A study on the prediction technology of resin piston wear

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Abstract. The resin piston pairs have been widely used in machinery industry. A prediction method of the resin piston wear is presented. The eccentric wear form and stress of the piston are given. On this basis, the mathematical model of resin piston wear is established. Taking the resin piston wear of the concrete pumping system as an example, the predicted and practical wear amount are compared. The result shows that the prediction error rate of the wear amount is less than 1% which fully meets the engineering requirements. This example shows that the proposed prediction method of resin piston wear is valid. This paper provides a technical support for optimizing structure of resin piston and improving service performance and life of mechanical products.

1. Introduction

The resin piston pairs have been widely used in machinery industry. As an important mechanical device component, the resin piston wear has a serious bad effect on the mechanical product’s performance and life [1]. Therefore, it is necessary to do some studies on the prediction of resin piston wear. The working form of resin piston pairs is reciprocating motion of the piston, and the friction surface between resin piston and cylinder tube plays a sealing role. The friction, wear, sealing and lubrication and other basic issues are occurred universally in this process [2]. The wear between resin and some other materials is main performance. The resin is a highly viscoelastic material. So, the different from the metal friction pair is that the deformation of resin piston pairs is coordinated by the elastic deformation of resin [3-4]. In the whole process, the service performance and life of mechanical products are determined by wear amount of resin piston. In order to quantitatively express the wear amount of piston, domestic and international scholars have gained some achievements in the wear characteristics, stress on the piston and calculation of wear amount [5-8]. It is not difficult to see that the recognized and effective prediction method for the wear amount is little due to the complexity of resin piston wear mechanism. But, some methods of these studies could be also applied in this study. In this paper, the eccentric wear form of piston is given. The stress on piston is analysed. On this basis, the mathematical model of the resin piston wear is established. The mathematical model is used in concrete pumping system, and the validity of above study is proved.

2. Eccentric wear form

The resin piston is mainly composed of flange, sealing body and cover plate, as shown in figure 1. The flange connects the resin piston to piston rod. The material of sealing body is resin-based material. The cover plate plays an important role in sealing the seal body. In the actual working process, piston rod
drives the piston to reciprocate in cylinder. The friction pair is consisted of highly viscoelastic sealing body and inner wall of the cylinder, and the resin piston is rubbed.

![Figure 1. Resin piston structure.](image1)

The wear forms of resin piston mainly include adhesive wear, fatigue wear and abrasive wear. Adhesive wear belongs to mechanical wear, which makes material migration between sealing body and the wall of cylinder due to adhesive. Fatigue wear is a peeling phenomenon caused by fatigue fracture of the sealing body. In the working process, there is a combination of rolling and sliding, and the sealing body is affected by alternating contact force. The hard phase particles often exist between the two friction surfaces and hurt sealing body under normal conditions, which arouses wear of resin piston. So, the abrasive wear is mainly studied in this paper.

3. Stress on the piston

The stress on the piston is complex and changeable when piston moves in cylinder, as shown in figure 2. \( F_f \) is frictional force on piston by cylinder. \( F_1 \) is pushing thrust on the piston. \( F_z \) is counterforce on the piston by cylinder. \( F_{j1} \) and \( F_{j2} \) are extrusion force. Due to the problem of cylinder’s straightness, the calculation of above force is different.

![Figure 2. Stress on the piston.](image2)

![Figure 3. Compression size of the piston.](image3)

3.1. Calculation of \( F_z \)

The counterforce on the piston by cylinder is shown as equation (1).

\[
F_z = \frac{qx}{2} + mg
\]  

(1)
Where \( q \) and \( x \) are gravity on the unit length piston and displacement of the piston rod respectively, \( m \) is the weight of piston.

