Study of the influence of particle velocity on adhesion strength of Cold Spray deposits

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The adhesion mechanism of deposits/substrate interface prepared by cold spray method has not been fully understood up to now. It seems that the adhesion strength is mainly determined by the mechanical (including the plastic deformation of particle and substrate) and thermal interaction between the particle and substrate when the particles impact onto the substrate with a high velocity. In order to understand the adhesion mechanism, the influences of particle impact velocity on the adhesion strength were investigated in this study. The particle velocity was obtained with DPV-2000 measurement and CFD simulation. The relationships between the adhesion strength of deposits/substrate interface and particle velocity were discussed. The results show that the more strong adhesion strength can be obtained with the increase of particle velocity. There are two available ways to improve the adhesion strength. One is to increase the temperature of working gas, and another is to employ helium gas as the working gas instead of nitrogen gas.

1 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 former Soviet Union [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 [2]. As a result, spray particles experience little oxidation or decomposition in cold spray [3 and 4]. So far, cold spray was used to spray not only ductile materials such as copper [5 and 6], aluminium [Ref], nickel [8], nickel based alloys [9], zinc [10] but also metal matrix composites [11], cermets [12] and ceramic materials [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 [14 and 15]. The experimental and theoretical results showed that the critical velocity is dependent on the properties of powder and substrate materials [16 and17], particle size and geometry [18], particle temperature [19], particle oxygen content [20] and the substrate preparation [21]. This may partially explain that even for the same powder materials the reported critical velocity was somewhat different [20 and 22].
Adhesion strength of coatings prepared by cold spray determins its applications in the industual field. Therefore, many researchers are forcus to the bonding mechanism in the last few years. Mäkinen and et al presented the influences of power, substrate and heat treatment on the adhesive strength[23]. Moreover, recently numerical simulation also help to find out the bonding mechanism [24-27]. These studies on the bonding mechanism of cold spray suggested that the the adhesive strength is mainly effected by the mechanical interlock [24 and 25] and impact molten for a physical-chemical adhesion[10 and 27] based on the shear instability[26],. But so far, the underlying mechanism of bonding of cold spray has not been well clarified [19].
In the present study, A novel methode was employed to measure the higher adhesive strength of copper coatings instead of the conventional method using the epoxy resin adhesive. In order to control the particle impact velocity,the coatings for adhesive strength experiment were prepared on three types of substrate, A5052, A6063 and copper, by a change of the working gas pressure and temperature. The velocity and temperature of working gas and in-flight particle were calculated by the commerical CFD software of FLUENT. The particle velocity was also measured by an on-line diagnostic system of DPV-2000. The relationships between the impact velocity and the adhesive strength of copper coatings were also discussed.

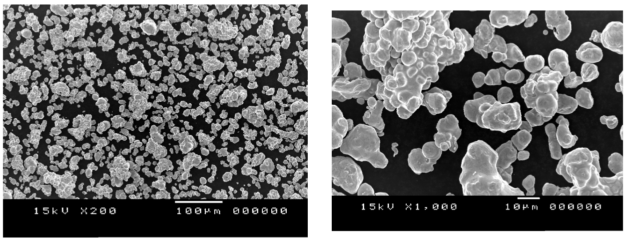
2 Experimental procedure

2.1 Feedstock Powder and Cold Spray Process

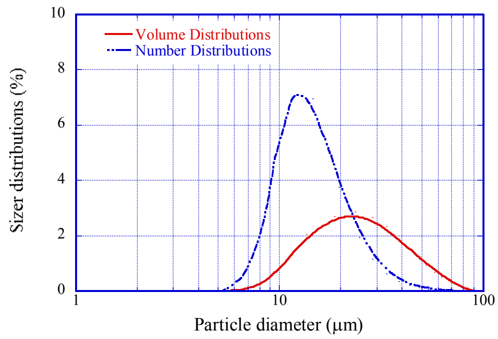
Owing to commercial availability of copper particles, in this study copper particles diameters ranging from 5 to 45μm are used. The morphology of the powder is presented in **Fig.1**(a). The powder size distribution was characterized by the laser diffraction particle size analyzer (Seishin Trading Co., Ltd. Kobe, Japan). The volume and number distributions of diameters are shown in Fig.1(b). The volume average diameter is about 30 μm, and the number average diameter is about 18 μm.
In this study, a commercial cold spray system, model number of PCS-305 designed by PLASMA GIKEN CO. LTD., was used to prepare the coatings for adhensive strength. The cold spray gun utilized in this experiment employed a water cooling, converging–diverging (De-Laval) nozzle allowing the particles to reach the high velocities required in the process. The spray conditions for cold spraying were shown in Table 1.

