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The Investigation of the Plasma Sprayed Coatings for the Application of OG Cooling Tube in Steel Making Plant

HyungJun Kim and †YoungGak Kwon

Research Institute of Industrial Science and Technology
P.O. Box 135, Pohang, KOREA, 790-600

Several plasma-sprayed ceramic coatings with two- and three-layers were characterized and tested for the application of cooling tube coatings of oxygen convert gas recovery system (OG cooling system) in the steel making plant. Thermal cycling tests using a torch heating with compressed air cooling were carried out and characterized before and after the tests. The effects of metallic bond coat as well as ceramic top coat were also studied. Possible failure mechanisms with low carbon steel substrate were assessed in term of microstructure, porosity, bond strength, thermal expansion coefficient, and the phase transformation. Finally, the results of field tests at the OG cooling system are presented and discussed their microstructural degradation. Test results have shown that three-layered coatings perform better than two-layered coatings.

Keywords : *plasma spray, coatings, steel making plant, OG cooling system, high temperature corrosion and erosion*

1. Introduction

Ceramic materials often have better resistance to corrosion, oxidation, erosion, and wear than do metal. They often allow higher process temperatures and are also good thermal and electrical insulators. In view of these specific material properties, ceramic materials offer a number of potential advantages for industrial applications.[1)-3)]

Plasma sprayed ceramic thermal barrier coatings (TBCs) have been the subjects of considerable research efforts in the context of protecting components operating in high temperature environments, particularly for aerospace applications. Thermal barrier coatings based on yttria stabilized and magnesia stabilized zirconia have been extensively studied in view of their potential to offer such wide ranging benefits as lower substrate temperatures, less severe heating and cooling transients, reduced coolant requirements, and higher operating temperatures.[4)-8)] The overall TBC performance depends upon numerous factors, including coating system chemistry, microstructure and morphology of the coated layers that are governed by feedstock powder variables and spray parameters, and the operating environments.[1),4)]

With TBCs, the primary interest is in the thermal cycle response. The number of thermal cycles to coating failure is usually defined as the thermal cycling lifetime, and coating failure is inspected by the unaided eye or optical microscope. Because samples are generally free from an external load, the sample failure caused by initiation and propagation of cracks is normally attributed to thermal mismatch between coating and substrate, residual stresses that develop during the application of the coating, and/or phase changes due to oxidation of the metallic components.

The investigation was conducted for the evaluation of the cooling tube coatings at the steel making factory. This paper reports on the results of the preliminary thermal shock tests in the laboratory and the field tests at the oxygen convert gas recovery system.

2. Experimental

All of the coatings were applied by plasma spraying in air using a Metco 7MB and a Sulzer F4 guns. The substrate was low carbon steel with a thickness of 5 mm. The plate samples (50 mm X 100 mm X 5 mm) were used for thermal shock tests. The coatings were deposited on one of the plate surfaces. Three samples per coating system were heated to approximately 900°C (heating time 5 min.) by a LPG-oxygen flame and cooled to approxi-

†Corresponding author: ygkweon@rist.re.kr

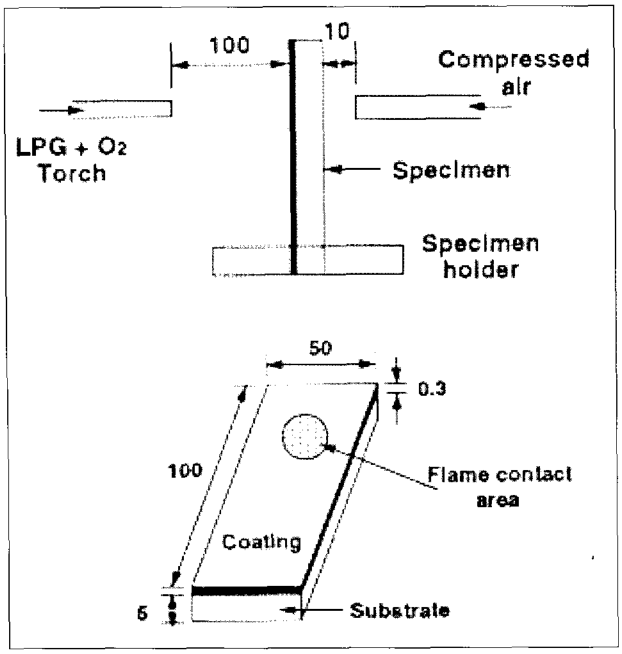


Fig. 1. Schematic representation of the specimen and the thermal cycling test configuration (unit=mm).

