New Approach for Advanced Zirconia Thermal Barrier Coatings by Plasma-Laser Hybrid Spraying Technique

SANG OK Chwa *, OHMORI Akira **, NAKADE Katsuyuki ***

Abstract

Laser treatment improved the thermal shock resistance of thermal barrier coatings (TBCs). Thermal diffusivity measurement revealed that post-treated coatings are not effective for reducing heat flux. However, laser-hybrid sprayed TBCs with segmented feather-like microcracks decreased the thermal diffusivity by 60% of the as-sprayed value at specific laser-hybrid conditions. The post-treated TBCs with dense layers showed abrupt collapse of laser-treated layers but hybrid sprayed coatings exhibited improved erosion resistance. And the reliability of TBC with segmented cracks was also confirmed from the cyclic oxidation test. From those investigations, a new approach for manufacturing advanced TBCs by laser-hybrid plasma spraying was suggested.

KEY WORDS : (Thermal barrier coatings (TBCs)) (Plasma spraying) (Laser-Hybrid) (Cracks) (Thermal shock resistance) (Microstructure) (Thermal diffusivity) (Erosion)

Introduction

TBCs are widely used in hot-section components of gas turbines [1,2]. The gas-inlet temperature in a gas turbine has been increased year by year. As a result, the protection of the metal substrate of hot-section components is an acute problem. Commonly, two types of deposition technique, atmospheric plasma spraying (APS) and electron beam physical vapor deposition (EB-PVD), are available for TBCs preparation [3,4].

Plasma sprayed coatings have a lower thermal conductivity but have a poor strain tolerance. In contrast, EB-PVD coatings have a considerably stronger lateral compliance than their APS counterparts due to the aligned columnar structure. But EB-PVD process needs considerable initial investment for equipment and cost per charge is much higher and leads to APS advantages for large parts.

In addition, new industrial diesel engines, and automotive applications may require much thicker coatings, over 1mm thickness, which are almost impossible to prepare by EB-PVD process. From this point, extensive researches have been carried out to enhance the lifetime of TBCs by post-treatment of coatings prepared by spraying technology which has many advantages over the EB-PVD process [5,6].

However, the relationship of microstructures and thermal shock resistance of TBC coatings prepared by post treatment is not clear.

Moreover, previous reports on the laser-treatment of TBCs were focused on post manipulation, and there are few reports about the new treatment process such as we tried (YAG laser combined spraying process)[7,8]. In

† Received on November 10, 2002
* Graduate Student
** Professor
*** Post doctoral research fellow

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan

this research, not just the thermal shock resistance, but other properties such as thermal diffusivity, erosion resistance and interface oxidation behavior were observed for practical application of post and hybrid-treated YPSZ-TBCs. From these investigations, a new approach for manufacturing advanced TBCs by laser-hybrid plasma spraying was suggested.

Experimental

Materials

Thermal barrier coatings consisting of 8 wt% yttria partially stabilized zirconia layer and CoNiCrAlY bond-coat were plasma sprayed on sandblasted JIS SUS304 plates and Inconel 738 LC coupons using commercially available powders (Showa Denko, Nagano, Japan). A bond coating of approximately 100μm thickness was prepared at a pressure of 13.3kPa argon gas atmosphere, and then a top-coating with a thickness of 330μm was produced in air by employing the conditions shown in **Table 1**.

Laser-Combined Spraying System

Post treatments of predeposited coatings were carried out using the laser combined spraying system [9,10]. Both the plasma gun and the laser gun were installed inside a chamber equipped with an exhaust system. A laser beam with a rectangular shape and uniform beam intensity was obtained by using the kaleidoscope composed of two pairs of gold mirror (3.6x51 mm^2), and the laser system was combined with the plasma spraying equipment. Laser treatment parameters are described in **Table 2**.

CO_2 Laser Thermal Shock Test

The thermal shock resistance of TBCs was evaluated by the CO_2 laser shock test as shown in **Fig. 1**. TBC specimens were placed in the specimen holder. The back surface of the substrate was cooled by compressed air, and the TBC top surface was heated by a CO_2 laser with 18mm of beam diameter to obtain the temperature gradient

Table 1 Plasma spraying parameters.

