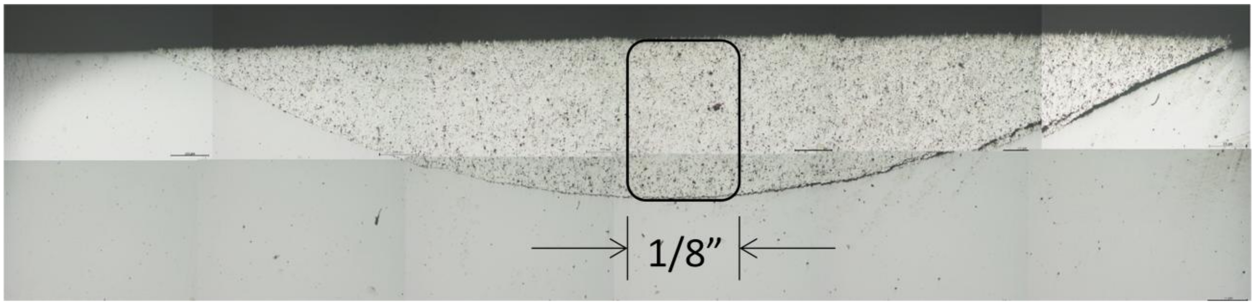

Figure 13: Cross section of sample #42 (1/8-inch sized hole)

A clear relationship between the hole size and the ability of the cold spray to fill the holes completely without any gap could not be made since such gaps were present in holes for all the sizes. Porosity (the black spots in all figures) is spread widely across the cold-sprayed region. Unlike images seen in research conducted by Ganesan [8], there are few or no cracks in the cold-spray filled holes, except for the interface gaps. There are some areas visible in cross section and top view where the cold sprayed material did not completely fill the cavity. An example of this is shown in Figure 14 (a) and (b)

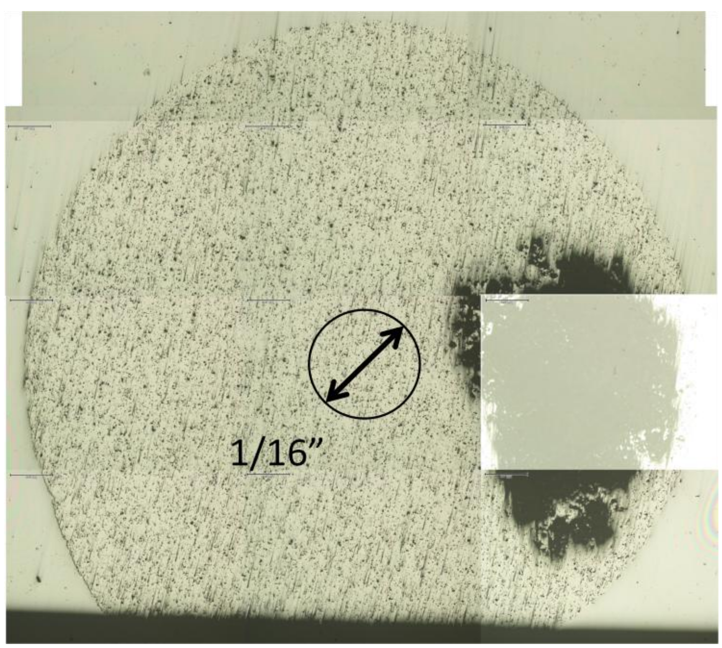

Figure 14(a): Top surface of sample #3, (1/16-inch sized hole)

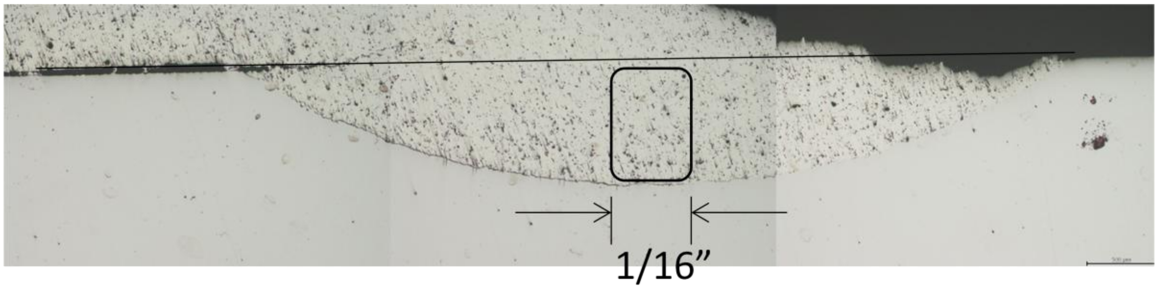

Figure 14(b): Cross section of sample #3. (1/16-inch sized hole)

Only in rare cases did the cold sprayed material show excellent adhesion. One such example of better adhesion is exhibited by sample #15 in Figure 15 (a) & (b). Excellent adhesion was seen in 8 % of the samples (4 out of 50).

