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Comparison of HVOF Thermal Spray Coatings of T800 and WC-Co Powders

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Abstract

Hard chrome plating has been used in surface hard coating over 50 years both for applying hard coating and re-building of worn components. Hard chrome plating solution and mist pollute environment with very toxic Cr^{6+}(hex-Cr) known as carcinogen which causes lung cancer. High velocity oxy-fuel (HVOF) thermal spray coatings of WC base cermet and Co-alloy powders are the most promising candidates for the replacement of the traditional hard chrome plating. Surface properties, wear, and friction behaviors of micron size Co-alloy (T800) and micron size WC-12Co (WC-Co) have been studied for the application as hard coatings. The temperature dependence of wear and friction behaviors of T800 and WC-Co have been investigated at the temperature of 25°C and 538°C for the application to high speed spindle.

Keywords: HVOF, WC-Co, T800, Thermal spray coating, Oxidation and abrasive wear assisted by oxide lubrication, Adhesion

1. Introduction

Electrolytic hard chrome (EHC), nickel (EHN), and ceramic coatings have been widely used in surface hard coatings over 50 years both for hard coating and re-building of worn components[1)]. Electrolytic solution and mist pollute the environment severely. In the widely used EHC plating, bath contains Cr^{6+} ion (hex-Cr) and emits hex-Cr mist into the air. Hex-Cr is known as carcinogen which causes lung cancer. HVOF thermal spray coatings are the leading candidate for replacement of EHC plating[1-3)]. Commercially available HVOF equipments can be used to deposit both metal alloy and ceramic/metal coatings that are dense, thick and highly adherent to the base materials. As the coating technology is developed, it begins to be applied to a wide range of applications, including a variety of aircraft components and outside the aircraft industry. Although there are wide application for these coatings, intense research is required since their qualification as a fully acceptable replacement for EHC has not yet been adequately demonstrated. Fatigue strength, corrosion, and wear properties of the coatings are intensively investigated for the replacement of EHC plating[1-8)]. In this work, T800 and WC-Co are coated on the Inconel 718 substrate by HVOF thermal spraying processes designed by Taguchi program for three levels of the four parameters, such as oxygen flow rate, hydrogen flow rate, feed rate and spray distance. The optimal coating processes are obtained from the best surface properties of hardness, porosity, and roughness for T800 and of hardness and porosity for WC-Co. The friction and wear behaviors of T800 and WC-Co coatings have been investigated by the reciprocating sliding test with counter sliding SUS 304 stainless steel ball both at 25°C and 538°C. The temperature dependence of friction and wear behaviors between T800 and WC-Co coatings are observed in

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this test. And the mechanism of the friction and wear of both T800 and WC-Co coating have been investigated at the temperature of 25°C and 538°C.

2. Experimental Work

2.1 Preparation of Coating

Commercially available T800 (50.0 wt% Co, 28.4 wt% Mo, 17.6 wt% Cr, 3.1 wt% Si, others) and WC-Co (88 wt% WC pieces in a 12 wt% Co matrix) powders are coated on Inconel 718 substrate by JK3500 HVOF thermal spraying equipment. Substrates are pre-cleaned in acetone for 5 minutes and then blast cleaned by 60 mesh aluminium oxides. As shown in Table 1, coatings are prepared by 9 different processes designed by Taguchi experimental program for three levels and 4 spray parameters of hydrogen flow rates, oxygen flow rates, powder feeding rates and spray distances[5-10]. Spray gun speed is 3 mm/s and argon gas is used as powder carrier gas. Coated substrate is cooled in the air.

As shown in Table 1, 16 T800 coatings are prepared by 16 different processes designed by Taguchi experimental program for four levels of four spray parameters of oxygen flow rate, hydrogen flow rate, powder feed rate and at spray distance 5 inch. And as shown in Table 2, 9 WC-Co coatings are prepared by the Taguchi program of three level of four parameters.