Process parameters	VPS (NiCrAlY)	APS(YSZ)
Primary gas (Ar), m^3/s	4.17×10^{-4}	4.17×10^{-4}
Secondary gas (H_2), m^3/s	6.7×10^{-5}	6.7×10^{-5}
Current/Voltage, (A/V)	600/49	600/50
Spray distance (mm)	150	100
Atmosphere (kPa)	13.3	101.3

Table 2 Post- and plasma-laser hybrid treatment parameters.

Process parameters	Post-treatment	Hybrid treatment
Laser power (kW)	1-3.5	2-3.5
Beam size (mm^2)	(5x5-12x12)	
Scan speed (mm/sec)	10-700	250
Shield gas flow rate (Ar, m^3/s)	1.67×10^{-4}	
Overlap (mm)	0-2	1

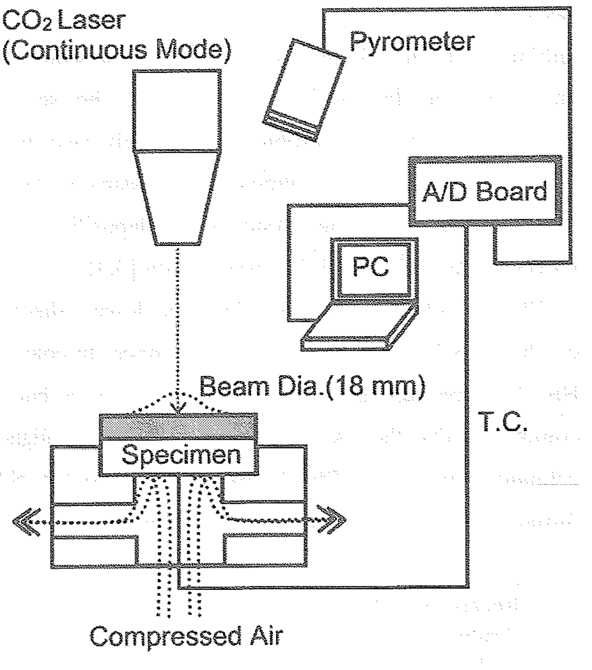

Fig. 1 Experimental set-up for CO_2 laser thermal shock test.

of about 1000 K. The test was interrupted when the TBC coat showed delamination or spalling.

Thermal Diffusivity Measurement and Erosion Test

Thermal diffusivity was measured on a specimen consisting of three layers of materials including the substrate using the laser flash method (TC-7000, ULVAC-RIKO, Tokyo, Japan). Wear property of coatings was evaluated by means of the erosion tester, ACT-JP (Arata Coating Tester with Jet Particles)[11]. The impact angle was fixed at 60 degrees, and mass loss from a sample determined by weighing before and after each exposure with a precise balance.

Cyclic Oxidation Test

Cyclic oxidation tests of TBCs were conducted in a programmable furnace. Each thermal cycle consisted of a heating rate of 10 K/min to 1423 K, isothermal holding at 1423 K for one hour, and then cooling in the furnace to 423 K. After every 10 cycles of heat treatment, specimens were removed from the furnace, visually inspected and weighed up to a failure (a visible spalling of coating). Bare Inconel 738LC substrates were also cycled at the same thermal history to estimate oxide scale on the un-coated specimen and calculate the specific weight gain at the interface between top-coat and bond-coat.

Results and Discussion

Microstructure of Post-Treated and Laser-Hybrid TBCs

In the post-treatment of TBCs, sintering of sprayed splats was observed and vertical cracks were found when the coating layer was remelted. However, in laser-hybrid sprayed coatings, the feature of cracks in the coating was different from the post-treated coatings as shown in **Fig. 2**. The feature of cracks in the coatings prepared by hybrid spraying processes was characterized as a feather-like structure that consists of a vertical crack with significant number of branching cracks that were not observed in the post-treated coatings.

