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Author(s)	Ohmori, Akira; Zhou, Zhan; Eguchi, Noritaka
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Hybrid Spraying of Zirconia Thermal Barrier Coating with YAG Laser Combined Plasma Beam†

Akira OHMORI*, Zhan ZHOU and Noritaka EGUCHI****

* Joining and Welding Research Institute, Osaka University
* * The Advanced Materials Processing Institute Kinki Japan, Amagasaki, Hyogo, Japan

Abstract

As an ideal zirconia thermal barrier coating, a microstructure with strong bonding among coating particles and with a certain amount of porosity in the coating, but without connected porosity, is desirable. However, it is difficult for normal plasma-spraying to create a zirconia coating with these characteristics. In order to obtain these characteristics, we prepared zirconia coatings on steel substrates under coated with NiCrAlY alloys, by means of a hybrid spraying (that is, YAG laser combined with plasma spraying) and studied the effect of this hybrid spraying process and plasma and laser conditions on the microstructure of the coating, and further compared the microstructure of the coating from this hybrid spraying with that in post-laser irradiation of as-sprayed zirconia coatings. It is known that microstructures with densification are formed by the post-laser irradiation of as-sprayed coatings and that microcracks are produced in the process of rapid cooling. However, by using this newly-developed hybrid spraying, the microstructure with partial densification in the coating and without connected porosity was formed and cracks which are generally produced in the post-laser irradiation treatment were inhibited completely. In addition, this hybrid spraying can be done without the post-treatment of coating. Furthermore, the coating properties, such as hardness and wear resistance arising from the bonding state among the coating particles in the zirconia coating created by this hybrid spraying were improved.

KEY WORDS: Hybrid spraying, YAG laser, Plasma, Thermal barrier coating, Zirconia coating, NiCrAlY coating, Densification

1. Introduction

Plasma-sprayed coating of zirconia has been widely applied to gas turbines as thermal barrier coatings[1,2]. However, all plasma-sprayed ceramic coatings, like zirconia contain connected porosities and such properties as high temperature corrosive resistance, mechanical strength and wear resistance are thereby greatly reduced. To improve the properties of these coatings, various methods have been reported[3-6] such as laser irradiation and seal sintering with liquid alloys. Laser irradiation is a rapid and simple method for the densification of microstructure of the ceramic coating. However, in the post-laser irradiation treatment, it is difficult to control new micro cracks created in the process of rapid cooling by the contraction of dense parts, because of the brittle property of the ceramics[7-14].

In this study, zirconia coatings were prepared by hybrid spraying (that is, YAG laser combined with plasma spraying). The properties of such coatings were compared with those from coatings the post-laser irradiated after plasma spraying.

The hybrid spraying described here prevents

† Received on May 19, 1997
* Professor
** Researcher

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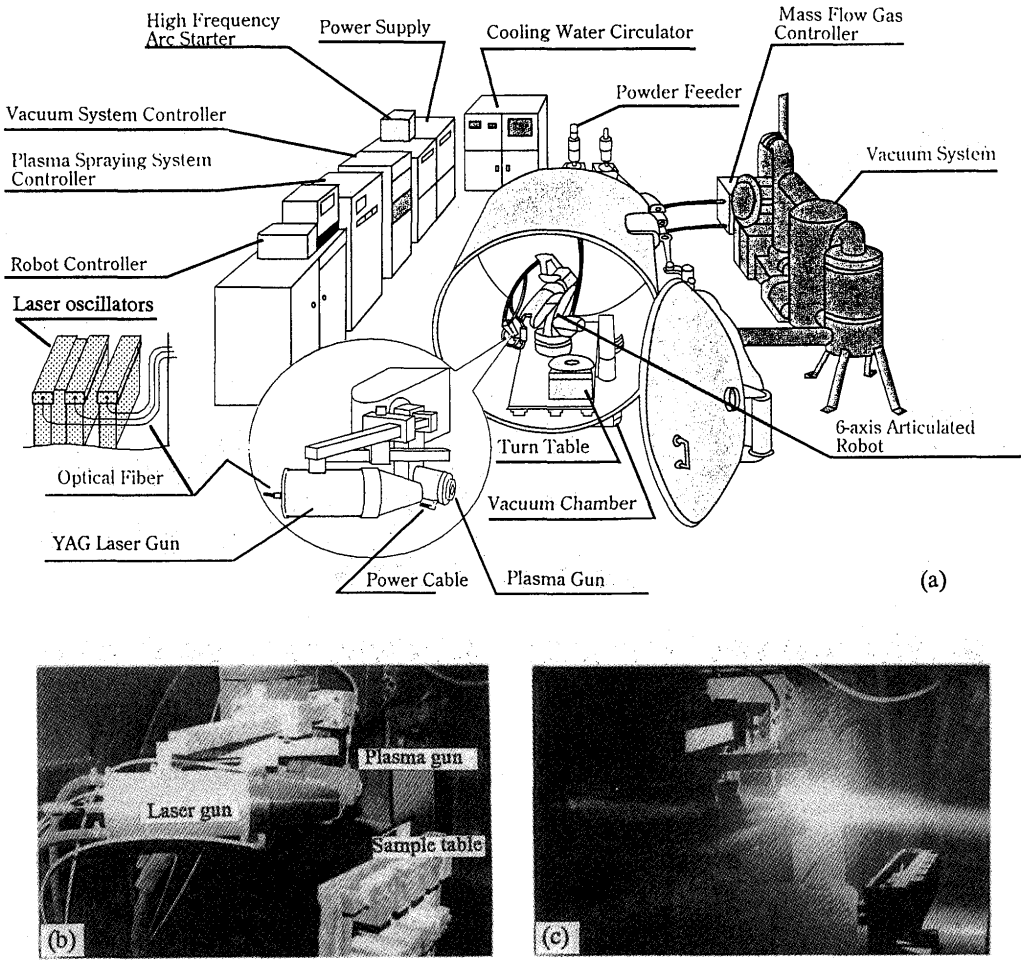