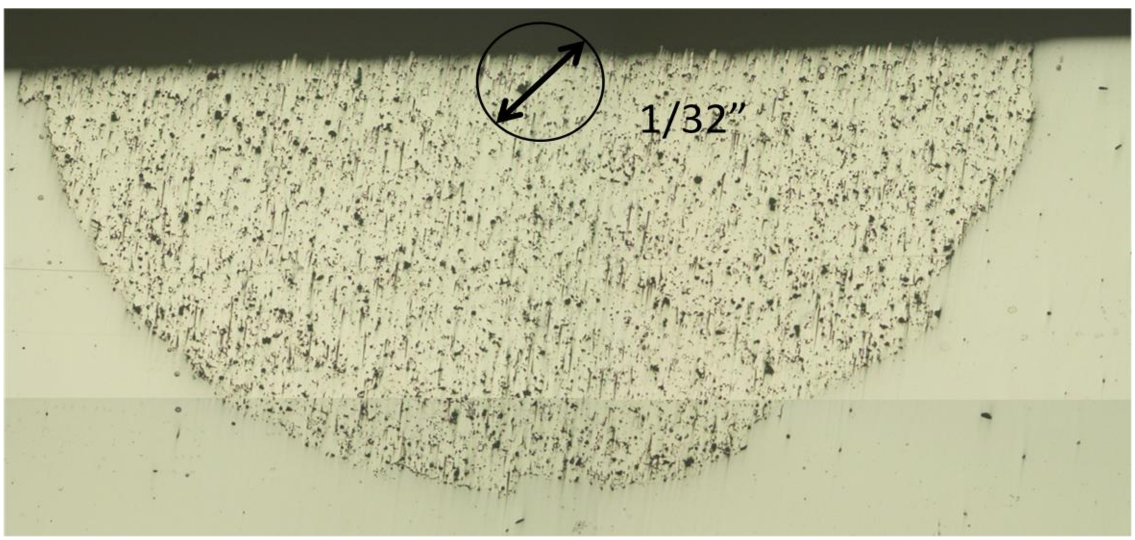

Figure 15(a): Top surface of sample #14 (1/32-inch sized hole)

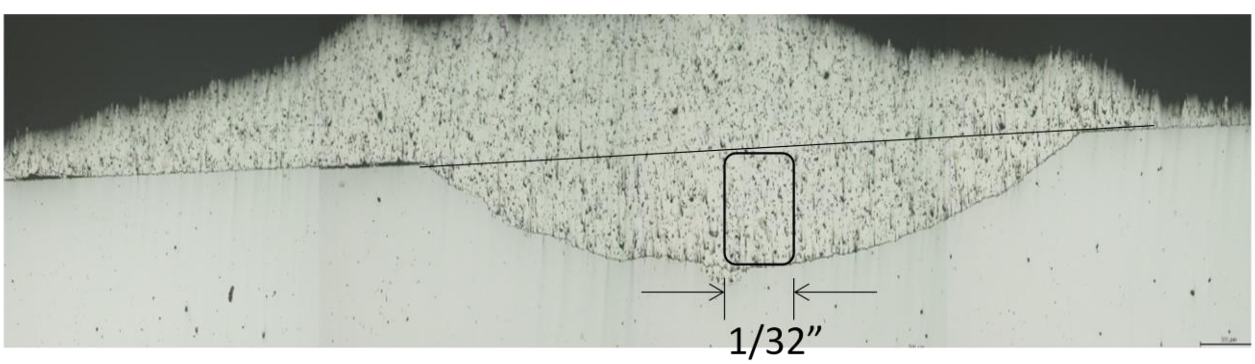

Figure 15(b): Cross section of sample #14 (1/32-inch sized hole)

3.3 Hardness Results

The average microhardness values obtained from samples where the cold-spraying was successful are shown in Table 4. Successful samples were ones which were completely filled after cold spray and did not pop out during the polishing step. A total of 20 samples were tested for hardness. Hardness measurements were taken at a distance of 100, 200 & 300 µm from the interface between the cold sprayed region and substrate as shown in Figure 16. The values in Table 4 are the average of 3 readings taken at these distances. There was no specific trend in hardness values from the interface towards the cold sprayed region as well as towards the substrate. Hardness was found to be constant throughout the coating deposition. The microhardness in the cold-sprayed region is lower when comparing to that of the substrate surface, however, the difference in the hardness values is not dramatic. The average microhardness values obtained from samples where the cold-spraying was successful are shown in Table 6.

Table 6: Hardness of cold-sprayed samples as a function of hole size.

Hole Size	Substrate (Hv)	Cold sprayed deposition (Hv)	# of samples
1/4"	324 ± 8	298 ± 10	4
1/8"	361 ± 2	327 ± 12	4
1/16"	363 ± 1	358 ± 10	6
1/32"	358 ± 2	331 ± 11	5

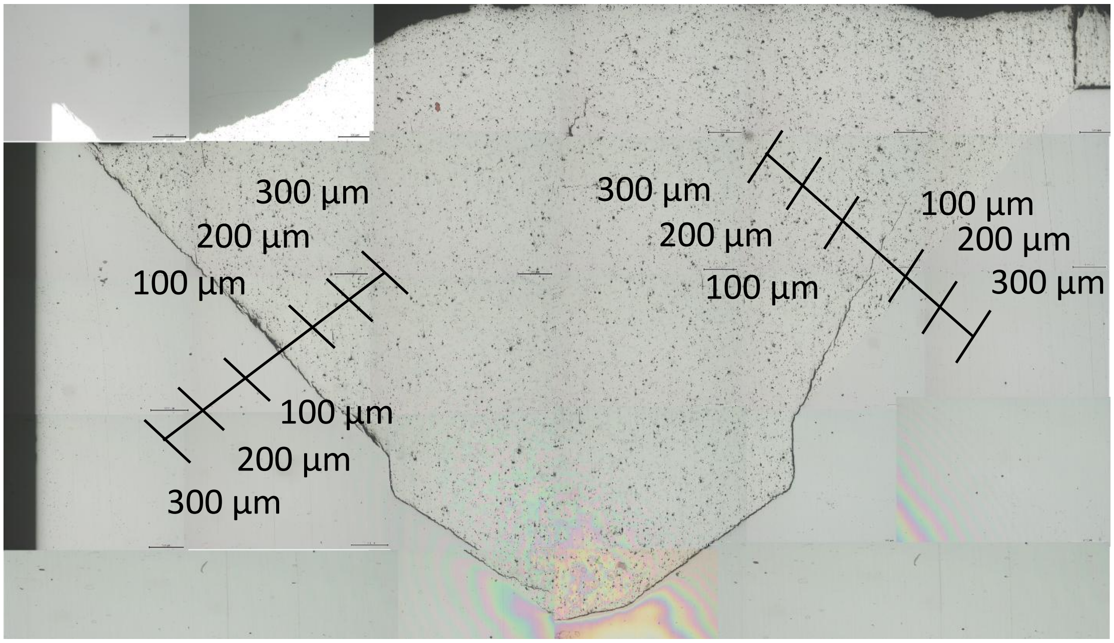

Figure 16: Hardness measurements locations on deposition and substrate.
(1/4 inch - #25 – cross section, minor chamfer)

For substrates harder than the spray particles, the kinetic energy is absorbed by the formed coating and the initial sprayed particles which results in slight deformation of the substrate and heavy deformation of the sprayed particles. In case of softer substrate, the kinetic energy is also absorbed in the deformation of the substrate which results in lower compression ratio of the sprayed particles or lower deformation of sprayed particles as compared to the harder substrates.

