J Mater Sci (2009) 44:6348–6355
DOI 10.1007/s10853-009-3875-z

The processing optimization and property evaluations of HVOF Co-base alloy T800 coating

J. Y. Cho · S. H. Zhang · T. Y. Cho · J. H. Yoon · Y. K. Joo · S. K. Hur

Received: 21 March 2009 / Accepted: 9 September 2009 / Published online: 23 September 2009

Abstract Co-base alloy Tribaloy-800 (T800) powders were coated on Inconel718 (IN718) by high velocity oxygen fuel thermal spraying. The optimal coating process (OCP) was obtained via studying the surface properties of 16 coatings prepared by Taguchi program. Surface hardness and porosity were 560–630 Hv and 1.0–2.7%, respectively, strongly depending on spraying processes. The OCP of hardness was oxygen flow rate (FR) 38 FMR, hydrogen FR 75 FMR, and feed rate 30 g/min at spray distance 5 inch. The adhesion strength of T800 coating with substrate had a slight increase and the thermal shock resistance of T800 coating was improved greatly by introduction of bonding layer Ni–Cr. Friction and wear behaviors have been investigated by a reciprocating sliding test at both 25 °C and an elevated temperature 538 °C (1,000 °F). Both friction coefficients (FC) and wear traces of the coating were smaller than those of IN718 substrate at both 25 and 538 °C. FC and wear traces of IN718 and coating decreased with increasing the surface temperature due to the lubricant effect of cobalt oxides formed on the sliding surface. As a result, T800 coating was highly recommended as a durability improvement coating for the protection of sliding surface, such as high speed spindle.

Introduction

Electrolytic hard chrome plating (EHC) has been widely used on the machine components for the durability improvement and repair of worn parts over last 60 years. The possibility of replacing of EHC has been studied since the hexa valence chrome ion (Cr^{6+}) in electrolytic bath and mist is known as carcinogen of lung cancer and its solution pollutes severely environment. The most promising candidate for the replacement of the plating is high velocity oxy-fuel (HVOF) thermal spray coating because of the clean and pollution free coating [1, 2]. The supersonic gas velocity and limited flame temperature (compared to other thermal spray techniques, like plasma-spraying) result in dense coatings with a limited oxide content [3]. Specifically, many recent articles have focused on HVOF-sprayed cermets, which have already been proven to possess excellent tribological properties as well as good corrosion resistance, if a suitable carbide and metal matrix are chosen [4–6]. Other studies deal with HVOF-sprayed metal alloy coatings, which, despite being less wear resistant than cermets, can be very useful in industrial applications, thanks to their higher deposition efficiency, far lower machining (grinding/polishing) costs, and (usually) lower powder cost [7–9]. They may also possess certain peculiar properties, such as great hardness at high temperatures and oxidation resistance. To date, fewer studies have examined other HVOF-sprayed alloys, such as Tribaloys or Ni–Cr–Mo–W–B alloys. Tribaloys, with composition M–Mo–Cr–Si (M = Co, Ni), possess high wear, corrosion, and oxidation resistance: they are mainly employed as coatings, since they are too brittle to be used in bulk form [10–12].

Thus, investigation on the wear resistance of HVOF-sprayed Tribaloy-based coatings is of technological interest, especially at high temperature environment. Moreover, in literature, much more knowledge exists on the characteristics of welded or laser-clad Tribaloys than thermally sprayed ones, and HVOF-sprayed in particular [13–15].

J. Y. Cho · S. H. Zhang (✉) · T. Y. Cho ·
J. H. Yoon · Y. K. Joo · S. K. Hur
School of Nano Advanced Materials Engineering, Changwon National University, Changwon 641-773, South Korea
e-mail: zsh10110903@hotmail.com

The microstructure of HVOF-sprayed Tribaloy coatings is significantly different from that of clad or welded ones, due to the peculiarities of HVOF-spraying. Welded Tribaloys display a fully crystalline microstructure resulting from melt solidification. In the case of hyper-eutectic compositions, like Tribaloy-800 (T800: Co–28 wt%Mo–17 wt%Cr–3 wt%Si), primary Laves-phase dendrites are formed in an eutectic matrix comprising fine Laves-phase and Co- or Ni-based solid solution lamellar crystals [16, 17]. In HVOF-sprayed Tribaloy coatings, first of all, the high velocity impact of heated particles generates a layered lamellar microstructure, like every thermally sprayed material. Besides, the cooling rate of each heated particle upon impact is extremely high (>10^5 K/s), causing splat quenching: this results in very fine submicrometric crystals, metastable supersaturated solid solutions, and even amorphous phases within each splat. Therefore, knowledge acquired for welded or clad Tribaloys cannot be directly transferred to HVOF sprayed coatings, which require specific research. Air bearing spindles are operated without any liquid or solid lubricants for clean fabrication of high precision and quality products. The expensive high precision spindles and machine components are damaged by friction and wear at high temperature, especially by sticking friction during starting and stopping the spindle operation [18, 19]. Besides on wear resistance of HVOF coatings, an important property of HVOF coatings for high-temperature application is the thermal shock resistance. But at present most investigations on the properties of HVOF coatings concern surface properties, corrosion, and wear resistances. In order to increase the use of HVOF T800 coatings, it is essential to improve the tensile bond strength (TBS) and thermal shock resistance as well as high-temperature creep resistance.

