

## Wear behaviors of HVOF spray coating of Co-alloy T800

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**Abstract** HVOF thermal spray coating of Co-alloy T800 is progressively replacing the classical hard coatings such as chrome plating because of the very toxic Cr<sup>6+</sup> ion known as carcinogen causing lung cancer. For the study of the possibility of replacing of chrome plating, the wear properties of HVOF Co-alloy T800 coatings are investigated using the reciprocating sliding tester both at room and at an elevated temperature of 1000°F (538°C). The possibility as durability improvement coating is studied for the application to the high speed spindles vulnerable to frictional heat and wear. Wear mechanisms at the reciprocating sliding wear test are studied for the application to the systems similar to the sliding test such as high speed spindles. Wear debris and frictional coefficients of T800 coatings both at room and at an elevated temperature of 1000°F (538°C) are drastically reduced compared to those of non-coated surface of parent substrate Inconel 718. This study shows that the coating is recommendable for the durability improvement coatings on the surfaces vulnerable to frictional heat. The sliding surfaces are worn by the mixed mechanisms such as oxidative wear, abrasion by the sliding ball, slurry erosion by the mixture of solid particles and small drops of the melts and semi-melts of the attrited particles, cavitation by the relative motions among the coating, sliding ball, the melts and semi-melts, and corrosive wear. The oxide particles and the melts and semi-melts play roles as solid and liquid lubricant reducing the wear and friction coefficient.

**Key words** HVOF, Co-alloy T800, Sliding wear test, Cavitation, Slurry erosion, Solid and liquid lubricant

### 1. Introduction

High velocity oxy-fuel (HVOF) thermal spray coating method has been widely used throughout the last 50 years mainly in defense, aerospace, all kinds of turbines and energy producing industries [1-5]. The HVOF thermal spray coating of metal and ceramic film is progressively replacing the traditional high wear resistant coatings such as hard chrome plating and ceramic coating because of the environmental pollution of very toxic hexa valence Cr<sup>6+</sup> resulting from chrome plating solution and chrome plated products and the brittle nature of ceramic coatings by other methods [5-7]. The HVOF coatings have been applied for the surfaces requiring high hardness and strength, high wear, thermal and corrosion resistant coatings. In this study, micron size Co-alloy T800 is coated by the HVOF thermal spraying on the Inconel 718 which is widely used in aerospace industry such as jet engine. The optimal spraying process for high quality coating is determined by the study

of the coating properties such as roughness, hardness and porosity of the coating surfaces. The possibility of durability improvement and economic restoration of high speed spindle are studied by the investigation of friction and wear behaviors obtained by the sliding wear test.

### 2. Experimental Work

#### 2.1. Preparation of Coatings

In this work, a commercially available Co-alloy T800 powder is coated on the Inconel 718 substrate using JK3500 thermal spraying equipment. As shown in Table 1, the major chemical compositions of the T800 prepared by Satellite Company are Co-45.7 wt%, Mo-28.4 wt% and Cr-17.6 wt% and the size distribution is 5 to 30 μm. T800 powder is sprayed on Inconel 718 used as jet engine material because of its high strength and cor-

Table 1  
Chemical composition of T800 (wt%)

Co	Mo	Cr	C	S	O	Fe	Ni	P	Si
bal.	28.370	17.550	0.019	0.003	0.021	0.680	0.650	0.009	3.100

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Table 2  
Process parameters of HVOF Co-alloy T800 coatings

	Oxygen (FMR)	Hydrogen (FMR)	Ratio (O <sub>2</sub> /H <sub>2</sub> )	Distance (inch)	Feed rate (g/min)
1	34	60	0.57	5	20
2	34	65	0.52	5	20
3	34	70	0.42	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

\*1FMR = 12 scfh

rosion resistant properties at high temperature of 700~980°C. As a precleaning, substrates are cleaned by ultrasonic cleaning in acetone solution for 5 minutes and then are blasted by 60 mesh aluminum oxides to increase the adhesion of the coatings. The optimal HVOF coating process is determined by the 16 experiments shown in Table 2 which are designed by the Minitab program for the spray parameters of spray distance, flow rates of hydrogen and oxygen and powder feed rate carried by argon gas.

### 2.2. Characterization of Coatings

Micro-structures and chemical compositions are investigated by optical microscope, SEM (scanning electron microscope) and EDX (energy dispersive X-ray spectrometer). Surface roughness is the average of 7 measurements by surface roughness tester. Hardness is the average of 9 measurements at the center of cross section of the coating layer. The porosity is the average value of 5 data obtained by analyzing the images photographed by optical microscope.

