Wear experiment and model of rolling balls in sliding-rolling conditions

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Received: 14 June 2017 / Accepted: 23 October 2017

Abstract. When the rolling bearing is working, sliding and rolling always exist in the friction pair simultaneously. The operating condition is complicated and fickle. For these kinds of behaviors, it is necessary to simulate the bearing sliding-rolling ratio (SRR), load, speed and other operating parameters in the wear-testing research between the rolling elements and the inner or outer ring. By the improvement of the transmission, measurement, and control system of an existing pure rolling contact fatigue test rig for bearing ball with three contact points, the simulation of bearing balls would be more realistic and test parameters are close to actual operating conditions. The rolling ball wear experiments were carried out under different SRRs operation conditions. By analyzing test data, the calculation model of wearing rate under the operation condition of sliding-rolling was established based on Archard model.

Keywords: Wear test / rolling ball / sliding-rolling ratio / wear performance model

1 Introduction

As an important part of rolling bearing, rolling ball contacts with its friction pairs frequently, the wear in the process of contacting has great effect for the assembly precision of bearing [1,2]. During the running of rolling ball, it not only rotates alone the inner or outer ring but also slides when the friction of contact point between rolling ball and its friction pairs is not enough, which is called the sliding-rolling state [3]. Cheng et al. [4] established a model for calculating surface friction heat in slide state. By analyzing factors which affect the part temperature in contact point, the variation trends of surface temperature was obtained. Sundar et al. [5] measured vibration to estimate coefficient of friction and a mechanical system with combined rolling-sliding contact. An empirical relationship for the coefficient of friction is suggested based on a prior model under a mixed lubrication regime. Sperka et al. [6] put forward amplitude decay theory, established a model of predicting tribology performance according to surface roughness, and analyzed how roughness would affect tribology performance at sliding-rolling state using optical interference film test rig. Ciulli et al. [7] measured film thickness of point contacts under steady state and transient conditions at different sliding-rolling ratios (SRRs). The experiments proved that under transient conditions, high slide-to-roll ratios seem to reduce the squeeze effect on the film thickness.

Although studies about bearing tribology performance in sliding-rolling state exist, researches only involved with wear performance of rolling ball are not sufficient [8,9]. The main contribution of our work lies on the experiments, by collecting real time wear identification with variation of SRRs, load and rotate speed based on self developed test rig. The wear performance in different states has been discussed. The calculation model of wearing rate under the operation condition of sliding-rolling was established based on Archard model.

2 Experiment rig and method

2.1 Experiment rig and material

Figure 1 shows the test rig instrumentation and control system.

Test rig is the self designed and developed three-point contact bearing ball fatigue life testing machine [10], and its structure is shown in Figure 2.

Motor 1 connects support wheels 2, 3, 4 with cog belt. Support wheels as middleware transmit velocity to slave rollers 5, 6. The driven wheel 9 transmit velocity between load wheel 8 and driver 10 which connects with motor 1. In this condition, the rolling ball 7 contacts with slave roller 5, 6 and load wheel 8 in three points.
For implementing sliding-rolling state and collecting real time wear volume, test rig has been improved. By changing transmission ratio between driven wheel 9 and driver 10, the velocity of load wheel 8 can be different from slave rollers 5, 6. At this time, the velocities of three contact points in rolling ball are not same any more, rolling ball is in a certain sliding-rolling state. Adjusting the transmission ratio between driven wheel 9 and driver 10, SRR can be controlled. Displacement sensor 11 is placed above load wheel 8. With proceeding of wear in rolling ball, diameter of rolling ball 7 is smaller and smaller, the change reflects in distance between sensor 11 and wheel, distance data are collected online using DAQ card and calculated to reality wear volume in Labview.

2.2 Experiment method

Operation condition is shown in Table 1.

A simple sliding-rolling condition is described by two speeds.

$$v_a = v_u - v_d$$

$$v_r = \frac{v_u + v_d}{2}$$

where $v_u$, $v_d$ are speeds of friction pair and counter-pair in sliding-rolling (m·s$^{-1}$), $v_r$ is rolling speed (m·s$^{-1}$). SRR [11] is defined as the ratio of slide velocity to rolling velocity:

$$S = \frac{v_a}{v_r} = \frac{2(v_u - v_d)}{v_u + v_d}$$

The SRRs in three contact points, $S_1$, $S_2$, $S_3$, are defined as:

$$S_1 = \frac{2(v_1 - v_{ball})}{v_1 + v_{ball}}$$

$$S_2 = S_3 = \frac{2(v_{ball} - v_2)}{v_{ball} + v_2} = \frac{2(v_{ball} - v_3)}{v_{ball} + v_3}$$

where $v_1$, $v_2$, $v_3$ are the velocities in three contact points, respectively (m·s$^{-1}$), $v_{ball}$ is velocity of test ball (m·s$^{-1}$), shown as Figure 3.

