Effect of non-metallic inclusions on fatigue life of high-speed railway bearings

Can Yang Ma¹, Gang Zhang¹³, Yong Wu Wang¹, Zhen Qiang Zhang³, Zhong Ming Ren²

¹ Research Institute Mechanical design and Bearing, School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200072, China;
² State Key Laboratory of Advanced Special Steel, Shanghai University, Shanghai 200072, China
³ Email: zg@shu.edu.cn

Abstract. In the process of smelting and manufacturing of high-speed bearing steel, non-metallic inclusions are always inevitable, which destroy the continuity of the metal matrix and decrease the fatigue life of high-speed railway bearings seriously. Under the condition of obtaining the position and the number of the maximum contact load of the high-speed railway bearings, according to the Hertz contact theory, the maximum contact stress $\sigma_{\text{max}}$ between the roller and the raceway of the high-speed railway bearings and the half-width $b$ of the contact surface is calculated, and then the stress distribution equation of the contact surface is obtained. According to the basic theory of fatigue life, the local stress-strain method was used to analyse the influence of the distance, depth and quantity between the inclusions contained in the raceway of the outer ring on the contact surface stress and the fatigue life of the high-speed railway bearings. Quantitative relationship between the influence of non-metallic inclusions and the contact fatigue life of high-speed railway bearings was determined, which provided scientific bases in the smelting process of high-speed railway bearing steel.

1. Introduction
The high-speed railway bearings are one of the important components of high-speed railway train in operation, and its structural safety requires the materials of high-speed railway bearings to have good static and dynamic properties. The above requirements are closely related to the purity and uniformity of materials[1]. In the process of smelting and manufacturing of high-speed railway bearing steel, there are inevitable for non-metallic inclusions and inhomogeneous zones[2]. The great economic losses and safety accidents were caused by the structural failure due to the evolution of these microscopic initial inclusions defects[3], so it is necessary to study the effect of non-metallic inclusions on the fatigue life of high-speed railway bearings.

The rings and the rollers of the high-speed railway bearings are subjected to high alternating contact stress in operation, which is very sensitive to non-metallic inclusions such as carbides and oxides in the material. The non-metallic inclusions in the steel destroyed the continuity of the metal and separated from the matrix partially, which was very detrimental to the fatigue strength of the bearing steel and affected the fatigue life of the bearings seriously[4]. Considering the force characteristics of the inclusions, it was necessary to study the distribution of stress around the inclusions, which was greatly affected by the properties of inclusions such as interface modeling and
inclusions stiffness. A new numerical method was proposed for calculating the distribution of stress around an ellipsoid inclusion. The result showed that the distribution of stress was not symmetrical when the axes of the ellipsoidal inclusions did not coincide with the contact problem axes[5]. The effect of inclusions on rolling contact fatigue was studied experimentally, which explained the mechanism of rolling contact fatigue in the presence of inclusions. The experimental results revealed that it was formed during testing after crack initiation[6]. The soft inclusions were assumed to be equivalent to the hole defects, and the influence of the size and distribution of the soft inclusions on the local stress and strain state inside the bearing steel was analyzed[7]. The analysis of inclusions in the failed product showed that the internal inclusions induced fatigue crack mode (and surface induced mode) was the main mode of material fatigue fracture under high cyclic loading conditions[8]. The inclusions had a critical dimension above which the stress concentration did not increase by the size of inclusions, and the different stiffness of inclusions had different stress distribution around the inclusions[9].

However, the above studies mainly focused on theoretical calculation, simulation of local stress and strain caused by inclusions, and explained the fatigue spalling and crack propagation caused by the inclusions. There is no quantitative and qualitative analyses of the fatigue life of bearings caused by inclusions and their coupling effects. Therefore, this paper carries out traditional theoretical calculation on contact stress of high-speed railway bearings under the action of a certain radial and axial forces, analyses the influence of the distance, depth and Elastic Modulus between the inclusions, and establishes the relationship between the local stress and the bearings fatigue life.