CO_2 Laser Shock Results

Detailed results of laser shock cycles of various TBCs were shown in **Fig. 3**, where P and E are laser

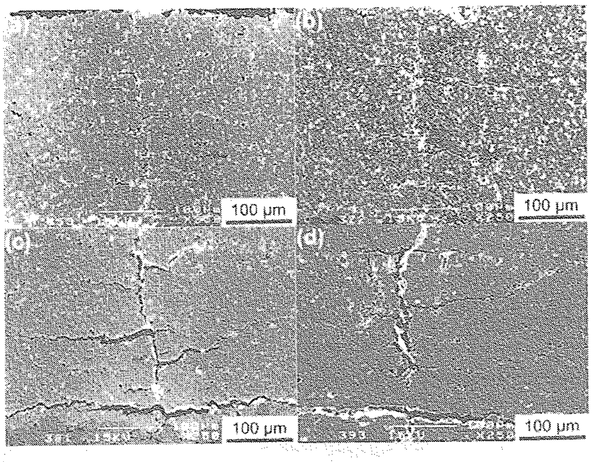

Fig. 2 SEM cross-sections of laser-hybrid sprayed coatings as a function of laser power density: (a) 80; (b)100; (c)120, and (d)140 W/mm^2, respectively.

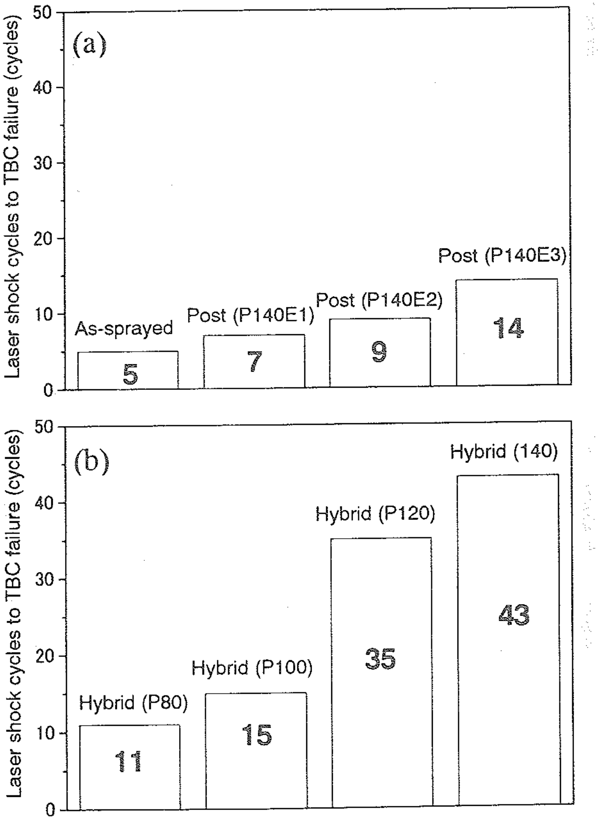

Fig. 3 Laser shock cycles of various TBCs: (a) post-treated; (b) laser-hybrid

power and energy density, respectively. Laser-hybrid sprayed coating exhibited the best thermal shock resistance, more than 8 times the lifetime improvement as compared with as-sprayed TBCs.

When the failure procedure was visually inspected, large-scale buckling and total separation of top-coat was observed in as-sprayed TBCs after the laser shock test. However, in laser-treated TBCs, such an abrupt total failure was not observed, and degradation was mainly initiated from near the center of the CO_2 laser-heated zone.

