Development of APS coatings

Introduction

Thermal spraying processes offers a wide range of applications coatings. As one of the most convenient method, atmospheric plasma spraying (APS) has been widely developed and employed during the past few decades. During the plasma spraying process, sprayed materials (usually solid particles) are injected into a plasma jet, where they are heated and accelerated towards the substrate. The particles are heated to be molten or partly molten and impact on the substrate surface. Through impacting, flattening, rapid solidifying, cooling and shrinking, the molten drops successive overlap and lead a coatings formation with a lamellar like structure. Because of the temperature of the plasma jet exceeding 10000 K, it can melt almost all materials and a lot of different combinations of materials. This makes it possible to use ceramics, cermets and refractory alloys as the coating materials. Applications include the production of wear-, corrosion-, or oxidation-resistant coatings, thermal barrier coatings, etc.

It is known that the structure has a significant influence on the coating performances. Researches of the lamellar structure have been one of the most important focuses in thermal spray deposits.

In this article, the characteristics of the lamellar structure are reviewed, coatings deposited by APS process. Emphasis is given to discuss a new kind of structure through control of substrate surface temperature, which has the "continuous growth of columnar grains across splat-splat interfaces" characteristic.

Lamellar structure of plasma spray deposit

A plasma sprayed deposit is formed by a stream of molten droplets impacting on the substrate. Fig. 1[1] shows the morphologies of YSZ splats deposited by APS process. It was clearly observed that the individual splats deposited on the mirror-polished substrate heated to 75℃exhibited an irregular splashed shape. With increasing preheating temperature to 230℃, a regular disk-shaped splat was formed. This result is consistent with that reported in previous studies[2-4]. According to splashing model developed by Li et al.[5], the evaporated gas resulting from adsorbing on the substrate surface has a strong effect on splat morphology. In present study, when the substrate was preheated to exceed a "transition temperature", the desorption and vaporization of adsorbate (moisture etc.) from the substrate surface take place prior to the impinging of droplets, resulting in regular disk splat. This kind of splats successive overlap, and finally lead a coatings formation.

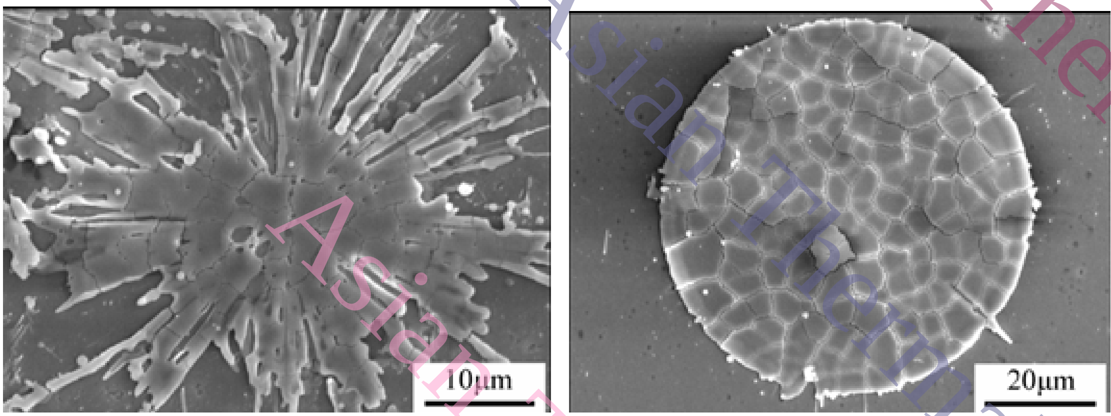

Fig. 1 Morphologies of collected YSZ splats deposited on YSZ substrate at different temperatures of (a) 75℃ and (b) 230℃[1].

Fig. 2 shows the microstructures of plasma-sprayed 8YSZ deposits[6]. It is clearly that the deposits display a lamellar like structure and voids can be formed in the deposit(as shown in Fig. 2(b), B and C). Some of the voids result from insufficient filling and incomplete wetting of molten liquid to previously formed rough deposit surfaces.

