The Lubricant Effect of Oxidation and Wear Products of HVOF Co-alloy T800 Powder Coating

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Micron size Co-alloy 800 (T800) powder is coated on the high temperature, oxidation and corrosion resistant super alloy Inconel 718 substrate by the optimal high velocity oxy-fuel (HVOF) thermal spray coating process developed by this laboratory. For the study of durability improvement of high speed spindle operating without lubricants, friction and sliding wear behaviors of the coatings are investigated both at room and at an elevated temperature of 1000 ˚F (538 ℃). Friction coefficients, wear traces and wear debris of coatings are drastically reduced compared to those of non-coated surface of Inconel 718 substrate both at room temperature and at 538 ℃. Friction coefficients and wear traces of both coated and non-coated surfaces are drastically reduced at higher temperature of 538 ℃ compared with those at room temperature. At high temperature, the brittle oxides such as CoO, Co_3O_4, MoO_2 and MoO_3 are formed rapidly on the sliding surfaces, and the brittle oxide phases are easily attrited by reciprocating slides at high temperature through oxidation and abrasive wear mechanisms. The brittle solid oxide particles, softens, melts and partial-melts play roles as solid and liquid lubricants reducing friction coefficient and wear. These show that the coating is highly recommendable for the durability improvement coating on the machine component surfaces vulnerable to frictional heat and wear.

***Keywords** : sliding wear test, melts, and partial-melts, solid and liquid lubricants.*

1. Introduction

Electrolytic hard chrome plating (EHC) has been widely used for the protective hard coating on the machine components for the durability improvement and rebuild of worn parts over last 60 years. The possibility of replacing of EHC and electrolytic plating 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. Micron size Co-alloy (T800) is coated on the high temperature oxidation and corrosion resistant super alloy Inconel 718 substrate by the optimal HVOF coating process developed in this laboratory.[1)]

Air bearing spindles operate 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, especially by sticking friction during starting and stopping the spindle operation. Temperature dependence on friction and wear behavior of both Inconel 718 and HVOF T800 coating are investigated both at room temperature and at an elevated temperature 1000 ˚F (538 ℃) for the life time improvement of air bearing spindles and machine components by HVOF T800 coating.

2. Experimental work

2.1 HVOF thermal spray coating of T800 powders on Inconel 718 substrate

The major elements of commercially available T800 powders prepared by Satellite Company are 45.7 wt% Co, 28.4 wt% Mo and 17.6 wt% Cr as shown in Table 1.

Powders are spherical shapes with diameters of 5-30

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Table 1. Chemical elements of T800 powder

Co	Mo	Cr	Si	Fe	Ni	O	C	P
bal	28.37	17.55	3.100	0.680	0.650	0.021	0.019	0.009

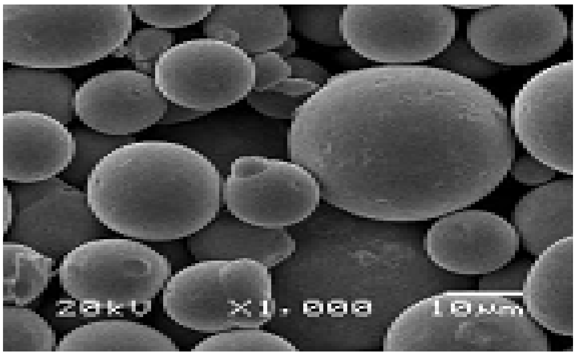

Fig. 1. T800 powders

um and mixed homogeneously as shown in Fig. 1. For the improvement of adhesion of HVOF T800 coatings on substrates, the surfaces of Inconel 718 substrates are pre-cleaned by ultrasonic cleaning in acetone for 5minutes and then blast cleaned by 60 mesh alumina particles. T800 powders are coated on 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.[1)-3)]

2.2 Characterization of T800 powders and coating surfaces

Chemical compositions and micro-shapes of T800 powders are investigated by SEM, EDS and optical microscope. Surface hardness is the average value of 9 measurements at the center of cross section of coating layer measured by Micro Vickers Hardness tester. Surface roughness is the average of 7 measurements by surface roughness tester. Porosity is the average of 5 data obtained by analyzing the images photographed by optical microscope.

2.3 Reciprocating slide test

Friction and wear behaviors of T800 coatings are 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 ℃. The reciprocating width (a sliding distance), reciprocating frequency, speed, load and test time are 2.3 mm, 35 Hz, 0.161 m/s, 10 N and 4 minutes respectively. Friction coefficients, weight loss and wear traces by sliding wear of non-coated Inconel 718 surface and coatings with various hardness are investigated both at 25 ℃ and 538 ℃.