This research therefore first aims to characterize and optimize the surface properties such as roughness, porosity, and hardness; and process of HVOF T800 coating; and then to improve the adhesion strength and thermal shock resistance of the coating by introduction of bonding layers such as Ni–Cr and Ni. In addition, temperature dependence on friction and wear behavior of both Inconel718 and HVOF T800 coating are investigated both at room temperature and at an elevated temperature 1000 °F (538 °C) for the life time improvement of air bearing spindles and machine components by HVOF T800 coating.

Experimental details

The preparation of coatings

The major elements of commercially available T800 powders were prepared by Satellite Company. Powders are spherical shapes with diameters of 5–30 μm and mixed homogeneously as shown in Fig. 4. For the improvement of adhesion of HVOF T800 coatings on substrates, the surfaces of Inconel718 substrates were pre-cleaned by ultrasonic cleaning in acetone for 5 min and then blast cleaned by 60 mesh alumina particles. Table 1 listed the chemical elements of T800 powder and substrate IN718 composition. T800 powders were coated on Inconel718 substrates by JK 3500 HVOF thermal spraying equipment by 16 coating processes designed by Taguchi program for four spray parameters, such as hydrogen flow rate, oxygen flow rate, powder feed rate by carrier Argon gas, and spray distance, as listed in Table 2.

Characterization of T800 powders and coating surfaces

Chemical compositions and micro-shapes of T800 powders were investigated by SEM, EDS, and optical microscope. Surface hardness was the average value of nine measurements at the center of cross-section of coating layer measured by Micro Vickers Hardness tester with a load of 300 g. Surface roughness was the average of seven measurements by surface roughness tester. Porosity was the average of five data obtained by analyzing the images photographed by optical microscope. The coatings for adhesion, thermal shock tests, and wear tests were prepared by the optimal process of hardness.

Adhesion and thermal shock tests

For TBS, and bond coatings (BC) NiCr (80% Ni, 114 ± 5 μm) and top coat T800 (260 ± 20 μm) were HVOF coated on substrate Ti-6Al-4V (Ti-64) (sub). Sub and coating were bonded to loading fixture by adhesive bonding agent FM1000 epoxy (minimum bond strength of 10,000 psi). TBS was measured by Tensile machine FM-10E, and was analyzed in accordance with ASTM C633 and Process Instruction of Sermatech Korea Ltd.

The thermal shock test was performed by water quenching method. Three pieces of the T800 coating

Table 1 Chemical elements of T800 powder and substrate IN718 composition, wt%

Element	Co	Mo	Cr	Si	Fe	Ni	Al	Nb	Ti
IN718	1.0	2.8–3.3	17–21	–	11.2–12.5	50–55	0.2–0.8	4.8–5.5	0.6–1.2
T800	Bal	28.37	17.55	3.100	0.680	0.650			

Table 2 Process parameters of HVOF T800 coatings by Taguchi method

No.	Oxygen (FMR)	Hydrogen (FMR)	Gas ratio (O_2/H_2)	Distance (inch)	Feed rate (g/min)
1	34	60	0.57	5	20
2	34	65	0.52	5	20
3	34	70	0.47	5	30
4	34	75	0.44	5	30
5	38	60	0.63	5	20
6	38	65	0.58	5	20
7	38	70	0.54	5	30
8	38	75	0.51	5	30
9	42	60	0.70	5	30
10	42	65	0.66	5	30
11	42	70	0.60	5	20
12	42	75	0.56	5	20
13	46	60	0.77	5	30
14	46	65	0.71	5	30
15	46	70	0.66	5	20
16	46	75	0.61	5	20

samples were put in one zirconia crucible before thermal shock testing each time. The samples were heated in box furnace in air for 30 min at 1100 °C, respectively, and then quenched into ambient water with 25 °C for 10 min.

