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Surface durability of WC/C-coated case-hardened steel gear [†]

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Abstract

The purpose of this study is to investigate the influence of tungsten carbide/carbon (WC/C) coating on the surface durability of case-hardened steel gear. Two kinds of WC/C coatings were deposited on the ground gear pair made of chromium molybdenum steel with carburizing and quenching. One is the conventional WC/C coating, and the other is WC/C coating with about 1 μm CrN interlayer. Here, the WC/C-coated test pinion and the WC/C-coated one with CrN interlayer are represented by WT and ST, respectively. Non-coated test pinion is represented by NT. The surface roughness along the tooth profile direction of WT and ST was almost the same as that of NT. A spur gear test was carried out with an IAE power circulating type gear test rig under EP gear oil lubricating condition. The fatal failure mode of the test pinions was pitting due to surface cracking. The fatigue life of WT was longer than that of NT under a maximum Hertzian stress $p_{\max}$=1700 MPa. On the other hand, under $p_{\max}$=1900 MPa, that of WT was as long as that of NT due to the peeling occurrence of the coated layer. Under the comparatively low load condition without peeling occurrence, the surface roughness of WT decreased with the increasing number of cycles, and their fatigue life became longer than that of NT. On the contrary, in the case of ST, the peeling of the coated layer occurred at a comparatively early stage of the gear test, and the dedendum was worn by tens of micrometers. Therefore, in the case of ST, the effect of the WC/C coating disappeared at a comparatively small number of cycles.

Keywords: Tribology; Gear; Surface durability; Pitting; Wear; Surface modification; Coating; WC/C; DLC

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1. Introduction

The severity of the operational condition of a gear system increases with the increasing demand for light weight, downsizing, low environmental impact, and so on. Hard coating such as diamond-like carbon (DLC) coating is one of the candidates for improving the surface durability of various kinds of machine elements. DLC coating generally has the superior tribological properties of low friction and high wear resistance. DLC can also be alloyed with other elements. In addition, many kinds of deposition processes such as physical and chemical vapor depositions (PVD, CVD) have been developed, and the tribological properties of the coated surfaces vary with the deposition process and the alloyed varieties. The tungsten carbide/carbon (WC/C) coating deposited with PVD was employed in this study. The WC/C coating was of DLC with tungsten carbide, which was expected to be superior in friction, wear resistance, adhesion performance, lubrication property, and so on.

In most cases, the effect of hard coating on rolling contact fatigue has been mainly investigated by using a roller tester, pin-on-ring tester, three ball-on-rod tester, and so on [1]. However, it is not always easy to evaluate the tribological properties of tooth surface in meshing using these fundamental testers. Therefore, in this study, a spur gear test was carried out with a gear test rig to investigate the surface durability of the coated steel gears.

2. Test gear pair

2.1 Manufacture of test gear pair

A test spur gear pair employed in the gear test consists of the driving test pinion and the driven mating gear. The specification of the test gear pair is shown in Table 1. The test gear pair was made of chromium molybdenum steel (JIS SCM415). The tooth surfaces of the test gear pair were finish-ground after case hardening (Carbonizing: CO_2 1.2vol%, C.P. 0.6wt%, 1193K×5h, Quenching: 1073K×0.5h, oil cooling, Tempering: 473K×1h, air cooling).

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Table 1. Specifications of the test gear pair.

	Test pinion	Mating gear
Module mm	5	
Pressure angle deg.	20	
Number of teeth	15	16
Addendum modification coefficient	0.571	0.560
Tip circle diameter mm	90.71	95.60
Center distance mm	82.55	
Facewidth mm	6	18
Contact ratio	1.302	
Accuracy	Class 1	Class 1

* JIS B 1702-1976

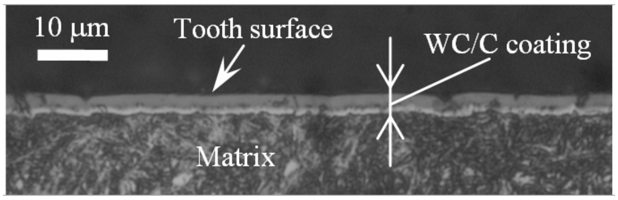

Fig. 1. Transverse section of the WC/C coated test pinion.