The angles of contact points in $v_1$ and $v_2$ or $v_1$ and $v_3$ are big ($\geq 160^\circ$). For calculating the sliding-rolling simply, each angles are assumed to be 180$^\circ$, relationship among speeds in test ball is shown in Figure 4.

Due to the existent of sliding, a part of speed transmitted to test ball may lost.

$$v'_{1} = v_{1} - v_{s1}$$

$$v'_{2} = v_{2} - v_{s2}$$

where $v'_{1}$ is the real speed what $v_1$ transmits to test ball (m·s$^{-1}$), $v'_{2}$ is the real speed what $v_2$ transmits to test ball (m·s$^{-1}$), $v_{s1}$ is the slide speed in point $v_1$ (m·s$^{-1}$), $v_{s2}$ is the slide speed in point $v_2$ (m·s$^{-1}$).

During the experiment, centre of test ball is fixed, so the speed of centre of test ball is zero called instantaneous center of velocity. It means the values of $v'_{1}$, $v'_{2}$ need to be equal, and the directions of $v'_{1}$, $v'_{2}$ are opposite. According to equations (6) and (7), we can get

$$v_{s1} = v_{s2}$$
According to the equations (1)–(3):

\[ S_1 = S_2 \]

Similarly, \( S_1 = S_3 \)

Assuming \( S_1 = S_2 = S_3 \), \( v_{ball} \) is defined as:

\[ v_{ball} = \sqrt{v_1 \times v_3} = \frac{2\pi \sqrt{i} \times r_s v_s}{60} \] (10)

where \( i \) is transmission ratio, \( r_s \) are radius of slave rollers and load wheel (mm), \( v_s \) are speeds of slave rollers and load wheel (m/s).

SRR \( S \) is defined as:

\[ S = \frac{2(v_1 - v_{ball})}{v_1 + v_{ball}} = \frac{2(1 - \sqrt{i})}{(1 + \sqrt{i})} \] (11)

Therefore, the SRR in experiment can be obtained by calculating the transmission ratio.

Due to the existent of vibration and thermal expansion, measured movement of load wheel by displacement sensor is not the real change of rolling ball. By some calibration experiments, real variation of rolling ball in radius is fitted using distance changes of load wheel, and relationship between them is defined as:

\[ \Delta r_t = 0.38927 \Delta L + 0.01283 \] (12)

where \( \Delta r_t \) is the real measured variation of rolling ball in radius (\( \mu m \)), \( \Delta L \) is the measured movement of load wheel (\( \mu m \)).

Wear volume is calculated by \( D_r \) as follows:

\[ D_V = \frac{4}{3} \pi [r_t^3 - (r_t - \Delta r_t)^3] \] (13)

where \( \Delta V \) is the real wearing volume (mm\(^3\)), \( r_t \) is the radius of tested rolling ball (mm), \( \Delta r_t \) is the real measured variation of rolling ball in radius (mm).

Wear rate is calculated as follows:

\[ V = \frac{\Delta V}{t} \] (14)

where \( V \) is the wearing rate (mm\(^3\)·min\(^{-1}\)), \( \Delta V \) is the real wearing volume (mm\(^3\)), and \( t \) is the wearing time (min).

3 Results and discussion

3.1 Wear performance in different SRRs

Figure 5 gives results of wear volume of different SRRs in 50 N and 3000 r·min\(^{-1}\).

As shown in Figure 5, when SRR is 0, tested ball is in pure rolling state, wear volume is only \( 7 \times 10^{-5} \) mm\(^3\), and it is hard to observe different wear stages at this condition. When SRR is 0.05, compared with pure rolling state, the wear volume increases to 0.0034 mm\(^3\), although SRR is still low. At the same time, different wear stages are obvious.
From 0 to 1000 min, the wear volume appears very high increase. Within 4000 min, wear volume increases continually but growth rate is lower, and this period is called running-in period. In running-in period, asperity-peak of contact zone is worn or flattened due to local high pressure. Surface topography of friction pairs is improved gradually [12]. After 4000 min, wear level is changed into stabilization period. When SRRs are increased to 0.095 and 0.15, wear volumes are 0.0078 mm$^3$ and 0.01745 mm$^3$, respectively. According to equation (3), the slide velocity is proportional to SRR. So in the same wear time, slide distance is proportional to SRR. According the model described by Archard, wear volume is proportional to slide distance. Therefore, the wear volume is proportional to SRR.

