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STUDY ON THE DURABILITY OF THERMALLY SPRAYED WC CERMET COATING IN PARTIAL EHL CONTACTS

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ABSTRACT
Using a two-roller testing machine, durability of thermally sprayed WC-Cr-Ni cermet coating was investigated under partial EHL condition. By means of the high energy type flame spraying (Hi-HVOF) method, the coating was formed onto the axially ground and circumferentially ground roller specimens made of a thermally refined carbon steel. The WC cermet coated roller finished to a mirror-like condition was mated with the carburized hardened rough steel roller without coating in line contact condition. As a result, the coating on the circumferentially ground substrate showed a lower durability compared with that on the axially ground substrate and this difference appeared more distinctly for the higher Hertzian stress. The surface durability of WC cermet coated steel roller was also compared with the durability of the steel roller without coating and the fatigue life of the non-coated roller was fairly shorter compared with that of the coated roller.

Keywords: WC Cermet, Partial EHL, Surface Durability.

1. INTRODUCTION
In recent years, the quality and reliability of thermally sprayed coatings have been improved remarkably to satisfy the growing needs of the market for high wear resistance of engineering components. This is due to the development of new processes so that the coating deposition system can be designed to optimize the velocity and temperature of the spray particles or due to the introduction of advanced techniques such as application of heat sources with higher energy and controlling the spray parameters [1]. Among the cermet coatings, the most attractive proved to be the hard coatings of tungsten carbide (WC) based cermets because of its excellent tribological properties such as wear resistance and sliding performance [2]. Under these circumstances, a wide variety of applications to the contact surfaces of machine elements are anticipated. However, so far, very few basic researches have been done to investigate the surface durability or the rolling contact fatigue performance of thermally sprayed coatings under rolling/sliding contact conditions [3,4].

With these points as background, using a two-roller testing machine, the authors examined the surface durability of thermally sprayed WC-Cr-Ni cermet coating in lubricated pure rolling or rolling with sliding contact conditions [5,6]. The coated roller formed by the conventional type high velocity oxy-fuel flame spraying (HVOF) or by the high energy type flame spraying (Hi-HVOF) [7] process, was mated with the smooth carburized steel roller without coating. The authors found that flaking of coating is apt to occur when the coated roller is placed on the slower side in rolling with sliding conditions and the life to flaking increases as the coating thickness is increased [5]. They also clarified that the spraying conditions and the substrate material have significant effects on the surface durability of coated roller [6].

In the present investigation, using a two-roller testing machine, durability of thermally sprayed WC-Cr-Ni cermet coating was investigated under partial EHL condition. The WC cermet coating was formed onto the axially ground and circumferentially ground roller specimens made of a thermally refined carbon steel by high energy type flame spraying (Hi-HVOF) method. The WC cermet coated steel roller finished to a mirror-like condition was mated with the carburized steel roller without coating having a surface roughness of about 4.0 μm and a maximum Hertzian stress of P_H=0.6 GPa or 0.8 GPa was applied in line contact condition. In the experiments, the oil film parameter Λ was less than 1 under partial EHL condition. Durability of WC cermet coated steel roller was compared with the durability of the non-coated steel roller under partial EHL condition (Λ<1). Before and after the experiment, profile curve of the mating surfaces and the surface roughness were also examined.

2. EXPERIMENTAL

2.1 Testing Machine and Test Rollers

Experiments were carried out using a two-roller testing machine which is shown in Fig. 1. The shapes and dimensions of test rollers are shown in Fig. 2. Cylindrical specimens F roller without coating and D roller with WC cermet coating were mated. The outside diameter of both rollers is 60 mm and the effective track width is 10 mm. In rolling with sliding conditions, rollers F and D were forcibly driven by gears with the gear ratios of 27/31 (slip ratio given for the coated D roller side, s=-14.8%) and 25/32 (s=-28%).

