Dry tribological properties of M50 bearing steel under different temperatures

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Abstract

Reducing wear and clarifying relation mechanism are essential to improve the life of engine bearings, so we investigate the influence of ambient temperature on the friction characteristics of M50 steel self-matching pairs under dry friction conditions. As the ambient temperature increases from 30 °C to 500 °C, friction coefficient decreases sharply from 0.78 and tends to be stable around 0.4, while wear rate firstly decreases and then increases. High temperature (More than 300 °C) induces the serious oxidation and softening on the wear surface, causing the main wear mode from abrasive wear to adhesive wear. The oxides include mainly of Fe2O3 and Fe3O4, and minor MoO3 and Cr2O3, which are benefit for forming a continuous tribolayer on the wear surface, thereby improving the friction performance.

1. Introduction

Aero-engine is the ‘heart’ of the airplane, and bearing is the critical safety component and core foundation department unit. Because of the harsh environment of aero-engines operation, the bearing material should have high reliability, high contact fatigue life and excellent dimensional stability [1–3]. M50 bearing steel is a high speed steel with high contents of Cr and Mo, and it was developed in 1950s and used widely as the bearing material of aeroengine [4–7].

As the aero-engine tends to be great thrust-to-weight ratio, high speed, high temperature and long life, their bearing material is required excellent comprehensive performances [8, 9]. The friction process of the bearings can easily induce high temperature in the contact area, which softens the properties of the surface material and changes the surface layer structure, thereby reducing the yield strength and finally causing the fatigue spalling and damage. Many researchers focused on the methods of improving the bearing life under the rolling friction condition [10–13]. Trivedi [14] and Rosado [15] reported that the wear rate of the M50 was related to the ambient temperature and the lubricant type, and reducing the cleanliness factor S and the pollution factor V could improve the bearing life. Helmick [16] studied the influence of environmental humidity on wear behavior, and the environmental humidity had a greater impact on the rolling wear condition when the surface humidity was less than 20 %. The above research works are tribology behaviors of the rolling friction under the normal operation condition of the bearing materials.

However, the instantaneous slip of rolling contact fatigue bearings is similar to the sliding speed of 40 m s⁻¹, and there are often tens of seconds of oil-free period during the lift-off process of aero engines [17–20]. There is a
micro-slip and rolling-slip mixing under the oil-free friction condition, and the sliding wear is the main wear mode for the bearing material, making the service conditions of engine bearings very harsh [21, 22]. Therefore, studying friction characteristics and clarifying wear mechanism of the bearing steel under the slipping friction condition are essential for exploring the wear mechanism and improving the service life of engine bearings. In this paper, the effect of ambient temperature on friction characteristics and wear mechanism of the M50 bearing steel was investigated using a ball-disc tester under the slipping dry friction tests, providing the theory supports for the life extension technology of engine bearings.

2. Experimental procedure

2.1. Material preparation

The elemental composition (wt%) of M50 is shown in table 1, containing 89.41 % Fe, 4.01 % Cr, 4.15 % Mo, 1.01 % V, 0.78 % C, 0.28 % Mn, 0.27 % Si and other elements (Cu, Ni and P). During hardening treatment, the steel was preheated to 850 °C and soaked for 50 min, then the temperature was raised from 850 °C to 1095 °C and soaked for 30 min, followed by oil quenching in vacuum. After that, the specimen was tempered three times at 535 °C for 135 min (figure 1).

![Figure 1. Schematic diagram of heating treatment for M50.](image)

| Elements | Fe  | C   | V   | Cr  | Mo  | Si  | Mn  | Other       |
|----------|-----|-----|-----|-----|-----|-----|-----|-------------|
| Content  | 89.41 | 0.78 | 1.01 | 4.01 | 4.15 | 0.27 | 0.28 | 0–0.095    |

2.2. Measurement of basic properties

Friction and wear behaviors were investigated on a ball-on-disc tester (MFT-5000 RTEC), as shown in figure 2. The M50 steel is prepared to the diameter of 9.5 mm for the ball, and the size of the disc is Φ 55 mm × 10 mm. The parameters of the friction tests were the load of 2000 MPa, the speeds of 0.3 m s⁻¹, the temperatures of 30 °C, 100 °C, 200 °C, 300 °C, 400 °C and 500 °C. The ball was cleaned using alcohol before each friction test, and then the friction test was finished for 30 min. Wear rate \( \omega \) was determined as volume loss during each friction test:

\[
\omega = \frac{SC}{L}
\]

Where \( S \) was the cross-sectional area of wear track, and it was measured by a 3D optical microscopy (Bruker Contour GT-K); \( C \) was the circumference of wear track; \( L \) was the trip of each friction test.

