DURABILITY AND TRIBOLOGICAL PROPERTIES OF THERMALLY SPRAYED WC CERMET COATING UNDER LUBRICATED ROLLING-SLIDING CONTACT

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Abstract: Durability and tribological properties of thermally sprayed WC-Cr-Ni cermet coating were investigated experimentally under lubricated rolling with sliding contact conditions. By means of the high energy type flame spraying (Hi-HVOF) method, the coating was formed onto the axially and circumferentially ground roller specimens made of a thermally refined carbon steel. In the experiments, the WC cermet coated steel roller was mated with the carburized hardened steel roller without coating in line contact condition. The coated roller was mated with the smooth non-coated roller under a contact pressure of 1.0 or 1.2 GPa. The coated roller was also mated with the rough non-coated roller under a contact pressure of 0.6 or 0.8 GPa. It was found that the coating on the circumferentially ground substrate shows a lower durability compared with that on the axially ground substrate. This difference appears more distinctly for the higher contact pressure for both smooth and rough mating surface. 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 mating surface roughness or substrate surface finish, remarkable differences in the tribological properties such as oil film formation, surface roughness, appearance of the coated surface ,depth of flaking etc. were found.

Keywords: *Thermally sprayed coating, WC cermet, Durability, Tribological properties*

1. INTRODUCTION

The thermal spraying process is one of the most versatile methods available for deposition of coating materials and it has been applied steadily in various fields of industry as one of the most important material processing or surface modification technologies [1, 2]. In recent years, the quality and reliability of thermally sprayed cermet coatings have been improved remarkably to satisfy the growing needs of the market for high wear resistance of engineering components. Among the cermet coatings, the most attractive proved to be tungsten carbide (WC) based cermets. This is because the hard WC particles lead to high coating hardness while the metal binder supplies the necessary coating toughness, thus forms not only very hard but also tough cermet system, making it suitable for numerous industrial applications to combat wear [3]. Thermally sprayed coatings were deposited using detonation gun (D-Gun) on bearing steel substrate and WC-Co coatings performed better than Al_2O_3 coatings in rolling contact fatigue resistance [4].

During the last 10-15 years, in the field of thermal spraying, main attention has been paid to various high velocity spray processes. The latest coating deposition systems are designed to optimize the velocity and temperature of the spray particles, hence decreasing the level of in-flight chemical reactions and improving the bonding throughout the coating. Experiments were carried out to investigate the rolling contact fatigue (RCF) performance of tungsten carbide cobalt (WC-Co) coatings deposited by the high velocity oxy-fuel (HVOF) process and test results revealed that the performance of the coating is dependent upon the combination of the substrate and the coating properties [5]. Using the conventional HVOF spraying, WC-Cr-Ni cermet coatings were deposited on the steel substrate and durability of the coatings was investigated in lubricated pure rolling or rolling with sliding contact conditions [6]. Test results showed that flaking of coating occurs when the coated roller is placed on the slower side in rolling/sliding contact and the life to flaking increases as the coating thickness is increased. Based on the theoretical analysis, the authors also discussed the durability of the coatings. The influence of spray parameters on the particle in-flight properties and coating properties during HVOF spraying of WC-CoCr powder was investigated [7]. It was found that the spray parameters such as the total gas flow rate, the powder feed rate and the spray distance influenced the particle properties and the coating properties to different degrees. In general, the higher the total gas flow rate, the lower powder feed rate and the shorter the spray distance, the higher the particle velocity and temperature. Moreover, the coating hardness increased with increasing the particle temperature and velocity and the coating porosity decreased. Experiments were carried out to investigate the relative RCF performance and failure modes of as-sprayed and post-treated functional graded WC-NiCrBSi coatings deposited on bearing steel substrates by JP5000 HVOF system [8, 9]. Hot Isostatically Pressed (HIPed) and vacuum heating are two types of post-treatments were adapted for this investigation. It was found that the performance of the coating is highly dependent on the microstructural changes due to post-treatment. Coatings heat-treated at elevated temperature 1200^0C exhibited superior RCF performance over the as-sprayed coatings in full film elastohydrodynamic lubrication. Moreover, in RCF tests, coatings HIPed at 850^0C showed no improvement in performance over the as-sprayed coatings. In addition, failure modes were significantly different depending on the contact stress. By means of high energy type flame spraying (Hi-HVOF), WC-Cr-Ni cermet coatings were deposited on the thermally refined steel substrate or induction hardened steel substrate [10]. In this investigation, the effects of substrate surface finish, substrate material and coating thickness on the durability of coating were examined under rolling/sliding contact. The effects of substrate surface finish and coating thickness on the durability of coating were also explained theoretically by elastic-plastic analysis of the subsurface layer. Experiments were carried out to investigate the durability of thermally sprayed WC cermet coating under partial elastohydrodynamic lubrication (EHL) condition [11]. It was confirmed that durability of cermet coated steel roller is much higher than that of steel roller without coating. Thermally sprayed WC-Cr-Ni cermet coatings were deposited on the steel substrates by means of Hi-HVOF spraying and durability of the coatings was investigated under lubricated rolling with sliding contact [12]. Experimental results showed that durability of the coatings is significantly influenced by the substrate surface finish and substrate material. In addition, the elastic-plastic behaviour of the subsurface layer under repeated rolling/sliding contact was analyzed using a finite element method (FEM) and the effects of substrate surface finish and substrate material on the durability of coating were discussed.