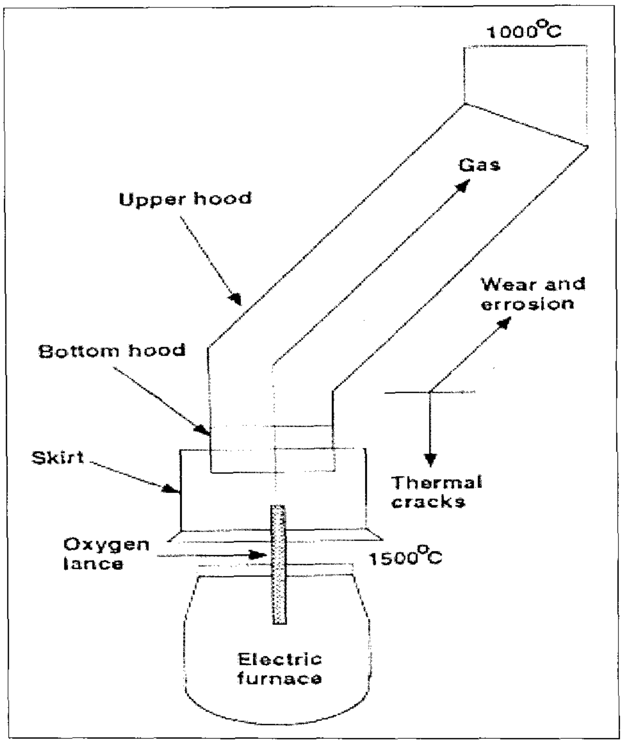


Fig. 2. Schematic representation of the oxygen convert gas recovery system.

mately 50°C (cooling time 5 min.) by rear compressed air cooling. Schematic representation of the thermal shock testing is shown in Fig. 1. Specimens were tested in the as-sprayed condition.

Field tests at the steel making factory were also conducted for the evaluation of optimum coating for the oxygen convert gas recovery system. Schematic representation of the oxygen convert gas recovery system is shown in Fig. 2. The skirt and hood are composed of water-cooled tube and the tube material is low carbon steel (KS STB35E) with a thickness of 5 mm. Primary deteriorating mechanism of the cooling tube is wear and erosion in upper hood area, while on the other hand primary deteriorating mechanism is thermal crack in bottom hood and skirt areas. Coating specimens at the bottom hood were tested for approximately 2 months for field evaluation.

Porosity (% area) measurements were made using a computer-based image analysis system (Luzex 500) by analyzing 20 fields at a magnification of 500x on each sample. Bond strength of each coating system was measured using a Sebastian IV coating adherence tester.

Details of the bond strength testing can be found in Reference 9. X-ray diffraction, optical microscopy, and scanning electron microscopy (JEOL JXA-8600) equipped with wavelength-dispersive X-ray analysis (WDS) and energy-dispersive X-ray analysis (EDS) were used to characterize the powder, as-sprayed coatings, and thermal cycled and field tested coating specimens.

3. Results and discussion

The characteristics of as-sprayed bond, intermediate, and top coatings are summarized in Tables 1 and 2, respectively. All of the coatings were sprayed using a Sulzer F4 gun except that Ni20Cr coatings (Code B) were sprayed using a Metco 7MB gun.

Table 1. The characteristics of as-sprayed bond coatings.

Code	Chemical composition (wt %)	Thickness (μm)	Porosity (%)	Hardness (HV)	Bond strength (kg/cm^2)
A	Co32Ni21Cr8Al0.5Y	50	11.3	241 (228-255)	477
B	Ni20Cr	100	13.5	190 (154-205)	384

Table 2. The characteristics of as-sprayed intermediate and top coatings.