2.2 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 flow, using the DPV-2000 system (Tecnar Automation Ltd., St-Bruno,Québec, 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 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. In this study, the velocity measurements were taken at a point of 30 mm from the spraying gun exit.



(a)



(b)

Fig.1. Morphology (a) and diameter distributions (b) of copper powder.

Table 1: The spray conditions

Gas Type	N_2	He
Working gas pressure (MPa)	3, 4	2
Working gas temperature (^{o}C)	200-1000	600
Spray distance (mm)	30	
Powder feed rate (g/min)	200	
Substrate	A5052, A6063, Cu	

2.3 The novel method to measure the adhesive strength

In the conventional adhensive strength test for thermal spray coatings, a epoxy resin adhesive is commonly employed to glue the sample with a sample no coated. The schematic illustration of the method is shown in the **Fig 2**. The testing method is tremendously restricted by the strength of glue. The strength of epoxy resin adhesive is not more than 70 MPa, and consequently the testing method cannot be employed to measure the high strength coatings more than the strength of adhesive.

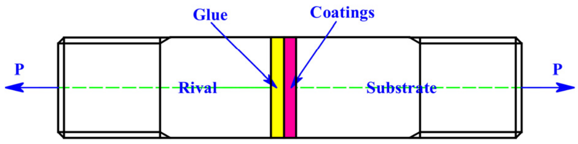


Fig.2. The conventiaonal method to test the adhensive strength of coatings.

For cold spray, a suitable spray condition can prepare the coatings with high adhensive strength. Therefore, the conventional testing method become invalid for the high adhensive strength coatings prepared by cold spray process. Fortunately, quite thick coatings can be obtained by the process of cold spray, simply. The adhensive strength of thick coatings can be measured using the novel testing method as shown in **Fig. 3**. First, the thick coatings are prepared as shown in the Fig. 3 (a), and then machined to be the shape as shown in the Fig. 3 (b). Finally, the sample can be pushed directly with a special jig as shown in the Fig. 3 (c).

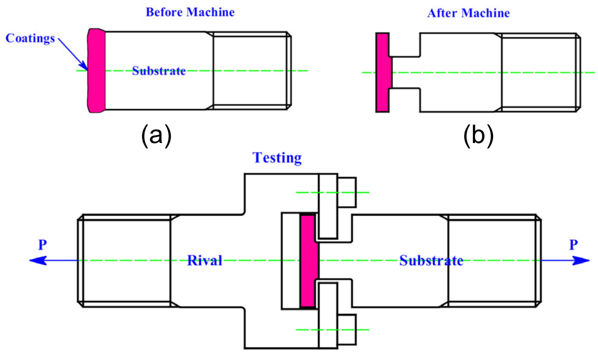


Fig.3. The novel method to test the cohesive strength of coatings.

2.4 The Numerical Simulation Method

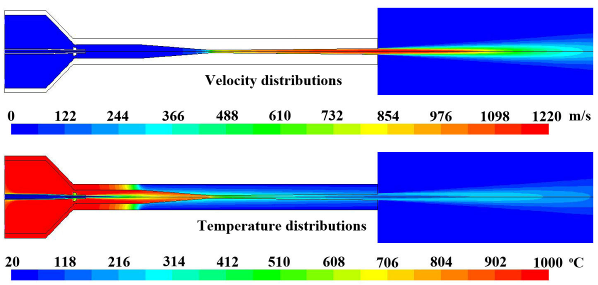
The CFD code of FLUENT was used to simulate the cold spray process. Due to the axisymmerical characteristic of flow in the gun, a two-dimensional symmetrical steady mode was used in the current study. According to the previous study, the presence of substrate had little influence on particle acceleration [28]. Therefore, the substrate was not involved in this simulation.

The working 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. For the calculation of particle, a particle with the diameter of 20 µm was fed into the gun at the axisymmetric center. The accelerating and heating of particles were computed using Discrete Phase Modeling (DPM) of FLUENT [29].

