CHARACTERISTICS OF THERMALLY SPRAYED WC CERMET COATING UNDER LUBRICATED ROLLING WITH SLIDING CONTACT

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Abstract: ***T****he characteristics of thermally sprayed WC-Cr-Ni cermet coating under lubricated rolling with sliding contact condition were examined experimentally. Experiments were performed using a two-roller testing machine. The coating was formed onto the blasted or ground roller specimens made of thermally refined carbon steel or induction hardened carbon steel by high energy type flame spraying (Hi-HVOF). A mirror-like finished cermet coated steel roller was mated with a non-coated carburized hardened steel roller. In the case of thermally refined steel substrate and for the mating surface roughness* R_{max}*=0.1 µm, coating on the ground substrate showed lower durability than that on the blasted substrate. For the mating surface roughness* R_{max}*=3.0 µm, coating on the ground substrate showed an extremely short life as compared with that on the blasted substrate. In general, durability of cermet coating was greatly increased due to the increase in the coating thickness. In the case of induction hardened steel substrate, coating on the blasted or ground substrate showed high durability for both* R_{max}*=0.1 µm and 3.0 µm. Coefficient of friction and oil film thickness were markedly influenced by the mating surface roughness but these were hardly affected by the substrate material. In addition, depending on the mating surface roughness, significant differences in the surface roughness of coated roller and depth of flaking on the coated roller were found.*

Keywords: *WC cermet, Mating surface roughness, Substrate surface kind, Substrate material*

INTRODUCTION

Modern technology is continually demanding low friction and high wear-resistant materials and ways to modify surface characteristics for the purpose of improving the rolling contact life of machine elements. In recent years surface modification technologies are going with a remarkable progress. Thermal spraying is one of the most important material processing or surface modification technologies and new advances in the technology have extended the applications of thermally sprayed coatings in various fields of industry to enhance the wear resistance of engineering components[1]. Cermets are widely used in many engineering applications for their high levels of wear resistance. Among them, the most attractive is the tungsten carbide (WC) based cermets because of the high hardness of the carbide[2]. Cermet coatings can be formed using advanced techniques and can be prepared by high velocity oxy-fuel flame spraying (HVOF) and high-energy type flame spraying (Hi-HVOF) processes[3]. However, there are only a limited number of investigations on the tribological properties of these thermally sprayed cermet coatings under rolling with sliding contact conditions[4-6].

Recently, the effects of coating thickness and slip ratio on durability of HVOF sprayed WC-Cr-Ni cermet coating were investigated under lubricated rolling/sliding contact conditions[7]. It was found that durability of cermet coating is significantly influenced by the slip ratio and coating thickness. The influence of spray parameters on the particle in-flight properties and coating properties during HVOF spraying of WC cermet powder was investigated[8]. It was found that the spray parameters such as the total gas flow rate, the powder feed rate and the spray distance influence the particle properties and the coating properties to different degrees. Durability of WC cermet coating was examined under lubricated rolling with sliding contact[9]. It was found that durability is significantly influenced by the substrate surface finish. Surface durability of WC cermet coated steel roller was examined and compared with that of non-coated steel roller[10]. It was found that life to flaking of coated roller is much higher than that of non-coated roller. It was also found that life to flaking of coated roller is greatly influenced by the substrate hardness. Effect of contact pressure on durability or life to flaking of thermally sprayed WC cermet coating was examined under partial elastohydrodynamic lubrication (EHL) condition[11]. It was shown that contact pressure and substrate surface finish has significant effect on the durability of WC cermet coating.

In the present investigation, WC-Cr-Ni cermet coating was formed onto the blasted or ground roller specimens made of thermally refined carbon steel or induction hardened carbon steel by means of high energy type flame spraying (Hi-HVOF). A mirror-like finished coated steel roller was mated with a non-coated carburized hardened steel roller under lubricated rolling with sliding contact condition. The effects of mating surface roughness, substrate surface kind, substrate material and coating thickness on the surface durability of coated roller were investigated. In addition, tribological properties such as coefficient of friction, oil film thickness, surface roughness of coated roller and depth of flaking were examined.

EXPERIMENTAL DETAILS

Test specimen (coated roller) and mating non-coated roller: Experiments were carried out combining coated and non-coated rollers under rolling/sliding contact. The substrate material of the test specimen is thermally refined carbon steel or induction hardened carbon steel. The coating material is WC-Cr-Ni cermet. Chemical compositions of the substrate material and the coating material are shown in Table 1. The material of the mating non-coated roller is carburized and hardened chromium molybdenum steel. Chemical composition of the mating non-coated roller is shown in Table 2.

