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Tribological Behavior of Thermally Sprayed WC Coatings under Water Lubrication

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Abstract

Thermally sprayed coatings have been used in various fields of industry for enhancing surface characteristics of materials and extending their service life. The contact surface of some mechanical equipment such as the fine pulverization equipment which is used in the woody biomass production process is required to have wear resistance in the water environment. Thermally sprayed coatings would be a good candidate to improve surface wear resistance under water lubrication. The objective of this study was to evaluate the tribological performance of thermally sprayed coatings under water lubrication. Thermally sprayed coatings which were classified into WC, WB and Ni spraying of three categories were compared with water-lubricated sliding test at a sliding velocity of 0.02 m/s and mean pressure of p_0 = 10 MPa with a ring-on-disk apparatus. Thermally sprayed coatings showed comparatively high friction coefficient and well wear resistance under water lubrication. WC contained coatings showed better wear resistance than WB and Ni coatings. Thermally sprayed coatings showed obviously different mechanical properties and tribological behaviors, and the effect of wettability and hardness on tribological characteristics was discussed under water lubrication. Friction coefficient increased as the surface contact angle of thermally sprayed coatings increased. The wear rate decreased as the surface hardness of thermally sprayed coatings increased. Wear resistance of thermally sprayed coatings was excellent under water lubrication. WC contained coatings showed lower wear rate than WB and Ni coatings. WC-14CoCr coating showed the lowest wear rate.

Keywords

Thermally Spraying, WC Coatings, Water Lubrication, Friction, Wear

1. Introduction

Water lubricant has many advantages such as low negative environmental impact and high cooling capacity. In contrast, water lubricant also has some problems such as high friction and wear due to the low lubricating property and corrosion [1]. The contact surface of some mechanical equipment such as the fine pulverization equipment which is used in the woody biomass production process would inevitably have to use water lubrication [2]. Therefore, it is a very important problem that to increase the surface wear resistance under water lubrication.

Recently, some new advances in the technology have extended the applications of thermally sprayed coatings in various fields of industry for enhancing surface characteristics of materials and extending their service life [3]. Thermally sprayed coatings have been applied to industrial machine parts for anti-wear purpose. In particular, the thermally sprayed coatings with some metallic carbide like WC cermet generally offer excellent tribological properties [3]-[6]. Therefore, thermally sprayed coating would be a good candidate for a tribological coating under water lubrication. In order to understand the tribological behavior of thermally sprayed coatings under water lubrication, WC contained coatings (WC-CrC-Ni, WC-CoCr and WC-Ni), WB contained coating (WB-CoCrMo) and Ni spraying coating were employed, and the sliding test was carried out under mean pressure of p_0 = 10 MPa and at a sliding velocity of 0.02 m/s with a ring-on-disk apparatus. Friction and wear characteristics of thermally sprayed coatings were evaluated under water lubrication.

Thermally sprayed coatings which composed with different powder types would display obviously different mechanical properties such as surface wettability and surface hardness. Due to the low viscosity of water, the wettability is very important for tribological behavior of thermally sprayed coatings under water lubrication. Hardness is one of the most important parameters of thermally sprayed coatings influencing the tribological behavior. Therefore, the mechanical properties of thermally sprayed coatings were characterized, and the effect of wettability and hardness properties on tribological characteristics of thermal sprayed coatings was also discussed. This research may help to understand tribological properties of thermally sprayed coatings under water lubrication, and to select the appropriate thermal spray coatings as the surface of finely pulverized parts which are used in woody biomass production process.

2. Experimental

2.1. Specimen

The test disk and ring were made of martensitic stainless steel (JIS SUS440C). The diameter and the thickness of disk were 40 mm and 10 mm, respectively. The inside diameter and the outside diameter of ring were 20 mm and 25.6 mm, respectively. The height of the ring was 15 mm. The specimens were finished by grinding after quenching and tempering, and the surface roughness was approximately 0.01 μm Ra. The surface Vickers hardness was around HV670.

2.2. Thermally Sprayed Coatings

In this paper, WC contained (WC-CrC-Ni, WC-CoCr and WC-Ni) and WB contained

(WB-CoCrMo) coatings which were deposited using high velocity oxyfuel spraying (HVOF) and Ni spraying coating were employed and evaluated their tribological properties under water lubrication. The coatings produced by different type powders in thermal spray processes exhibit a broad range of coating hardness, porosity and microstructural features. Thermally sprayed coatings were sprayed on the ring and disk surfaces. The coating specifications were summarized in Table 1.

WC-1 and WC-2 were formed with WC (Bal.)-CrC (20 mass%)-Ni (7 mass%) powders whose particle size range were 15 - 45 μm and 10 - 38 μm, respectively. WC-3 and W-4 were formed with WC (Bal.)-CrC (18 mass%)-Ni (18 mass%) powders which had lower WC containing ratio than that of WC-1 and WC-2, and their particle size were 15 - 45 μm and 5 - 38 μm, respectively. WC-5 was formed with WC (Bal.)-CoCr (14 mass%) powders whose particle size 15 - 53 μm. WC-6 was formed with WC (Bal.)-Ni (12 mass%) powders which had comparatively large particle size 20 - 53 μm, and had the highest WC containing ratio. WB was formed with WB (Bal.)-CoCrMo (30 mass%) powders whose particle size was 15 - 53 μm. Ni coating was sprayed with high temperature.

