Effect of Non-metallic Inclusions on Subsurface Stress and Fatigue Life of High-speed Railway Bearings

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Abstract. The contact simulation model of high-speed railway train axle box bearing is simplified into a two-dimensional plane with an elastic semi-infinite body subjected to semi-elliptical cylindrical compressive stress in one direction. The ANSYS software was used to solve the effects of single inclusion size, the depth of the contact surface and the elastic modulus on dynamic shear stress and Von Mises stress of high-iron bearing subsurface, and compared with the calculation results of bearing material uniformity assumption. Using the modified Basquin equation, the relevant assumptions are made. The maximum Von Mises stress is used as the key stress for fatigue life calculation. The bearing fatigue life calculation method is established to study the influence of the inclusion size, the depth of the contact surface and the elastic modulus on the bearing fatigue life.

1. Introduction

The rapid development of high-speed railways has put forward the requirements of high precision, high strength, high reliability and long life for the key components of high-speed railway train axle box bearings. High-speed railway bearings in China are imported due to insufficient performance of domestic bearings. Materials in bearing steel is an important reason for the difference in bearings performance, and the presence and form of non-metallic inclusions in bearing steel are the key factors affecting the performance of materials. Therefore, the aim of this paper is to evaluate the effect of non-metallic inclusions in bearing steel on subsurface stress and fatigue life of high-speed railway bearings.

The high-speed railway bearings studied in this paper are double-row tapered roller bearings whose model is LY-Z028 including inner ring, outer ring, cage, rolling element and intermediate spacer ring. The schematic diagram of the basic structural dimensions for the bearing is shown in Figure 1, and the specific parameters are shown in Table 1.
2. Influence of size and position for inclusion in bearing steel on bearing subsurface stress

![Figure 1. Sectional view of high-speed railway bearing.](image)

Table 1. Structural parameters of high-speed railway bearings.

| Parameter                                | Value  |
|------------------------------------------|--------|
| Nominal outer diameter $D$ (mm)          | 240    |
| Nominal bore diameter $d$ (mm)           | 130    |
| Width of bearings $T$ (mm)               | 160    |
| Small end diameter of roller $D_{min}$ (mm) | 24.5   |
| Large end diameter of roller $D_{max}$ (mm) | 26.7   |
| Mean diameter of roller $D_m$ (mm)       | 25.6   |
| Pitch circle diameter of bearings $d_m$ (mm) | 185    |
| Contact angle of inner ring $\alpha_i$ (°) | 7°34′  |
| Contact angle of outer ring $\alpha_o$ (°) | 10°    |
| Average contact angle                    | 8°47′  |
| Length of roller $L$ (mm)                | 50     |
| Number of rollers $Z$                    | 2×17   |
| Half cone angle of roller $\phi$ (°)     | 1°12′30″ |
| Effective length of roller $l$ (mm)      | 45     |

Bearing material is usually idealized as an isotropic and uniform material in bearing design and performance analysis. In fact, bearing steel is not an ideal uniform material due to the presence of non-metallic inclusions, which are formed with a small amount of slag, refractory materials and reaction products from smelting entering the molten steel during steelmaking process. As an important special purpose steel, bearing steel is subjected to cyclic alternating stress in use. The presence of non-metallic inclusions contained in bearing steel will destroy the continuity of metal matrix and lead to the stress concentration at the junction of inclusions and matrix forming a source of fatigue. The number, shape, size and distribution of inclusions affect the fatigue life of bearing steel.

In order to facilitate the research, this paper starts with bearing steel containing single inclusion, and study the influence of size for inclusions and the depth from the contact surface on the subsurface stress.
Contact area of non-coordinated elastic contact objects with dissimilar shapes is usually very small compared with size of object body according to the theory of elastic contact stress analysis. Contact stress is highly concentrated in the vicinity of contact area, and strength not affected by the shape of the object away from the contact surface decreases rapidly with the distance from the contact point. The area of actual concern is located near the contact interface where the stress not depends on the shape of the object away from the contact area and the specific way of the support. Elastic half-space treats each object as a semi-infinite elastic solid bounded by a flat surface [1], and the relevant stress can be calculated very closely. Objects with arbitrary surface contours are regarded as semi-infinite in size and have a flat surface in this idealized model, which simplifies the boundary conditions. Combined with literature [2] describing the load and stress distribution of high-speed railway bearing, the stress on the contact surface reaches the maximum when the roller contacts the inner ring raceway with the greatest force. Therefore, this paper considers the situation where the subsurface of bearing raceway contains inclusions when the roller contacts the bearing ring and raceway with the greatest force. Equivalent spherical inclusion is used to replace complex-shaped inclusion, and the simulation model is simplified as an elastic semi-infinite body subjected to compressive stress of a semi-elliptical cylinder in one direction.

