Effect of observation position of SUJ2 bar specimens on inclusions distribution

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Abstract. The size and distribution of non-metallic inclusions are strongly related to rolling contact fatigue (RCF) life. SUJ2 steel is manufactured as a round bar, and is cooled from the surface during casting. This indicates that the inclusions may be distributed non-uniformly in the center direction. The objective of this study is a clarification of the difference of the inclusion distribution in the SUJ2 round bar. It was found that the distribution of inclusions in SUJ2 was distributed uniformly in a transverse direction.

1. Introduction

High carbon chromium steel SUJ2 is used in rolling contact applications when high wear and fatigue resistance are required. It is well known that flaking failures of bearings originate from non-metallic inclusions under Rolling Contact Fatigue (RCF). These non-metallic inclusions are mainly made of oxide, sulfide and nitride. The size of these non-metallic inclusions is strongly related to RCF life.

These inclusions are contaminated in the steel during the steelmaking process. The inclusions are generated in the solidification process by the casting. SUJ2 steel is manufactured as a round bar, and is cooled from the surface during the casting process. This indicates that the inclusions may be distributed non-uniformly in the center direction because of the difference in cooling rate. Therefore, we need to study distribution of inclusions in the round bar.

The statistics of extreme value are one of the major methods to estimate the maximum inclusion size based on the inclusion distributions. Many researchers studied the relation between the inclusions and RCF life. Hashimoto, et. al. [1] studied effect of oxide inclusion size and chemical composition on RCF life of SUJ2 bearing steel. They found that RCF life was improved with decrease in the size of oxide inclusions. Nagao, et. al. [2] studied effect of size and types of inclusions on the RCF life of SUJ2 bearing steel. The RCF life was not related to inclusion type, but to the largest inclusion size.

In this study, we observed inclusion distribution of SUJ2 steel based on the statistics of extreme value method. We measured the maximum size of inclusions in the view field of microscope, and evaluated the inclusion distribution of SUJ2 steel by comparing the inclusions in two areas which are near the core of the bar specimen and below the rolling track.
2. Test method

2.1. Specimens and heat treatment

Figure 1 shows a schematic illustration of plate sample. The outer diameter was 52 mm and the inner diameter was 20 mm. The thickness of the samples was 10 mm. Figure 2 shows a schematic illustration of heat treatment processes. The SUJ2 plate was heated at 830 ℃ for 40 minutes in a furnace and after that quenched. Subsequently, it was tempered at 180 ℃ for 120 minutes.

![Figure 1 Schematic illustration of sample. (dimension in mm)](image1)

![Figure 2 Schematic illustration of heat treatment processes.](image2)

2.2. Rolling contact fatigue tests and Hardness tests

We measured Vickers hardness in two regions using a Hardness tester (MATSUZAWA, VMT-X7S). An indentation load was 10 kgf and the loading time was 15 seconds. The measurements were done below the rolling track and at 5 mm depth from the surface. Increment of measuring points was 0.5 mm. Figure 3 shows a schematic illustration of the measurement regions.

We performed RCF tests up to $4.30 \times 10^6$ cycles using a thrust-type machine [3]. The tests were stopped when we found flaking failures. The rotation speed was 2000 rpm and the maximum contact pressure was 5.3 GPa. The value was calculated by Hertzian contact theory [4]. Young’s modulus and Poisson’s ratio were 210 GPa and 0.3, respectively.

![Figure 3 Schematic illustration of the measurement points of Vickers hardness test.](image3)
2.3. Inclusion observation and evaluation methods
After the RCF tests, the specimen was cut and polished to observe the inside. The sectional surfaces were ground by grind papers from #800 to #4000 and polished by 1 μm diamond paste.