Table 1. T800 coating process

Process	Oxygen flow rate (FMR)	Hydrogen flow rate (FMR)	Feed rate (g/min)	Spray distance (inch)
1	34	60	20	5
2	34	65	20	5
3	34	70	30	5
4	34	75	30	5
5	38	60	20	5
6	38	65	20	5
7	38	70	30	5
8	38	75	30	5
9	42	60	30	5
10	42	65	30	5
11	42	70	20	5
12	42	75	20	5
13	46	60	30	5
14	46	65	30	5
15	46	70	20	5
16	46	75	20	5

Flow rate; FMR = 12 scfh

Table 2. WC-Co coating process

Process	Oxygen flow rate (FMR)	Hydrogen flow rate (FMR)	Feed rate (g/min)	Spray distance (inch)
1	30	53	25	6
2	30	57	30	7
3	30	61	35	8
4	34	53	35	7
5	34	57	25	8
6	34	61	30	6
7	38	53	30	8
8	38	57	35	6
9	38	61	25	7

2.2 Charcterization of the Coatings

Microstructure and phase are investigated by SEM, XRD and EDX. The surface hardness is measured by micro vickers hardness tester. Hardness is the average value of 9 measurements at the center of cross section of the coating layer. Porosity is the average value of 5 data obtained by analyzing the images photographed by optical microscope. Surface roughness is the average of 7 measurements by surface roughness tester.

2.3 Sliding Wear and Friction Test

Friction and wear behaviors of both coatings are investigated by the reciprocating slide tester (TE77 AUTO, Flint & Partners). Coatings are slided by the SUS 304 counter sliding ball (diameter 9.53 mm and hardness 227 Hv) without using lubricant. The reciprocating slide distance, frequency, speed, load and sliding time are 2.3 mm, 35 Hz, 0.161 m/s, 10 N, and 4 minutes respectively. Sliding test is carried out at room temperature and at an elevated temperature of 538°C (1,000°F) for T800 and 500°C for WC-Co for the study of the temperature effects on friction and wear behaviors.

3. Results and Discussions

3.1 T800 Coatings

The chemical compositions of T800 are 45.7 wt% Co, 28.4 wt% Mo, and 17.6 wt% Cr shown in Fig. 1. The powders are the homogeneous mixture of spherical particles with diameter 5-30 μm as shown in Fig. 2. According to the phase diagram, αCo and εCo phases of Co-Mo system, and αCo of Co-Cr system melt at a temperature lower than the pure cobalt melting point 1,495°C which is much lower than the flame temperature of up to 3,500°C[1,4].

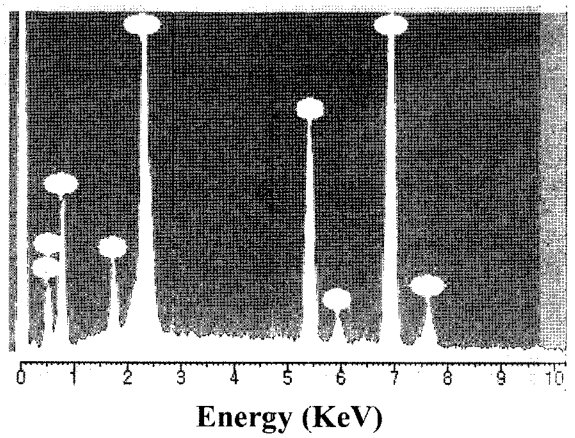

Fig. 1. Chemical composition of T800 powder.

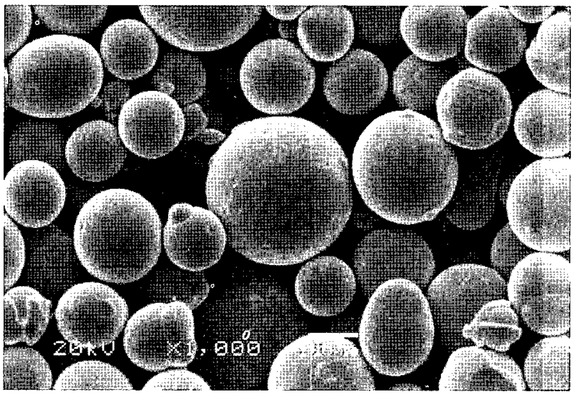

Fig. 2. Particles of T800 powder.