Figure 6 gives results of wear rates of different SRRs in 50 N and 3000 r·min$^{-1}$.

As shown in Figure 6, when SRR is 0 called pure rolling state, wear rate is only $10^{-12}$ mm$^3$·min$^{-1}$, and variation of wear rate is not obvious during process of wear. When SRR is 0.05, stabilization wear rate is $4.1 \times 10^{-10}$ mm$^3$·min$^{-1}$, and much larger than the wear rate in pure rolling period. In the beginning of wear, for forming a favourable surface quality which is suitable for operation condition such as surface pressure and friction coefficient, wear rates are lower and lower and tend to be in stable state. It’s called stabilization period. Compared with pure rolling condition, wear rate in SRR is 100 times than one in pure rolling state. In 0.095 and 0.15 SRRs, stabilization wear rates are $5.3 \times 10^{-10}$ mm$^3$·min$^{-1}$ and $6.1 \times 10^{-10}$ mm$^3$·min$^{-1}$, respectively. As shown in Figure 6, greater the SRR is, the duration reaching stabilization wear stage is shorter, but the stabilization wear rates are almost same. It means that in the same operation condition and tribology performance of surface, wear rate is independent of SRR.

### 3.2 Effect of SRR in different loads

Figure 7 give results of wear rates of different SRRs in 3000 r·min$^{-1}$ and different loads.

As shown in Figure 7(a), when load is 50 N, due to low load, stabilization wear rates, about $5.9 \times 10^{-10}$ mm$^3$·min$^{-1}$ and $6.1 \times 10^{-10}$ mm$^3$·min$^{-1}$, are close for three SRRs. The main wear behavior is slight abrasive wear as shown in Figure 8 (a).

In Figure 7(b), when load is elevated to 100 N, stabilization wear rates in 0.05 and 0.095 SRRs are $5.9 \times 10^{-10}$ mm$^3$·min$^{-1}$ and $6.1 \times 10^{-10}$ mm$^3$·min$^{-1}$, and they are similar with the operation condition in 50 N. When SRR increases to 0.15, wear rate is stable at $8.4 \times 10^{-10}$ mm$^3$·min$^{-1}$. It can be seen in Figure 8(b), the wear behavior in this condition is not only abrasive wear but also slight adhesive wear in area A1. Adhesive wear is not a wear performance appearing on oxide layer. Adhesion point breaks the surface of material [13], and metal inside is exposed in air, so wear rate is increased.

As shown in Figure 7(c), when load is changed to 150 N, stabilization wear rate in SRR 0.05 is $5.8 \times 10^{-10}$ mm$^3$·min$^{-1}$, and surface is still in slight wear like condition in load 100 N. In 0.095 and 0.15 SRRs, stabilization wear rates are $1.12 \times 10^{-9}$ mm$^3$·min$^{-1}$ and $1.43 \times 10^{-9}$ mm$^3$·min$^{-1}$, respectively. It can be seen in Figure 8(c) which is divided into area B1 and B2. Because of high contact stress, compared with normal contact surface B2, area B1 presents obvious depth differences, called plastic deformation appearance.
causes cold-work hardening in metal [14], and surface of metal is more and more fragile. This characteristic results in that it is easier to form abrasive particles in surface. With the increase of abrasive wear, the wear rate is higher and higher.

The conclusion of these experiments is described. In low load condition, effect of SRR in different load is not obvious. With the load increased, the SRR has a great significance for wear rate. Compared with operation condition in low load, wear performance and shapes in surface are changed from abrasive wear to adhesive wear, and the surface area presents plastic deformation gradually. All changes above reflect in the increase of wear rate.

3.3 Effect of SRR in different rotate speeds

According to effect of SRR in different loads, load is higher and the degree of wear is severer. For avoiding adhesive wear, the experiments about wear rates of different SRRs in various rotate speeds are carried out in load 50 N.

