Analysis of Cold Spray coating Sprayed at Angles

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Abstract

Experimental and computational studies were conducted to analyze the cold spray coating as it is sprayed at varying angles relative to the substrate surface. The prepared coatings were compared in terms of adhesive bond strengths. The results show that the coatings sprayed at angles gave up to 25% higher adhesive bond strengths. Computational analysis using Abaqus software was performed to validate this observation.

Introduction

The phenomenon of Cold Spray deposition was first discovered by chance in the mid-1980s at the Institute for Theoretical and Applied Mechanics, under the Siberian Division of the Russian Academy of Science, Novosibirsk. It was in the supersonic wind tunnel during a study of supersonic two-phase flow consisting of both solids and gas, \(^1\) where small particles injected into high-velocity gas streams were found to be adhering to objects instead of erosion as expected, once the particles were found to have exceeded a particular minimum particle velocity. It was also found that the phenomenon was increased with increasing gas temperatures. \(^2\) This discovery was what
led to today’s cold spray technology. The process was patented in the USA and Europe in 1994 and 1995 respectively. [iii]

The cold spray process involves the use of high-velocity gases, usually nitrogen, helium or compressed air, exiting from a “de Laval” nozzle with a converging-diverging internal geometry at velocities of more than Mach 1. Powder particles of sizes around 1 to 50 µm in diameter are then injected into this gas stream, and then expelled from the nozzle at particle velocities of more than 500 m/s onto the substrate surface. [iv]

In cold spray, the powder particles do not have to be melted for coating to happen. Experiments have shown that the adhesion of the powder to the substrate is due purely to the kinetic energy of the powder particles from the gas stream. Experiments have also shown that coating is successful only if the powder particles possess enough velocity (critical velocity). The critical velocity is dependent on equipment parameters such as gas pressure and gas temperature, as well as powder morphology and material properties. The mechanism was theorised to be due to adiabatic shear instability at the powder particle interface occurring only at velocities above critical velocity. [v]

However, the mechanism of coating bonding is still not fully understood, and several researches have suggested that a mixture of mechanisms were responsible for the bonding of coatings, mainly mechanical interlocking [vi] and metallurgical bonding due to adiabatic shear instability. [vii]

There have been many research papers published on the topic of potential applications of the Cold Spray, especially in the field of aerospace materials.

Previous work was also done together with SIM University on the potential application of Amorphous Aluminium coatings deposited using Cold Spray [viii] for the corrosion protection of aluminium structures, which are commonly found on aircrafts. It has been found that Amorphous Aluminium coatings can be a harder surface-wearing alternative to Alclad coatings, and still offer significant corrosion resistance.

There have been many recent publications relating to the application of Cold Spray for repair of components. V. Champagne [ix] described the use of Cold Spray to deposit various types of Aluminium-based alloys on Magnesium alloys used for hovercraft components. He found that the coatings displayed satisfactory results in tests for coating adhesion, corrosion resistance and coating microstructure, and concludes that Cold Spray has matured from an emerging technology to a promising, cost-effective and environmentally-friendly technology to protect and repair magnesium aircraft components.

Usually the main concerns after a thermal spray application will be how well the coating adhesion to the substrate is, and how to evaluate the adhesion strength of the coating in service on actual applications. [x]

Basic coating adhesion is a summation of all of the inter-molecular and inter-atomic interactions between coating components and the substrate, and ultimately gives us the interfacial bond strength. An adhesion test will be able to give us the “practical adhesion”, which will be a function of both basic adhesion and all the other factors that will affect coating interaction with the substrate. [xi]
Schimdt et al.\textsuperscript{[xii]} also reported simulation results which show the shear instability effects on splats, which possibly lead to the adherence of splats onto substrates and the consolidation of splats into coatings. The simulation shows that the splat peripheries may experience localised temperatures close to the melting temperature of the splat material, and suggests that splat adherence begins at the rims of splats, and possibly the strongest point of contact is also at the rims of splats.