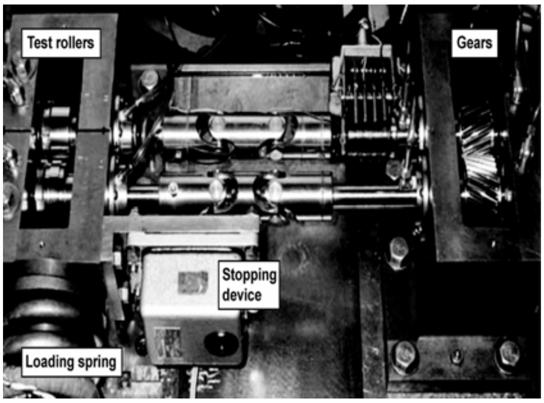


Fig 1. Two-roller testing machine

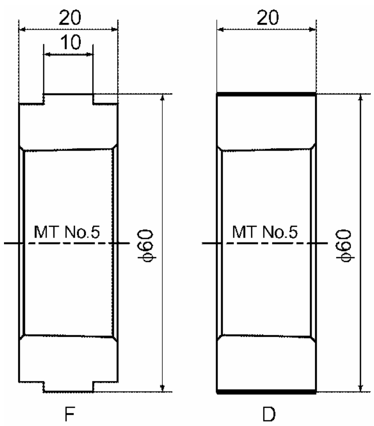
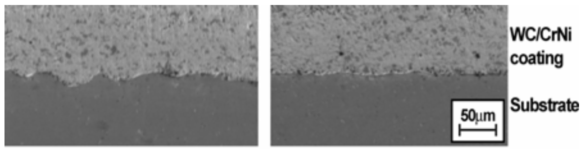


Fig 2. Test rollers

The testing machine was equipped with an automatic stopping device which worked in response to the abnormal vibration induced by the occurrence of flaking or any other surface damages. The life to flaking or the rolling contact fatigue life N is defined as the total number of revolutions of the flaked roller side. When the testing machine continued to run without any serious damage, the running was discontinued at $N=2.0\times10^7$ cycles.

The material of F roller was a carburized and hardened chromium molybdenum steel (SCM415 according to JIS G 4105, the surface hardness HV≈800). The contact surface of F roller was finished to a roughness of Ry≈4.0 μm (Ry: maximum height of the profile according to ISO 4287-1997 or JIS B 0601-1994, sampling length 0.25 mm) by cylindrical grinding. As the substrate material of D roller, a thermally refined carbon steel (S45C according to JIS G 4051, the surface hardness HV≈320) was used. Prior to spraying, the substrate surface of D roller was finished to a roughness of Ry=5.0~7.0 μm by axially grinding and circumferentially grinding.

As shown in Fig. 3, the WC(Bal.)-Cr(20 mass%)-Ni(7 mass%) cermet coating was formed onto the axially ground and circumferentially ground substrate surface of D rollers by the high energy type flame spraying (Hi-HVOF) process and the spraying conditions are shown in Table 1. The coatings of about 60 μm and 110 μm in thickness were prepared. The contact surface of D roller after spraying was finished smooth to a mirror-like condition with a roughness of Ry≈0.2 μm by grinding and subsequent polishing. The micro-Vickers hardness of the coating formed by Hi-HVOF was HV≈1100 (test load: 2.94 Newton).



Axially ground substrate | Circumferentially ground substrate

Fig 3. Cross-sections of sprayed coating (Sections perpendicular to roller axis)

Table 1: Spraying conditions

Spraying process		Hi-HVOF
Pressure, MPa	Oxygen	1.0
	Fuel*	0.9
Flow rate, m^3/h	Oxygen	53.6
	Fuel*	0.02
Sprayed distance, mm		380
Velocity of particles, m/s		1080
Velocity of gas, m/s		2160

*Fuel: Kerosene

2.2 Experimental Conditions and Procedures

The Hi-HVOF sprayed D roller and the carburized steel F roller without coating were mated under rolling with sliding conditions, and the coated D roller was placed on the slower (driven) side (slip ratio s=-14.8% or s=-28.0%). Using a coil spring, the normal load was applied and experiments were continued to run under partial EHL condition (Λ<1). The rotational speed of the driving side roller was 3580±15 rpm. The normal load which gives a maximum Hertzian stress of P_H=0.6 or 0.8 GPa for thermally refined carbon steel and P_H=1.4 GPa for induction hardened caron steel or carburized hardened steel substrate was applied in line contact condition. As lubricant, a paraffinic mineral oil without EP additives (kinematic viscosity ν: 62.9 mm^2/s at 313 K, 8.5 mm^2/s at 373 K, pressure-viscosity coefficient α: 13.3 GPa^{-1} at 313 K, specific gravity 288/277 K: 0.878) was supplied to the inlet side of rotating rollers at a flow rate of 15 cm^3/s and at a constant oil temperature of 318 K. The state of oil film formation between two rollers was continuously monitored by means of an electric resistance method [8] and the friction force between rollers was measured using strain gauges stuck on the driving shaft (via slip rings).

