2015 WJTA-IMCA Conference and Expo
November 2-4 · New Orleans, Louisiana

Paper

ENHANCING THE ADHESION STRENGTH OF COLD GAS DYNAMIC SPRAYED COATINGS BY PREPARING THE SUBSTRATES WITH THE HIGH-FREQUENCY PULSED WATERJET

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ABSTRACT

It is known that surface preparation can affect performance of thermal spray coatings more than any other variables. The objective of this study is to gain an understanding of the effect of different surface preparations on the adhesion strength of coatings applied by the cold gas dynamic spraying technique. Preparation methods under consideration are: polishing, grit blasting and high-frequency pulsed waterjet. The results demonstrate that adhesion strength of the grit blasted substrates is lower than the one achieved with the pulsed waterjet substrates. Furthermore, the results indicate that pulsed water jet provides a very simple method to control surface roughness by simply varying the standoff distance.

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1. INTRODUCTION

As highlighted in the JPCL article (Bamhart et al.), the surface preparation of the substrate is one important part of a coating system. That is, the surface preparation can deeply affect the performance of the coating. The effectiveness of a coating depends on its bond to the substrate which is highly dependent on how the surface has been prepared. The ubiquitous method of preparing a surface is grit blasting (Helsel; Groff). However, for many coatings, the imbedding of grit particles is highly undesirable. In order to avoid this problem, use of continuous waterjet has been attempted for preparing surfaces, primarily for epoxy coatings (Groff).

The adhesion strength level of thermal spray coatings in general and more precisely in the case of cold gas dynamic sprayed coatings, is highly dependent on surface preparation and surface roughness level (Varacalle et al.). Conventional methods for surface preparation using grit blasting are aimed to improve adhesion strength of coatings by primarily enhancing the substrates surface area by increasing roughness profiles. The main disadvantage of using grit for creating such profiles are: a) grit particle embedment and b) limited roughness attainability. Grit contamination poses a considerable health issue for biomedical applications where costly revision surgeries have been performed to replace damaged joint implants. Even if the health effects of contamination are ignored, it is not possible to markedly increase the coating adhesion strength as particle embedment leads to early crack propagation, thus reducing considerably fatigue life of the coated part.

A novel technique used to increase surface roughness by using pulsed water jet has shown dramatic improvements in coating adhesion, superior to that of grit blasting, without the potential disadvantage of particle embedment at the interface. The main advantages of using water only to roughen surfaces is to i) eliminate grit embedment that can cause contamination and reduce fatigue life. ii) increase roughness beyond what grit blasting technique can produce to further promote adhesion strength.

This paper shows that using pulsed water jet to prepare surfaces to be coated using the cold gas dynamic spray process increases the coating adhesion strength by a factor of 4 over that of grit blasting methods. This increase in adhesion strength appears to be the result of unique nanometer to micrometer sized surface features.

2. EXPERIMENTAL PROCEDURE

2.1 Pulsed Water Jet – PWJ

PWJ has been in the industrial scene for past 20 years. It has mainly been used as an alternative technology to ultra-high pressure water jet for removing coatings such as epoxy based paint and much harder coatings such as thermal barrier coatings typically found on aircraft engine hot-section components. However, recent studies have shown that PWJ can also deliver embedment-free surface preparation that is superior to conventional grit blast method (Samson et al.). This patented process can be applied on any material and water is the only required medium (Vijay et al.).

With PWJ, substrate material such as aluminum and high strength steel alloys all can be roughened with operating water pressures as low as 5000 psi. The fundamental physics behind the workings of pulse jet has been presented previously (Vijay et al.; Vijay). To completely explain how pulsed water jet can easily alter the surface characteristics without using any abrasives is beyond the scope of the paper. In general, pulsed jet generates and directly deposits cavitation bubbles via a water jet to implode on the targeted area. As intense cavitation bubbles collapses on one another, a stochastic surface profile is produced.

2.2 Cold Gas Dynamic Spraying – CGDS

CGDS is becoming a more common thermal spray technique used to deposit metallic coatings for a variety of applications (Irissou et al.). The value of this process resides in the fact that it allows coatings to be deposited without exposing the feedstock particles to high in-flight temperatures that may cause notable oxidation or phase change (Davis; Grujicic et al.; Richer et al.). This is accomplished by injecting particles into a flow of compressed gas (often nitrogen, although helium or air can be used) accelerated through a converging-diverging nozzle. Feedstock particles in this stream are accelerated to high velocities before impacting the substrate. Upon impact with the substrate, both the particles and substrate experience adiabatic shear instabilities (Schmidt et al.; Assadi et al.; Wu et al.; Hussain et al.; Grujicic et al.), resulting in jetting of material. This jetting often leads to the removal of oxide layers allowing for metal to metal contact, localised melting (at the nanometer scale) due to friction forces, as well as producing mechanical anchoring points which are enveloped by the impacting particles. This leads to a mix of two types of bonding mechanisms that have been identified in CGDS: metallurgical and mechanical. The parameters used in the current work for the CGDS deposition can be found in Table 1.