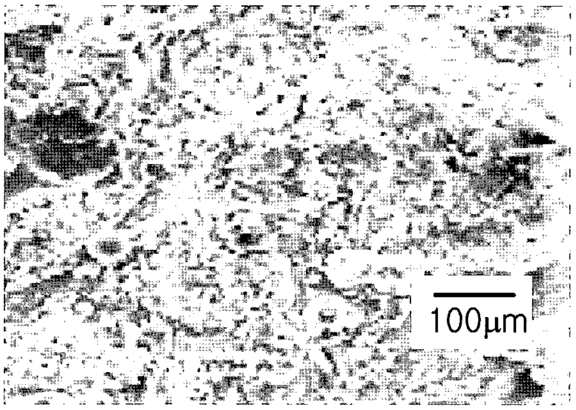

Fig. 3. Microstructure of T800 coating surface.

The micro-structure of coating surface in Fig. 3 shows that the particles with various sizes are molten, partially-molten or softened during the short flight time of 0.1-1 ms by the high temperature of up to 3,500°C of the flame formed by the combustion of the hydrogen and oxygen[1,4,10]. The splats impact on the coating surface with supersonic velocity of up to 1,000 m/s. Upon impact, a bond forms with the surface, with subsequent particles causing thickness buildup and forming a lamella structure. The thin splats undergo quenching at a very high cooling rate, in excess of 10^6 K/s[1,4,10].

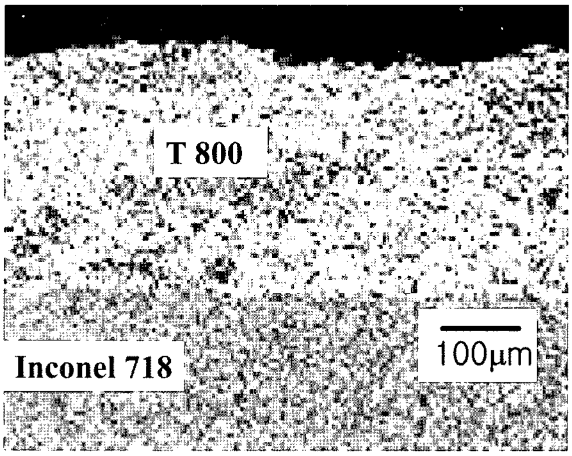

Fig. 4. Cross section of T800 coating.

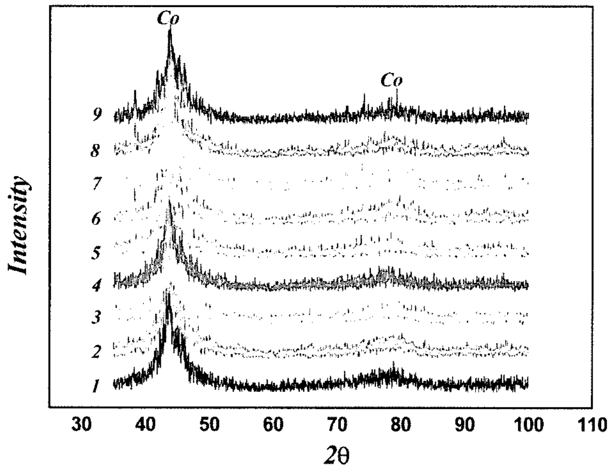

Fig. 5. XRD pattern of T800 coating.

The splats form fine-grained coatings of 300-350 µm thickness with very high adhesion as shown in Fig. 4. In coating Co is in crystalline phase and the other phases are in non-crystalline phases as shown in Fig. 5.