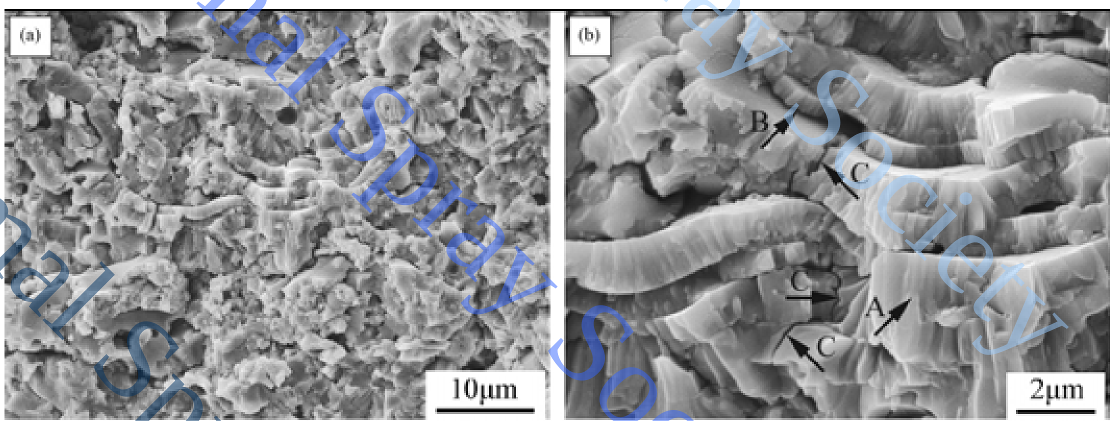

Fig. 2. Microstructures of plasma-sprayed 8YSZ deposits.

(a) low magnification; (b) high magnification[6].

Because the porosity in porous materials processed by conventional methods such as sintering influence significantly their performance. It is believed that the porosity in the deposit will influence many parameters such as mechanical (e.g., elastic modulus and stress at failure) and physical properties (e.g., thermal conductivity and dielectric break down voltage) of the deposits[7].

Many attempts were made, trying to display the lamellar structure and the voids or the porosity. One of the most important and visual method is the use of infiltration techniques[8]. The lamellar structure and the porosity were visually revealed when copper was electroplated into a plasma sprayed Al_2O_3 deposit by Arata et al.[9,10]. The typical microstructure of a copper-plated Al_2O_3 deposit is shown in Fig. 3[8], where the white strings in the microstructure are the copper plated into voids in the as-sprayed deposit. The copper strings clearly reveal the void structure in the sprayed ceramic deposit, and indicate the existence of a substantial non-bonded interface area between lamellae. The non-bonded interface areas constitute the 2D voids in the deposits.

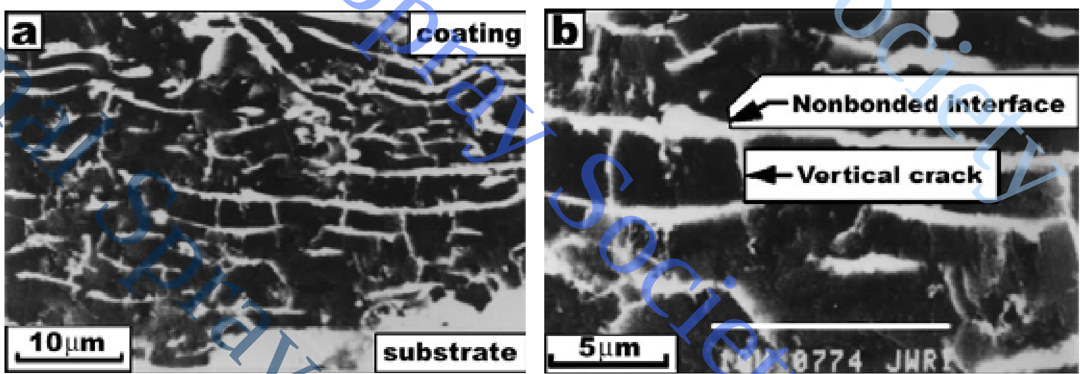

Fig. 3 Typical microstructure of copper-plated Al_2O_3 coating[8].

The porosity is a commonly used parameter to characterize the deposit microstructure. However, the properties of the deposits generally exhibit much lower property values compared with identical bulk materials of the same porosity level[8]. Therefore, the total porosity of the deposit does not have significant meaning from the viewpoint of quantitative interpretation of deposit properties, mainly because of the 2D characteristics of voids in the deposits. The empirical relationships between properties and porosity for conventional processed porous bulk materials cannot be successfully applied to represent the dependency of the deposit property on the microstructure.

An agreement of theoretical with observed values suggests that the lamellar structure of the deposit with limited interface bonding is the dominant factor controlling the performance of the deposit. Using the infiltration of copper into the Al_2O_3 deposits, we measured the interface bonding ratio rather than void–related porosity. The systematic investigation into lamellar bonding revealed that bonding ratio up to around 32% could be achieved for plasma sprayed ceramic deposit. This implies that two-thirds of the interfaces between lamellae in ceramic deposit are separated by an inter-lamellar gap in sub-micrometer dimension. And this limited mean bonding ratio was proposed to be the most important parameter, which had significant influences on the coating properties[8,11,12]. Moreover, the relationships between properties (thermal conductivity, Young's modulus, fracture toughness and erosion resistance) and structural parameters have been announced[8].

