Reliability life analysis of blades of twin-shaft mixer based on wear failure

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Abstract. As an important part of mixing material, the study on the reliability life of the blade of mixer is very necessary. According to the Arcard wear formula, the mathematical model expression of the wear amount and the load on the blades of the twin-shaft mixer in a single cycle is established. The discrete element method is used to obtain the load on the blade in the mixing process. The law of load distribution of mixer blades is obtained by Lilliefers method. Furthermore, Lagrange interpolation method is used to analyze the static simulation results of the mixing blade, and the total wear amount when the blade reaches the critical thickness is obtained. By establishing the functional relationship between wear and blade life, Monte Carlo method is used to simulate the load distribution law to predict the reliability life of the mixer blade. The results show that the reliability of the life of the mixer blade is 85.02%.

1. Introduction

Mixer is widely used in the field of road construction [1]. It mainly pushes the mixture movement through the blades, which makes the mixture collide with each other and achieve the mixing purpose by friction [2]. In the long-term contact process between the blade and the mixture, the surface material of the blade will gradually wear and make the strength of the blade gradually decrease. When the amount of wear exceeds a certain value, the external load is greater than the strength of the blade material, which eventually leads to plastic deformation or fracture failure of the mixing blade in the mixing process. Therefore, it is necessary to analyze the reliability life of the mixer.

In the aspect of blade reliability analysis, scholars at home and abroad have carried out relevant research. Tang et al. [3] put forward the formula of wear rate of mixing blade by analyzing the wear mechanism. Using the finite element analysis software, the distribution law of the surface wear rate of the mixing blade is obtained, and the reliability life of the blade is predicted. Su et al. [4] used the direct integration method to evaluate the reliability life of the improved blades, and found that the reliability of the fan blades can reach more than 99% after 20 years. Zhu et al. [5] combined the test with stochastic finite element analysis to quantify the uncertainty of test data, material performance and load. The fatigue reliability life of turbine blade is analyzed. Zhang et al. [6] proposed a RBDO method based on machine learning, drawing on the advantages of fuzzy theory, SVR and multi response surface method. By optimizing the structure, the reliability life of the turbine blade is improved. Han et al. [7] proposed a new combined life prediction model of high and low cycle fatigue based on damage mechanics theory. Based on the material data and blade data, the model parameters are determined. Through verification, it is concluded that the reliability prediction model of blade life based on blade data has high accuracy.
At present, there are few researches on the reliability life of mixer blades. In the mixing process, the mixer is in constant contact with materials, and the failure caused by abrasion cannot be ignored. This paper aims at the widely used twin-shaft mixer. Considering from the aspect of wear, the mathematical model of mixer wear is established. The abrasion of twin-shaft mixing blades during mixing of foamed asphalt mixture is studied. Finally, the service life of the mixing blade is calculated, and the reliability meeting the specified life is obtained.

2. Establish the mathematical model of blade wear of mixer

Wear is a basic failure form of common mechanical equipment components. When two materials with different hardness rub against each other, the local stress on the contact surface makes the material plastic deformation. The adhesion points on the two materials will move along the sliding direction with the harder materials, so that the softer materials will wear. The wear process is shown in Figure 1.

The amount of wear has a great influence on the service life of mechanical equipment parts. In determining the amount of wear, Arcard put forward a simple calculation formula of adhesive wear, which has been widely used[8]. The volume of wear is:

\[ V_0 = \frac{1}{3} K \frac{N}{\sigma_s} L \]  

(1)

\( V_0 \) is the wear volume of parts. \( K \) is the wear coefficient. \( N \) is the positive pressure on the contact surface. \( L \) is the relative sliding distance of the material. \( \sigma_s \) is the compressive yield strength of the material. Since the compressive yield strength of metallic materials is approximately one-third of the hardness \( H \), it can be concluded that:

\[ V_0 = K \frac{N}{H} L \]  

(2)

In the mixing process of mixing equipment, due to the constant friction between the mixture and the blade surface, the size and surface state of the mixing blade will gradually change, and its strength will gradually reduce. During mixing, the contact diagram of blade and mixture is shown in Figure 2.

According to the analysis of the mixing process of the twin-shaft mixer, a single blade only contact with the material for a period of time in each rotation cycle, and the other period is no load. The
contact area of single blade and mixture is shown in the shadow of Figure 3. Take the equivalent radius 
\( R_\text{eq} = (R_1 + R_2)/2 \) as the length of the mixing arm.