3. RESULTS AND DISCUSSION

3.1 Comparison of Surface Durability

Fig. 4 shows the effects of substrate surface finish and Hertzian stress on the surface durability or life to flaking of WC cermet coated roller made of a thermally refined carbon steel substrate. Experiments were carried out for the coating thickness of about 60 µm and under a slip ratio s=-14.8%. In partial EHL condition, the oil film parameter Λ was less than 1 for every test. From the figure it is apparent that under a Hertzian stress of P_H=0.6 GPa, the axially ground substrate roller exhibited a high durability and it was possible to run up to N=2.0×10^7 cycles whereas durability of the circumferentially ground substrate roller was lowered to N=3.4×10^6 cycles. Under a higher Hertzian stress of P_H=0.8 GPa, durability of the coated roller was remarkably affected by the substrate surface finish. Namely, the axially ground substrate roller showed a long life up to N=2.0×10^7 cycles whereas the circumferentially ground substrate roller showed a very short life and flaking of coating occurred at early stage of running N=2.5×10^5 cycles.

Fig. 5 shows the effect of coating thickness on durability or life to flaking of WC cermet coating. From the figure it can be seen that in the case of circumferentially ground substrate and under the Hertzian stress of P_H=0.8 GPa, surface durability or life to flaking of the coated roller was remarkably improved from N=2.5×10^5 cycles to N=2.0×10^7 cycles with the increase in the coating thickness from 60 µm to 110 µm.

Fig. 6 illustrates a comparison of the surface durability of WC cermet coated steel roller with that of steel roller without coating under partial EHL condition. Experiments were carried out under a Hertzian stress of P_H=1.4 GPa and slip ratio s=-28.0%. From the figure it is clear that the coated roller showed a long life up to N=2.0×10^7 cycles whereas the non-coated roller showed a fatigue life N=4.5×10^6 cycles which is fairly shorter compared with that of the coated roller.

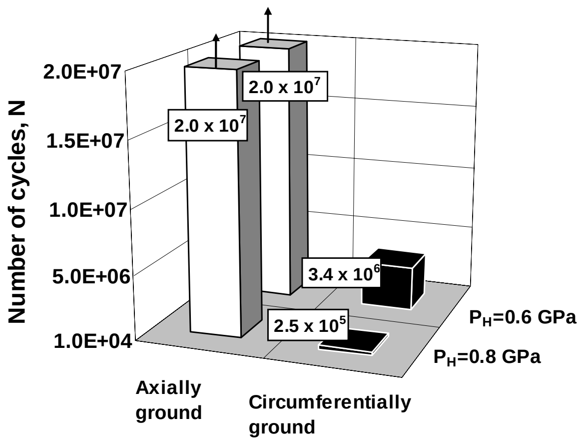


Fig 4. Effects of substrate surface finish and Hertzian stress on durability of WC cermet coating

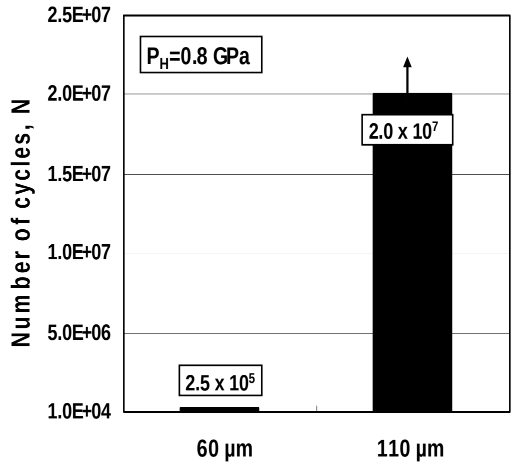


Fig 5. Effect of coating thickness on durability of WC cermet coating (circumferentially ground)

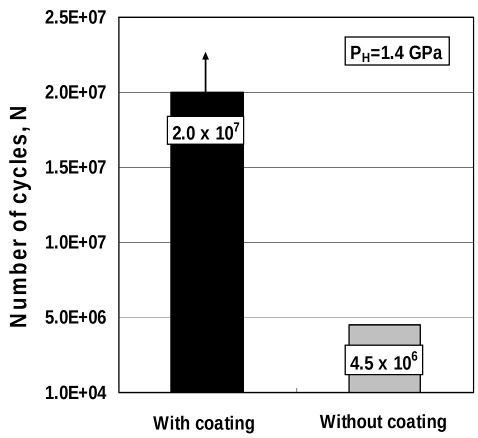


Fig 6. Comparison of durability of WC cermet coated steel roller with that of steel roller without coating