### 2.3. Friction and Wear Test

The friction and wear behaviors of coatings are investigated by the reciprocating sliding wear tester (TE77 AUTO, Plint & Partners) with SUS 304 counter sliding balls (diameter 9.53 mm and 227 Hv) without using lubricant. The sliding distance, frequency, speed, load

and sliding time are 2.3 mm, 35 Hz, 0.161 m/s, 10 N and 4 minutes respectively. Friction coefficient, wear traces of coatings and counter sliding balls, and the weight of wear debris are studied both at room and at an elevated temperature of 538°C (1000°F).

## 3. Results and Discussion

### 3.1. Co-alloy T800 Powder and Micro-structure of Coating

As shown in Fig. 1, powders are homogeneous mixture of spherical particles with diameter 5~30 µm.

According to the phase diagram, εCo phase of both Co-Mo and Co-Cr system melts at a temperature lower than the pure cobalt melting point 1495°C. Micro-structure of coating surface in Fig. 2(a) shows that the particles with various sizes are molten or partially-molten during the short flight time of 0.1~1 ms by the high temperature (up to 3000°C) of the flame formed by the burning of fuel gas hydrogen and oxygen [1]. The melts and semi-melts impact on the coating surface with supersonic velocity (up to 1,000 m/s). Upon impact, a bond forms with the surface, with subsequent particles causing thickness buildup and forming a lamellar structure. The thin splats undergo quenching at a very high cooling rate, typically in excess of 10<sup>6</sup> K/s [1, 9]. The splats form fine-grained coatings of 300~350 µm thickness with very high adhesion as shown in Fig. 2(b). As shown in Fig. 3, XRD shows that cobalt is in crystalline phase but the others are in non-crystalline states.

### 3.2. Coating Properties and Optimal Coating Process

Optimal coating process is determined from the best

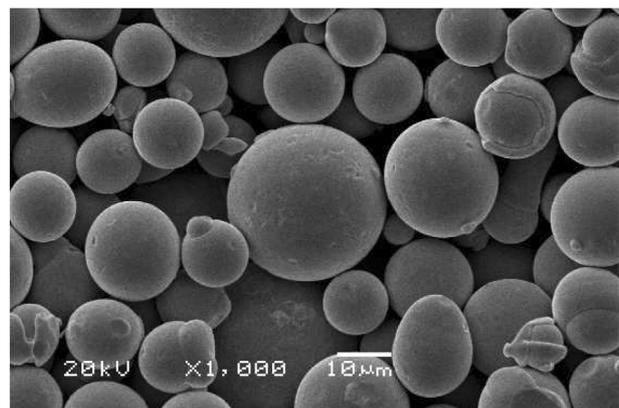


Fig. 1. Particle shapes of Co-alloy T800 powders.

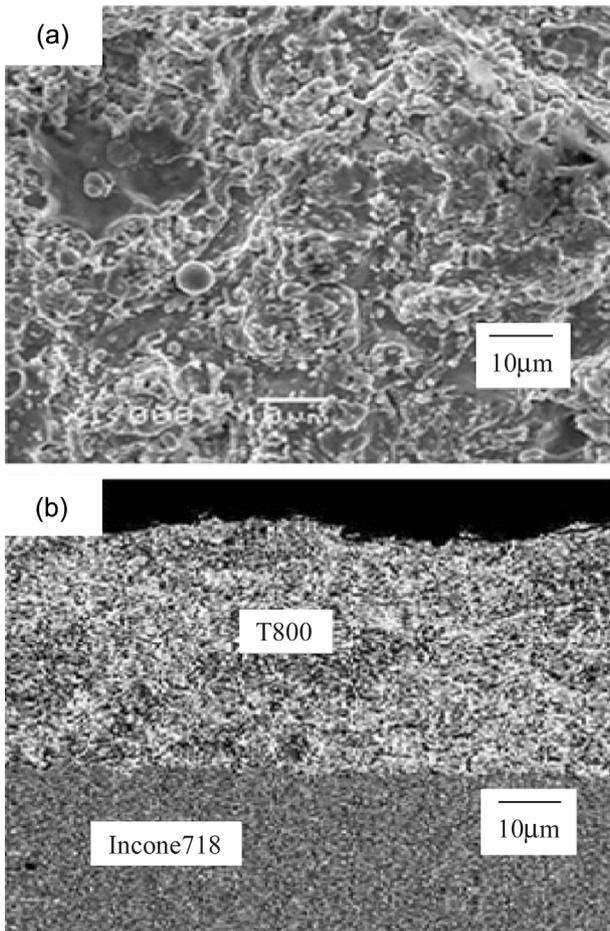


Fig. 2. SEM micrographs showing microstructure of coating of Co-alloy T800; (a) surfaces and (b) cross section.