The model containing a single inclusion in an elastic semi-infinite body is shown in Figure 2. Where $D_{inc}$ is the diameter of the inclusion; $Z_{inc}$ is the depth of the inclusion from the contact surface; $b$ is the half width, and $p(x)$ is the surface contact stress between the roller subjected to the greatest force and the raceway of the ring. The specific parameters of the simulation model for inclusions in the elastic semi-infinite body are shown in Table 2.

![Figure 2. Single inclusion model in an elastic semi-infinite body.](image)

**Table 2.** Related parameters of the simulation model in elastic semi-infinite body.

| $p(x)$ (MPa)                  | b (mm) | 10b (mm) | 5b (mm) |
|-------------------------------|--------|----------|---------|
| $742.13 \times \sqrt{1 - (x/132)^2}$ | 0. 132 | 1. 32    | 0. 66   |

2.1. Establishment of the finite element model

2.1.1. Establishment of geometric model. Half of the model is used to analyse the stress distribution law considering the symmetrical distribution of the model. The z-axis of the model is replaced with the y-axis in the opposite direction due to the convenience of the coordinate system during the simulation. The geometric model of a single inclusion is shown in Figure 3.
2.1.2. Set element type and material properties. Select the calculation unit as Solid Quad 4 node 182. The material for the elastic semi-infinite body is GCr15 with the elastic modulus of 210GPa and the Poisson's ratio of 0.3. Inclusions are assumed to be hard inclusions, and their elastic modulus and Poisson's ratio are taken as 315GPa and 0.3 respectively.

![Figure 3. Geometric model of a single inclusion.](image)

2.1.3. Meshing. The mesh of the elastic semi-infinite body is divided into layers to divide the 0~b area and the b~2b area into 2μm and 4μm respectively under the contact surface to save the calculation time. The freely divided way is used to mesh the inclusion with a grid size of 0.2 μm and the semi-infinite body around the inclusions. The overall and local meshing of inclusions is shown in Figure 4.

![Figure 4. Overall meshing and local subdivision around inclusion.](image)

2.1.4. Create contact pairs. The flexible-body to flexible-body contact method and the surface-to-surface contact type are used to consider the deformation during the interaction between matrix of bearing steel and inclusion, and select the outer surface of inclusion as the target surface and the inner surface of matrix as the contact surface to create a contact pair
2.1.5. *Impose constraints and loads.* Symmetric constraint is applied on the line generated when dividing by the z-axis, and full constraint is applied on the right and lower edges. The defined and called load function changing with the x-axis is shown in Table 2 as the surface contact stress.

2.1.6. *Define analysis type and analysis options.* The analysis select static analysis type, activate the large strain effect, set the end time of the load step to 100, turn off the automatic time step control, and specify the load step to 1.

2.1.7. *Solution.* The solution process is the same as the general nonlinear solution process, and then read the results to view displacement, stress, strain and other related results.

2.2. *The influence of inclusion size on the subsurface stress*

![The distribution of dynamic shear stress](image1)

(a) The distribution of dynamic shear stress

![The distribution of Von Mises stress](image2)

(b) The distribution of Von Mises stress

**Figure 5.** The distribution of stress for inclusion with a diameter of 8 μm
The maximum dynamic shear stress is usually placed in the first place in the study of contact fatigue failure for bearing, and the maximum static shear stress is also considered. The Von Mises stress is used as a criterion simultaneously considering the 6 components of the stress state and fully indicating the strength of the contact pair for fatigue failure from the perspective of strain energy. This paper will mainly study the distribution of dynamic shear stress and Von Mises stress in the subsurface. Related research shows the current smelting technology of bearing steel has been able to control diameter of inclusions within 15μm, and inclusions with a diameter of less than 3μm in bearing steel have negligible effect on the performance of bearing steel [3]. Assuming that inclusion is located at a depth of 0.5b below the contact surface, the effect of size for inclusion on the dynamic shear stress and Von Mises stress in the subsurface is studied by changing the diameter of the inclusion from 4μm to 14μm.

The distribution of stress is reflected in Figure 5 with different colors representing the magnitude of the subsurface stress in the contact area. Different stress bands are represented by different colors in the reference standard on the left of the graph with blue the smallest and red the largest. The stress at the inclusion with the stress concentration obviously in the red part are significantly greater than the surrounding stress. The stress concentration effect will cause inclusion to detach from matrix or cause inclusion to rupture themselves, and then form a source of fatigue spalling.