Table 1: CGDS Parameters used for Deposition

Gas Temperature	300°C
Gas Pressure	3.45 MPa
Carrier Gas	Nitrogen
Traverse Speed	20 mm/s
Step Size	1 mm
Passes	1
Feed Rate	14 g/min
Feed Wheel Type	320 Small Hole
Powder Feeder Gas Flow Rate	0.85 NCMH
Powder Feeder Carrier Gas	Nitrogen
Standoff Distance	15 mm

2.3 Substrate and Coating Material Selection

To evaluate the efficiency of PWJ prepared surfaces, coatings adhesion strength are to be compared to grit blasted and polished surfaces that have been coated using the same spray process and parameters. The deposition of pure aluminium powder onto 6061 aluminum alloy substrates has been used successfully accomplished in the past and can serve as a reliable reference point. The substrate material used in this study was 6061-T6511 aluminium alloy. The substrates were machined into 25.4 mm diameter cylinders in accordance to the ASTM C633 adhesion strength standard. To ensure consistency between sprays, the samples were thermally insulated during deposition using a high temperature polymer (polybenzimidazole) holder. The powder used in this investigation was pure aluminium powder (SST-A5001) [Centerline Ltd., Windsor, Ontario, Canada].

2.4 Substrate Preparation

Three different surface preparing techniques were used for comparisons namely, PWJ, grit blasting and mirror-finish polishing. A minimum of three samples were used for each group to assess process variances. The parameters for polishing and grit blasting can be found in Tables 2 and 3, respectively.

Table 2: Polishing Disks Used In Order of Decreasing Roughness Used To Prepare Polished Samples

Grinding / Polishing Disk	Expected Surface Finish
MD - Piano 220 solution	~ 68 µm
MD - Largo with Largo suspension solution	~ 3-9 µm
MD - Mol with Mol suspension solution	≤ 3 µm

Table 3: Surface Preparation Parameters for Grit Blasting

Abrasive	Aluminium Oxide
Size	177 µm
Process Gas	Filtered / Dry Air
Spraying Pressure	~ 400 kPa
Spray Angle	45°
Standoff Distance	51 mm

To evaluate the effect of substrate surface roughness on coating adhesion strength, PWJ samples were prepared with low, intermediate, high, and very high surface roughness. Low level is considered to be equivalent to surface roughness values obtained using grit blasting, whereas intermediate and above levels are typically not attainable by the grit blasting process. PWJ roughness can be controlled via standoff distance, pressure, flowrate and/or dwell time. Process parameters for the PWJ process are presented in Table 4.

Table 4: Parameters Held Constant For All PWJ Surface Preparations

Traverse Velocity	455 mm/s
Water Pressure	69 MPa
Nozzle Diameter	1.0 mm
Pulse Frequency	20,000 Hz
Step Index	0.1 mm/pass

2.5 Adhesion Strength Testing

The adhesion strength between the coatings and the substrates was determined in compliance with ASTM C-633. A thermally cured elastomeric adhesive with a tensile strength of 76.9 MPa was used. The samples were placed in a vertical fixture and then placed in a 177ºC oven for two hours to ensure the adhesive had properly cured. The testing was performed using an Instron universal tensile testing machine.

2.6 Evaluation of Substrate Roughness

3D digital imaging by depth composition was performed with a digital microscope (VHX – 1000, Keyence Corporation, Osaka, Japan) on the substrates prior to coating deposition. These images were then used to perform roughness measurements and perform surface area calculations.

3. RESULTS & DISCUSSIONS

3.1 Substrate Roughness

In the experiment, surface roughness for the PWJ samples was altered by changing the standoff distance of the jet. Table 5 presents the roughness values determined for each substrate preparation method used in this work. It also presents the calculated increase in projected surface area compared to an ideally flat surface.