Fig.1 Hybrid spraying system. (a) scheme of YAG laser combined plasma spraying equipment; (b) arrangement of hybrid spraying; (c) hybrid spraying of zirconia coatings.

the formation of the cracks effectively and maintains the densification of microstructure in the coating by means of both controlling the offered energy density of the laser and spraying an under coat between the zirconia coating and the steel substrate. Furthermore, we evaluated the hardness and wear resistant properties of the zirconia coatings created by this hybrid spraying and examined the relationships between the microstructure and these properties.

2. Laser Combined Plasma Spraying System

This hybrid spraying system combines plasma-spraying and laser irradiation systems. Both of the plasma gun and the laser gun are carried on a 6 axis articulated robot installed inside of chamber equipped with an exhaust system (**Fig 1a**). The relative positions of plasma spraying gun and laser irradiation gun to specimen surface were adjusted by the holder fixed in the robot and the hybrid spraying was carried out by robot which can provide all posture control in pressures at over the range of 5 to 760 Torr. Maximum powers of the plasma spraying gun (Miller Thermal, SG-100) and the laser gun (NEC) are 100kW and 2kW respectively. The laser source used is a Nd:YAG laser (1.064 μm wave length) with continuous or pulsed wave form and the laser beam was delivered by optical fiber from oscillator to laser nozzle where the beam was focused by an optical lens. Hybrid spraying was under taken mainly in a horizontal direction for specimens in this study (**Fig 1b**). The relationship between defocus distance and spot diameter of the laser beam (with single beam) and distribution of the energy density of the laser beam measured by beam analyzer is shown in **Fig 2**.

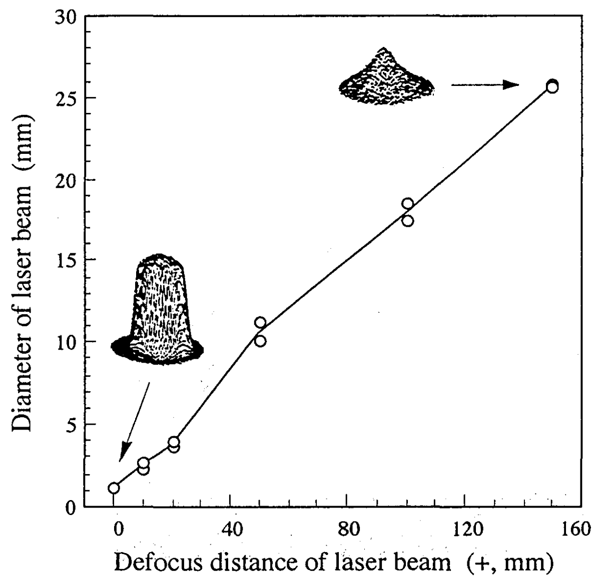

Fig.2 Relationship between defocus distanceof laser beam and diameter of laser beam.

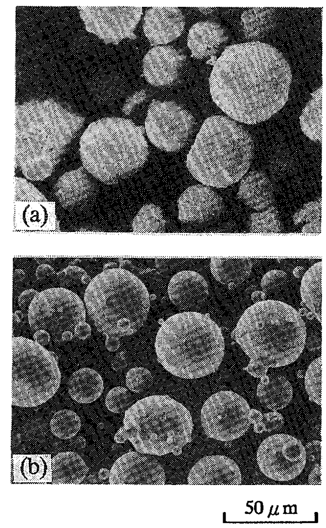

Fig.3 Typical morphology of spraying powders used. (a) ZrO_2-8%Y_2O_3 powder; (b) NiCrAlY powder.