The value of the maximum dynamic shear stress and the maximum Von Mises stress in the subsurface without inclusion and different diameter of inclusions is shown in Figure 6.

![Figure 6. The Maximum dynamic shear stress and the maximum Von Mises stress for different diameter inclusions](image-url)

The stress value will increase due to the presence of inclusion from Figure 6 which is in line with the fact inclusion will cause stress concentration in the subsurface and fatigue failure. The stress in the subsurface increase with the incensement of diameter for the inclusion. The maximum dynamic shear stress and the maximum Von Mises stress reach 403.249MPa and 716.275MPa respectively, increase by 118.7% and 73.9% compared with the case without inclusions, and increase by 86.05% and 46.3% compared with the case of 4μm diameter inclusions.

2.3. The influence of the depth for the inclusion on the stress concentration
Inclusions have little effect on the subsurface stress with the depth of the inclusion in the bearing steel from the contact surface exceeding 0.8b [4]. The diameter of inclusion is kept constant at 6μm to study
the influence of the depth for the inclusion on the subsurface stress, and change the depth of the inclusion from the contact surface from 0.2b to 0.8b.

Figure 7. The stress distribution at 0.4b from the contact surface

The distribution of stress in the subsurface is shown in Figure 7 with the diameter of the inclusion remaining unchanged at a depth of 0.4b, the dynamic shear stress and the Von Mises stress around the inclusion are the largest with obvious stress concentration.

The change of the stress in the subsurface is shown in figure 8 with the depth of the inclusion in the bearing steel remaining unchanged and the depth of the bearing changing. The stress decreases as the depth of the inclusions increases obtaining approximately the same distribution. The maximum dynamic shear stress and the maximum Von Mises stress are 192.394MPa and 443.187MPa respectively when the depth of the inclusion from the contact surface is 0.8b, which is only increased by 4.34% and 6.59% compared to the case without inclusion, and the stress of the inclusion is not significant while the depth of the inclusion from the contact surface exceeds 0.8b additionally.
2.4. The influence of elastic modulus for inclusion on the subsurface stress

The influence of inclusion type on the subsurface stress in the contact area is studied by changing the elastic modulus of the inclusion. The elastic modulus of inclusion is gradually increased from 105 GPa to 315 GPa while keeping the diameter of inclusions at 6 μm and the depth of inclusions at 0.5 b. The change of the stress in the subsurface with the elastic modulus is shown in Figure 9.
The change trend in figure 9 is mainly divided into two parts, one of which has an elastic modulus less than that of the matrix, and the other has an elastic modulus more than that of the matrix. The stress decreases with the increase of the elastic modulus when the inclusion is soft inclusion, and increases with the increase of the elastic modulus when the inclusion is hard inclusion. The change trend of stress is not linear and continuous on the whole. The increase of the difference in elastic modulus between inclusion and the matrix results in a greater difference in material properties between them and severe stress concentration leading to the inclusion detached from the matrix and the occurrence and expansion of fatigue cracks, which eventually form the surface fatigue phenomenon.

3. Effect of non-metallic inclusions on fatigue life for bearing

The presence of inclusions has a great influence on the stress distribution in the subsurface of the bearing raceway, which is likely to cause stress concentration. There is a great relationship between the magnitude of the stress and the fatigue life of the bearing.

3.1. The calculation method for fatigue life

The influence of inclusion on bearing fatigue life in this section will be further studied based on the results calculated in the previous section. The following assumptions are made to simplify the calculation.

1) There are differences between inclusions due to the regular shape of each inclusion. In order to eliminate the influence of shape, the influence of shape on the fatigue behaviour of the material can be ignored if the equivalent length $S$ referring to the projected area of the defect on the plane perpendicular to the direction of maximum tensile stress for two defects is equal according to Murakami et al.’s study, so equivalent spherical inclusions are used instead of complex-shaped inclusions.

2) Inclusions exist in the elastic semi-infinite body in contact with the roller and the raceway, that is, the subsurface. The maximum Von Mises stress is applied as an alternating stress while the roller is in contact with the raceway.

Traditional fatigue life models are based on the uniformity of bearing materials. The basic theory of fatigue life and the local stress-strain method are used to calculate bearing life for bearings containing inclusions [5-6]. The fatigue reduction coefficient $K_f$ is used to modify the commonly used curve equation Basquin formula describing stress-strain to calculate the life prediction formula.

$$N_f = \frac{1}{2} \left( \frac{K_f \Delta \sigma}{\sigma_f'} \right)^{\frac{1}{\lambda}}$$  \hspace{1cm} (1)

Where $\Delta \sigma$ is the alternating stress; $N_f$ is the fatigue life value corresponding to the stress; $\sigma_f'$ is the fatigue strength coefficient; $\lambda$ is the fatigue strength index; $\sigma_b$ is the tensile strength of GCr15 bearing steel with a value of $1.75 \sigma_b$, and $\lambda$ can be taken as -0.12 by slope method.

