Proceedings of the
International Conference on Mechanical Engineering 2007
(ICME2007) 29- 31 December 2007, Dhaka, Bangladesh

ICME07-AM-01

INFLUENCE OF SUBSTRATE SURFACE FINISH ON TRIBOLOGICAL PERFORMANCE AND SURFACE TOPOGRAPHY OF Hi-HVOF SPRAYED WC-Cr-Ni CERMET COATING

A. Nakajima[1], **D. M. Nuruzzaman**[2], **and T. Mawatari**[1]

[1]Department of Mechanical Engineering, Saga University, Japan,
[2]Department of Mechanical Engineering, Dhaka University of Engineering and Technology, Bangladesh.

ABSTRACT
In the present study, tribological characteristics and surface topographies of thermally sprayed WC-Cr-Ni cermet coating were investigated experimentally under lubricated rolling with sliding contact conditions. Hi-HVOF sprayed WC cermet coatings were deposited onto the axially ground, blasted and circumferentially ground roller specimens made of an induction hardened carbon steel. It was found that under a contact pressure 1.4 GPa, cermet coating showed a high durability and life of the coating was not influenced by the substrate surface finish. It was also found that coefficient of friction, oil film formation and surface temperature were hardly affected by the substrate surface finish. On the other hand, after running, surface topographical parameters such as skewness, kurtosis and surface roughness were significantly influenced depending on the substrate surface finish. Namely, after the running-in process, the skewness in the case of circumferentially ground substrate became much more negative than that in the case of axially ground or blasted substrate. In addition, kurtosis and surface roughness of the coated surface were much more influenced in the case of circumferentially ground substrate than that in the case of axially ground or blasted substrate.

Keywords: Tribological Performance, Surface Topography, WC-Cr-Ni Cermet.

1. INTRODUCTION
Modern technology is continually demanding low friction and high wear-resistant materials in order to improve the tribological performance of machine elements such as rolling element bearings, gears, cams and tappets. The strongest demand has been for the coating materials particularly tungsten carbide (WC) based cermets for enhancing the surface characteristics of a material or extending its service life. 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 [1]. These cermet coatings can be prepared by the conventional type high velocity oxy-fuel flame spraying (HVOF) or by the high energy type flame spraying (Hi-HVOF) [2]. However, the investigations on the tribological properties of these thermally sprayed cermet coatings under rolling with sliding contact conditions have been limited [3-5].

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 [6]. It was found that durability of cermet coating was 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 [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. Durability of WC cermet coating was examined under lubricated rolling with sliding contact [8]. It was found that durability was significantly influenced by the substrate surface finish. Surface durability of WC cermet coated steel roller was examined under rolling with sliding contact and it was found that durability or life to flaking of coated roller was greatly influenced by the substrate material [9].

In the present research, tribological characteristics and surface topographies of thermally sprayed WC-Cr-Ni cermet coating were investigated experimentally under lubricated rolling with sliding contact conditions. Coatings were deposited onto the axially ground, blasted and circumferentially ground roller specimens made of an induction hardened carbon steel by means of Hi-HVOF spraying. The effects of substrate surface finish on durability of cermet coating, coefficient of friction, oil film formation and surface temperature were investigated. In addition, the effects of substrate surface finish on surface topographical parameters such as skewness, kurtosis and surface roughness 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 an induction hardened carbon 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

2.2 Substrate Surface Preparation and Thermal Spraying Conditions

Before applying the thermally sprayed coating onto the induction hardened carbon steel substrate, the substrate surface was prepared so that coating material can adhere with the substrate material. Three types of substrate surfaces were prepared by axially grinding, shot-blasting and circumferential grinding. After surface preparation, the maximum surface roughness was R_{max}=7.0 μm. After that, WC-Cr-Ni cermet coating was formed onto the axially ground, blasted and circumferentially ground roller specimens by means of the high energy type flame spraying (Hi-HVOF) and the spraying conditions are shown in Table 3.

2.3 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 R_{max}=0.2 μm by grinding and subsequent polishing. The micro-Vickers hardness of the coating formed by Hi-HVOF was HV≈1130 (test load: 2.94 Newton). The maximum surface roughness of non-coated roller was R_{max}=5.0 μm. The detail specifications of coated roller and mating non-coated roller are shown in Table 4.