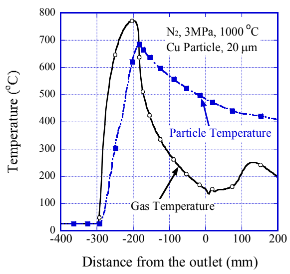
3 Results and Discussions

3.1 Simulation results Compared with measured results by DPV-2000

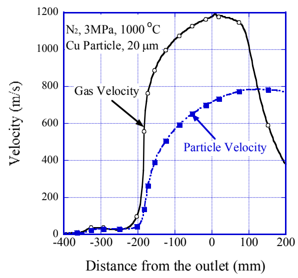
The distributions of temperature and gas velocity calculated by Fluent are shown in **Fig. 4** (a) under the conditions of N_2, 3MPa, 1000^{o}C. In this study, the boundary conditions of adiabatic wall were not used but a constant temperature for nozzle outer wall was taken into consideration because the water-cooling gun was used. Therefore, it can be seen that the temperature of nozzle is low. A copper particle with the diameter of 20 μm was fed into the gas field at the the axisymmetric center, and the calculated temperature and velocity of particle are shown in the Fig. 4 (b) and (c). The particle is preheated before passing through nozzle throat and temperature drops with fast descend of the gas temperature while passing through the nozzle throat due to the expansion of gas. On the contrary, the particle is accelerated only while passing the nozzle throat until the location beyond about 100 mm from the nozzle exit.



(a) Velocity and temperature distributions



(b) Gas and particle temperature



(c) Gas and particle velocity

Fig. 4. Results of simulations under the conditions of N_2, 3MPa, 1000^{o}C.

Taking the particle velocity calculated at the location beyond 30mm of nozzle exit, the extracted particle velocities are show in **Fig. 5** under different spray conditions. It reveals that the particle velocity rises with the increase of working gas temperature from 200 to 1000^{o}C. However, only little increase of particle velocity was observed with the increase of working gas pressure from 3 to 4 MPa. When helium gas utilized as working gas, higher particle velocities are obtained even under a lower gas temperature compared with the ones when it employed N_2 gas. It seems that the valid ways to obtain a high particle velocity are to develop a high temperature cold spray system or use helium gas instead of nitrogen gas as the working gas.

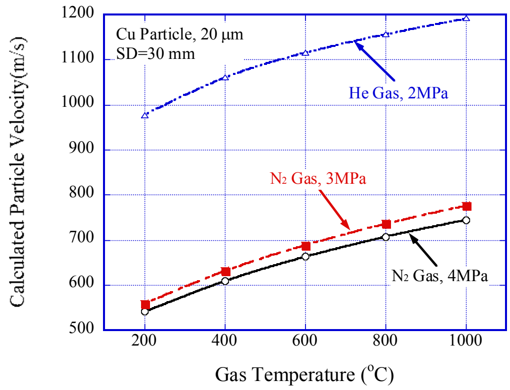
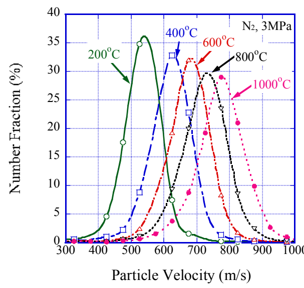
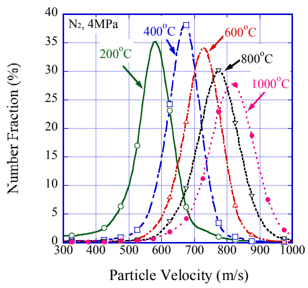


Fig. 5. Calculated particle velocity at the distance of 30 mm beyond nozzle outlet under different spray conditions.

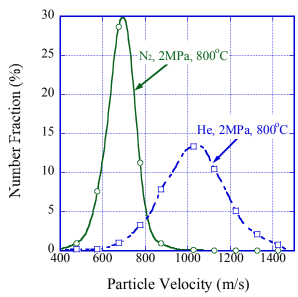
Depending on the detection of scattering light in the experiment, DPV-2000 system cannot measure particle diameter correctly. Therefore, the number distributions and average of particle velocities can be calculated instead of volume ones. The number distributions of particle velocity measured by DPV-2000 are shown in **Fig. 6**. Similar to the results of simulations, the gas temperature and gas type have great influences on the particle velocity, and the gas pressure has little influences on the particle velocity. The distributions presents that the particle velocity ranged from 300 to 1000 m/s if the nitrogen gas used, and from 600 to 1400 m/s if helium gas used.