![Figure 4](image)

**Figure 4.** Mathematical model of mixer.

In order to represent the wear amount \( V_\text{Q} \) of single blade of twin-shaft mixer in a cycle, the twin-shaft mixer is abstracted as a mathematical model as shown in Figure 4. \( a \) is the center distance of the two mixing shafts. \( h \) is the height of the material to be put at one time. \( R \) is the radius of the inner wall of the mixing barrel. \( \theta \) is the angle between the two limit positions of the mixing shaft. According to the geometric relationship shown in Figure 4.

\[
\theta = \begin{cases} 
\arccos \frac{R-h}{R_m} & h \leq R \\
\frac{2\pi - \arccos \frac{R-h}{R_m}}{R_m} & h > R
\end{cases}
\]  

(3)

Sliding distance between blades and mixture:

\[ L = \theta R_m \]

(4)

From the above formula, it can be seen that the abrasion of mixer blade is related to the load it is subjected to. In order to further determine the wear of mixer blades, it is necessary to study the load on the blades.

\[
V_\text{Q} = \begin{cases} 
\frac{2KN}{H} R_m \arccos \frac{R-h}{R_m} & h \leq R \\
\frac{2KN}{H} R_m \left(2\pi - \arccos \frac{R-h}{R_m}\right) & h > R
\end{cases}
\]

(5)

3. Analysis of blade working load

3.1. Numerical simulation of mixer mixing process

Through the analysis of the mixing behavior of the mixer, it can be seen that the mixing process is mainly through the collision, sliding and friction between the materials and the materials, and between the materials and the mixer components, so that the materials can be evenly distributed. In the process of blade rotation, the load is affected by the uniformity of material, the position of contact point between material and blade and the angle of blade. The load on the blade is of dynamic complexity. It is difficult to analyze the load on the blade by conventional statics. As a new numerical method for the dynamic problems of complex discontinuous system, discrete element method has been applied to simulate the mixing process of mixer. Based on the EDEM software, the discrete element method is used to simulate the mixing process of materials, and the load data of materials on mixer blades can be obtained.

According to the manual of road construction machinery, the radius, width and length of mixing drum are calculated by formula (6) - (8).
\[
R = \sqrt[3]{\frac{m}{10\phi \beta \rho}} 
\]

(6)

\[
W = 2R(I + \cos \phi) 
\]

(7)

\[
L = W \times \varphi 
\]

(8)

\(R\) is the radius of the mixing drum. \(W\) is the width of the mixing drum. \(L\) is the length of the mixing drum. \(m\) is the weight of the test sample. \(\beta\) is the filling ratio of the mixture. \(\rho\) is the density of the mixture. \(\varphi\) is the shape coefficient of the mixing drum shell. \(\phi\) is the angle between the tangent line and the horizontal line at the intersection of the radius of the mixing drum. After calculation, the values of key parameters of the mixer are shown in Table 1.

### Table 1. Model design parameters of twin-shaft mixer.

| \(R/\text{mm}\) | \(m/\text{Kg}\) | \(W/\text{mm}\) | \(L/\text{mm}\) | \(\varphi\) | \(\phi^\circ\) | \(\rho/(\text{t/m}^3)\) | \(\beta\) |
|---|---|---|---|---|---|---|---|
| 136.5 | 30 | 455 | 494 | 1.08 | 48.1 | 1.7 | 0.64 |

The foamed asphalt mixture is used as an example. Select sickle blade. The single axis phase angle is 90°. The blade installation angle is 45°. The angular speed of mixer is 1.2m/s. In addition, considering the viscous force between asphalt and aggregate, the Hertz-Mindlin with JKR Cohesion contact model is selected, and the material contact properties are set as shown in Table 2.

### Table 2. Contact properties of materials.

| Contact | Restitution coefficient | Coefficient of static friction | Coefficient of rolling friction |
|---|---|---|---|
| aggregate - aggregate | 0.2 | 0.5 | 0.001 |
| aggregate - steel | 0.25 | 0.7 | 0.001 |

The mixing process of foamed asphalt mixture is numerically simulated by EDEM software. The selected measuring blade of the research is shown in Figure 5.