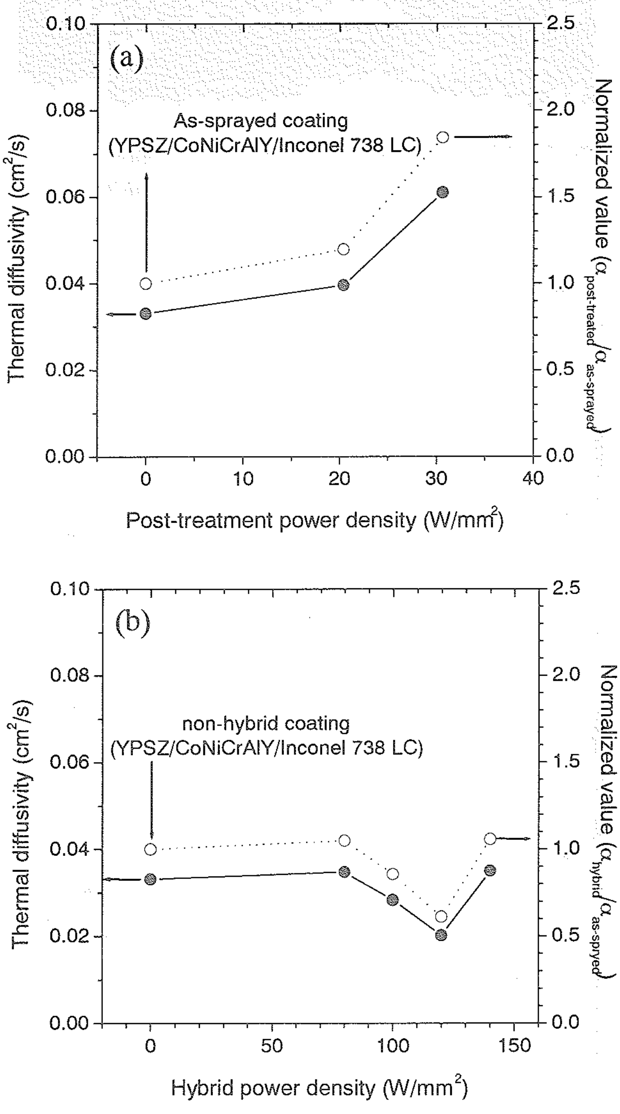

Fig. 4 Thermal diffusivity of various TBCs: (a) post-treated; (b)laser-hybrid

Thermal Diffusivity of Post-Treated and Laser-Hybrid TBCs

Thermal diffusivity of post-treated coatings are shown in **Fig. 4a**. Generally, the sprayed coatings have very thin tenths of a micron. Therefore, the sintering effect of laser treatment lowers the thermal resistance between the splats, interlamellar pores or cracks with a thickness of fewconsequently, results in a higher thermal diffusivity of the coating. Laser-treated coatings (P = 30.6 W/mm^2, E = 21 J/mm^2), which have a thoroughly remelted layer and sharp vertical cracks, showed about 85 % increase of thermal diffusivity compared with the value for as-sprayed coatings. There was no considerable increase of thermal diffusivity in the plasma-laser hybrid TBCs as shown in **Fig. 4(b)**.

Moreover, it was possible to decrease the thermal diffusivity by 60 % of the as-sprayed value at the specific laser-hybrid condition (P = 120 W/mm^2). Thermal diffusivity of TBCs prepared at the higher power density (P = 140 W/mm^2) of a hybrid condition was slightly increased because the higher laser power results in the formation of very dense layers and columnar structures, as shown in Fig. 1d.

Erosion Behavior of Post-Treated and Laser-Hybrid TBCs

It was confirmed that post-treated coatings at excessive power and energy densities have numerous defects such as entrapped gas bubbles [8]. Therefore, the coating treated at excessive energy density severely eroded in the early stages of the test and showed an unsteady erosion rate as shown in **Fig. 5a**. Weigh losses of laser-hybrid sprayed coatings (P = 80 and 120 W/mm^2) were lowered compared with the usual plasma sprayed coatings and a constant erosion rate was confirmed as showin in **Fig. 5b**.

Failure progress of various TBCs under cyclic oxidation

Photographs showing the failure progress of as-sprayed, post-treated (P = 140 W/mm^2, E = 3 J/mm^2), and laser-hybrid sprayed TBCs (P = 120 W/mm^2, E =

2.4 J/mm^2) specimens under cyclic oxidation tests are shown in **Fig. 6**. For the laser-hybrid TBC those which had 50% of laser-hybrid ceramic layer were used. As shown in the photographs, the cyclic oxidation test of various TBC specimens revealed significant difference in lifetimes of TBCs. In the case of as-sprayed TBCs, stress induced surface cracks were clearly observed after 100 cycles. The cracks grew and connected with continued cycling, and finally the large scale buckling of the coating was observed near the center of the specimen