Li\textsuperscript{[xiii]}, Gilmore\textsuperscript{[xiv]} and Binder et al.\textsuperscript{[xv]} all reported that the deposition efficiency of cold spray can be correlated to the spray angle, and for the spraying of fine powders, the DE only varied by around 10\% even at a spray angle of 45°.

However there are limited work done to establish the splat formation during spraying at angles and the effects of spraying at angles, apart from deposition efficiency. This paper attempts to compare experimental observations with computer simulations on Aluminium sprayed at angles.

**Experimental Methodology**

The Cold Spray equipment used in this work is the commercially-available PCS-1000 high-pressure cold spray system from Plasma Giken (Japan).

The system has a maximum spray temperature of 1,000°C and a maximum spray gas pressure of 5MPa, with the capability to use either Nitrogen or Helium as the main process gas. The system currently is only fitted with one powder feeder unit. The system is controlled by PLC controls through a touch-screen user interface.

The cold spray gun is manipulated using an ABB 6-axis industrial robot.

The powder used for cold spraying is commercially-available Aluminium 6061 alloy from Valimet (USA), -325-mesh sieve grade, gas-atomised. All of the Aluminium 6061 cold spray samples were made using the same batch of powder.
The test method used was based on the ASTM C633-01 standard test method for adhesion or cohesion strength of thermal spray coatings. This test method is able to quantitatively determine the degree of bonding or adhesive strength of thermal spray coatings, under a load normal to the coated surface. The test starts with the cold spraying of one side of a 1-inch diameter stud, and then attaching this coated side to the face of another similar (uncoated) stud using epoxy glue. Once the epoxy has cured (time and temperature for curing dependent on the type and brand of epoxy that was used), the bonded studs will be subjected to a tensile load tester to establish the failure stress of the coating, and the mechanism of coating failure. The epoxy glue used is chosen to have a higher failure stress than the coating.

The test studs are made of Aluminium 6061 alloy. To facilitate the ease of test stud fabrication, 1”-diameter Aluminium 6061 extruded rods were used as the starting stock, and then cut into 50mm-length sections, after which the 7.8mm-diameter through-holes were drilled into each section to form the test studs. The test stud design is a modification of the test stud design specified within the ASTM C633-01 test method, although the coated surface is maintained at the same 1”-diameter.

The test studs were attached to jigs which were attached onto the tensile tester. The tensile tester used in all of these tensile adhesive bond strength tests is the Universal Testing Machine made by MTS (SINTECH 65G), with the testing conducted at a crosshead speed of 1mm per minute.

The Finite Element simulations are conducted using Thermal-Mechanical Coupling Finite Element Method available in Abaqus/Explicit, shown in Figure 2. In the FEM simulations, all particles are assumed to be in ideal sphere shape with the average diameter $60\mu m$. The initial temperature of the powder particles and substrate are all assumed to be 300K. The initial impact velocity magnitude of the powder particles are assumed to be $600 – 620$ m/s, which will deliver high deposition efficiency as observed in our experiments. The constitutive material model for both
powder particle and substrate employs Johnson-Cook plasticity model, with Mie-Grüneisen Equation of State. The material properties used for the simulation modeling are shown in Table 1.

![3D single-particle 1/2-symmetric model based on FEM in Eulerian framework using Abaqus.](image)

Figure 2 - A 3D single-particle 1/2-symmetric model based on FEM in Eulerian framework using Abaqus.

Table 1 - Material Properties of Al6061-T6 used in the simulation modeling. (Unit SI: Kg m s K)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific heat</td>
<td>8.96E+02</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.67E+02</td>
</tr>
<tr>
<td>Density</td>
<td>2.70E+03</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>2.60E+10</td>
</tr>
<tr>
<td>A</td>
<td>3.24E+08</td>
</tr>
<tr>
<td>B</td>
<td>1.14E+08</td>
</tr>
<tr>
<td>n</td>
<td>4.20E-01</td>
</tr>
<tr>
<td>m</td>
<td>1.34E+00</td>
</tr>
<tr>
<td>C</td>
<td>2.00E-03</td>
</tr>
<tr>
<td>Reference strain rate</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>C0</td>
<td>5.24E+03</td>
</tr>
<tr>
<td>s</td>
<td>1.40E+00</td>
</tr>
<tr>
<td>tao_0</td>
<td>1.97E+00</td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>8.80E+02</td>
</tr>
<tr>
<td>Transition Temperature</td>
<td>2.98E+02</td>
</tr>
</tbody>
</table>