3.2. Calculation of \( F_j \)
The material of sealing body is resin-based material. Due to the diameter of piston slightly larger than cylinder diameter, there is elastic deformation of the resin material. It plays a sealing effect. So the extrusion force can be obtained as follow.

\[
F_j = A\sigma = \pi d L_0 \frac{E}{L} l
\]

(2)

Where \( A \) is the contact area between piston and cylinder, \( \sigma \) is allowable stress, \( d \) is the cylinder’s diameter, \( E \) is elastic modulus of resin material, \( l \) is the compression of sealing body, which means the difference between the original diameter of seal and existing diameter after compression. \( L_0 \) and \( L \) are thickness and diameter of sealing body [9], details are shown in figure 3.

3.3. Calculation of normal load of the piston
The load on top and bottom of piston is different. The pushing thrust \( F_1 \) and frictional force \( F_f \) are in different direction during the reciprocating motion of piston. When the piston goes off, the upper load \( F_{s1} \) and lower load \( F_{s2} \) are shown in equation (3). When the piston rod returns, the upper load \( F_{s2} \) and lower load \( F_{s1} \) are shown as equation (4). And \( F_{s1}, F_{s1}, F_{s2} \) and \( F_{s2} \) are the joint force of extrusion force and pushing thrust along the compression direction of piston.

\[
\begin{align*}
F_{s1} &= \pi d l_0 E \frac{l_1(x)}{L} \cos \theta(x) - F_1 \sin \theta(x) \\
F_{s2} &= (\pi d l_0 E \frac{l_1(x)}{L} + F_f) \cos \theta(x) + F_1 \sin \theta(x)
\end{align*}
\]

(3)

\[
\begin{align*}
F_{s2} &= \pi d l_0 E \frac{l_2(x)}{L} \cos \theta(x) + F_1 \sin \theta(x) \\
F_{s1} &= (\pi d l_0 E \frac{l_2(x)}{L} + F_f) \cos \theta(x) - F_1 \sin \theta(x)
\end{align*}
\]

(4)

Where \( \theta(x) \) is the angle between cylinder side busbar and horizontal plane when the piston rod sticks out at \( x \), \( l_1(x) \) is upper compression of the piston when piston rod sticks out at \( x \), \( l_2(x) \) is lower compression of the piston when piston rod sticks out at \( x \).

4. Piston wear amount prediction model
When partial wear does not occur on the piston, the wear between resin piston and slight peak of inner surface of cylinder is normal wear. If the load on the piston is unbalance, the piston will appear partial wear. On this occasion, the wear is abrasive wear, the model shown in figure 4, and mathematical model is shown in equation (5) [10].

\[
V = \frac{K_s F L}{H}
\]

Figure 4. Abrasive wear.
Where $V$ is wear amount, $K_s$ is wear coefficient, $F$ is normal load, $L$ is wear distance, $H$ is material hardness.

There is different load on the top and bottom of the piston. And the wear amount is different which is calculated as follows.

$$V = n\pi d \int_0^s K_s \left( \pi d \frac{2l_1(x) + l_2(x)}{L} \cos \theta(x) \right) d(x)$$

(6)

Where $n$ is the reciprocating time of piston, $a$ is the perimeter of cylinder.

5. Experiment

Taking the resin piston wear of concrete pumping system as an example, experiment is carried out. The predicted wear amount of resin piston in concrete pumping system is calculated by equation (6). The piston weight before and after construction is measured, and the actual wear amount also is given. The validity of mathematical model of the resin piston wear is verified by analyzing the prediction error rate of the wear amount.

5.1. Experimental material

The polyurethane is one of the most common type of resin piston material as shown in figure 5. The material parameter of the piston is shown in table 1.

![Figure 5. The resin piston.](image)

Table 1. The parameter of the piston.

| Density (Kg $\cdot$ m$^{-3}$) | Hardness(HA) | Tensile strength(MPa) | Compressive strength(MPa) | Roughness(μm) |
|-------------------------------|--------------|-----------------------|---------------------------|--------------|
| 1260                          | 92           | $>35$                 | 80                        | 1.6          |

This type of piston is often used in concrete pumping systems. The parameter of the cylinder is shown in table 2.