2.4 Testing Machine, Test Conditions and Lubricating Oil

Using a two-roller testing machine shown in Fig. 1, experiments were carried out to investigate the tribologi

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

Induction hardened carbon 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 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 coated and non-coated rollers

Diameter of coated and non-coated rollers, mm	60
Micro-Vickers hardness of coating (Hi-HVOF), HV	1130
Micro-Vickers hardness of substrate (Induction hardened), HV	680
Micro-Vickers hardness of non-coated roller, HV	800
Maximum surface roughness of the substrate, µm	7.0
Maximum surface roughness of coated roller, µm	0.2
Maximum surface roughness of non-coated roller, µm	5.0
Effective track width in line contact condition, mm	10
Coating thickness, µm	60

cal characteristics and surface topographies of thermally sprayed WC-Cr-Ni cermet coating under lubricated rolling with sliding contact conditions. In the experiments, using a coil spring the normal load was applied in line contact condition. The normal load which gives the Hertzian contact pressure P_H=1.4 GPa was applied. Moreover, under rolling with sliding contact condition, using the gear ratio 25/32, a slip ratio s=-28.0% was applied. An automatic stopping device was attached with the testing machine and this device worked in response to any abnormal vibration induced by the occurrence of flaking/delamination of coating. In the experiments, 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=2.0×10^7 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 resistance method [10], and the friction force between coated roller and non-coated roller was measured by strain gauges.

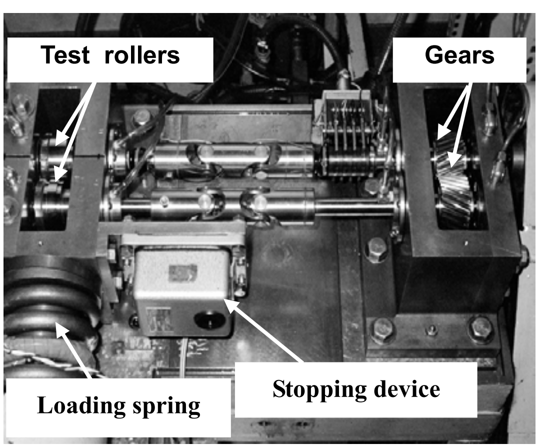

Fig 1: Two-roller testing machine

3. RESULTS AND DISCUSSION

Fig. 2 shows the effect of substrate surface finish on durability or life to flaking of WC cermet coating under a contact pressure P_H=1.4 GPa and slip ratio s=-28.0% when the substrate material was induction hardened carbon steel. From the figure it can be seen that the axially ground substrate roller showed high durability and coating showed a long life over N=2.0×10^7 cycles. From the figure it can also be observed that cermet coating showed a high durability and it was possible to run over N=2.0×10^7 cycles when the substrate surface was blasted or circumferentially ground

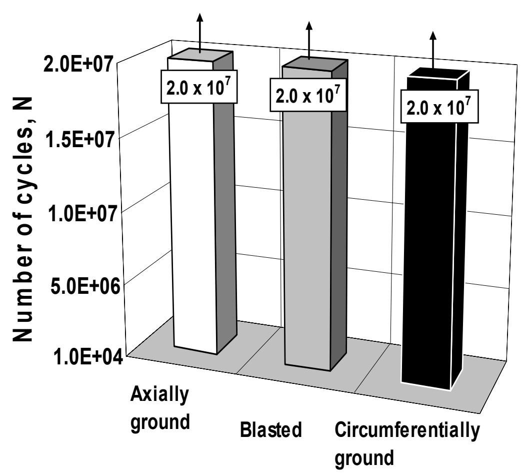

Fig 2: Effect of substrate surface finish on durability or life to flaking of WC cermet coating (P_H=1.4 GPa, s=-28.0%)

Fig. 3 illustrates the effect of substrate surface finish on change in the coefficient of friction with the number of cycles. From the figure it can be seen that in the case of axially ground substrate and at the start of running, coefficient of friction was about 0.055 and it decreased gradually with the number of cycles and came to a steady value within a short time. From the figure it can also be noticed that the change in the coefficient of friction with the number of cycles followed almost the same trend when the substrate surface was blasted or circumferentially ground. From the obtained results it was confirmed that coefficient of friction was hardly influenced by the substrate surface finish. However, it could be considered that there was a very little difference in the coefficient of friction during running-in depending on the running conditions.