2.3. Sliding Test

Friction and wear properties were evaluated using a ring-on-disk type tribometer. The tests were performed at room temperature under water lubrication. In order to keep the water temperature constant the water was circulated at a rate of 200 mL/min. The ring specimen was installed on rotating shaft and the ring was installed on the loading shaft. The surface pressure was 10 MPa, and the sliding velocity Vs was 0.02 m/s. Total sliding distance in each experiment was set to 10,000 m. In order to observe the change of surface during sliding test, the test was interrupted at an interval of 2500 m and measured the surface characteristics.

The friction coefficient was calculated with the measured friction force and normal force. The wear masses of both disk and ring were measured using the electronic balance with a minimum measurement of 10^{-4} g. Before and after each sliding test, the ring and the disk were ultrasonic cleaned in an acetone for one hour, then dried in the

Table 1. Specifications of thermally sprayed coatings.

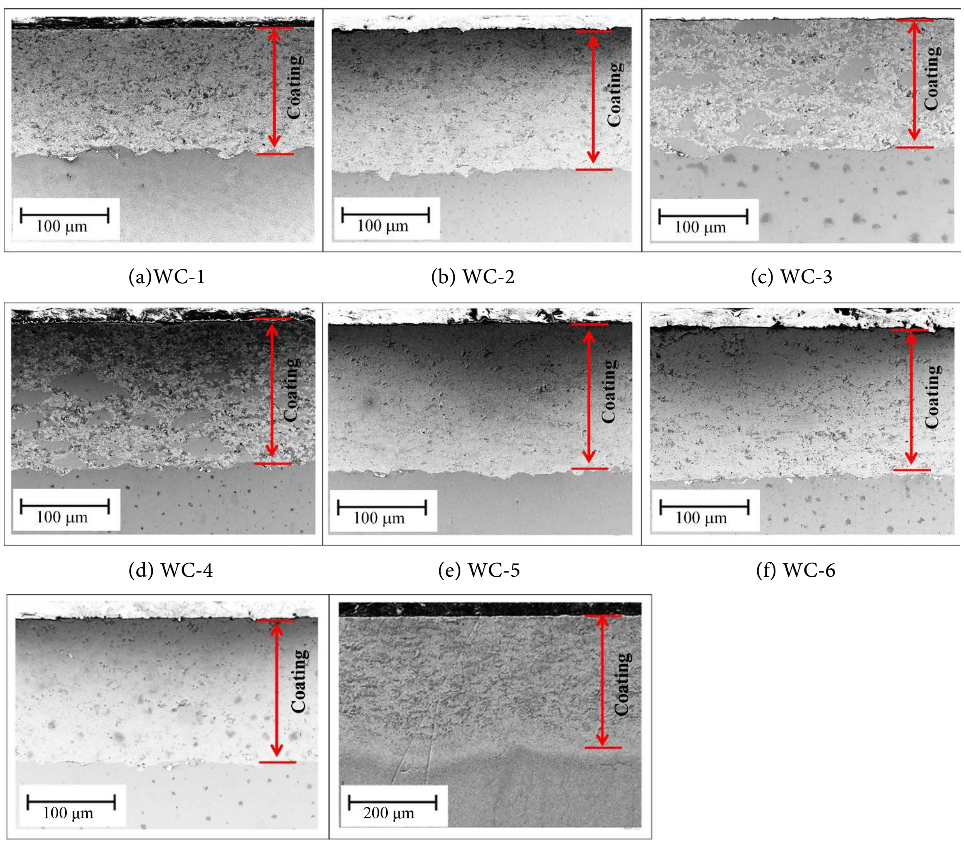
Sample code	Powder type	Spraying temperature [K]	Particle size [μm]	Thickness [μm]	Hardness [HV]	Roughness [μm·Ra]
WC-1	WC-20CrC-7Ni	373 - 473	15 - 45	160	1020	0.53
WC-2	WC-20CrC-7Ni	373 - 473	10 - 38	160	1010	0.54
WC-3	WC-18CrC-18Ni	373 - 473	10 - 53	150	800	0.58
WC-4	WC-18CrC-18Ni	373 - 473	5 - 38	160	750	0.44
WC-5	WC-14CoCr	373 - 473	15 - 53	160	1050	0.33
WC-6	WC-12Ni	373 - 473	20 - 53	160	760	0.66
WB	WB-30CoCrMo	373 - 473	15 - 53	160	1000	0.79
Ni	Ni spraying	1273 - 1373	-	300	650	0.49

vacuum chamber for one hour to remove contaminants.

3. Experimental Results and Discussion

3.1. Surface Characteristic

Due to different powder types and particle size, thermally sprayed coatings showed the obviously different surface characteristics. Figure 1 and Figure 2 showed the Scanning Electron Microscope (SEM) observations of the microstructure of thermally sprayed coatings as measured from the cross-section. The microstructure of thermally sprayed coatings is one of the most important parameters influencing mechanical properties, such as hardness and toughness [7]. The polished surface morphology of microstructure of thermally sprayed coatings was presented in Figure 1 and Figure 2. The film thickness was evaluated with Figure 1 was summarized in Table 1. WC and WB coatings had thickness of approximately 150 - 160 μm, and Ni coating had a rather thick film thickness of 300 μm. In Figure 1, the black dots were observed on the coatings were the pores distributed on the surface of thermally sprayed coatings. WC contained coatings showed larger porosity than that of WB and Ni coatings. WB and Ni coatings were uniformly dispersed and showed little porosity. Larger particles which may be no unmolten particles were observed on the surface of WC-3 and WC-4, and they were



