Wear behaviors of polyurethane rubber used in pipeline inspection gauge

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Abstract. This study is concerned with the wear behaviors of the polyurethane rubber (UR) used in the pigging industry under the condition of interference fit. The pin-on-disc tribological tests were conducted to obtain the wear rate of the UR, and the wear mechanisms were identified by observing the worn surface via an optical microscope. Additionally, the relationship between the wear rate and the contact pressure was presented with the method of quadratic fitting.

1. Introduction
Polyurethane rubber (UR) combines the material performance advantages of vulcanized rubber with a thermoplastic polymer. They are selected to substitute other materials and employed in many fields because of their high cost-performance ratio, superior mechanic properties, and excellent resistance to tear, oxidation and oil [1-2]. Especially in sealing industry, they are more appreciated due to the greater flexibility and toughness and fast elastic recuperation [3-4].

The researches of wear on polyurethane rubber (UR) have become a hotspot in recent years. Many researchers have carried out several studies with the method of diverse configurations, and different wear mechanism which helps to enhance the comprehensive understanding of UR wear were mentioned. The present study contraposes the fundamental correlation between the interference and the wear behaviors of the UR under the condition of interference fit. To achieve this objective, a pin-on-disc wear test was conducted for obtaining the wear loss, and the corresponding finite element model was established for investigating the contact pressure between the UR and the steel counterface. Besides, the relationship between the wear rate and the contact pressure was quantitatively presented. In addition, and improved wear model was built for describing the wear process of the UR under the condition of an interference fit, and several additional analyses of the wear law of UR under interference contacts were carried out. Finally, an empirical model appropriate for engineering application was obtained for predicting the wear loss of the UR sealing element under the condition of interference fit.
2. Tribological test

During the wear process of the UR under interference contacts, the contact pressures on the UR surface change continuously with the variation of the interference. Therefore, compared to the conventional wear conditions, the wear rate of the UR seal under interference contacts is not constant. To obtain the relationship between the wear rate and the contact pressures, a pin-on-disc micro tribometer (model: WTM-2E, Zhongke kaihua technology development Corp., Ltd, China) was adopted to conduct a dry sliding wear test, as shown in Fig. 1. The UR specimens with a hardness of 75±5 Shore A were processed in the shape of a block with a length of 30mm, a width of 20mm and a height of 5mm. The counterface is the undersurface of the cylindrical pin with a diameter of 2mm which is made of Q235 steel. The specimen was fixed on the pallet of the apparatus which can rotate at a constant speed driven by an electric motor. The tests were carried out with a period of 30mins, a rotation radius of 5mm and a rotation velocity of 300r/min. As for the applied load, values of 1N, 1.5N, 2N, 2.5N and 3N are considered. Three times repeated tests were conducted for each experimental condition. All tests were conducted under a relative humidity of 40%~50% and a room temperature of 23℃.

3. Wear mechanism

The worn surfaces were observed using an optical microscope (model: DVM6, Leica Instruments, Germany). The 2D micrographs of the identical partial location on the worn surface under the different applied loads are presented in Fig. 2(a)–(e), consequently, the wear mechanisms of the UR are possible to identify based on the research results mentioned in the related literatures [5-9].

As shown in Fig. 2(a), during the repeated frictional sliding, the micro-cracks generated on the surface of the UR specimen resulted in surface tearing, consequently, the half-detached debris was formed and became to the strip roll under the alternating compression-tension stresses. Meanwhile, stress concentration appears in the contact zone where the UR surface contacts with the edge of the steel pin, which leads to the ploughing formation. Therefore, it is plausible that the abrasive wear and adhesive wear are two main wear mechanisms when the applied load is 1N. As for the condition of applied load 1.5N, wave formation was identified between the parallel strip roll, as in Fig. 2(b), this mechanism is associated with surface fatigue which is caused by cyclic pass of the hard asperities on the soft materials. When applied load increase to 2N, the sharp and obvious strip rolls formed at the low applied load conditions are turning to blunt because of the repeated grinding of steel pin, as shown in Fig. 2(c). The enlarged view of the blunt strip roll presents the wear mechanism of delamination which is caused by the propagation and accumulation of the cracks generated in the subsurface of the UR specimen due to the shear stresses. Fig. 2(d) shows the worn surface of the UR specimen under the applied load 2.5N, a large area of the wave formation can be observed, and the ploughings disappear along with the increase of wear depth. As for the condition of applied load 3N, it can be seen from Fig. 2(e) that several molten polymers in white irregularly shaped formed at the worn surface, which indicate the apparent melting wear.
4. Relationship between the contact pressure and wear rate

According to the previous study, the relationship between the wear rate and the contact pressure can be expressed by a quadric function. Therefore, by introducing the boundary conditions (when $P = 0$, $k = 0$), the wear rate can be expressed as Eq. (1). Where M and N are the undetermined coefficients.

$$k = MP^2 + NP$$  \hspace{1cm} (1)

Eq. (2), taking into account of Eq. (1), becomes:

$$dH = (MP^3 + NP^2) \cdot dL$$  \hspace{1cm} (2)
Fig. 3 3D micrograph of the partial UR worn surface (applied load 3N).

Fig. 4 Profiles of the worn surface along the radial path.

Fig. 5 The travel trajectory of the steel pin.

Fig. 3 is obtained from the optical microscope and presents the 3D micrograph of a partial area on the worn surface (applied load 3N). One radial path on the worn surface (marked as a white line) is presented, and the wear depth of the points along the path under five applied load conditions is given by the measurement system of the optical microscope, as shown in Fig. 4.

