Friction and wear characteristics of alloy steel 18CrNiMo7-6 sliding on 42CrMo4

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Abstract. This paper studies the friction and wear behavior of 18CrNiMo7-6 alloy steel sliding on 42CrMo4 via cylinder-on-plate tests. The specimen cylinders are carburized for a hardness of 60 HRC and the plates are quenched and tempered for two hardness classes HRC 52 and HRC 46. On the test rig the specimens were lubricated with grease Gleitmo® 100 S in a specially installed rubber bellows. The friction coefficients and wear intensities of 18CrNiMo7-6 then are tested with improved normal load from 150 N to 900 N on the contact surface. The testing results show that both friction coefficient and wear coefficient decrease rapidly within 1×10⁶ load cycles. Wear mechanism shows that there is obvious adhesive, abrasive and oxidation wear forms after 3×10⁶ load cycles, among which the adhesive and oxidation wear forms were always not focused on in the researches till now. After 9×10⁶ load cycles the wear on the specimens is stable.

1. Introduction

18CrNiMo7-6 steel, according to DIN EN 10084 [1], a Chrome–Nickel–Moly carburizing alloy steel, is widely used in many heavy and high strained industry components such as heavy-duty arbors, bushings, bearings, gears, shafts, sprockets, and wear pins [2, 3]. As a result of the frictional loads between the contact parts, stress concentration is developed at the edge of the contact interface, resulting in rapid nucleation of surface micro cracks. These micro cracks then coalesce to a leading crack and are responsible for contact surface wear and fatigue damages, and finally defect of the whole system [4–6]. To improve the contact conditions between the parts, surface treatments are often applied to 18CrNiMo7-6 material for the improvement of surface mechanical characters, among which carburizing, coating and shot peening are commonly used methods in the industry [7–10].

In recent years researchers mainly focused on the mechanical and wear behaviors of parts from 18CrNiMo7-6 material in machine systems, e.g. splines, gears pairs as well as interference fittings [11–15]. The friction and wear behavior of these parts has a very complex mechanism and can be influenced by many parameters, including loading and contact conditions, material behavior and environmental conditions [11, 12]. Most of the existing researches handled with a single wear form. There were few research results indicating the weights of each wear form in a complex wear process. It is thus important to carry out relevant detailed studies to address the specifications.
The current work presents an investigation on major aspects affecting the friction and wear characteristics of 18CrNiMo7-6. The friction coefficients and wear intensities of specimens from this material under different surface hardness and load conditions were measured at a commercial test rig, which sets up a basis for the wear assessments of parts from this material in diverse application systems. The wear mechanism was also studied to provide an increased understanding on fretting wear phenomenon of this material. Based on Achard’s equation a wear intensity calculation formula is developed.

2. Experiments

2.1. Test configuration

The friction and wear tests were set up with a cylinder-on-plate configuration and performed at a UMT-3 multifunctional friction tester. The schematic of friction tester and cylinder-on-plate specimen were shown in figure 1a. The cylinder was fixed on the upper holder of the tester, the plate was set on the lower holder which is connected with an electromagnetic motor to generate rotating speed 150 rpm. The central distance of the two specimens was 7.5 mm, Figure 1b. The tests used a fixed weight through a force sensor to apply normal load from 150 N to 900 N which was required for producing frictional effect. During the friction test, the specimens were applied with commercial grease Gleitmo® 100 S. The testing time was 80,000 min and the corresponding wear cycle was 12×10⁶ for each specimen.

![Figure 1. Schematic of friction tester and cylinder-on-plate configuration.](image)

Besides the friction and wear coefficients, investigation on the wear mechanism is important for understanding the wear behavior of this material. Its worn morphology and chemical composition of specimen were analyzed using a scanning electron microscope (SEM, JSM-6460) equipped with energy dispersive spectrometer (EDS, Oxford INCA).

2.2. Test configuration

The specimens and contact plates were taken from 18CrNiMo7-6 and 42CrMo4 [16] steel stocks, respectively. In total there were 30 cylinder specimens and 30 contact plates prepared. The cylindrical specimen located at clamping was 5 mm in diameter and at working part 3 mm in diameter. The dimension of plate was Φ30 mm×5 mm, Figure 1b.