Table 1 Composition and size of powder used

Material	Composition (wt%)						Size (μm)
NiCrAlY	Cr	Al	Y	O	N	Ni	
	21.70	9.98	1.13	0.04	0.01	bal.	10~45
ZrO_2-8%Y_2O_3	Y_2O_3	Al_2O_3	SiO_2	Fe_2O_3	ZrO_2		
	7.88	0.02	0.07	0.08	bal.		10~45

3. Experimental Procedures

Two kinds of commercially available spraying powder ZrO_2(8%Y_2O_3) and NiCrAlY were used in this experiment. The chemical compositions and the sizes of these powders are given in **Table 1** and the typical appearance of these powders is shown in **Fig 3**. The coatings were sprayed onto specimens of sandblasted JIS SPCC mild steel of a size of 50×60×3 mm. **Table 2** summarizes the plasma spraying parameters of zirconia coatings and the conditions of applied laser irradiation. Before the hybrid spraying, a heat-resistant NiCrAlY coating of approximate 40 μm was prepared on the steel substrate as an under coating at pressure at 100 Torr Ar gas atmosphere. The zirconia coatings were sprayed at 760 Torr atmosphere. In the hybrid spraying, the top layer of zirconia coatings were plasma-sprayed onto the NiCrAlY coated substrate and then the hybrid

Table 2 Conditions of plasma spraying and laser irradiation

Plasma spraying:	
Arc current (A)	600
Arc Voltage (V)	53
Arc Power (kW)	32
Plasma gas Ar (l/min)	60
Plasma gas N_2 (l/min)	4
Spraying distance (mm)	100
Powder feed rate (g/sec)	0.0833
Laser irradiation:	
Wave form	continuous wave
Laser Power (kW)	2.0
Defocus Distance (+, mm)	20~100
Shield and purge gas Ar (l/min)	70
Hybrid spraying:	
Traverse speed (mm/sec)	15~30
Interval distance of spray pass (mm)	4

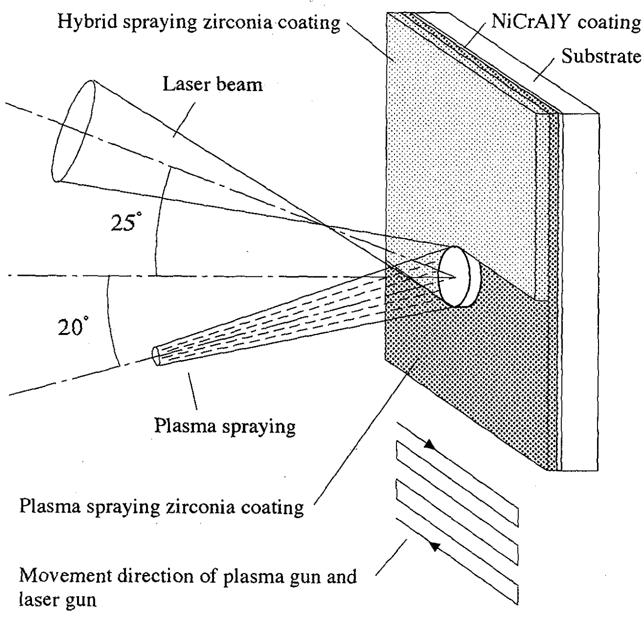

Fig.4 Scheme of hybrid spraying.

Table 3 Conditions of abrasion test used

Material of wear paper	SiC
Roughness of wear paper	#320
Width of wear paper (mm)	6
Move distance of wear (mm)	10
Rate of wear (DS/min)	40

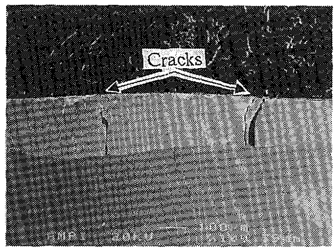

Fig.5 Typical results of cross-sections of zirconia coatings treated by post-laser irradiation.

spraying was carried out. When the hybrid spraying was carried out, the laser beam was combined at the spraying point which was overlapped with the plasma-spray jet and transmitted together with the plasma-spraying gun at the same speed, direction and pass interval by the robot of 6 axes (**Fig 4**). The changes of energy density offered during hybrid spraying were controlled by adjusting the defocus distance of the laser beam irradiating the specimen surface, whereas the power of plasma spraying was maintained at a constant value. Furthermore, the inclination angle between the center line of the spraying jet and the vertical line of the specimen surface plus the angle between the laser light and the vertical line of the specimen surface were kept at 20° and 25° respectively. For comparison with hybrid spraying, post-irradiation of the zirconia coating was also carried out under the conditions shown in Table 2. The microstructure of cross-sections of the coatings was observed by scanning electron microscopy. The hardness of the coatings was measured by micro-Vickers hardness testers at loads of 300 g and press times of 15 sec, while the property of wear resistance was evaluated by using an abrasion test of SUGA type with straight return motion and a certain vertical pressure on the coating surface with the tests being made under the condition of return motions of 1,400 times at pressure of 1500g. The parameters of the tester are shown in **Table 3**.