As shown in Figure 9(a), when the rotate speed is 1000 r·min\(^{-1}\), with the SRR increasing, the wear rate achieves the stable state more quickly. All wear still occur on oxide layer with slight abrasive wear, as shown in Figure 10(a). Therefore, three stabilization wear rates, all about \(5.7 \times 10^{-10}\) mm\(^3\)·min\(^{-1}\) in three different SRRs, are similar.

In Figure 9(b), the variation of SRR affects wear rate in 2000 r·min\(^{-1}\) before 6000 min. The stabilization wear rates of SRR 0.05, 0.095, 0.15 are \(4.9 \times 10^{-10}\) mm\(^3\)·min\(^{-1}\), \(5.9 \times 10^{-10}\) mm\(^3\)·min\(^{-1}\) and \(6.1 \times 10^{-10}\) mm\(^3\)·min\(^{-1}\), respectively. In Figure 10(b), compared with low speed, although the speed is twice as much as before, wear volume didn’t multiply as speed, and wear performance of this condition are also slight abrasive wear. With elevated speed, performance of abrasive wear do not be worse. It means that because of limited abrasive particles, in high rotate speed, most of abrasive particles formed by slide wear are threw away by rolling of ball. All of characters result in the phenomenon that wear performance and wear rate are not changed obviously.

In Figure 9(c), the variation of SRR affects wear rate in 3000 r·min\(^{-1}\) before 6000 min. The stabilization wear rates in three SRRs are \(5.6 \times 10^{-10}\) mm\(^3\)·min\(^{-1}\), \(6.3 \times 10^{-10}\) mm\(^3\)·min\(^{-1}\) and \(6.5 \times 10^{-10}\) mm\(^3\)·min\(^{-1}\), respectively. Compared with the experiment results in 1000 r·min\(^{-1}\) and
2000 r·min⁻¹, wear rates are changed a little with increase of rotate speeds. Within the range of the temperature which wouldn’t influence surface tribology performance [15,16], the increase of rotate speed can only cause the decline of ability of heat dissipation on surface [17] and then affect the wear rate. But in this experiment, the influence is limited.

In the process of rolling-wear, the main failure mode is fatigue failure in high stress cycles. So in this favorable operation condition, time of experiment is lengthened to research the relationship between sliding-rolling and fatigue failure.

As shown in Figure 9(d), experiments data are all after 60 000 min. In 0.15 SRR, wear rate keeps stable before 66 000 min. After 66 000 min, wear rate has a sudden increase from 6.2 \times 10^{-10} \text{mm}^3\cdot\text{min}^{-1} together with the increase of temperature. At this time, the surface of tested ball presents obvious spalling appearance, called fatigue wear phenomenon. In 0.095 SRR condition, wear rate is changed in 87 720 min suddenly. Compared with condition in 0.15 SRR, time of appearing fatigue wear phenomenon is 21 720 min longer. In 0.05 SRR, required duration time of appearing phenomenon of fatigue wear is too long, so this experiment is terminated. As seen in Figure 10(c), fatigue spalling [18] can be observed in surface area C1 in high stress cycles. Around the spalling area, surface of ball is hard to be observed the obvious wear performance in area C2. Unless fatigue wear occurs, otherwise fatigue spalling data is not easy to obtain from variation of wear rates.

According to experiment results, in normal wear condition, SRR affects the wear rate a little, but has a significant influence for the time of fatigue wear. With the increase of SRR, sliding friction accelerates crack formation and crack propagation on ball surface, and shortens the time of occurring fatigue wear.

4 Wear performance model

By analyzing the experiment data, a model of variation of wear rate with time in sliding-rolling condition can be established. According to the conclusion of experiments above, variation of wear rate is divided into two periods, running-in period and steady-state period. Firstly, the influence of SRR to steady wear rate needs to be figured out.

