DURABILITY AND TRIBOLOGICAL PROPERTIES OF THERMALLY SPRAYED WC CERMET COATING IN FULL FILM AND PARTIAL EHL CONTACTS

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Abstract: *Durability and tribological properties of thermally sprayed WC-Cr-Ni cermet coating were investigated experimentally under full film and partial elastohydrodynamic lubrication (EHL) conditions. 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 thermally refined carbon steel. The WC cermet coated steel roller was mated with the carburized hardened smooth steel roller under full film EHL condition and carburized hardened rough steel roller under partial EHL condition. It was found that, in general, the coating on the circumferentially ground substrate shows a lower durability compared with that on the axially ground substrate and this difference appears more distinctly for the higher contact pressure for both full film and partial EHL conditions. It was also found that there are significant differences in the tribological properties of WC cermet coating depending on the contact pressure. In addition, depending on the lubrication condition, remarkable differences in the tribological properties were found.*

Keywords: *WC cermet, Full film EHL, Partial EHL, Durability, Tribological properties*

INTRODUCTION

The quest for improving the tribological performance and reliability of the contact machine elements demands new approaches towards material selection and the optimization process. The technology of the surface modification treatments that modifies the contact surface of machine elements and gives rise to the properties such as low friction, high abrasion resistance and high scuffing resistance is making remarkable progress. Overlay coatings, like thermal spraying, have the versatility of coating any material on any substrate. Harada[1] developed new processes so that the coating deposition system can be designed to optimize the velocity and temperature of the spray particles and introduced advanced techniques such as application of heat sources with higher energy and controlling the spray parameters. Knapp and Nitta[2] studied the wear resistance and sliding performance of tungsten carbide (WC) based cermets. Tani et al.[3] studied the properties of thermally sprayed cermet coatings and these coatings can be formed by the conventional type high velocity oxy-fuel flame spraying (HVOF) and by the high energy type flame spraying (Hi-HVOF) processes. Nakajima[4] showed that depending on the roughness of combined surfaces, the pitting-determined lifetime is different for steel rollers. In this paper, the change in the coefficient of friction with the number of cycles and the states of oil film formation between the contacting surfaces was also explained. Yoshida et al.[5] and Ahmed and Hadfield[6,7] investigated the tribological properties and the surface durability of thermally sprayed coatings under rolling/ sliding contact conditions.

Nakajima et al.[8,9] studied the durability of thermally sprayed WC-Cr-Ni cermet coating in lubricated pure rolling or rolling with sliding contact conditions. It was 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. They investigated the effect of substrate surface finish on durability of WC cermet coating under rolling/ sliding contact and depending on the coating thickness, the relation between the depth of flaking or delamination and the substrate surface finish was examined. Using a two-roller testing machine, Nuruzzaman et al.[10,11] investigated the effects of substrate surface finish and substrate material on durability of WC cermet coating. It was clarified that in the case of thermally refined steel substrate, life to flaking of coating is greatly influenced by the substrate surface finish whereas, in the case of induction hardened steel substrate, life to flaking is not influenced by the substrate surface finish. They also examined the durability of thermally sprayed WC cermet coating under partial EHL condition and it was confirmed that durability of coated steel roller is much higher than that of steel roller without coating.

In the present study, experiments were carried out to investigate the durability and tribological properties of thermally sprayed WC-Cr-Ni cermet coating under full film and partial EHL conditions. The coating was formed onto the axially ground and circumferentially ground roller specimens made of thermally refined carbon steel by the high-energy type flame spraying (Hi-HVOF) method. The coated steel roller was mated with the carburized hardened smooth steel roller under full film EHL condition and carburized hardened rough steel roller under partial EHL condition. The effects of substrate surface finish and contact pressure on the durability of WC cermet coating were examined for both full film and partial EHL conditions. Depending on the substrate surface finish, contact pressure and lubrication condition, the tribological properties of WC cermet coating were also examined.