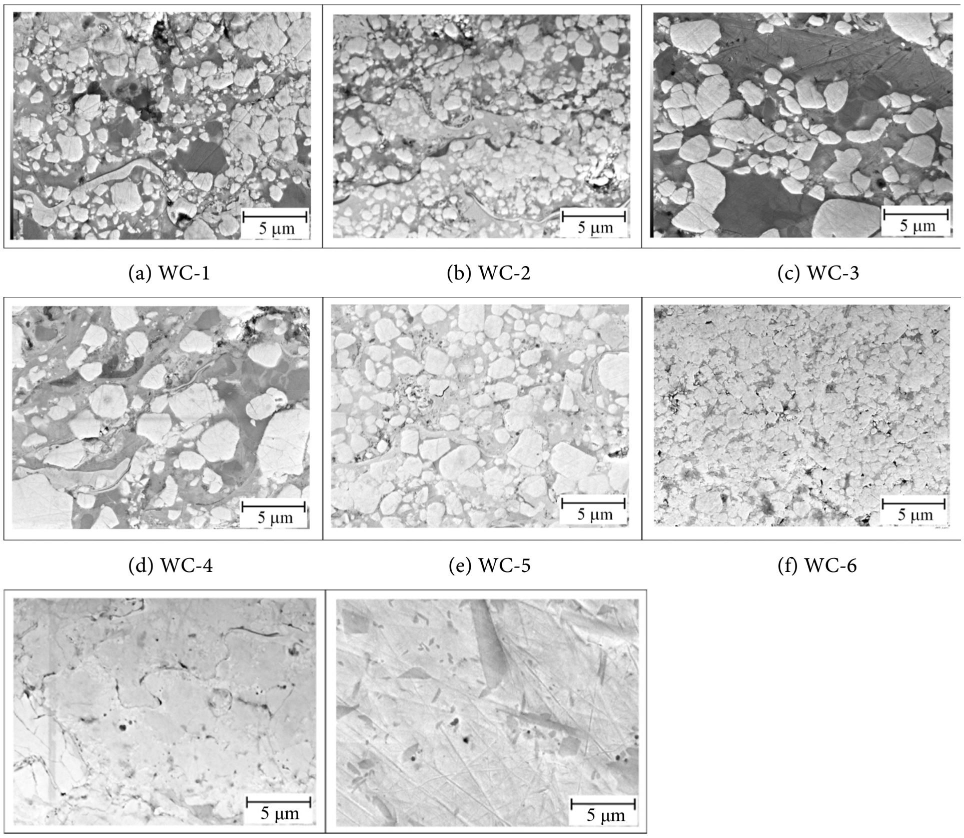
(a)WC-1 (b) WC-2 (c) WC-3

(d) WC-4 (e) WC-5 (f) WC-6

(g) WB (h) Ni

Figure 1. Cross section of thermally sprayed coatings.

analyzed by the SEM equipped with Energy Dispersive X-ray Spectrometer (EDS) shown in the Figure 3.



(a) WC-1 (b) WC-2 (c) WC-3

(d) WC-4 (e) WC-5 (f) WC-6

(g) WB (h) Ni

Figure 2. Microstructure of thermally sprayed coatings.

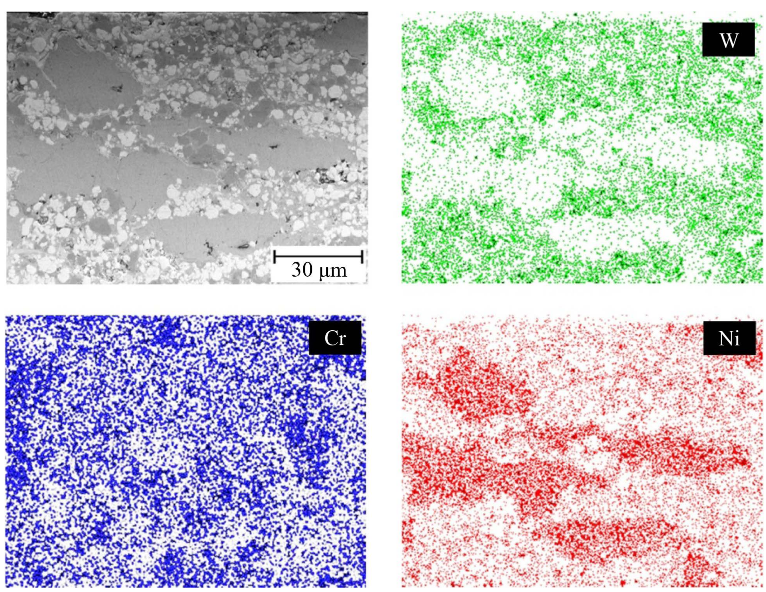


Figure 3. SEM/EDS results on the cross-section.

High magnification images in Figure 2 showed the aspects of the dissolution of particles grain and homogeneity surface structure. It can be seen that the thermally sprayed coatings display good appearance with small pores and well dispersed in the coatings layer, and large cracks were not observed. WC-1 and WC-2 showed a very wide distribution of WC grain size, and high mass fraction of WC grains (73 mass%) with comparatively small particle size. WC-3 and WC-4 showed comparatively low mass fraction of WC grains (64 mass%) and comparatively large particle size. WC-5 showed high mass fraction of WC grains (86 mass%) and comparatively large particle size. WC-6 showed highest mass fraction of WC grains (88 mass%) and comparatively small particle size, and more homogenized binder. Compared with WC contained coatings, WB and Ni coatings showed more homogenized binder.

Figure 3 showed the surface image and elemental mapping of WC-3. The large particles were observed in Figure 1. The big grey regions and small white grains were distributed on the cross-section. The elemental mapping results showed a greater detection intensity of Ni in the big grey regions, a greater detection intensity of W in the white regions, and uniformly distributed Cr on the surface. Therefore, it could be speculate that the unmolten particles of WC and Ni were existed on the surface. The porosities and different phases in the structure have significant contribution to mechanical properties of thermal sprayed coatings [8]. Due to different powder types and surface microstructure, thermally sprayed coatings would obtain the different surface mechanical properties such as wettability and hardness which will significantly affect the tribological behavior of thermally sprayed coatings under water lubrication.