4.1 Steady wear rate model based on Archard

According to Archard theory [19]:

\[
\frac{\Delta V}{L} = \frac{k_s W}{3\sigma_s} \tag{15}
\]

where \( \Delta V = \int V_A dt, \) \( V_A = \frac{\Delta V}{\Delta t}, \) \( v \) and \( V_A \) is constant at steady state, so \( L = v_A \int dt, \) \( \Delta V = V_A \int dt. \) Equation (15) is changed to:

\[
V_A = \frac{k_s W v_a}{3\sigma_s} \tag{16}
\]

where \( \Delta V \) is wear volume (mm³), \( L \) is wear distance (m), \( W \) is load (N), \( \sigma_s \) is yield strength of softer material (Pa), \( V_A \) is theoretical wear rate (mm³·min⁻¹), \( t \) is wear time (min), \( v_a \) is slide speed (m·s⁻¹), and \( K_s \) is coefficient of adhesive wear. Assuming \( K = \frac{k_s}{3\sigma_s} \), equation (16) is changed to:

\[
V_S = V_A = K W v_a \tag{17}
\]
where \( V_S \) is steady wear rate \((\text{mm}^3\cdot\text{min}^{-1})\). Wear coefficient in lubrication condition is \( K_s = 10^{-7} \), yield strength \( \sigma_y = 518.42 \text{ MPa} \), so \( K = 6.43 \times 10^{-17} \).

### 4.2 Corrected steady wear rate model

Archard theory is adhesive wear theory \([20]\), due to the existence of SRR in these experiments, wear performance is not adhesive wear any more, and it is changed with the variations of load, speed and SRR. Even so, Archard model is able to expound the relationships among factors affecting wear rate \([21]\). Considering this, the equation (17) is corrected in sliding-rolling operation condition.

According to experiment result above, with the increase of load, wear performance is changed from abrasive wear to adhesive wear, and the wear rate is enhanced gradually, but the rate of increase is lower and lower. The approximate trend is shown in Figure 11.

The load \( W \) is corrected with adding SRR \( S \):

\[
\frac{W'}{W} = ae^{-bS} + c \tag{18}
\]

where \( W' \) is the corrected load (N), \( W \) is the real load (N), \( S \) is SRR, \( a, b, c \) are related correct coefficient.

At \( S = 0 \), equation (18) is defined as:

\[
\left(\frac{W'}{W}\right)_0 = a + c, \tag{19}
\]

where \( \left(\frac{W'}{W}\right)_0 \) is the ratio of corrected load to real load at time zero.

At \( S = \infty \), equation (18) is defined as:

\[
\left(\frac{W'}{W}\right)_{\infty} = c, \tag{20}
\]

where \( \left(\frac{W'}{W}\right)_{\infty} \) is the ratio of corrected load to real load at steady state.

So \( a = \left(\frac{W'}{W}\right)_0 - \left(\frac{W'}{W}\right)_{\infty}, \ c = \left(\frac{W'}{W}\right)_{\infty} \), equation (18) is changed to:

\[
\left(\frac{W'}{W}\right) = \left[\left(\frac{W'}{W}\right)_0 - \left(\frac{W'}{W}\right)_{\infty}\right]e^{-bS} + \left(\frac{W'}{W}\right)_{\infty}. \tag{21}
\]

According to the experiment result about effect of SRRs in different rotate speeds, rotate speed has a little influence to wear rate in low load condition. Some of wear particles formed in sliding wear the surface twice, called three-body wear, and the wear rate increases substantially. The approximate trend is shown in Figure 12.

This experiment is not in very high speed. The relationship between SRR \( S \) and \( \delta \) is assumed to be linear simply. The rotate speed \( v_r \) is corrected with adding SRR \( S \):

\[
\frac{v'_r}{v_r} = dS + f \tag{22}
\]

where \( v'_r \) is the corrected rotate speed \((\text{r-min}^{-1})\), \( v_r \) is the real rotate speed \((\text{r-min}^{-1})\), \( S \) is SRR, \( d \) and \( f \) are related correct coefficient.

The speed \( v_j \) is not the slide speed directly in this experiment. The slide speed needs to be calculated indirectly, according to equation (4).

\[
v_{ball} = \frac{(2 - S)v_j}{2 + S} \tag{23}
\]

\[
v_a = v_j - v_{ball} = \left(\frac{2S}{2 + S}\right)v_j \frac{2\pi \left(\frac{2S}{2 + S}\right)v_sr}{60} \tag{24}
\]

\[
v'_a = \frac{2\pi \left(\frac{2S}{2 + S}\right)v'_sr}{60}, \tag{25}
\]

where \( v_{ball} \) is speed of test ball \((\text{m-s}^{-1})\), \( S \) is SRR, \( v_j \) is speed of slave pairs \((\text{m-s}^{-1})\), \( v_s \) is sliding speed \((\text{m-s}^{-1})\), \( v'_r \) is corrected sliding speed \((\text{m-s}^{-1})\), \( v'_j \) is the corrected rotate speed \((\text{r-min}^{-1})\).