Reciprocating slide test

Friction and wear behaviors of T800 coatings were investigated by reciprocating slide tester (TE77 AUTO, Plint & Partners) with SUS 304 counter sliding ball (hardness 227 Hv and diameter 9.525 mm) without any lubricants at room temperature and an elevated temperature of 538 °C. The reciprocating width (a sliding distance), reciprocating frequency, speed, load, and test time were 2.3 mm, 35 Hz, 0.161 m/s, 10 N, and 4 min, respectively. Friction coefficients, weight loss, and wear traces by sliding wear of non-coated Inconel718 surface and coatings with various hardness were investigated both at 25 and 538 °C.

Results and discussion

Process optimization and microstructure of the coatings

Coating properties strongly depend on the coating process. The optimal coating process is the process that prepares the coating with best property. Hardness of 560–640 Hv is obtained by the processes of this experiment. Before optimization, the highest hardness 640 Hv is obtained by the process of oxygen flow rate 38 FMR, hydrogen flow rate 75 FMR, powder feed rate 30 g/min, and spray distance 5 inch as shown in Table 2 and Fig. 1. The least porosity of about 0.1% and roughness of 2.2–2.6 μm are obtained by the processes shown in Table 3 and Figs. 2 and 3.

In Fig. 4, XRD patterns indicate that, while spray powders display sharp diffraction peaks, the as-sprayed coatings possess broad diffraction peaks and exhibit an amorphous hump at $40° < 2\theta < 50°$. Several crystalline phases are identifiable. Particularly, the T800 coating contains Co_7Mo_6, Co_3Mo_2Si, $CoSi_2$, and a Co–Mo–Cr solid solution with *fcc* lattice.

In this HVOF thermal spray coating the maximum flame temperature and particle velocity are up to 3,500 °C and 1,000 m/s, respectively [20–22]. And the particle flight time of 0.1–1 ms is estimated from the spray distance [23–25]. The distribution of flight particles temperature, velocity, and time are very widely dependent on the particle positions and flight time in flame. According to phase diagram and dictionary of metal engineering [26–28], the

Table 3 Optimal coating processes at spray distance of 5 inch

Properties	O_2 flow rate (FMR)	H_2 flow rate (FMR)	Feed rate (g/min)
Hardness (738 Hv)	38	75	30
Porosity (0.08%)	46	60	30
Roughness (2.0 μm)	42	60	20

