Abstract

In the cold spraying process, particle velocity and temperature are commonly regarded as the key factors that influence the deposition efficiency and properties of the coating. In this study, pure Al coatings were prepared under different working gas temperatures. The velocity and temperature of in-flight particles were calculated by the CFD (Computational Fluid Dynamics) method. The particle velocity was also measured by DPV-2000 system experimently. The results show that the in-flight particles velocity calculated by CFD method are consistent with the ones measured by DPV-2000. The particle velocity increases and the critical velocity decreases with the increase of gas temperature, consequently, the deposition efficiency of Al increases to more than 95%. From the tensile strength results, it is shown that the adhesive strength of Al coatings is greatly dependent on the type of substrate materials compared with the influences of gas temperature.

Introduction

Cold spray is a emerging spray coating technology that was first developed in the mid 1980’s at the Institute of Theoretical and Applied Mechanics in Russia (Ref 1). In Cold spraying process, spray particles are injected into a supersonic jet of compressed gas and accelerated to a high velocity (300-1200 m/s). The deposition of particles takes place through the intensive plastic deformation upon impact in solid state at a temperature well below the melting point of spray materials (Ref 2). As a result, spray particles experience little oxidation or decomposition in cold spray (Ref 3, 4). So far, cold spray was used to spray not only ductile materials such as copper (Ref 5, 6), aluminum (Ref 7), nickel (Ref 8), nickel based alloys (Ref 9), zinc (Ref 10) but also metal matrix composites (Ref 11), cermets (Ref 12) and ceramic materials (Ref 13). Previous studies suggested that particle deposition depends on the impact velocity and only the particles with a velocity higher than a critical velocity can be deposited. Below the critical velocity, impacting particles would only cause erosion of the substrate (Ref 14, 15). The experimental and theoretical results showed that the critical velocity is dependent on the properties of powder and substrate materials (Ref 16, 17), particle size and geometry (Ref 18), particle temperature (Ref 19), particle oxygen content (Ref 20) and the substrate preparation (Ref 21). This may partially explain that even for the same powder materials the reported critical velocity was somewhat different (Ref 20, 22). Moreover, recent numerical simulation studies on the bonding mechanism of cold spray suggested that the particle velocity corresponding to the onset of shear instability was consistent with the critical velocity (Ref 19, 20, 23). But so far, the underlying mechanism of bonding of cold spray has not been well clarified (Ref 19).

In the present study, pure Al powder was used to prepare coatings by cold spray process. The temperature and velocity of working gas and in-flight particle were calculated by the commercial CFD software of FLENT. The particle velocity was also measured by an on-line diagnostic system of DPV-2000. The coatings were prepared on different substrate by a change of the working gas temperature. The deposition efficiency of the coatings was measured, and the tensile strength of Al coatings was also investigated.

Experimental Procedures

Feedstock Powder and Cold Spray Process
The commercially available Al powder (Al > 99.7%) with the nominal size of ~ 45µm was used as feedstock. The powder exhibited spherical morphology as shown in Fig. 1. The powder size distribution was characterized by a laser diffraction sizer (MASTERSIZER, Malvern Instruments Ltd.) as shown in Fig. 2.
Three kinds of materials, Cu, Al (A5052) and stainless steel 304 were used as substrates. Prior to spraying, the substrate surfaces were sandblasted using 36 mesh alumina grits. A cold spray system with a typical converging-diverging (De-Laval) nozzle developed by Plasma Giken Co. Ltd was employed in the experiments. Nitrogen gas was used as the driving gas. The spray conditions for cold spraying were shown in Table 1.

Table 1: The spray conditions

| Working gas pressure (MPa) | 3 |
| Working gas temperature (℃) | 200, 300, 400 |
| Spray distance (mm) | 20 |
| Powder feed rate (g/min) | 9 |
| Traverse speed (mm/s) | 50 |

The Measurement of In-flight Particle Velocity

The in-flight particle velocity under the conditions of preparing coatings was measured at the centre line of the particles flow, using the DPV-2000 system (Tecnar Automation Ltd., Canada). The substrate was removed during the particle velocity measurement process. For cold spray process, the radiation intensity emitted from the in-flight particles is too weak to be detected by the optical sensor because of low temperature of the particles. Therefore, a high-power diode laser system of CPS-2000 (HPLD - 785 - 3W) was equipped in the DPV-2000 system to beam the in-flight particles. By detecting the monochromatic light scattered by particles, the velocity of particles can be measured by DPV-2000 system.