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

Thermally refined steel or induction hardened steel (substrate)	**Fe**	**C**	**Si**	**Mn**	**P**	**S**	**Cu**	**Ni**	**Cr**
	Balance	0.44	0.19	0.75	0.01	0.03	0.16	0.5	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

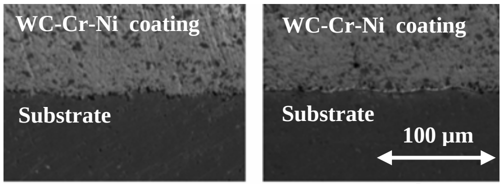
Table 3: Spraying conditions

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

Table 4: Specifications of the coated and the non-coated rollers

Diameter of the coated and the non-coated rollers, mm	60
Micro-Vickers hardness of the coated (Hi-HVOF) roller, HV	1150
Micro-Vickers hardness of the substrate (thermally refined), HV	310
Micro-Vickers hardness of the substrate (induction hardened), HV	640
Micro-Vickers hardness of the non-coated roller, HV	780
Surface roughness of the substrate (blasted or ground), R_{max}, µm	5.0
Surface roughness of the coated roller, R_{max}, µm	0.2
Surface roughness of the non-coated roller (smooth), R_{max}, µm	0.1
Surface roughness of the non-coated roller (rough), R_{max}, µm	3.0
Effective track width in line contact condition, mm	10
Coating thickness, µm	60, 110, 210



Blasted **Ground**

Figure 1: Cross-sections of thermally sprayed cermet coating

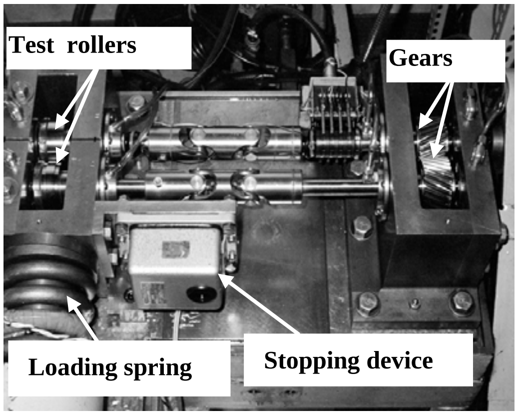


Figure 2: Two-roller testing machine

Substrate surface preparation, spraying conditions and specifications of rollers: Before application of thermally sprayed coating on the steel substrate, the substrate surface was prepared so that coating material can adhere to the substrate material. Two types of substrate surfaces were prepared by shot-blasting and circumferential grinding. After surface preparation, the maximum surface roughness was 5.0 µm for blasted surface or ground surface. After that, WC-Cr-Ni cermet coating was formed onto the blasted substrate or ground substrate by high-energy type flame spraying (Hi-HVOF). The cross-sections of thermally sprayed coating for blasted substrate and ground substrate are shown in Fig. 1 and the Hi-HVOF spraying conditions are shown in Table 3. The coatings of about 60, 110 and 210 µm thickness were prepared. The contact surface of coated roller was finished smooth to mirror-like condition with a maximum surface roughness, R_{max}=0.2 µm by grinding and subsequent polishing. The micro-Vickers hardness of the coating formed by Hi-HVOF was HV≈1150 (test load: 2.94 N). The detail specifications of coated roller and mating non-coated roller are shown in Table 4.

Testing machine, lubricant and test conditions: Experiments were performed using a two-roller testing machine as shown in Fig. 2. In the experiments, test rollers were rotated under rolling/sliding contact conditions and using a coil spring the normal load was applied in line contact. 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 to $N=2.0\times10^7$ cycles.

A paraffinic mineral oil without extreme pressure (EP) additives (kinematic viscosity: 62.9 mm^2/s at 313 K, 8.5 mm^2/s at 373 K, pressure-viscosity coefficient: 13.3 GPa^{-1} at 313 K) was used as lubricant. The oil flow rate was 15 cm^3/s and oil temperature was maintained at 318 K. During running-in, the state of oil film formation between rollers was continuously monitored by means of an electric resistance method[12]. The friction force between the coated roller and the non-coated roller was measured using strain gauges. Tests were conducted in rolling with sliding contact condition, and using the gear ratio of 27/31, a slip ratio s=-14.8% was applied. Normal loads giving Hertzian contact pressure P_H=0.8, 1.0, 1.2 and 1.4 GPa were applied. In the experiments, the coated roller was mated with the smooth (maximum surface roughness R_{max}=0.1 µm) and rough (maximum surface roughness R_{max}=3.0 µm) non-coated rollers.