Table 2. The parameter of the cylinder.

| Thickness(mm) | Hardness(HV) | Diameter(mm) | Straightness(mm) | Roughness(μm) |
|---------------|--------------|--------------|------------------|--------------|
| 0.25-0.3      | 800          | 260          | 0.15             | 0.4          |

5.2. Experimental method

To accurately forecast the wear amount, the wear coefficient is obtained by experiment. The resin piston is rubbed by chromium coating in friction wear testing machine as shown in figure 6. The weight of polyurethane block before and after experiment is measured, and the wear amount is obtained by equation (5).
Figure 6. Friction wear testing machine. Figure 7. Piston wear test.

The wear experiment of resin piston is executed by concrete pump truck, which is shown in figure 7. The weight of resin piston before work is measured. The construction site of concrete pump truck is conducted and tracking, the weight of resin piston after work is measured, and practical wear amount is obtained. According to equation (6), predicted wear amount is calculated. The practical wear amount is compared with predicted wear amount to verify validity of above study.

5.3. Experiment result analysis
For the polyurethane wear coefficient, 30 sets of experiments were carried out. The wear coefficient were shown as table 3. The average value of test results is $9.98 \times 10^{-8}$.

| Experiment times | Wear amount(mg) | Wear coefficient $(10^{-7})$ | Experiment times | Wear amount(mg) | Wear coefficient $(10^{-7})$ |
|------------------|-----------------|------------------------------|------------------|-----------------|------------------------------|
| 1                | 0.109           | 0.995                        | 16               | 0.110           | 1.000                        |
| 2                | 0.108           | 0.986                        | 17               | 0.112           | 1.020                        |
| 3                | 0.110           | 1.000                        | 18               | 0.113           | 1.030                        |
| 4                | 0.109           | 0.995                        | 19               | 0.112           | 1.020                        |
| 5                | 0.106           | 0.967                        | 20               | 0.111           | 1.010                        |
| 6                | 0.104           | 0.949                        | 21               | 0.109           | 0.995                        |
| 7                | 0.108           | 0.986                        | 22               | 0.109           | 0.995                        |
| 8                | 0.108           | 0.986                        | 23               | 0.107           | 0.977                        |
| 9                | 0.110           | 1.000                        | 24               | 0.107           | 0.977                        |
| 10               | 0.107           | 0.977                        | 25               | 0.109           | 0.995                        |
| 11               | 0.109           | 0.995                        | 26               | 0.112           | 1.020                        |
| 12               | 0.111           | 1.010                        | 27               | 0.113           | 1.030                        |
| 13               | 0.109           | 0.995                        | 28               | 0.109           | 0.995                        |
| 14               | 0.107           | 0.977                        | 29               | 0.113           | 1.030                        |
| 15               | 0.108           | 0.986                        | 30               | 0.110           | 1.000                        |
The practical and predicted wear amounts are shown in figure 8. The maximum deviation is calculated as 0.008 cm$^3$. It is less than 0.01 cm$^3$ and meet the engineering requirements. On this basis, the pump track can deliver the concrete about 9050.9 m$^3$, which can be used as the prediction life of piston. The actual life is obtained by tracking the construction which is 9000 m$^3$. The error rate is 0.56% and meets the engineering requirements. The result shows that this study is valid.

![Figure 8. Practical and predicted wear amounts.](image)

6. Results and discussions
This paper studies on analysis for the eccentric wear form and the stress on the piston, building the mathematical model of the resin piston wear and experimental verification. The following conclusions are obtained:

1. The main form of the resin piston wear is abrasive wear.
2. The prediction error rate of the resin piston wear amount based on this study is 0.56%. It fully meets the engineering requirements.
3. This paper provides a technical support for optimizing structure of the resin piston and improving the service performance and life of mechanical products.

We should make efforts to improve the technology of production in order to reduce the wear amount to improve the life of piston and work efficiency of pump truck.

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