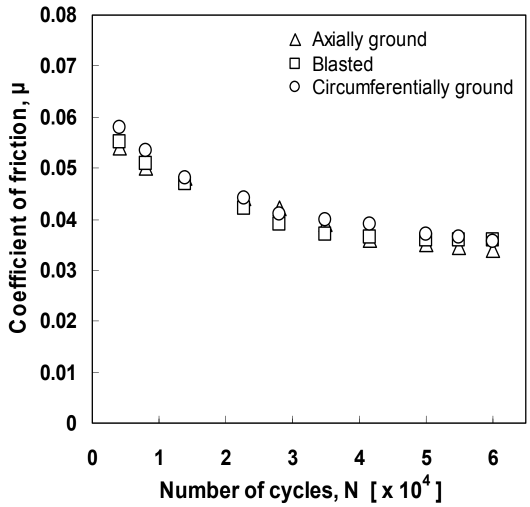

Fig 3: Effect of substrate surface finish on change in the coefficient of friction (P_H=1.4 GPa, s=-28.0%)

Fig. 4 exhibits the effect of substrate surface finish on change in the electrical contact voltage with the number of cycles. 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 is apparent from the figure and in the case of axially ground substrate, at the very early stage of running, the separation voltage was very near to zero or extremely low value and it increased very steadily with the number of cycles. From the figure it can also be observed that formation of oil film followed almost the same trend when the substrate surface was blasted or circumferentially ground. From the obtained results it could be considered that oil film formation was hardly influenced by the substrate surface finish. However, there was a very little difference in the state of oil film formation during running-in depending on the running conditions.

Fig. 5 represents the effect of substrate surface finish on surface temperature of coated roller. From the figure it is apparent that in the case of axially ground substrate, at the start of running, the surface temperature was about 125^{0}C and it increased very steadily with the number of cycles and came to a constant value within a short time. It can also be seen that change in surface temperature followed almost the same trend when the substrate surface was blasted or circumferentially ground. The obtained results revealed that surface temperature was not influenced by the substrate surface finish.

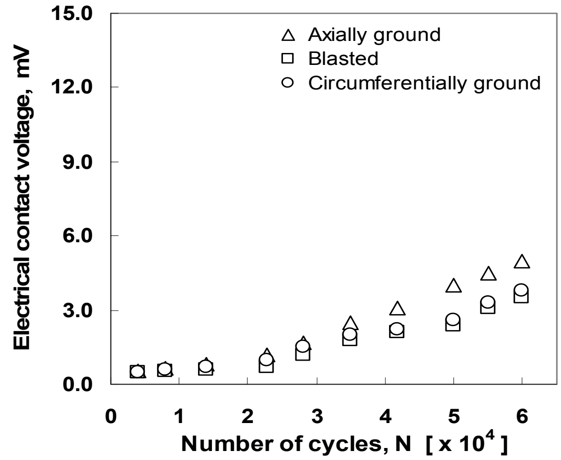

Fig 4: Effect of substrate surface finish on change in the electrical contact voltage (P_H=1.4 GPa, s=-28.0%)

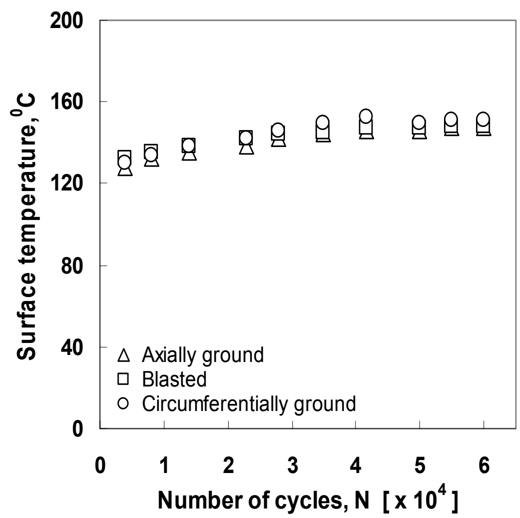

Fig 5: Effect of substrate surface finish on surface temperature (P_H=1.4 GPa, s=-28.0%)

Fig. 6 shows the effect of substrate surface finish on skewness of the coated surface. From the figure it can be observed that before the test, the skewness of coated surface was about -0.6. From the figure it can also be seen that in the case of axially ground or blasted substrate, after the test the skewness became about -3.0. On the other hand, in the case of circumferentially ground substrate, after the test the skewness became about -4.0. The obtained results revealed that after the running-in process, the skewness of the coated surface became much more negative in the case of circumferentially ground substrate than that in the case of axially ground or blasted substrate. This means that after the test, the coating on the circumferentially ground substrate became more valley-biased than that on the axially ground or blasted substrate.