In the present study, durability and tribological properties of Hi-HVOF sprayed WC-Cr-Ni cermet coating were investigated experimentally under lubricated rolling/sliding contact. The coatings were deposited onto the axially ground and circumferentially ground roller specimens made of thermally refined carbon steel. The cermet coated steel roller was mated with the carburized hardened non-coated steel roller in line contact condition. The effects of substrate surface finish and contact pressure on the durability of WC cermet coating were examined for both smooth mating surface and rough mating surface. The effects of mating surface roughness, contact pressure and substrate surface finish on the tribological properties of WC cermet coating were also examined.

2. Experimental Details

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

The substrate material of the test specimen is thermally refined steel and the coating material is WC-Cr-Ni cermet. The material of the mating non-coated roller is 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.

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

	Fe	C	Si	Mn	P	S	Cu	Ni	Cr
Thermally refined steel (substrate)	Balance	0.44	0.19	0.75	0.01	0.03	0.16	0.50	0.1 4

	WC	Cr	Ni
Thermally sprayed coating	Balance	20	7

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

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

2.2 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.

2.3 Specifications of rollers

WC-Cr-Ni cermet coating of about 60 μm and 110 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 maximum surface roughness of smooth non-coated roller was 0.2 μm and rough non-coated roller was 4.0 μm. The detail specifications of coated roller and mating non-coated roller are shown in Table 4.

Table 3: 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 coating particles, m/s		1080
Velocity of gas, m/s		2160

- Fuel: Kerosene

2.4 Testing machine, test conditions and lubricating oil

Experiments were carried out using a two-roller testing machine which is shown in Figure 1. In the experiments, using a coil spring the normal load was applied in line contact condition. For smooth mating surface, the normal load which gives the Hertzian contact pressure P_H=1.0 GPa or P_H=1.2 GPa was applied. For rough mating surface, 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 4: Specifications of coated and non-coated rollers

Diameter of coated and non-coated rollers, mm	60
Micro-Vickers hardness of coated roller, HV (load: 2.94 N)	1120
Micro-Vickers hardness of steel substrate, HV (load: 2.94 N)	290
Micro-Vickers hardness of non-coated roller, HV (load: 2.94 N)	800
Surface roughness of the substrate (axial or circumferential), μm	7.0
Surface roughness of coated roller, μm	0.2
Surface roughness of smooth non-coated roller, μm	0.2
Surface roughness of rough non-coated roller, μm	4.0
Effective contact width in line contact condition, mm	10
Coating thickness, μm	60, 110

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 extreme pressure (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 electrical contact resistance method [13], and the friction force between coated roller and non-coated roller was measured by strain gauges.

3. Results and Discussion

Figure 2a 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. 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. In this case, the coating thickness was 60 μm. Under a higher contact pressure of $P_H=1.2$ GPa, durability of the coated roller was remarkably influenced by the substrate surface finish even though the coating thickness was 110 μm. 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.