Results & Discussion

Finite-Element Modelling, Analysis & Predictions
At a spray angle of 30°, it was predicted that the splat and substrate would undergo adiabatic shearing and deformation, however there will not be significant resultant bonding at the splat-substrate interface and it is not expected to see significant coating build-up by spraying at this angle. The process is illustrated in Figure 3.

![Figure 3 - Al6061T6 – Al6061T6. Impact Velocity: 600m/s, Impact angle: 30°. Contour plots of temperature field. Local melting has been observed at the impact interface. No significant bonding of splats are expected.](image)

At a spray angle of 60°, the splat and substrate would undergo more significant adiabatic shearing and deformation, giving a much greater resultant bonding at the splat-substrate interface and it is expected to see significant coating build-up when spraying at this spray angle. The process is illustrated in Figure 4.
At a spray angle of 90°, the splat and substrate would undergo the most predicted adiabatic shearing and deformation, giving a much greater resultant bonding at the splat-substrate interface and it is expected to see the best coating build-up when spraying at this spray angle. The process is illustrated in Figure 5. The modelling results show close similarity to what was also observed by Peter King et. al. \[^{[xvi]}\] in single-splat Titanium coatings. This correlates with the computer simulations as shown in Figure 6, where the highest contact point temperatures are at the splat peripheries.
Figure 5 - Al6061T6 – Al6061T6. Impact Velocity: 600m/s, Impact angle: 90°

Figure 6 – Sequences of a copper particle impacting onto a copper substrate. [xii]
Modelling was also conducted for the coating build-up of Al 6061 at various spray angles (30°, 40°, 60°, 80°) with respect to time.

Figure 7 - t=1.0ms, impact angle 30°

Figure 8 - t=4.0ms, impact angle 30°

Figure 7 and Figure 8 show the contour plots of temperature field simulated using Thermal-thermal-mechanical coupling FEM. Heat conduction is considered, and particle impact velocity is assumed to be 600m/s with impact angle of 30°. The modeling shows that while the splats could interact with the substrates and other splats enough to form coating build-up, there is a region of localized high temperature at the coating-substrate interface which appeared to limit coating build-up in the simulation (the Aluminium melting point of 660°C is demarcated in yellow from Figure 7 to Figure 18, orange and red would mean the local temperature is higher than the melting point of Aluminium). With the impact angle of 30°, the coating appeared to be unable to be formed in the simulation; few particles can be deposited due to the rough surface with larger effective local impact angle.
Figure 9 to Figure 12 show the contour plots of temperature field simulated using Thermal-mechanical coupling FEM. Heat conduction is considered, particle impact velocity is assumed to be 600m/s, with impact angle of 40°. Heat conduction is considered in the modelling because the time scale of the simulation exceeds 100ns. At the initial stage of the impact, at the interfaces (particle-particle and particle-substrate) the local melting has been observed, and the material are softened and behaves as free material flow locally. At this spray angle, the coating build-up will not happen until the local temperature has fallen below 660°C (demarcated in yellow from Figure 7 to Figure 18). The deposition efficiency is expected to be low at this spray angle as shown in the modelling.
Figure 13 to Figure 16 show the contour plots of temperature field simulated using Thermal-mechanical coupling. Heat conduction is considered, particle impact velocity is assumed to be 600m/s with a particle impact angle of 60°. At this spray angle, the bonding can be formed even at the initial stage of impact with minimal local melting. The deposition efficiency is expected to be higher than that with the impact angle of 40°.