3.2. Friction

The tribological characteristics of eight kinds of thermally sprayed coatings under water lubrication were evaluated by measuring the sliding distance dependency of friction coefficient. The coatings used in this study were classified into three categories: WC metallic coatings, WB metallic coatings, and Ni coatings. The difference in the chemical composition and mechanical characteristics among these coatings were also reflected in their frictional characteristics [9]. In order to compare with thermally sprayed coatings, the sliding test was carried out for the substrate material JIS SUS440C and the result of friction coefficient was generally around 0.55. Figure 4 showed the relation between friction coefficient and sliding distance L, the plots displayed in the figure showed the averaged friction coefficients in the same sliding interval, and the error bar showed the maximum and minimum friction coefficient during the measurements.

As shown in Figure 4, WC-1 and WC-2 whose coatings were sprayed with WC-20CrC-7Ni showed high and stable friction coefficient throughout the sliding test, and WC-1 with the larger particles size showed the lower average friction coefficient than WC-2. WC-3 and WC-4 whose coatings were sprayed with WC-18CrC-18Ni showed lower friction coefficient than WC-1 and WC-2, and WC-3 with larger particles showed the lower friction coefficient than WC-4. WC-5 with WC-14CoCr showed comparatively large fluctuation of friction coefficient. The average friction coefficient of WC-5

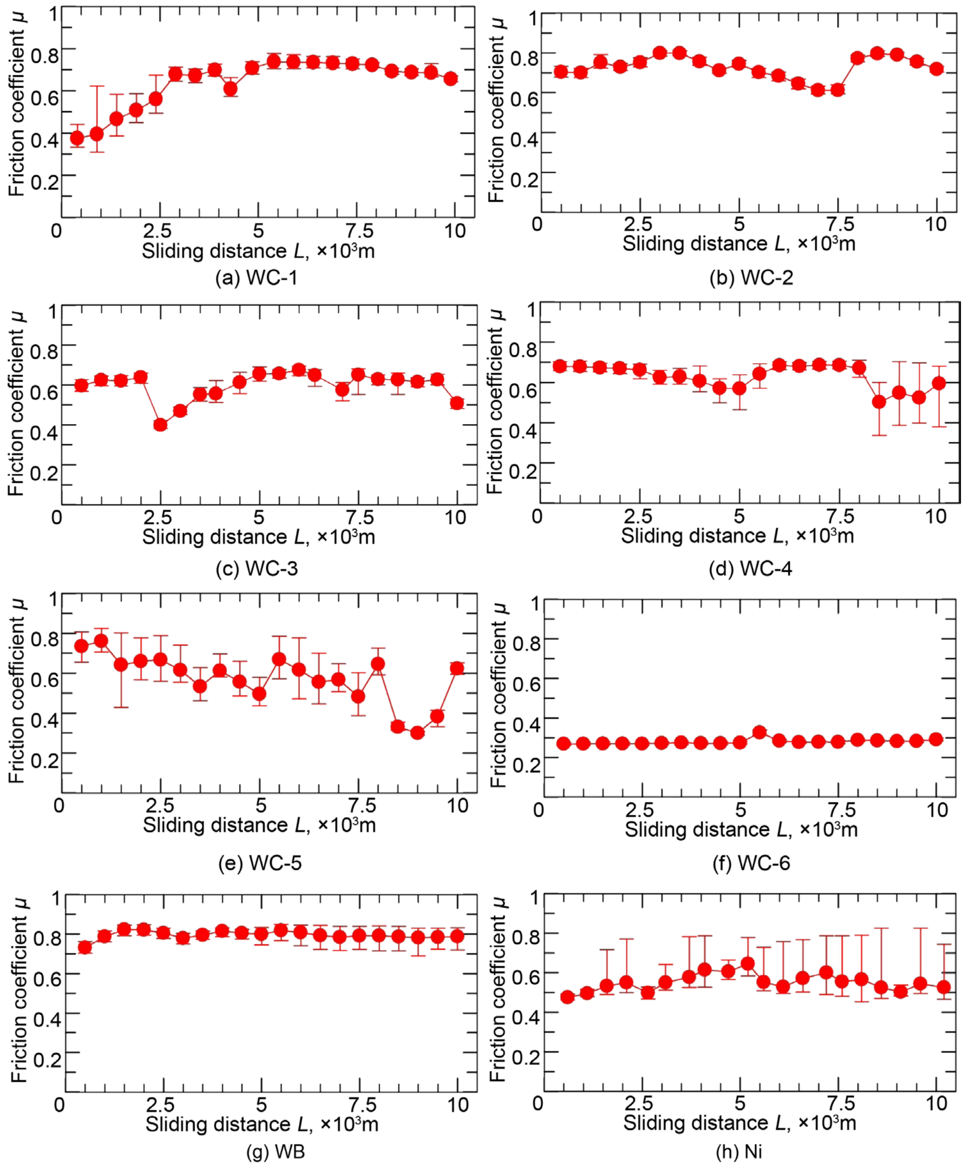


Figure 4. Relation between steady-state friction coefficient and sliding distance.