In this study, two kinds of WC/C coatings were deposited on the ground tooth surface of the test gear pair by PVD technique. One is the conventional WC/C coating, and the other is the WC/C coating with about 1 μm CrN interlayer. Here, NT, WT, and ST denote the non-coated test pinion, WC/C-coated test pinion, and WC/C-coated test pinion with metallic interlayer, respectively.

Fig. 1 shows the transverse section near the working pitch point of the WC/C-coated test pinion WT. Although the thickness of the WC/C-coated layer was comparatively small at the tooth root, it ranged from 2-3 μm.

2.2 Surface properties of the test gear pair

Fig. 2 shows the surface photographs and the roughness curves of the test pinions before the test, and Table 2 presents the surface properties of the test pinions. The tooth surface photographs in this Fig. were taken by a stereomicroscope using the replica method. The grinding marks were observed on the tooth surface of the NT. Meanwhile, on the tooth surfaces of WT and ST, the grinding marks were not observed due to the pre-treatment of the blasting.

The surface roughness along the tooth profile direction of WT and ST was almost the same as that of NT. On the other hand, that along the tooth trace direction of WT and ST was larger than that of NT. This indicates that the grinding marks along the tooth trace direction disappeared, and the surface roughness was increased by the WC/C coating process.

The surface hardness (HUT) in Table 2 is the dynamic hardness measured with a nano-indentation hardness tester under an initial measuring load of 1 mN and a maximum measuring load of 20 mN. The surface hardness of the coated surface was more than 1.5 times as large as that of the non-coated surface.

Table 2. Surface properties of the test pinions.

Specimen		NT	WT	ST
Tooth profile dirction	R_a μm	0.29	0.32	0.25
	R_z μm	2.03	2.42	2.45
Tooth trace dirction	R_z μm	0.07	0.19	0.23
	R_z μm	0.45	1.96	2.15
Surface hardness	HUT	324	517	584
Surface hardness of matrix	HV	713	721	702

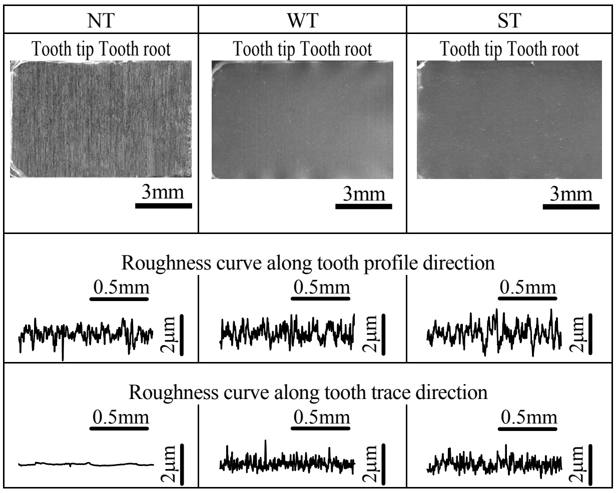

Fig. 2. Surface photographs and roughness curves of the test pinions.

The hardness distributions of the subsurface of the test gear pairs were also measured with a micro-Vickers hardness tester under a measuring load of 2.94 N for 30 sec. The Vickers hardness (HV) of the matrix surface in Table 2 is the surface hardness determined from the hardness distributions of the test pinions. The effective case-hardened depth of all the test gear pairs was about 0.8 mm. The hardness distributions of WT and ST were similar to that of NT, and the matrix hardness was hardly influenced by the PVD process.

3. Test method and test result

3.1 Test method

The fatigue tests of the gears were performed at a test pinion rotating speed of 1800 rpm using an IAE power circulating type gear test rig [2]. The maximum Hertzian stress $p_{\max}$ [3] at the working pitch point was adopted as the standard of the loading for the tooth meshing of the test gear pair. The lubricating oil employed in the gear tests was EP gear oil (Kinematic viscosity: 190.9 mm^2/s at 313K, 17.47 mm^2/s at 373K). The flow rate of the supplied oil was about 750 ml/min for the test gear pair. During the tests, the oil temperature was adjusted to 313±4 K.