Code	Chemical composition (wt %)	Thickness (μm)	Porosity (%)	Hardness (HV)	Bond strength (kg/cm^2)
A1	Al_2O_3-30MgO	170	5.8	616 (440-757)	422
A2	Al_2O_3-3TiO_2	190	7.1	728 (670-795)	410
A3	Al_2O_3-30(Ni20Al) Al_2O_3-3TiO_2	100 150	9.7 8.4	416 (366-511) 699 (675-740)	437
A4	$MgZrO_3$-35NiCr Al_2O_3-30MgO	120 120	12.1 9.1	316 (284-359) 443 (402-491)	240
A5	ZrO_2-15MgO-26Ni7Cr2Al Al_2O_3-30MgO	100 120	17.8 7.8	246 (212-270) 427 (348-485)	155
B1	Al_2O_3-30MgO	175	8.9	564 (477-606)	232
B2	Al_2O_3-3TiO_2	200	11.3	816 (719-952)	421
B3	Al_2O_3-30(Ni20Al) Al_2O_3-3TiO_2	110 125	8.4 6.4	382 (334-441) 704 (614-770)	344
B4	$MgZrO_3$-35NiCr Al_2O_3-30MgO	125 110	10.8 6.9	298 (255-343) 520 (481-557)	229
B5	ZrO_2-15MgO-26Ni7Cr2Al Al_2O_3-30MgO	100 90	15.9 10.4	276 (223-307) 686 (640-738)	186

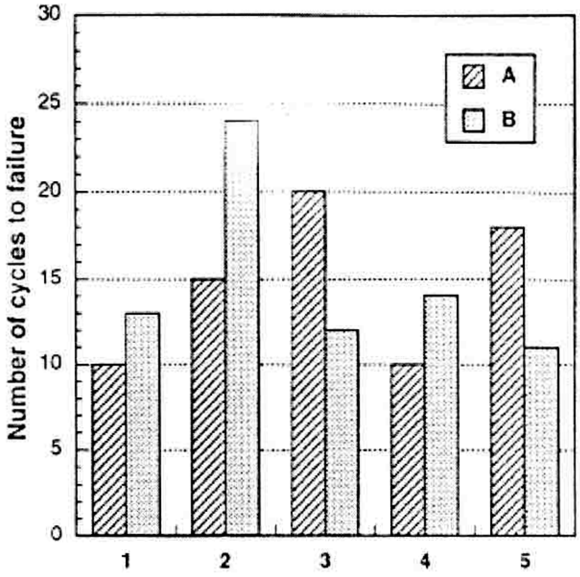


Fig. 3. The results of the thermal shock tests.

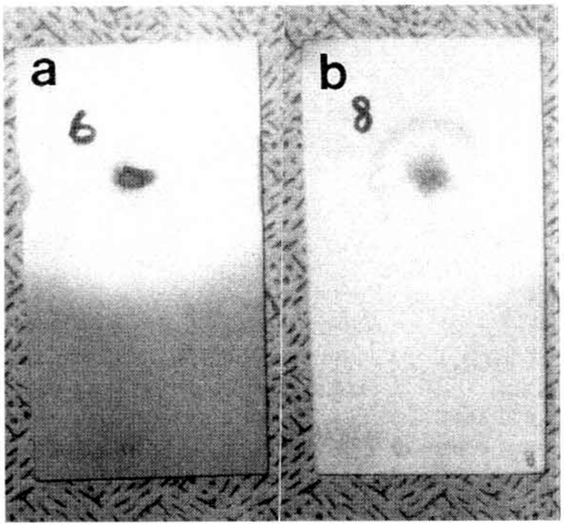
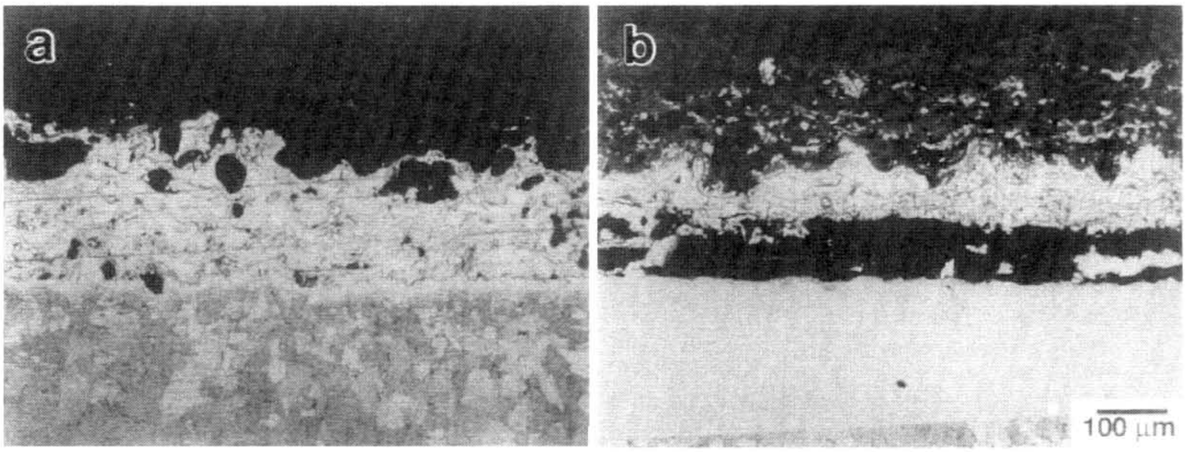