(a) N_2, 3MPa



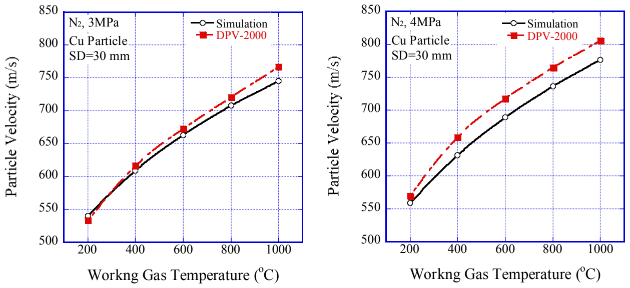
(b) N_2, 4MPa



(c) Compared with He gas

Fig. 6. Particle velocity number distributions measured by DPV-2000.

From the distubutions of particle velocity above, the number average velocities can be obtained.The comparision between the number average velocities measured by DPV-2000 and the ones calculated by Fluent is shown in **Fig. 7**. It reveals that the particle velocities calculated are very close to the ones measured, and moreover the same change tendency of particle velocity to the gas temperaure can be observed no matter which ways were used.



(a) N_2, 3MPa (b) N_2, 4MPa

Fig. 7. Compare the particle velocities calculated with the ones measured.

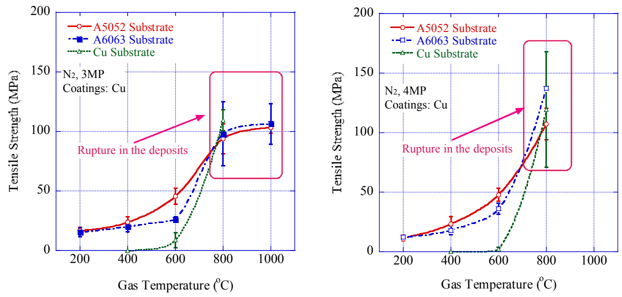
3.2 Adhesive strength of coatings

The adhensive strength of copper coatings on the three substrate is shown in the **Fig. 8**. It can be seen that the tensile strength of coatings rises with the increase of gas temperature. The tensile strength have a little increase adjusting the gas pressure from 3 to 4 MPa. While helium gas is employed as working gas, the tensile strength is much stronger compared with the one prepared with nitrogen gas.

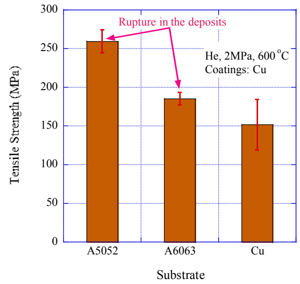
If the gas temperature exceeded the temperature of 800°C, almost all the specimens ruptured in the coatings instead of the interface of coatings/substrate as shown in **Fig. 9**. It shows that the adhesive strength is stronger than the vertical strength of coatings resulted to the rupture inside the coatings.

3.3 Discussions

From the results mentioned above, it seems that the spray conditions have similar influences on the adhensive strength of coatings and the particle velocity. **Figure 10** shows the relationship between the tensile strength and particle velocity. It reveals that the adhesive strength is low with a lower particle velocity, and sharply increases with the particle velocity exceeding about 700 m/s. The adhesive strength is stronger than the strength of coatings with high particle velocity, and consequently the adhensive strength cannot be tested but vertical tensile strength of coatings due to the rupture position inside coatings. It can be seen that the increase of particle velocity is also benefit to the coatings strength although the adhesive strength cannot be obtained for the specimens which ruptured inside coatings.

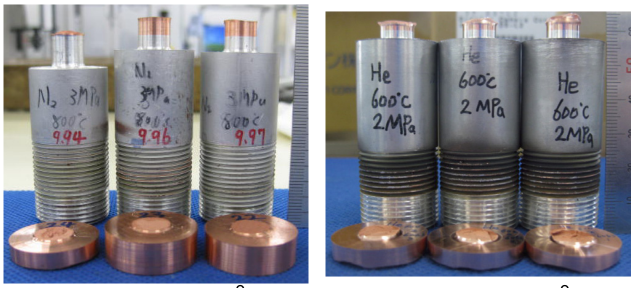


(a) N_2, 3MPa (b) N_2, 4MPa



(c) He, 2MPa, 600°C

Fig. 8. Tensile/adhensive strength of copper coatings prepared under different conditions.