4. Results and Discussion

Fig 5 shows a typical result of a zirconia coating cross-section treated by the post laser irradiation at a defocus distance of +20 mm and laser input power of 2 kW at the traverse speed of 15 mm/sec. Densification of microstructure of the coating was observed and the thickness of the dense layer in the coating increased with the applied energy density of laser irradiation. But new micro cracks created in the rapid cooling process were seen in the coating despite irradiation with different energy densities of the laser . The relationship of the thickness and width of the dense layer in the post laser treated coating and the traverse speed of the laser beam is shown in **Fig 6**.

Fig 7 shows typical cross-sections of plasma-sprayed coatings and the changes of the microstructure obtained by hybrid spraying at traverse speeds of 25 mm/sec and laser input powers of 2 kW (b~f). It was found that the porosities in the coatings decreased as compared with the plasma-sprayed coating and that a good interface between the coating and the substrate was obtained. The density degree of the microstructure of hybrid spraying layer in the coating increased with a decrease in the defocus distance of the laser beam from +90mm to +30mm. Furthermore, the new cracks generally produced in the post laser irradiation were not seen in the coatings except for the case of a defocus distance of +30 mm. **Fig 8**

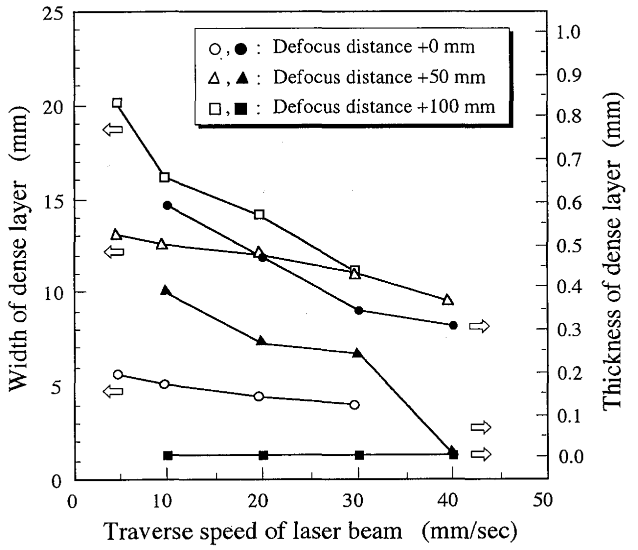

Fig.6 Change of thickness and width of dense layer in post-laser treated coatings with traverse speed change of the laser beam irradiation.

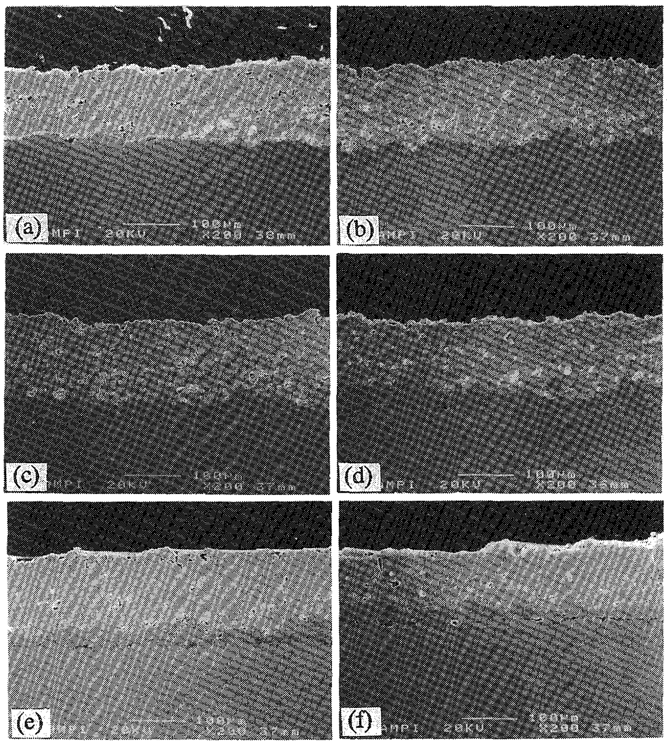

Fig.7 A typical cross-sections of plasma-sprayed coatings (as-coat) and the cross-section of coatings obtained by hybrid spraying at a traverse speed of 25 mm/sec and laser input power of 2 kW. a) usual plasma-sprayed coating (as-coat); (b) laser defocus distance of +90 mm; (c) laser defocus distance of +70 mm; (d) laser defocus distance of +50 mm; (e) laser defocus distance of +40 mm; (f) laser defocus distance of +30 mm.

shows the microstructure of the upper part of the zirconia layer in those coatings shown in Figure 7. As shown in Fig 8, the existence of connected porosities, the non-bonded areas between flattened particles and the vertical micropores in individual flattened particles in the plasma as coating was observed, while the non-bonded areas decreased in the hybrid sprayed coatings when the defocus distance of the laser beam was smaller than +70 mm, and vertical micropores in the coatings also decreased and disappeared in the case of the defocus distance of +50 and +40 mm while densification of the microstructure was seen in the case of +30 mm. It is clear that the densification in the coatings was caused by the heating effect of laser irradiation in the hybrid spraying.