EXPERIMENTAL DETAILS

Test specimen (coated roller) and mating non-coated roller

The substrate material of the test specimen is a thermally refined steel and the coating material is WC-Cr-Ni cermet. The material of the mating non-coated roller is a carburized and hardened chromium molybdenum steel. Chemical compositions of the substrate material and the coating material are shown in Table 1. Chemical composition of the mating non-coated roller is shown in Table 2.

Thermal spraying conditions

By thermal spraying, the WC-Cr-Ni cermet coating was prepared onto the axially ground and circumferentially ground roller specimens made of a thermally refined carbon steel substrate. The coating was formed by means of the high energy type flame spraying (Hi-HVOF) method and the spraying conditions are shown in Table 3.

Specifications of rollers

WC-Cr-Ni cermet coating of about 60 μm in thickness was prepared. After spraying, the contact surface of coated roller was finished smooth to a mirror-like condition with a maximum surface roughness of 0.2 μm by grinding and subsequent polishing. The micro-Vickers hardness of the coating formed by Hi-HVOF was HV≈1120 (test load: 2.94 Newton). The detail specifications of coated roller and mating non-coated roller are shown in Table 4.

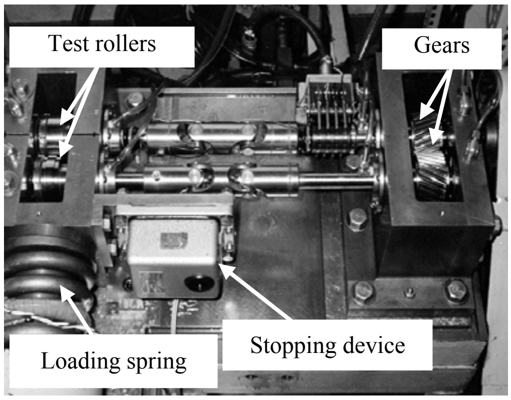

Fig. 1 Two-roller testing machine

Testing machine, test conditions and lubricating oil

Experiments were carried out using a two-roller testing machine which is shown in Fig. 1. In the experiments, using a coil spring the normal load was applied in line contact condition. For full film EHL condition (oil film parameter, $\Lambda>3$), the normal load which gives the Hertzian contact pressure P_H=1.0 GPa or P_H=1.2 GPa was applied. For partial EHL condition (oil film parameter, $\Lambda<1$), the normal load which gives the Hertzian contact pressure P_H=0.6 GPa or P_H=0.8 GPa was applied. In rolling with sliding condition, using the gear ratio 27/31, a slip ratio s=-14.8% was applied.

Table 1: Chemical composition (by mass%) of test specimen (coated roller)

Thermally refined steel (substrate)	**Fe**	**C**	**Si**	**Mn**	**P**	**S**	**Cu**	**Ni**	**Cr**
	Balance	0.44	0.19	0.75	0.01	0.03	0.16	0.50	0.14
Thermally sprayed coating	WC			Cr			Ni		
	Balance			20			7		

Table 2: Chemical composition (by mass%) of mating non-coated roller

Carburized hardened steel	**Fe**	**C**	**Si**	**Mn**	**P**	**S**	**Cu**	**Mo**	**Cr**
	Balance	0.18	0.30	0.90	0.01	0.03	0.10	0.35	1.25

Table 3: Spraying condition

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 coating particles, m/s		1080
Velocity of gas, m/s		2160

* Fuel: Kerosene

Table 4: Specifications of coated and non-coated rollers

Diameter of coated and non-coated rollers, mm	60
Micro-Vickers hardness of coated roller, HV	1120
Micro-Vickers hardness of substrate, HV	290
Micro-Vickers hardness of non-coated roller, HV	800
Surface roughness of the substrate (axial or circumferential), μm	6.0
Surface roughness of coated roller, μm	0.2
Surface roughness of non-coated roller (smooth), μm	0.2
Surface roughness of non-coated roller (rough), μm	4.0
Effective contact width in line contact condition, mm	10
Coating thickness, μm	60