In the current research, the sprayed particles of SS 316 L have lower hardness as compared to the CA6NM substrate. Thus, we should expect slight deformation of the substrate and heavy deformation of the sprayed particles. The typical hardness level of 316 L falls between 150 Hv to 220 Hv. The higher side of the range is for annealed flat rolled product (plate, sheet and coil). These values are lower as compared to the approximate hardness of 360 HV noted in the current research. This could be attributed to the strain hardening phenomena resulting from the extensive plastic deformation of the 316 powder particles upon impact on the substrate.

3.4 Porosity Results

Line profile image analysis was done to find the percent porosity in the coatings. Porosity measurements were conducted on the top surface and cross section of sample #15 (1/32-inch sized hole, minor chamfer, 45°). This sample was selected at random. 10 measurements were taken across the sample at different locations and the average was calculated. The results of porosity measurement revealed 9% porosity. The higher porosity could be from the turbulence created inside the substrate hole during filling up. Porosity is also affected by stand-off distance. It has been found that increasing the stand-off distance to 20 mm reduces the porosity concentration. The unevenness in the stand-off distance from manual spraying could also affect the porosity in the cold spray process.

CHAPTER 4. DISCUSSION

In the cold spray process, it has been commonly accepted that the bonding between substrate and the cold-sprayed coating is a result of the plastic deformation of substrate and particle during the impacting process. The adiabatic shear instability at the interface is caused by the intensive localized deformation and consequently material extrudes from the interface and forms a metal jet at the rim. [24]. There are two main reasons which result in effective bonding: the mechanical interlocking between the substrate and the coating materials at the interface and the formation of a metallurgical bond caused by the localized rise in temperature as a result of strain heating. Experimental studies and computational modeling [24] have revealed that adhesion only occurs when the powder particles exceed a critical impact velocity since the adiabatic shear instability occurs beyond the critical velocity.

In the cold spraying process, it is commonly regarded that the deposition efficiency and properties of the coating are primarily influenced by the temperature of the process gas and particle velocity. Since the objective of this study is to examine the effects of selected variables on the coating formation during the cold spraying process, the effects of the selected parameters on the coating quality are discussed in relation to the parameters studied.

4.1 Preparation Technique

In the cold spray process, the effect of substrate surface roughness remains a matter of controversy since some researchers have shown that increased roughness enhances deposition efficiency, while others have shown that substrate roughness is detrimental to the deposition efficiency and bond strength [17].

Ghelichi et al. [21] reported that the deposition efficiency of metallic powders increases with higher roughness of the substrate surface. Severe deformation of the impacting particles on the rough surface as compared to smooth surfaces causes enhanced mechanical interlocking on the roughened surface. As a result, higher bond strength values are achieved for grit-blasted substrates in comparison to smooth substrates.

Kumar et. al [22] conducted the characterization of the bonded particles for different substrate surfaces. Fig. 17a-c shows simulated shapes of the deposited copper particles on different aluminum substrates having different roughness values. Fig. 17e shows the cross-section of embedded copper particles onto smooth aluminum substrate and Fig. 17f–h shows the same for grit-blasted substrates. He found out that the flattening ratio is increased by increasing roughness and then decreases after certain critical limits. [22]

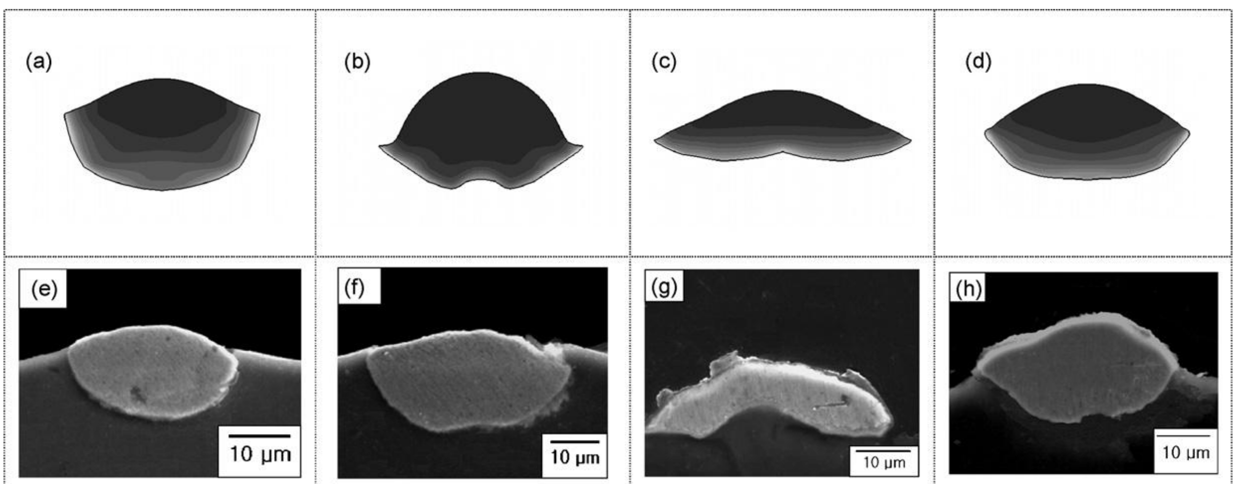

Figure. 17. Cross-section of deposited powders on different substrates and corresponding simulated images. [22]

Marrcco et al. [22] proposed that work hardening is caused as a result of grit blasting of the substrate, which limits substrate deformation during impact of the particles. It can be seen in Figure 18, reproduced from this study, that the polished and ground surfaces resulted in higher bond strengths while the grit-blasted surface condition resulted in the lowest bond strength.