2. Structure and maximum contact load of the high-speed railway bearings
This paper takes a high-speed railway bearing with a radial force of 86kN, an axial force of 17kN, and model 352226X3 as an example. The structural diagram and sectional view of the bearing are shown in Figure 1 and Figure 2 respectively, and the specific structural parameters are shown in Table 1.

![Figure 1. Structural diagram of high-speed railway bearing.](image1)

When the train is running at 350km/h and the bearings bear with radial force of 86kN and axial force of 17kN, Kai Y et al.[10] have solved the contact load distribution of the two rows of rollers of
the high-speed railway bearings under the action of radial and axial forces, to determine the roller which carried the maximum contact load and calculate the surface contact stress distribution and the subsurface stress distribution between the roller and the raceway. The roller that bears the maximum contact load in the first row of rollers is taken as the roller that receives the maximum stress, that is, the roller whose azimuth angle is $\varphi = 0^\circ$, and the contact load between the roller and the outer ring is 6.92KN.

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) | 24.497  |
| Large end diameter of roller $D_{max}$ (mm) | 26.7    |
| Mean diameter of roller $D_m$ (mm)     | 25.599  |
| Pitch circle diameter of bearings $d_m$ (mm) | 185     |
| Contact angle of inner ring $\alpha_i$ ($^\circ$) | 7°34’   |
| Contact angle of outer ring $\alpha_o$ ($^\circ$) | 10°     |
| Length of roller $L$ (mm)              | 51.95   |
| Number of rollers $Z$                  | 2×19    |
| Half cone angle of roller $\phi$ ($^\circ$) | 1°13’   |
| Effective length of roller $l$ (mm)    | 45      |

In the case where the contact angle of the tapered roller is small, according to the Hertz contact theory, the maximum contact stress $\sigma_{\text{max}}$ between the tapered roller and the raceway and the half width $b$ of the contact surface can be approximately expressed as [11]:

$$\sigma_{\text{max}} = \frac{2Q}{\pi lb}$$  

$$b = 3.35 \times 10^{-3} \left( \frac{Q}{l \sum \rho} \right)^{1/2}$$

where $l$ is the effective length of roller; $Q$ is the maximum contact load between the roller and the outer ring, and $\sum \rho$ is the curvature sum. Combining equations (1) and (2), the maximum contact stress of the bearings can be found to be 742.13Mpa, and the half width $b$ is 132um.

GCr15 bearing steel is commonly used in high-speed railway bearings, whose inclusions can mainly be divided into four categories according to their structural composition[12]: (1) Sulfide inclusions of class A mainly composed of sulfur with little effect on fatigue life; (2) Al2O3 inclusions, which composed of oxygen and aluminum elements, are more harmful to the fatigue life of bearing steel; (3) Silicate and aluminate inclusions, which tend to cause stress concentration during operation and reduce the fatigue life of bearing steel; (4) The inclusions with the main components of magnesium aluminum spinel and titanium nitride. The distribution of inclusions mainly exhibit the following characteristics: (1) The shape of inclusions is very irregular with long strips, spheres and clusters. The distribution of inclusions is uneven with high contents of local inclusions; (2) The inclusions are not well bonded to the matrix material. The soft inclusions are prone to form voids, and the hard
inclusions are easily separated from the matrix to form a gap. In the establishment of the simulation model, the main consideration is the hard inclusions that have a great influence on the fatigue life of bearings and the clustering effect between the multiple inclusions.

3. The prediction of fatigue life of high-speed railway bearings

3.1. The calculation model of Contact stress with inclusions

In the previous section, the distribution of maximum contact stress of the roller has been obtained. The influence of the inclusions contained in the raceway of outer ring on the fatigue life of bearings are calculated when the roller with the largest force is in contact with the outer ring. The distribution of non-metallic inclusions in bearing steel are very uneven, so it is difficult to describe this phenomenon with an accurate model. The bearing steel containing double inclusions and multiple inclusions is used to simplify the calculation. The contact stress between the outer ring and the roller is analyzed using the elastic contact mechanics, and the edge effect at both ends of the roller is neglected. The calculation model can be simplified as an elastic semi-infinite body subjected to uniform load in one direction [13], and then the stress distribution equation of the contact surface is obtained:

$$ p(x) = 742.13 \times \left[ 1 - \left( \frac{x}{b} \right)^{1/2} \right]^2 $$

Consider the inclusion in the elastic semi-infinite body, and make the following assumptions:

1. Hole is easily formed in the smelting process of bearing steel for non-metallic inclusions with a lower Elastic Modulus than the matrix material. Hard inclusions such as Al₂O₃ are easily separated from the matrix to form a gap, and its micromechanical behaviors are close to the hole. Therefore, hole defects can be used instead of inclusions for equivalent studies.