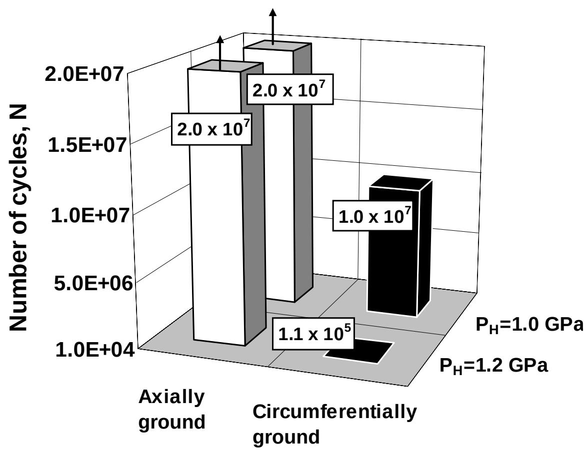

Fig. 2 Effects of substrate surface finish and contact pressure on durability of WC cermet coating (Full film EHL condition, Λ>3)

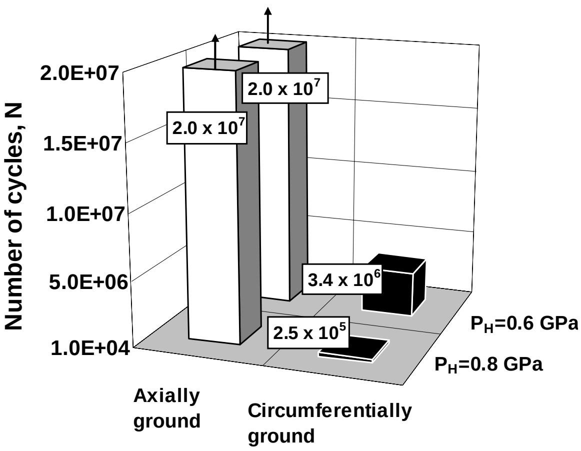

Fig. 3 Effects of substrate surface finish and contact pressure on durability of WC cermet coating (Partial EHL condition, Λ<1)

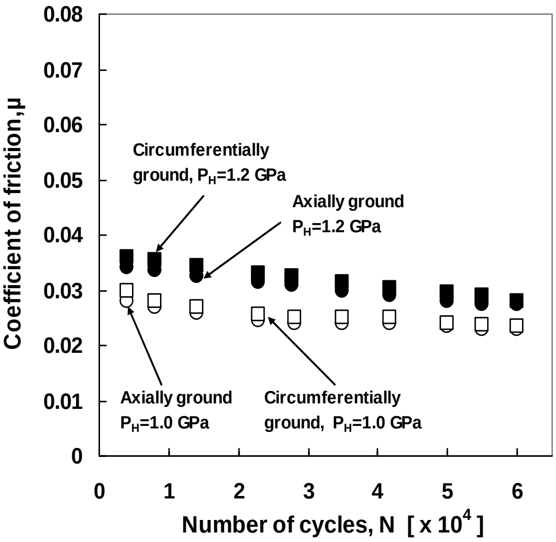

Fig. 4 Effects of substrate surface finish and contact pressure on changes in coefficient of friction (Full film EHL condition, Λ>3)

The testing machine was equipped with an automatic stopping device which worked in response to the abnormal vibration induced by the occurrence of flaking/ delamination of coating. In the tests, durability or life to flaking of coating N is defined as the total number of revolutions of the coated roller. When the testing machine continued to run without any flaking of the coating, the running was discontinued at $N=2.0\times10^7$ cycles. 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) was supplied at a flow rate of 15 cm^3/s and at a constant oil temperature of 318 K. The state of oil film formation with the number of cycles was measured by means of an electric resistance method[12], and the friction force between the coated roller and the non-coated roller was measured by strain gauges.

