Wear Performance of GCr15 Friction Pairs with Effect of Initial Radial Micro-Grooves

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Abstract: Background: Grooves may inevitably occur on the surface of the friction pair caused by severe wear or residual stress, which will play an important role on the reliability of machine parts during operation.

Objective: The effect of the micro-grooves perpendicular to sliding direction on the wear performance of the friction pairs should be studied.

Method: Micro-grooves can be machined on discs of friction pairs using electrical discharge machining. On-line visual ferrograph method was used to monitor the wear process to research the wear rate changing characteristic. Profilometer and metallurgical microscope were used to observe the wear scars.

Results: Comparing to the non-groove test, i) in one-groove test, wear volume and rate were approximate the same, and the wear scar was smooth, ii) when the grooves more than 4, the test running-in stage will be obviously prolonged, particularly for the test with 8 grooves on the disc, the duration of running-in stage is 4 times than that without grooves on specimen, and the wear rate and volume increase significantly, and then decrease with fluctuation, iii) the abrasive wear can be avoid with the debris stagnating in the groove, however, fatigue wear will significantly emerge.

Conclusion: Abrasive wear can be avoided and smooth running-in surfaces can be obtained with proper amount of initial radial micro-grooves.

Keywords: Radial groove, friction pairs, wear properties, debris features, ferrograph, wear scar cycle.

1. INTRODUCTION

It is inevitable that grooves or slits perpendicular to the direction of motion will occur on the surface of the friction pair that is relatively moved in the machines or equipment. For example, the micro-grooves left after the splicing of the crankshaft bearings, and the residual internal stress during the processing of the differential gear spherical washers in the differential often cause the radial cracks of the material [1]. Micro-grooves perpendicular to the relative sliding direction play an important role in the wear performance and reliability of machine parts during operation. Since the defect appears on the sliding pairs at the early running-in stage, during which non-severe wear failure occurs, and the defect width is very small compared with the length of the sliding trace in the wear scar cycle [2], which cannot lead to a fatal defect. However, the wear performance characteristics of the grooved friction pairs have attracted wide attention of manufacturers and researchers.

In the previous research, initial grooves were set on the surfaces of friction pairs mainly by an artificial machine, and the tribological experiment was carried out on the samples with initial grooves. A crack with the width of about 1 mm was set on the surfaces of friction pairs, and the characteristics of stress-strain and material strength at the contact surfaces were studied by Fischer [3]. He et al. [4] analyzed the stress distribution on the surface of a semicircular crack.

Artificial cracks or micro-grooves, machined by the electric discharge machine, are often used for accelerating the wear process and friction performance to shorten the test duration [5]. The presence of frictional interface grooves [6] can change the continuity and isotropy of the material, and then change the instantaneous contact state of the contacting pairs [7]. However, it has the ability to capture wear debris and store lubricating oil [8], thereafter, the impact of produced wear debris on the interface wear under the action of alternating loads can be reduced [9], otherwise, abrasive wear caused by wear particles will induce other wear forms.

With the existence of initial radial micro-grooves on the sliding pairs, the friction and wear characteristics of widely used wear-resistant materials (such as GCr15) were studied by ball-on-disc friction and wear test bench. The high frequency on-line monitoring techniques can more effectively monitor the friction and wear states of the friction pair in experiments, which is beneficial to the study of the evolution process of the wear [10]. At present, on-line ferrography technique has been widely applied and developed in real-time monitoring of wear and dynamic prediction. Particularly, the On-Line Visible Ferrograph (OLVF) [11, 12] developed by Xi'an Jiaotong University can effectively and frequently monitor and analyze the worn particles, which can be applied to judge the wear condition. In addition, the observation and analysis combined with the wear scar morphology and wear particle characteristics can determine the wear modes of the friction pairs under different working conditions and running processes more accurately [13].