2. The inclusions are only present in the elastic semi-infinite body in which the roller is in contact with the raceway. The roller is subjected to the maximum contact stress as an alternating stress while it is in contact with the raceway.

Combine the above analysis and simplify the model, it is assumed that there are double inclusions in the elastic semi-infinite body, which are symmetric about the z-axis. In the contact area, the case of the presence of double inclusions in the elastic semi-infinite body is shown in Figure 3. The effect of the numbers of inclusions on the surface stress of the bearings is discussed assuming that the distance between the nearest inclusions is the same and constant. The distribution model of multiple inclusions in an elastic semi-infinite body is shown in Figure 4.

![Figure 3. The model of double inclusions in elastic semi-infinite body.](image)

![Figure 4. The model of multi-inclusions in elastic semi-infinite body.](image)
where $M_{inc}$ is the distance between the inclusion; $Z_{inc}$ is the depth of the inclusion from the contact surface; while $D_{inc}$ is the diameter of the inclusion.

3.2. Fatigue life prediction model

Traditional fatigue life models such as the L-P life model and the I-H life model are based on the uniformity of the bearings material. There is no longer applicable here for bearings containing inclusion. In this paper, the basic theory of fatigue life, the local stress-strain method, and the fatigue life reduction factor $F_K$ are used to modify the Basquin formula describing the common curve equation of stress-strain to obtain the life prediction formula [14]:

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

(4)

where $\Delta \sigma$ is the stress amplitude; $N_f$ is the fatigue life value corresponding to the stress amplitude; $\sigma_f$ is the fatigue strength coefficient, $\lambda$ is the fatigue strength index; $\sigma_b$ is the tensile strength of the GCr15 bearing steel, $\sigma_f$ can take 1.75 $\sigma_b$, and $\lambda$ can take -0.12 using the slope method [15]. The Basquin formula is suitable for high-cycle fatigue calculations, so it can be used in the calculations of bearings fatigue life as an approximate calculation method, where $K_f$ can be calculated by the Neuber formula:

$$K_f = 1 + \frac{K_i - 1}{1 + \sqrt{a / \rho}}$$

(5)

where $a$ is the material constant, which can be taken as 0.26 for GCr15 [15]; $\rho$ is the radius of the inclusion in the bearing steel, and $K_i$ is the microscopic stress concentration factor generated at the inclusion.

Bearing steel was used for simulation in the case of double inclusions in elastic semi-infinite body [7], and the least square fitting method was used to calculate the microscopic stress concentration factor $K_i$, which was the empirical expression of the size and position of inclusion:

$$K_i = 2.2842 + 2.5735e^{(Z_{inc}/M_{inc})/4.5551}$$

(6)

where $M_{inc}$ is the distance between the inclusion; $Z_{inc}$ is the depth of the inclusion from the contact surface.

For the case of multi-inclusions in elastic semi-infinite body, the fatigue basic theory is used to approximate the calculations using equations (4) and (5). The empirical expression of the local microscopic stress concentration factor $K_i$, the distance between inclusions and the number of inclusions [7]:

$$K_i = 3.2842 + 2.5734e^{13.6418/M_{inc}} + 2.1965N^{1.147}$$

(7)

It should be pointed out that it is an approximate expression of the local microscopic stress concentration factor of multiple inclusions in bearing steel used to quantitatively study the effect of inclusions on the fatigue life of bearings. According to the maximum contact stress while the
maximum force roller is contacted with the raceway in the outer ring, the quantitative relationship between the size, position and number of inclusions on the fatigue life of the bearings can be calculated.