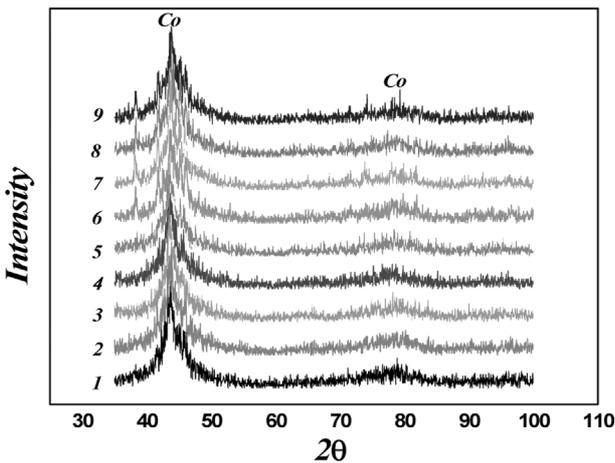


Fig. 3. XRD results showing of Co-alloy coating.

coating properties of roughness, hardness and porosity prepared by the spray process designed by Daguchi program for the spray parameters such as spray distance, fuel gas flow rates of hydrogen and oxygen and powder feed rate as shown in Fig. 4, 5 and 6.

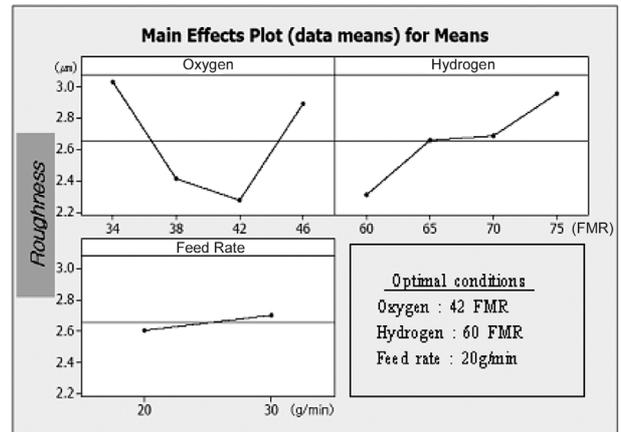


Fig. 4. Variation of roughness with spraying parameters.

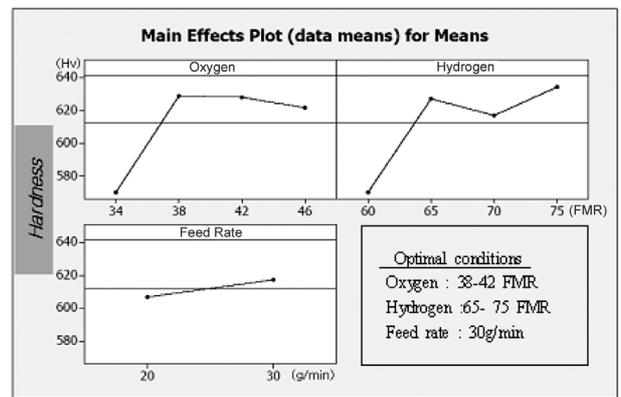


Fig. 5. Variation of hardness with spraying parameters.

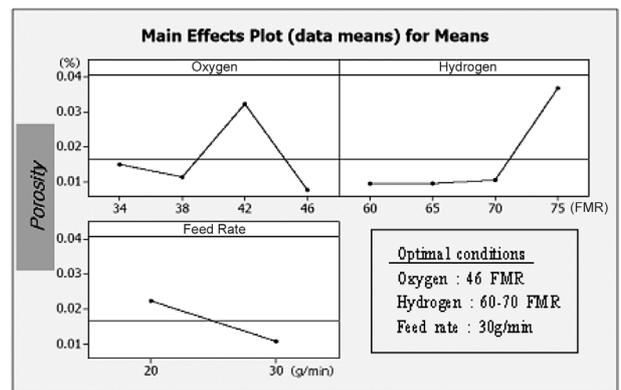


Fig. 6. Variation of porosity with spraying parameters.