The material compositions of the specimen and the plates are obtained using EDXRF apparatus Tianrui® EDX1800D. The chemical composition is: 0.170 C, 0.250 Si, 0.50 Mn, 1.650 Cr, 0.320 Mo, 1.55 Ni, 0.006 P, 0.003 S, 0.028 Al, 0.120 Cu, 0.025 Nb, and the balance Fe (w%). The plates from steel 42CrMo4 (EN 10083) has the chemical composition as following: 0.420 C, 0.250 Si, 0.75 Mn, 1.10 Cr, 0.220 Mo, 0.03 S, and the balance Fe (w%).
All the 30 specimens were carburized at 950°C for 4.5 h, subsequently heated at 850°C for 2 h and quenched in oil. Specimen treatment was followed by tempering at 180°C for 3 h and finally cooling in air. The plates were quenched at 850°C for 2 h and then tempered at 100°C, and 300°C in furnace for 2 h, respectively. After heat treatment both specimens and plates were polished with sandpaper. For the contact faces between specimen and plate, the specimens reached a surface roughness of Rz = 1.6, and the plates Rz = 3.2. The hardness of the contact surface on the specimen is 60 HRC, and on the plate were 52 HRC, and 46HRC respectively.

2.3. Measurements and calculations

Prior to the friction testing, the specimens were cleaned by an ultrasonic cleaning machine. The mass and height of the specimens were measured by a microbalance with accuracy of 0.1 mg and a micrometer with accuracy of 0.01 mm, respectively. After every $10^6$ load cycles, the testing was interrupted to measure the mass loss $\Delta m$ of cleaned specimens and calculate the worn volume $V$ using Eq. (1).

$$V = \frac{\Delta m}{\rho}$$ (1)

where $V$ denotes worn volume (mm$^3$), $\Delta m$ is the mass loss (g), $\rho$ is the density of alloy steel 18CrNiMo7-6 (g/mm$^3$).

The friction coefficient ($\mu$) and wear intensity ($k$) were calculated by Eqs. (2) [17] and (3), respectively.

$$\mu = \frac{F_f}{W}$$ (2)

$$k = V/(2 \cdot \pi \cdot R \cdot t \cdot N_w \cdot n \cdot W)$$ (3)

where $F_f$ and $W$ are the maximum friction force and applied normal load (N), respectively; $s$ is the slide distance (mm), $R$ denotes the central distance of the cylinder and plate (7.5 mm), $N_w$ is the number of load cycles, $n$ is the rotating speed (150 rpm), and $t$ is testing time (min).

3. Results and discussion

3.1. Wear mechanism

Figure 2 presents the SEM morphology of the specimen contact surface after $3 \times 10^6$ load cycles. Figure 2a and 2b show the complex mixed wear behavior at the edge position of the contact area. In figure 2a the deformation of the material (bright area) is to be found after the abrasive wear happens. In view of the phenomenon of metal transfer observed on the worn surface, it is suggested by the metal transfer and crack formation (figure 2a) that the adhesive wear mechanism is also generated (figure 2b). Thus, it can be concluded through the above discussions that the wear is composed of abrasive wear, oxidation wear and adhesive wear in the contact area on the tested specimens, even the test configuration is defined for a typical abrasive sliding problem. The integrative actions of these three wear forms accelerate the damage of contact interfaces, which can lead to an irregular wear rate described as fretting fatigue.

![Figure 2](image_url)

**Figure 2.** SEM morphology of worn surface on the specimen. (a) material deformation, (b) adhesive wear at point 7-8-9
After $3 \times 10^6$ load cycles, the specimens were taken out of the rubber bellows for material composition check using a scanning electron microscope (SEM, JSM-6460) equipped with energy dispersive spectrometer (EDS, Oxford INCA). The fact of oxygen detected indicates that oxidation of iron is generated in the contact area, Figure 3 a, b.

![Figure 3](image_url)

**Figure 3.** EDS patterns of worn surface of specimen. (a) Sliding position, (b) edge position.

3.2. Friction coefficients

Figure 4 shows the friction coefficients as the functions of load cycles at different normal loads. The friction coefficients at the normal load of 350 N, 500 N, and 900 N increase with the increasing load cycles. The reason is that a lot of wear debris formed on the friction surfaces enhance the interactions between the metal surfaces and wear debris as well as the wear debris themselves, which increases the friction coefficients. However, the friction coefficient at 150 N exhibits a slight decrease. When the number of load cycles exceeds $8 \times 10^6$, the wear debris and surface micro-peaks are gradually compacted into friction surfaces and thus the friction coefficients start to decrease until reaching a stable value about 0.11 for the tested pairs with specimen hardness 60 HRC and plate hardness 52 HRC, and 0.122 for the pairs with specimen hardness 60 HRC and plate hardness 46 HRC. Within $6 \times 10^6$ load cycles, when the normal load increases from 150 N to 900 N, the average friction coefficient decreases from 0.195 to 0.123, Figure 4a. It is because the interfacial shear stress is related to the average contact pressure $p$ and a constant value $\tau_0$ and the interfacial shear stress coefficient $\gamma$ [18]. This variation of friction coefficient with the normal load is consistent with previous study [19].

