ROLLING CONTACT FATIGUE DAMAGE OF
WC-Co CERMET SPRAYED COATING AND ITS AE ANALYSIS

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Abstract

Rolling contact fatigue tests were performed for three kinds of WC-Co cermet-sprayed steels in order to study the influence of spraying conditions on the rolling contact fatigue damage. Testing machine for rolling contact fatigue with AE monitoring system was developed using a thrust bearing. Displacements of the pulley were measured for real-time observation of the peeling, while acoustic emission (AE) method was utilized to detect both the peeling and flaking. Two modes of damage were found in the WC-Co cermet-sprayed coatings, i.e. peeling and flaking. The former was initiated by micro-fracture around the WC particles near the surface due to the contact force, and the latter by macro-crack initiation attributed to repeated shear stress by the plane-sphere contact. The peeling damage initiated in the early stage of rolling contact fatigue test, and increased contact areas and thus reduced damage rate. Subsequently, flaking damage took place by Mode-II crack initiation developed by cyclic shear stress under contact stress distribution.

Keywords: Rolling contact fatigue, Sprayed coating, WC-Co cermet, Peeling, Flaking

1. Introduction

WC-Co cermet coatings sprayed by high-velocity oxygen fuel (HVOF) method have been widely used for wear-resistant applications since high-performance coatings are available [1]. It was observed that cracks initiated in the coating progressed to the substrate boundary and led to the final fracture of specimens, when the coating was harder than the substrate and the boundary was well bonded [2]. This behavior is important for fatigue strength evaluation of sprayed components, because the coating cracks determine the fatigue strength of sprayed components [3]. Therefore, it is important to evaluate fatigue resistance of the sprayed coatings. We constructed a contact fatigue testing machine to evaluate the fatigue resistance of sprayed coating itself so that the maximum amplitude of cyclic shear stress is within the sprayed coating.

In the present study, rolling contact fatigue tests were performed for three kinds of WC-Co cermet-sprayed steels in order to study the influence of spraying conditions on the rolling contact fatigue damage. Detailed observation of fatigue damage and acoustic emission (AE) monitoring were simultaneously conducted in order to analyze the influence of spraying conditions on the strength and fracture mechanism of rolling contact fatigue.

2. Experimental Procedures

The substrate material is 12-mm-thick alloy steel, JIS-SCM440, oil-quenched from 870°C after 1h heating and tempered at 560°C for 2h. The specimens were spray-coated WC-12%Co...
by HVOF method using CJS system of OSU Co. with constant conditions of hydrogen gas supply: 4 Nm³/h, spraying distance: 350 mm, gun velocity: 500 mm/s, pitch: 5 mm and 8 passes. Other spraying conditions are listed in Table 1, where the spraying conditions A, B and C are used for sprayed specimens A, B and C, respectively. Table 1 also presents the mechanical properties estimated by the inverse analysis of surface acoustic waves (SAW) and residual stress by cutting method [4]. The sprayed thicknesses A, B and C were 390, 500 and 500 µm, respectively. The sprayed surfaces were polished by diamond paste and the finished thicknesses were between 100 and 200 µm.

The rolling contact component is a steel ball made of high-carbon chromium steel, JIS-SUJ2, with the diameter of 5.56 mm. It is a part of thrust bearing, No.51200, with the inner and outer diameters of 10 and 26 mm, respectively, having 9 steel balls. Figure 1 shows the rolling contact fatigue machine developed in house. The sprayed specimen was mounted on a holder supported by a steel ball at the center. Thrust force, $P_t$, was applied to the bearing rotating on the specimen at 400 rpm. Cyclic frequency of rolling contact by the 9 balls was then controlled as 30 Hz. Maximum shear stress by the ball contact was confirmed to be 25 to 30 µm below the surface by finite element analysis using a commercial code, MARC. The cyclic rolling contact made a groove on the coating surface due to fatigue damage. The depth of the groove was monitored indirectly in terms of the pulley displacement measured by eddy current sensor using our special averaging software. The resolution of the measurement was about 1 µm.

Figure 2 shows a schematic illustration of AE monitoring system. Four small AE sensors (PAC, PICO) were mounted on the side surfaces of the specimen. AE signals were amplified by 40 dB, and acquired by a PC-based wave analyzer (Gage Applied Science). In order to detect damage signals properly, AE signals of channels 1 and 2 were added and filtered out the lower frequency component. The high-pass filter reduced the signal amplitude by 8.7 dB at 100 kHz.
and by 1.8 dB at 1 MHz. Without the high-pass filter, no AE signal from fatigue damage was obtained because of continuous acquisition of low frequency noise from cyclic contacts.