Fig. 4. Macrographs of the failed specimen surface after thermal shock tests.

3.1 Thermal shock tests

The results of thermal shock testing using a torch are shown in Fig. 3 and the examples of failed specimen surface are shown in Fig. 4. It is difficult to say that which bond coating system performs better in our experimental setup. That is, the effects of bond coating are negligible. Fig. 3 shows that B2 coating which has a top coating of Al_2O_3-TiO_2 and highest hardness performs best. It seems that the effects of intermediate coating on the thermal shock resistance are negligible. Fig. 3 also shows that A3 coating among coatings with Co-based bond coating performs best. This is attributed to higher hardness and



(a) B1 (b) B4

Fig. 5. Cross sectional optical micrographs of the failed specimen after thermal shock tests.

thickness of the intermediate and top coatings.

Cross sectional optical micrographs of failed coating specimens are shown in Fig. 5. Examination of the cross sections of the failed specimens exhibits that all of the bond coatings are almost intact although some of the substrate show phase transformation and/or some of the bond coatings show partial melting with substrate. Thus, the failure from the thermal shock testing with a torch flame means a failure of the top coating. This is typically illustrated in Fig. 5(b) showing that the intermediate coating is still intact and most of the top coatings are gone.

The phases and the average thermal expansion coefficients of the as-sprayed coatings are summarized in Table 3. It is evident that the performance of the thermal shock resistance is not directly related to the thermal expansion behavior as shown in Fig. 3 and Table 3. It seems that erosion resistance of the coatings due to high velocity torch flame and compressed cooling air in addition to the nature of coating-substrate bond and the residual stresses is more crucible factor than the thermal expansion mismatch to the performance of the thermal shock testing using a torch flame.

Table 3. Summary of phases and thermal expansion coefficients of as-sprayed coatings.

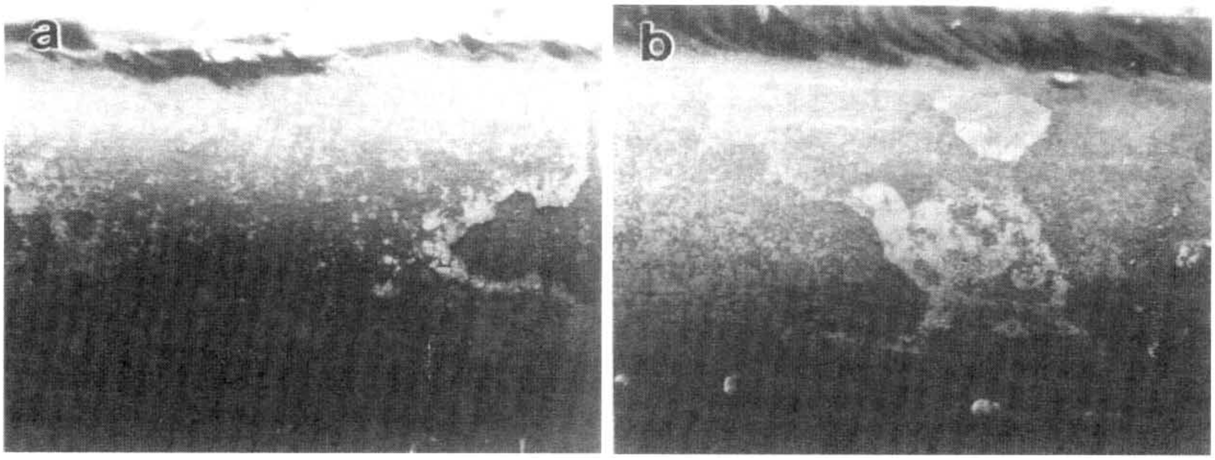
Coating	Phases	Average thermal expansion coeff., X 10^{-6} K^{-1} (Temp. range, ℃)
Al_2O_3-30MgO	$MgAl_2O_4$	9.4 (100-1200)
Al_2O_3-3TiO_2	γ-Al_2O_3, α-Al_2O_3	6.7 (100-1000)
Al_2O_3-30(Ni20Al)	Ni, γ-Al_2O_3, α-Al_2O_3	9.6 (100-1100)
$MgZrO_3$-35NiCr	Ni, c-ZrO_2	10.6 (100-1000)
ZrO_2-15MgO-26Ni7Cr2Al	Ni, c-ZrO_2	12.4 (100-1200)
Co32Ni21Cr8Al0.5Y	Co	12.3 (100-1200)
Ni20Cr	Ni	16.2 (100-1000)