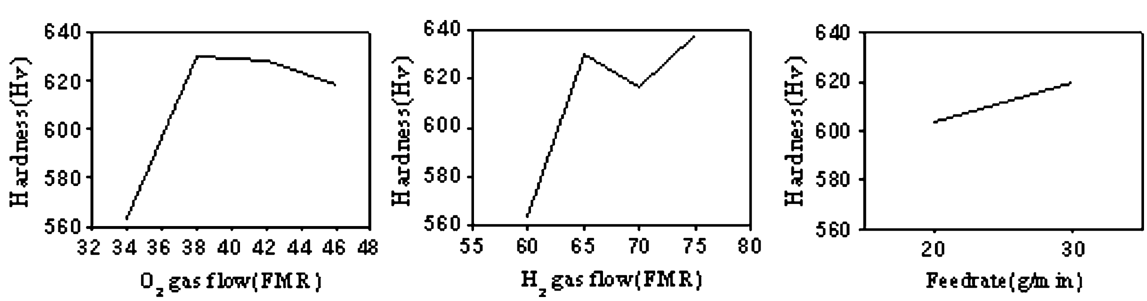

Fig. 1 Hardness of coating versus spray parameters

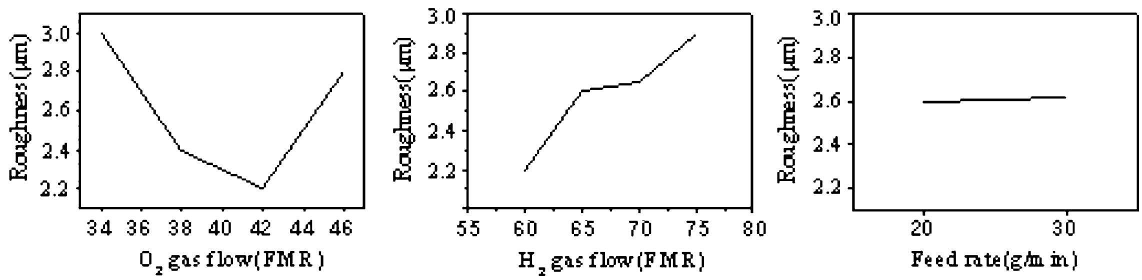

Fig. 2 Roughness of coating versus spray parameters

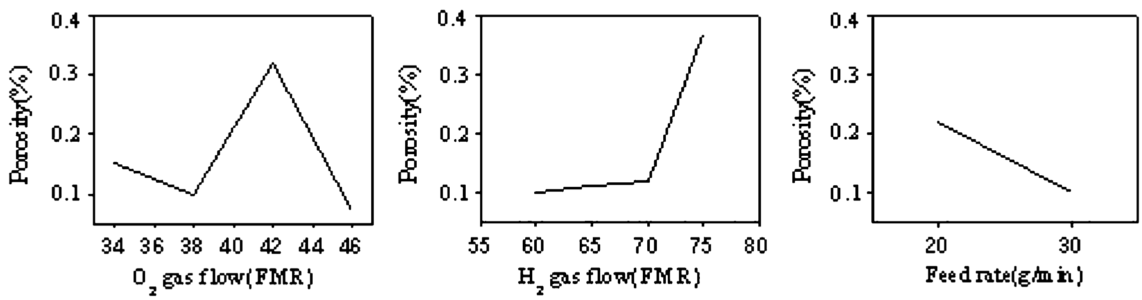

Fig. 3 Porosity of coating versus spray parameters

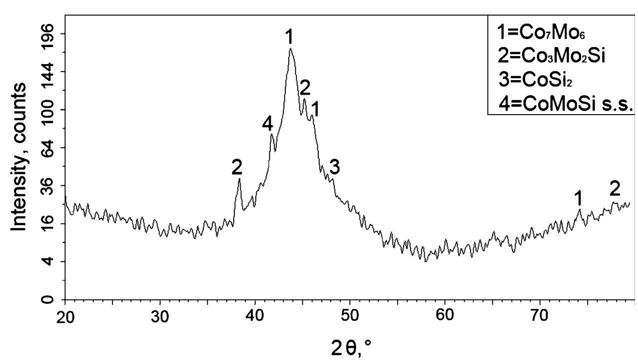

Fig. 4 XRD pattern of T800 with optimal process of hardness, the peak characters same to the coatings before optimized

melting points of pure Co, Mo, Cr, and ε-Co phase of both Co–Mo and Co–Cr systems are in the range of 1,495–2,623 °C, much lower than the highest temperature of spraying flame of 3,500 °C. Therefore, T800 particles with various sizes experience various temperature and velocity in the flame, and they are molten, partially molten, or soften during the short flight time, and impact on the cool coating surface with high velocity. Upon impact, strong adhesion forms with the surface, with subsequent splats causing thickness buildup and forming a lamella structure as shown in Fig. 5b. The splats undergo quenching at a very high cooling rate in excess of 10^6 K/s [20–22]. In this experiment the splats form coating of 300–350 μm thickness with good adhesion on substrate as shown in Fig. 5c.

Evaluation on the TBS and thermal shock of the coatings

As shown in Fig. 6, the TBSs of Ni–Cr/sub, T800/sub, and T800/Ni–Cr/sub are 11576 ± 300 (79.8 ± 2.1 MPa), 8738 ± 200, 8768 ± 200, and 7500 ± 200 psi, respectively. As shown in Fig. 7, the fracture location of Ni–Cr/sub is between interface and Ni–Cr coating; the fracture location of T800/sub is at interface, and the fracture location of T800/Ni–Cr/sub is at interfaces with the top coatings of T800 and Ni–Cr. The adhesion of Ni–Cr/sub is much stronger (about 30%) than the adhesion of T800/sub and T800/Ni–Cr/sub. This result indicates that adhesion is much stronger between metal/similar metal (NiCr/Ti-64) than between metal/cermet (T800/Ni–Cr or Ti-64) because of the easy diffusion between similar metal atoms. In addition, the adhesion strength of T800 coating with substrate has a slight increase by introduction of bonding layer Ni–Cr.