### 3. Results and Discussion

#### 3.1 Observation of Rolling Contact Fatigue Damage

Variations of displacement of pulley, $D$, with the number of cycles, $N$, are presented in Figs. 3 and 4, which demonstrate influences of spraying conditions and contact force, respectively. For all the cases, $D$ increased rapidly just after starting the tests, followed by moderate increase in $D$. Subsequently, $D$ increased again except for specimen C at $P_t = 180$ N for the cases in Figs. 3 and 4. The changes in $D$ tend to occur at larger values of $N$, when the $P_t$ value is lower or the spraying pressure is higher, namely it is the largest for the specimen C. As will be discussed later, the three stages of the changes in $D$ resulted from damage mechanisms developed by rolling contact fatigue.

After the tests shown in Fig. 3, the grooves were observed on the specimen surfaces by a surface roughness measuring instrument (Taylor Hobson, FORM TAYSURF). Figure 5 shows three dimensional configurations together with the sections indicated by A-A’, B-B’ and C-C’ in the upper figures. The depth of the grooves can be determined by drawing inscribed circle in the section profiles, and these agreed fairly well with the final displacement, $D$, in Fig. 3.

![Fig. 3 Displacement change for different sprayed conditions at $P_t = 180$ N.](image1)

![Fig. 4 Displacement change at different $P_t$ values for specimen B.](image2)

The groove surfaces were observed by scanning electron microscope (SEM) and presented in Fig. 6. The surface exhibits fine granular appearance observed as dark area, while the bright area is flat and damaged much less than the dark area by rolling contact fatigue. The dark area is dominant in the specimen A, but it is reduced in specimens B and much reduced in specimen C. The lower micrographs of Fig. 6 are magnified appearances of the upper micrographs. Figure 6(d) shows a small hole, which might be a trace of removal of a small particle with several tens of $\mu$m. Figures 6 (e) and (f) demonstrated crack initiation on the groove surface in specimens B and C.
Fig. 5 Three dimensional configurations and sections of grooves at $P_t = 180$ N.

Fig. 6 SEM micrographs of damaged surfaces at $P_t = 180$ N. (a) specimen A: $N = 1.7 \times 10^6$, (b) specimen B: $N = 1.6 \times 10^6$ (c) specimen C: $N = 1.5 \times 10^6$. The magnified micrographs of specimens A, B and C, are shown in (d), (e) and (f), respectively.

After the surface observations, the specimens were cut and observed on the section of the grooves. The SEM micrographs are presented in Fig. 7. Subsurface lateral cracks were observed in specimens B and C at the depth of about 30 $\mu$m from the surface. This depth coincides with the location of maximum shear stress predicted by FEM analysis. On the other hand, cracking around the particles and the particle removals can be found in specimen A.

3.2 AE analysis

Other specimens were prepared for AE analysis during the rolling contact fatigue tests at $P_t = 180$ N. Figure 8 represents the simultaneously monitored displacement $D$ and cumulative AE event counts, $N_{AE}$, with the number of rolling contact cycles, $N$. The variations of $D$ are slightly different from those in Fig. 3. However, general trends are the same, which support the repro-
Fig. 7 Sectional view of grooves at $P_t=180$N. (a) specimen A, (b) specimen B, (c) specimen C. The magnified micrographs of specimens A, B and C, are shown in (d), (e) and (f), respectively.

Fig. 8 Displacement of pulley and cumulative AE event on $P_t=180$N.

Fig. 9 Detected AE signals.
ducibility of these experiments. For the specimen A, AE signals were detected just after the beginning of the test, and then showed higher rates of increase in \( N_{AE} \) after \( N = 5 \times 10^5 \) cycles together with the second increase of \( D \). For the specimen B, the first increase of \( D \) was obscure in this experiment. The first AE signal was detected at \( N = 3.5 \times 10^5 \) cycles, and the rate of increase in \( N_{AE} \) became higher after \( N = 8 \times 10^5 \) cycles. Subsequently, the second increase of \( D \) was found after \( N = 1 \times 10^6 \) cycles. For the specimen C, the first AE signal was detected at \( N = 9.5 \times 10^5 \) cycles, then \( N_{AE} \) slowly increased, but the rate of increase was constant and the second increase of \( D \) was not observed.