RESULTS AND DISCUSSION

Figure 3 shows the effect of mating surface roughness and substrate surface kind on durability or life to flaking of WC cermet coating in the case of thermally refined steel substrate at a coating thickness of 60 µm. In the case of smooth mating surface where the maximum surface roughness R_{max}=0.1 µm and P_H=1.0 GPa, the coated roller showed high durability and it was possible to run over $N=2.0\times10^7$ cycles for blasted substrate whereas the coated roller showed a shorter life $N=1.0\times10^7$ cycles for ground substrate. In the case of rough mating surface where the maximum surface roughness R_{max}=3.0 µm and P_H=0.8 GPa, durability or life to flaking of the coating occurred at $N=1.2\times10^7$ cycles for blasted substrate. On the other hand, coating on the ground substrate showed an extremely short life and flaking/delamination of the coating occurred at early stage of running $N=2.5\times10^5$ cycles.

Figure 4 represents the effect of coating thickness and substrate surface kind on durability or life to flaking of WC cermet coating. Results are shown (from Fig. 3) for R_{max}=3.0 µm and the coating thickness 60 µm. From the figure it is very clear that due to the increase in the coating thickness from 60 µm to 110 µm, durability of coating was significantly increased. Namely, due to the increased thickness, the blasted substrate roller showed an improved life from $N=1.2\times10^7$ cycles to $N=2.0\times10^7$ cycles and durability of ground substrate roller was remarkably improved from $N=2.5\times10^5$ cycles to $N=2.0\times10^7$ cycles. Moreover, with the increased coating thickness, the effect of substrate surface kind on durability was hardly recognized.

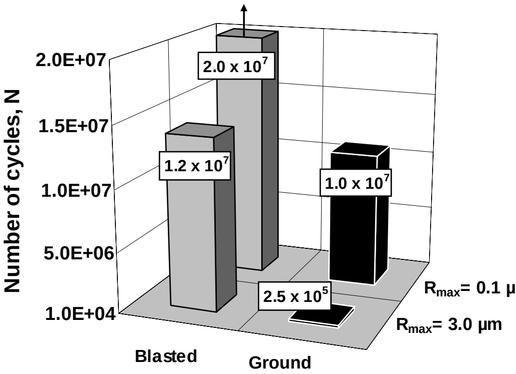


Figure 3: Effect of mating surface roughness and substrate surface kind on durability of WC cermet coating (Thermally refined)

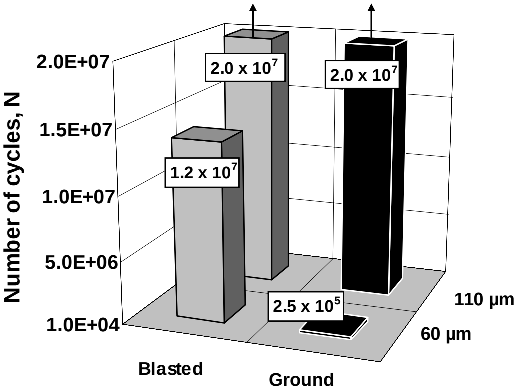


Figure 4: Effect of coating thickness and substrate surface kind on durability of WC cermet coating (R_{max}=3.0 µm, Thermally refined)

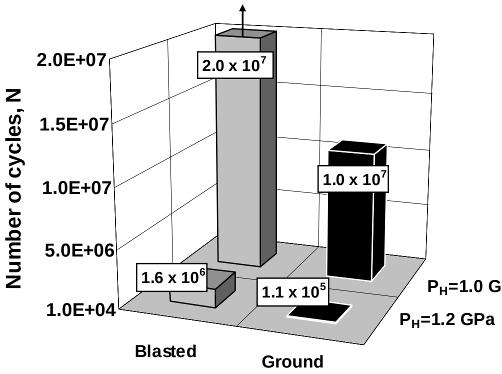


Figure 5: Effect of contact pressure and substrate surface kind on durability of WC cermet coating (R_{max}=0.1 µm, Thermally refined)