Microstructures were investigated using scanning electron microscopy (SEM, JSM-6380LV) and 3D optical profilers (Nanofocus AG). Phase compositions were investigated by Raman spectrometry (Raman, LRS Invia Renishaw) using a wavelength of 532 nm and Electron probe micro-analyzer (EPMA,).
3. Results and discussion

3.1. Friction coefficient and wear rate

Figure 3 shows friction curves with increasing time and average friction coefficients under the test conditions of the sliding speed of 0.3 m s$^{-1}$, the normal load of 2 GPa and the temperatures of 30 $^\circ$C–500 $^\circ$C. After a running-in process (Before 200s), friction coefficients gradually stabilize with time instead of fluctuating, and the stable stage is selected to calculate the average values and standard deviations of friction coefficient in figure 3 (a). Fitting analyses of the friction coefficient are finished to clearly compare with friction behavior under different ambient temperatures in figure 3 (b). Increasing the temperature from 30 $^\circ$C (Room temperature) to 200 $^\circ$C, the average friction coefficient has a sharp decrease of 43.75%. Going on increasing the temperature to 500 $^\circ$C, the friction coefficient tends to be stable around 0.42. The friction coefficient has a nearly logarithmic relationship with the ambient temperature.

As shown in figure 4, the width of wear track is calculated based on the SEM images, which is used to investigate wear condition of M50 during the sliding friction tests [23]. According to the fitting analysis results, the relation between the width of wear track and surface temperature is a parabola equation, and the minimum value of the width of wear track presents between 200 $^\circ$C and 300 $^\circ$C. As the temperature increases from 30 $^\circ$C to 200 $^\circ$C, the width of wear track has a 21.16% decrease. However, when the temperature is above 200 $^\circ$C, the width of wear track shows a growing tendency, especially more than 400 $^\circ$C. Above all, the ambient temperature has a significant effect on friction and wear behaviors of M50.

Figure 5 shows surface hardness of M50 varies with increasing surface temperatures. As the surface temperature increases from 30 $^\circ$C to 340 $^\circ$C, the surface hardness decreases (By 10.65%) from 62.9 HRC to 56.2 HRC. When the surface temperature is more than 500 $^\circ$C, the M50 happens to soften, and the surface hardness falls off a cliff. However, the width of wear track appears a sharply growing tendency as the friction
testing temperature increases from 400 °C to 500 °C. It is because when the friction testing temperature is 400 °C–500 °C, combining with friction heat, the temperature of wear surface usually reaches more than 500 °C.

### 3.2. Morphology and microstructure of wear surface

Figure 6 shows SEM images and 3D profiles of M50 (The disk) wear surfaces under the friction testing conditions of different temperature. As shown in figures 6(a), (e), (i) for the temperature of 30 °C, a smooth region with ribbon shape appears on the wear surface, and the width of the continuous tribolayer is about 1/4 that of the wear track. The roughness (Sa) of smooth surface is about 3.742 μm. Meanwhile, there are some spalling pits existing on the wear surface under the actions of shearing stress, especially the region outside the tribolayer area, so the main wear mode is abrasion wear. For the specimen at 200 °C in figures 6(b), (f), (j), the bigger and smoother surface (Sa = 2.863 μm) is formed on the wear surface, and the area reaches above 70% of the wear track. Therefore, friction coefficient appears a sharp decrease as the temperature increases from 30 °C to 200 °C in figure 3(b).

With increasing the temperature to 300 °C, the smooth surface further expands and has the same area with wear track on the wear surface in figures 6(c), (g), (k), whose surface roughness is 2.33 mm, and the width of wear track is 2.941 μm. Meanwhile, some materials with irregular in shape and dark grey exhibit on the wear surface at 300 °C, which indicates slight adhesion. When the temperature increases to 500 °C, the dark grey materials become bigger and more, and the wear surface becomes smoother, whose roughness is about 2.719 μm, but the wear track further widens to 2.78 mm, causing excessive wear.