Fig. 5 illustrates the travel trajectory of steel pin in wear test, the red lines present three moments (marked as $S'$, $S$ and $S''$ in turn) when the radial path passes through the undersurface of the steel pin. There are three points, marked as $A$, $B$, and $C$, which are evenly distributed on the radial path, and the travel trajectories (marked as blue solid arcs) of them are different.

A finite element (FE) model was established by Abaqus 2016 (Dassault Systèmes, France) to
investigate the contact pressure on the UR surface during the wear test.

The FE model consists of a steel pin and a UR specimen and it is identical with the actual experimental apparatus in structure sizes. A contact pair was established between the undersurface of the pin and upper surface of the UR specimen, and the contact algorithm was set as a penalty. One displacement-loading sequence which considers the boundary condition of the model and one normal-loading sequence which applies the pressure on the upper surface of the pin was set as two sequential analysis steps.

The material parameters of the UR and the steel pin were listed in Tab.1. In this paper, the two-parameter Mooney-Rivlin model which is appropriate for describing the hyperelastic material was adopted to simulate the UR. The UR model has 19830 hybrid formulation reduced integration elements while the pin model has 1248 hex elements.

| Parameters          | Steel pin | UR       |
|---------------------|-----------|----------|
| Young’s modulus     | 210GPa    | 7.08MPa  |
| Poisson’s ratio      | 0.3       | 0.48     |
| Hardness            | —         | 75±5HA   |
| $C_{10}$            | —         | 0.735    |
| $C_{01}$            | —         | 0.185    |

Based on the FE model mentioned above, the test condition of applied load 3N was calculated for investigating the distribution of contact pressure on the UR surface. The nephogram of contact pressure is presented in Fig. 6. It is clear that the contact area presents a regular circle, and the distributions of contact pressure on each radius are almost identical.

As shown in Fig. 7, considering that the travel trajectory is an arc, the polar coordinate system is adopted for simplifying the calculation, and it is established with the rotation center $O$ as the pole, the rotation radius $R_T$ as the polar radius and the rotation angle $\theta$ as the polar angle. As a consequence, the travel distance can be presented by the rotation radius and the rotation angle. Eq. (2) can be transformed as:

$$H = \int_M \left[ M P^1(L) + N P^2(L) \right] \cdot dL$$

$$H = \int_0^{2\pi} \left[ M P^1(\theta) + N P^2(\theta) \right] \cdot \frac{R_T}{180} d\theta$$

![Fig. 6 Contact pressure on the UR surface (Applied load 3N).](image-url)
Eqs. (3) and (4) shows that the relationship between wear depth and travel distance is transformed into the relationship between wear depth and rotation angle. As illustrated in Fig. 8, the contact pressures on Tra1 were extracted from the simulation results and were employed to illustrate their variation curve with the rotation angle. It is obvious that the variation curve on the first and second half trajectory, i.e. when $\theta \geq 0$ and $\theta \leq 0$, is symmetrical about the straight line $\theta=0$. For the convenience of the calculations, the curves of contact pressure on trajectory were fitted in the form of the piecewise function and were uniformly expressed as:

$$P_1(\theta) = 9.9 \times 10^6 e^{1.072|\theta|} + 0.492$$  \hspace{1cm} (5)

When point A passes through the undersurface of the steel pin for one time under the applied load 3N, the generated wear depth of point A is denoted as $h$. By substituting the Eq. (5) into Eq. (6), $h$ is expressed as:

$$h = \frac{\pi R}{180} \int_{\theta_1}^{\theta_2} \left[ MP_1(\theta)^2 + NP_1(\theta)^2 \right] \cdot d\theta$$  \hspace{1cm} (6)

Besides, the wear depth of the point A after the whole wear test is denoted as $H$, which can be obtained from Fig. 6. The relationship between $h$ and $H$ is given as:

$$h = \frac{H}{n \cdot t}$$  \hspace{1cm} (7)

Where $n$ is the rotational speed of the steel pin and $t$ is the test time.

The other condition of applied load 1N was investigated according to the same method introduced above. With the method of undetermined coefficients, the coefficients (M and N) of the wear rate equation can be obtained as follows:
\[
\pi R_h \left[ \int_0^\theta P_1^2(\theta) d\theta - \int_0^\theta P_2^2(\theta) d\theta \right] M = \left[ \begin{array}{c} h_1 \\ h_2 \end{array} \right]
\]  

(8)

Where \( P_1(\theta) \) and \( P_2(\theta) \) are the equations of the contact pressure on Tra1 when applied load are 3N and 1N respectively. \( h_1 \) and \( h_2 \) are the wear depths of point A which passes through the undersurface of the steel pin for one time under the applied load 3N and 1N respectively.

Therefore, the relationship between the wear rate and the contact pressure is found as follows:

\[
k = 1.423P^2 + 0.424P
\]

(9)

5. Conclusions

This work comprises a study of the wear law for the polyurethane rubber (UR) under interference contacts. Wear behaviors of the UR components under interference contacts change simultaneously with the variation of the contact pressure during the wear process. Pin-on-disc wear tests were conducted, and the wear loss of the UR specimens under five applied load conditions (1N, 1.5N, 2N, 2.5N, and 3N) were measured. Then, the wear mechanisms such as tearing, ploughing, wave formation, delamination, and melting were identified by experimental observation, via an optical microscope. Additionally, the relationship between the wear rate and the contact pressure was proved to satisfy the quadric function which was determined by the method of undetermined coefficients.

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