Figure 17 & Figure 18 shows splats with impact velocity of 600m/s and impact angle of 80°. The modeling shows a good deposition efficiency and a dense deposited build-up.
Experimental Observations

In Table 2, the cross-section microscope images of single-splat coatings of Aluminium 6061 on Aluminium 6061 substrates are shown. The substrates were finely-polished to a mirror-finish prior to cold spraying the single-splat coatings. The single-splat coatings were sprayed at 90° spray angle.

![Microscope image of a top-view of Aluminium 6061 single-splats on an Aluminium 6061 fine-polished substrate. 400x magnification.](image)

It is observed that voids were present, especially at the particle bases, with closure of the voids at the particle peripheries. This is in line with the modeling simulations shown in Figure 3, Figure 4 & Figure 5.
Table 2 – As-Sprayed Single-Splats of Aluminium 6061 powder on a fine-polished Aluminium 6061 substrate. (400x Magnification, scale bar is 10µm) Etched with Keller’s reagent. Spray angle is 90° for all of the single-splat samples.
Figure 20 to Figure 25 shows the cross-sectional microstructures of coatings sprayed at 40°, 60°, and 90° spray angles. The microstructures visually correlate closely to what the modeling simulations predicted in Figure 7 to Figure 18.
Figure 20 - Micrograph of Aluminium 6061 cold sprayed coating sprayed at 90° angle on Aluminium 6061 substrate (non-grit-blasted). 200x magnification. Etched with Keller’s reagent.

Figure 21 - Micrograph of Aluminium 6061 cold sprayed coating sprayed at 90° angle on Aluminium 6061 substrate (non-grit-blasted). 200x magnification. 400x magnification. Etched with Keller’s reagent.

Figure 22 – Aluminium 6061 coating sprayed at 60° angle. 200x magnification. Etched with Keller’s reagent.

Figure 23 – Aluminium 6061 coating sprayed at 60° angle. 400x magnification. Etched with Keller’s reagent.
Tensile adhesive bond strength testing was conducted for coating samples sprayed from 40° to 90°. Notably, the tensile adhesive strengths of the as-sprayed coatings sprayed at 40° and 60° were found to be 81% and 99% higher than the as-sprayed coatings sprayed at 90°, with the coating sprayed at 60° to give the highest tensile adhesive bond strength.

Table 3 - Comparison of average tensile adhesive strength values from Al 6061 coatings on Al 6061 substrates sprayed from 40° to 90° angles.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Average Adhesion Bond Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90° As-sprayed</td>
<td>43.78</td>
</tr>
<tr>
<td>80° As-sprayed</td>
<td>52.96</td>
</tr>
<tr>
<td>70° As-sprayed</td>
<td>55.95</td>
</tr>
<tr>
<td>60° As-sprayed</td>
<td>58.35</td>
</tr>
<tr>
<td>50° As-sprayed</td>
<td>57.55</td>
</tr>
<tr>
<td>40° As-sprayed</td>
<td>53.08</td>
</tr>
</tbody>
</table>

Discussion

While the simulation models have corresponded with the experimental observations for the single-splat and coating microstructures, the tensile adhesive bond strengths of the coatings sprayed at angles from 40° to 90° were not as expected. An alternative explanation can be offered based on the simulation models shown in Figure 7 to Figure 18. One notable observation from the models shown the presence of a very high-temperature region at the coating-substrate interface which was
observed for the models of coatings sprayed at 30° and 40° angles, and not observed for coatings sprayed at 60° and 80°.

One possible explanation of the higher tensile adhesive strengths observed for coatings sprayed at 40° - 80° could be due to this high-temperature interfacial region which is more-likely to occur when coatings are sprayed at angles. More work will be required to hypothesize the possible reasons of the formation of the high-temperature region during the spraying of coatings at angles.

Summary

In this work, the following was done:
2. Simulation modelling of coating build-up sprayed at angles.
3. Experimental work of single-splats sprayed at 90°.
4. Experimental work of coating build-up sprayed at angles.
5. Experimental work of tensile adhesion bond strength testing of coating build-up sprayed at angles.

References