(a) N_2, 3MPa, 800°C, A5052 substrate (b) He, 2MPa, 600°C, A6063 substrate

Fig. 9. Photo of ruptured specimens after tensile testing.

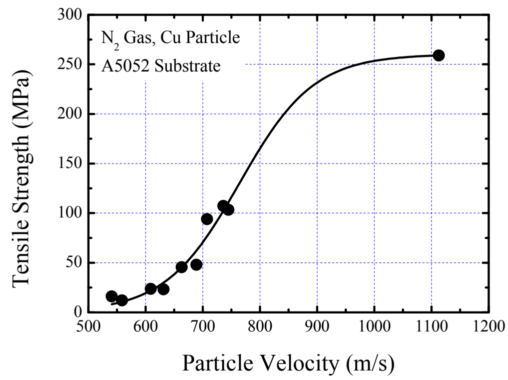
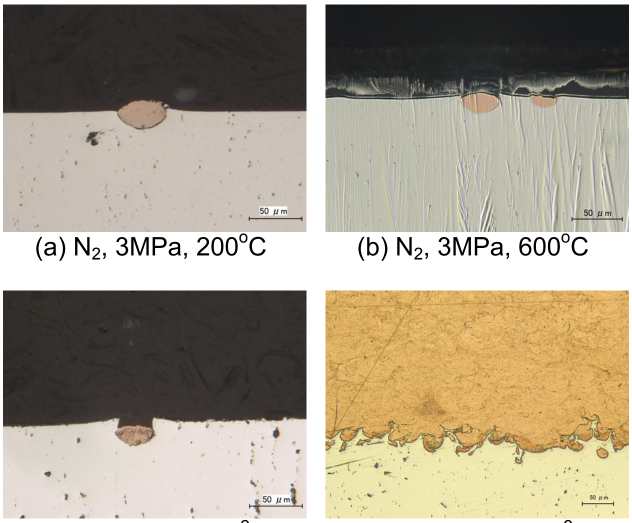


Fig. 10. Relationship between the particle velocity and adhensive/tensile strength.

The spats that copper particles impact to A5052 substrates are shown in **Fig. 11**. With the particle velocity increasing, the copper particles deeply embedded into the A5052 substrate, and more intensive plastic deformation occurred both particles and substrates. The “jetting” can almost not be observed under the conditions of N_2, 3MPa, 200^{o}C, and small jetting obstain while the gas temperature increased to 600^{o}C. If the particle velocity increased further such as the conditions employing the helium gas as the working gas, the particle deeply embedded the substrate and consequently a big jetting can be generated. Unlike the splat only one particle impacting on the substrate in the actual cold spray process, the subsequent particle will impact on the jetting and the mechanical interlock will occure between the coatings and substrate as shown in the Fig. 11 (d). The severe mechanical interlock resulted from the intensive plastic deformation results to a high adhensive strength more than 250 MPa under the conditions of He gas, 2 MPa, 600^{o}C.



(a) N_2, 3MPa, 200^{o}C (b) N_2, 3MPa, 600^{o}C

(c) He, 2MPa, 600^{o}C (d) He, 2MPa, 600^{o}C

Fig. 11. Cross-section of splat and coatings on A5052 substrate.

4 Conclusions

In this study, the copper particle velocity was measured by DVP-2000 system and calculated by the CFD software of Fluent. The copper coatings were prepared using cold spray process under different spray conditions and the adhesive strength on three substrate was also tested. It seems that the simulation is a valid way to predict the in-flight particle velocity because the calculated particle velocity was well identical to the one measured in this study. The results showed that, the in-flight particle velocity increased with the increase of gas pressure and temperature or using helium gas instead of nitrogen gas. The adhesive strength of coatings have the same change trend to the spray conditions similarly to the particle velocity. It seems that the particle velocity plays a important role to improve the adhesive strength base on the plastic deformation. A higher particle velocity increases the mechanical interlock effect resulting to a excellent bonding between the coatings and substrate.

5 References

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