The Numerical Simulation Method

The CFD code of FLUENT was used to simulate the cold spray process. Due to the axisymmetrical characteristic of flow in the gun, a two-dimensional symmetrical mode was used as shown in Fig. 3. According to the previous study, the presence of substrate had little influence on particle acceleration (Ref 24). Therefore, the substrate was not involved in this simulation.

![Figure 3: Schematic diagram of the computational domain and boundaries.](image)

The wall was taken as the no-slip boundary condition and no heat exchange with ambient atmosphere. The gas was taken as an ideal and compressible one. A coupled implicit method was used to solve the flow field. The realizable K-ε turbulence model was utilized in the simulation because of the high pressure gradients. The accelerating and heating of particles were computed using Discrete Phase Modeling (DPM) of FLUENT (Ref 25). Taking account of the average diameter of Al using in the experiment, a spherical Al particle with the diameter of 30 µm was employed in the numerical simulation. The boundary condition of driving gas inlet was equal to the value in the experiment. The boundary condition of powder feed inlet was set at a pressure of 0.1 MPa higher than the driving gas and temperature of 75℃.

The Tensile Strength and Microstructure of Coatings

The tensile strength of coatings was tested with tensile testing equipment, STM-F-2000BP, manufactured by Toyo Baldwin Co., Ltd. The samples have a 16 mm diameter and 40 mm length. The top portion of the coating was glued to an uncoated specimen before the measurement. The microstructure of the coatings was examined using an optical microscope (Olympus, BX51M).

Results

The Microstructure and Deposition Efficiency

Figure 4 shows the typical microstructures of the as-sprayed Al coatings. It is clear that dense coatings were formed even at a low working gas temperature of 200℃ as shown in the Fig. 4a. Especially when the gas temperature was increased to 400℃, almost not any porosity can be observed in the microstructure of coatings as shown in the Fig. 4c.
The deposition efficiency of Al coatings is shown in Fig. 5. It is seen that the spraying deposition efficiency increased significantly with the increase of the gas temperature. A high deposition efficiency of 95% was acquired using nitrogen gas at a gas pressure of 3 MPa and a gas temperature of 400°C.

![Figure 4: Microstructure of Al coatings on a stainless steel substrate prepared under the conditions of working gas temperature of 200°C (a), 300°C (b) and 400°C (c).](image)

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![Figure 5: Deposition efficiency of Al powder.](image)

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**Particle Velocity Measured by DPV-2000**

Figure 6 shows the influences of working gas temperature on the Al particles velocity distribution measured with the DPV-2000 system. It was found that the in-flight particle velocity nearly lies between 400 - 900 m/s. It was also revealed that the measured velocity of in-flight particles increases with the increase of gas working temperature. The average particle velocity increased from 580 to 660 m/s with the increase of gas temperature from 200 to 400°C at a gas pressure of 3 MPa.

![Figure 6: Influence of the gas temperature on the Al particles velocity distribution.](image)

**Figure 6:** Influence of the gas temperature on the Al particles velocity distribution.

**Numerical Simulation**

Figure 7 shows the change of gas and particle variables calculated at the symmetry axis under a driving gas inlet pressure of 3 MPa and a temperature of 300°C. It is seen that with the gas passing through the convergence-divergence part of nozzle, the gas temperature significantly decreases and the gas velocity increases owing to the fast gas expansion. At the straight part of the nozzle near the exit, the gas temperature gradually increases and the gas velocity decreases owing to the gas viscosity. Compared with the gas, the particle temperature and velocity are close to the ones of gas before flowing into the convergence-divergence part of nozzle. The particle temperature decreases and the particle velocity increases after leaving the nozzle throat owing to the lower gas temperature and faster gas velocity.

![Figure 7: The temperature and velocity of gas and particle at the symmetry axis under the inlet condition of N₂ pressure of 3MPa and temperature 300°C.](image)

**Figure 7:** The temperature and velocity of gas and particle at the symmetry axis under the inlet condition of N₂ pressure of 3MPa and temperature 300°C.