Table 5: Roughness results for substrates prepared by polishing, grit blasting, and PWJ

Sample	**Standoff Distance [mm]**	**Measured Roughness, R_a [µm]**	**Increase in surface area [%]**
Polished	N/A	0.5 ± 0.1	1.4 ± 0.1
Grit Blasted	51	1.7 ± 0.3	3.7 ± 0.6
Waterjet A	56	2.1 ± 0.3	6.4 ± 4.2
Waterjet B	51	4.6 ± 0.4	13.1 ± 4.6
Waterjet C	46	15.9 ± 1.3	49.3 ± 8.1
Waterjet D	42	21.7 ± 2.3	60.8 ± 20.2

3.2 Evaluation of Substrate Surfaces

Figure 1 shows that the grit blasted surface contained traces of embedded aluminum oxide. This feature is important, as it may result in reduced adhesion strength due to crack propagation. Figure 2 shows a PWJ surface at the same magnification. Unlike roughened surfaces created by grit blasting or traditional machining methods, pulsed water jet roughened surfaces are teeming with intricate networks of voids where the coating can find a firm grip to produce strong mechanical bond.

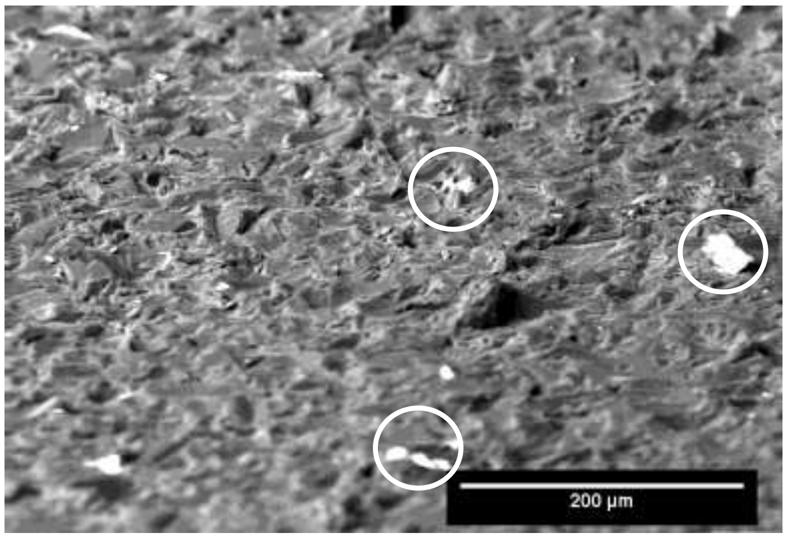

Figure 1: SEM image of grit blasted aluminum showing traces of alumina oxide grit embedment at 200X magnification at angle.

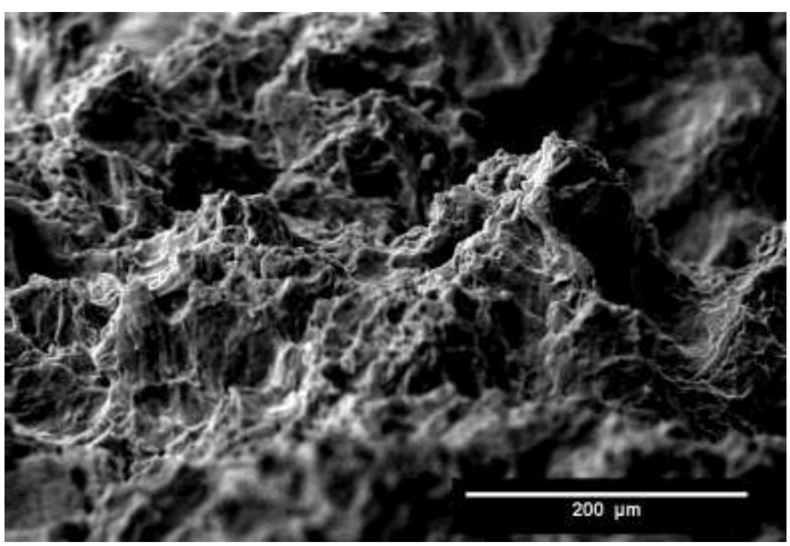

Figure 2. SEM image (200X) showing PWJ roughened surface free of grit contamination.

Figure 3 shows the top view of a 20-30 micrometer (Ra) surface produced by PWJ. This picture demonstrates that there are not only features at the micrometer scale, but also many features at the nanometer scale. These images lead to a clearer understanding into the way that the coating particles could entrench themselves into the cavities generated by the PWJ process.