4. Analyses of the calculation results

4.1. The effect of double inclusions on the fatigue life of high-speed railway bearings

The local micro-stress in the bearing steel will become very complicated due to the interaction between multiple inclusions for many inclusions inside the bearing steel, so it is difficult to generalize a uniform law to describe the change of the number of inclusions and to establish a suitable model to describe this phenomenon. Therefore, the model is simplified to quantitatively study the influence of multiple inclusions in bearing steel on the fatigue life and used to consider the case of double inclusions in elastic semi-infinite body firstly.

In view of the fact that the simulation analyses of inclusions containing elastic semi-infinite body take a long time and are difficult to solve, the calculation scale should be reduced, and half of the model is used to analyze the stress distribution considering the symmetric distribution of the model.

The non-metallic inclusions introduced during the smelting process of bearing steel are mostly hard inclusions such as oxides, so the elastic modulus can be assumed to be twice that of the bearing steel matrix, which is 420 GPa and Poisson's ratio of 0.3. Local meshing is performed around the inclusion shown in Figure 5.

![Figure 5. Local meshing.](image)

In the failure analyses of high-speed railway bearings, it was found that the inclusions of fatigue source were mostly 2-14 $\mu m$ and most of the inclusions were at 4-8 $\mu m$ in diameter, so the diameter of the inclusions was set to $6 \mu m$ while studying the effect of the size on the fatigue life of bearings.

While keeping the distance between the double inclusions to the contact surface $Z_{inc}$ $0.5 b$ and applying a symmetry constraint on the line divided by the z-axis, $M_{inc}$ changes from 10 $\mu m$ to 40 $\mu m$ to calculate the dynamic shear stress distribution in the subsurface of the bearings. Figure 6 shows the distribution of dynamic shear stress for a distance of 20 $\mu m$ between double inclusions, and Figure 7 shows the corresponding distribution of Von Mises stress.

It can be seen from Figure 6 and Figure 7 that the maximum dynamic shear stress and the maximum Von Mises stress are the largest at the junction of the inclusions and the matrix, so that the fatigue source is easily formed at the joint of the inclusion and the matrix, and further causes the fatigue failure of the bearings. The dynamic shear stress and Von Mises stress corresponding to different distances between the double inclusions are shown in Table 2.

It can be seen from the Table 2 that the maximum dynamic shear stress and the maximum Von Mises stress of the subsurface of the bearings decrease as the distance between the double inclusions increase, which indicates that it is easier to causes stress concentration on the subsurface of the bearings with double inclusions gather together.
For the case of double inclusions in elastic semi-infinite body, combing the equation 4, the equation 5 and the stress concentration factor $K_t$ obtained with using equation 6, we can get the fatigue life value $N_f$ corresponding to the stress amplitude $\sigma = \sigma_{tM}$ obtaining using the FEA. According to the calculation model of fatigue life, the relationship between the distance $M_{inc}$ of the double inclusion and the fatigue life is shown in Figure 8.

**Figure 6.** The distribution of dynamic shear stress with a distance of 20 $\mu m$ between double inclusions.

**Figure 7.** The distribution of Von Mises stress with a distance of 20 $\mu m$ between double inclusions.

**Table 2.** Comparison of maximum dynamic shear stress and maximum Von Mises stress by changing the distance between double inclusions.

| The distance between the double inclusions/$\mu m$ | 10   | 20   | 30   | 40   |
|------------------------------------------------|------|------|------|------|
| The maximum dynamic shear stress /MPa          | 568.498 | 518.853 | 470.638 | 411.488 |
| The maximum Von Mises stress /MPa              | 924.698 | 830.907 | 732.457 | 627.115 |

It can be seen from Figure 8 that the distance between the double inclusions has a great effect on the fatigue life of the bearings. The fatigue life increases as the distance increases, and the maximum fatigue life is 28.78 times of the smallest. This is because as the distance between the double inclusions increases, the local microscopic stress concentration caused by the interference of the double inclusions decreases, and the corresponding bearings fatigue life also increases. Therefore, in the actual control of the smelting process of bearing steel, the occurrence of multiple inclusions gather together should be avoided.