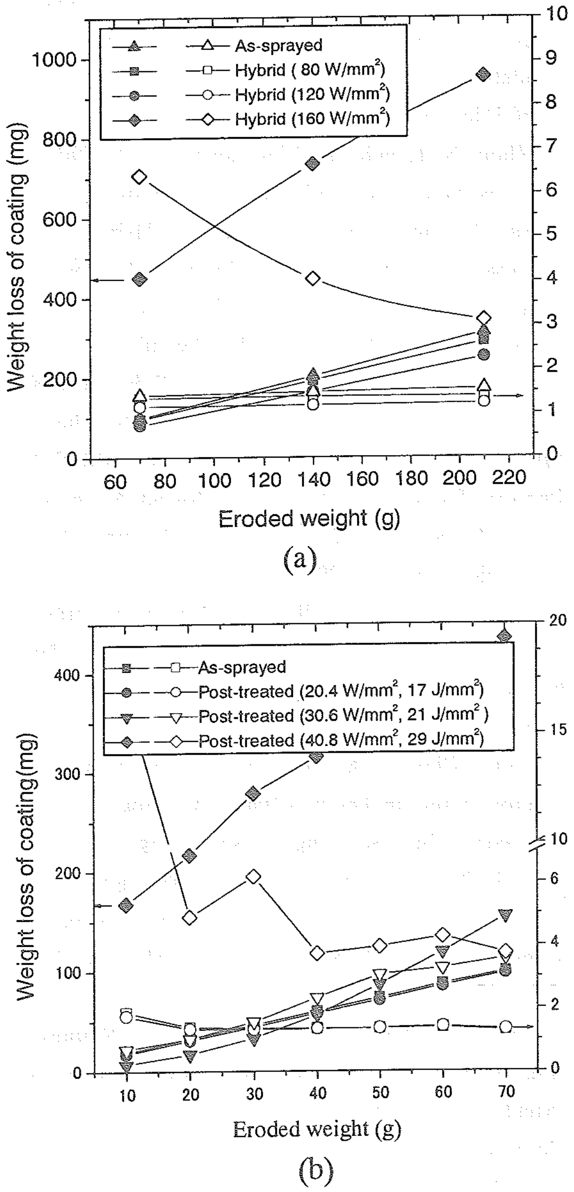

Fig. 5 Weight loss and erosion rate of various TBCs: (a) post-treated; (b) laser-hybrid.

surface (270 cycles). On the other hand, post-treated TBCs did not show conspicuous thermal induced visible cracks up to 200 cycles, and post treated TBCs revealed a 50% increase of lifetime (410 cycles) as compared to as-sprayed TBCs. If the patterns of surface crack are examined, finely distributed cellular domains are observed.

It can be also found that the progress of cracks is mainly from the previous laser-induced cracks, introduced for the improvement of thermal shock resistance. Therefore, it can be concluded that the assprayed coating, which have no intentionally introduced cracks, is fractured from the large scale buckle-driven failure, and laser-treated coatings, which retain finely distributed vertical cracks produced from local surface melting of coating, failed from edge delamination. Laser-hybrid sprayed coatings also exhibit similar delamination behavior to the post-treated coatings and the most improved lifetime (420 cycles) under the cyclic oxidation.

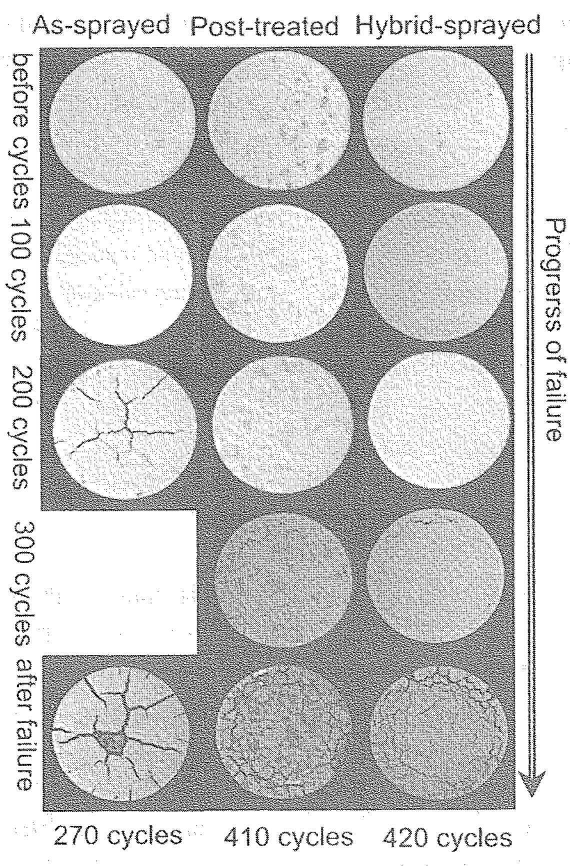

Fig. 6 Photographs showing the failure progress of various TBCs under cyclic oxidation.