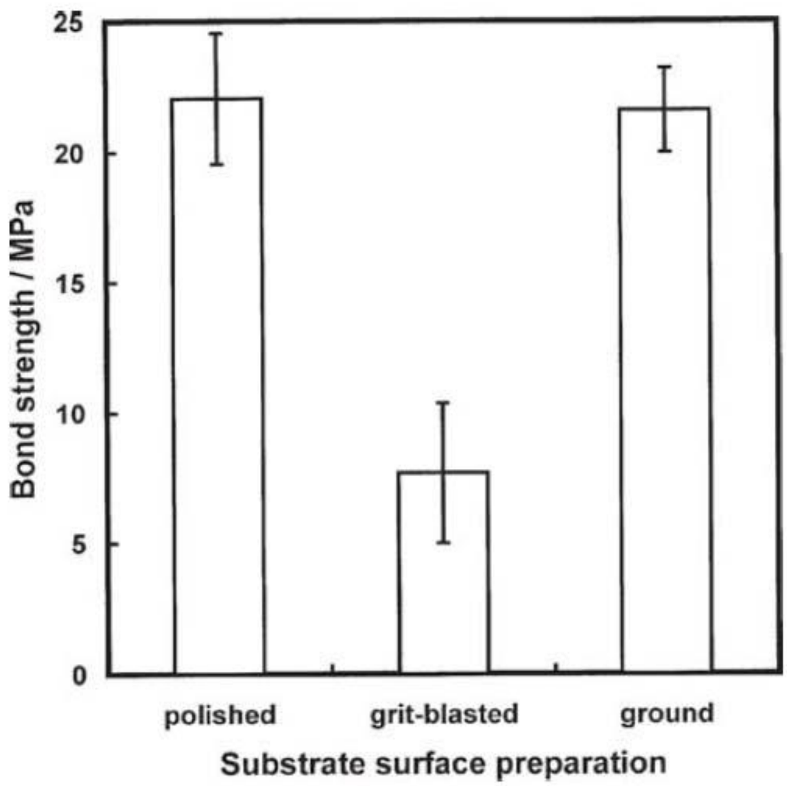

Figure 18: Bar chart showing the effect of substrate condition on the bond strength of deposits sprayed at 29 bar gas pressure using CTi powder (coarse powder) [55].

Wu et al. [22] studied cold sprayed Al-Si deposits onto both polished and grit-blasted mild steel. They observed micro-pores and defects in the grit-blasted surface. They asserted that micro-pores on the grit-blasted surface results in lower particle deformation.

The question of surface roughness was tested in the current study by comparing a smooth surface to a grit-blasted surface and to a Scotch-Brite™ roughened surface. Considering the previous studies, it was predicted that increasing the substrate roughness would improve the bonding since it provides a greater range of nooks and recesses wherein the sprayed particles can lock. As successive particles impact the substrate the particles at the bottom are subjected to additional compaction. Surfaces with lower roughness would be expected to have lower bond strength resulting from the little surface area to bind with.

In the current research the level of roughness generated by the various preparation techniques should follow the trend described below:

Less rough (NONE << SCOTCH-BRITE™ << GRIT BLAST << GRIND) more rough

The substrate holes with no surface preparation will have the lowest roughness while grinding with a ball end mill should have the highest surface roughness. Roughness generated by grit blast is assumed to be higher as compared to roughness achieved by scuffing with Scotch-Brite™ abrasion pad. Since the samples received were already cold sprayed, roughness measurements were not made.

Based on the theory resulting from studies previously discussed, one should expect that the samples prepared by grinding with a ball end mill should have the better adhesion as a result of higher surface roughness as compared to substrates sprayed without any surface preparation. Grit blasted surfaced should have better adhesion results than samples prepared by scuffing with abrasion pads. So, the best adhesion results should be seen for samples prepared by grinding, followed by grit blasted samples which should be better than samples prepared by scuffing with Scotch-Brite™ abrasion pads. Samples cold sprayed without any surface preparation should have the poorest adhesion as compared to other techniques. In the current study, it is clear from the cross-section images obtained by optical microscope that most cracks exist at the coating substrate interface because of the poor adhesion.

4.1.1 Minor and medium chamfer

Sharp angles are known to act as sites for stress concentration. Adhesion is deteriorated by the sharp angles of the holes which serve as the point of stress concentration causing the coating to pop up with minimal effort. Also, problems could arise from turbulence at the sharp edges which could cause the spray particles to rebound from the substrate surface resulting in adhesion issues. However, most research regarding turbulence in a cold spray process consider a flat substrate, hence, the effect of turbulence may or may not be affecting the cold spray process for the substrate with holes, Grinding the hole with a ½” ball end mill while eliminating the sharp angles seems to be the best preparation technique since only 2 out 15 samples were defective. Grinding the drilled hole with a 1” ball end mill and tapering the leading edges with a grinding stone resulted in 8 defective samples out of 15.