Figures 8 and 9 show that cross-sections and surfaces of T800/Ni–Cr/Sub, T800/Ni/Sub, and T800/Sub coatings present severe micro-cracks after thermal shock at $T =$ 600 °C. Such severe micro-cracks indicate that thermal shock resistance of T800/Ni/Sub and T800/Sub is unsatisfactory compared with T800/Ni–Cr/Sub. The result is due to the difference in thermo-conductivity for three sets of the coatings that the sequence of thermo-conductivity of T800/Ni–Cr/Sub, T800/Ni/Sub, and T800/Sub coatings is, respectively, T800 > Ni–Cr > Ni > Ti-64. Therefore, the

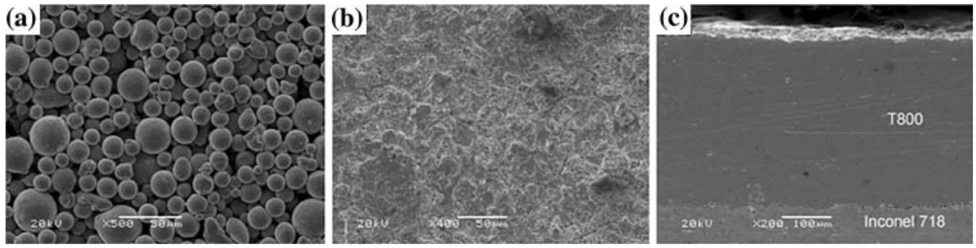

Fig. 5 SEM micrographs of T800 coating: **a** T800 powder, **b** surfaces, and **c** cross-section

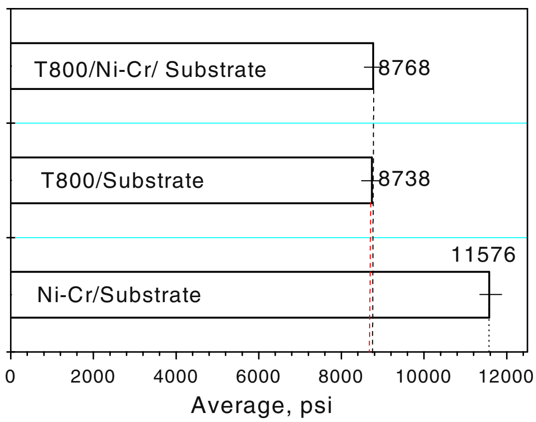

Fig. 6 Tensile bond strength of the coatings

thermal shock resistance of T800 coating has an evident increase by introduction of bonding layer Ni–Cr.

Improvement of friction property by HVOF T800 coating

As shown in Fig. 10, friction coefficient of T800 coating with optimal hardness is smaller than about a half of non-coated Inconel718 surface both at 25 and 538 °C. This shows that T800 coating is highly recommendable for the life-time improvement of sliding machine components, such as air bearing spindles operating without any lubricants. Friction coefficients of coatings at a higher temperature 538 °C are lower than those at lower temperature 25 °C. This shows that T800 coating is highly recommendable for the coating on the sliding machine components vulnerable to frictional heat, such as high speed spindles.

At high temperature of sliding test, oxides such as CoO, Co_3O_4, MoO_2, and MoO_3 are actively formed on the sliding surface heavily at the asperities by oxidation of reactive metallic Co-alloy of T800 due to the excess oxygen reagent in flame and oxygen from atmospheric environment [25, 26]. The brittle oxides are easily attrited as debris by the sliding through oxidation wear and abrasion [20, 21, 23–26]. Wear debris such as small solid particles, softens, melts, and partial-melts have play roles as solid and liquid lubricants, and the role is higher at higher surface temperature.

The sliding weight loss of T800 coating is more than 10 times smaller than that of non-coated Inconel718 surface as shown in Fig. 10. This also shows that T800 coating is highly recommendable for wear resistant coating on the surface of sliding machine components. This shows that the major wear mechanism is not only adhesive wear, but other

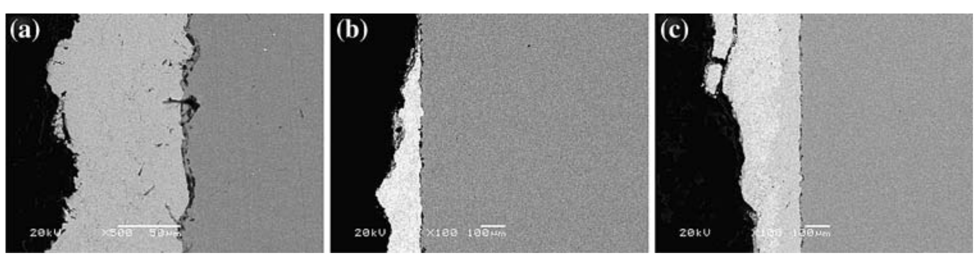

Fig. 7 Fracture location of the coatings: **a** Ni–Cr/Sub, **b** T800/Sub, and **c** T800/Ni–Cr/Sub