Wear rate equation, equation (17) after being corrected is:

\[
V_S = V_A = KW'v_a' \tag{26}
\]

Equation (26) is fitted using experiment data by least square method. Known from equation (17), \( K = 6.43 \times 10^{-17} \). The wear rate equation is corrected as:

\[
V_s = (-281.7e^{0.00377S} + 282.7)W \times (0.699S + 0.068) \frac{2\pi}{2S} \left(\frac{60v_{ball}}{2S}\right) \times 10^{-14} \tag{27}
\]

or the equation can be described with rolling speed \( v_r \) in this experiment as:

\[
V_s = (-281.7e^{0.00377S} + 282.7)W \times (2.22S + 0.216)v_r \times 10^{-14} \tag{28}
\]

### 4.3 Verification of steady wear rate model

The accuracy of the corrected model of steady wear rate is verified using relative error:

\[
\delta = \frac{|V_f - V_i|}{V_i} \times 100\% \tag{29}
\]

where \( \delta \) is relative error, \( V_f \) is predicted wear rate, \( V_i \) is real measured wear rate.

Test operation condition is shown in Table 2.

Comparison of relative errors between Archard model and corrected model are shown in Figure 13.

Using root-mean-square error as standard of model-error, Archard model’s error is 3.775, and corrected model’s error is 1.197. As shown in Table 2 and Figure 13, in low load, predictions of two models are both accurate.
With the load increasing, considering the influence of SRR to contact area, the corrected model is more precise than Archard model. Therefore, the corrected model is more effective in sliding-rolling condition, and wear rate of corrected model is applied to be the steady wear rate in whole model next.

4.4 Relationship between wear rate and time

The variation of wear rate with time is shown schematically in Figure 14. Initially the wear rate is high which reduces exponentially with time and reaches steady-state after some time. This trend is expressed mathematically as follows [23]:

$$ V = \left( \frac{V_0}{C_0} - V_S \right) e^{ht} + V_S $$  \hspace{1cm} (30)

where $V$ is wear rate (mm$^3$·min$^{-1}$), $V_0$ is wear rate at time zero (mm$^3$·min$^{-1}$), $V_S$ is wear rate at steady state (mm$^3$·min$^{-1}$), $t$ is time of wear (min), and $h$ is related coefficient.

The equation (30) is fitted using experiments data by least square method, and related correct coefficient $h = 0.0009$. The wear rate changed with time is defined as follows:

$$ V = \left[ \left( V_0 - V_S \right) e^{-0.0009t} + V_S \right] \times 10^{-10} $$  \hspace{1cm} (31)

4.5 Model verification

Model verification operation condition is shown in Table 3. As shown in Table 3, average relative errors of four groups are not larger, all errors are under 0.2, so it can be identified that fitting results are credible. The specific fitting results are shown in Figure 15.

In Figure 15, overall, fitting curves are similar with the real wear rate. Especially in steady wear period, precision is higher. Due to variation of machine or unstable state of ball’s rolling in the beginning of experiment, the wear rate at time zero is hard to be obtained accurately, and the fitting results at the beginning of experiments or running-in period are barely satisfactory.

### Table 2. Test operation condition.

| Group | 1   | 2   | 3   | 4   |
|-------|-----|-----|-----|-----|
| Load (N) | 50  | 100 | 100 | 150 |
| Rotate speed (r·min$^{-1}$) | 1000 | 2000 | 3000 | 3000 |
| Sliding-rolling ratio | 0.15 | 0.095 | 0.05 | 0.095 |
| Real measured wear rate (10$^{-10}$ mm$^3$·min$^{-1}$) | 2.38 | 7.71 | 10.25 | 19.23 |
| Steady wear rate base on Archard (10$^{-10}$ mm$^3$·min$^{-1}$) | 2.51 | 7.92 | 12.24 | 22.56 |
| Corrected steady wear rate (10$^{-10}$ mm$^3$·min$^{-1}$) | 2.30 | 7.67 | 9.28 | 17.27 |
| Relative error of Archard model | 0.054 | 0.027 | 0.194 | 0.173 |
| Relative error of corrected model | 0.033 | 0.005 | 0.094 | 0.101 |

### Table 3. Model verification operation condition.

| Group | 1   | 2   | 3   | 4   |
|-------|-----|-----|-----|-----|
| Load (N) | 50  | 100 | 100 | 150 |
| Rotate speed (r·min$^{-1}$) | 1000 | 2000 | 3000 | 3000 |
| Sliding-rolling ratio | 0.15 | 0.095 | 0.05 | 0.095 |
| Relative error | 0.112 | 0.097 | 0.195 | 0.107 |
The corrected model may be unable to be applied directly in complex practical production, but it describes the change trend of wear rate and the relationship among load, rotate speed and SRR. By amending the relative coefficient of equation (31), the corrected model can be applied in other operation condition with sliding-rolling state.