3.2 WC-Co Coatings

As shown in Fig. 6, WC-Co powder prepared by spray drying method shows the mixture of crystalline WC and 12 wt% Co phases. The particles have the shapes of broken pieces of 1-40 µm sizes as shown in Fig. 7. Various size WC-Co particles are injected into the high temperature flame of up to 3,500°C. This maximum temperature of the flame is much higher than Co melting point of 1,495°C, WC decomposition temperature of 1,250°C, W_2C melting point of 2,785 ± 10°C, and comparable to W melting point of 3,422°C[6,7,10,11]. Therefore αCo (W solubility limit

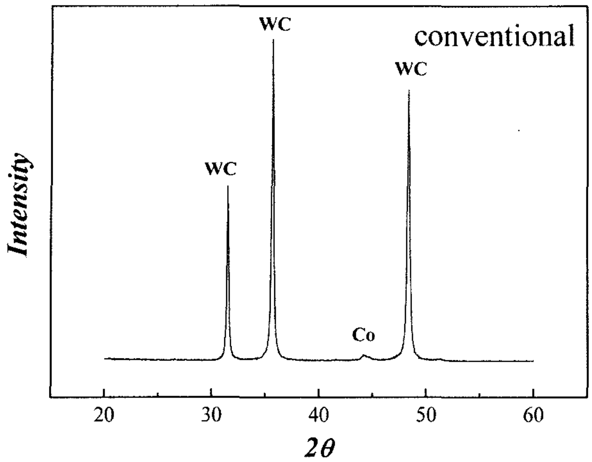

Fig. 6. XRD pattern of WC-Co piece.

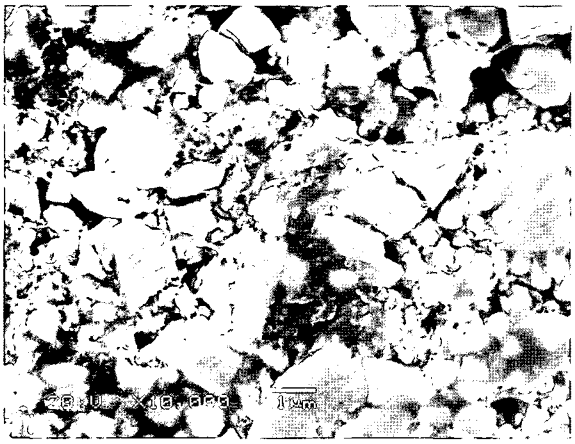

Fig. 7. Pieces of WC-Co powder.

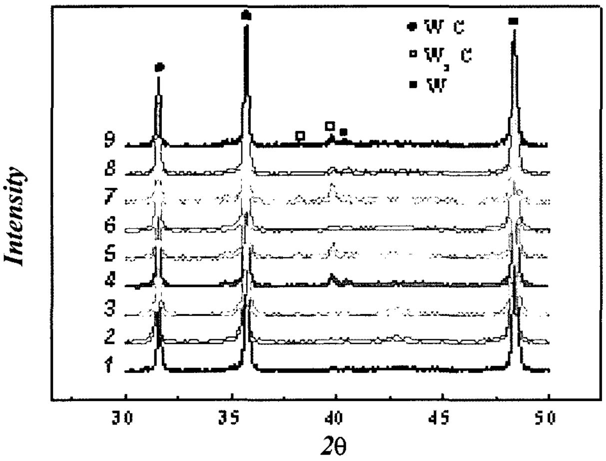

Fig. 8. XRD pattern of WC-Co coating.

of 0.5 at %-17.5 at %) melts almost completely and a small portion of WC pieces decomposes to W_2C, W and C as shown in Fig. 8, and they melt, partially melt or soften[1,4,7].

These various splats impact on the coating surface and form fine grained coatings of 300-350 μm thickness with strong adhesion to substrate as shown in Fig. 9 and 10 through the same process shown above in 3.1. T800 coating. As shown in Fig. 8, XRD pattern of coating shows small amount of W_2C and W phases formed by the decomposition of WC during the short time of flight in the hot flame. According to phase diagram[11] δWC decomposes to βW_2C, W and graphite at the temperature above 1,250°C. And βW_2C melts and decomposes to W and graphite at temperature above 2,785 ± 10°C. The decomposed products W_2C, W and graphite phases reduce the surface hardness.

