Understandings of Solid Particle Bonding Behaviors in Warm Spray Deposition

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Introduction

Coatings have become increasingly important to protect a substrate material from various degradation and damage such as wear, corrosion, and oxidation. Those protective functions lead to enhancement of durability of materials and to save total amounts of resources and energy consumptions. Thermal spraying is one of the most popular coating technologies because it can provide thick coatings over 100 μm over a large area in relatively much shorter deposition time compared with other coating processes such as electroplating, PVD and CVD. Among various thermal spray processes, Cold Spray (CS) and Warm Spray (WS) depositions are characterized by relatively high particle velocity (400 ~ 1000 m/s) and low particle temperature during deposition. In these processes, the temperature of sprayed particles can be lower than the melting point of the powder material.
Warm Spray (WS) deposition [1], which has been developed in National Institute for Materials Science (NIMS) in Japan, is new spray process (Fig. 1). In conventional thermal sprayings such as high velocity oxy-fuel (HVOF) and plasma spraying (PS), feedstock particles are melted by combustion or plasma flame and deposited on a substrate. On the other hand, in WS, particles are not melted but moderately warmed up by controlling flame temperature, and then, impacted on a substrate with supersonic velocity to form a coating. Since the reduction of particle temperature can suppress detrimental reactions such as oxidation and decarburization during flight [2], it is possible for WS to fabricate a coating with high purity in air or a nanostructured coating by keeping the original microstructure of feedstock powder. However, the bonding mechanism of solid particle impact in WS processes is not fully understood. For WS it is essential to understand the effect of particle temperature and to reveal the correlation with the coating properties.
In the present research, numerical simulation of a titanium particle impact has been carried out by finite element method and the effects of particle temperature on the deformation behaviors and critical velocity were investigated. In addition, the effect of particle size was studied by applying thermal conduction model. Obtained results were directly compared with the cross sectional images of a single splat.

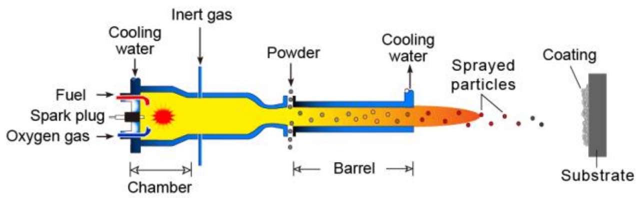

Fig. 1 Schematic of Warm Spray deposition.

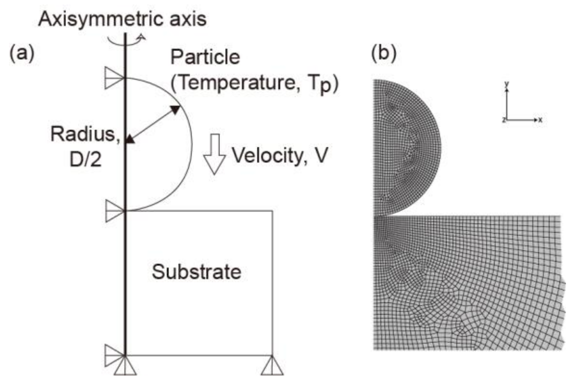

Fig. 2 Schematic of analysis model: (a) a particle impacting on a substrate, (b) typical finite element mesh used in the simulation.

Analysis

In order to understand the effect of particle temperature on impact behavior, the finite element simulation was carried out by using a commercial finite element code (ABAQUS/explicit version 6.5). Fig. 2 shows the axisymmetric model used in this study. A particle with diameter *D* is impacting on the substrate. The values of particle diameter and temperatures were varied to investigate the effect of particle size. Johnson-Cook plastic deformation model was applied to express high strain rate plastic hardening of the materials [3,4]. Since most of coating formation process is based on the impact of a particle on the pre-deposited coating, the material properties of the particle and the substrate were assumed to be the same. The case of a titanium particle was studied. Apart from the typical simulation results reported so far [3,4], in the present study, the heat conduction was taken into account during whole simulation. The critical velocity was defined as the impact velocity at which the highest temperature in the particle can reach melting point of it.