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In this article, different samples of radial grooved disc samples were used for comparative experiments. On-line real-time visual monitoring of wear debris via OLVF was used to obtain wear rate signals. Accelerated experiments were set by increasing the contact specific pressure, using white oil without additives, and low speed to ensure that no dynamic lubrication is formed by centrifugal force. The TR200 profilometer and Scanning Electron Microscope (SEM) were used to observe the cross-sectional profile and micro morphology of the wear scar, and the wear mechanism of the specific wear phenomenon was explored.

2. IPCA PARAMETERS

The On-Line Visual Ferrograph (OLVF) [14] is the application of electromagnetic coils to generate a controllable strong magnetic field force, which causes the ferromagnetic wear particles deposited onto the visual zone of the oil line with spectral chain distribution. After the particle deposition, the CMOS camera embedded into OLVF will capture the ferrographic photographs. The color image is converted into a grayscale image by processing of ferrographic images, and the Index of Particle Coverage Area ratio (IPCA) parameter is calculated and denoted as $K_t$.

During the wear particle deposition process, the following assumptions are made: 1) the wear particles are evenly distributed in the oil, 2) the shape of all wear particles is approximately spherical, and the sizes are evenly distribution and there are no exogenous ferromagnetic particles, 3) there is no particle overlapping. Therefore, the two-dimensional coverage area of the particles deposited during the collection cycle has approximate positive correlation with the wear rate. The change of the IPCA parameter value during the wear process can indicate the change of the wear rate of the friction pairs to achieve on-line wear monitoring [15]. According to the IPCA definition, the wear characterization parameter $K_t$ can be calculated as equation (1) [16],

$$K_t = \frac{C}{w \times h} \times 100\%$$

where $C$ is the number of the visual deposition area pixels, $w$ and $h$ are the pixel numbers of the width and height of the visible deposition area, respectively. This parameter is based on strict assumptions, but the wear process dynamic data obtained through online high-frequency acquisition during wear monitoring has overall effectiveness and significant value.

3. SAMPLES AND EXPERIMENTS

Experiments were carried out on a ball-on-disc friction test rig, which consisted of a sample fixing device, a lever loading system, a drive motor and a fuel supply system. The ball and disc samples are made of bearing steel GCr15 with hardness of 420 HV. The ball and disc samples have the diameters of 6 mm and 60 mm, respectively. The thickness of discs is 5 mm with a surface roughness $R_a = 0.2$ μm. In the experiment, the relative sliding linear velocity was 12.5 m/s. According to the Archard wear calculation model, when the contact specific pressure $p > H/3$ ($H$ is the Brinell hardness of the material), the wear growth will greatly be significant. Therefore, the corresponding critical load $F_c$ is 25 N and the normal load of 50 N in the accelerated wear tests was set, and then the Hertz contact diameter of 0.211 mm can be obtained. A micro-groove was machined on the disc sample in the radial direction. The width of the micro-groove is approximately equal to the Hertz contact diameter and was set to 0.25 mm, and the depth is 5 mm which is the thickness of the disc sample, as shown in (Fig. 1). Therefore, when the ball sample passes through the groove region, the contact pressure of the friction pair increased significantly with the decrease of the contact area.

During the experiment, the IPCA parameter curves were given as output by OLVF under online monitoring of the wear debris in the oil. The disc samples were no longer subjected to any heat treatment after polishing for reducing the disc wear resistance and then shortening the experimental period. To prevent the wear particles from magnetizing during tests which would affect the OLVF monitoring results, the disc samples were demagnetized after grinding. Then, the disc samples were finely ground and polished with a surface roughness of 0.2 μm, and ultrasonically pulsed and washed in deionized water. 32# white mineral oil with poor lubrication properties was used in tests for extending the running-in period and increasing the wear rate, and the characteristics of wear process can be indicated by the values of IPCA parameter $K_t$.

