Shroud Gas Effects on Thermal Diffusivity of Plasma Spray Coated Tungsten for Plasma Facing Components in Fusion Reactors

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Abstract: Tungsten coatings on the metal substrates are prepared by atmospheric plasma spraying (APS) combined with shroud gas injection. The effects of shroud gas on the material properties of the tungsten coatings are investigated to examine the feasibility of their application to plasma facing component in tokamaks. The APS incorporated with the shroud gas produces the tungsten layers with improved thermal diffusivity in addition to lower oxide content and porosity, compared to the conventional APS without the shroud gas.

Keywords: Shroud gas injection, plasma spraying, tungsten coating, thermal diffusivity

1. Introduction

Tungsten is a promising candidate for plasma facing materials in the International Thermonuclear Experimental Reactor (ITER). It is expected to be used for divertor plates due to its excellent material characteristics, such as low sputtering yield, high thermal diffusivity, high erosion resistance, and highest melting point among refractory metals [1]. In these properties, thermal diffusivity is most important for plasma facing components, because the divertor plates which are confronting high energy particles and heat fluxes from the core plasma must rapidly transfer heat load to the substrate material [2].

Armored tiles of tungsten will be used for plasma facing components in fusion reactors, because bulk tungsten is hard to machine and its price is expensive. High isostatic pressing (HIP), casting, brazing, and plasma spraying have been main techniques for joining between tungsten and substrates [3]. The advantages of plasma spraying using plasma torches compared with the other techniques are the ability of high coating thickness, large area treatment, and in-situ repair of damaged part. However, plasma spraying at atmosphere pressure results in oxidation and high porosity of the coating inevitably. Consequently, the atmospheric plasma spraying (APS) introduces low thermal diffusivity of coated material [4], but it can be complemented by shroud gas injection surrounding the plasma jet flame ejected from a plasma torch.

The shroud gas effects on the formation of oxide contents and porosity in the coated material have been investigated by many researchers. Oxidation process of pure metal coating powder occurs mostly during trajectory motions of in-flight particles in the thermal plasma jet [5]. Since the injected shroud gas enclosing the plasma jet flame reduces the velocity gradient and turbulent mixing between the plasma jet and ambient air, it prevents the thermal plasma jet from entrainment of the ambient air [6]. The shroud gas injection also has an effect to increase the velocity of thermal plasma jet. Since a high-speed thermal plasma jet accelerates sprayed particles to the substrate with reduced shadow effect on the coating, the coated layers with improved porosity and adhesion strength are formed by the shroud gas injection. It was also reported by numerical analysis that the mole fraction of engulfed ambient air in the plasma jet was reduced with increasing the flow rate of shroud gas [7]. However, comprehensive effects of the shroud gas on the thermal diffusivity correlated with oxide content and porosity have not been sufficiently investigated.

In this experimental work, the effects of shroud gas velocity on thermal diffusivity of the coated tungsten are investigated in order to improve the coating quality deposited by the APS with shroud gas injection. Since a wastefully large amount of shroud gas over 100 lpm was typically used in previous studies, a fixed argon flow rate of 40 slpm is supplied for the shroud gas in this work to make the process more practical.

2. Experimental Setup

As shown in Fig. 1, a plasma torch is modified by the attachment of the shroud gas caps to the plasma torch exit plate. Each cap has 16 holes, which are coaxially located 3 mm away from the edge of the
torch exit. The argon shroud gas of a constant flow rate, 40 slpm, is launched through these holes independently from the plasma jet. The shroud gas injection velocity at the cap exit is controlled by a hole diameter (0.0, 0.5, 1.0, 1.5, 2.0, and 2.5 mm) of each cap for the same flow rate. The argon shroud gas is expected to shield the plasma flame from ambient air entrainment effectively due to its mass relatively heavier than that of ambient air.

A stepped nozzle in the plasma torch is adopted to stabilize voltage fluctuations which affect the jet velocity and momentum transfer to coating powder. Furthermore, the stepped nozzle produces low velocity gradients around the peripheral region of plasma jet, and thus reduces gas mixing between the plasma jet and ambient air, compared with a conventional cylindrical nozzle. [8] 36 slpm of argon is introduced as a plasma gas and 4 slpm of hydrogen is mixed with it to generate higher velocity and thermal power. Two processing conditions are employed: i) 500 A / 60 V (30 kW) for DC power and d=100 mm for spraying distance, and ii) 600 A / 60 V (36 kW) and d=130 mm.

A non-transferred DC torch developed in the authors’ laboratory is mounted on a traversing unit moving with a velocity of 0.6 m/s. Twenty reciprocating paths of spraying deposit about 100 μm of coated tungsten layer on the substrate. The average size of tungsten powder, AI-1061F produced by Praxair, is 44 μm, and the powder is injected into the plasma jet by an argon carrier gas of 7 slpm at a feeding rate of 58 g/s. The tungsten is coated on the copper and stainless steel substrates, respectively, in the form of circular disk with 12.7-mm (0.5-inch) diameter and 3-mm thickness. A cold air gun cooled the back of the substrate to form solid-state coating layer effectively from molten tungsten.

Before plasma spraying, grit blasting was conducted to clean and rough the substrate surface for molten tungsten to be easily adhered to the substrate. After the spraying process, the tungsten coated substrates are molded by mixing an epoxy resin and a hardener. Then, the molded substrates are grinded and polished to examine a cross-section of the coated layer.