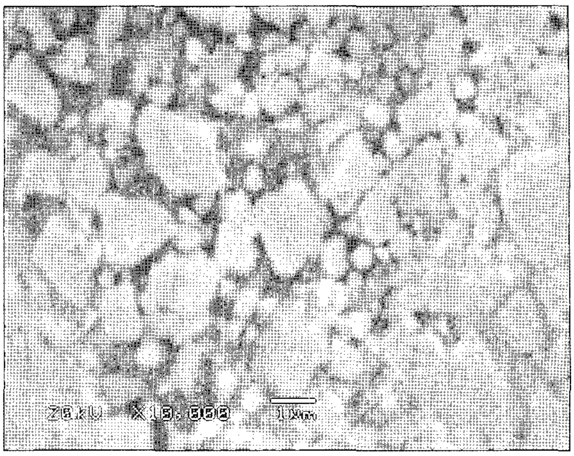

Fig. 9. Microstructure of WC-Co coating.

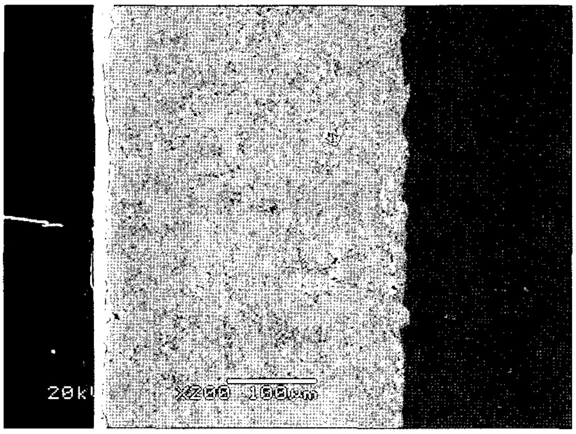

Fig. 10. Cross section of WC-Co coating.

3.3 Optimal Coating Processes of T800 and WC-Co Coatings

The optimal coating process is obtained from the best coating (properties) prepared by Daguchi program shown in 2.2. Preparation of coatings, Table 1 and 2. The optimal T800 coating process is the flow rates of hydrogen and oxygen gas and the feed rate of powder are 65-70 FMR, 38-42 FMR and 30 g/min, respectively at spray distance 5 inch. The optimal

WC-Co coating process is the process of oxygen flow rate 34 FMR, hydrogen flow rate 61 FMR, feed rate 35 g/min, and spray distance 7 inch.

3.4 Surface Properties of T800 and WC-Co Coatings

3.4.1 Surface Hardness vs. Spray Parameters

Surface hardness depends on the spray parameters as shown in Fig. 11. Hardness 940-1,200 Hv of WC-Co coating is about twice higher than hardness 570-630 Hv of T800. In WC-Co coating, the highest hardness 1,200 Hv is obtained when the ratio of hydrogen and oxygen gas flow rate is 1.6 to 1, in excess oxygen reagent.

The hardness increases with increasing feed rate, since the flame temperature is lowered by increasing feed rate, causing less decomposition of hard WC to less hard W_2C, W and graphite. The hardness decreases from 1,200 Hv to 980 Hv with increasing the spray distance from 6 inch to 8 inch, because of the increase of WC decomposition time by increasing the particle flight distance.

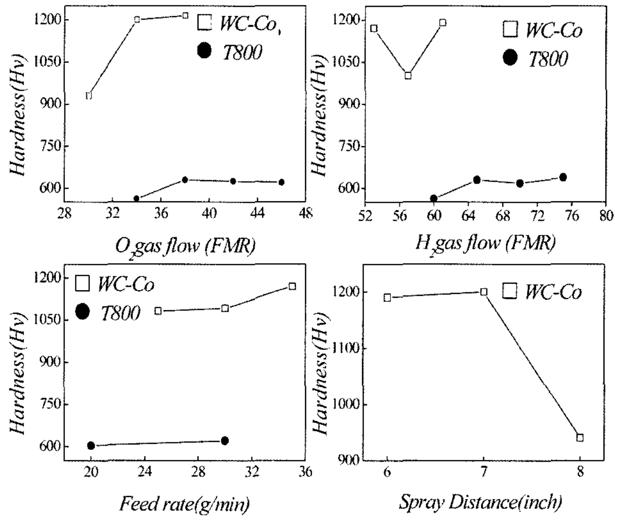

Fig. 11. Hardness vs. spray parameters of T800 and WC-Co coating.