![Figure 4](image_url)

**Figure 4.** Friction coefficient of 18CrNiMo7-6 specimen sliding on 42CrMo4 plate.
3.3. Wear intensities

Achard’s equation [20,21] is widely used to predict the wear intensity. For the adhesive wear, the Achard's equation is Eq. (4):

$$\frac{dv}{ds} = k_n \frac{W}{3\sigma} \quad (4)$$

where $k_n$ is adhesive wear intensity, $W$ is the normal load, $\sigma$ is the yield stress. Since the compressive yield strength is correlated with the hardness $H$ of the material, the Eq. (4) can be expressed by Eq. (5).

$$\frac{dv}{ds} = k_n \frac{W}{3H} \quad (5)$$

The Achard's equation of abrasive wear is similar to that of abrasive wear and can be expressed using Eq. (6).

$$\frac{dv}{ds} = k_m \frac{W}{H} \quad (6)$$

where $H$ is the hardness, $k_m$ is the abrasive wear intensity.

For the oxidation wear, the Achard's equation is Eq. (7) [22]:

$$\frac{dv}{ds} = k_y \frac{W}{3H} \quad (7)$$

In the formula, $k_y$ is the oxidation wear intensity expressed by Eq. (8) [23]:

$$k_y = A_0 \exp(-E/RT_k) \cdot A/v \xi^2 \rho^2 \quad (8)$$

where $A_0$ is a constant, $E$ is the activation energy, $R$ is the gas constant, $T_k$ is the oxidation temperature, $A$ is the area of contact surface, $v$ is the slide speed, $\xi$ and $\rho$ denote the thickness and density of oxide film, respectively.

From the mechanism analysis in Section 3.1, it is implied that the wear of specimen surface is a kind of fretting wear and consists of oxidation wear; abrasive wear, and adhesive wear. Previous work in the prediction of fretting wear is performed primarily according to the Achard's equation of abrasive wear. Thus, the predicted result is inconsistent with the actual wear mechanism. In order to estimate accurately the wear intensity in the contacting parts, the present work considers the integrative effects of the adhesive wear, abrasive wear and oxidation wear. Therefore, the wear intensity is calculated by Eq. (9).

$$k = a \cdot k_y + b \cdot k_m + c \cdot k_n \quad (9)$$

where $a$, $b$, and $c$ are weights of oxidation wear, abrasive wear, and adhesive wear in the total wear volume of the specimens, and can be assumed as 0.3, 0.5 and 0.2, where $a+b+c=1$.

![Figure 5. Wear intensities of 18CrNiMo7-6 specimens sliding on 42CrMo4 plate lubricated with Gleitmo® 100 S. Specimen: Rz = 1.6, surface hardness 60 HRC, plate Rz = 3.2 (a) plate surface hardness 52 HRC (b) plate surface hardness 46 HRC.](image)

For plates with hardness 52 HRC and 46 HRC, normal load 900 N, the specimens have wear intensities $k = 6.6 \times 10^8$ MPa$^{-1}$ and $k = 6.8 \times 10^8$ MPa$^{-1}$, respectively, measured after $1 \times 10^6$ load cycles. The wear intensity then reduces continuously till the load cycles reach $6 \times 10^6$. After that the wear intensity is kept stable till $12 \times 10^6$ load cycles. For plates with hardness 52 HRC and 46 HRC, the wear intensities of the specimens vary from $6.3 \times 10^8$ to $2.3 \times 10^8$ MPa$^{-1}$ after $12 \times 10^6$ load cycles. For normal load $N = 350$ N, the wear intensities of the specimens are $4.1 \times 10^8$ for plate hardness 52 HRC, and
4.4×10⁻⁸ MPa⁻¹, figure 5a and figure 5b. This indicates that the hardness of the sliding pair has vital influence on the wear intensity, especially in the stable wear phase. Compared with the normal load, the load cycles have a small influence on the friction properties in stable wear phase.

4. Conclusions
This work investigates the wear mechanism and wear behavior of 18CrNiMo7-6 cylinder sliding on 42CrMo4 plate under different normal loads. The friction coefficients and wear intensities are tested at different stages within 12×10⁶ load cycles. The test results show rapid running-in wear, and after 3×10⁶ load cycles both wear coefficients and wear intensities decrease till ca. 6×10⁶ load cycles. At a stable wear phase beginning after 6×10⁶ load cycles the wear behavior is stable afterwards to 12×10⁶ load cycles. Via wear mechanism analysis it is to be ensured that even a typical metal to metal sliding process generates mixed adhesive wear, abrasive wear and oxidation wear, whereas the adhesive and oxidation wear forms in such a sliding wear process were not focused on in researches till now. It has been demonstrated that the lubrication condition as well as the contract stress distribution play a vital role on the sliding wear behavior by the current work. For a good understanding why, the fretting wear happens in so a metal to metal sliding, further tests for specimens under different lubrication conditions are necessary. It is also to suggest that numerical simulations e.g. Finite Element analyses are to be applied to assess the contact conditions in such wear phenomena.

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