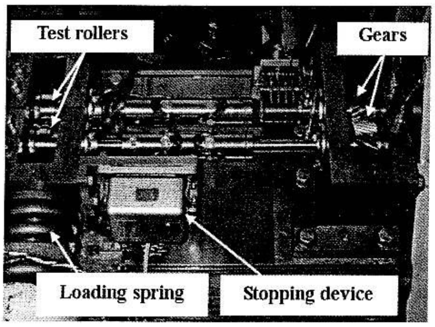


Fig. 1: Two-roller testing machine.

Figure 2b also 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) and when the coating thickness was 60 μm. From the figure it is apparent that durability of WC cermet coating was significantly influenced by the substrate surface finish and contact pressure. 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=2.0×10^7 cycles whereas the circumferentially ground substrate roller showed a short life N=3.4×10^6 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=2.0×10^7 cycles whereas the coating on the circumferentially ground substrate showed a very short life and flaking of coating occurred at N=2.5×10^5 cycles.

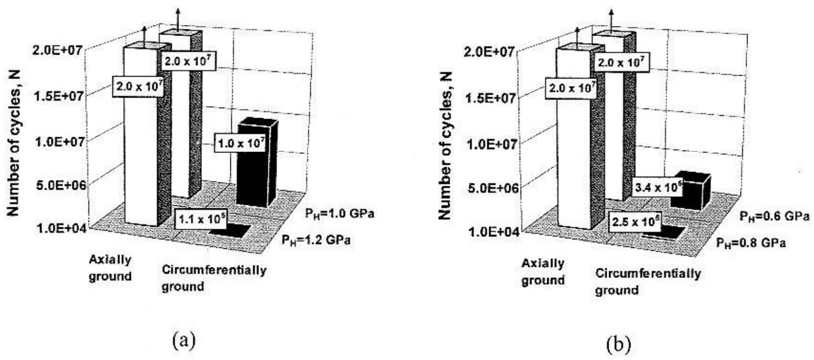


Fig. 2: Effect of substrate surface finish and contact pressure on durability of WC cermet coating for (a) smooth mating surface and (b) rough mating surface.

Figure 3a shows the effects of substrate surface finish and contact pressure on changes in coefficient of friction in the case of smooth mating surface. From 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 surface roughness of the contacting surfaces and oil viscosity.

Figure 3b shows the effects of substrate surface finish and contact pressure on changes in coefficient of friction for rough mating surface. As shown in the figure, under a contact pressure of P_H=0.6 GPa, at the start of running, the coefficient of friction was high due to much asperity interactions of the contacting surfaces and it decreased rapidly owing to the decrease in the mating surface roughness with the number of cycles and became steady. On the other hand, under a higher contact pressure of P_H=0.8 GPa, at the start of running, the coefficient of friction was higher due to severe asperity interactions of the contacting surfaces and it followed almost the same trend as before and became steady. Figure 3b showed that the coefficient of friction was lower for P_H=0.6 GPa. From the obtained results it was observed that coefficient of friction is hardly influenced by the substrate surface finish. There is a little difference in the coefficient of friction during running-in depending on the running conditions and mating surface roughness. Comparing these results with the results shown in Figure 3a it is clear that, due to high asperity interactions of the contacting surfaces, the coefficient of friction for the rough mating surface was higher than that for the smooth mating surface.

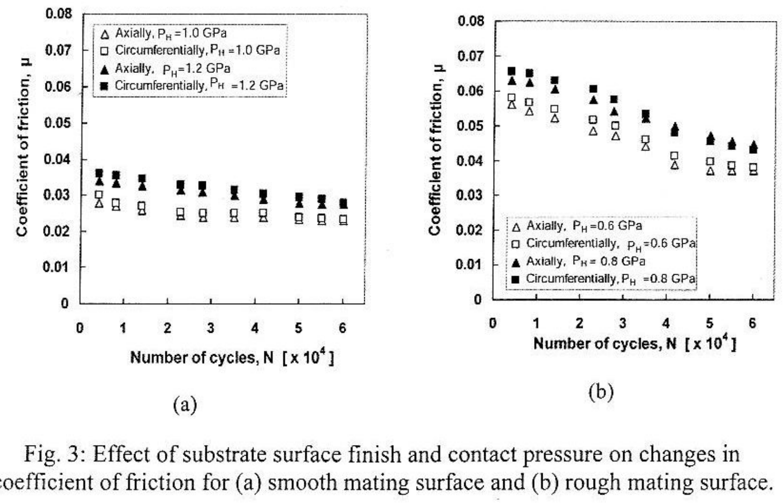


Fig. 3: Effect of substrate surface finish and contact pressure on changes in coefficient of friction for (a) smooth mating surface and (b) rough mating surface.