3.2 Field tests

The results of field tests at the oxygen convert gas recovery system are summarized in Table 4 and examples of surface macrographs after field-testing are shown in Fig.

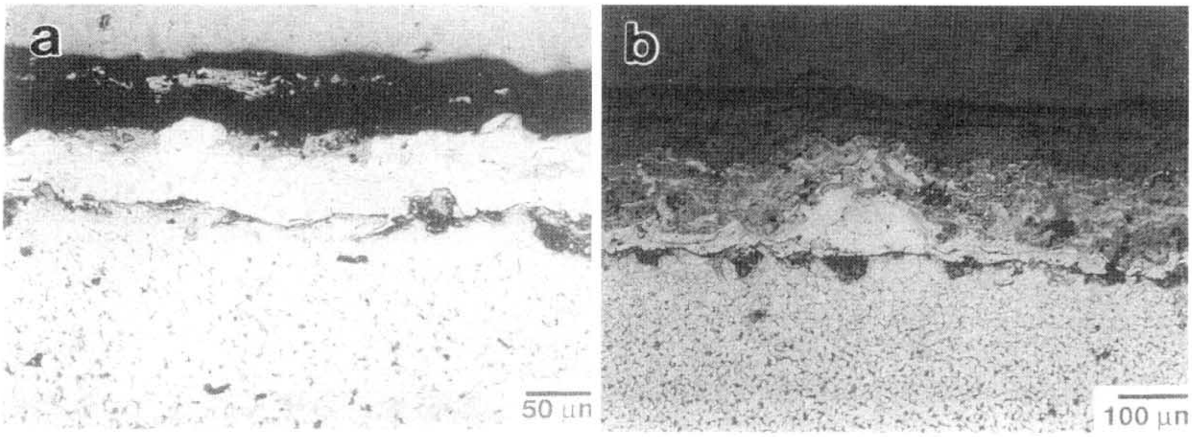
Table 4. Summary of field test results.

Code	Surface proportion that are intact	Cross sectional observation
A1	1/2	Bond coat good Top coat no
A2	2/3	Bond coat good Top coat good
A3	3/4	Bond coat good Intermediate coat good Top coat poor
A4	1/2	Bond coat good Intermediate coat good Top coat no
A5	9/10	Bond coat good Intermediate coat good Top coat poor
B1	1/3	Bond coat good Top coat good
B2	2/3	Bond coat good Top coat poor
B3	1	Bond coat good Intermediate coat good Top coat poor
B4	9/10	Bond coat good Intermediate coat good Top coat good
B5	2/3	Bond coat good Intermediate coat good Top coat good