During the experiment, the continuous open-loop lubrication manner was set. The lubrication oil was drawn continuously from the oil reservoir by the peristaltic pump to the contact position of the samples, and then the oil was forced into the waste oil pool caused by the centrifugal force. The oil supply speed of 3.5 ml/min was set to ensure that the amount of supplied oil was equal to the amount of the sampled oil in a single monitoring cycle of OLVF. Therefore, the abrasive particles were prevented from stagnation in the oil pool and the sampling period of the OLVF from the waste oil pool was set to 12 min. Different tests of no groove (T1-0), single groove (T2-1), four grooves (T3-4) and eight grooves (T4-8) were set, and the friction and wear properties of the GCr15 material friction pairs with radial grooves were evaluated by comparing the experimental results.

4. RESULTS AND DISCUSSION

4.1. IPCA Parameter Curves

The wear process of the experiments T1-0, T2-1, T3-4 and T4-8 was monitored by OLVF to obtain the IPCA parameter curves, as shown in (Fig. 2). According to the classical tribology theory, the wear process can be divided into three typical stages, the running-in period, the stable wear period and the severe wear period. The wear rate is typical of the “bathtub curve”. The IPCA parameter curves obtained during the experiment show that 1) when the contact surface of the disc sample is continuous in the experiment T1-0, the running-in period is shorter than 25 min. 2) In the experiments T2-1, T3-4 and T4-8, the running-in periods were longer with the increase in the number of micro-grooves, at 60, 150 and 200 min, respectively, and the $K_t$ curves showed oscillating decrease. 3) When the number of micro-grooves on the disc sample was 4 and 8, the $K_t$ curves appeared relatively low in the periods of 25-50 and 80-130 min, respectively, and wear increased again after 60 min.
Fig. (2). IPCA curves for different tests.

Based on the monitored data as shown in (Fig. 2), the $K_t$ values of about 100 to 200 during test T3-4 were twice more than the $K_t$ values of about 50 to 100 during tests T1-0 and T2-1 before 150 min, which showed approximately the same wear rate during experimental process. When the micro-grooves were 8 on the disc, the $K_t$ values can remarkably reach to 800 with the minimum value of about 50 at 120 and 160 min.

It can be concluded that the influence of a single micro-groove on the wear process of the friction pairs is not significant, however, when multiple micro-grooves are on the disc sample, the wear rate of the friction pair during the running-in period sharply increases. Therefore, wear process of the relatively sliding contact surface during the running-in phase was unstable when multiple micro-grooves were set on the discs.

The two-dimensional profilometer of TR200 was used to obtain the cross-sectional profiles of the wear scar on the T1-0, T2-1, T3-4 and T4-8 disc samples. Each disc specimen was measured at four locations far away from the micro-groove position. The results show that the profile and area of the cross-section at different locations on the same sample are approximately the same. The average areas of the cross-sectional wear region at four locations were taken for each sample. It can be seen from the results (as shown in Fig. 3) that the cross-sectional area loss of the disc wear scars in the experiments T1-0 and T2-1 did not change significantly (about $3.6 \times 10^{-9}$ m$^2$) which is consistent with the IPCA monitoring results. However, when the number of micro-grooves was 4 and 8, the cross-sectional area of wear scars loss increased significantly, reaching $9.1 \times 10^{-9}$ and $26.5 \times 10^{-9}$ m$^2$, which are approximate 2.5 and 7 times than those in tests T1-0 and T2-1, respectively.

Fig. (3). Disc sample wear cross-sectional area.

On the basis of on-line monitoring of wear rate and wear section analysis of disc specimens, it is shown that under the same normal load, single groove has a little effect on wear and wear rate. However, when the number of micro-grooves is large, the running-in period is significantly prolonged, and the wear rate and wear amount are significantly highly.

4.2. Analysis of Wear Scar Characteristics

The disc samples after the experiment were ultrasonically shaken and washed in absolute ethanol or acetone, and then placed in a Scanning Electron Microscope (SEM) to observe the wear scar morphologies. The observation point is 15 mm away behind the groove position, and the results are shown in (Fig. 4). In the experiment T1-0, when the disc sample has
no groove, mild furrow wear appears on the wear scar, and the main wear form is abrasive wear. In experiment T2-1, the wear scar surface on the single grooved disc sample is smoother than the no-groove disc sample, but a few fatigue pitting appears at the middle region of the wear scar where the contact pressure is higher than the edge region. The wear scar morphologies of the specimens of tests T3-4 and T4-8 showed that there was severe plastic deformation on the contact surface of the disc specimen during the wear process. Especially when the micro-grooves were 8, the contact surface material tended to show plastic flow. Fatigue wear occurred and left more pits after material flow and wear.