Examples of the AE signals are shown in Fig. 9. For the AE waves in Fig. 9(a), or type 1, polarities of the first peaks were all positive, while in type 2 they were reversed between diagonal locations, i.e., ch. 1 vs. ch. 2 or ch. 3 vs. ch. 4, as shown in Fig. 9(b). These AE signals were denoted as type 1 and 2, respectively. Most of the detected AE signals represented the characteristics of type 1. However, four signals of type 2 were found in the test for specimen B, and distinguished by open circles in Fig. 8(b).

![Fig. 9: Examples of AE signals](image)

Fig. 9 Examples of the AE signals (a) type 1, (b) type 2.

In order to analyze the AE signals, traveling velocity of the longitudinal (P-) wave was determined for specimen B. Here, YAG laser pulses were radiated on the specimen surface and the first arrival waves were detected on the back surface using a laser interferometer. The P-wave velocity, \( V_p \), was measured as 5929 m/s. Next, the AE sensor was mounted on the side surface of the specimen, and the YAG laser pulse was radiated at the distance of 20 mm from the sensor. The traveling time was 3.35 \( \mu \)s, and resulted in the wave velocity of 5970 m/s, which agreed with the \( V_p \). Therefore, the first peaks of the detected AE signals are the P-wave, and used for the analysis of AE source location. The results are demonstrated in the upper illustrations of Fig. 10, where the numbers of analyzed AEs were limited because of small amplitudes of the first peaks. The circles in the figures indicate the rolling contact location, where the grooves are observed.
The analyzed locations are distributed near the grooves. The lower micrographs of Fig. 10 show contact damages at the rectangular marks shown in the upper illustrations. Specimen A exhibits uniform damage on the specimen surface, while the specimens B and C present removals of larger particle. Those damage mechanisms are denoted as peeling and flaking, respectively.

AE source analysis was conducted by the simulation of AE wave pattern, using artificial AE source. Figure 11 represents schematic illustrations of the artificial AE source excited by line focused pulse YAG laser and shear type PZT element for Mode I and II cracking, respectively. Figure 11 presents corresponding AE waveforms with the AE sources. The polarities of the first peaks are the same between the diagonal AE sensors for Mode I cracking, while they are reversed for Mode II cracking. Therefore, type-2 AE signals shown in Fig. 9 reflect the subsurface Mode-II crack initiation, which leads flaking damage on the specimen surface.

Fig. 11 Detected AE waves from simulated AE sources of mode I and mode II cracking.

3.3 Fracture Mechanism of Rolling Contact Fatigue

The above observation and AE analysis reveal the fracture mechanism of rolling contact fatigue of WC-Co cermet-sprayed materials as schematically illustrated in Fig. 12. When the rolling contact stress is applied, small cracks initiate around WC particles, which are peeled off from the specimen surface. This behavior corresponds to the initial increase in displacement \(D\) in Figs. 3 and 4 and produces the groove resulting in the increase in contact area and decrease in contact stress. Therefore, the peeling damage becomes less significant with increasing \(D\). In the subsequent rolling contacts, cyclic shear stress initiates the subsurface lateral crack as shown in Fig. 12(b) and leads to the flaking mechanism caused by Mode-I cracks. The AE analysis monitored these cracking mechanisms and agrees with this sequence of events.

The spraying condition affected the strength of rolling contact fatigue. As shown in Figs. 3 and 8, \(D\) and \(N_{AE}\) increased most rapidly for the specimen A, whose spraying pressure is the
lowest. For specimen A at $P_v = 180$ N, the peeling damage developed so quickly that the lateral crack did not grow large enough to develop flaking damage. In contrast, specimen C exhibits the highest fatigue strength. For specimen C at $P_v = 180$ N, peeling damage was hardly seen, but the subsurface lateral cracks developed and lead the flaking damage. The strength characteristics of specimen B was in between those of specimens A and C.

4. Conclusion

Rolling contact fatigue tests were performed for three kinds of WC-Co cermet-sprayed steels in order to study the influence of spraying conditions on the rolling contact fatigue damage. Results are summarized as follows.

(1) Two modes of rolling contact fatigue damage were found in the WC-Co cermet-spray coatings. They are peeling and flaking.
(2) The strength of rolling contact fatigue is enhanced with increasing spraying pressure.
(3) The rolling contact damage developed more quickly with increasing contact stress.

References