decreased with increasing the sliding distance. WC-6 showed the lowest friction coefficient around 0.3 in the eight kinds of thermally sprayed coatings, and it was steady during the test. WB whose coating was sprayed with WB-30CoCrMo showed the highest average friction coefficient value around 0.8. Ni coating showed rather low value of average friction coefficient around 0.55 and a larger fluctuation of friction coefficient during the test. From the test results, eight kinds of thermally sprayed coatings with different chemical composition and mechanical properties showed obviously different frictional characteristics, and most of thermally sprayed coatings showed higher friction coefficients than the substrate material JIS SUS440C. WB sprayed coating showed higher friction coefficient than WC and Ni sprayed coatings. Based on the test results, WC-6 showed the lowest average friction coefficient, and Ni spraying coating showed rather low average friction coefficient. Average friction coefficient of higher Ni containing WC-3 and WC-4 (18 mass%) were lower than that of WC-1 and WC-2 (7 mass%), therefore, it could be speculated that Ni element would play an important role for decreasing friction coefficient under water lubrication. In addition, the larger particles size of thermally sprayed coating showed the lower friction coefficient for the same composition of thermally sprayed coatings.

3.3. Wear

Thermal spraying is often considered as a potential alternative to traditional coating manufacturing techniques for the production of wear-resistant coatings, and especially ceramic thermally sprayed coatings have been applied to industrial machine parts for anti-wear purposes [10].

Thermally sprayed coatings are mostly used to enhance service life of the parts exposed to wear. **Figure 5** showed the specific wear rate, and **Figure 6** showed the profile curve and the surface photos of thermally sprayed coatings. Thermally sprayed coatings showed a range of specific wear rates of 0.5×10^{-3} - 3.0×10^{-3} mg/m, and they are clearly smaller than that of the substrate material JIS SUS440C 2.8×10^{-2} mg/m. As shown in **Figure 5**, WC contained coatings showed smaller wear rate than WB and Ni coatings. WC-5 showed the lowest wear rate.

WC-1 and WC-2 showed smaller wear rate than WC-3 and WC-4 which contained a lower WC. WC-6 showed the largest wear rate in the WC contained coatings. There was a tendency that thermally sprayed coatings contained the higher WC showed the smaller wear rate. In addition, the larger particles size of coatings showed the lower wear rate for the same composition of thermally sprayed coatings.

WC contained coatings also showed obviously different profile curves measured stylus type surface roughness tester and the surface characteristics. In **Figure 6** WC-1 and WC-2 showed the smooth profile curve and rather low wear depth. WC-3 and WC-4 showed high wear depth and rough profile curves which had some comparatively deep grooves and some craters on the surface. From the EDS analysis, a greater intensity of Ni elements was detected in the craters portion. It could be speculated that unmolten WC and Ni particles were observed in **Figure 3** were separated from each other during

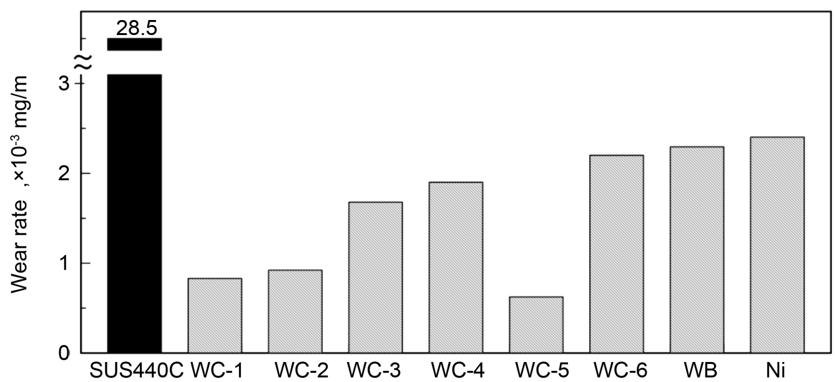
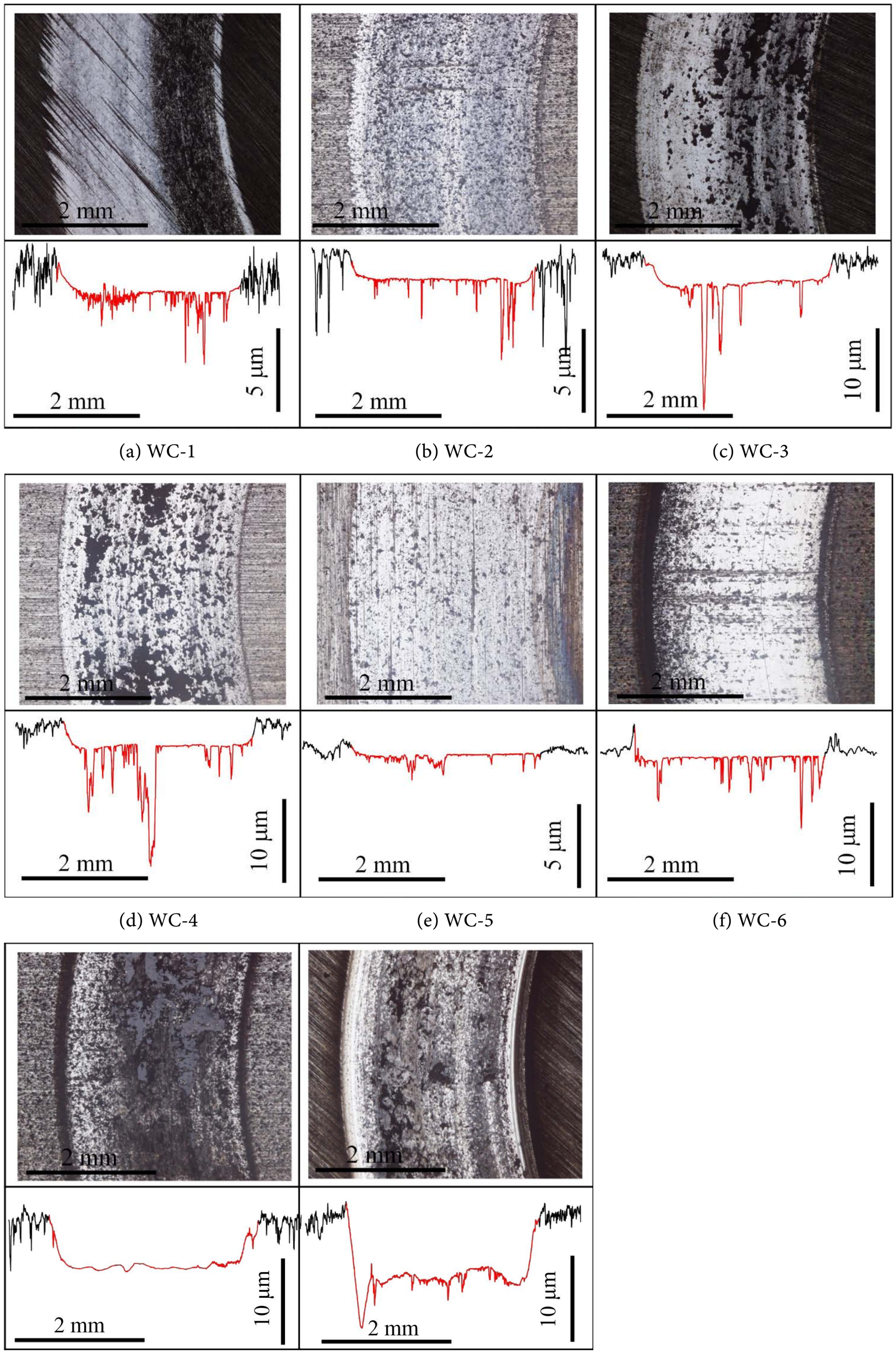


