Numerical Simulation and Life Prediction of Steel Ball Unfolding Wheel Wear

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Abstract. Wear is the main failure form of unfolding wheel for bearing steel ball. When the wear increase to a certain extent, the function of the wheel is ineffective. According to the unfolding wheel structure and unfolding principle, the critical failure condition of the unfolding wheel is established. Based on the classical Archard wear model and combined with the finite element method, a discrete Archard wear model is proposed, and a prediction model of the wear life of the unfolding wheel is established. Using Ansys software to simulate the wear of the unfolding wheel, the relationship equation between the wear depth and the wear times is obtained, and the wear life prediction of the unfolding wheel is carried out.

1. Introduction
Under the action of the driving wheel, the unfolding wheel relies on the friction caused by its asymmetric double cone surface to make the steel ball rotate [1]. At the same time the steel ball lateral rotate, so that the steel ball to achieve the full surface unfolding. So as to achieve the automatic nondestructive testing of the steel ball. The unfolding wheel motion and the constant friction given by steel ball result in wear failure of the unfolding wheel.

2. The Failure Condition of Steel Ball Unfolding Wheel
As shown in Figure 1, the left and right conical wheels of the unfolding wheel have the same tiny angle $\epsilon$ corresponding to the rotating axis [2]. Respectively, the angle between the generatrix of the cone and the horizontal axis of the cone wheel varies in the range of $(45^\circ - \epsilon) \sim (45^\circ + \epsilon)$. When $\epsilon < 1^\circ$, The asymmetrical friction provided by the asymmetrical cone on the left and right sides will reduce the deflection of the ball during the rotation of the ball, and then reduce the lateral rotation of steel ball. When $\epsilon = 0^\circ$, the symmetric conical surfaces will lose the ability to unfold the steel balls. In the sentence, the wear depth is recorded as the maximum allowable wear depth $h_{\text{max}}$.

The coordinate system is established, using the unfolding wheel axis as the x-axis. The y-axis goes through the center of the ball and is perpendicular to the x-axis. $O$ is the origin of the coordinates. $Q_1$ point is the intersection of the conical axis of the unfolding wheel and the horizontal rotary shaft, and $A_1$ is the contact point between the contour of the unfolding wheel and the steel ball at a certain moment. $A_2$ is the intersection of the vertical line and the generatrix of cone at the bottom of the unfolding wheel, $M_2$ is the vertex of the conical surface on the side of the unfolding wheel. $M_1M_2$ is parallel to the horizontal rotary axis of the unfolding wheel. $O_1$ is steel ball center, $M_2A_1$ is tangent to the steel ball, $O_1A_1$ is perpendicular to $M_2A_1$. $N_1$ is the vertical foot from $A_1$ to $O_1O$. The radius of the steel ball is $r$, $\angle M_2Q_1O$ is $\epsilon$. According
to the geometric principle Neicho equal knowledge, $\angle Q_1M_2M$ is also $\varepsilon$. Known by the unfolding wheel structure, the $\angle A_1M_2Q_1$ is 45°, $\angle A_1M_2A_2$ is 90°.

Figure 1. Geometric relation diagram of wheel wear.

Based on the above known geometric conditions, the lengths of line $A_1N_1$ and $M_1M_2$ can be deduced as

$$l_{A_1N_1} = l_{M_1M_2} \cdot r \sin (45^\circ + \varepsilon)$$  \hspace{1cm} (1)

The triangular function relation of several other lengths is

$$\frac{l_{M_1M_2}}{l_{A_1M_2}} = \sin (45^\circ - \varepsilon)$$  \hspace{1cm} (2)

$$\frac{l_{A_1M_2}}{l_{A_1A_2}} = \sin (45^\circ + \varepsilon)$$  \hspace{1cm} (3)

$$\frac{l_{M_1A_2}}{l_{M_1M_2}} = \tan (45^\circ - \varepsilon)$$  \hspace{1cm} (4)

That is

$$l_{M_1A_2} = l_{M_1M_2} \tan (45^\circ - \varepsilon) = r \cdot \sin (45^\circ + \varepsilon) \cdot \tan (45^\circ - \varepsilon)$$  \hspace{1cm} (5)

$$l_{A_1A_2} = \frac{r}{\sin (45^\circ - \varepsilon)}$$  \hspace{1cm} (6)

According to the unfolding principle of the unfolding wheel, when $l_{A_1M_1} = l_{M_1A_2}$, $\varepsilon = 0^\circ$. Then, the unfolding wheel can not provide asymmetric friction to make the steel ball unfold. The maximum wear depth is

$$h_{\text{max}} = l_{A_1A_2} - 2l_{M_1A_2} = \frac{r}{\sin (45^\circ - \varepsilon)} - 2r \sin (45^\circ + \varepsilon) \cdot \tan (45^\circ - \varepsilon)$$  \hspace{1cm} (7)
Formula (7) is the critical failure condition for the steel ball to detect the unfolding wheel wear. When the wear depth reaches or exceeds $h_{\text{max}}$, the unfolding wheel fails.

3. Numerical Simulation of Wear of Steel Ball Unfolding Wheel

The general formula for the Archard wear model is expressed as

$$W_V = K_m \frac{PL}{H}$$  \hspace{1cm} (8)

Where $W_V$ is the wear volume, $P$ is the method load, $L$ is the sliding distance, $H$ is the Brinell hardness, and $K_m$ is the wear coefficient.