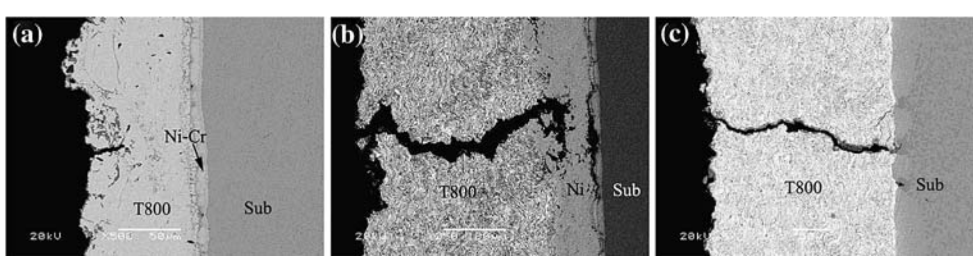

Fig. 8 Cross-section of the coatings after thermal shock tests: **a** T800/Ni–Cr/Sub, **b** T800/Ni/Sub, and **c** T800/Sub

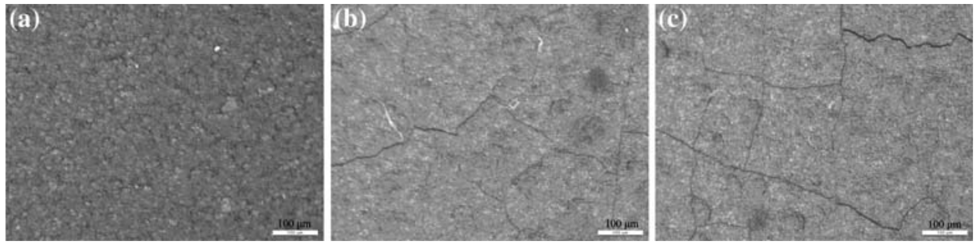

Fig. 9 Surface morphologies of the coatings after thermal shock tests: **a** T800/Ni–Cr/Sub, **b** T800/Ni/Sub, and **c** T800/Sub

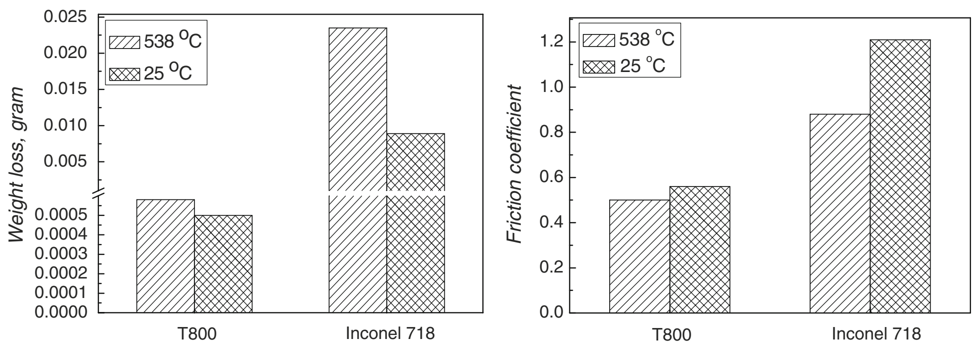

Fig. 10 Weight loss and friction coefficients of T800 coating and substrate IN718

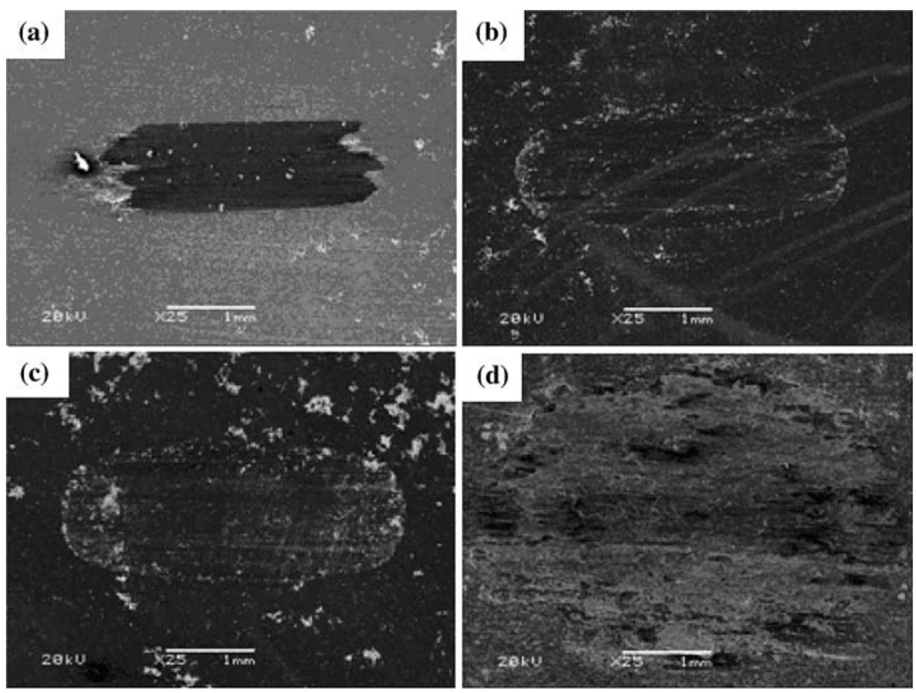

Fig. 11 Wear traces of the coating and IN718 at room temperature: **a** T800, **b** IN718 and at 538 °C **c** T800 and **d** IN718