The low rough surface is prepared when the flow rates of hydrogen and oxygen, and the feed rate are 38-42 FMR and 60 FMR and 20 g/min respectively as shown in Fig. 4. The highest hardness is obtained when the flow rates of hydrogen and oxygen, and the feed rate are 38-42 FMR and 65-75 FMR and 30 g/min respectively as shown in figure 5. And the lowest porosity is obtained when the flow rates of hydrogen and

oxygen, and the feed rate are 48 FMR and 60~70 FMR and 30 g/min respectively as shown in Fig. 6.

### 3.3. Friction and Wear

Larger wear traces are expected at the substrate with smaller hardness since the volume of wear trace is

inversely proportional to the surface hardness in adhesive wear, but no clear relationship between the wear traces and hardness of coating is observed from the wear traces in Fig. 7. Wear traces of coating at high temperature of 538°C are reduced more than a half compared with those at room temperature. At high temperature, the oxides such as CoO, Co<sub>3</sub>O<sub>4</sub>, MoO<sub>2</sub>, MoO<sub>3</sub> are

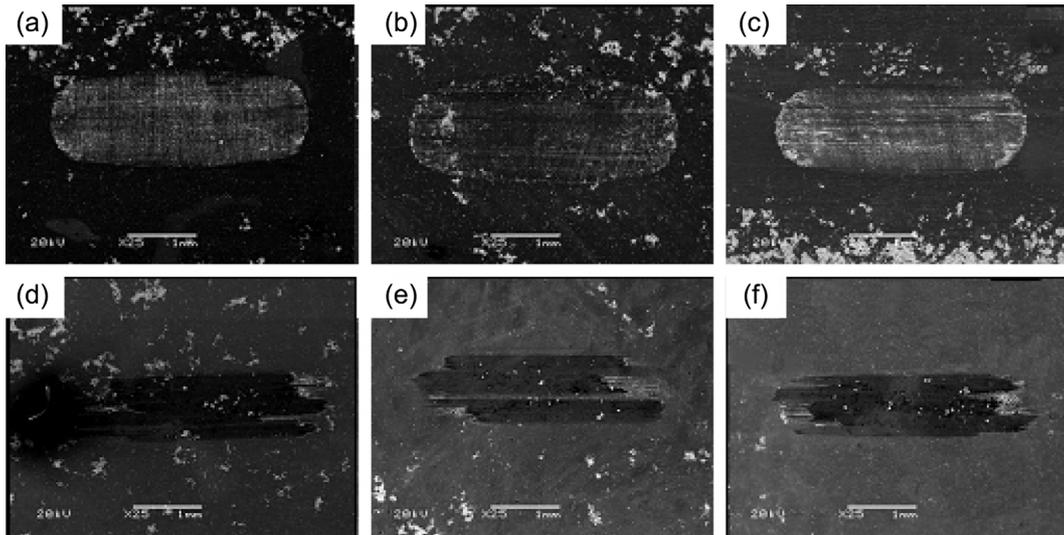


Fig. 7. Hardness of coating (Hv) and wear traces; (a) 738, (b) 610, (c) 480 at room temperature, (d) 738, (e) 610, (f) 480 at high temperature of 538°C.