Figure 4a shows the variation in electrical contact voltage between rollers with the number of cycles in the case of smooth mating surface. These results were the measurements of the state of oil film formation using the electrical contact resistance method. During running-in, the variations of average electrical contact voltage which corresponds to the changes in the electrical contact resistance arising from the formation/breakdown of oil film were plotted. In the figure, contact voltage=0 mV represents metal-to-metal contact, while contact voltage=15 mV indicates complete separation of the surfaces by oil film. As shown in the figure, at the very early stage of running, the contact voltage was about 6.0 mV under a contact pressure of P_H=1.0 GPa and during running-in it increased quickly with the number of cycles. It was also found that oil film formation is hardly influenced by the substrate surface finish. Under a higher contact pressure of P_H=1.2 GPa, the voltage showed lower value due to more asperity interaction during running-in. At the early stage of running, the contact voltage showed nearly 3.0 mV and the formation of oil film showed almost the same trend as before. From the obtained results it can be observed that the process of oil film formation is hardly affected by the substrate surface finish. However, there is little difference in the state of oil film formation during running-in depending on the surface roughness of the contacting surfaces and oil viscosity.

Figure 4b represents the measurements of the electrical contact voltage and these results indicate the process of oil film formation in the case of rough mating surface. As described before, contact voltage=0 mV indicates contact, while contact voltage=15 mV indicates separation. As is apparent from the figure, at the very early stage of running, the separation voltage was low due to much asperity interactions of the contacting surfaces and it was about 1.0 mV under a contact pressure of P_H=0.6 GPa and it increased very steadily with the number of cycles. Under a higher contact pressure of P_H=0.8 GPa and due to severe asperity contacts, immediately after the start of running, the contact voltage was very near to zero or extremely low value and then the voltage rose very steadily with the number of cycles. From the obtained results it could be considered that oil film formation is hardly influenced by the substrate surface finish. Comparing these results with the results shown in Figure 4a it can be observed that in general, due to severe asperity interactions of the contacting surfaces, the contact voltage was much lower for the rough mating surface than that for the smooth mating surface.

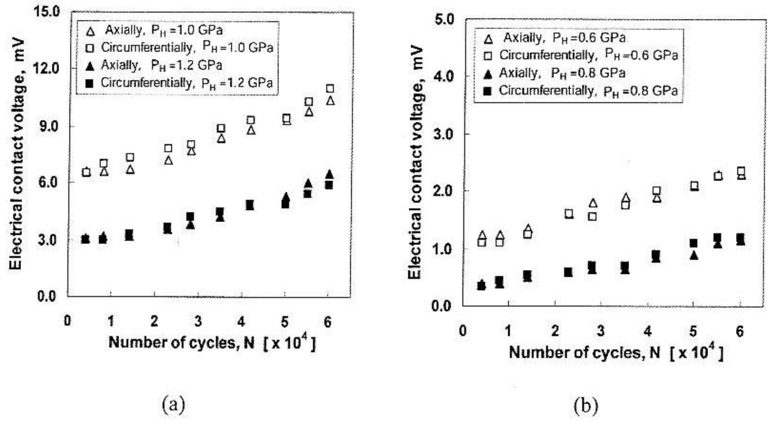
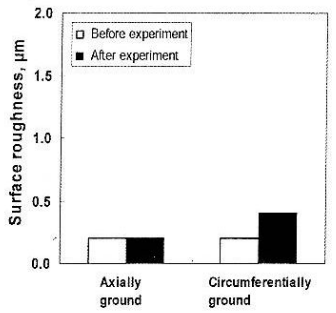


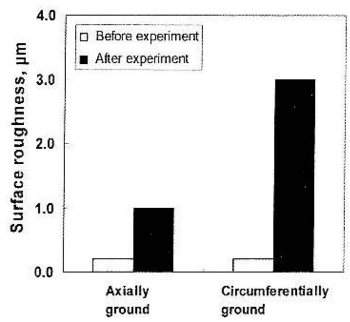
Fig. 4: Variation in electrical contact voltage between rollers with the number of cycles for (a) smooth mating surface and (b) rough mating surface.