From the formula (8), after lots of little bit of wear can be expressed as

$$dW_V = K_m \frac{dp}{g_{1668}} \frac{dL}{H}$$  \hspace{1cm} (9)

The $W_V$ of wear volume, the method of vertical load $P$ and the slip distance $L$ can be expressed as

$$dh = K_m \frac{\sigma A}{H} \frac{v dt}{t}$$  \hspace{1cm} (10)

Where $h$ indicates the wear depth, $A$ indicates the wear area, $\sigma$ indicates the contact stress of the friction pair contact point, $v$ indicates the relative sliding velocity between the contact two objects, and $t$ is the wear time.

From formula (9) and formula (10), the wear depth can be expressed as

$$dh = K_m \frac{\sigma A}{H} \frac{v dt}{t}$$  \hspace{1cm} (11)

Through the integral, the maximum wear depth is

$$h_{\text{max}} = K_m \frac{\sigma A}{H} T_{\text{max}}$$  \hspace{1cm} (12)

Where $T_{\text{max}}$ is the wear time of the maximum wear depth, $h_{\text{max}}$ is the critical value of the maximum wear depth.

The wear frequency as a measure of its wear life, the relationship between wear times and wear depth can be expressed as

$$N_{\text{max}} = \frac{H}{\sigma K_m} h_{\text{max}} + B$$  \hspace{1cm} (13)

Where $N_{\text{max}}$ indicates the maximum wear number corresponding to the maximum wear depth, that is, the wear life; $B$ represents a linear compensation value. Set $K_s = \frac{H}{\sigma K_m}$, then the wear life prediction model of the expansion wheel can be expressed as

$$N_{\text{max}} = K_s h_{\text{max}} + B$$  \hspace{1cm} (14)

The diameter of the unfolding wheel wear numerical simulation selected the steel ball of 16.6688mm diameter. The steel ball is stressed by $F$ in the system, the steel ball material is GCR15, the unfolding wheel material is T10A, the surface hardness is HRC40, and the surface roughness is Ra1.6. The finite element model of the unfolding wheel and the steel ball is suppressed as shown in Figure 2.
To ensure that there are no errors during the operation, set each face on the unfolding wheel double cone surface to a contact surface, the contact algorithm selects the extended Lagrange algorithm [3]. Finally, the method of Ansys numerical simulation is used to solve the final wear value. Using the APDL module to solve the wear value of the corresponding wear. The wear process of the steel ball and the unfolding wheel is repeated 9 times. The wear value of the corresponding wear cloud map is shown in Figure 3.

![Finite element numerical model of expansion wheel and steel ball.](image)

**Figure 2.** Finite element numerical model of expansion wheel and steel ball.

![Unfolding wheel wear numerical simulation finite element cloud map.](image)

**Figure 3.** Unfolding wheel wear numerical simulation finite element cloud map.
Using the max value of every picture in figure 3, and through MATLAB software calculation, the relationship equation of wear depth and wear number of smooth unfolding wheel of surface can be fitted as

$$h = 2.8212 \times 10^{-7} n - 0.21345 \times 10^{-7}$$

(15)

4. Example of Unfolding Wheel Wear Life Prediction
When the diameter of the steel ball is 16.6688mm, the radius is $r = 8.3344$mm, and $\varepsilon = 1^\circ$. From equation 7, the maximum wear depth value to be allowed is $h_{\text{max}} = 0.41872$mm. The relationship between the maximum wear depth and the corresponding wear times at a point in the working surface of an unfolding wheel paired with a steel ball with a diameter value of 16.6688mm can be expressed as

$$h_{\text{max}} = 2.8212 \times 10^{-7} N_{\text{max}} - 0.21345 \times 10^{-7}$$

(16)

According to Formula (14), the formula (16) is converted to the wear life prediction model as

$$N_{\text{max}} = 3.5446 \times 10^6 h_{\text{max}} + 0.07566$$

(17)

Taking $h_{\text{max}} = 0.41872$mm into the formula (17), we obtain $N_{\text{max}} = 1484195$. Usually, each test of a steel ball requires a steel ball to turn around 30 times on the unfolding wheel. For a certain node on the unfolding wheel, the friction is 30 times. Therefore, the unfolding wheel wear life to the number of steel balls detected is expressed as

$$N_{\text{max}}' = \frac{N_{\text{max}}}{30}$$

(18)

That is $N_{\text{max}}' = 49473$, this means the unfolding wheel detection numbers of 49,473 for diameter of 16.6688mm steel ball will cause failure. This result is consistent with the need for replacement for each test of about 50,000 steel balls in the actual unfolding wheel due to wear.

5. Conclusion
The critical failure condition of steel ball unfolding wheel is established, based on the classical Archard wear model and finite element theory. The discrete Archard wear model and the prediction model of steel ball unfolding wheel are established. Through numerical simulation of the wear process of the unfolding wheel work, the cumulative wear of a single node on the surface of the unfolding wheel is obtained. The relationship equation between the wear times and the wear depth of the unfolding wheel is established by data fitting. Calculating the life of the unfolding wheel by an example, the validity of the prediction model of the wear life of the unfolding wheel is verified, which provides a theoretical basis for the design and popularization of the unfolding wheel series of bearing steel ball detection.

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7. References
[1] Zhao Y L. Analysis and Numerical Simulation of Rolling Contact Between Sphere and Cone [J]. Chinese Journal of Mechanical Engineering, 2015, 163.
[2] Zhao Y L. Kinematics and dynamics analysis of steel ball unfolding process [J]. Chinese Journal of Mechanical Engineering, 2015, 51.
[3] Su Y W. Finite element analysis and pin wear prediction of sliding wear process [J]. Chinese Journal of Mechanical Engineering, 2009, 13.