The above-mentioned results reveal that bonding among zirconia particles in the coating can be increased by both of the post-laser treatment and the hybrid spraying. However, the hybrid spraying can form a coating with close porosities but without connected cracks which is generally produced in the post-laser treatment. It is considered that this difference is caused by the different process of heating and cooling in post-laser treatment and hybrid spraying. As it is illustrated in **Fig 9**, in the case of post-laser treatment (a and b), when a laser beam with high energy density was directed onto the plasma-sprayed coating, the melting and fusion of the coating particles occurred at the area of irradiation and new cracks were produced by the tensile stress. A large contraction of the dense part in an extremely short time occurred in the process of rapid cooling after the laser beam irradiation. On the other hand, in the case of hybrid spraying (c), when the plasma-sprayed particles at the state of melting or half melting entered into the area of laser irradiation and accumulated on the surface of the coating layer, the surface temperature of the particles was held or raised and resulted in an increase of bond areas among the particles. The vertical micro cracks in individual particles of the coating, produced in the process of plasma-spraying, were inhibited by the heating effect of

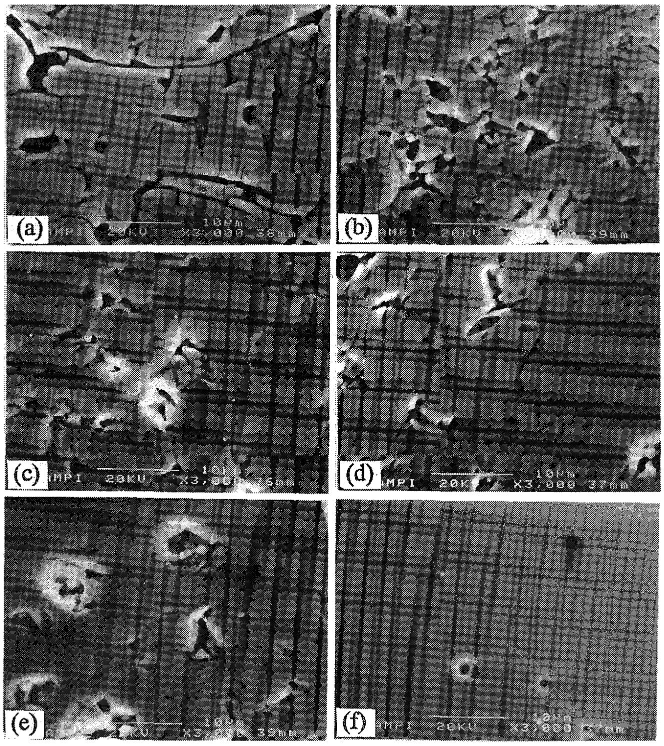

Fig.8 Typical microstructures of plasma-sprayed coatings and microstructures of hybrid sprayed coating layers ob-tained at conditions of traverse speed of 25 mm/sec and laser input power of 2kW. (a) usual plasma -sprayed coating; (b) laser defocus distance of +90mm; (c) laser defocus distance of +70 mm; (d) laser defocus distance of +50 mm; (e) laser defocus distance of +40 mm; (f) laser defocus distance of +30 mm.

laser irradiation and the thermal barrier effect of layers of sprayed particles, which make the particles cool at a slow speed. We call this effect the "effect of furnace keeping". Moreover the strain produced in the coating was limited because the regions of contraction were smaller and the temperature of the heated particles was lower than in the post-laser treatment. The influence of the "effect of furnace keeping" on the temperature curve of sprayed particles at certain distances from the coating surface in hybrid spraying may be evident in **Fig 10**, when compared with the temperature curve in post-laser treatment and usual plasma spraying . There are sharp thermal cycles in the process of post-laser treatment and there is also a sharp cooling curve in usual plasma spraying , whereas there is a slower cooling curve in the process of the hybrid thermal spraying. The