Figure 5. Specific wear rate.



(a) WC-1 (b) WC-2 (c) WC-3

(d) WC-4 (e) WC-5 (f) WC-6

(g) WB (h) Ni

Figure 6. Profile curve and micrograph.

the test, and this might be caused comparatively greater wear rate and deep grooves on the coating layer. WC-5 with the lowest wear rate showed rather low wear depth and the smooth profile curve, and grinding marks were clearly remained on the surface.

WC-6 showed high wear depth and smooth profile curve. In addition, surface roughness of WC contained coatings gradually decreased with increasing the sliding distance. The surface roughness of WC-1 and WC-2 reduced to about 0.2 μm Ra, and those of WC-3 and WC-4 reduced to about 0.4 μm Ra, and those of WC-5 and WC-6 reduced to about 0.12 μm Ra and 0.3 μm Ra, respectively. WB and Ni coatings showed comparatively large wear rate in the employed thermally sprayed coatings. WB showed rather high wear depth but the most smooth profile curve, and little quantity of wear debris was observed on the surface. Ni coating showed rough profile curve and rather high wear depth in the profile curve, and little quantity of wear debris was also observed on the surface. With increasing the sliding distance, surface roughness of WB and Ni coating gradually reduced to about 0.1 and 0.15 μm Ra, respectively.

From the test results, WC sprayed coatings showed better wear resistance than that of WB and Ni coatings, and the more WC containing, the smaller wear rate was shown, and WC-14CoCr coating showed the lowest wear rate. Thermally sprayed coatings showed the tendency that the roughness of wear track gradually decreased with increasing wear. In addition, the larger particles size of coatings showed the lower wear rate for the same composition of thermally sprayed coatings.

3.4. Wettability

The importance of wetting is becoming increasingly obvious and its control is inevitable in many engineering applications including tribology [11]. Especially the water lubrication, due to the low viscosity of water, the water lubrication film thickness is very thin, the wettability would be very important for thermally sprayed coatings under water lubrication. Therefore, the relation between wettability and tribological behavior of thermally sprayed coatings was investigated. The wettability of solid surface is usually described by the contact angle θ. **Figure 7** showed the contact angle of thermally sprayed coatings. Thermally sprayed coatings showed basically hydrophobic wetting surface and the range of the contact angle of $74^\circ < \theta < 84^\circ$. Eight kinds of thermally sprayed coatings had different contact angle. WC contained coatings showed comparatively large different contact angle with each other. WC-6 showed the lowest contact angle of 74˚, and WC-1 showed comparatively low contact angle of 79˚ and the other WC contained coatings showed comparatively high contact angle over 80˚. Whereas WB and Ni coatings showed comparatively low contact angle of 77˚ and 78˚, respectively. From the results, thermally sprayed coatings showed similar contact angle with ceramic material which had the properties of good adhesiveness and high solid surface free energy [12]. Therefore, good wetting properties of thermally sprayed coatings would significant affect the friction and wear behavior under water lubrication.