Figure 5 exhibits the effect of contact pressure and substrate surface kind on surface durability of coated roller for mating surface roughness R_{max}=0.1 µm in the case of thermally refined steel substrate. Under P_H=1.0 GPa, the blasted substrate roller showed a long life over $N=2.0\times10^7$ cycles but the ground substrate roller showed a short life $N=1.0\times10^7$ cycles when the coating thickness was 60 µm. Under P_H=1.2 GPa, both blasted and ground substrate rollers generally exhibited very short life particularly the ground substrate roller showed an extremely short life $N=1.1\times10^5$ cycles even when the coating thickness was 110 µm.

Figure 6 illustrates the effect of coating thickness and substrate surface kind on durability of cermet coating in the case of thermally refined steel substrate. Results are shown (from Fig. 5) for R_{max}=0.1 µm and the coating thickness of 110 µm. It can be observed that due to the increase in the coating thickness from 110 µm to 210 µm, durability of coating was remarkably improved for blasted substrate or ground substrate and life was prolonged up to $N=2.0\times10^7$ cycles without flaking/delamination of the coating.

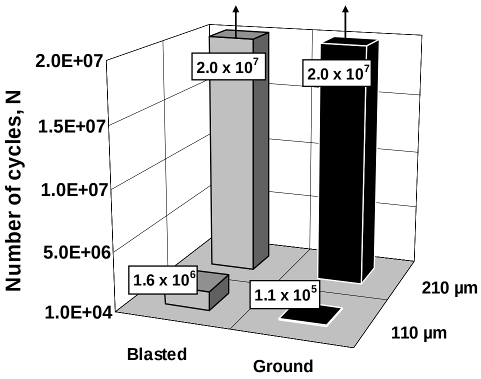


Figure 6: Effect of coating thickness and substrate surface kind on durability of WC cermet coating (R_{max}=0.1 µm, Thermally refined)

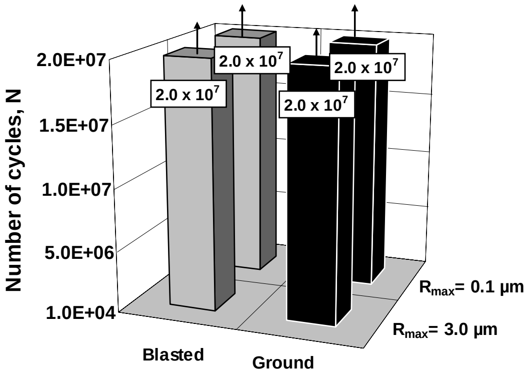


Figure 7: Effect of mating surface roughness and substrate surface kind on durability of WC cermet coating (Induction hardened)

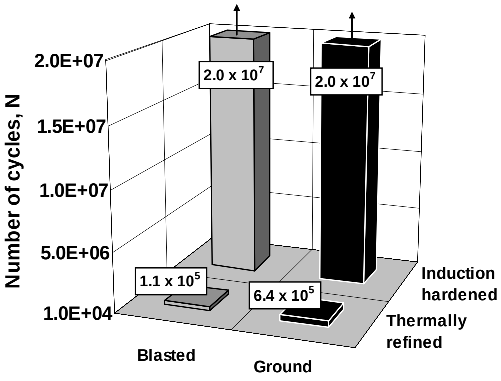


Figure 8 Effect of substrate material and substrate surface kind on durability of WC cermet coating (P_H=1.4 GPa, R_{max}=0.1 µm)

Moreover, because of the increased coating thickness, durability was hardly affected by the substrate surface kind.

Figure 7 represents the effect of mating surface roughness and substrate surface kind on durability in the case of induction hardened steel substrate under P_H=1.4 GPa and with the coating thickness 60 µm. As shown in the figure, for the smooth mating surface (R_{max}=0.1 µm), durability of coating was prolonged and it was possible to run over N=2.0×10^7 cycles for blasted substrate or ground substrate. It can also be seen that for rough mating surface (R_{max}=3.0 µm), cermet coating again showed a high durability for blasted substrate or ground substrate and the effect of substrate surface kind on flaking/delamination of the coating was hardly recognized.