Through-lamella grain growth in plasma sprayed deposits

The bonding at the interface between flattened particles is the most important factor in controlling deposit properties. Due to its limited bonding ratio and 2D voids, the deposit properties change a lot.

As to the plasma sprayed ceramic coatings, lamellar structure and limited mean bonding ratio significantly influence the deposits properties. The deposits may have low thermal conductivity, low Young's modulus and low fracture toughness. These properties may have both advantages and disadvantages, when the deposits were using as functional coatings. For example, plasma sprayed YSZ deposits, which were widely used as the thermal barrier coatings(TBCs), the low thermal conductivity can promise a better thermal barrier effects. And the low Young's modulus could enhance the thermal shock resistance property. However, the low fracture toughness may decrease the lifetime of the TBCs. Therefore, many efforts were made, trying to improve the deposits properties, through the adjustment and control of the coating structure. One of the involved methods is the controlling of the substrate temperature(T_s).

Bengtosson et al. reported that both inter-lamellar gaps and micro-cracks in plasma sprayed YSZ decreased by raising T_s[13]. Sampath et al. reported that the bonding between splats was enhanced, when deposited at higher T_s[14]. Jung et al. have recently observed trans-lamellar columnar grain growth by increasing the T_s during plasma sprayed YSZ[15,16].

Based on our previous studies, the Thermal Spray Laboratory of Xi'an Jiaotong University has been making great efforts to research the effects of T_s on the coating structure and properties. A method is developed to control the microstructure or the bonding ratio between the lamellae in plasma sprayed coatings through controlling the substrate surface temperature during spraying process.

Xing et al. preheated the substrate to a temperature above 1000℃. Fig. 4 shows the typical micro-structures of a fractured YSZ deposit sprayed on to a preheated substrate. The columnar grain structure in a direction perpendicular to the lamellar plane is clearly observed in individual splats[6].

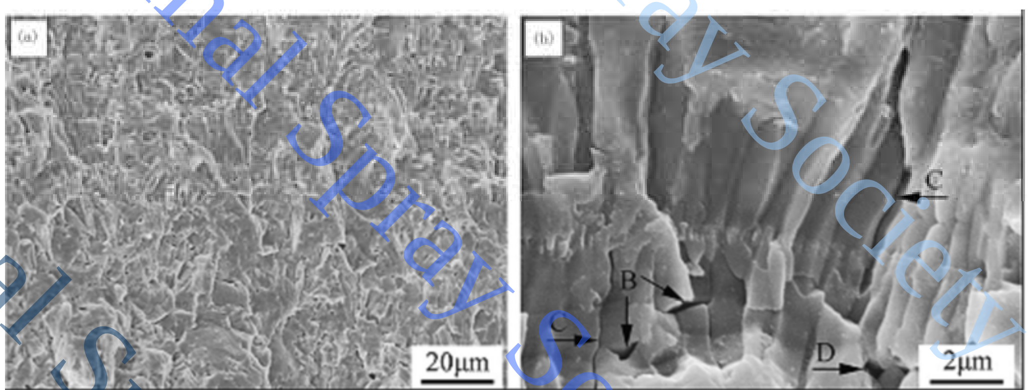

Fig. 4 Microstructures of the fractured 8YSZ deposits plasma-sprayed at high substrate temperature. (a) low magnification; (b) high magnification[6].

By increasing the surface temperature of the substrate to a sufficiently high level, the columnar grains could be grown continuously from underlying splat surface, and the interface between splats was almost chemically bonded. This microstructure change led to significant influences on the properties(i.e. ionic conductivity) of plasma sprayed 8YSZ deposit. The results also revealed that the surface temperature of the previous deposit on to which spray molten droplets spread dominates the bonding at the interface. The deposition temperature can be controlled through the substrate surface temperature prior to droplet impact.

conclusions

Plasma spraying is expected to be a cost-effective process for manufacturing all kinds of coatings. The deposits produced by conventional APS process, display a lamellar like structure and consist of many 2D voids. The bonding at the interface between flattened particles is much less than the apparent total interface area. It has been revealed using the copper electroplating technique that for Al_2O_3 deposit the bonding ratio can be achieved up to 32%. This limited bonding ratio is proposed to be the most important parameter, which significantly influences the deposit properties, including thermal conductivity, Young's modulus, fracture toughness, and so on.

Through the controlling of the substrate temperature, a new kind of deposit structure, different from the conventional lamellar structure, can be produced. By preheating the surface temperature of the substrate to a sufficiently high level, the columnar grains could be grown continuously through lamella grains. This kind of through-lamella grain growth can improve the bonding ratio of the plasma sprayed deposits, which may significantly change the deposit properties.

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