Conclusions

TBCs prepared by laser-combined plasma spraying formed finely distributed feather-like segmented cracks, and showed a lifetime improvement of more than 8 times over the usual plasma sprayed TBCs evaluated by the CO_2 laser shock test. Post-laser treatment also improved the thermal shock resistance of thermal barrier coatings (TBCs). However, thermal diffusivity measurement revealed that post-treated coatings are not effective for reducing heat flux. Laser-hybrid sprayed TBCs with segmented feather-like microcracks decreased the thermal diffusivity by 60% of the as-sprayed value at specific laser-hybrid conditions. Post-treated TBCs with dense layers but vertical cracks show abrupt collapse of laser-treated layers but hybrid sprayed coatings exhibited improved erosion resistance and a steady erosion rate. From the observation of the failure progress of various TBCs under cyclic oxidation, the reliability of TBCs, which have a segmented cracks from laser treatments, was confirmed. In the case of as-sprayed TBCs, stress induced surface cracks were clearly observed after 100 cyclic oxidation tests, and finally the large scale buckling of coating was observed near the center of the specimen surface after 270 cycles. On the other hand, post-treated and laser-hybrid sprayed TBCs did not show conspicuous thermal induced visible surface cracks up to 200 cycles, and revealed more than a 50% increase of lifetime as compared to as-sprayed TBCs. From these investigations, a new approach for manufacturing advanced TBCs by laser-hybrid plasma spraying was suggested.

References

1) N. P. Padture. M. Gell, and E. H. Jordan, “Thermal Barrier Coatings for Gas-Turbine Engine Applications”, Science, 296 (2002) 280.

2) G. W. Meetham, “Coating Requirement in Gas Turbine Engines”, Journal of Vacuum Science and Technology A, 3 (6) (1985) 2509.

3) O. Unal, T. E. Mitchell, and A. H. Heuer, “Microstructures of Y_2O_3-stabilized ZrO_2 Electron Beam-Physical Vapor Deposition Coatings on Ni-Base Superalloys”, Journal of the American Ceramic Society, 77 (4) (1994) 984.

4) S. Gu, T. J. Lu, D. D. Hass, and H. N. G. Wadley, “Thermal Conductivity of Zirconia Coatings with Zig-Zag Pore Microstructures”, Acta Materialia, 49 (2001) 2539.

5) H. L. Tsai and P. C. Tsai, “Performance of Laser-glazed Plasma-Sprayed ZrO_2-12wt.%Y_2O_3)/(Ni-22wt.%Cr-10wt.%Al-1wt.%Y) Thermal Barrier Coatings in Cyclic Oxidation Tests”, Surface and Coatings Technology, 71 (1995) 53.

6) I. Zaplatynsky, “Performance of Laser-glazed Zirconia Thermal Barrier Coatings in Cyclic Oxidation and Corrosion Burner Rig Tests”, Thin Solid Films, 95 (1982) 275.

7) Z. Zhou, N. Eguchi, H. Shirasawa, and A. Ohmori, “Microstructures and Characterization of Zirconia-Yttria Coatings Formed in Laser and Hybrid Spray Process”, Journal of Thermal Spray Technology, 8 (3) (1999) 405.

8) C. Coddet, G. Montavon, S. Ayrault-Costil, O. Freneaux, F. Rigolet, G. Barbezat, F. Folio, A. Diard, and P. Wazen, “Surface Preparation and Thermal Spray in a Single Step: The PROTAL Process–Example of Application for an Aluminum-Base Substrate”, Journal of Thermal Spray Technology, 8(2) (1999) 235.

9) S. O. Chwa and A. Ohmori, “Microstructures of ZrO_2-8wt.%Y_2O_3 coatings prepared by plasma laser hybrid spraying technique”, Surface and Coatings Technology, 153 (2002) 302.

10) S. O. Chwa, A. Ohmori, “Observation of Microstructure in Thermal Barrier Coatings Prepared by Laser Hybrid Spraying Process Using Fluorescent Dye Infiltration Technique”, Proceedings of the International Thermal Spray Conference, E. Lugscheider Ed., ASM International, Materials Park, OH, 2002, pp253-259.

11) Y. Arata, A. Ohmori, and C. J. Li, “Basic Studies on Plasma Sprayed Ceramic Coatings-Erosion Mechanism at ACT-JP Process”, Transactions of Joining and Welding Research Institute, 15 (2) (1987) 339.