3.2 Profile Curves of Mating Surfaces

Fig. 7 shows the profile curves of the mating surfaces before and after running. From the figure it can be seen that in the case of axially ground substrate where the coated D roller exhibited a high durability, after the test, the surface profiles of F roller and D roller were not much changed. It can also be observed that after the test, the surface roughness of F roller was decreased and D roller was increased slightly. On the other hand, in the case of circumferentially ground substrate where the coated D roller showed a short life, after running, the surface profiles of F roller and D roller were much changed. From the figure it is also apparent that after the test, the surface roughness of F roller and D roller was increased remarkably.

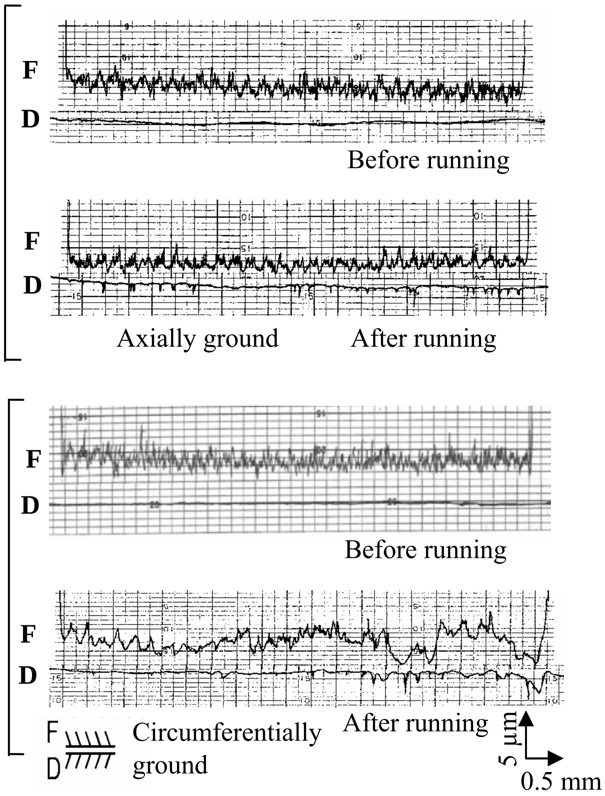
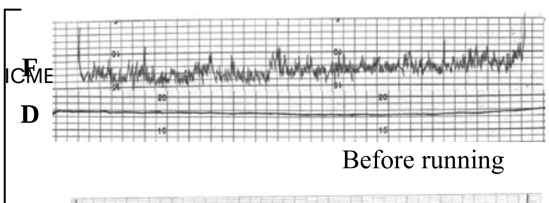


Fig 7. Profile curves of mating surfaces in axial direction (P_H=0.6 GPa, s=-14.8%)

Fig. 8 shows the profile curves of the mating surfaces where experiments were carried out with the coated D roller and non-coated D roller. In the case where coated D roller was used, after the test, the surface profiles of F roller and D roller were not muchchanged. Moreover, after the test, the surface roughness of F roller was decreased and D roller was increased. In the case where non-coated D roller was used, after the test, the profile curves of the mating surfaces were not much changed. From the figure it is also clear that after running, the surface roughness of F roller was decreased slightly and D roller was increased significantly.



3.3 Changes in Coefficient of Friction

Fig. 9 shows the results of friction measurement as the coefficient of friction at the initial stage of running. It illustrates the effects of substrate surface finish and Hertzian stress on changes in coefficient of friction under partial EHL condition. From the figure it can be seen that under a Hertzian stress of P_H=0.6 GPa, at the start of running, the coefficient of friction was high due to the asperity contacts of the mating surfaces and it decreased rapidly with the number of cycles and came to a steady value. It is considered that substrate surface finish has hardly effect on the coefficient of friction. On the other hand, under a Hertzian stress of P_H=0.8 GPa, at the start of running, the coefficient of friction was high and it followed almost the same trend as before and came to a steady value. But in this case, the coefficient of friction was higher than that under P_H=0.6 GPa. From the obtained results it was confirmed that coefficient of friction is hardly influenced by the substrate surface finish. However, it could be considered that there is a little difference in the coefficient of friction during running-in depending on the running conditions.