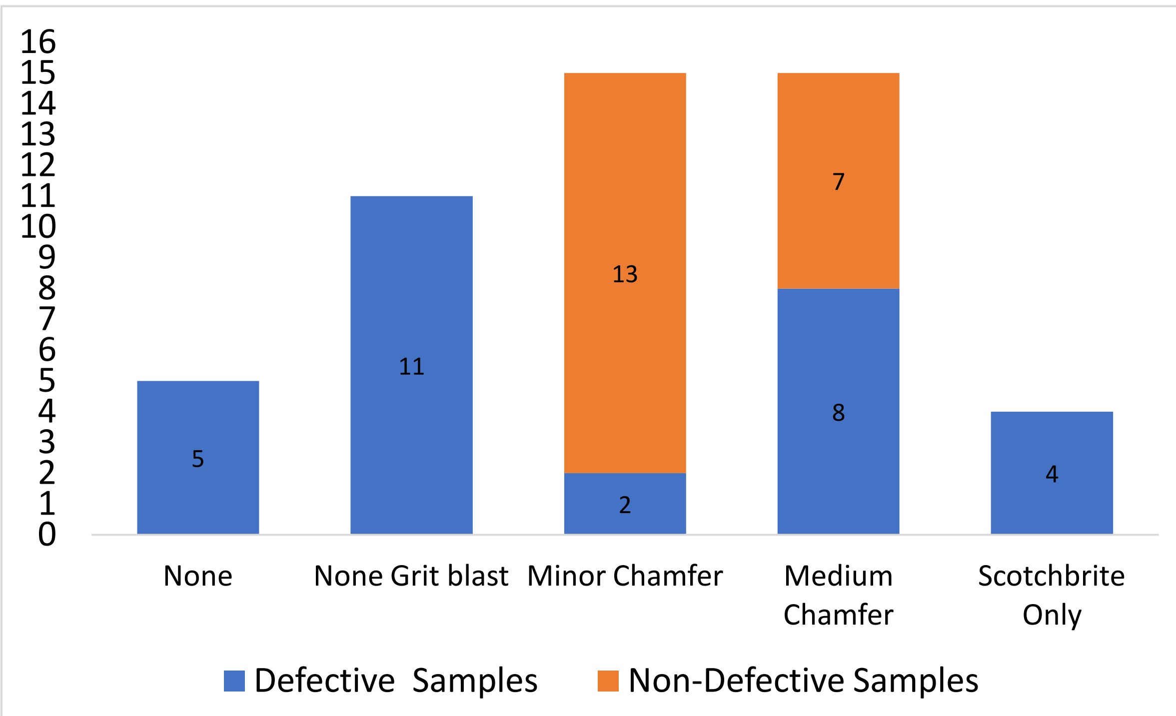

Figure 19: Defective samples w.r.t. preparation technique.

From our results, it can be seen that samples with chamfered edges show better adhesion as compared to samples prepared without chamfered edges.

As seen in Figure 19, samples belonging to the category of no surface preparation, grit blast and Scotch-Brite™ have failed (either hole not completely filled or coating popped out during the polishing step) completely. Samples prepared by grinding with a ball end mill and chamfering perform better as expected. This supports the theory that surfaces with higher roughness should have better adhesion than surfaces with lower roughness.

It is important to note that many samples prepared by medium chamfering technique also had a hole size of 1/64” while none of the samples prepared by minor chamfering technique had a 1/64” hole size. Since all of the samples belonging to the 1/64” hole size failed (popped out during polishing) the results for medium chamfering are worse than minor chamfering. Thus, hole size seems to play as important a role in obtaining a good coating as does chamfering.

4.2 Hole Geometry and Size:

Very little research on the effect of substrate geometry, hole size and contact area on coating deposition exists. Initially the 5 different hole sizes were 1/2”, 1/8”, 1/16”, 1/32” and 1/64”. However, after conducting the minor and medium chamfering surface preparation, the hole sizes were altered. Holes which were minor chamfered ended having a hole size of 1/2” since 1/2” ball end mill was used. Similarly, medium chamfered holes had a hole size of 1” since 1” ball end mill was used. Further, minor and medium chamfering altered the geometry of the hole making it more shallow and semi-spherical in shape as seen in many microstructures.

The foremost theory in cold spray coatings is considered to be mechanical interlocking which is promoted by particle impingement of the substrate surface [25]. As the hole size increases, the contact area for the oncoming cold spray material increases. Bigger holes provide more points of contact for the impinging material to mechanically interlock with the substrate. In the current research, all the holes for 1/4”, 1/8”, 1/16”, 1/32” and 1/64” size failed while 53% of the 1” size hole failed and 13% of the 1/2 “size hole failed. This shows that there should be other factor than the contact area which plays a major role for successful deposition of the cold spray.

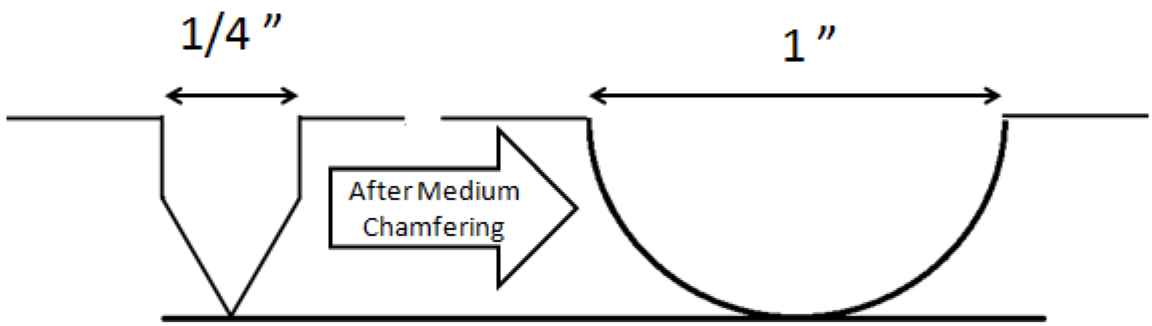

Figure 20: Change in hole geometry due to chamfering.

As shown in the above figure, minor and medium chamfering alters the geometry of the substrate holes which could have a pronounced effect on the deposition behavior. Grinding with the ball end mill creates a semi spherical shape eliminating sharp edges, turbulence prone regions, etc. bringing the substrate closer to a flat contour which creates best conditions to achieve high deposition efficiency with cold spray. It can also be expected that semi spherical geometry will allow for better gas flow into the hole during the deposition process, reducing the number of eddies and disruption that occurs at the edges of the hole.

By studying the new hole sizes, it is evident that hole size does not have a great effect on the deposition efficiency. However, it can be clearly seen that the hole geometry plays a major role in improving the deposition efficiency. Also, it is important to note that for all the 1/64” sized holes, the cold spray popped out during the polishing step. Although the reason for the high failure rate is not known, it is theorized that within these small, constrained holes the cold spray's carrier gas is unable to effectively penetrate the small volume, possibly due to disruption of the flow by the edges and eddying of the gas at the bottom of the small hole.