mechanisms such as oxidation wear and abrasive wear influenced by the attrited solid and liquid oxide lubricants.

As observed in Fig. 11, the wear traces at a higher temperature 538 °C is much smaller than those at lower temperature 25 °C both for the coatings and counter sliding SUS 304 ball surfaces, due to lubricant effect of attrited oxide debris. This also shows that T800 coating is highly recommendable for durability improvement coating on the sliding machine component surface vulnerable to frictional heat and wear.

Figure 12 shows the wear traces on counter sliding SUS 304 ball both at room and at 538 °C. The wear trace on the ball slides on T800 coating is smaller than those slide on non-coated Inconel718 surfaces, and the traces of melt by sliding on coating is larger than those by sliding on non-coated surfaces. These show that T800 coating plays a role

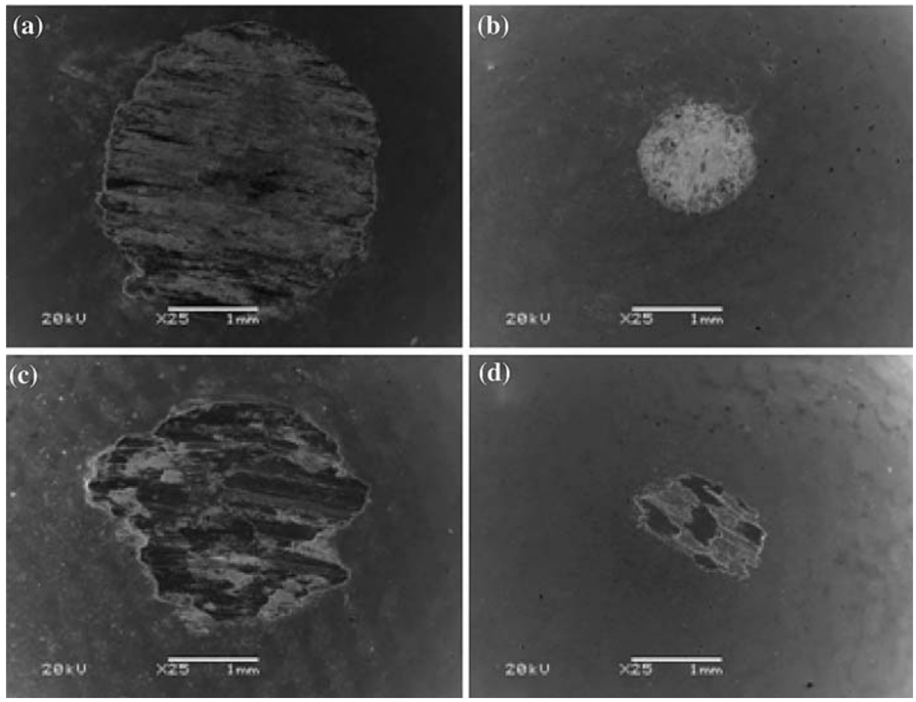

Fig. 12 Wear traces on counter sliding SUS 304 ball sliding on IN718 at 25 °C (**a**) and at 538 °C (**b**), T800 coating with optimal hardness at 25 °C (**c**) and at 538 °C (**d**)

as lubricants and are essential as a durability improvement coating. The traces on the balls by the sliding on both coated and non-coated surface are drastically reduced at high temperature compared with those at room temperature. This shows the lubricant role of the oxides is increased as the sliding temperature increases.

Conclusions

The followings are concluded in this study:

(1) The OCP is oxygen FR 36–42 FMR, hydrogen FR 70 FMR, and feed rate 30 g/min at spray distance 5 inch. Surface hardness and porosity are 560–630 Hv and 1.0–2.7%, respectively, strongly depending on spraying processes. The adhesion strength of T800 coating with substrate has a slight increase and the thermal shock resistance of T800 coating was improved greatly by introduction of bonding layer Ni–Cr.