Fig. 10 shows the comparison of the friction measurement in the cases of with and without WC cermet coating. From the figure it can be seen that in the test where coated D roller was used, at the start of running, the coefficient of friction was high and it decreased rapidly with the number of cycles and came to a steady value. On the other hand, in the test where non-coated D roller was used, at the start of running, the coefficient of friction was extremely high and it decreased vary rapidly with the number of cycles and came to a steady value. But in this case, the value of the frictional coefficient was much higher than that in the case where coated D roller was used.

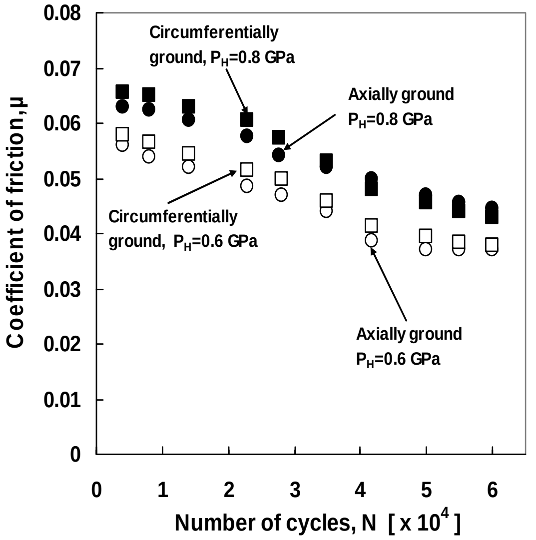


Fig 9. Effects of substrate surface finish and Hertzian stress on changes in coefficient of friction

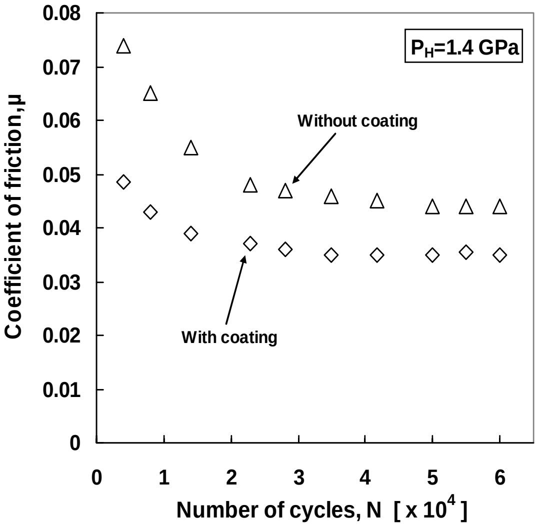


Fig 10. Changes in coefficient of friction: Comparison of with and without WC cermet coating

4. CONCLUSIONS

Using a two-roller testing machine, surface durability of thermally sprayed WC-Cr-Ni cermet coating was investigated under partial EHL condition. The WC cermet coating was formed onto the roller specimens by the high energy type flame spraying (Hi-HVOF) method. Mating the WC cermet coated steel roller with the carburized steel roller without coating, the effects of substrate surface finish and Hertzian stress on the durability of cermet coating were examined. Durability of the steel roller without coating was also examined and compared with that of the coated steel roller. Changes in coefficient of friction and profile curves of the mating surfaces were also examined. The results are summarized and the following conclusions are drawn:

(1) Surface durability of WC cermet coated steel roller was significantly influenced by the substrate surface finish. Under the Hertzian stress of P_H=0.6 GPa, the axially ground substrate roller showed a long life while the circumferentially ground substrate roller showed a short life.

(2) Under the higher Hertzian stress of P_H=0.8 GPa, durability of the cermet coated steel roller was remarkably affected by the substrate surface finish. Namely, flaking of coating was remarkably restrained when the substrate was axially ground whereas life to flaking was very short when the substrate was circumferentially ground.

(3) It was confirmed that durability of WC cermet coated steel roller is much higher than that of steel roller without coating.

(4) It was found that coefficient of friction is significantly influenced by the Hertzian stress and substrate surface finish has no effect on the frictional coefficient.

5. ACKNOWLEDGEMENT

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7. NOMENCLATURE

Symbol	Meaning	Unit
P_H	Hertzian stress	(GPa)
Λ	Oil film parameter	
s	Slip ratio	(%)
N	Number of cycles	
HV	Hardness Vicker's	
Ry	Maximum surface roughness	(μm)
ν	Kinematic viscosity	(mm^2/s)
α	Pressure-viscosity coefficient	(GPa^{-1})