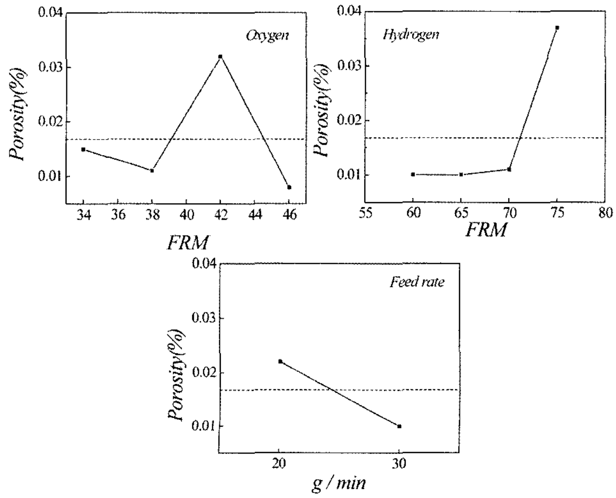

Fig. 12. Porosity vs. spray parameters of T800.

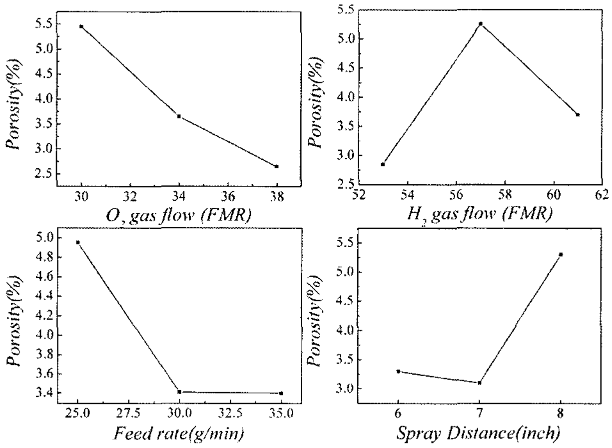

Fig. 13. Porosity vs. spray parameters of WC-Co.

3.4.2 Porosity vs. Spray Parameters

The porosity depends on the spray parameters as shown in Fig. 12 and 13.

Porosity 2.8-5.4% of WC-Co coating is more than ten times larger compared to 0.01-0.035% of T800 coatings. T800 powders with lower melting point 1,495°C are almost completely molten, and form dense coating during the longer solidification time. In WC-Co coatings, small portion of Co (12 wt %) is almost completely molten. However, large portion of WC pieces are left as coarse solid pieces. A small portion of WC-Co powder decomposes to W_2C, W and graphite at the temperature above 1,250°C. The decomposed graphite reacts with the excess oxygen and evolves carbon oxide gasses causing porous coatings.

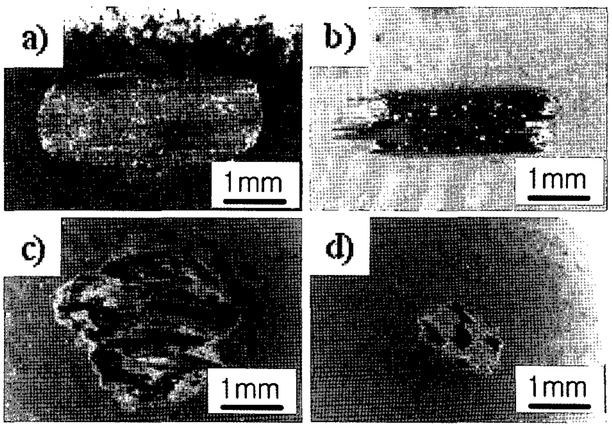

Fig. 14. Wear traces: T800 coating at a) 25°C, b) 538°C. counter sliding SUS 304 at, c) 25°C, d) 538°C.

