

## Plasma-Sprayed $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$ Multi-Oxide Films on Stainless Steel Substrate

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### Abstract

The advantage of plasma-sprayed coating is their good resistance against thermal shock due to the porous state of the coated layer with a consequently low Young's modulus. However, the existence of many pores with a bimodal distribution and a laminar structure in the coating reduces coating strength and oxidation protection of the base metals. In order to counteract these problems, there have been many efforts to obtain dense coatings by spraying under low pressure or vacuum and by controlling particle size and morphology of the spraying materials. The aim of the present study is to survey the effects of the HIP treatment between 1100 and 1300°C on plasma-sprayed oxide coating of  $\text{Al}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  on the metal substrate (type C18N10T stainless steel). These effects were characterized by phase identification, Vickers hardness measurement, and tensile test before and after HIPing. These results show that high-pressure treatment has an advantage for improving adhesive strength and Vickers hardness of plasma-sprayed coatings.

**Keywords :** plasma-sprayed, HIP treatment, Vickers hardness

### 1. Introduction

Plasma spraying is typical of a relatively inexpensive and rapid method of applying thick ceramic coatings on metal components to improve their resistance against wear, heat, and oxidation. A remarkable feature of plasma-sprayed coatings is their good resistance against thermal shock due to the porous state of the coated layer with a consequently low Young's module. There have been investigations on such thermal barrier coatings, applied to aircraft gas turbine components [1-4]. However, the existence of many pores with a bimodal distribution and a laminar structure in the coating reduces coating strength and oxidation protection of the base metals

[5-6]. In order to counteract these problems, there have been many efforts to obtain dense coatings by spraying under low pressure or vacuum and by controlling particle size and morphology of the spraying materials [7-8].

The aim of the present study is to survey the effects of the HIP treatment on plasma-sprayed oxide coating of  $\text{Al}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  on the metal substrate (type C18N10T stainless steel). These effects were characterized by phase identification, Vickers hardness measurement, and tensile test before and after HIPing.

### 2. Experimental Procedure

Tables 1-2 summarize the typical compositions and particle size ranges of the starting materials and the processing conditions used in the present study. The substrate of stainless steel was a rod 7mm in diameter and 7mm high. The cylinders were

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decreased with trichloroethylene. The desired temperature and pressure for 1 h, they were cooled to room temperature at a rate of 5°C/min. Finally, the residual pressure was released.

Table 1. Specification of Coating Materials

Coating Materials	Other phases (wt %)	Size range (m)	Spray distance (mm)
No1 Al <sub>2</sub> O <sub>3</sub>	-	3-5	100
No2 Al <sub>2</sub> O <sub>3</sub>	2.0 SiO <sub>2</sub>	2-4	80

Table 2. Plasma Spraying Conditions

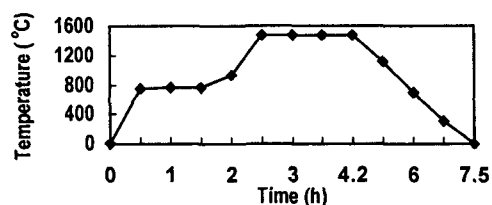
Primary gas		Secondary gas		Current (A)	Voltage (V)	Powder feed rate (g/min)
Pressure rate(kPa)	Flow (m <sup>3</sup> /h)	Pressure rate(kPa)	Flow (m <sup>3</sup> /h)			
245(N <sub>2</sub> )	21	245(H <sub>2</sub> )	0.4	500	70	30
245(N <sub>2</sub> )	21	245(H <sub>2</sub> )	0.4	500	70	30

The phase of the starting powders, as-sprayed coatings, and HIPed coatings were determined by X-ray powder diffractometry (XRD) with crystal monochromatized Cu K<sub>α</sub> radiation. Vickers hardness measurements were performed at a load of 300g for 30s. the specimens were polished with various grades of alumina polishing films to obtain flat surfaces for the measurements. Adhesion strength was evaluated by a tensile adhesion test using a testing machine at a cross head speed of 0.5mm/min. Before measurements, the specimens were filled with acrylic resin in a vacuum dryer and cured at 150 °C for 1 h to prevent adhesive penetration. After removing the protruded acrylic resin, the specimens were fixed with tensile jigs using epoxy adhesives and then cured at 150°C for 2h. The tensile strength of the epoxy adhesive was only 60 - 70 MPa, so strengths more than those values could not be estimated by this method. Element distribution near the interface between the plasma-sprayed layer and the substrate before and after HIPing was analyzed by using an electron probe microanalyzer.