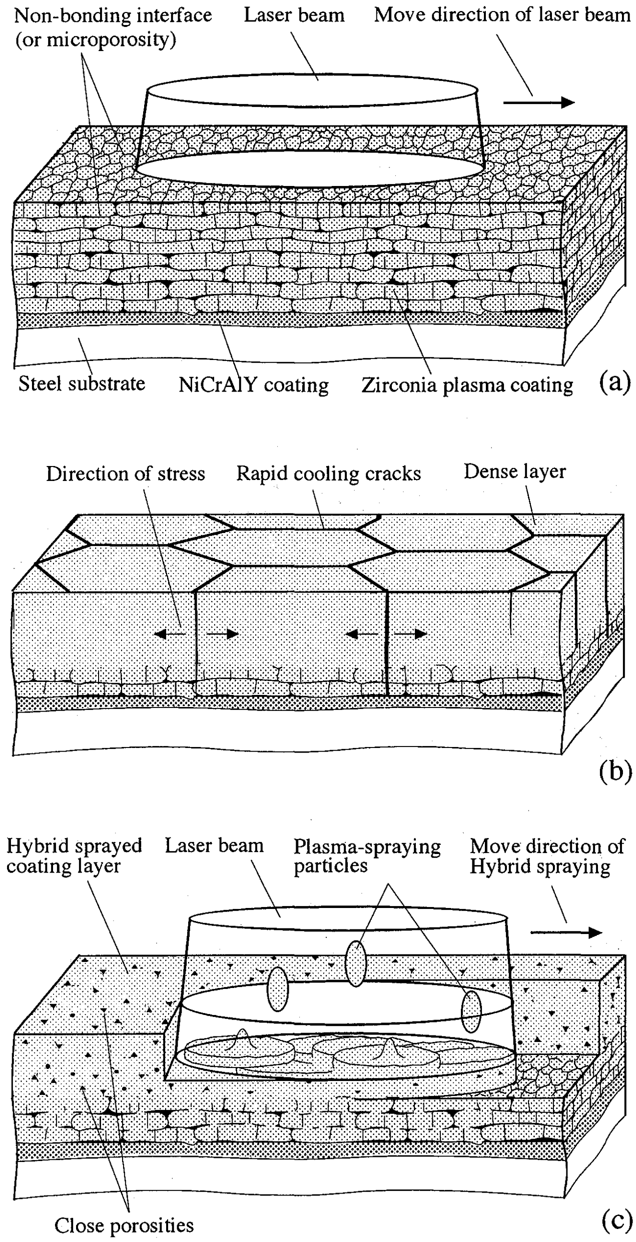

Fig.9 Scheme of forming process of zirconia coatings for post-laser irradiation treatment (a,b) and hybrid spraying (c). (a) laser beam irradiated surface of plasma as -sprayed coating; (b) coating obtained after post-laser irradiation; (c) process of hybrid spraying and characteristic of coating obtained after hybrid spraying.

temperature of the sprayed particles which melted in the plasma jet and subsequently cooled is held or raised when the particles enter into the area of laser irradiation, and then, in the irradiated region the particles cool slowly because of the "effect of

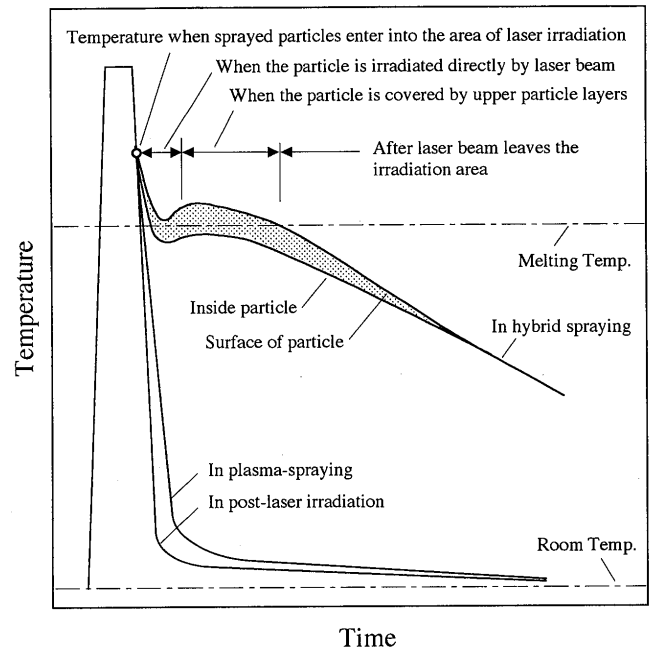

Fig.10 Schematic illustration of the temperature curve of a sprayed particle at certain distances from the coating surface during hybrid spraying, post-laser irradiation and usual plasma spraying.