Figure 7 shows EBSD images of the vertical section through wear surface of M50 at 30 °C, containing BC map and IPF map. From wear surface to the matrix, there are three parts according to the material structure: (1) the tribolayer is about 9 μm thickness, and there are many defects and oxides due to the combined actions of
high temperature and shear force; (2) the deformation layer is 21 μm thickness, which is composed of the crystalline gains of 2–10 μm in diameter, and the crystal orientations are disorder due to the shearing action of friction force; (3) this layer is the matrix of M50, and the size of crystalline gains is about 5 μm–25 μm. Therefore, the oxidization has happened during the friction test of 30 °C, and the tribolayer is formed on the wear surface.
Meanwhile, the crystalline gains have been broken into small size under the actions of friction shearing force and loading stress, causing the work hardening around the wear surface region, which is good for the formation of smooth tribolayer and the decrease of friction coefficient.

Figure 8 shows Raman images of smooth region on the wear surface at the friction testing temperatures of 30°C, 100°C, 200°C, 300°C, 400°C and 500°C. There is an obvious diffraction peak (663 cm⁻¹) for Fe₂O₃ and Fe₃O₄ (A compound composed of FeO and Fe₂O₃) between the Raman shift of 100 cm⁻¹ and 1800 cm⁻¹, providing the information that M50 oxidation already occurred and Fe₃O₄ was formed on the wear surface at the testing temperatures of 30°C and 100°C. When the temperature is 200°C, Fe₂O₃ (Corresponding to the diffraction peaks of 225 cm⁻¹, 290 cm⁻¹, 410 cm⁻¹, 497 cm⁻¹, 610 cm⁻¹, 660 cm⁻¹ and 1300 cm⁻¹) begins to appear on the wear surface. As the temperature increases to 300°C, the diffraction peaks of Fe₂O₃ become higher and sharper, while the diffraction peaks of 610 cm⁻¹ and 660 cm⁻¹ means the Cr₂O₃ might be present. Meanwhile, two new diffraction peaks arise at 818 cm⁻¹ and 994 cm⁻¹ for MoO₃, and it indicates that serious oxidization causes the formation of more wear debris (Fe₂O₃, MoO₃ and Cr₂O₃) on the wear surface at 300°C. With increasing continuously the temperature to more than 400°C, the diffraction peaks have no obvious change, and the elemental compositions of wear debris tend to be stable [24].

Figure 9 shows EPMA images of smooth region for elemental composition (Fe, O, Cr and Mo) of tribolayer on the wear surface of M50 under the friction testing condition of 200°C. The elements of Cr and Mo have similar distribution areas, which are not easily oxidized, and they disperse evenly on the wear surface and present in micro and nano scale. The materials with dark grey and irregular in shape are iron oxides, and there are two kinds of areas according to the Fe: O ratios: (1) Low oxygen area has green color, where the mass ratios of Fe:O is (63.74–68.97): (19.19–21.25), corresponding to the atom ratios of (1.31–1.39): 1, and the main component of the iron oxide is Fe₃O₄ combined with the Raman results. (2) High oxygen area has yellow and red colors, and the mass ratios and atom ratios of Fe:O are (53.27–58.52): (25.39–29.52) and (1.47–1.72): 1 respectively, which is correspond to Fe₂O₃.

Figure 10 shows EPMA images of smooth region for elemental compositions (Fe, O, Cr and Mo) of tribolayer on the wear surface at the testing temperature of 500°C. Both green color (Low radio of O: Fe) and red color (High radio of O: Fe) of the O areas have bigger size than those at 200°C, meaning there are higher contents of Fe₂O₃ and Fe₃O₄ on the tribolayer at 500°C. The materials with dark grey and irregular shape (figures 6(g) and (h)) are the mixed metal oxides, which include 30.88–37.21 wt% O, 54.93–60.18 wt% Fe, 2.01–4.85 wt% Cr and 1.94–3.44 wt% Mo, and the atom ratios of O, Fe, Cr and Mo are about 60.3: 38.1: 3.2: 1. Therefore, the dark grey and irregular material are composed mainly of Fe₂O₃ and Fe₃O₄, and minor MoO₃ and Cr₂O₃.

3.3. Morphology of wear debris
Wear debris are collected and investigated after the friction tests at 30°C, 200°C, 400°C and 500°C, and the SEM images are shown in figure 11. Figure 11(a) shows morphology of wear debris at the testing temperature of 30°C, and the wear debris are oval in shape and 0–50 μm in diameter, which are produced by abrasive wear
As the temperature increases to 200 °C, the size of wear debris is reduced to micro and nano scale in figure 11(b), which is attributed to high temperature causing oxidization and the formation of Fe3O4 and Fe2O3 (figure 8) on the wear surface, and they are beneficial for repairing the spalling pits and forming smooth and continuous surface. Therefore, with increasing the temperature from 30 °C to 200 °C, both the wear surface roughness and friction coefficient presents significant decrease.