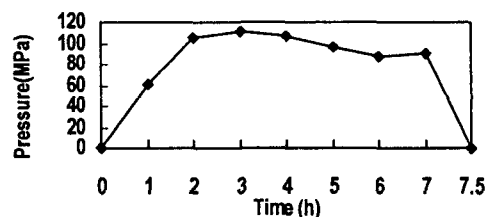
### 3. Results and Discussion

Alumina starting powder consisted mainly of amorphous phase and of small amount of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. After plasma spraying,  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> was mainly obtained with a little amount of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, which might be non-melted

particles. Distinction between  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> was examined by the presence of splitting in the (400) and (440) reflections for  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. After HIPing, phase constitutions were converted to  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> having a trace of (9Al<sub>2</sub>O<sub>3</sub> · 2B<sub>2</sub>O<sub>3</sub>), included in the BN capsule as a binder. There was no change in Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> phase composition after plasma spraying nor after HIPing except for the appearance of a small amount of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. Temperature and pressure profile of HIP treatment is shown in Figs. 1(a) and 1(b) respectively.



(a)



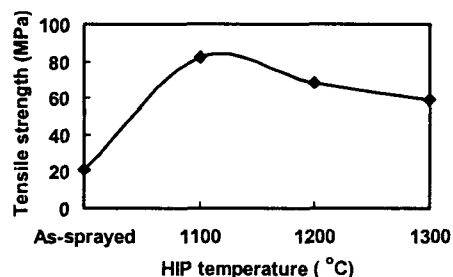
(b)

Fig.1 Temperature (a) and pressure (b) profile of HIP treatment

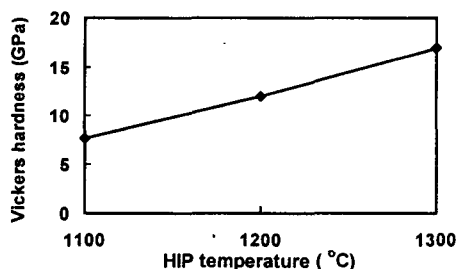
Vickers hardness and tensile strength of Al<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> coatings before and after HIP treatment are shown in Figs. 2-3 respectively. The Vickers hardness of as sprayed Al<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> coatings could not be measured because of their rough surfaces with a lot of pores even after polishing. The Vickers hardness of the Al<sub>2</sub>O<sub>3</sub>-coated surface showed an improvement to 12.2GPa after HIPing at 1300°C. This value reaches to 60 % of the hardness of sintered Al<sub>2</sub>O<sub>3</sub>. The tensile strength also increased from 5MPa to > 40MPa. The fracture path in the as-stayed specimen was close to the interface between the coated layer and metal substrate. However, after HIPing the fracture occurred mostly at the edge area within the coated layer. The

maximum tensile stress seemed to appear in the edge area due to a thermal expansion mismatch between the coated layer and the metal substrate during HIPing. Consequently, the decrease of maximum value of each tensile strength with increasing HIP temperature, as seen in Fig. 2 would be ascribed to the increase of thermal stress with HIP temperature. It is considered that the above mentioned HIP effects would be further improved by introducing some interlayer which can relax the thermal stress. The range of temperature and pressure in HIP treatment was limited, owing to the properties of substrate metal, so the efficient densification of coated  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  could not be completed.

The as-sprayed  $\text{Al}_2\text{O}_3$  coating had a laminar texture consisting of the flattened particles rapidly solidified by spraying, which partially contacted each other. After HIPing, the coated layer changed into a granular structure consisting of  $\gamma$ - $\text{Al}_2\text{O}_3$  with large voids diminishing remarkably. When the samples were HIPed at  $1200^\circ\text{C}$ , the stainless steel penetrated into the coated layer near the interface by plastic deformation.