3. Results and Discussion

The X-ray diffraction (XRD) patterns shown in Fig. 2 indicate the constituent of the tungsten coating sprayed on copper substrate by the APS with or without shroud gas injection in a process condition of 30 kW and d=100 mm. Fig. 2(a) shows full range intensities of the X-ray diffraction according to the hole size on the shroud cap. The peaks around 40, 58, and 74 degrees indicate coated pure tungsten, while those around 44 and 52 degrees represent the peaks of copper substrate due to an imperfect process condition producing a thin and porous tungsten coating. Fig. 2 (b) is the magnified graphs of left part in Fig. 2(a), and the local maximum peaks at 24 and 34 degrees indicate tungsten trioxide (WO₃) which has been created during in-flight of molten tungsten powder in the plasma jet invaded by ambient air. Upper distinctive line in the graphs comes from the coating by the conventional APS with no shroud gas injection, while below diminishing lines are from the ones by the APS with shroud gas injection. These results reveal that the shroud gas injection reduces the oxide content by shielding the plasma jet from intrusion of ambient air. However, since the line intensities for different hole sizes, i.e., for different shroud gas velocities, are distributed within error ranges, it is difficult to verify the effects of shroud gas velocity on the formation of oxide content in the tungsten coating.

On the other hand, no peaks of copper appear in the XRD patterns of the tungsten coating produced in a process condition of 36 kW and d=120 mm, which means that the coating in this condition is more perfect.
than the one in the previous condition at 30 kW and d=100 mm. As shown in Fig. 3, the differences in the peak intensities of the coatings sprayed with and without shroud gas injection are not appreciable unlike the previous case. All the peaks of the XRD data are overlapped, and thus the shroud gas effects on the oxide formation are indistinguishable. The intensities of WO3 peaks range from 200 to 300 cps in both Fig. 3 and Fig. 4. Therefore, there is a possibility that this range is the saturated oxide content obtained with shroud gas processing at atmosphere pressure. However, the shroud gas injection may influence the porosity of the coating layer.

Fig. 4(a) shows a cross-section of the tungsten coating sprayed at 36 kW and d=130 mm with a shroud gas injection through 2-mm holes. This SEM image is magnified by one thousand times, and the thickness of coating layer is about 140 μm. The lamella structure clearly seen in this image causes degradation of the coating layer compared with bulk material property. The interface between copper substrate and tungsten coating is rough owing to the grit blasting pre-treatment. Fig. 4(b) is a picture obtained after computer processing of the SEM image. The porosity of the coating can be estimated from the total dark area in Fig. 4(b). The estimated porosity ratios of the tungsten layer coated according to the diameter of shroud gas holes are plotted in Fig. 4(c). The APS with no shroud gas injection produces a higher porosity ratio than that with shroud gas injection except for 1-mm diameter, which means that the shroud gas injection generally reduces porosity and produces a denser lamella structure. In the 1-mm hole case showing an unexpectedly large porosity, it is probable that other uncontrolled experimental factors have affected such a coating result rather than the shroud gas effect.

Fig. 5 represents the thermal diffusivities of the tungsten coatings sprayed on the copper and stainless steel substrates, respectively, at 36 kW and d=130 mm according to the shroud gas hole size. As seen in Fig. 5(a), the average thermal diffusivity for no shroud gas case is lowest compared with higher ones for shroud gas cases. It is thus apparent that the shroud gas injection improves the thermal diffusivity of the tungsten layer sprayed on the copper substrate. It is, however, ambiguous what the optimum shroud gas velocity is for the maximum thermal diffusivity, because it is hard to find any correlation between the thermal diffusivity and the shroud hole diameter in Fig. 5(a). The thickness of the tungsten coating with 2-mm shroud gas injection is 140 μm, which is thicker than 100 μm obtained with any other shroud gas injections. Thus, the thermal diffusivity of the coating produced with 2-mm shroud gas injection is relatively low as appeared in Fig. 5(a) due to its thickest layer effect.
On the contrary, the thermal diffusivities of the tungsten coating on the stainless steel substrate, appeared in Fig. 5(b), do not show any effect of shroud gas injection. The average thermal diffusivity of no shroud gas case is almost the same as those of the shroud gas injection. Most of the diffusivities are around 4 mm²/s, which is apparently too low value compared with those on the copper substrate ranging from 80 to 100 mm²/s. The thermal diffusivity of stainless steel is much lower than those of copper and tungsten. It is thus certain that the tungsten layer coated on the stainless steel is affected by the thermal diffusivity of the stainless steel substrate itself.

4. Conclusion

In general, the thermal diffusivity of the sprayed coating layer is inversely proportion to oxide content and porosity. Increase in oxide content of the coating layer is attributed to the large intrusion of ambient air in the APS, and the porosity in the coating is also enlarged due to the deceleration of the plasma jet invaded by air. The APS with shroud gas injection produces a dense lamella structure in the coating layer, which means that low porosity is achieved at atmospheric pressure by the shroud gas injection method. Moreover, the shroud gas injection shields the plasma jet flame from the entrainment of surrounding air conveniently, and produces lower oxide content and improved thermal diffusivity of the coated material.

The oxide content observed in the XRD data of the coated tungsten turns out to be reduced by the shroud gas injection. However, it is difficult to determine what the optimum velocity of shroud gas is for the maximum thermal diffusivity due to an irregular tendency of their correlation. Consistent effects of shroud gas velocity on oxide content and porosity do not appear in the present experiments, and also apparent relationships of the oxidation and porosity with the thermal diffusivity could not be found easily. Nevertheless, an optimum velocity of the shroud gas should exist under other appropriate operating conditions in the process experiment. Therefore, an additional experimental work is planned to verify in more detail the effects of shroud gas velocity on the tungsten coating quality. Moreover, the plasma jet velocity and air mole fraction in the flame will be diagnosed by the enthalpy probe method to find the shroud gas effect on the thermal plasma jet characteristics.

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