(2) The T800 coating contains Co_7Mo_6, Co_3Mo_2Si, $CoSi_2$, and a Co–Mo–Cr solid solution with *fcc* lattice. Brittle oxides such as CoO, Co_3O_4, MoO_2, and MoO_3 are actively formed on the sliding surface heavily at the asperities of T800 coating. They are easily attrited and play role as solid and liquid lubricants. This role is more active at higher temperature.

(3) At the sliding wear test, weight loss, wear traces, and friction coefficients of T800 coating are much smaller at higher temperature 538 °C compared with those at lower room temperature. Therefore, T800 coating is highly recommendable for the durability improvement coating on the surface of machine components vulnerable to frictional heat and wear such as air bearing spindles.

Acknowledgement This research is financially supported by Changwon National University in 2007.

References

1. Zhang S-H, Cho T-Y, Yoon J-H, Li M-X, Shum PW, Kwon S-C (2009) Mater Sci Eng B 162:127
2. Kim KS, Baek NK, Yoon JH, Cho TY, Youn SJ, Oh SK, Hwang SY, Chun HG (2006) J Kor Inst Surf Eng 39–4:179
3. Zhang S-H, Cho T-Y, Yoon J-H, Fang W, Song K-O, Li M-X, Joo Y-K, Lee CG (2008) Mater Charact 59:1412
4. Sayman O, Sen F, Celik E, Arman Y (2009) Mater Des 30:770
5. Matthews S, James B, Hyland M (2009) Surf Coat Technol 203:1144
6. Mahesh RA, Jayaganthan R, Prakash S (2009) J Alloys Compd 468:392
7. Ni HS, Liu XH, Chang XC, Hou WL, Liu W, Wang JQ (2009) J Alloys Compd 467:163
8. Souza RC, Voorwald HJC, Cioffi MOH (2008) Surf Coat Technol 203:191
9. Cho TY, Yoon JH, Kim KS, Song KO, Joo YK, Fang W, Zhang SH, Youn SJ, Chun HG, Hwang SY (2008) Surf Coat Technol 202:5556
10. Bolelli G, Cannillo V, Lusvarghi L, Montorsi M, Mantini FP, Barletta M (2007) Wear 263:1397
11. Bolelli G, Lusvarghi L, Giovanardi R (2008) Surf Coat Technol 202:4793
12. Kim H-J, Yoon B-H, Lee C-H (2003) Wear 254:408

13. Navas C, Cadenas M, Cuetos JM, de Damborenea J (2006) Wear 260:838
14. Sahraoui T, Feraoun HI, Fenineche N, Montavon G, Aourag H, Coddet C (2004) Mater Lett 58:2433
15. Zhang Y, Yang Z (2007) J Iron Steel Res Int 14:30
16. Yao MX, Wu JBC, Liu R (2005) Mater Sci Eng A 407:299
17. Przybylowicz J, Kusinski J (2000) Surf Coat Technol 125:13
18. Ishikawa Y, Kuroda S, Kawakita J, Sakamoto Y, Takaya M (2007) Surf Coat Technol 201:4718
19. Khameneh Asl Sh, Heydarzadeh Sohi M, Hokamotoa K, Uemurad M (2006) Wear 260:1203
20. Davis JR (2004) Handbook of thermal spray technology. ASM Thermal Spray Society, USA, pp 1–10
21. Sartwell BD et al (2004) Validation of HVOF WC/Co thermal spray coatings as a replacement for hard chrome plating on aircraft landing gear. Naval Research Laboratory Report Number NRL/MR/6170-04-8762, pp 1–15
22. Sartwell BD, Legg K, Bodger B (1999) HVOF thermal spray coatings as an alternative to hard chrome plating on military and commercial aircraft, AESF/EPA. Conference for environmental excellence, 231, USA, pp 1–150
23. Cho TY, Yoon JH, Kim KS, Baek NK, Hwang SY, Youn SJ, Chun HG (2006) HVOF coating for the improvement of the performance and durability of military hardware components. In: 15th aero technology symposium. Logistics Command ROKAF
24. Li M, Christofides PD (2006) Chem Eng Sci 61:6540
25. Cho TY, Yoon JH, Kim KS, Park BK, Youn SJ, Baek NK, Chun HG (2006) J Kor Cryst Growth Cryst Technol 16(3):121
26. Cho TY, Yoon JH, Kim KS, Baek NK, Song KO, Youn SJ, Hwang SY, Chun HG (2006) J Kor Inst Surf Eng 39–6:295
27. Massalski TG et al (1986) Am Soc Metals 1:600
28. Kim NJ (2003) Dictionary of metal engineering, Junyong, p 2031