Figure 8(a) showed the relation between friction coefficient and contact angle. The effect of contact angle on friction coefficient appeared among WC contained coatings. WC-6 with the lowest contact angle showed the lowest friction coefficient around 0.3, and WC-2, WC-3, WC-4 and WC-5 coatings with higher and similar contact angle showed higher friction coefficient over 0.6. WC-1 with comparatively low contact angle

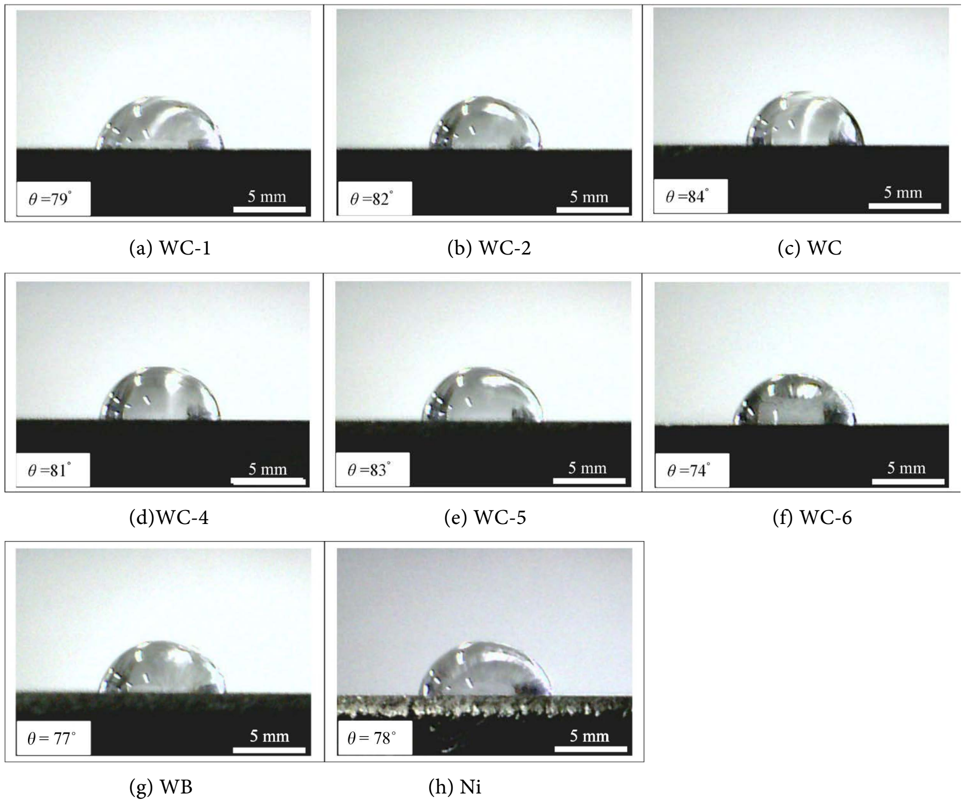


Figure 7. Surface contact angle.

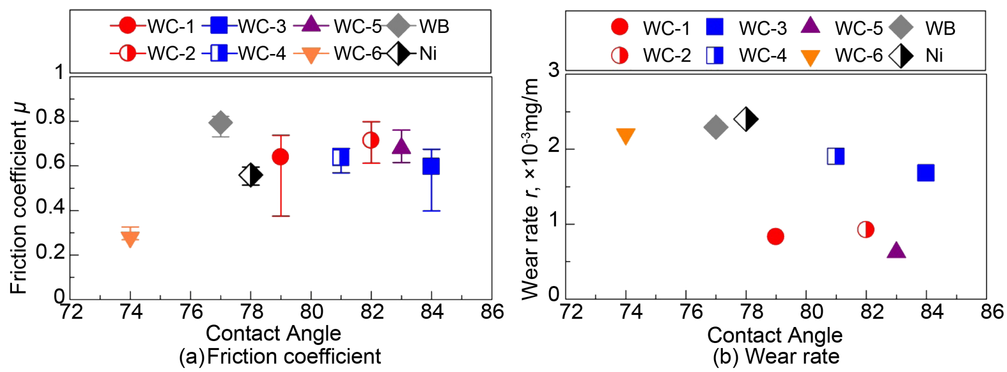


Figure 8. Relation between contact angle and (a) friction coefficient (b) wear rate.

showed smaller averaged friction coefficient and a larger fluctuation of friction coefficient than WC-2 which with the same powder. WB which had comparatively low contact angle showed the highest friction coefficient around 0.8. Ni coating which had comparatively low contact angle showed rather low friction coefficient around 0.55. There was a tendency that friction coefficient increased with increasing the contact angle.

Therefore, it seemed reasonable to speculate that the comparatively porous and highly hydrous surface of thermally sprayed coatings caused the rather low contact angle, and it would play an important role for decreasing friction coefficient under water lubrication.

Figure 8(b) showed the relation between wear rate and contact angle of thermally sprayed coatings. WC-6 with the lowest contact angle showed the largest wear rate in the WC contained coatings, but the other WC contained coatings not showed obviously affected by contact angle. WB and Ni coatings which with comparatively low contact angle showed rather large wear rate. From these result, it could be concluded that the contact angle not shown obviously effect on the wear rate overall the eight kinds of thermally sprayed coatings.

3.5. Hardness

Hardness is one of the most important parameters influencing the tribological behavior, and the hardness of thermally sprayed coatings is basically determined by the powder types. The thermally sprayed coating hardness is presumed to be the main influential factor that dominates wear behavior [13]. In this paper, the different kinds of powder types were used for the thermally sprayed coatings, and the effect of the hardness on friction and wear properties under water lubrication was discussed. The hardness was measured using the Vickers hardness tester. An average of 10 measurements was used to determine the hardness of the thermally sprayed coating in order to obtain a good statistical representation. In order to avoid the influence of surface roughness, the hardness of cross section near the surface was measured using an indentation load of 300 g with a dwell time of 30 seconds. The values were summarized in the Table 1. WB sprayed with WB-30CoCrMo showed rather high hardness 1000 HV. Ni coating showed the smallest hardness 650 HV. WC contained coatings showed a large range of hardness from 750 to 1050 HV, due to the different WC and metal containing ratio in the coating powder. Figure 9 showed the relation between surface hardness and WC and Ni content. It was observed that surface hardness of thermally sprayed coatings increased with the ratio of WC content growth. In contrast, the ratio of Ni content was inversely proportional to surface hardness, and it was showed that surface hardness of thermally sprayed coatings decreased with the ratio of Ni content growth. Therefore,