RESULTS AND DISCUSSION

Fig. 2 shows the effects of substrate surface finish and contact pressure on durability or life to flaking of WC cermet coating. In the experiments, the coated roller was mated with the carburized hardened smooth steel roller (maximum surface roughness=0.2 μm) under full film EHL condition (oil film parameter, Λ>3). From the figure, it is apparent that under a contact pressure of P_H=1.0 GPa, the axially ground substrate roller exhibited a high durability and it was possible to run up to $N=2.0\times10^7$ cycles whereas durability of the circumferentially ground substrate roller was lowered to $N=1.0\times10^7$ cycles. Under a higher contact pressure of P_H=1.2 GPa, durability of the coated roller was remarkably influenced by the substrate surface finish. Namely, the axially ground substrate roller showed a long life up to $N=2.0\times10^7$ cycles whereas the circumferentially ground substrate roller showed a very short life and flaking/delamination of coating occurred at early stage of running $N=1.1\times10^5$ cycles.

Fig. 3 illustrates the effects of substrate surface finish and contact pressure on durability or life to flaking of WC cermet coating. In this case, the coated roller was mated with the carburized hardened rough steel roller (maximum surface roughness=4.0 μm) under partial EHL condition (oil film parameter, Λ<1). From the figure it is apparent that durability of WC cermet coating was significantly influenced by the substrate surface finish. It can be seen that under a contact pressure of P_H=0.6 GPa, the axially ground substrate roller showed a long life up to $N=2.0\times10^7$ cycles whereas the circumferentially ground substrate roller showed a short life $N=3.4\times10^6$ cycles. It can also be seen that for the higher contact pressure of P_H=0.8 GPa, durability of the coated roller was remarkably influenced by the substrate surface finish. Namely, the WC cermet coating on the axially ground substrate showed a long life up to $N=2.0\times10^7$ cycles whereas the coating on the circumferentially ground substrate showed a very short life and flaking occurred at $N=2.5\times10^5$ cycles.

Fig. 4 shows the effects of substrate surface finish and contact pressure on changes in coefficient of friction under full film EHL condition at the initial stage of running. From

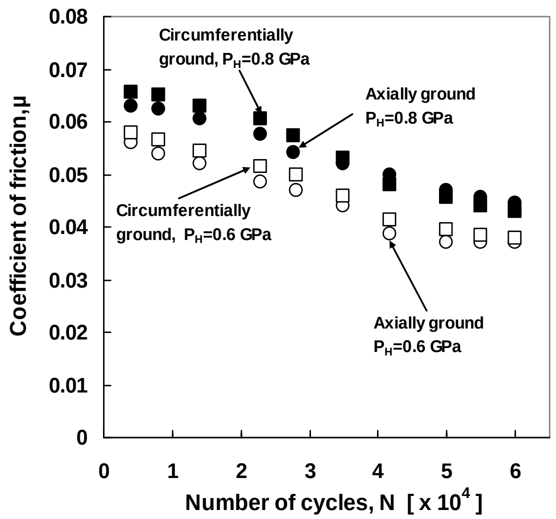

Fig. 5 Effects of substrate surface finish and contact pressure on changes in coefficient of friction (Partial EHL condition, Λ<1)

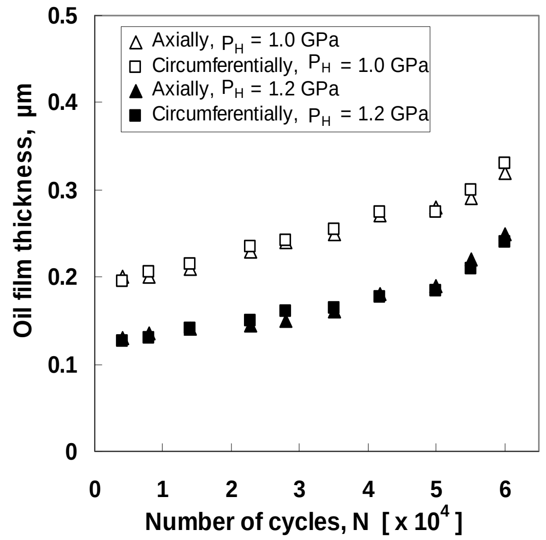

Fig. 6 Effects of substrate surface finish and contact pressure on oil film thickness (Full film EHL condn, Λ>3)