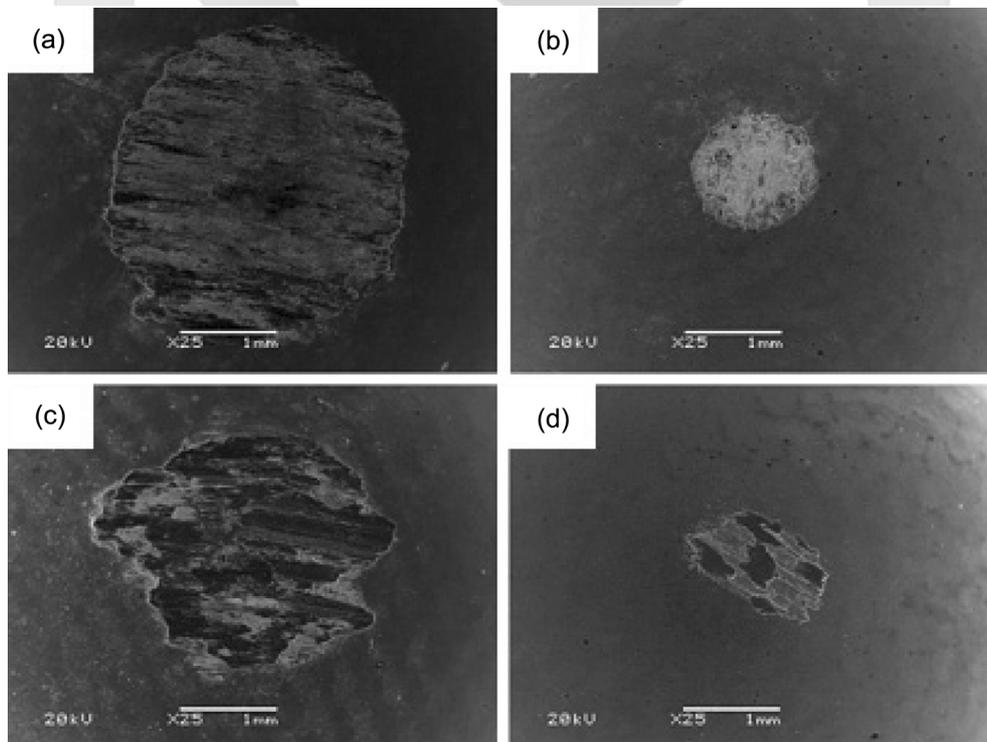


Fig. 8. Wear traces of counter sliding SUS304 ball sliding on : (a) non-coated at room temperature, (b) non-coated at 538°C, (c) coated at room temperature and (d) coated at 538°C.

rapidly formed on the surface [8]. The brittle oxides are easily attrited in the severe wear environment created by the reciprocating sliding through the complicated mixed wear mechanisms such as oxidation wear by direct reaction with oxygen, abrasion by scratching and gouging at the oxidized asperities by the sliding, slurry erosion by the mixture of solid oxide particles and the drops of melts and partially-melts, cavitation by the relative motions between the coating surface and sliding ball in attrited particles, melts and partially-melts, and subsequent corrosion reactions and corrosive wear. At high temperature, the wear traces are smaller than those at room temperature since the oxide wear debris and the melts play a role as solid and liquid lubricant, and the role is higher at higher temperature. This shows that HVOF thermal spray coating of Co-alloy T800 is highly recommendable as a durability improvement coating on the surface vulnerable to frictional heat and wear such as

high speed spindles [1, 10, 11].

As shown in Fig. 8, at both room and an elevated temperature of 538°C, the wear traces of the counter sliding ball slid on coating is smaller than those slid on non-coating surfaces, and the traces of melt by sliding on coating is larger than those by sliding on non-coating surfaces. These show that Co-alloy coatings play a role as lubricants and are essential as a durability improvement coating. The traces on the balls resulting from 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.

Figure 9 shows the relationship of friction coefficients and weight loss by sliding versus the hardness of both coating and non-coating at both room temperature and 538°C. For coatings, friction coefficients of both room and high temperature, and the weight loss are smaller compared with those of non-coatings. Also the

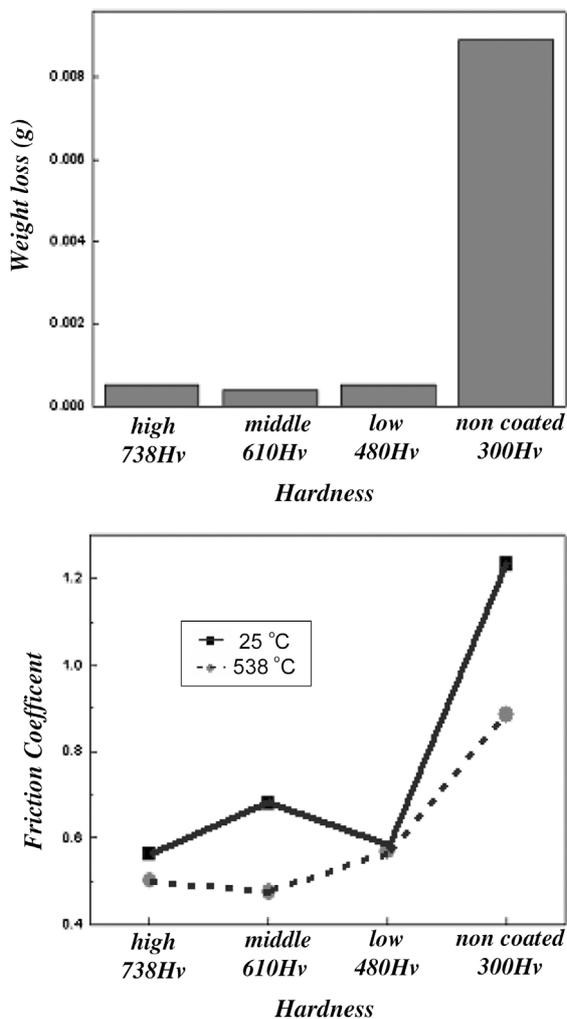


Fig. 9. Effect of hardness on weight loss and friction coefficients at 25°C and 538°C.