3. Results and discussions

3.1. Preparation of HVOF T800 coatings

In this HVOF thermal spray coating the maximum flame temperature and particle velocity are up to 3,500 ℃ and 1,000 m/s respectively.[4)-6)] Particle flight times of 0.1-1 ms are estimated from the spray distance.[7)-10)] The distribution of flight particles temperature, velocity and flight time very widely depended on the particle sizes and positions in flame. According to phase diagram and dictionary of metal engineering,[11),12)] the melting points of pure Co, Mo, Cr and e Co phase of both Co-Mo and Co-Cr systems are in the range of 1,495-2.623 ℃, much lower than the highest temperature 3,500 ℃ of spraying flame. 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

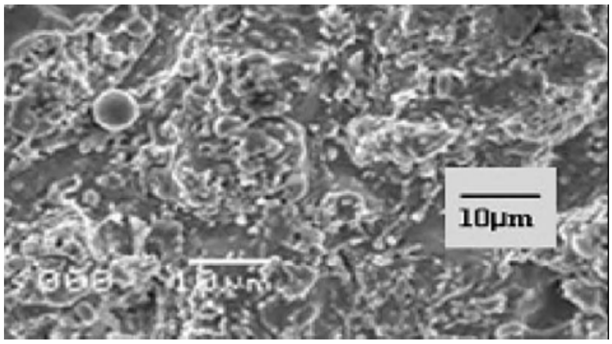

Fig. 2. Microstructure of HVOF T800 coating

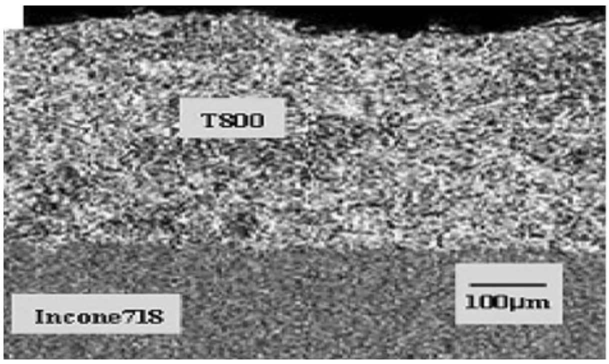

Fig. 3. Cross section of T800 coating on Inconel 718 surface

a lamella structure as shown in Fig. 2. The splats undergo quenching at a very high cooling rate in excess of 10^6 K/s.[4)-6)] In this experiment, the splats form coating of 300-350 um thickness layer with good adhesion on substrate as shown in Fig. 3.

3.2 Dependence of coating properties on spray parameters

Coating properties strongly depend on the coating process. The optimal coating process is the process that prepares the coating with best property. The highest hardness 640 Hv is obtained by the process of oxygen flow rate 38-42 FMR, hydrogen flow rate 65-75 FMR, powder feed rate 30 g/min and spray distance 5 inch in this experiment as shown in Table 2 and Fig. 4. The least porosity of about 0.1 % and roughness of 2.2 - 2.6 um are obtained by the processes shown in Table 2 and Fig. 5 and 6.

Table 2. Optimal coating processes at spray distance 5 in

Properties	O_2 flow rate (FMR)	H_2 flow rate (FMR)	Feed rate (g/min)
Hardness (640 Hv)	38－42	65－75	30
Porosity (0.1 %)	46	60－65	30
Roughness (2.2-2.6 um)	42	60	20