As an approximate calculation method, Basquin formula is suitable for high cycle fatigue calculation where $K_f$ can be calculated by Neuber formula.

$$K_f = 1 + \frac{K_i - 1}{1 + \sqrt{a / \rho}}$$  \hspace{1cm} (2)

Where $a$ is the material constant, which can be taken as 0.26 for GCr15; $\rho$ is the radius of inclusion in bearing steel, and $K_i$ is the microscopic stress concentration factor generated at inclusion. The influence of inclusions on the fatigue life for bearings can be quantitatively studied using the above formula.
3.2. Effect of inclusion size on fatigue life for bearing

Keep the depth of the inclusion constant and change the diameter $D_{inc}$ of the inclusions from 4μm to 14μm to study the effect of inclusion size on bearing fatigue life.

![Figure 10. Effect of inclusion size on bearing fatigue life](image)

The fatigue life of the bearing is continuously decreasing by keeping the depth of the inclusion constant and varying the diameter of the inclusions from 4μm to 14μm, which indicates the bearing fatigue failure is more likely to happen with the size of inclusions increasing and is consistent with the fact controlling the size of inclusions can improve bearing fatigue life.

3.3. The effect of depth for inclusions on the fatigue life of bearings

The effect of the depth for inclusions on bearing fatigue life is studied by keeping the diameter of inclusions at 6 μm unchanged and changing the depth of inclusions from 0.2b to 0.8b from the contact surface, and the result is shown in figure 11.

![Figure 11. Effect of the depth of inclusions on bearing fatigue life](image)
The fatigue life of the bearing increases by 89.45% as the depth of the inclusion changes from 0.2b to 0.8b, and the Von Mises stress in the subsurface has little effect while the depth of the inclusion from the contact surface is greater than 0.8b. As the inclusion moves away from the contact surface, it has less effect on bearing fatigue life. The impact on the bearing fatigue life is greater, and the bearing fatigue life changes more drastically. Inclusions with shallow depth and large size have a huge impact on the performance of bearing steel, which can easily lead to fatigue failure of bearings.

3.4. The influence of elastic modulus for inclusions on the fatigue life of bearings

The relationship between elastic modulus and bearing fatigue life as shown in Figure 12 is obtained by keeping the size and depth of the inclusion and changing the elastic modulus for the inclusion from 105GPa to 315GPa gradually.

Contrary to the above stress change trend, the fatigue life of the bearing gradually decreases as the difference in the elastic modulus between inclusion and matrix increases whether it is soft or hard inclusion from the figure 12. The impact of the elastic modulus on the fatigue life for the bearing from the inclination angle of the line segments at both ends in figure 12 is greater than that of soft inclusions when inclusions are hard inclusions, which means hard inclusions such as alumina have a greater harm to the fatigue life of high-speed railway bearings.

4. Conclusion

(1) There will be obvious stress concentration around non-metallic inclusions existing in the subsurface of the contact area for the high-speed railway bearings, and the stress concentration in inclusions and their surroundings will make the inclusions fatigue the birthplace of micro-cracks due to the low binding force between inclusions and matrix, which seriously reduces the life of high-speed railway bearings.

(2) The size of non-metallic inclusions affects the stress distribution in the subsurface of the contact area. The maximum dynamic shear stress and the Von Mises stress in the subsurface both increase with the size of inclusions increasing when the conditions such as the depth of inclusions are kept constant, and the fatigue life of high-speed railway bearings will be reduced accordingly.
(3) According to finite element analysis, the maximum dynamic shear stress and the maximum Von Mises stress decreases as the depth of inclusions increases with the size of inclusions keeping constant and the depth of inclusions changing from 0.2b to 0.8b from the contact surface, which makes the fatigue life of high-speed railway bearings gradually increase theoretically.

(4) The dynamic shear stress and the Von Mises stress increase as the difference in elastic modulus between non-metallic inclusions and matrix increases, and then the fatigue life decreases. The damage of hard inclusions to the fatigue life for the bearing is greater than that of soft inclusions, and the fatigue damage is more likely to occur at hard inclusions due to stress concentration.

(5) The size and depth of non-metallic inclusions for high-speed railway bearing steel have a great influence on the stress distribution in the subsurface of the bearing contact area and the fatigue life of the bearing. Therefore, the size, depth and type of inclusions need to be strictly controlled in the smelting process of high-speed railway bearing steel to achieve the required fatigue life.

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