Results and Discussion

Fig. 3 shows the shapes of deformed particles at 200 ns later after beginning of impact for the different initial particle temperature with the particle velocity of 800 m/s and the diameter of 75 μm. Both particles and substrate are titanium. The contour indicates the variation of temperature. The aspect ratio, which is defined as the ratio of hight and diameter of a deformed splat, was 0.72, 0.59, 0.29 for T_p = 293, 773, 1273 K, respectively. The highest temperature increase occurred near the edge of the contact region due to large shear flow in all cases. On the other hand, there is little defamation and temperature increase at the epicenter region. Even though the impact velocity was same for all cases, the particle with T_p = 1273 K deformed 2.5 times more in terms of the aspect ratio. Since the temperature is the sum of the contributions of the initial temperature and the temperature increase due to heat generation during deformation and the reduction due to heat dissipation by thermal conduction, the highest temperature near the interface was achieved in the case of T_p = 1273 K. In the substrates, the heat affected area was the largest for T_p = 293 K because the particle was not thermally softened and the energy absorption by plastic deformation of itself was the lowest resulted in the largest deformation in a substrate. On the other hand, since this model takes into account the thermal conduction, the highest temperature in a substrate was also achieved for T_p = 1273 K.

In Fig. 4, the critical velocity predicted by the analysis was indicated as a function of particle temperature T_p and particle diameter D. The critical velocity rapidly decrease from 800 ~ 960 m /s for T_p = 293 K to 400 m/s for T_p = 1273 K. In Fig. 3, higher T_p leads to larger deformation and wider area of high temperature region at interface. Thus higher particle temperature can be expected to increase the deposition efficiency, to obtain larger bonded area and to decrease pores. Particle size showed relatively small effect compared with particle temperature. The difference in critical velocity is about 200 m/s between the smallest particle (30 μm) and the largest (200 μm) at 293 K and the difference becomes small as the particle temperature increases and almost negligible over 773 K. This tendency would depend on the thermal diffusivity of a particle and a substrate. For a material of high thermal diffusivity such as copper and aluminum, particle size would have much larger effect on critical velocity and thus on microstructure and performance of their coatings.

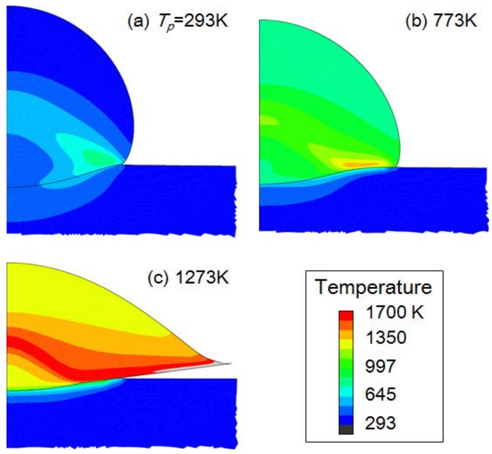

Fig. 3 Variation of particle deformation and temperature distribution at 200 ns after impact.

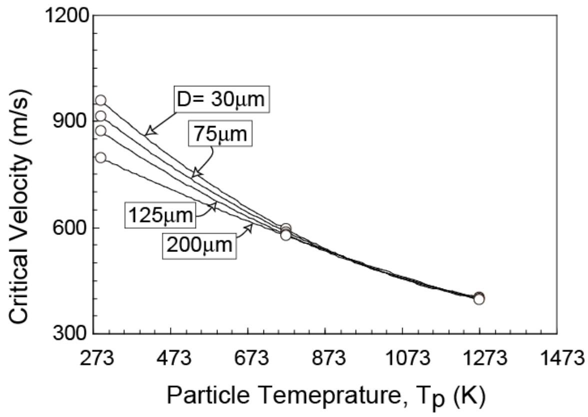

Fig. 4 Effect of particle size on the critical velocity of a titanium particle impacting on a titanium substrate.

Conclusions

Finite element simulations with thermal conduction model were carried out to understand the impact behavior of a titanium particle deposited on a metal substrate for various particle temperatures, velocities, and sizes. The results imply that a higher particle temperature can compensate for a lower particle velocity and that the deposition of a solid particle should be easier at a higher particle temperature.

References

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