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Effect of Spray Angle on Deposition Characteristics in Cold Spraying

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Abstract

A typical feature of cold spray process is that a deposit can be formed without change of the original structure and compositions of spray materials. Only particles which reach the velocity higher than the critical velocity can be deposited on a substrate in cold spraying. When the spray particle impacts on the substrate at an off-normal angle, the normal component of particle impact velocity will change with the approaching angle of spray particle to substrate. In the present study, copper and titanium powders are used to deposit coating using cold spray process at different impact angles with regard to substrate. The deposition characteristics of spray materials are examined. The results show that the impact angle has a significant influence on the deposition characteristics. The relative deposition efficiency changes with the spray angle. It has been found that there is a critical impact angle at certain particle conditions below which no deposition occurs. The relation between spray angle and relative deposition efficiency can be divided into three spray angle ranges: maximum deposition angle range, transient angle range and no deposition angle range. In the transient angle range, the relative deposition efficiency increases with an increase in spray angle from zero at the critical spray angle to 100%. The transient angle range depends on the particle velocity distribution. A model is proposed to explain the relation between the spray angle and the relative deposition efficiency.

Introduction

Cold spray is a coating technology, in which spray particles in a solid state are deposited via plastic impact on a substrate at a high velocity and a temperature that is much lower than the melting point of the starting powder [1]. In deposition, spray materials experience little change in microstructure and little oxidation or decomposition. Most metals such as Cu, Al, Ni, Ti and Ni-based alloys can be deposited by cold spray [1-7], and even cermets [8] and ceramics [9] can be embedded into a substrate to form a thin layer in cold spray.

Many factors influence the deposition behavior of the spray particles in cold spray, such as operating conditions including gas nature, pressure and temperature and material properties [10,11]. However, the most important parameter in cold spray process is the velocity of a spray particle prior to impact on a substrate. For a given material, there exists a critical particle velocity above which a coating can be produced. Particles with a velocity lower than the critical velocity will lead to the erosion of substrate. The critical velocity changes with spray material. It has been reported that the critical velocities of Cu, Fe, Ni and Al are about 560-580m/s, 620-640m/s, 620-640m/s and 680-700m/s, respectively [1]. The critical velocity may be influenced by the size of the particles, the size distribution of particles [1,12] and substrate materials [10]. On the other hand, particle velocity for a certain material will be determined by the nature, pressure and temperature of accelerating gas, and nozzle design [10,11]. The material parameters such as density, particle size [10,13] and morphology will influence the particle accelerating and subsequently deposition behavior.

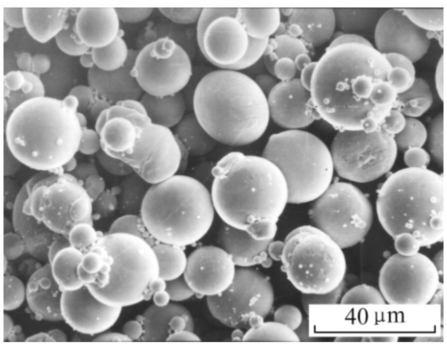
When particles are sprayed at off-normal angles relative to substrate surface, the normal component of the particle velocity will be decreased compared with that at the normal angle. Because the deformation of impacting particle mainly depends on the normal impact velocity, it can be considered that the spray angle in cold spray will influence the deposition behavior and microstructure of the coating. Although the effect of off-normal spray on the microstructure and properties of deposits formed by thermal spray process have been reported [14-17], such effect will be completely different in cold spray because the spray particles are in a solid state instead of in a molten state. However, there are few papers which are involved in investigation of the effect of spray angle in cold spray except one result reported by Gilmore et al. [10].

In this paper, the effect of off-angle spray on deposition characteristics of copper and titanium coatings was studied through the examination of the microstructure and estimation of the deposition efficiency of spray particles in cold spray.