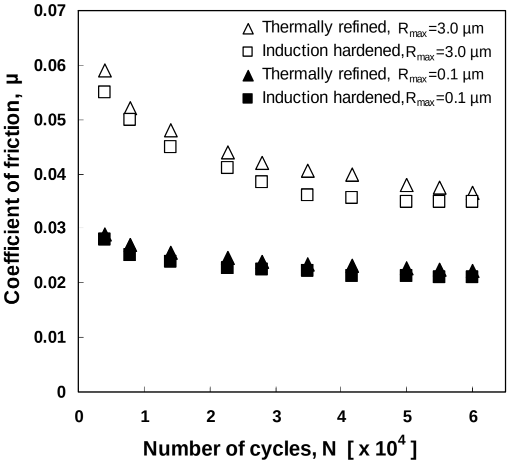


Figure 9: Effect of mating surface roughness and substrate material on change in the coefficient of friction (P_H=1.4 GPa)

Fig. 8 shows the effect of substrate material and substrate surface kind on durability of WC cermet coating under a contact pressure of P_H=1.4 GPa for R_{max}=0.1 µm. As is apparent from the figure, durability was remarkably influenced by the substrate material. Namely, in the case of induction hardened steel substrate, cermet coating exhibited a long life over N=2.0×10^7 cycles and durability was not affected by the substrate surface kind when the coating thickness was 60 µm. On the other hand, in the case of thermally refined steel substrate, coating showed extremely short life and flaking of coating occurred at early stage running for both blasted substrate and ground substrate even when the coating thickness was 210µm.

Figure 9 illustrates the effect of mating surface roughness and substrate material on change in the coefficient of friction. From the figure it can be observed that for rough mating surface (R_{max}=3.0 µm) and in the case of thermally refined steel substrate, at the start of running, the coefficient of friction was high which was about 0.06 and it decreased very rapidly with the number of cycles and came to a steady value within a short time. In the case of induction hardened steel substrate, the coefficient of friction showed almost the same value and same trend with the number of cycles as before. On the other hand, for smooth mating surface (R_{max}=0.1 µm), at the start of running, the coefficient of friction was low which was about 0.03 and decreased slowly with the number of cycles and came to a steady value. Moreover, depending on the substrate material, the coefficient of friction was almost identical.

Figure 10 represents the effect of mating surface roughness and substrate material on oil film thickness. As shown in the figure, for rough mating surface (R_{max}=3.0 µm) and in the case of thermally refined steel substrate, the oil film was very thin like 0.015 µm at the start of running and it increased steadily at the initial stage of running but it increased quickly as the number of cycles increased. In the case of induction hardened steel substrate, oil film formation was almost similar with the number of cycles. As is apparent from the figure, oil film formation was

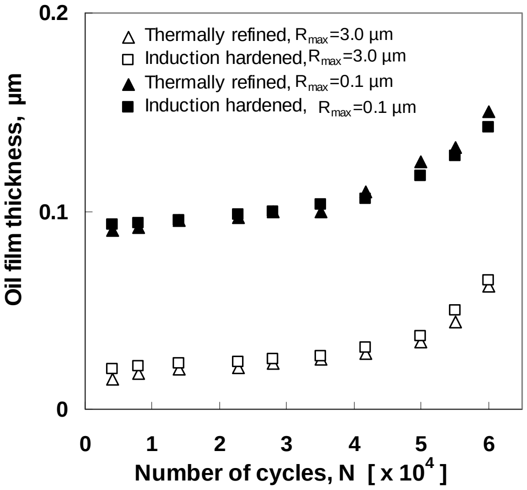


Figure 10: Effect of mating surface roughness and substrate material on oil film thickness (P_H=1.4 GPa)

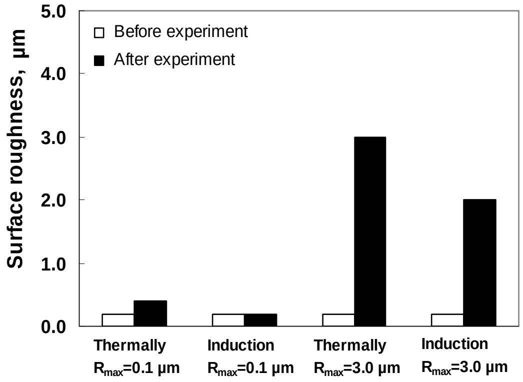


Figure 11: Effect of mating surface roughness and substrate material on surface roughness of WC cermet coating