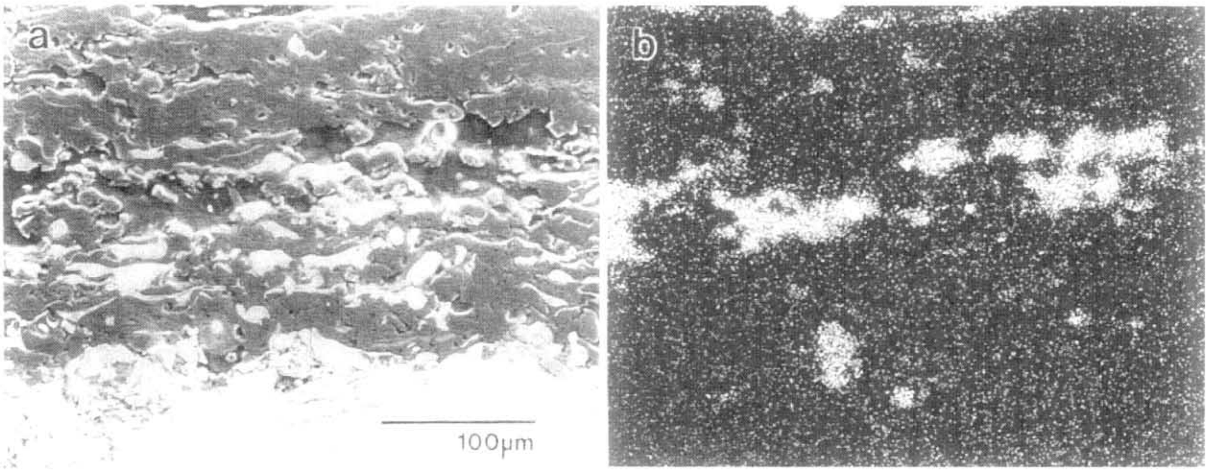
(a) A5 (b) B1

Fig. 6. Surface morphologies of field tested specimens.



(a) A1 (b) B4

Fig. 7. Cross sectional optical micrographs of field tested specimens.



(a) Scanning electron micrograph (b) Silicon X-ray mapping

Fig. 8. Cross sectional view of field tested A3 specimen.

6. Note that cross sectional observations were made at the best conditioned surface region. Cross sectional examination indicates that all of the bond coatings are almost intact after 2 month service. It seems that three-layered coatings perform better than two-layered coatings since all of the intermediate coatings are still in good condition. Code B coating systems perform better than code A coating systems possibly resulting from higher thickness of the bond coating.

Examples of cross sectional optical micrographs after field testing are shown in Fig. 7. Most of specimens show oxidation near the interface between the bond coating and the steel substrate. The steel substrate near the interface also shows decarburization due to oxidation. Substrate decarburization is more severe as shown in Fig. 7(b) when the top coating is gone or poor because thermal insulation effect is no longer available.

Fig. 8 shows a cross sectional scanning electron micrograph and a X-ray Si mapping after field testing. It is clearly seen that Si element is concentrated at the interface between the top coating and the intermediate coating although most of environmental gas are composed of Fe and Ca.

4. Conclusions

(1) It seems that the effects of bond and intermediate coatings on the thermal shock resistance using a torch flame are negligible.

(2) Erosion resistance of the coatings due to high velocity torch flame and compressed cooling air in addition to the nature of coating-substrate bond and the residual stresses is more crucible factor than the thermal expansion mismatch to the performance of the thermal shock testing using a torch flame.

(3) Three-layered coatings perform better than two-layered coatings since all of the intermediate coatings are still in good condition after field tests for 2 months.

(4) Performance of the top coating is a crucial factor at the oxygen convert gas recovery system. Optimization of the top coating with the bond and intermediate coats is necessary to extend the life of the coating system.

References

1. R. Taylor, J. R. Brandon, and P. Morrell, *Surf. Coat. Technol.*, **50**, 141 (1992).
2. G. Jiacheng and Z. Yaping, *Surf. Coat. Technol.*, **63**, 93 (1994).
3. Y. Shimizu, M. Sato, M. Kobayashi, and T. Ikeda, "Applicability of thermally sprayed zirconia coatings to casting mold dressings", *Proc. of the Third National Thermal Spray Conf.*, Long Beach, CA, USA, 20-25 May, 1990, p.521.
4. S. V. Joshi and M. P. Srivastara, *Surf. Eng.*, **11**, 233 (1995).
5. R. A. Miller and C. C. Berndt, *Thin Solid Films*, **119**, 195 (1984).
6. H.-D. Steffens and U. Fischer, *Surf. Coat. Technol.*, **32**, 327 (1987).
7. H. C. Chen, Z. Y. Liu, and Y. C. Chuang, *Thin Solid Films*, **223**, 56 (1992).
8. H. Wang and W. Montasser, *J. of Thermal Spray Technol.*, **2**, 31 (1993).
9. H. J. Kim, Y. G. Kweon, and R. W. Chang, *J. Thermal Spray Technol.*, **3**, 169 (1994).