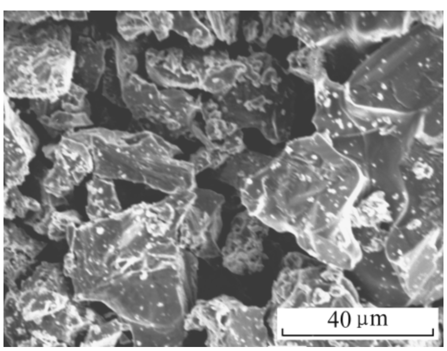
Materials and Experimental Procedures

Materials

The commercially available copper powder (15-37 μm) and titanium powder (37-44 μm) were used as starting materials. The copper powder was produced via an atomization process and had a spherical shape as shown in Fig. 1(a). The titanium powder was manufactured via a hydrogenising and dehydrogenating method and had an angular shape as shown in Fig. 1(b).



(a)



(b)

Figure 1: Typical morphologies of copper(a) and titanium (b) powders.

Stainless steel was used as a substrate. Prior to deposition, the substrate used to examine the deposition efficiency of copper was sandblasted using 24 mesh alumina grits and the substrate used to examine the deposition efficiency of titanium and investigate the microstructure of copper was polished.

Preparation and characterization of deposits

The cold spray system developed in Xi'an Jiaotong University was used to produce deposits. The system included gas pressure regulators, gas preheater, powder feeder and spray gun. Fig. 2 shows a schematic diagram of the spray gun. The spray gun mainly consisted of a gas pre-chamber and a convergent-divergent accelerating nozzle. The nozzle had a throat of 2 mm in diameter and an exit of 6 mm in diameter. The length from the throat to the exit was 100 mm. The powder was fed axially into the upstream of the nozzle from the back of the gun and the accelerating gas was introduced from the gas inlet into the pre-chamber. The gas temperature and pressure in the pre-chamber were measured via the thermocouples and pressure gauge mounted on the spray gun.

Nitrogen was used as the accelerating gas operating at the pressure of 2.0MPa and at the temperature of 220°C for copper and 240°C for titanium. Nitrogen was also used as powder carrier gas. The substrate was fixed at the specially designed fixture at a standoff distance of 15 mm from the gun exit as shown in Fig. 3. During deposition, the spray gun was manipulated by a robot (Motoman®) and moved at a speed of 80 mm/s across the substrates at all different angles in one pass.

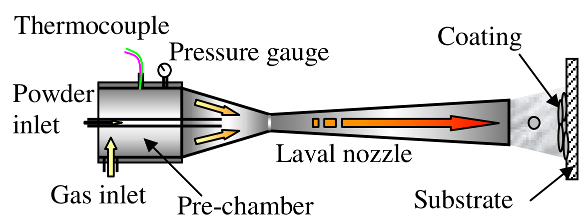


Figure 2: Schematic diagram of cold spray gun.

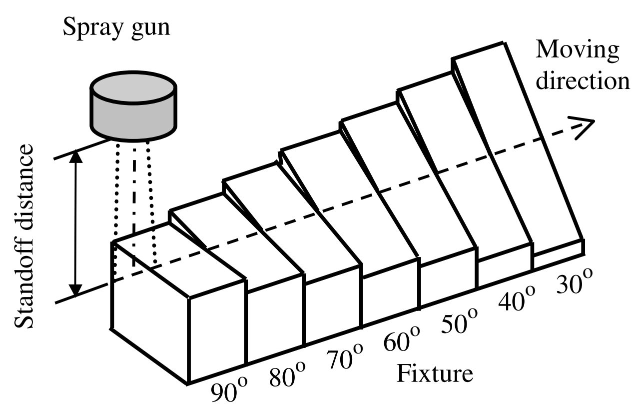


Figure 3: Schematic diagram of spray setup.

The deposition was characterized by the relative deposition efficiency, which is defined as the ratio of weight gain of specimen to the maximum weight gain among specimens deposited at all spray angles in one pass. The microstructure of the deposits was analyzed using scanning electron microscope (JEOL, JSM5800).

Results

<u>Effect of spray angle on the deposition efficiency</u>

Figure 4 shows the effect of spray angle on the relative deposition efficiency of copper in cold spraying. It can be recognized that the relative deposition efficiency was maximum at spray angles ranging from 80^o to 90^o (normal impact). This means that spray angle influences little the deposition efficiency in such angle range. However, with the further decrease in spray angle from normal impact, the relative deposition efficiency decreased with a decrease in spray angle. When the spray angle was decreased to approximately 40^o, there was almost no particle deposited on the substrate and the relative deposition efficiency tends to zero. This result suggests that there is a spray angle below which no particle deposition occurs. Since only particles at a velocity larger than the critical velocity at the normal impact are deposited on the substrate, one can speculate that the normal component of particle velocity is the main significant factor influencing thedeposition of spray particle during cold spray. With the decrease in the spray angle, the normal component of the velocity will be decreased. When the normal velocity component of the particle becomes less than the critical velocity, the particle will not be deposited on the substrate.