The gear tests were performed within the range of $p_{\max}$=1650 MPa to 1900 MPa. In the test gear pair, the minimum oil film thickness by Dowson [4], that is, $h_{\min}$ ranged from 1.3-1.5 μm during the gear tests. The D value defined by Dawson [5] was above 1 for all the test gear pairs. In the

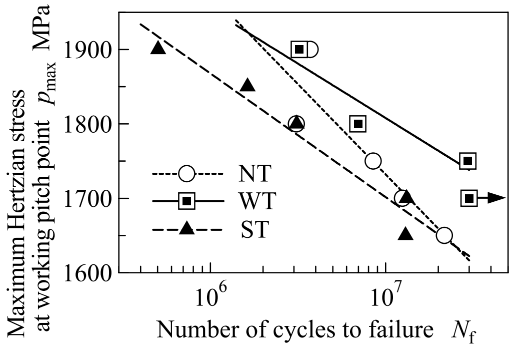

Fig. 3. p_{max}-N_f curves of the test pinions.

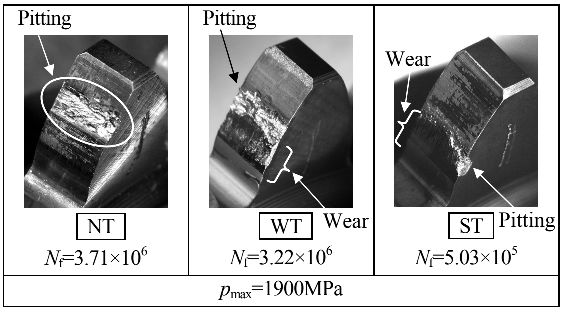

Fig. 4. Observations of failed teeth of the test pinions.

calculation of h_{min} and the D value, the oil temperature between the operating surfaces was taken as 313K, which was the supplied oil temperature in the gear test.

In this study, the fatigue life N_f of the test pinion was defined as the number of cycles when the percentage of the pitted area in a test gear pair reached 1% or the test rig stopped automatically by detecting the increase in vibration due to large surface failure.

3.2 Fatigue life and surface durability

Fig. 3 shows the p_{max}-N_f curves of the test pinions obtained in the gear tests. The arrow in this Fig. indicates that no fatal surface failure occurs on the tooth surface when the number of cycles of test pinion exceeds 3×10^7 cycles. The fatigue life of WT is longer than that of NT under p_{max}=1700 MPa. Under p_{max}=1900 MPa, that of WT is as long as that of NT due to the peeling occurrence of the coated layer. On the contrary, the fatigue life of ST is shorter or equal compared with those of NT under the same load condition because of the wear induced by the peeling occurrence of the coated layer. Here, the surface durability of the test pinion is defined as p_{max} at 3×10^7 cycles. The surface durability of NT, WT and ST is 1617, 1700, and 1622 MPa, respectively.

3.3 Fatigue life

In this study, surface failure occurred on the tooth surfaces of both the test pinions and the mating gears. Fig. 4 shows the observations of the failed teeth of the test pinions. As shown in this figure, the fatal failure mode of the test gear pairs employed in this study is the pitting near the working pitch point. In the cases of WT and ST, wear occurred on the dedendum flank due to the peeling occurrence of the coated layer, while pitting occurred near the working pitch point.

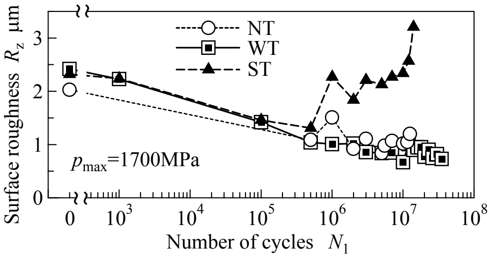

Fig. 5. Surface roughness of the test pinions during gear tests.

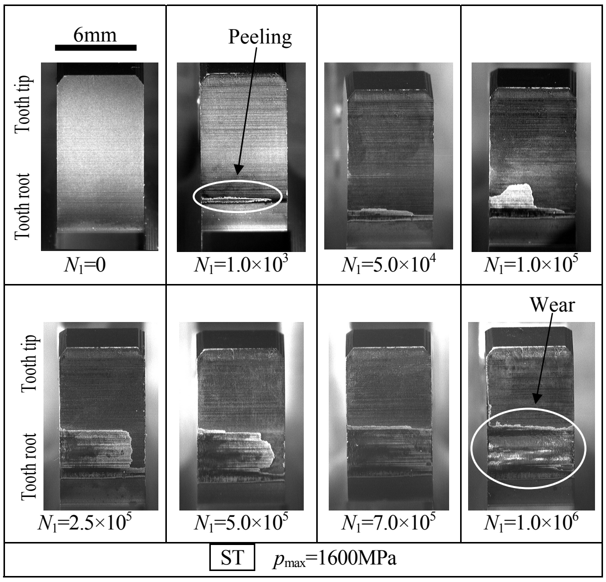

Fig. 6. Tooth surfaces of the test pinion at the early stage of the gear test.