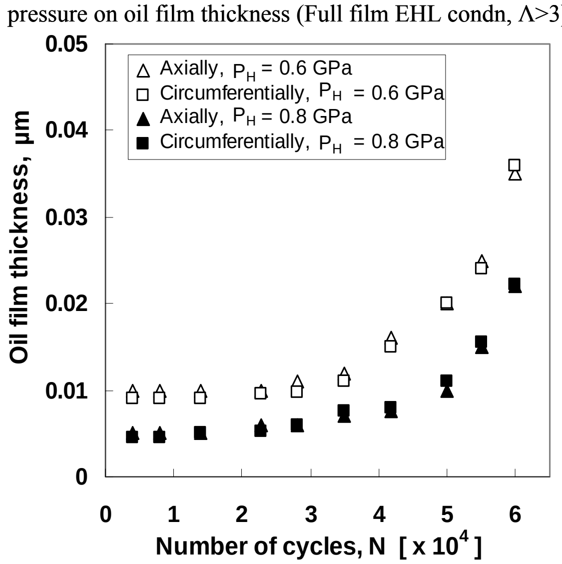

Fig. 7 Effects of substrate surface finish and contact pressure on oil film thickness (Partial EHL condition, Λ<1)

the figure, it is apparent that under a contact pressure of P_H=1.0 GPa, at the start of running, the coefficient of friction was low due to the smooth mating surface and it decreased slowly with the number of cycles and came to a steady value. It is also clear that coefficient of friction was hardly influenced by the substrate surface finish. Under a higher contact pressure of P_H=1.2 GPa, the coefficient of friction was little higher than that under P_H=1.0 GPa and it followed almost the same trend as before. It can also be seen that coefficient of friction was hardly affected by the substrate surface finish. However, it could be considered that there is a very little difference in the coefficient of friction during running-in depending on the running conditions.

Fig. 5 exhibits the results of friction measurement as the coefficient of friction under partial EHL condition at the initial stage of running. From the figure it can be seen that under a contact pressure of P_H=0.6 GPa, at the start of running, the coefficient of friction was high due to the asperity interaction of the rough mating surface and it decreased rapidly with the number of cycles and came to a steady value. It is considered that substrate surface finish has hardly any effect on the coefficient of friction. On the other hand, under a contact pressure 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 and there is a little difference in the coefficient of friction during running-in depending on the running conditions. Comparing these results with the results shown in Fig. 4 it is very clear that in general, the coefficient of friction under partial EHL condition was much higher than that under full film EHL condition.

Fig. 6 shows the effects of substrate surface finish and contact pressure on oil film thickness under full film EHL condition. From the figure it can be seen that at the start of running, the oil film thickness was about 0.2 μm under a contact pressure of P_H=1.0 GPa and during running-in it increased gradually with the number of cycles. It was also found that oil film thickness is hardly influenced by the substrate surface finish. Under a higher contact pressure of P_H=1.2 GPa, at the start of running, oil film thickness was about 0.12 μm which is much lower than that under P_H=1.0 GPa. In this case, oil film thickness followed almost the same trend as before and substrate surface finish had no effect on oil film thickness. However, it is considered that there is a very little difference in the states of oil film formation during running-in depending on the running conditions.