In order to confirm the above mentioned relation between the relative deposition efficiency and spray angle, the deposition of titanium was investigated. Fig. 5 shows the effect of spray angle on the relative deposition efficiency of titanium particles in cold spraying. It can be clearly found that the relative deposition efficiency of titanium exhibited a similar dependency on spray angle to that of copper. The relative deposition efficiency of titanium particles yielded about 100% values and changed little when the spray angle was ranged from about 70^o to 90^o. With the decrease in spray angle from about 70^o to 50^o, the relative deposition efficiency decreased rapidly. Moreover, when the spray angle was lower than about 50^o, no deposition occurred. It can be also found that the range of angle in which the relative deposition efficiency changed from 100% to zero depends on the spray powder particle conditions as seen from Fig. 4 and Fig. 5.

<u>Effect of spray angle on the microstructure of coating</u>

Figure 6 shows the typical microstructures of cold spraying of copper coatings deposited on polished substrate at different spray angles. The copper particles had experienced notable plastic deformation in cold spraying and the deformation direction of particle changed with the spray angle. The flow direction of the particles was approximately perpendicular to the particle approaching direction. Therefore, it is clear that the spray angle had significant influence on the particle impact behavior and, consequently, on the layering direction of the spray particles.

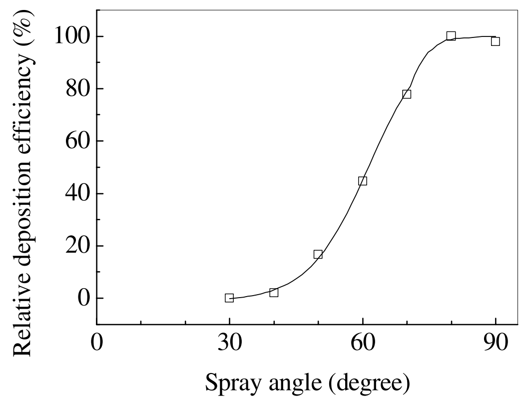


Figure 4: Effect of spray angle on the relative deposition efficiency of copper.

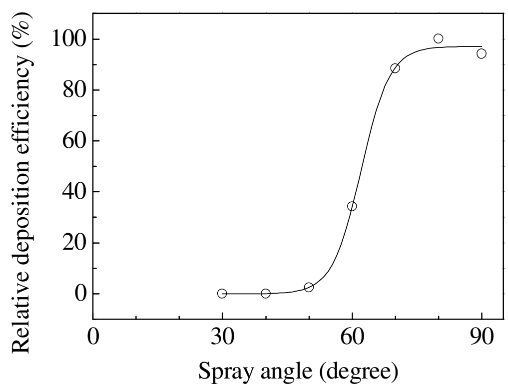
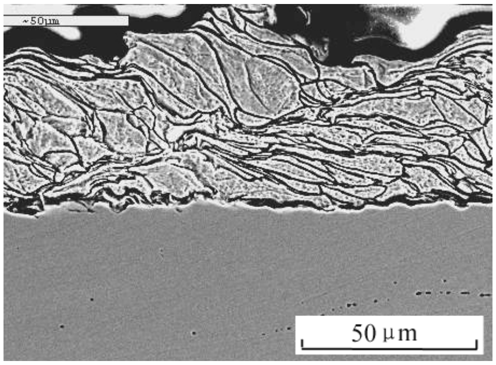


Figure 5: Effect of spray angle on the relative deposition efficiency of titanium.

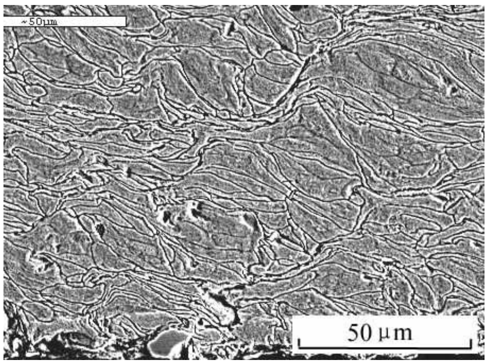
Discussion

Generally, it is considered that the deposition of spray particle and erosion of the deposit occur in cold spraying. The former occurs for the particles that reach a velocity higher than the critical velocity. The latter results from the particles that reach velocity lower than the critical velocity.