5 Conclusion

- A test rig is designed and improved. SRR can be changed and wear data is collected online.
- Compared with pure rolling state, even though in low speed, wear rate of sliding-rolling state is considerably higher than pure rolling state. Sliding-rolling state presents obvious running-in wear and stable wear performance.
- Within the certain range of speed, in low load, SRR affects the wear rate in a low extent. With load increase, SRR has a significant influence for wear rates. High SRR and heavy load change the form of contact area from only abrasive wear to adhesive wear, and the wear rate increases obviously.
- In non-heavy load condition, variation of SRRs and velocities have a limited influence for wear rate, but has a great effect for time of fatigue wear appearance. The increment of SRR accelerates crack formation and crack propagation on ball surface, and shorten the time of fatigue wear appearance.
- According to the relationship among load, velocity, SRR, a wear rate prediction model based on Archard model is corrected in sliding-rolling state. The veracity of corrected model shows great improvement over Archard model.

Nomenclature

- $a, b, c, d, f, h$: Related correct coefficient
- $i$: Transmission ratio
- $r_s$: Radius of slave rollers and load wheel (mm)
- $r_t$: Radius of tested rolling ball (mm)
- $t$: Wear time (min)
- $v_p$: Sliding speed (m·s$^{-1}$)
- $v_a$: Corrected sliding speed (m·s$^{-1}$)
- $v_{ball}$: Velocity of test ball (m·s$^{-1}$)
- $v_r$: Rolling speed (r·min$^{-1}$)
- $v_r$: Corrected rotate speed (r·min$^{-1}$)
- $v_s$: Speeds of slave rollers and load wheel (m·s$^{-1}$)
- $v_{s1}$: Slide speed in point $v_1$ (m·s$^{-1}$)
- $v_{s2}$: Slide speed in point $v_2$ (m·s$^{-1}$)
- $v_{us}, v_d$: Speeds of friction pair and counter-pair in sliding-rolling (m·s$^{-1}$)
- $v_{1}, v_{2}, v_{3}$: Velocities in three contact points, respectively (m·s$^{-1}$)
- $v_1^*$: Real speed what $v_1$ transmits to test ball (m·s$^{-1}$)
- $v_2^*$: Real speed what $v_2$ transmits to test ball (m·s$^{-1}$)
- $K_s$: Coefficient of adhesive wear
- $L$: Wear distance (m)
- $S$: Sliding-rolling ratio
- $S_1, S_2, S_3$: Sliding-rolling ratios in three contact points, respectively
- $V$: Wear rate (mm$^3$·min$^{-1}$)
- $V_f$: Prediction wear rate (mm$^3$·min$^{-1}$)
- $V_i$: Real measured wear rate (mm$^3$·min$^{-1}$)
- $V_A$: Theoretical wear rate (mm$^3$·min$^{-1}$)

Fig. 15. Specific fitting results.
$V_s$ Wear rate at steady state (mm³·min⁻¹)
$V_0$ Wear rate at time zero (mm³·min⁻¹)
$W$ Load (N)
$W'$ Corrected load (N)
$\Delta r_t$ Real measured variation of rolling ball in radius (mm)
$\Delta L$ Measured displacement of load wheel (mm)
$\Delta V$ Real wearing volume (mm³)
$\sigma_s$ Yield strength of softer material (Pa)
$\delta$ Relative error
$(\frac{W'}{W_0})$ Ratio of corrected load to real load at time zero
$(\frac{W'}{W_\infty})$ Ratio of corrected load to real load at steady state

Acknowledgments. This work was carried out with financial support from the National twelfth five-year project of China for science and technology under Contract D.50-0109-15-001.

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Cite this article as: J. Xi, X. Shen, X. Chen, Wear experiment and model of rolling balls in sliding-rolling conditions, Mechanics & Industry 18, 511 (2017)