![Figure 5. Numerical simulation of mixing model.](image)

![Figure 6. Load spectrum of blade.](image)

### 3.2. Blade load spectrum and its probability distribution

Through the numerical simulation of the mixing process of the foamed asphalt mixture, it is obtained that the load variation of the single blade of the mixer with time is shown in Figure 6. The abscissa is the time and the ordinate is the load on the blade. It can be seen from the figure that the blade is only partially loaded in a rotation cycle, and the rest is no-load. With the increase of blade contact depth, the load increases gradually until the blade is in the vertical down state, the load reaches the peak value. Then, with the continuous rotation of the blade, the load on the blade decreases gradually. When the blade is separated from the material, the load on the blade is 0. As shown in Figure 6, the
variation of single blade with time conforms to the actual mixing process.

In order to further reveal the distribution of the load on the blade and quantitatively describe the change rule of the load on the blade, statistical analysis of the load data is needed. Because the mixer blades are not continuously loaded, the blade no-load condition is not considered, only the data obtained when the blades are loaded are statistically analyzed. The frequency distribution histogram is shown in Figure 7. It can be seen from the figure that during the mixing process, the load on the blade presents a normal distribution.

Figure 7. Frequency distribution histogram of load.

In order to verify the accuracy of conjecture, hypothesis testing is needed. Since the mean and variance of the population are unknown, the Lilliefors method is used to test [9]. The mean and variance of samples are used to replace the mean and variance of population, and then Kolmogorov-Smirnov method is used to test the data. Assume \( H_0 \): blade load data conform to normal distribution. When the actual observation value \( D > D_L(p, \alpha) \), \( H_0 \) is rejected, otherwise, \( H_0 \) is accepted in the confidence interval. The test shows that the load data meet the requirements of \( H=0, P=0.425 > 0.05 \). Therefore, the original assumption is accepted. It is found that the working load of blade obeys the normal distribution of \( X \sim N(158.96, 19.7) \).

4. Load critical wear of blade

4.1. Static analysis of mixing blade

In the process of mixing materials, the materials and blades constantly collide and rub, which makes the blade surface wear gradually. With the passage of time, the thickness of the blade will continue to reduce, resulting in the decline of the strength of the blade. In addition, the blades are subjected to the random load which obeys the normal distribution. When the blade thickness is worn to a certain critical value, the stress produced by the load will be greater than the blade strength, resulting in plastic deformation or even fracture failure of the blade. Therefore, the static analysis of blade strength is carried out.

In order to simulate the wear process of blades, four kinds of mixing shafts with blade thickness of 8mm, 7mm, 6mm and 5mm are established. It is assumed that the initial blade thickness is 8 mm. With the wear of the blade surface, the thickness of the blade gradually becomes thinner, and finally becomes 5 mm. Take the 8mm thick blade mixer as an example, and its 3D model is shown in Figure 8.

Figure 8. Mixing shaft model.

Import the model into the ANSYS software. Set the mixing shaft material as Q235 structural steel, and then mesh. After the partition, the mesh quality is checked, and the mesh is locally modified to ensure the mesh quality. Then the boundary conditions are constrained. Through the analysis of the mixing process, it can be seen that when the blade moves to the vertical down position, the load on it reaches the peak value. At this time, the failure is most likely to occur, so the time is mainly checked. In addition, the blade is subjected to random load of normal distribution. In order to facilitate the
calculation, it is necessary to simplify the load on the blade reasonably, and take the mean value of the normal distribution load on the blade as the instantaneous load at that time.

![Blade deformation](image1)

**Figure 9.** Blade deformation.

When the blade thickness is 8mm, through analysis and calculation, the total deformation is as shown in Figure 9 and the stress is as shown in Figure 10. It can be seen from the figure that when the blade moves to the vertical down position, the maximum deformation of the blade under the load is 0.529mm, and the maximum stress is 176.29 MPa < 235 MPa. The maximum stress is less than its yield limit, meeting the strength requirements.

The blade thickness of 7mm, 6mm and 5mm are analyzed in sequence. The data of maximum stress and deformation of blade under different blade thickness are shown in Table 3. It can be seen from table 3 that with the continuous reduction of blade thickness, the stress on the blade increases nonlinearly. When its thickness is 5mm, the maximum stress on the blade is 345.5MPa. At this point, the material fails.

![Blade stress](image2)

**Figure 10.** Blade stress.

**Table 3.** Stress and deformation data of blade.

| Blade thickness (mm) | Maximum stress (MPa) | Total deformation (mm) |
|---------------------|----------------------|-----------------------|
| 8                   | 176.29               | 0.5295                |
| 7                   | 208.85               | 0.6138                |
| 6                   | 236.46               | 0.7558                |
| 5                   | 345.5                | 1.01                  |

4.2. Determination of critical blade thickness

In order to further determine the thickness when the stress of the blade is equal to its yield limit value, the Lagrange interpolation method [10] is used to solve the data in Table 3.