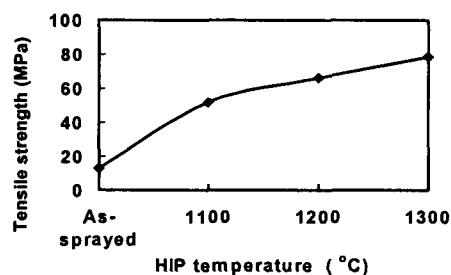
(a)



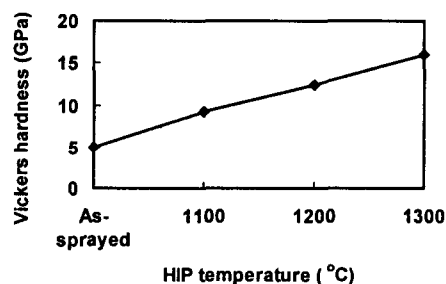
(b)

Fig. 2. Variations of Vickers hardness (b) and tensile strength (a) of  $\text{Al}_2\text{O}_3$  coating HIPed at various temperature

In case of  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  coating, Vickers hardness and tensile strength were remarkably improved, from  $5\text{GPa}$  to  $13.3\text{GPa}$  and from  $5\text{MPa}$  to  $> 60\text{MPa}$  after HIP treatment at  $1300^\circ\text{C}$ , respectively. The fracture positions before and after HIPing were similar to those of  $\text{Al}_2\text{O}_3$  coating. In such an interface a coating strength is expected to increase by a mechanical interlocking. The substrate metal infiltrated deeply into the coated layers after HIP treatment at  $1300^\circ\text{C}$ . The deep infiltration of metal should reduce resistance against wear, heat, and oxidation.



(a)



(b)

Fig. 3. Variations of Veckers hardness (b) and tensile strength (a) of  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  coating HIPed at various temperature

It has been reported that the densification of  $\text{Al}_2\text{O}_3$  occurred at  $> 1500^\circ\text{C}$  by HIPin [9]. Therefore, the HIP conditions in the present investigation are not enough to densify the coating. It is considered that the stainless steel penetrated into both the remaining original pores and the spaces produced by volume shrinkage from  $\gamma$ - $\text{Al}_2\text{O}_3$  to  $\alpha$ - $\text{Al}_2\text{O}_3$ . In the  $\text{Al}_2\text{O}_3$ - $\text{SiO}_2$  coating, the pores still existed, but the laminar structure (splat quenched droplets) disappeared after the HIP treatment at  $1100^\circ\text{C}$ . The size and amount of pores decreased at  $1200^\circ\text{C}$ , and the coated layer

was completely densified at 1300°C by HIPing process. The elements consisting of stainless steel could not be detected in the specimen HIPed at 1200°C but could be detected in that at 1300°C. The fracture pattern of as-sprayed Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> coating was similar to that of as-sprayed Al<sub>2</sub>O<sub>3</sub> coating. Transgranular type fracture was common in HIPed specimens of which particle sizes were 0.2-0.4µm by TEM observation. In cases of Al<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> coatings, there was neither an apparent reaction layer nor a diffusion layer at the interface between the stainless steel and the coated layers.

#### 4. Conclusions

The effects of HIPing treatment between 1100°C and 1300°C on the plasma-sprayed Al<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> coatings onto the stainless steel substrate are summarized as follows:

- 1) both Vickers hardness and bonding strength were remarkably improved to 12.2GPa and 40MPa, respectively, in Al<sub>2</sub>O<sub>3</sub>; to 13.3GPa and > 60MPa in Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> coating;
- 2) each coated layer before HIPing had a laminar texture (splat quenched droplets), but after HIPing it changed into the granular structure with remarkably decreased micro cracks;
- 3) the Al<sub>2</sub>O<sub>3</sub> coatings could not be densified adequately in spite of decreased large voids. However, the Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> coating could be fully densified.

The fracture position by tensile adhesion testing was mainly in the edge area within every coated layer, attributed to the tensile stress caused by thermal expansion mismatches between the coated layer and substrate. The lower tensile strength of specimens HIPed at 1300°C, compared with those HIPed at 1200°C, seems to be due to thermal stress. These results show that HIP treatment has an advantage for improving adhesive strength and Vickers hardness of plasma-sprayed coatings.

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