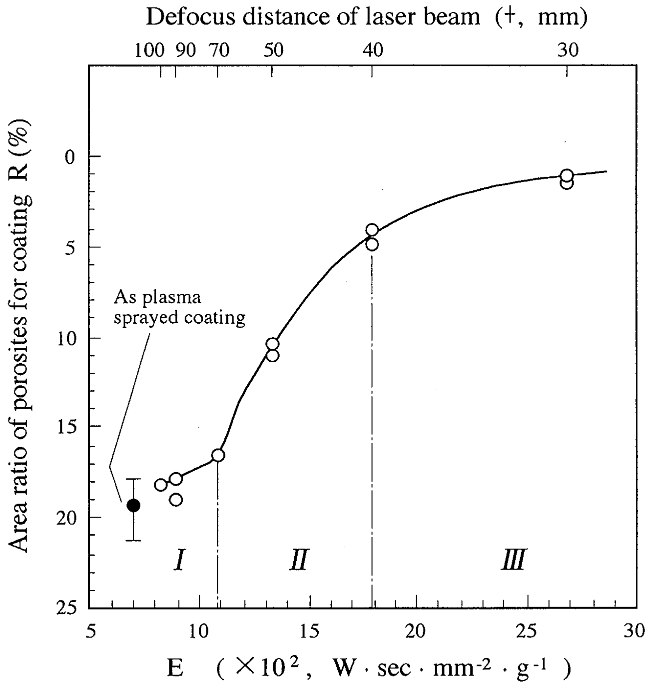

Fig.11 Relationship between porosity ratio of hybrid sprayed coating and energy density of laser irradiation at a given rate of zirconia powder feed.

furnace keeping", even after the laser beam is removed from the area. Therefore, it is considered that the stress remaineing in the coating is decreased.

Fig 11 shows the effect of energy density (E) of the laser irradiation at a certain rate of zirconia powder feed on the ratio (R) of area of porosities in the cross-section of zirconia coating measured at the hybrid spraying speed of 25 mm • sec^{-1}. Here, E and R are calculated from the following equations (1) and (2) respectively.

$$E = \rho / V = \rho \cdot t / P = \rho \cdot L / v \cdot t \cdot V \quad (1)$$

$$R = p / (p+s) \quad (2)$$

Where, the ρ is the energy density of the laser irradiation, V is the rate of zirconia powder feed, P is the amount of zirconia powder feed at t time, v is the moving speed of the hybrid spraying (v = L / t) and L is the moving distance at t time in (Eq.1) , and p is the total area of porosity per cross-section of coating area; s is the total area of zirconia particles in the cross-section of the coating in (Eq.2) .

This result shows the ratio of the porosities in the zirconia coating decrease with increasing energy density of the laser irradiation and the effect of the energy density of the laser irradiation on the microstructure of the coating can be divided into three stages. The bond areas among the particles increase and some amount of porosity remains in the coating at the stage Ⅱ, ranging from 1,080 to 1,800 W • sec • mm^{-2} • g^{-1}. The degree of density of the coating increases greatly (higher than 98%) but the cracks are produced at the stage Ⅲ (Figure 7(f)). Furthermore, the bonding areas among the particles increase when the E value increase to stage Ⅱ from stage Ⅰ, which may be considered as the temperature at an area of laser irradiation with the energy density reaching to or beyond the melting point of the zirconia particles.

Fig 12 shows the hardness of the cross-section of as-plasma-sprayed zirconia coatings and the coating created by the hybrid spraying under the conditions of defocus distance from +90 mm to +30 mm. Any hardness of the hybrid sprayed coatings was higher than that of the plasma coating and the value of hardness in the range of

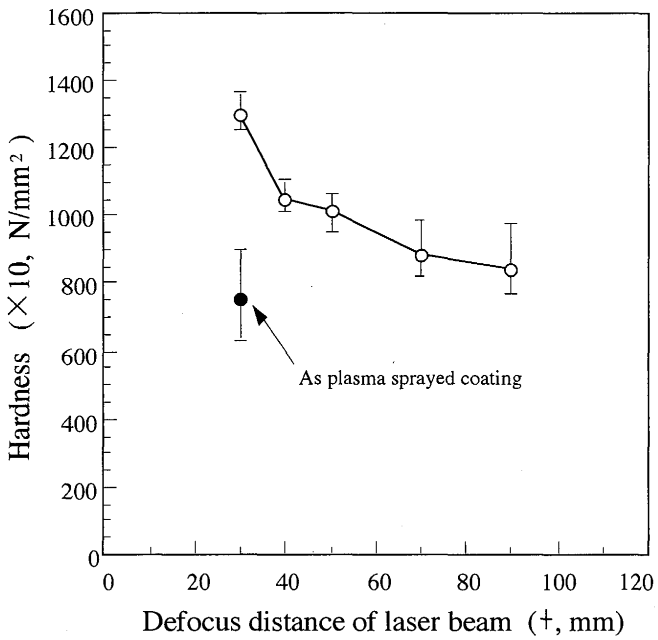

Fig.12 Hardness of cross-section of as-sprayed coating and coating created by hybrid spraying at various defocus distances of laser beam.