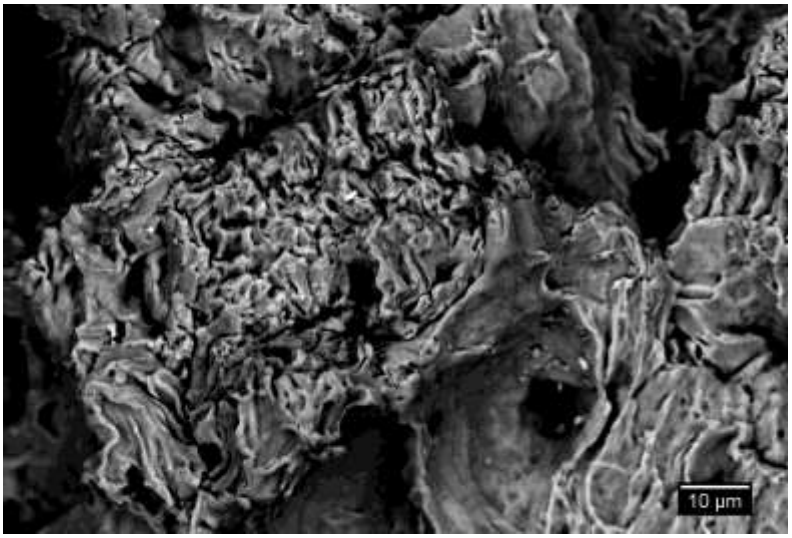

Figure 3. SEM image (1000X) of PWJ roughened surface topography. Note the density of random pits and crevices created by cavitation.

3.3 Evaluation of Adhesion Strength

The results of adhesion strength vs substrate roughness values can be found in Figure 4. It reveals a direct correlation between surface roughness and adhesion strength i.e, the rougher the surface the higher the adhesion strength. However, it can be observed that the adhesion strength levels off at the higher end of substrate roughness and suggests that increasing roughness beyond these levels will not translate into higher adhesion values. It is hypothesized that this is mainly due to poor coating quality; such that as the surface gets rougher than a specific value, the coating integrity diminishes. More work needs to be performed to clearly assess the physics behind these observations and hypothesis.

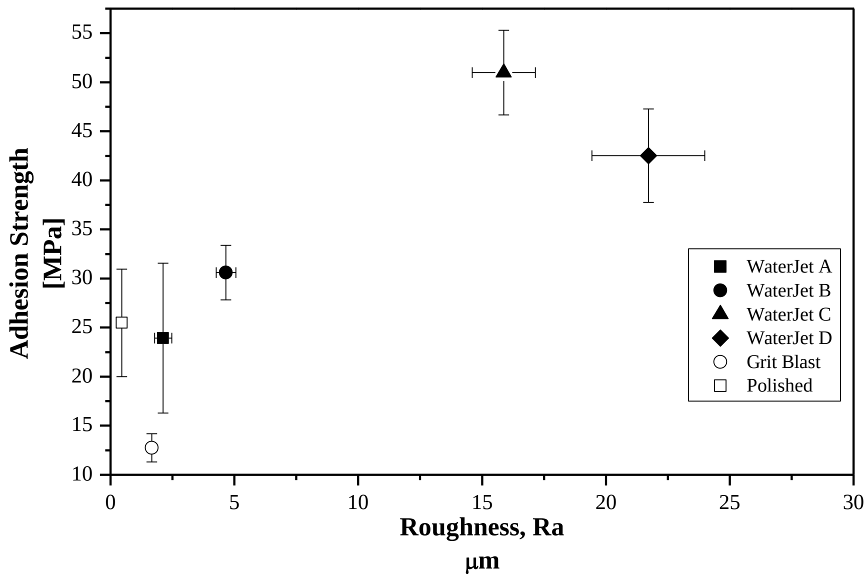

Figure 4. Plot showing the effect of surface roughness (surface preparation) on the adhesion strength of CGDS coatings.

Figure 4 also shows that the adhesion strength is higher on polished surface over grit blasted surface. This is counter intuitive in terms of increased surface area as discussed previously. However, the CGDS process is known to act as grit blasting for the first few particles impinging the substrate. As such, a polished surface would present some level of surface roughness due to that effect without foreign grit particle embedment that reduces the effectiveness of coating adhesion strength. The coating cross section of Figure 5 reveals that grit remained embedded at the substrate/coating interface for the grit blasted samples, which would substantially decrease the adhesion strength of the coatings.