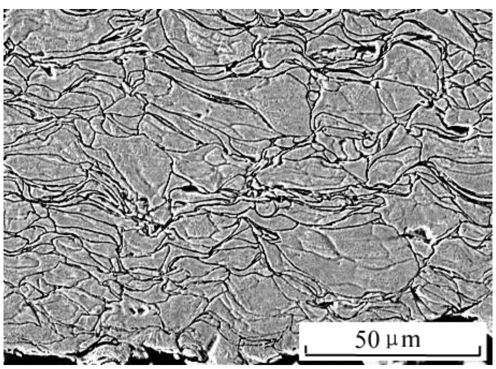
In cold spraying, it can be supposed that the particle velocities exhibit a distribution under a given condition. When the particle velocities present a distribution as given by the curve marked “A” as shown schematically in Fig. 7(a), this means that all the particles reach velocity higher than the critical velocity. Ideally, all particles will be deposited in the coating. In the case as given by the curve marked “D”, no particle deposition occurs. When spray particles present a velocity distribution across the critical velocity as given by the curve marked “C”, only a fraction of the particles having a velocity



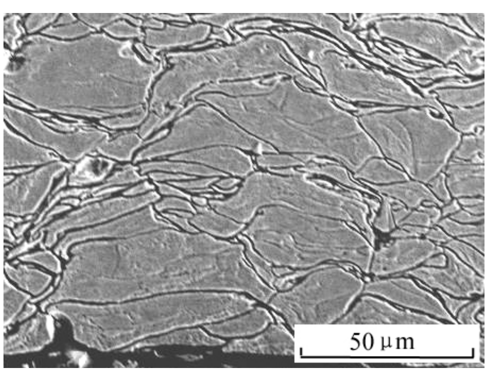
(a) Spray angle: 60^o



(b) Spray angle: 70^o



(c) Spray angle: 80^o



(d) Spray angle: 90^o

Figure 6: Effect of spray angle on the microstructure of cold sprayed copper coating. (etched)

higher than the critical velocity will be deposited on the substrate. On the other hand, particles with a velocity lower than the critical velocity will rebound off and erode the deposited coating.

In the impact of particles at off-normal angle, the particle impact velocity can be decomposed in a normal component and a tangential one relative to the substrate surface as shown in Fig. 8. The normal and tangential velocities can be expressed as:

$$V_n = V_p \sin\theta \quad (1)$$

$$V_t = V_p \cos\theta \quad (2)$$

Here, V_p is particle impact velocity , V_n is normal component of V_p, V_t is tangent component of V_p and θ is the spray angle between the nozzle axis and substrate surface. V_n decreases with a decrease in θ from 90^o to zero.

Supposing that the effect of the tangential velocity component on the particle deposition is negligible, the deposition of the particles will mainly depend on the normal velocity component. Accordingly, the relative deposition efficiency will change little with a decrease in spray angle from 90^o to such an angle that the normal velocity component of particle of low velocity region reaches to the critical velocity. With a further decrease of spray angle, the relative deposition efficiency will be decreased from 100% to zero as the velocity distribution changes from curve marked “B” to curve marked “D” as shown in Fig. 7(a). When the mean particle velocity becomes equal to the critical velocity as given by curve marked “C”, a relative deposition efficiency of 50% will be achieved. As a result, the relative deposition efficiency will change with spray angle as shown schematically by Fig. 7(b).

The present experimental results as shown by Fig. 4 and Fig. 5 supported the model mentioned above. In the present study, the angle range in which the relative deposition efficiency decreases from 100% to zero is defined as the transient angle range. Regarding the dependency of the relative deposition efficiency on spray angle, the spray angle can be divided into three angle ranges: maximum deposition angle range, transient angle range and no deposition angle range. At the maximum deposition angle range, the relative deposition efficiency reaches 100%. Following the present model, it can be suggested that the transient angle range depends on the distribution of particle velocity. For the particles presenting a wide velocity distribution, the transient angle range is quite broad, while for particles of narrow velocity distribution, the transient angle range tends to be narrower. From Fig. 4 and Fig. 5, it can be found that the transient angle range corresponding to the change of relative deposition efficiency from 100% to zero is influenced by spray particle condition. It can be estimated that the transient angle ranges were about 40^o and 20^o for copper and titanium, respectively.