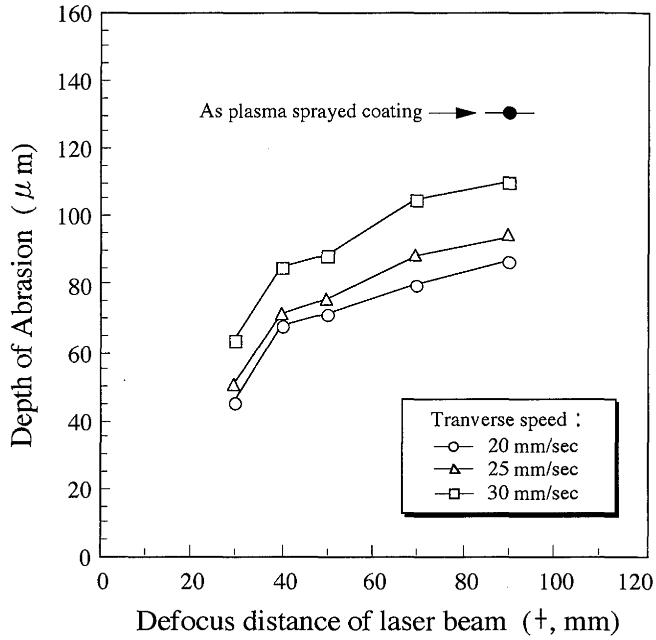

Fig.13 Relationship between defocus distance of laser beam and depth of abrasion wear for hybrid sprayed coating.

8,400~12,980 N/mm^2 increased with a decrease in the defocus distance. The increase of hardness is considered the result of strengthening of the bonding among the particles and a decrease in the ratio of the porosities in the coating.

Fig 13 shows the abrasion wear resistance evaluated on the surface of the hybrid coating and the as sprayed coating. The wear depth of the plasma sprayed coating was about 131 μm and the wear depth of the hybrid sprayed coatings decreased considerably with a decrease in the defocus distance of laser irradiation. It was considered that the increase of bonding areas and strengthening of the bonding force among the particles resulted in the improvement of the abrasion property of the hybrid sprayed coatings.

6. Conclusion

The hybrid spraying using YAG laser irradiation combined with plasma spraying was applied to the preparation of zirconia thermal barrier coatings with the strong bonding among coating particles and without connected porosities and cracks. It was found that the bonding force among the particles in the coating increased greatly and the connected micropores and cracks generally produced in post-laser irradiation were prevented. A good interface between the coating and the substrate was obtained by hybrid spraying. The change of the microstructure was controlled by adjusting the energy density of the laser irradiation and the prevention of the rapid cooling cracks in the hybrid spraying may be attributed to the thermal barrier effect of the so-called "effect of furnace keeping" in the process of the hybrid spraying.

References

1) C.C.Berndt and H.Herman, Thin Solid Films 108, (1983) pp.427-433

2) Y.Itoh, M.Saitoh, M.Takahashi, K.Ikeda, H.Okamoto and K.Takahara, J. High. Temp. Soc. Jpn. 23, (1997) pp. 137-142

3) A.Ohmori and K.Kamada, J. Mater Sci Letters 11, (1992) pp.108-110

4) T.Ishikawa, T.Toshiyuki, T.Hashida, H.Takahashi, M. Kanazawa, T.Yoshioka and K.Fujii, Spray. Jpn 28, (1991) pp.190-195

5) A.Ohmori, Z.Zhou and K.Inoue, Thin Solid Films 251, (1994) pp.141 -146

6) A.Ohmori, Z.Zhou, K.Inoue and T.Sasaki, J.Thermal Spray Technology 5(2), (1996) pp.134-138

7) A.Ohmori and K.Kamada, Trans. JWRI. Jpn 18, (1989) pp.305-307
8) A.Ferriere, G.Flamant, J-F.Robert, P.Pekshev, I.Smurov and A.Chystyi, Collogue De Physique C5, (1990) pp. 393-402
9) K.M.Jasim, R.D.Rawlings and D.R.F.West, J. Mater Sci 26, (1991) pp. 909-916
10) A.Petitbon and L.Boquet, Surface and Coatings Tech 49, (1991) pp.57-61
11) I.Smurov, A.Uglov, Y.Krivonogov, S.Sturlese and C. Bartuli, J. Mater Sci 27, (1992) pp.4523-30
12) P.C.Tsai, H.L.Tsai and D.C.Tu, Mater Sci and Engine A165, (1993) pp.167-173
13) K.M.Jasim, Rawlings and D.R.F.West, Surface Engineering Ⅲ, (1993) pp.50-63
14) K.A.Khor and S.Jana, Surface Modification Technologies, (1995) pp.793-99