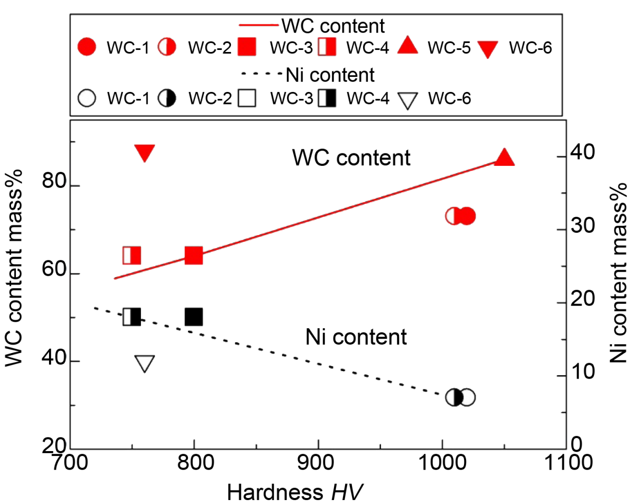


Figure 9. Relation between surface hardness and WC, Ni content.

WC and Ni containing ratio together determined the hardness of thermally sprayed coatings.

Figure 10(a) showed the effect of surface hardness on friction behavior. Although Ni coating with lowest hardness and WC-6 with comparatively low hardness showed lower friction coefficient, surface hardness not shown obviously effect on the friction coefficient overall the eight kinds of thermally sprayed coatings under water lubrication. Figure 10(b) showed the relation between hardness and wear rate of thermally sprayed coatings. WC contained coatings showed the tendency that the specific wear rate decreased with increasing surface hardness. WC-1, WC-2 and WC-5 which had the comparatively high hardness showed the rather small wear rate. WC-3, WC-4 and WC-6 which had the comparatively low hardness showed rather high wear rate. Therefore, although with the comparatively large WC containing ratio, WC-6 which had the comparatively low hardness showed rather high wear rate. The lowest hardness Ni coating showed the highest wear rate in the eight kinds of thermally sprayed coatings. However, WB contained coating which had comparatively high hardness showed rather high wear rate. As the results, the specific wear rate decreased with increasing the hardness of thermally sprayed coatings under water lubrication.

Based on the above discussion, thermally sprayed coatings showed obviously different tribological characteristics under water lubrication. WC-12Ni coating showed the lowest friction coefficient. Ni element would play an important role for decreasing frictional behavior. The larger particles size of coatings showed the lower friction coefficient for the same composition of coatings. Friction coefficient increased with increasing the surface contact angle. Thermally sprayed coatings showed clearly smaller wear rate than that of the substrate material JIS SUS440C. WC contained coatings showed smaller wear rate than WB and Ni coatings, and the more WC contained coatings showed the smaller wear rate. WC-14CoCr coating showed the lowest wear rate. The specific wear rate decreased with increasing the surface hardness. Furthermore, the surface pressure of fine pulverization parts was about 0.048 MPa in an actual production process of woody biomass, and it greatly smaller as compared with the surface pressure of this test 10 MPa. Therefore, thermally sprayed coatings extremely suited for using on the surface of fine pulverization parts which used in the woody biomass production process.

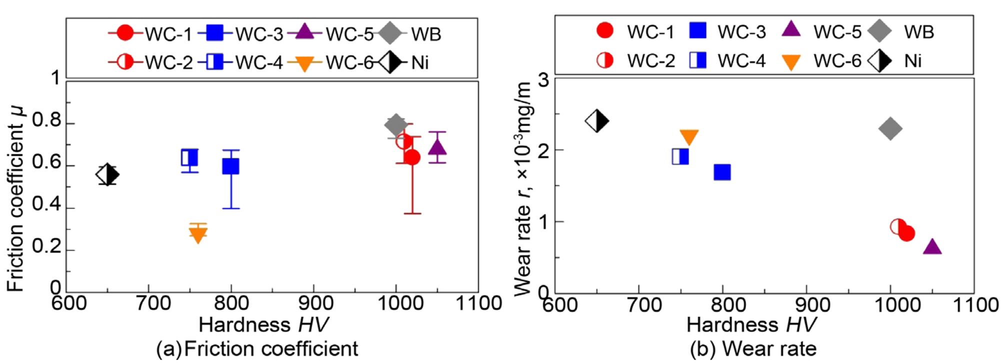


Figure 10. Relation between hardness and (a) friction coefficient and (b) wear rate.

4. Conclusions

The tribological behavior of thermally sprayed coatings and their surface mechanical characteristics have been investigated, and the relationship between the test results and surface mechanical characteristics has also been investigated. The main conclusions that can be drawn from the results are the following:

1) The friction coefficient of thermal sprayed coatings was significantly different from each other under water lubrication, and showed comparatively large range from 0.3 to 0.8. WC-12Ni coating showed the lowest friction coefficient. The larger particles size of coatings showed the lower friction coefficient for the same composition of thermally sprayed coatings.

2) Wear resistance of thermally sprayed coatings was excellent under water lubrication. WC contained coatings showed lower wear rate than WB and Ni coatings. WC-14CoCr coating showed the lowest wear rate.

3) Tribological behavior of thermally spray coatings was obviously affected by mechanical characteristics under water lubrication. Friction coefficient increased as the surface contact angle of thermally sprayed coatings increased. The wear rate decreased as the surface hardness of thermally sprayed coatings increased.

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