Fig. 5 shows the change in surface roughness of the test pinions during the gear tests performed under p_{max}=1700 MPa. The maximum height R_z in this Fig. is measured at the working pitch point along the tooth profile direction. Under a comparatively low load condition of p_{max}=1700 MPa without peeling occurrence, where the fatigue life of WT was longer than that of NT, the surface roughness of WT decreased with the increasing number of cycles of pinion N_1.

Fig. 6 shows the tooth surfaces of ST at the early stage of the gear test under p_{max}=1600 MPa. In the case of ST, the peeling of the coated layer occurred at a rather early stage of the gear test, and then it spread over the dedendum flank as the number of cycles of pinion N_1 increased. After the peeling occurrence, wear and pitting easily occurred on the dedendum flank of ST. Eventually, the surface roughness of ST increased due to wear and pitting occurrence, as shown in Fig. 5.

Fig. 7 shows the samples of the tooth profile curves of certain teeth of the test pinions during the gear tests. The wear with a depth of over 10 μm occurred on the dedendum flank of ST by N_1= 1.0×10^5. The depth of wear exceeded the thick-

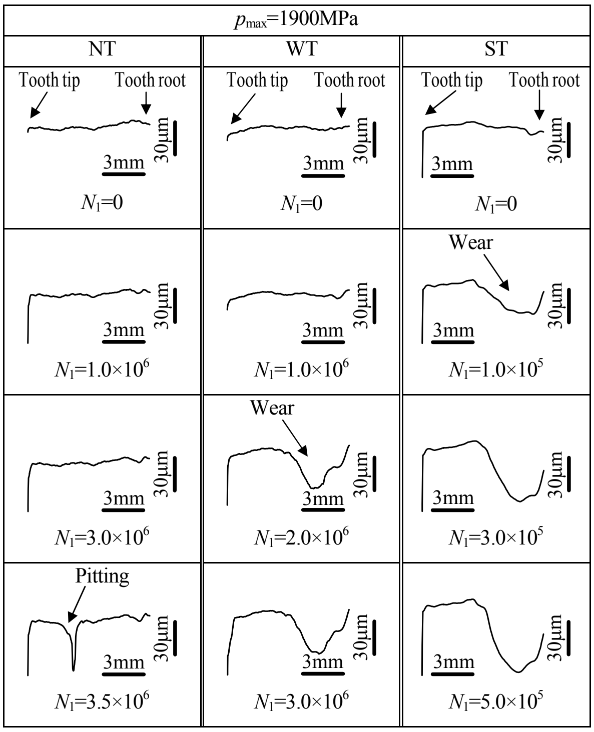

Fig. 7. Tooth profile curves of the test pinions.

ness of the WC/C coating ranging from 2–3 μm. All the gears of ST employed in this study showed the same tendency of wear behavior of ST shown in Fig. 7. This indicates that the WC/C coated layer of ST delaminates completely on the dedendum flank at the early stage of the tests. While the peeling of the dedendum flank of the mating gear also occurs, the WC/C coating layer remains at the addendum flank. Once the peeling of the coated layer occurs, the peeled dedendum flank comes in contacts with the coated addendum flank of the mating gear. The wear penetrates the matrix and progresses. The large wear leads to a large variation of the load distribution and dynamic load, and eventually the tooth surface failure such as pitting occurs. However, the peeling occurrence of the coated layer of WT is revealed much later than that of ST. Hence, the fatigue life of WT is long under a comparatively low-load condition. The fatigue life of the coated gear is remarkably affected by the peeling occurrence of the coated layer.

4. Conclusions

Under a comparatively low-load condition where the peeling of the coated layer did not occur, the fatigue life of the WC/C coated gears was longer than that of the non-coated gear. However, under a comparatively high-load condition where the peeling of the coated layer occurred, the fatigue life of the WC/C coated gears was shorter or equal compared with that of the non-coated gear. The peeling of the coated layer led to the wear and pitting on the tooth flank. Hence, the peeling occurrence of the coated layer is the dominant factor in the surface durability of the WC/C coated gear.

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