Figure 8 shows the effect of working gas temperature on calculated particle temperature and velocity at the exit of nozzle. It is seen that particle temperature and velocity increases respectively with the increase of working gas temperature. Fig. 8b shows evidently that the value of particle
velocity calculated is consistent with the one measured by DPV-2000.

![Figure 8: The particle temperature calculated (a) and the particle velocity calculated compared with the measured ones (b) at the center of gun exit.](image)

**Critical Velocity**

Basing on the assumption that only the particles with a velocity higher than the critical velocity can be deposited, the critical velocity of Al particles can be estimated according to the particle velocity distribution measured by DPV-2000 and the deposition efficiency obtained from the experiments. According to the particle velocity distribution as shown in Fig. 6, a velocity boundary can be found, more than which the cumulative volume fraction is equal to the value of deposition efficiency, namely the ratio of faster particle velocity than the velocity boundary is equal to the deposition efficiency. The corresponding velocity boundary is regarded as the critical velocity of particle.

Figure 9 shows that effect of working gas temperature on the particle critical velocity. The particle critical velocity decreases significantly from 620 to 520 m/s when the gas temperature increases from 200°C to 400°C.

![Figure 9: Effect of working gas temperature on the particle critical velocity.](image)

**Tensile Strength**

Figure 10 shows the tensile strength of the Al coatings deposited on three kinds of substrates. With the increase of working gas temperature, a significant improvement of tensile strength of Al coatings on all three substrates is observed. The fracture of almost all samples occurred at the substrate-coating interfaces except for the stainless steel substrate at the gas temperature of 400°C. Therefore, the type of substrate material greatly influences the tensile strength of Al coatings. The relatively high strength up to 55 MPa was obtained on the stainless steel substrates at a gas temperature of 400°C. The fracture of this specimen occurred inside of coatings as shown in Fig. 11.

![Figure 10: Tensile Strength of Al coatings.](image)

**Discussions**

In the cold spray process, a supersonic jet of compressed gas is generated via a converging/diverging de Laval nozzle. For a supersonic gas flow, the gas velocity in the nozzle is determined by the gas species, gas temperature and nozzle geometry. For spray particles, its velocity is dependent on gas velocity and density, particle size and density and the coefficient of drag force between the spray particle and the gas (Ref 26).
In comparison of results in Fig. 4 to Fig. 9, it can be seen that the increase of gas temperature not only leads to a higher particle temperature, but also a faster particle velocity. The higher particle temperature improves the ductility of Al particle, and consequently decreases the critical velocity. Both the increase of particle velocity and the decrease of critical velocity are beneficial to the formation of coatings. Therefore, the deposition efficiency significantly increases with the increasing the gas temperature as shown in Fig. 5. The higher particle velocity and the easier deformation of particle result in a dense coating as shown in Fig. 4.

The actual mechanism by which the solid particles deform and bond during the cold-spray process is still not well understood. According to the most prevailing theory for cold spray bonding, during impact the solid particles undergo plastic deformation, disrupt thin (oxide) surface film and, in return, achieve intimate conformal contact with the target surface (Ref 27).

The increase of working gas temperature leads to a larger impact energy of particle (particle velocity and particle temperature), and consequently a larger plastic deformation of both the particle and the substrate. A relatively high tensile strength was obtained as shown in Fig. 10.

Beside the impact energy, the material of substrate has a great influence to the bond of coating and substrate. The stronger bond between Al coating and stainless steel substrate suggests the generation of metallic bonding. Further research is necessary to clarify the bonding mechanisms.

Conclusions

In this study, the pure Al coating was prepared using cold spray process under different working gas temperatures. The experiment results showed that, the in-flight particle velocity increases and the critical velocity of particle decreases simultaneously with the increase of working gas temperature. As a result, the deposition efficiency increased to 95% when the working gas temperature increased to 400°C. The higher gas temperature is beneficial to the impact velocity and temperature of particles, consequently improving the bonding strength of Al coatings. On the other hand, the bonding strength of coating-substrate interface is significantly influenced by the material of substrate. A relatively high strength of Al coatings was obtained on the stainless steel substrate.

References


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