This results in low deposition force of the powder and the material that is deposited is unable to develop significant bond strength.

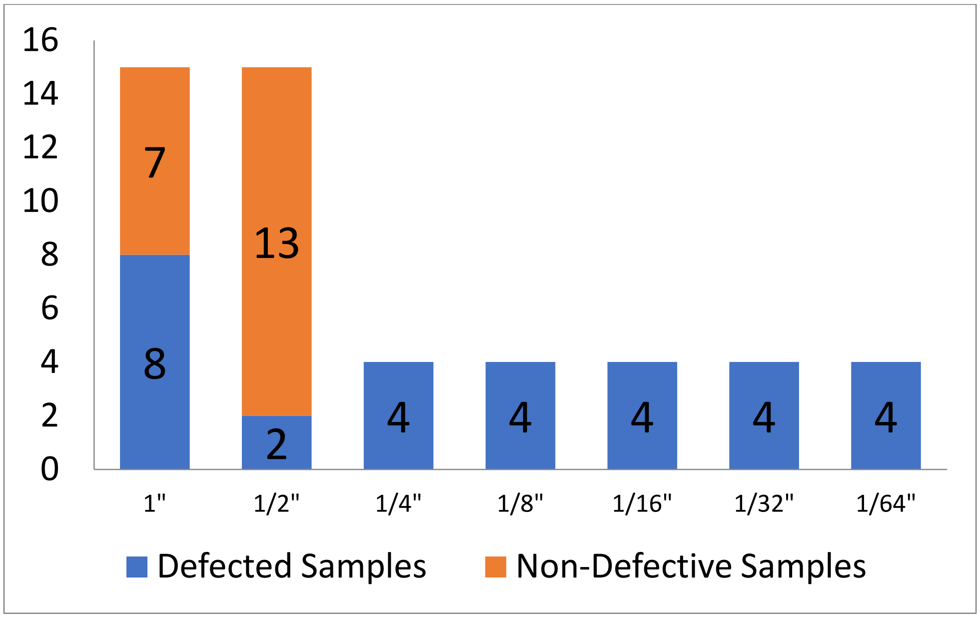

Figure 21: Defective samples w.r.t hole size.

4.3 Spray Angle

C.-J. Li et.al [16] studied the effect of spray angle on deposition characteristics in cold spraying. This study found that for successful deposition onto a substrate, the particles must reach a velocity higher than a certain critical velocity. The deformation of the impacting particle mainly depends on the normal impact velocity. The normal component of the particle velocity is highest at 90˚ while it decreases if the particles are sprayed at off-normal angles relative to substrate surface. Thus, spray angle in cold spray will influence the deposition behavior and microstructure of the coating [16]. Figure 22 shows the effect of spray angle on the relative deposition efficiency in cold spraying. [16]

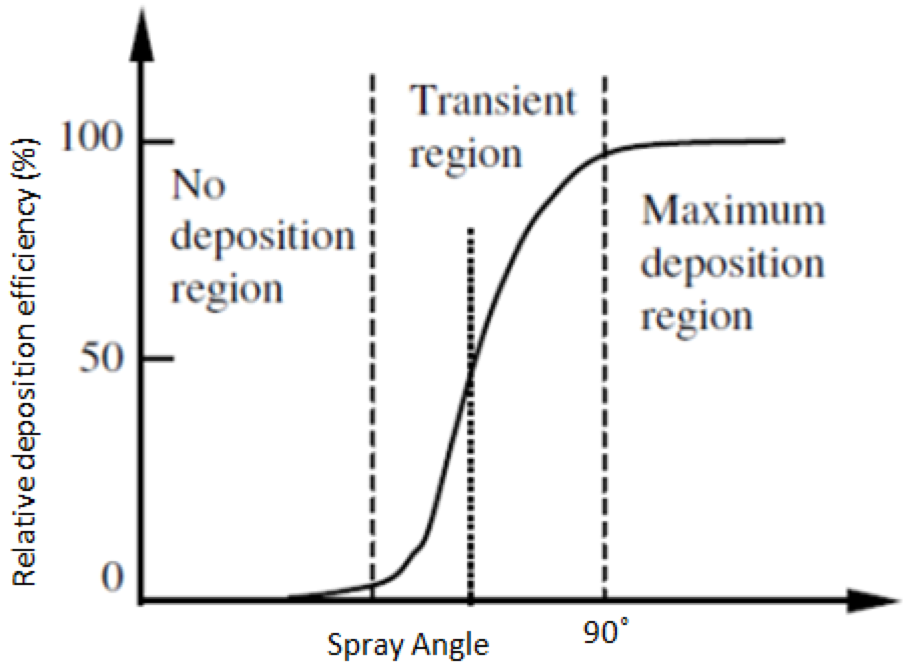

Figure 22: Dependency of relative deposition efficiency on spray angle. [16]

As the spray angle gets closer to 90˚ (normal impact), the relative deposition is the highest. With a decrease in spray angle, the relative deposition efficiency decreased. Almost no particles were deposited on the substrate at lower spray angles and the relative deposition efficiency tended to zero. This result suggests that there is a spray angle below which no particle deposition occurs [16]. Based on these studies, one might predict that spraying at 45˚ will not be as effective as spraying at 90˚. Hence, the samples sprayed at 90˚ should provide better bonding as compared to samples sprayed at 45˚.