Figure 5a shows the effect of substrate surface finish on surface roughness of WC cermet coated roller. In this case, 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.

Figure 5b exhibits the effect of substrate surface finish on surface roughness of WC cermet coated roller and 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 these results with those shown in Figure 5a it is apparent that, after running, the change in surface roughness of coated roller was distinct in the case of rough mating surface but the surface roughness of coated roller was not much changed in the case of smooth mating surface.



(a)



(b)

Fig. 5: Effect of substrate surface finish on surface roughness of WC cermet coated roller for (a) smooth mating surface and (b) rough mating surface.

Figure 6a illustrates the effects of substrate surface finish and contact pressure on surface temperature of coated roller in the case of smooth mating surface. 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 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.

Figure 6b shows the results of surface temperature measurement of coated roller in the case of rough mating surface. 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. Comparing these results with those shown in Figure 6a it is very clear that surface temperature was much influenced by the contact pressure.

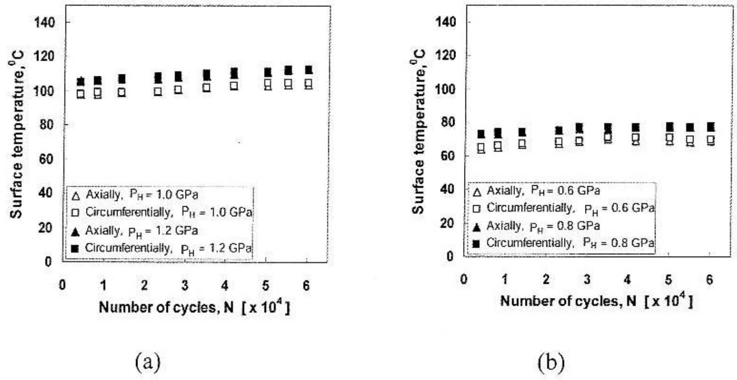
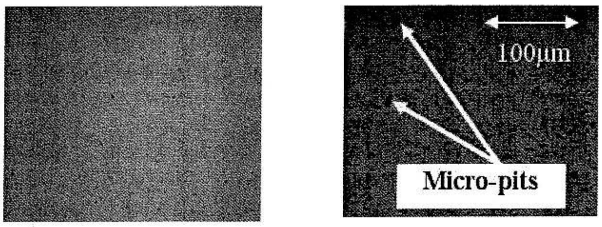


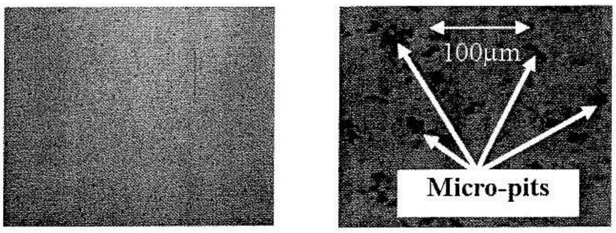
Figure 6. Effects of substrate surface finish and contact pressure on surface temperature for (a) smooth mating surface and (b) rough mating surface.

Figure 7 shows the photomicrographs of the coated surface before and after running and in the case of axially ground substrate. After thermal spraying, the contact surface of the WC cermet coated roller was ground and polished to a mirror-like finish and the surface was magnified by an optical microscope as shown in figure (before running). As shown in the Figure 7(a), after running, the coated roller only underwent minor surface changes when the mating surface was smooth. In this case, few micro-pits were observed on the coated surface. Moreover, it was found that there is no weight loss from the coated roller. On the other hand, it can be seen from Figure 7(b) that after running, the coated roller underwent some surface changes when the mating surface was rough. In this case, numerous randomly spread micro-pits were found on the coated surface but any surface damage or surface distress was not observed. It was also found that there is no weight loss from the coated roller.