3.5 Friction and Wear behaviors of T800 and WC-Co Coatings

As shown in Fig. 14, both wear traces of T800 coating and the counter sliding surfaces at higher temperature 538°C are smaller than those at 25°C. Also figure 15 shows that the friction coefficients of T800 coatings at 538°C are lower than those at 25°C. These show that friction and wear decrease with increasing sliding surface temperature, due to the wear mechanism of oxidation and abrasive wear assisted by oxide lubrication. Fig. 15 also shows that friction coefficient of T800 coatings is much smaller than that of non-coated Inconel 718 substrate. This shows that T800 coating is highly recommendable for the durability improvement coating on high speed spindle. At high temperature, brittle oxides such as CoO, Co_3O_4, MoO_2 and MoO_3 are rapidly formed on the soft and highly reactive metallic Co[5,6,13]. The brittle oxides are easily attrited by the sliding. The attrited solids and softened particles, and melts and partially-melt drops play roles as solid and liquid lubricants, causing the decrease of wear traces and friction coefficients at higher temperature[4-6,10,13]. In the WC-Co coatings, friction coefficients are increased along with increasing surface temperature from 0.6-0.7 at 25°C to 0.7-1.0 at 500°C as shown in Fig. 16. This is opposite phenomenon to T800 coating.

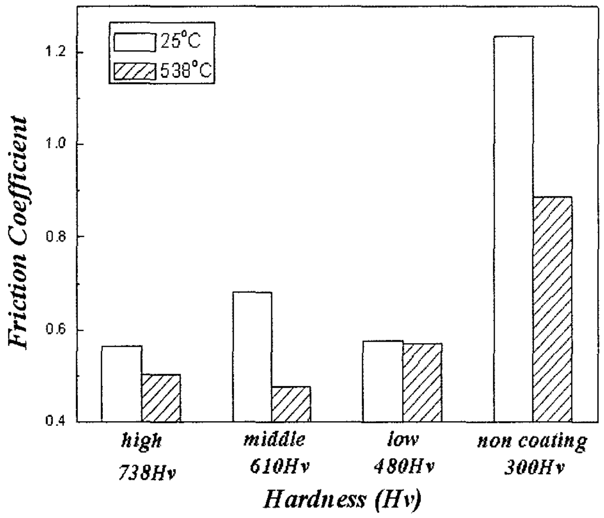

Fig. 15. Friction coefficient of T800 coating both at 25°C and 538°C.

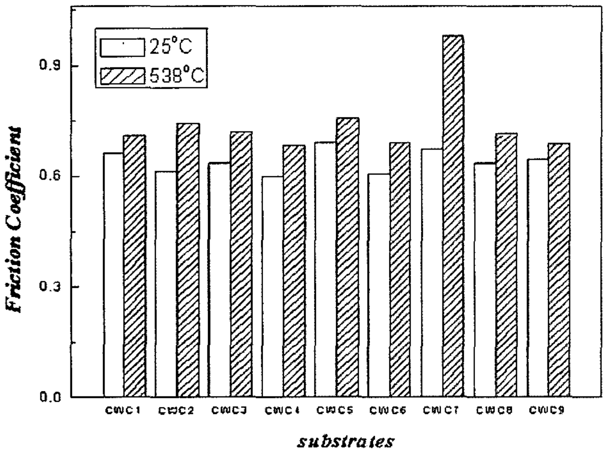

Fig. 16. Friction coefficients of WC-Co coating both at 25°C and 500°C.

At the beginning of the sliding, the soft, low melting (1,495 °C) and reactive metallic Co alloy, which surrounds the hard, high melting (2,785 ± 10°C) and chemically stable WC pieces, plays major role. Wear and friction decrease with increasing the sliding temperature through oxidation and abrasive wear assisted by oxide lubrication. Subsequently, the stable ceramic WC pieces take over the major role, increasing friction coefficients with increasing the sliding temperature through adhesive wear mechanism. In this sliding test environment, the chemically stable WC pieces do not easily form brittle products, and do not easily attrit wear debris which function as solid and liquid lubricants. Normally, true contact area of asperities is about 0.01% of apparent area of two contact surfaces[12]. The asperities are under very high local pressure of about 10^4 times of the test load. This high local pressure causes local cold-welding by the intermolecular and interatomic bonds between the contact area. The adhesion is stronger at higher temperature, and increases friction coefficient.

