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Role of ambient pressure on splat formation and coating adhesion strength during thermal spraying process†

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KEY WORDS: (Thermal spraying) (Ambient pressure) (Disk-shaped splat) (Splash splat) (Adhesion strength)

1. Introduction

Thermal spraying is a process that can provide thick coatings over a large area at high deposition rate. As the splat is unit cell for the entire coating build–up, it is necessary to study in detail the basic process of flattening behavior of the sprayed particles. In this study, the flattening behavior of the individual thermal sprayed particle collected under various ambient pressures was investigated. The heat transfer of the free-falling droplet was conducted to simulate the thermal conduct process from molten droplet to substrate. Moreover, properties, in particular of the adhesion strength of the coatings fabricated under the similar ambient pressure as the splats collection were evaluated.

2. Experimental Procedures

Cu powders were thermally sprayed onto mirror polished AISI304 substrate surface by low pressure plasma spraying (LPPS) at various ambient pressures ranging from 6.7kPa to 101.3kPa. Splat morphologies in detail were observed using scanning electron microscope (SEM) and focus ion beam (FIB). ImageJ imaging software was employed to quantify pore size and distribution on the bottom surface of the splats. Millimeter-sized molten Cu droplets were deposited on AISI304 substrate surface by free falling experiment. The droplet was melted by radio-frequency heating equipment prior to the falling. The thermal history of molten droplet was measured at splat-substrate interface using J-type thermocouple. Thick coatings were deposited on blasted AISI304 substrate using controlling ambient pressure. The shear adhesion strength of the coatings was evaluated by Autography AGS-L. Moreover, the coating's cross section microstructure and elements distribution was evaluated using Energy Dispersive X-Ray (EDX).

3. Results and Discussion

Most splats deposited at the atmospheric pressure performed a typical splash-like shape with a center splat surrounded by a ring of fragments (**Fig. 1**(a)). With the reduction of ambient pressure, the splash fingers always connect with the center solidification area (Fig. 1(b)). While the ambient pressure was lowered to 6.7kPa, the splat pattern changed from the form with splashing to the one without splashing (Fig. 1(c)). The fraction of splash splat increases significantly with increasing the ambient pressure, which agrees with the BET isotherm [1]. This indicates that the adsorption/desorption of adsorbed gas/condensation plays an important role on the flattening behavior of thermal sprayed particles. The microstructure observation on the bottom surfaces of Cu splats were conducted as shown in Fig. 1(d, e, f). It is clearly recognized that with the decrease of ambient pressure, the amount of the pores decreased remarkably, while the solidification structure become more homogeneous. Moreover, no substrate melting can be observed from the cross section view, significant interface exist between splat and substrate at any ambient pressures. However, the gain size is coarser than that of the splat deposited at low pressure condition, which may be due to the lower thermal conductivity at high pressure condition.

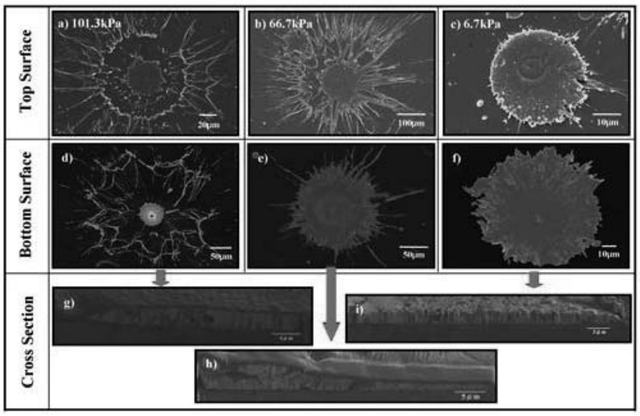

Fig. 1 Splat morphologies of Cu sprayed onto AISI304 substrate under various ambient pressures

The bottom surface analysis was conducted using ImageJ imaging software as shown in **Fig. 2**. Both of the area fraction and average size of the nano-pores increase

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gradually with the increase of ambient pressure. It is known that water and other substances can be adsorbed on clean solid surface, the most common condensate is water from moisture. There has a lack of a true chemical bond between adsorbed gas molecular and substrate surface, desorption tends to occur when the ambient pressure decreases. Because there has no chemical modification and surface topography change occurs when the ambient pressure change, desorption is the only possible physical change taking place on the surface. It must be the reason of pore characteristic change transitionally along with the reduction of ambient pressure [2].