The groove region morphology is shown in (Fig. 5), it can be seen from the SEM images at the micro-groove region of the disc wear scars that when the ball sample passes through the micro-groove, the nominal contact area decreases first and then increases, and the wear scar width gradually increases from the groove front. When the ball passes the disc micro-groove region, the contact width increases more significantly. Such phenomenon is due to the fact that the ball sample has a certain impact on the trailing edge of the micro-groove during the sliding process, and the impact causes fatigue pitting on the trailing edge wear surface. Compared to the surface morphology of the ball samples, it can be seen that (Fig. 6) in test T1-0, the wear shape of the ball sample is approximately spherical, with many furrows along with the relative sliding direction. In test T2-1, the ball sample wear scar is typically elliptical and the surface is smooth due to the fact that the micro-grooves detained the wear particles to avoid abrasive wear and changed the contact shape and area.

Fig. (4). Scar morphology of different test disc samples.

Fig. (5). SEM images of experimental T2-1 wear scar.
The SEM topographies of the ball and disc wear indicate that the initial radial micro-groove can change the contact characteristics of the sliding contact pair and reduce the abrasive wear. However, as the number of grooves increases, the fatigue wear is more obvious, especially in the middle area where the contact pressure is large on the wear scars.

4.3. Typical Wear Particle Characteristics

According to the sampling monitoring results of OLVF, the wear particles of the monitored samples with higher $K_t$ values in the experiment were collected again, after cleaning and discretization treatment, and then single particles were observed by an offline method with a metallographic microscope. As shown in (Fig. 7), in experiment T1-0 without micro-groove on the disc, typical cutting particles can be found. Combined with the corresponding wear scars of the disc sample, it can be suggested that the main wear form in the experiments is abrasive wear. In experiment T2-1, the observed particle morphology was mainly as shown in Fig. (7) (middle), and we did not find the slender abrasive particles. When the micro-grooves increase to 8 (experiment T4-8), each time the ball passes through the micro-grooves on the disc, a certain vibration inevitably generates which will result in fatigue wear of the disc specimen. The cold hardened layer on the material surface during the running-in process is crushed, resulting in well-defined characteristic wear particles. Therefore, under the same working conditions, the number of micro-grooves has an important influence on the wear form of GCr15 material; especially when the number reached 8, the effect of grooves on the wear performance was more remarkable.

CONCLUSION

Wear performances of GCr15 sliding pairs with micro-grooves on the discs were assessed by self-designed ball-on-disc rig. The grooves perpendicular to the direction of sliding were manufactured on the discs by electric discharge machining. The IPCA curves and SEM photographs of the wear scar indicate the characteristics of the tribological process of the sliding pairs. When there are many radial micro-grooves on the sliding friction pair, the wear rate fluctuates greatly during the running-in period. Especially, when the amount of micro-grooves is 8, the $K_t$ value fluctuates significantly, and the running-in period lasts longer with a large wear amount. In the case of no groove, the lower friction pair wears less, the main wear form was abrasive wear, meanwhile, wear mass of the sliding pairs had not obvious increment with one groove on the disc. Fatigue pitting occurred on the wear scar as the amount of grooves increased to 4, especially in the case of 8 micro-grooves, the fatigue pitting was very remarkable and the plastic deformation of the groove front was obvious. The friction pairs without the initial radial micro-groove tended to show abrasive wear and produce slender cutting wear particles, and with the effect of the micro-groove, the abrasive wear increased significantly, and the wear form changed. However, when the number of micro-grooves is high, fatigue wear is liable to occur, and sheet-like wear particles are generated, and the wear is deteriorated severely. Further research will be carried out on heavy machinery to quantitatively analyze the wear performance under different wear types.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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