The position of the inclusions has a certain influence on the fatigue life of the bearings. Keep the diameter of the double inclusions $D_{inc} = 6\mu m$ and the distance between the inclusion $M_{inc} = 20\mu m$, and
change the distance of the inclusions to the contact surface from $0.2b$ to $b$, the relationship between the fatigue life and the distance of the inclusions from the contact surface is obtained.

![Figure 8](image8.png)

**Figure 8.** The effect of the distance between inclusions on the fatigue life of bearings.

The fatigue life is drastically reduced as the distance from the inclusions to the contact surface increases from Figure 9. The maximum fatigue life is 25.12 times the minimum fatigue life when the distance changes from $0.2b$ to $b$, which is caused by the strengthening effect between the inclusions. The stress concentration factor of the inclusions is bigger as the distance between the inclusions and the contact surface is closer to $b$, and causes the shorter fatigue life.

4.2. The effect of the number of inclusions on the fatigue life of high-speed railway bearings

In order to control the variables, the effect of the number of inclusions on the subsurface stress of the bearings is discussed under the assumption that the distance between the nearest inclusions is the same and constant.

Keep the diameter of the double inclusions $6\mu m$, the depth of the uppermost inclusions is $0.5b$ from the contact surface, the distance $M_{inc} 10\mu m$, and change the number of inclusions from 2 to 8, the distribution of dynamic shear stress and Von Mises stress are calculated, which is shown in Figure 10 and Figure 11.

![Figure 9](image9.png)

**Figure 9.** The effect of the depth of the inclusions on the fatigue life of bearings.
Table 3 shows the maximum dynamic shear stress and maximum Von Mises stress values for the subsurface of the bearings without any inclusions and the variations in the number of inclusions.

The maximum dynamic shear stress and the maximum Von Mises stress of the subsurface of the bearings reach 709.304 MPa and 1085.699 MPa when the number of inclusion is 8, which is 284.69% and 163.58% higher than that of without inclusions. Combined with Table 3, the relationship between the number of inclusion and the fatigue life of the bearings is obtained according to the calculation model containing inclusions of fatigue life of the bearings.

For the case of multi-inclusions in elastic semi-infinite body, combing the equation 4, the equation 5 and the stress concentration factor $K_i$, obtained with using equation 7, we can get the fatigue life value $N_f$ corresponding to the stress amplitude $\sigma_w$ obtaining using the FEA again. According to the calculation model of fatigue life, the relationship between the number of inclusions and the fatigue life is shown in Figure 12. It can be seen from Figure 12 that the influence of the number of inclusions on the fatigue life is very large. When the number of inclusion increases from 2 to 8, the fatigue life is continuously reduced by 92.23%. Moreover, as the number of inclusions increases, the increasing inclusions which have deeper distance from the surface have less and less influence on the fatigue life of the bearings.

![Figure 10. The distribution of dynamic shear stress with 8 inclusions.](image1)

![Figure 11. The distribution of Von Mises stress with 8 inclusions.](image2)

| Number of inclusion | None  | 2      | 4      | 6      | 8      |
|---------------------|-------|--------|--------|--------|--------|
| The maximum dynamic shear stress / MPa | 184.385 | 568.498 | 630.089 | 682.688 | 709.304 |
| The maximum Von Mises stress / MPa | 411.903 | 924.698 | 1002.179 | 1055.095 | 1085.699 |
5. Conclusions
Based on the basic theory of the fatigue life and the contact stress distribution of high-speed railway bearing, the local stress-strain method is used to link the inclusions with the fatigue life bearings creatively, and analyse the influence of inclusions on the fatigue life qualitatively and quantitatively. Suggestions are provided during the smelting process of bearing steel: Smaller size and less inclusions, dispersed inclusions, and inclusions farther away from the contact surface are beneficial for increasing the operation time of bearings.

However, due to the complex shape and distribution of inclusions and the complex force mechanism of the contact area, it is difficult to reproduce in the simulation process, so it is necessary to combine a large number of experiments for comparative analyses and verification. In addition, since the simulation model of the inclusions is based on the simple spherical hard inclusions, in the following research, the effects of different forms of inclusions on the fatigue life can be considered.

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