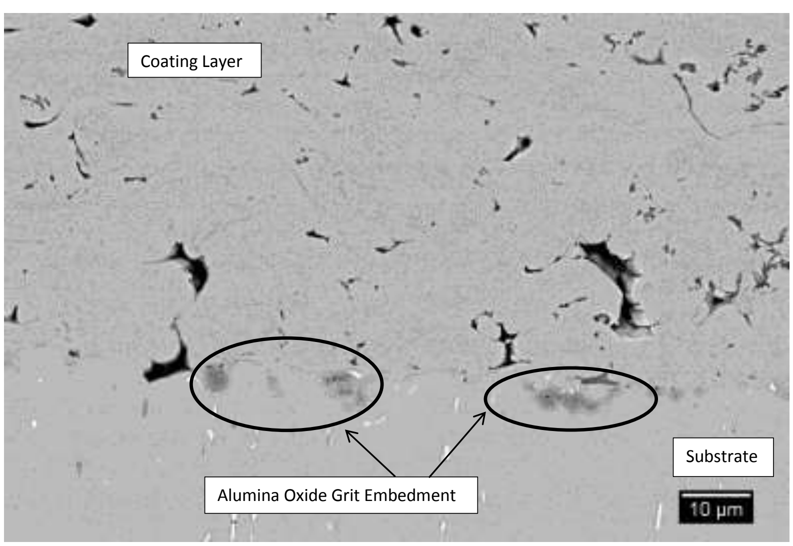

Figure 5. SEM image (500X) showing a cross sectional view of the coating and substrate interface. Note the grit particle contamination.

The high adhesion strength of the PWJ samples can be attributed to abundance of 3-dimensional roughness features that allow more mechanical anchoring and an increased surface area. Such high adhesion strength leads to cohesion failure which can be observed during the pull test where the tensile strength of the coating material itself is lower than the adhesion strength. A clear example of mechanical anchoring can be observed in Figure 6.

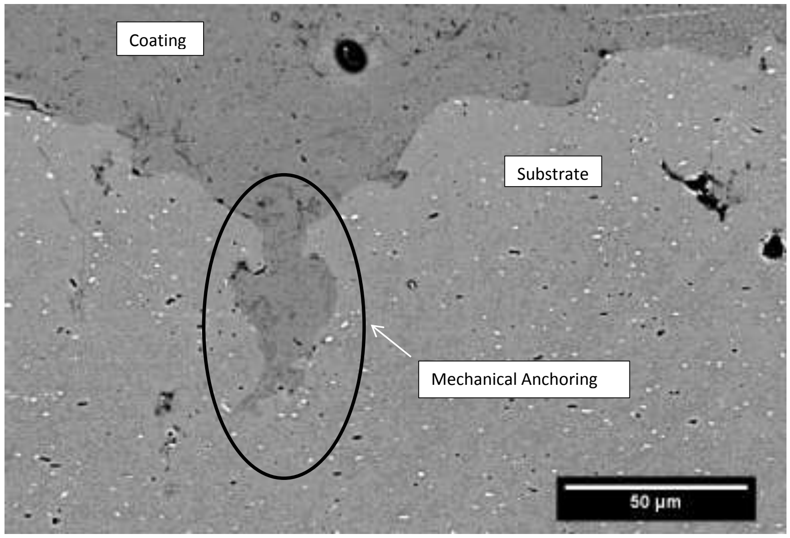

Figure 6. SEM image (500X) showing a cross sectional view of the coating and substrate interface. Note the interlocking effect offering strong mechanical anchoring.

Given that the coating spray parameters are kept constant throughout the various roughening techniques, the only variable that remains is the change in surface texture. These results demonstrate two very the important aspects when it comes to understanding and improving coating adhesion:

1) Consideration of the complex nature of the surface topography and not just measured values from a roughness meter.

2) Grit embedment is to be avoided.

4. CONCLUSIONS

This investigation highlighted the relationship between substrate surface roughness and coating adhesion strength. Substrate samples were prepared by polishing, grit blasting, and PWJ processing. Substrates were then coated with using cold spray of pure aluminium powder. The results presented suggest that increased adhesion strength is a result of increased surface area and increased mechanical anchoring features. It is hypothesized that these features allow incoming particles to conform and eventually encapsulate acting as a mechanical interlock.

PWJ was also evaluated as a novel method of surface preparation for cold gas dynamic spray operations. The system provides the ability to increase the surface roughness beyond what can be expected from grit blasting. It also provides the additional benefit of not using entrained particles. This ensures that embedded particles, often an issue with grit blasted substrates, are not present which removes the possibility of bond weakening caused by embedded grit.

5. ACKNOWLEDGEMENTS

VLN authors acknowledge the technical support provided by Dr. Bertrand Jodoin, Tyler Samson, Daniel MacDonald, Mohamed Yandouzi and Rubén Fernández from Cold Spray Research Laboratory at the University of Ottawa in Ottawa, Ontario, Canada.

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7. NOMENCLATURE

CGDS: Cold Gas Dynamic Spray
PWJ: Pulsed Water Jet
Ra: Arithmetic Average of Roughness
SEM: Scanning Electron Microscope