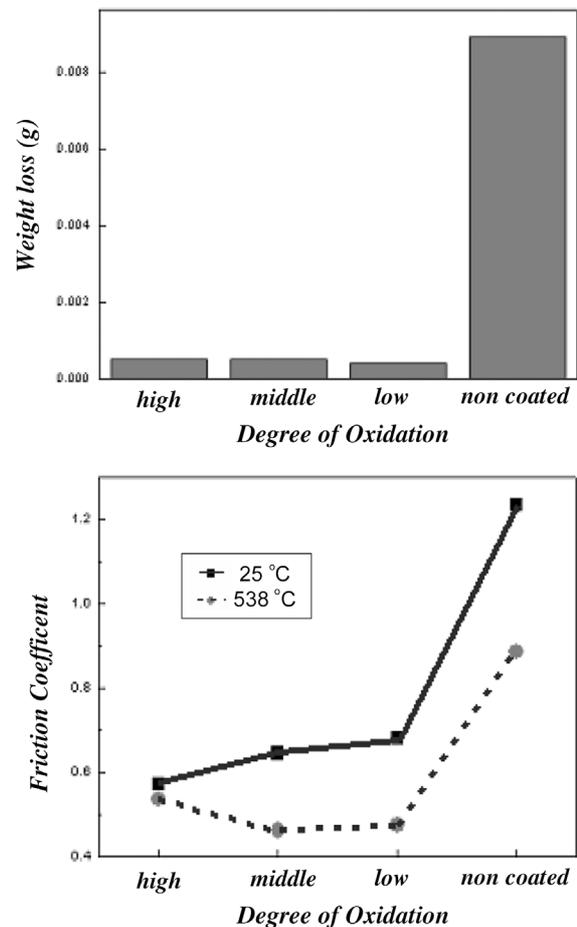


Fig. 10. Effect of degree of oxidation on weight loss and friction coefficients at 25°C and 538°C.

friction coefficients are smaller at high temperature compared with those at room temperature for both coating and non-coating. These show that Co-alloy coating is highly recommendable as a durability improvement coating at room and high temperature because of the superior lubricant properties of the coatings. Any clear relationship between the friction coefficients and weight loss versus hardness of coatings are not observed in this experiment.

Figure 10 shows the relationship of friction coefficients and weight loss by sliding versus the degree of oxidation of coating surfaces, and friction coefficients versus coating temperatures. No clear relationship between friction coefficients and the weight loss versus the degree of oxidation are observed since the preexisted oxides (native oxides) are much smaller than that formed by the sliding test. The friction coefficients are decreased at high temperature in comparison with those at room temperature for both coated and non-coated surfaces. This also shows that oxides play a role as lubricants during sliding. These observations agree with the NRL report of Sartwell [5] that the wear coefficients of T800 coating is remarkably smaller than those of other high wear resistant coatings.

#### 4. Conclusions

In this study, the following conclusions are reached.

1) In the optimal HVOF coating process of Co-alloy T800 powder, 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.

2) At both room and elevated temperature 538°C, the friction coefficients, wear traces and wear debris of Co-alloy T800 coating are smaller than those of non-coated Inconel 718 surface. This shows that Co-alloy coating improves the wear resistance, and also can improve the durability of high speed spindles.

3) The friction coefficients, wear traces and wear debris of Co-alloy T800 at an elevated temperature 538°C are much smaller than those at room temperature. This shows that Co-alloy T800 coating is highly recommendable for the coating on the surfaces vulnerable to frictional heat and wear such as high speed spindles.

4) The brittle oxides such as CoO, Co<sub>3</sub>O<sub>4</sub>, MoO<sub>2</sub>, MoO<sub>3</sub> are rapidly formed on the coating at elevated temperature. The brittle oxides are easily attrited by the

sliding through the complicated mixed wear mechanisms such as oxidation wear, abrasive wear, slurry erosion, cavitation and corrosive wear. The attrited oxide solid particles, melt and partially-melt drops play a role as solid and liquid lubricants.

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