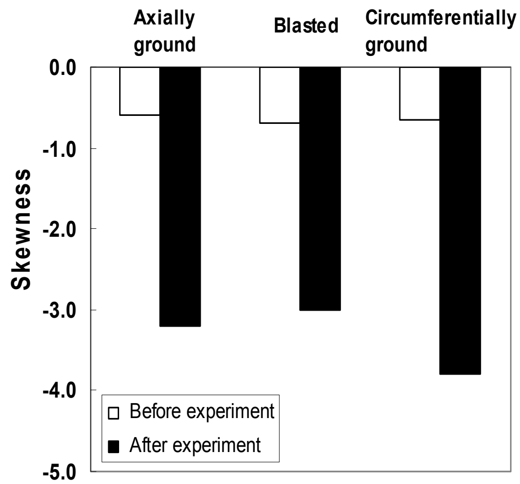

Fig 6: Effect of substrate surface finish on skewness (P_H=1.4 GPa, s=-28.0%)

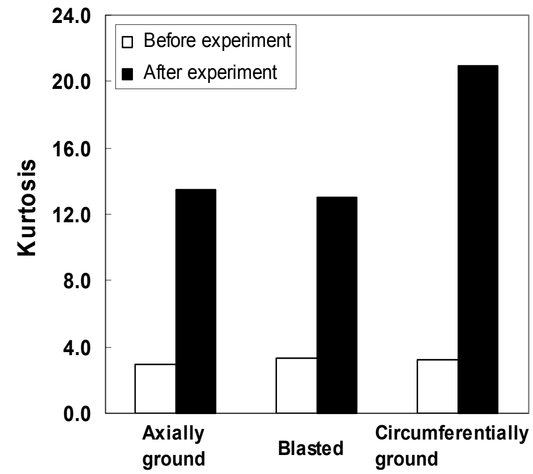

Fig 7: Effect of substrate surface finish on kurtosis (P_H=1.4 GPa, s=-28.0%)

Fig. 7 exhibits the effect of substrate surface finish on kurtosis of the coated surface. From the figure it can be observed that before the test, the kurtosis of coated surface was about 3.0 but after the test it was increased significantly. Namely, in the case of axially ground or blasted substrate, after the test, the kurtosis of the coated surface became about 14.0. On the other hand, in the case of circumferentially ground substrate, after the test, the kurtosis of the coated surface was remarkably increased and it became about 21.0. From these results it is apparent that after the running-in process, the kurtosis of the coated surface was much more influenced in the case of circumferentially ground substrate than that in the case of axially ground or blasted substrate. This means that after the test, the coating on the circumferentially ground substrate became much more pointed than that on the axially ground or blasted substrate.

Fig. 8 shows the effect of substrate surface finish on surface roughness of WC cermet coated roller. In the experiments, the coated steel roller was mated with the non-coated carburized hardened 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 about 0.2 µm and after experiment, the surface roughness was greatly increased and it became about 1.5 µm. In the case of blasted substrate, after experiment, the surface roughness of the coated roller was also significantly increased and it became about 1.8 µm. From the figure it is apparent that in the case of circumferentially ground substrate, before experiment, the surface roughness of coated roller was about 0.2 µm whereas after experiment, the surface roughness of coated roller was remarkably increased and it became about 3.0 µm. The obtained results revealed that after running, roughness of the coated surface was much more influenced in the case of circumferentially ground substrate than that in the case of axially ground or blasted substrate.