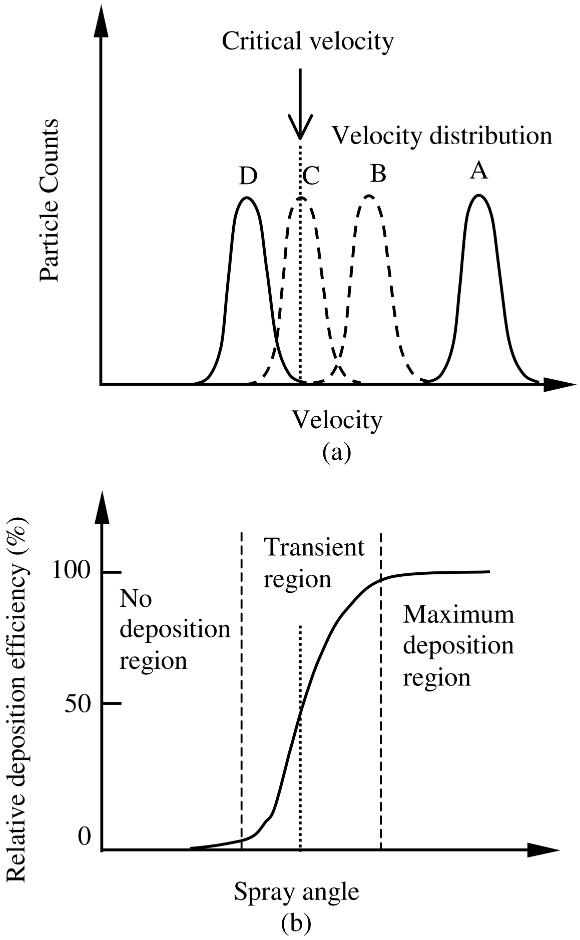


Figure 7: Schematic diagram of particle velocity distribution in cold spray (a) and the dependency of relative deposition efficiency on spray angle (b).

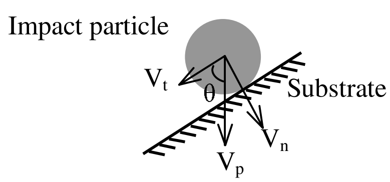


Figure 8: Decomposition of particle impact velocity at spray angle of θ.

Generally, the acceleration of particles by gas stream is influenced by particle size. The smaller the particle size the higher the particle velocity and consequently the higher the maximum velocity that the particle can achieve. With the design of the present nozzle and the limited spray distance, it can be considered that the final particle velocity on impact is inversely related to the particle size. Therefore, the large powder particle size distribution leads to a large velocity distribution. The copper powder used in the present study had a relative wide size distribution and consequently resulted in large transient angle range. On the other hand, titanium powder used in the present study was sieved to nominal narrow size range of 37-44 μm. It can be considered that such size distribution results in a velocity distribution of small range and consequently small transient angle range. Moreover, the acceleration of particle is inversely related to powder density. The low density of titanium compared with copper resulted in a high mean velocity with a narrow distribution. As a result, the relative deposition efficiency of titanium reached 100% in a large angle range and small transient angle range.

Conclusions

The spray angle influenced significantly deposition characteristics in cold spraying. It was recognized that there exist three typical angle ranges: maximum deposition angle range, transient angle range and no deposition angle range. The maximum deposition angle range is close to normal angle, in which the relative deposition efficiency reaches 100%. The no deposition angle range is from zero degree to the critical angle. In the transient angle range, the relative deposition efficiency increases with an increase in spray angle from zero to 100%. The transient angle range and maximum deposition angle range depend on the particle mean velocity and velocity distribution. A proposed model explained well the dependency of relative deposition efficiency on spray angle.

The spray angle had also notable effect on the microstructure of cold-sprayed coating. The deformation flow direction of the particles in the coating was approximately perpendicular to the particle approaching direction.

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