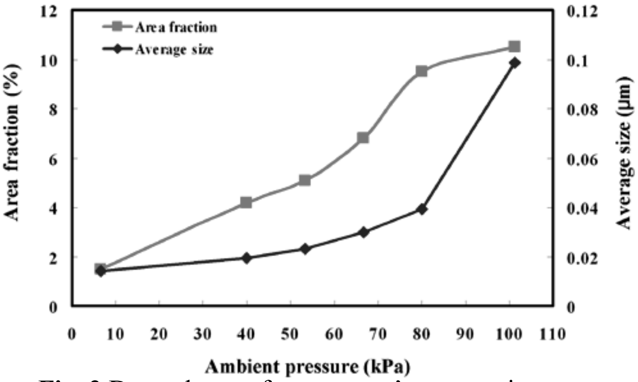

Fig. 2 Dependence of nano-pores' average size and area fraction on ambient pressure

To clarify the effect of ambient pressure on heat transfer at interface between molten droplet and substrate surface, temperature history of free-falling droplet was measured under the designated pressure conditions. The results of temperature histories and corresponding cooling rates in the splats kept at various ambient pressures are shown in **Fig. 3**. All measurements were conducted on non-heated substrate, and ambient pressure was 101.3kPa, 40.0kPa and 6.7kPa, respectively. According to Fig. 3(b), it is found that cooling rate in the splat increases with decrease of ambient pressure, increasing from 4.4×10^3 K/s on the substrate under atmospheric pressure to 1.1×10^4 K/s on the substrate located at an ambient pressure of 6.7kPa [3].

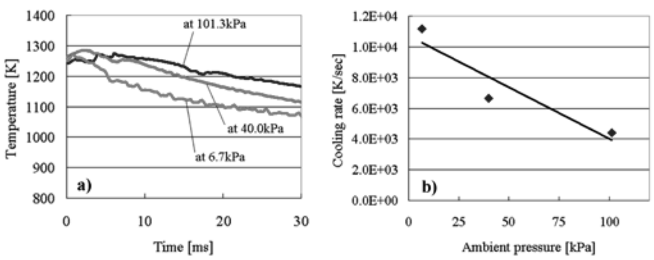

Fig. 3 Droplet temperature history and cooling rate by controlling ambient pressure

Figure 4 shows the cross section morphology and shear adhesion strength of Cu coating fabricated on blasted substrate under various pressures. Similar typical multi-layer structures were observed of the coating fabricated at different ambient pressures, no remarkable differences of contact condition between coating and substrate could be observed. It is noted that the shear adhesion strength changed transitionally along with the ambient pressure reduction, which corresponded well with the splat shape change with the ambient pressure. Hence, the splat shape likely has a strong influence on the coating adhesion. The coating and substrate elements distribution was evaluated by EDX. Cu couldn't be found on the substrate side, also, no substrate composition elements (for example, Fe, Cr, Ni) could be observed on the coating fabricated under various ambient pressures, which indicates that there has no significant diffusion and chemical reaction occur at the interface between the coating and substrate. Mechanical adhesion is the only possible adhesion mechanism during the thermal spraying process. In other words, not the adhesion mechanisms change, but the individual splat formation behavior under the designated conditions likely affects the adhesion strength.

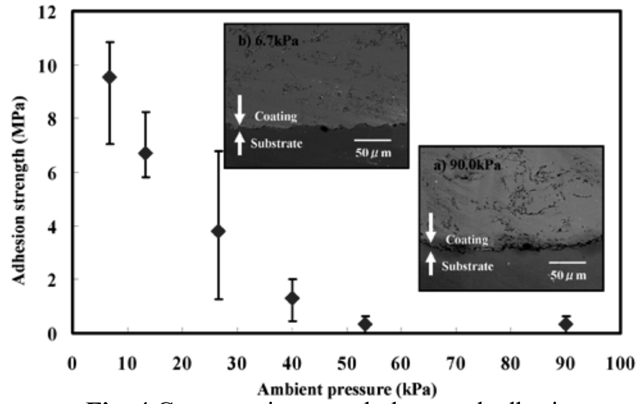

Fig. 4 Cross-section morphology and adhesion strength of Cu coating fabricated on AISI304 substrate under various ambient pressures

4. Conclusions

(1) The splat shape from a splash splat to a disk one was recognized by reducing the ambient pressure. This transition is likely attributed to the adsorption/desorption of the adsorbed gas/condensation.
(2) The conduct condition at splat/substrate interface was improved by pressure reduction. Therefore, the heat transfer should be enhanced, followed by the improved cooling rate, which results in the disk-shaped splat formation.
(3) The adhesion strength of the coating and splat shape obtained under various ambient pressures correspond quite well with each other. The results suggest that the coating adhesion change was attributed remarkably to the individual splat formation behavior.

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