Fig. 7 demonstrates the measurement of oil film thickness under partial EHL condition. At the start of running, the oil film thickness was about 0.009 μm under a contact pressure of P_H=0.6 GPa and it increased very steadily at the initial stage of running but it increased rapidly as the number of cycles increased. Because of the rough mating surface, oil film was thin at the initial stage of running but oil film became thick as the mating surface became smooth with the number of cycles. Under a higher contact pressure of P_H=0.8 GPa and because of the severe asperity interaction of the mating surfaces at the initial stage of running, oil film was very thin and it was about 0.005 μm which is much lower than that under P_H=0.6 GPa. From the figure it is apparent that oil film formation followed almost the same trend as before and substrate surface finish had no effect on

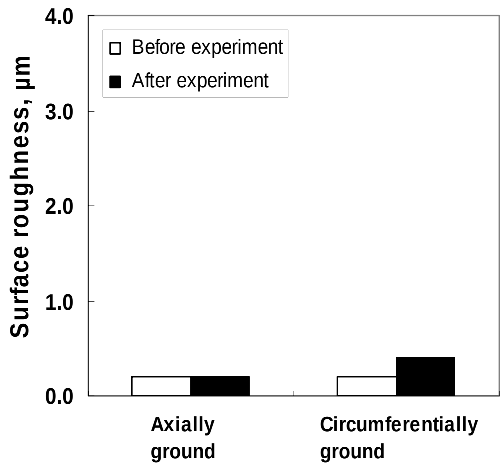

Fig. 8 Effect of substrate surface finish on surface roughness of WC cermet coated roller (Full film EHL condition, Λ>3)

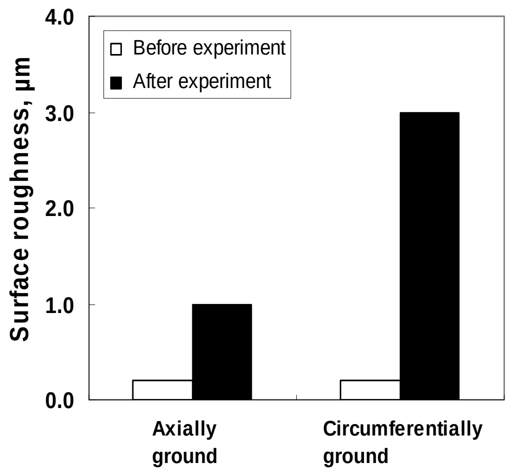

Fig. 9 Effect of substrate surface finish on surface roughness of WC cermet coated roller (Partial EHL condition, Λ<1)

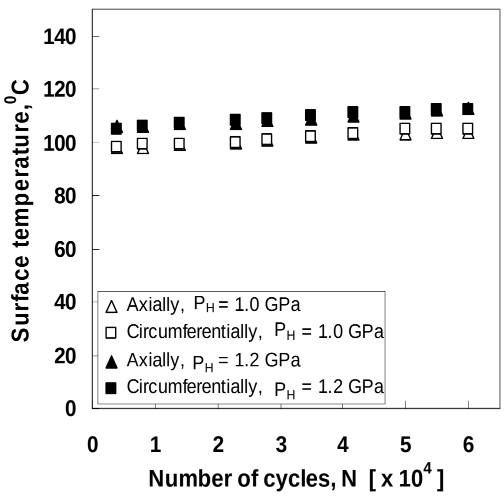

Fig. 10: Effects of substrate surface finish and contact pressure on surface temperature (Full film EHL condition, Λ>3)

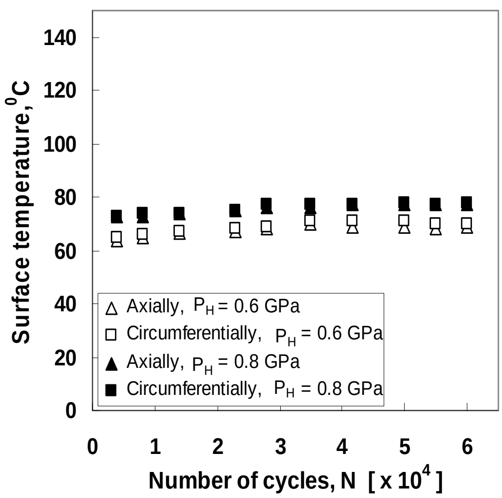

Fig. 11: Effects of substrate surface finish and contact pressure on surface temperature (Partial EHL condition, Λ<1)

oil film thickness. These results also reveal that oil film under partial EHL condition was extremely thin as compared to the oil film under full film EHL condition.