Figures 11(c), (d) show morphologies of wear debris at the temperatures of 400 °C and 500 °C, and there are two main types of the wear debris. Some are wear debris with micro and nano scale and oval structure, containing Fe3O4, Fe2O3, Cr2O3 and MoO3, and they are produced by the combining actions of oxidization and grinding. Others are large size and flaky structure, which are composed of the Fe2O3 and mixed metal particles, and they fall off from wear surface caused by oxidation wear and adhesive wear under the softening effect of high temperature (More than 400 °C).
3.4. Wear mechanism

In fact, the process of forming and breaking tribolayer is a dynamic balance state on the wear surface during the sliding friction tests [25–27]. The wear surface is broken under the combined actions of shearing stress and oxidation, and the particles fall off from the matrix, leading to the formation of the spalling pits [28, 29] Some of the particles escape out of the wear surface and form wear debris, and others are filled in the spalling pits and compacted again to restore the tribolayer. Meanwhile, the different temperature causes the differences of wear mechanism and tribology behaviors during the dynamic balance of forming and breaking tribolayer.

Wear models are schematically illustrated to clarify the wear mechanisms of the M50 during the sliding friction tests at different temperatures, as shown in figure 12. When the friction testing temperature is 30 °C–100 °C, the slight oxidation occurs to form the Fe3O4 (figure 8), and the main mode is abrasive wear. Under the shearing stress and normal force, the hard phase particles scratch the wear surface, causing the formation of the spalling pits (figure 6(e)). Meanwhile, the wear debris is inadequate to fill up the spalling pit, so there is high wear surface roughness and high friction coefficient (figure 3). As the temperature increases to 200 °C–300 °C, the
oxidization speeds up and the oxides of Fe₂O₃, Fe₃O₄, MoO₃ and Cr₂O₃ are formed on the wear surface. The oxides are the circular particles with small size (figure 11 (b)), and they not only can fill up the spalling pits and decrease the wear surface roughness, but also bring the friction condition from the rolling mode into the sliding mode. Meanwhile, the high temperature softs the wear surface of M50, and the metal debris is formed and smooth the wear surface, so both the friction coefficient and wear surface roughness have sharp decrease with increasing the temperature from 30 °C–100 °C to 200 °C–300 °C (figures 3 and 6). However, there are still the discontinuous and coarse regions on the surface of wear track. The wear mode is the mix of abrasive wear and slight adhesive wear. Continuing on increasing the temperature to 400 °C–500 °C, the temperature of wear surface is higher than the softening point (500 °C) with the help of friction heat, and the main wear mode is adhesive wear. The metal debris has good liquidity and is easily oxidized for oxides debris, which causes severe wear on the wear surface. The wear debris of metal debris and metal oxides are benefit for forming smooth wear surface, so there is a continuous tribolayer on the entire surface of wear track (figure 6). However, the high temperature causes excessive wear. Therefore, as the temperature increases from 200 °C–300 °C to 400 °C–500 °C, the friction coefficient further decreases and tends to be stable, and the width of wear track has a sharp increase.

4. Conclusion

To clarify friction and wear behavior of bearing steel M50 under the rigorous wear condition, we investigated the effect of the environment temperature on the tribological performances and relevant mechanism during sliding dry-friction tests. From the results obtained, it can be concluded that:

(1) As the environment temperature increases from 30 °C to 500 °C, friction coefficient firstly decreases sharply and tends to be stable, and the width of wear track exhibits a firstly decreasing and then increasing tendency. M50 has the best tribology performances at 200 °C.

(2) Morphology of wear debris changes from micro scale and oval structure to large size and flaky structure under the influence of increasing temperature, and the main wear mode becomes adhesive wear from abrasive wear.

(3) High temperature (More than 300 °C) induces the serious oxidation and softening on the wear surface, improving friction performance but causing excessive wear. The oxides include mainly of Fe₂O₃ and Fe₃O₄, and minor MoO₃ and Cr₂O₃, which are benefit for forming a continuous and smooth tribolayer on the wear surface.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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