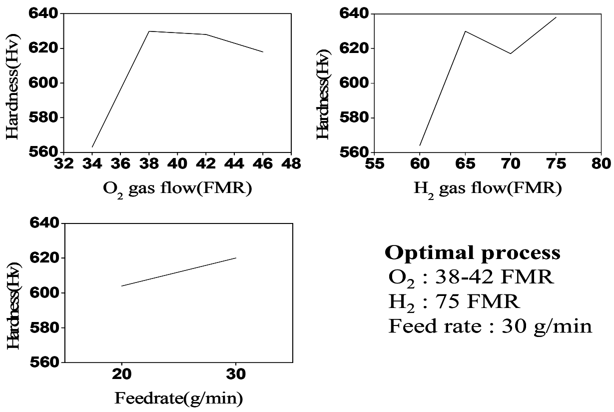

Fig. 4. Hardness of coating vs spray parameters

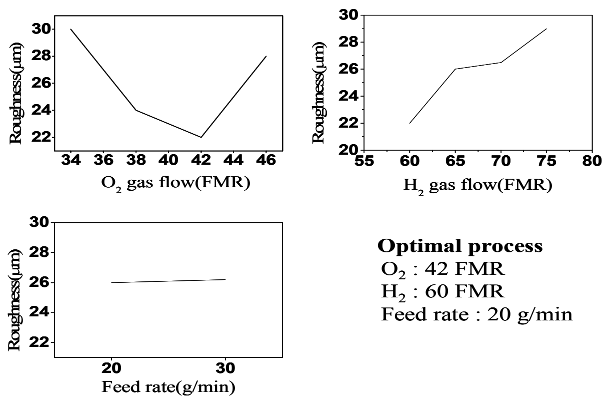

Fig. 5. Roughness of coating vs spray parameters

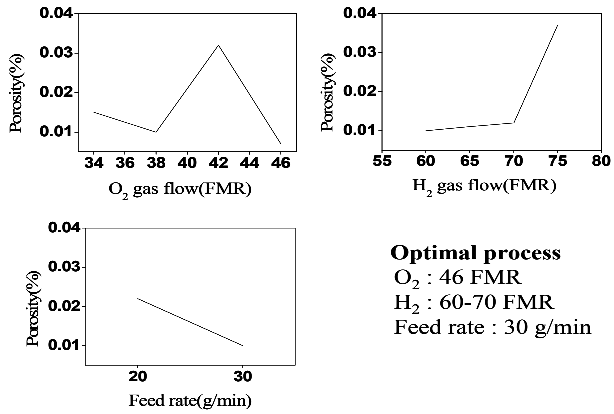

Fig. 6. Porosity of coating vs spray parameters

3.3 Improvement of friction property by HVOF T800 coating

As shown in Fig. 7 friction coefficient of T800 coating with various surface hardness are smaller than about a half of non-coated Inconel 718 surface both at 25 ℃ and 538 ℃. 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. The higher friction coefficients are expected for the coatings with higher hardness, but no clear relationship between friction coefficient and hardness of T800 coatings are observed in this experiment as shown in Fig. 7. Friction coefficients of coatings at a higher temperature 538 ℃ are lower than those at lower temperature 25 ℃. 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.

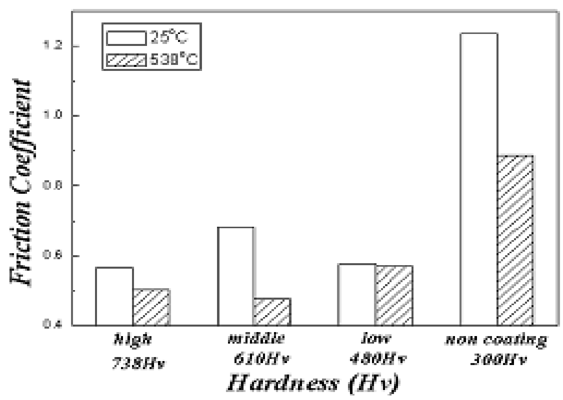

Fig. 7. Friction coefficients of T800 coatings and Inconel 718

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.[9),10)] The brittle oxides are easily attrited as debris by the sliding through oxidation wear and abrasion.[4)-5),7)-10)] 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.

3.4 Wear behaviors of non-coated Inconel 718 surface and T800 coating

The sliding weight loss of T800 coating is more than ten times smaller than that of non-coated Inconel 718 surface as shown in Fig. 8. This also shows that T800 coating is highly recommendable for wear resistant coating on the surface of sliding machine components. The smaller weight loss by sliding wear is expected at the hard coating surfaces since the wear volume is inversely proportional to surface hardness in adhesion wear, but no clear relationship between the weight loss and hardness of coating is observed in this experiment as shown in Fig. 8. This shows that the major wear mechanism is not adhesive wear, but other mechanisms such as oxidation wear and abrasive wear influenced by the attrited solid and liquid oxide lubricants.

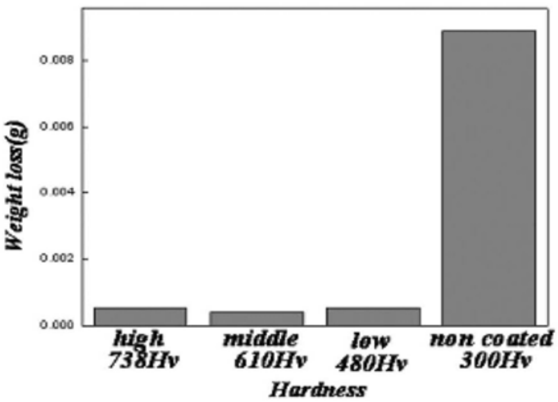

Fig. 8. Weight loss by sliding wear

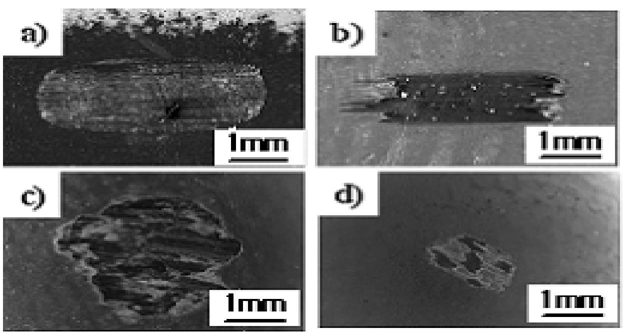

Fig. 9. Wear traces: T800 coating with 610 Hv at; a) 25 ℃ and b) 538 ℃. Sliding ball SUS 304 at; c) 25 ℃ and d) 538 ℃

The wear traces at a higher temperature 538 ℃ is much smaller than those at lower temperature 25 ℃ 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.

4. Conclusion

The followings are concluded in this study:

(1) 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.

(2) T800 coating is highly recommended for the durability improvement coating on the surface of machine components surface since the weight loss and friction coefficients of T800 coating by sliding wear test are much smaller compared to those of non-coated Inconel 718 surface.

(3) At the sliding wear test, weight loss, wear traces and friction coefficients of T800 coating are much smaller at higher temperature 538 ℃ 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.

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