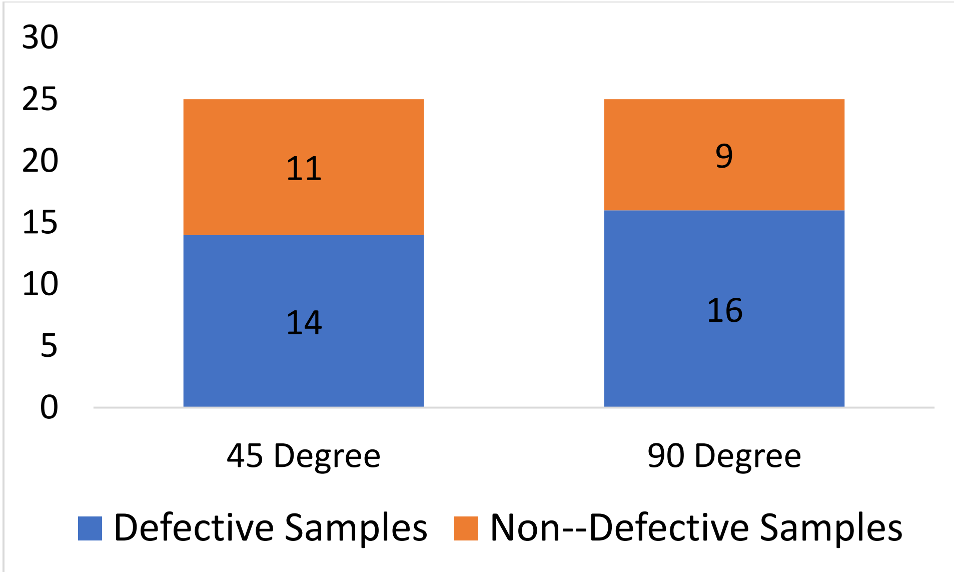

Figure 23: Defective samples w.r.t. spray angle.

However, in the current study, the effect of spraying at 45 ˚ versus spraying at 90 ˚ is not clear as shown in the Figure 23. The 45˚ spray was made from one side and then after rotating the sample 180˚ from the opposite side. Spraying at a specific angle does not seem to make a major difference. This could be for a couple of reasons. Firstly, the inconclusive results could be because of a change in the stand-off distance, which is the distance from the nozzle to the sample surface. The stand-off distance affects impact velocity, which in turn affects deposition efficiency. Minor changes in stand-off distance can affect the impact velocity causing the deposition efficiency to increase or decrease [25]. Cetin et. al [26] studied the effect of stand-off distance on the coating structure and amount of porosity present. In that study a surface was cold sprayed at stand-off distances of 5, 10, 20 and 30 mm. Coating disintegration was observed in a sample cold sprayed at a distance of 5mm as shown in Figure 24.

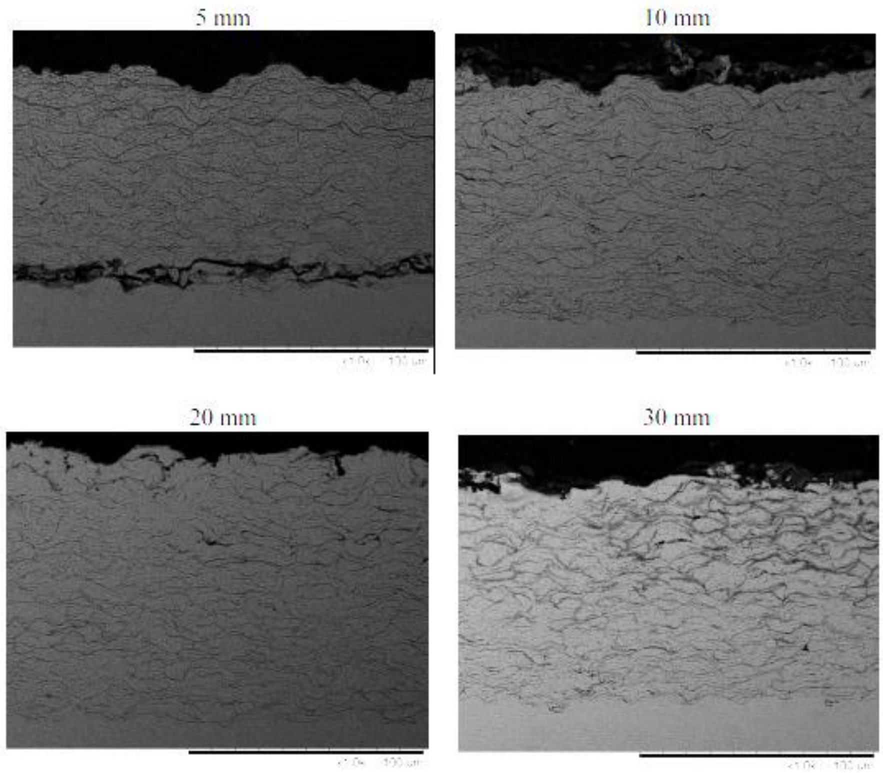

Figure 24: SEM images of the coatings produced on the substrate with different stand-off distance. [26]

Further, it was found that increasing the stand-off distance up to 20 mm reduced the porosity concentration and increased coating thickness. [26]

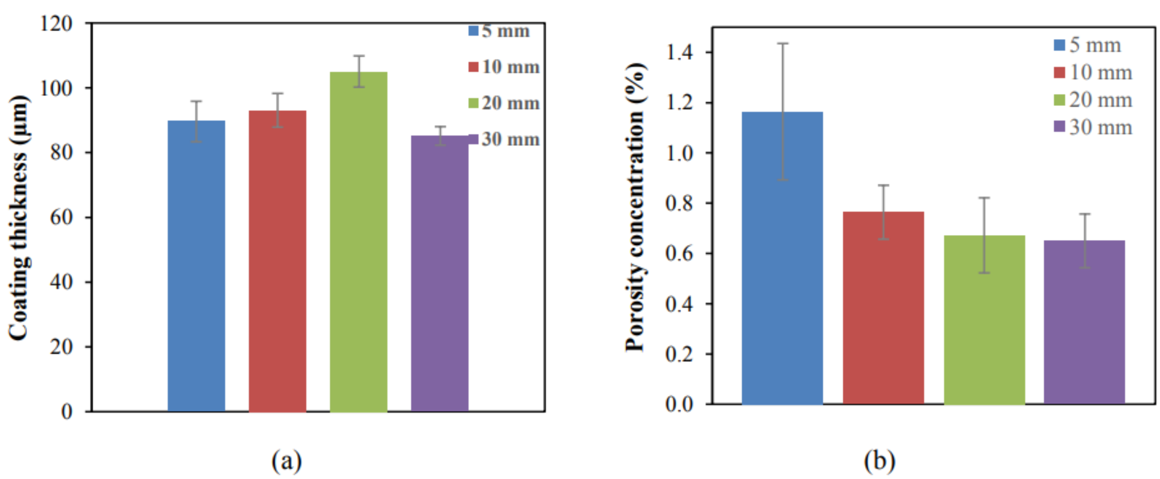

Figure 25: (a) Stand-off distance-coating thickness relation,
(b) Stand-off distance-porosity concentration relation. [26]

In the current study, cold spray was done manually and therefore chances of variation in stand-off distance are present. Since the stand-off was not monitored it is impossible to say if this had an effect on the results.