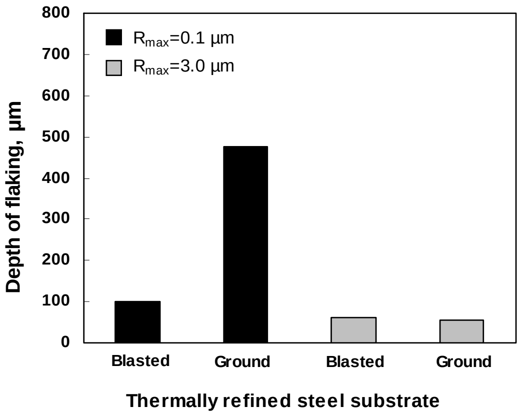


Figure 12 Effect of mating surface roughness on depth of flaking of WC cermet coating

considerably different for the smooth mating surface (R_{max}=0.1 µm). Namely, at the start of running, the oil film was thick like 0.1 µm and it increased gradually with the number of cycles. However, from the obtained results it could be considered that oil film formation was not influenced by the substrate material.

Figure 11 exhibits the effect of mating surface roughness and substrate material on surface roughness of WC cermet coated roller. As shown in the figure, there is a noticeable difference in the surface roughness of coated roller depending on the mating surface roughness. In the case of thermally refined steel substrate and for R_{max}=0.1 µm, before experiment, the surface roughness of coated roller was 0.2 µm and after experiment, it was slightly increased and became 0.4 µm. In the case of induction hardened steel substrate, after experiment, the surface roughness of coated roller was not changed. On the other hand, after experiment, the surface roughness of coated roller was significantly increased for R_{max}=3.0 µm. In the case of thermally refined steel substrate, it became 3.0 µm and in the case of induction hardened steel substrate it became 2.0 µm.

Figure 12 shows the results of depth of flaking developed on the thermally sprayed coated roller when the substrate material was thermally refined steel. As shown in the figure, in the case of smooth mating surface (R_{max}=0.1 µm), the depth of flaking was about 100 µm for blasted substrate whereas depth of flaking was very deep from the contact surface of the coated roller and it was about 500 µm for ground substrate. On the other hand, in the case of rough mating surface (R_{max}=3.0 µm), depth of flaking was shallow and it was about 50 µm for both blasted substrate and ground substrate.

CONCLUSION

In this study, the effects of mating surface roughness, substrate surface kind, substrate material and coating thickness on the durability of WC-Cr-Ni cermet coating were investigated under lubricated rolling/sliding contact condition. The effects of mating surface roughness on the coefficient of friction, oil film thickness, surface roughness of coated roller and depth of flaking were also examined. The obtained results are summarized to give the following conclusions:

In the case of thermally refined steel substrate and with the coating thickness 60 µm, coating on the blasted substrate exhibited a long life whereas coating on the ground substrate showed a short life for the mating surface roughness R_{max}=0.1 µm. For the mating surface roughness R_{max}=3.0 µm, coating on the ground substrate showed an extremely short life as compared with that on the blasted substrate. Due to the increase in the coating thickness from 60 µm to 110 µm, coating showed a long life and durability was not influenced by the substrate surface kind. With the coating thickness 110 µm and under P_H=1.2 GPa, coating on the blasted or ground substrate showed a very short life for R_{max}=0.1 µm, and due to the increase in the coating thickness from 110 µm to 210 µm, coating on blasted or ground substrate showed a high durability.

In the case of induction hardened steel substrate and with the coating thickness 60 µm, coating on the blasted substrate or ground substrate exhibited a long life for both R_{max}=0.1 µm and R_{max}=3.0 µm and the effect of substrate surface kind was hardly recognized. Under P_H=1.4 GPa and for R_{max}=0.1 µm, durability was strongly influenced by the substrate material. In this case, coating on the induction hardened steel substrate showed a long life whereas coating on the thermally refined steel substrate showed an extremely short life.

Coefficient of friction and oil film thickness were considerably different depending on the mating surface roughness. It was also found that substrate material has no effect on the coefficient of friction and oil film thickness.

Surface roughness of coated roller was significantly influenced by the mating surface roughness and it was slightly affected by the substrate material.

For R_{max}=0.1 μm, depth of flaking for the ground substrate was much deeper than that for the blasted substrate. Moreover, for R_{max}=3.0 μm, depth of flaking was shallow and independent on the substrate surface kind.

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