4. Conclusions

In this study, the following conclusions are reached.

1. T800 powders are almost completely molten during the flight. In WC-Co particle, However, only Co (12 wt%) is almost completely molten and a small portion of WC piece decomposes to less hard W_2C, W and graphite.
2. WC-Co coatings are about twice hard compared to T800 coatings.
3. In WC-Co coating, hardness decreased with increasing flame temperature and flight time because of increased decomposition of WC piece to less hard W_2C, W, and graphite.
4. Porosity of WC-Co coatings are much larger compared to T800 coatings since a small portion of WC-Co particle decomposes to W_2C, W, and graphite, and evolves carbon oxide gasses from the coating.
5. T800 coating is highly recommendable for the coating on the surface vulnerable to frictional heat,

such as high speed spindle since friction and wear decrease with increasing coating temperature.

6. Compared to T800 coating, WC-Co coating may be easily stuck on the surface vulnerable to frictional heat, such as spindle, since friction coefficient increases with increasing sliding surface temperature.

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References

1. B. D. Sartwell *et al.*, Validation HVOF WC/Co, WC/CoCr and Tribaloy 800 Thermal Spray Coatings as Replacement for Hard Chrome Plating on C-2/E-2/P-3 and C130 Propeller Hub System Components, NRL Report No. XYZ, Naval Research Laboratory, Washington DC 20375 (2003) 1-50.
2. B. D. Sartwell *et al.*, 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, (2004) 1-30.
3. B. D. Sartwell, K. Legg, B. Bodger, HVOF Thermal Spray Coatings as an Alternative to Hard Chrome Plating on Military & Commercial Aircraft, AESF/EPA Conference for Environmental Excellence, 231 (1999) 1-20.
4. J. R. Davis, Handbook of Thermal Spray Technology, ASM International, USA (2004) 1-30.
5. T. Y. Cho, J. H. Yoon, K. S. Kim, N. K. Baek, S. Y Hwang, S. J. Youn, H. G. Chun, HVOF Coating of Co-alloy T800 for the Improvement of the Performance and Durability of Military Hardware Components, 15th Aero Technology Symposium, Logistics Command ROKAF, September 15, 2006.
6. T. Y. Cho, J. H. Yoon, K. S. Kim, S. J. Youn, N. K. Baek, B. C. Park, S. Y. Hwang, H. G. Chun, Kor. Soc., Machine Tool Engineers, 15-6 (2006) to be published.
7. K. S. Kim, N. K. Baek, J. H. Yoon, T. Y. Cho, S. J. Youn, S. Y. Oh, S. Y. Hwang, H. G Chun, J. Kor. Inst. Surf. Eng., 29-4 (2006) 179-188.
8. N. K. Baek, K. S. Kim, J. H. Yoon, T. Y. Cho, S. J. Youn, S. Y. Oh, S. Y. Hwang, H. G Chun, J. Inst., Kor. Metal & Mater., To be published in 2006.
9. B. Hwang, J. Ahn, S. Lee, Mater. Trans. 33A (2002) 2933.
10. T. Y. Cho, J. H. Yoon, K. S. Kim, B. G. Park, S. J. Youn, N. K. Baek, H. G. Chun, J. Kor. Crystal Growth and Crystal Technology, 16-3 (2006) 121-126.
11. T. G. Massalski *et al.*, Binary Alloy Phase Diagram, Am. Soc. for Metals, 1 (1986) 600.
12. A. W. Adamson, Physical Chemistry of Surfaces, 4th Ed. John Wiley and Sons, (1982) 404-405.
13. F. A. Cotton, W. Wilkinson, Advance Inorganic Chemistry, 5th ed., Wiley Interscience, (1988) 724-730.