A second reason why the effect of deposition angle may not be apparent is due to the type of samples used. The cold spray technician pointed out that spraying at a specific angle results in losing the flexibility of the hand spray technique. Often the best way to produce a sound deposition is to vary the spray angle as deemed suitable by the technician at the time of deposition. If one considers the various shapes of the samples produced due to chamfering, milling, etc. a fixed deposition angle could strike some regions of the hole surface at 90˚ even if the deposition angle is set at 45˚ and vice versa. When a technician is allowed to adjust angle during the deposition process the result may be that they unconsciously adjust the angle "on the fly" to maintain a 90˚ impingement angle on the surface. Such an adjustment comes as they see particles rebounding and the hole not filling as the angle the spray makes with the varying surface changes.

For any given angle the impinging particle can detach or rebound from the surface after the impact. Whether this occurs or not must surely be a function of factors such as particle size, local angle of the surface with respect to the impinging particle due to roughness, turbulence of the gases in the hole being filled, etc.

The effect of other variables, which either were not measured or cannot be measured easily, make a conclusive statement about the effect of spray angle difficult. For example, it is known that turbulence and the position of the particles in the jet can also affect the adhesion properties [23]. The core of the jet has higher in-flight velocities, hence, particles in and near the core of the jet undergo higher deformation and penetration when they impact the substrate [23]. It is likely that parameters such as these play an important role in deposition quality also and should be studied to better understand what needs to be controlled to obtain the desired properties in a cold spray deposit. Various other parameters which are anticipated to affect the deposition efficiency and the quality of the deposit are:

- Particle size – Particle size will affect the critical impact velocity and in turn influences particle deformation. Differences in heat capacity, thermal conductivity, cooling rate, and the degree of shear instability for differently sized particles will result during impact.
- Optimum stand-off - Reduced property levels of cold spray deposits result from long stand-off distances and it is apparent that an optimum distance exists for obtaining the best properties.
- Turbulence and position in the jet stream - The position of the particle in the jet stream can affect particle velocity and deformation characteristics since the particle velocity in the cone-shaped jet is non-uniform. Turbulence around the edges of holes can affect many things such as local impingement velocity and angle.
- Operating Parameters - The level of particle deformation is also affected by the type of carrier gas, pressure and temperature.
- Temperature - Temperature of the substrate, carrier gas and gas velocity will determine local temperature at the particle / substrate interface, affecting properties and powder bonding.
- Material properties – Mechanical and physical properties of the substrate and the deposited powder itself will have a critical role in determining the quality of the deposited coating.

CHAPTER 5. SUMMARY AND CONCLUSIONS

The ability of the cold spray process to effectively fill holes of various sizes in a casting was studied by drilling holes of different sizes into a weld plate to mimic porosity in castings. These drilled holes were prepared by various surface preparation techniques and cold sprayed. Initial trials on the test block using minimal or no surface preparation before cold spraying resulted in many holes being unfilled; other showed little or no bonding. Deposited material in the smaller holes tended to pop out while 50% of the larger holes did not fill.

Various surface preparation techniques for preparing porosity to be cold sprayed were then examined. These included grinding the hole with a ½" and 1" ball end mill, grit blasting, and roughening with Scotch-Brite™ to increase surface roughness. The edges of some holes were also chamfered. These efforts showed that chamfering and increasing the surface roughness clearly improved the ability to bond. Samples without any preparation, Scotch-Brite™ or grit blasting, failed.

The effect of spray angle also was examined in the current research. Mixed results were seen as a result of varying the spray angle.

Microstructural homogeneity is important for any technique used to salvage casting with surface porosity. Hence, microstructure examination of the cold sprayed weld plate was conducted. Microstructure showed porosity, internal cracks and voids, and some separation at the interface. Average porosity was on the order of 9%.

Similar to microstructural homogeneity, variations in hardness between the substrate and deposition should be minimum. Hardness of the deposition was lower than the substrate, but higher than what is typically expected for the deposited powder, in this case 316L.

Hardness throughout the deposition as well as the substrate was relatively constant as no specific trend near the interface was observed.

From the experiments carried out during the course of this study it is possible to draw the following conclusions:

- It appears that the chamfering with a ball end mill to change the substrate hole geometry to semi spherical improves deposition efficiency. Hole geometry seems to be critical parameter as compared to hole size. Grinding out to a larger size is suggested. Increasing the hole size should increase contact area for the deposit, consequently increasing the points of mechanical interlocking resulting in better adhesion.
- Removal of sharp edges by chamfering of the hole appears essential for producing a good deposit. Chamfering the edges improves coating adhesion by removing the effect of stress concentration resulting from sharp edges. Minor chamfer was the best prep technique for cold spraying.
- The effect of spray angle is not established at this time. This could be because of the effect of other parameters such as stand-off distance and turbulence of the particles in the spray. These parameters are difficult to control in manual cold spray process.
- Microporosity should be expected, even in well bonded samples. Some bonded samples had voids inside the holes. Parameters need to be refined to produce denser fills. However, minimum or no cracks are seen in most of the deposits. This is a major improvement as compared to results observed by Ganesan. [8]
- Hardness measurements indicate that hardness of the substrate is not affected by the cold spray. The hardness of the deposited SS 316 L is higher than typical SS 316 L hardness

values. This could be because of the strain hardening resulting from the high plastic deformation at interface with the substrate and with adjoining particles.

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