Before running After running

(a)



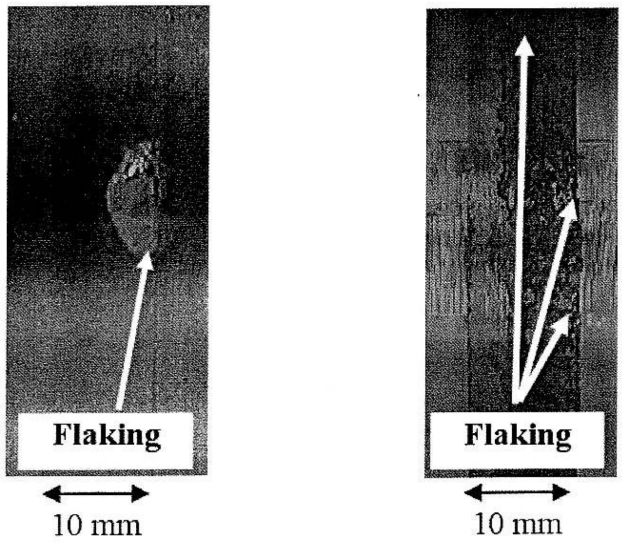
Before running After running

(b)

Fig. 7: Optical micrograph of the coated surface of axially ground substrate for (a) smooth mating surface and (b) rough mating surface

Figure 8 shows typical photographs of the flaked/damaged surface in the case of circumferentially ground substrate. As shown in the Figure 8(a), for the smooth mating surface, flaking occurred on the thermally sprayed coated roller close to the end of the contact surface and the development of the flaking was not over the contact surface. In this case, the weight loss from the coated roller was approximately 0.07 gm. On the other hand, for the rough mating surface, flaked/damaged surface is shown in Figure 8(b). In this case, appearance of damage or flaking of the coating was observed over the entire contact surface and the weight loss from the coated roller was approximately 0.23 gm.

Figure 9 shows the results of depth of flaking developed on the thermally sprayed coated roller when the substrate surface was circumferentially ground. The results are shown for the experiments performed at P_H=1.0 or 1.2 GPa in the case of smooth mating surface (from Figure 2a) and at P_H=0.6 or 0.8 GPa in the case of rough mating surface (from Figure 2b). From the figure it is apparent that depth of flaking was very deep from the contact surface of the coated roller and it was about 500 μm for both the experiments in the case of smooth mating surface. On the other hand, depth of flaking was shallow and it was about 60 μm for both the experiments in the case of rough mating surface.



(a) (b)

Fig.8: Photographs of flaked/damaged surface of circumferentially ground substrate for (a) smooth mating surface and (b) rough mating surface.

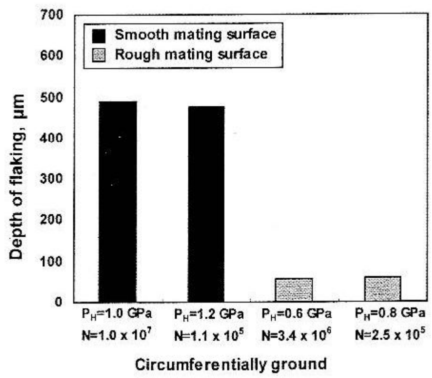


Fig. 9: Effects of smooth mating surface and rough mating surface on depth of flaking for circumferentially ground substrate.

4. Conclusions

The effects of substrate surface finish and contact pressure on durability and tribological properties of cermet coating were investigated for both smooth and rough mating surface. The following conclusions can be drawn from the result of this present study.

1) Coating on the axially ground substrate showed higher durability compared to circumferentially ground substrate. This difference appeared more distinctly for the higher contact pressure for both smooth and rough mating surface.

2) Coefficient of friction increased with the increase in contact pressure especially for rough mating surface. Oil film developed more quickly in the case of smooth mating surface than that for the rough mating surface and oil film formation was significantly influenced by the contact pressure. Moreover, coefficient of friction and oil film formation was not influenced by the substrate surface finish.

3) After running, the surface roughness of circumferentially ground substrate was increased significantly especially in the case of rough mating surface.

4) There was no flaking or damage for the pair of circumferentially ground substrate and smooth mating surface. Whereas flaking occurred over the entire contact surface when the mating surface was rough.

5) In addition, depth of flaking on the coated roller was deeper for smooth mating surface than rough mating surface.

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