Fig. 8 shows the effect of substrate surface finish on surface roughness of WC cermet coated steel roller. Under full film EHL condition, the coated roller was mated with the carburized hardened smooth steel roller. From the figure it can be seen that in the case of axially ground substrate, before experiment, the surface roughness of coated roller was 0.2 µm and after experiment it was not changed. On the other hand, in the case of circumferentially ground substrate, after running, the surface roughness of coated roller was slightly increased and it became 0.4 µm.

Fig. 9 exhibits the effect of substrate surface finish on surface roughness of WC cermet coated steel roller under partial EHL condition. In this case, the coated roller was mated with the carburized hardened rough steel roller. From the figure it is apparent that in the case of axially ground substrate, before experiment, the surface roughness of coated roller was 0.2 µm whereas after experiment, the surface roughness was significantly increased and it became 1.0 µm. On the other hand, in the case of circumferentially ground substrate, after running, the surface roughness of coated roller was remarkably increased and it became 3.0 µm. Comparing the results shown in Fig. 9 with that shown in Fig. 8 it is apparent that under partial EHL condition, after running, the change in surface roughness of coated roller was distinct but under full film EHL condition, the surface roughness was not much changed.

Fig. 10 illustrates the effects of substrate surface finish and contact pressure on surface temperature of coated roller under full film EHL condition. From the figure it is apparent that at the start of running, the surface temperature was about 100^0C under a contact pressure of P_H=1.0 GPa and it increased steadily with the number of cycles and came to a constant value within a short time. It was also found that the axially ground substrate or circumferentially ground substrate has no effect on the surface temperature. Under a higher contact pressure of

P_H=1.2 GPa, the surface temperature was slightly higher than that under P_H=1.0 GPa and it came to a constant value within a short time as before. Moreover, it was found that substrate surface finish has no effect on the surface temperature.

Fig. 11 shows the results of surface temperature measurement of coated roller under partial EHL condition. From the figure it can be seen that under a contact pressure of P_H=0.6 GPa, at the start of running, the surface temperature was about 64^0C and it increased very steadily with the number of cycles and came to a constant value. Under a higher contact pressure of P_H=0.8 GPa, at the start of running, the surface temperature was about 72^0C and it followed almost the same trend as before. The obtained results reveal that surface temperature is hardly influenced by the substrate surface finish and it only depends on the contact pressure.

CONCLUSIONS

The effects of substrate surface finish and contact pressure on the durability of WC-Cr-Ni cermet coating were investigated for both full film and partial EHL conditions. Depending on the substrate surface finish, contact pressure and lubrication condition, the tribological properties of cermet coating were also examined. The results are summarized as follows:

Thermally sprayed WC-Cr-Ni cermet coating on the axially ground substrate showed higher durability compared with that on the circumferentially ground substrate and this difference appeared more distinctly for the higher contact pressure for both full film and partial EHL conditions.

Coefficient of friction increased with the increase in contact pressure and it was hardly influenced by the substrate surface finish. Moreover, coefficient of friction under partial EHL condition was much higher than that under full film EHL condition.

Oil film thickness decreased with the increase in contact pressure and it was found that substrate surface finish has no effect on oil film thickness. In addition, oil film under partial EHL condition was extremely thin as compared to the oil film under full film EHL condition.

After running, surface roughness of WC cermet coated roller was markedly different depending on the lubrication condition. Under full film EHL condition, generally the surface roughness was not much changed whereas under partial EHL condition, the surface roughness was significantly increased particularly in the case of circumferentially ground substrate.

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