Suppose \( D \) is a set of subscripts about point \((x,y)\), \( D = \{0,1,...,n-1\} \). \( n \) polynomials \( p_j(x) \) are generated, and the following formula holds for \( k \in D \) and \( B_{nj} = \{i \mid i \neq k, i \in D\} \).

\[
p_k(x) = \prod_{i \in B_{nj}} \frac{x - x_i}{x_k - x_i}
\]  

(9)

Finally, the Lagrange interpolation polynomials are obtained as:

\[
L_n(x) = \sum_{j=0}^{n-1} y_j p_j(x)
\]

(10)

After calculation, the relationship between blade thickness and stress function is as follows.

\[
L(x) = 967.1x^3 - 1.19 \times 10^4 x^2 + 1.25 \times 10^4 x - 2.69 \times 10^5
\]

(11)
Through the Lagrange interpolation method, it is concluded that when the blade thickness is 6.37mm, the stress value is equal to the yield limit of Q235 structural steel. Therefore, the critical size of mixing blade is 6.37mm.

It can be seen from the analysis that the product of blade area and wear thickness is the wear amount. When the blade reaches the critical size, it is regarded as failure. Therefore, it can be seen from the calculation that when the blade fails, the wear amount is \( V_m = 600.8 \text{mm}^2 \).

5. The calculation and analysis of reliability life of mixer blades

The blade of the mixer is worn to a certain extent. Because the stress produced by the load is greater than the yield strength of the material itself, the blade will fail in the process of material mixing. Therefore, it is necessary to replace the blade when the blade thickness reaches the critical value. The time from blade installation to failure is blade service life. According to formula, the wear of blade in one working cycle can be obtained. When the total wear is known, the total number of turns the blade can run can be obtained, and then the service life of the blade can be inferred.

The hardness of Q235 structural steel \( H \) is 165HB. The wear coefficient \( K \) is \( 8 \times 10^{-5} \). The equivalent radius \( R_m \) is 110mm. According to the mass of the material, the height \( h \) is 85.3mm, which satisfies the requirement of \( R > h \). It can be concluded that the blade wear \( V_Q \) in a single rotation cycle is as follows:

\[
V_Q = \frac{2Kn}{H} R_m \arccos \left( \frac{R - h}{R_m} \right)
\]  

Working load \( N \) of loaded blade obeys normal distribution. After analyzing the relationship between wear amount, rotating speed and service life, the following formula can be obtained.

\[
T = \frac{V_m}{V_Q \omega}
\]  

In the above formula, \( V_m \) is the volume of blade wear in case of failure, \( V_Q \) is the volume of blade wear in a single cycle, and \( \omega \) is the angular velocity of mixing shaft.

When the material is mixed, it needs to be refilled, so the mixer has intermittent time. The mixer is required to work 8 hours a day, with a period of 180 days. Monte Carlo method [11] was used to analyze the reliability of mixer blade service life. By setting the random process, load samples are generated repeatedly, and the parameter estimation is calculated. Through the statistical analysis of the results, the corresponding blade life reliability can be obtained.

![Figure 11. Simulation results of Monte Carlo method.](image)

In this research, 5000 random load sample points are randomly generated by MATLAB. The service life of mixer blade under different load conditions is obtained by test. The simulation results are shown in Figure 11. The critical life is 180 days. When the test point is above the critical line, it means that the service life of mixer is more than 180 days. Otherwise, it means that the mixer blade fails within 180 days. According to the statistical analysis of 5000 sample points, there are 749 test
points that do not meet the life requirements. Therefore, under the above working conditions, the reliability of the mixer for 180 days is 85.02%.

6. Conclusion
Through the analysis of blade wear of mixer. Based on the combination of Arcard wear theory and mixer model, the functional relationship between blade wear and load in a single rotation cycle of a twin-shaft mixer is established.

The discrete element method is used to simulate the mixing behavior of the mixer, and the load spectrum of the blade of mixer in the mixing process is obtained. The load spectrum is further analyzed and the load distribution law is obtained.

According to the relationship between wear and service life of mixer blades, the reliability life of mixer blades under certain conditions is analyzed by Monte Carlo method. The results show that the reliability of the mixer blade to reach the specified life is 85.02%. It provides a method for reliability life prediction of blades of mixer.

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