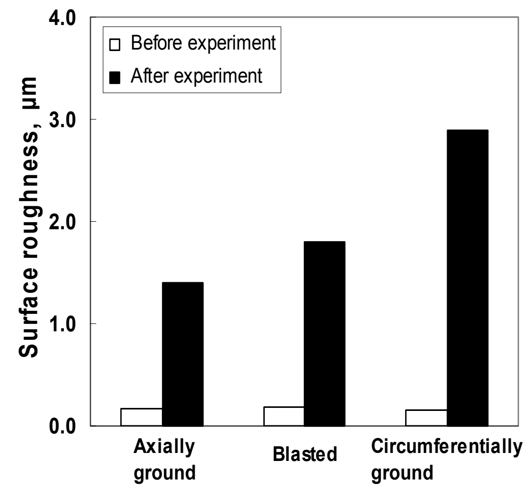

Fig 8: Effect of substrate surface finish on surface roughness (P_H=1.4 GPa, s=-28.0%)

4. CONCLUSIONS

In this study, tribological characteristics and surface topographies of Hi-HVOF sprayed WC-Cr-Ni cermet coating were investigated under lubricated rolling with sliding contact conditions. The substrate material was an induction hardened carbon steel. The effects of substrate surface finish on durability of cermet coating, coefficient of friction, oil film formation and surface temperature were investigated. The effects of substrate surface finish on surface topographical parameters such as skewness, kurtosis and surface roughness were also examined. The obtained results are summarized to give the following conclusions:

(1) WC-Cr-Ni cermet coating showed a long life and it was found that life of the coating was not influenced by the substrate surface finish.

(2) Coefficient of friction, oil film formation and surface temperature were hardly influenced by the substrate surface finish.

(3) After the running-in process, the skewness of the

coated surface was considerably changed. It was found that the skewness became much more negative in the case of circumferentially ground substrate than that in the case of axially ground or blasted substrate.

(4) After the running-in process, kurtosis and surface roughness of the coated surface were significantly increased. It was found that the kurtosis and surface roughness of the coated surface were much more influenced in the case of circumferentially ground substrate than that in the case of axially ground or blasted substrate.

.

5. REFERENCES

1. Knapp, J. K. and Nitta, H., 1997, "Fine-Particle Slurry Wear Resistance of Selected Tungsten Carbide Thermal Spray Coatings", Tribology International, 30:225-234.
2. Tani, K., Nakahira, H., Miyajima, K. and Harada, Y., 1992, "Thermal and Elastic Anisotropy of Thermally Sprayed Coatings", Material Transaction JIM, 33:618-626.
3. Ahmed, R. and Hadfield, M., 1997, "Wear of High Velocity Oxy-fuel(HVOF)-Coated Cones in Rolling Contact", Wear, 203-204:98-106.
4. Ahmed, R. and Hadfield, M., 1997, "Rolling Contact Fatigue Performance of Detonation Gun Coated Elements", Tribology International, 30:129-137.
5. Ahmed, R. and Hadfield, M., 1996, "Rolling Contact Fatigue Behavior of Thermally Sprayed Rolling Elements", Surface and Coatings Technology, 82:176-186.
6. Nakajima, A., Mawatari, T., Yoshida, M., Tani, K. and Nakahira, A., 2000, "Effects of Coating Thickness and Slip Ratio on Durability of Thermally Sprayed WC Cermet Coating in Rolling/Sliding Contact", Wear, 241:166-173.
7. Zhao, L., Maurer, M., Fischer, F., Dicks, R. and Lugscheider, E., 2004, "Influence of Spray Parameters on the Particle In-flight Properties and the Properties of HVOF Coating of WC-CoCr", Wear, 257:41-46.
8. Nakajima, A., Nuruzzaman, D. M., Mawatari, T. and Yoshida, M., 2005, "Effect of Substrate Surface Finish on Durability of Thermally Sprayed WC Cermet Coating under Rolling/Sliding Contact", Japanese Journal of Tribology, 50:437-448.
9. Nuruzzaman, D. M., Nakajima, A. and Mawatari, T., 2006, "Effects of Substrate Surface Finish and Substrate Material on Durability of Thermally Sprayed WC Cermet Coating in Rolling with Sliding Contact", Tribology International, 39:678-685.
10. Ichimaru, K., Nakajima, A. and Hirano, F., 1981, "Effect of Asperity Interaction on Pitting in Rollers and Gears", ASME Journal of Mechanical Design, 103:482-491.

6. NOMENCLATURE

Symbol	Meaning	Unit
P_H	Hertzian contact pressure	(GPa)
s	Slip ratio	(%)
N	Number of cycles	
HV	Hardness Vicker's	
R_{max}	Maximum surface roughness	(μm)
ν	Kinematic viscosity	(mm^2/s)
α	Pressure-viscosity coefficient	(GPa^{-1})