Figure 4 shows a schematic illustration of the observation area. The extending direction on the section is shown as ED, and the transverse direction is as TD. We observed two areas as shown in figure 4. They will be referred to as \( A_{\text{track}} \) and \( A_{\text{core}} \), respectively. \( A_{\text{track}} \) is a red area which is below the rolling track. \( A_{\text{core}} \) is a green area which is near the core of the bar specimen. The size of both areas was 10 mm\(^2\) (1 mm width × 10 mm length). There is no flaking failure around the \( A_{\text{track}} \).

The inclusions were observed by a LCM (laser scanning confocal microscope, Keyence, VK-9700). We measured the size of inclusion which was selected as the largest inclusion in a field of LCM view. The measurement window of the LCM was 90 μm × 67 μm \((S_0 = 6.03 \times 10^{-3} \text{ mm}^2)\). We took 30 photos from both \( A_{\text{track}} \) and \( A_{\text{core}} \). We measured the maximum inclusion size in each photo and evaluated the distribution of inclusions with the statistics of extreme values of all 30 photos for each area.

Murakami studied the relation between fatigue life and inclusion size [5]. He proposed the \( \sqrt{\text{area}} \) theory to evaluate without considering the shape of inclusion. Based on his theory, we defined the square root of the largest inclusion size as \( \sqrt{\text{area}_{\text{max}}} \) μm in this paper.

![Figure 4 Schematic illustration of the observation area.](image)

3. Results and Discussion
Figures 5 (a) and (b) show the Vickers hardness distributions in the two measurement regions of figure 3. The average values of Vickers hardness below the rolling track and 5 mm depth from the surface are HV730 and HV736. The Vickers hardness values distribute evenly.

![Figure 5 Vickers hardness distributions.](image)
Figure 6 shows an example of sulfide inclusions. We found many sulfide inclusions which were extended in the ED direction. The sulfide inclusions have low hardness compared to oxide and nitride inclusions. Therefore, the shape of sulfide inclusions follows the deformation behavior of matrix steel when processing.

Hashimoto et al. [6] reported that the sulfide inclusions which was stretched in a direction parallel to the load movement affected RCF lives. In our observations, we ignored the sulfide inclusions because the ED direction was perpendicular to the load movement. But, the sulfide inclusions which composited with other inclusions were counted. Figure 7 shows an example of the sulfide composition inclusion.

![Figure 6 Photograph of sulfide inclusions which were extended in the extending direction.](image1)

![Figure 7 Photograph of sulfide inclusion which composited with other inclusions.](image2)

In the observation, we found some types of inclusions, such as oxide, nitride and sulfide. Figure 8 shows the photograph of oxide and nitride inclusions. We counted and evaluated the distribution of these inclusions with the statistics of extreme value method.
Figure 8 Photograph of oxide and nitride inclusions.

Figure 9 shows the extreme values distribution in the $A_{\text{track}}$ and $A_{\text{core}}$. The vertical axis of the graph shows the cumulative distribution frequency, reduced variate and return period. The horizontal axis shows the $\sqrt{\text{area}_{\text{max}}}$ values.

The average values of $\sqrt{\text{area}_{\text{max}}}$ of $A_{\text{track}}$ and $A_{\text{core}}$ are 4.68 μm and 4.26 μm. The regression linear equations (y) are described as follows.

$$A_{\text{track}} : \ y = 0.63\sqrt{\text{area}_{\text{max}}} - 2.41$$
$$A_{\text{core}} : \ y = 0.58\sqrt{\text{area}_{\text{max}}} - 1.95$$

This indicates that the distribution of the maximum inclusion size in $A_{\text{track}}$ is similar to that in $A_{\text{core}}$. Furthermore, the inclusions in SUJ2 bar specimen were uniformly distributed in a direction of TD.

Figure 9 Extreme value distribution in the SUJ2 steel.
We calculate the maximum inclusion size in a hazardous volume from measurement results of the inclusions. In the calculation, we define the maximum inclusion size in the hazardous volume as MCI with the statistics of extreme value distribution of all inclusions. We use a virtual thickness of inclusions to deduce the MCI based on the 2D observation results [7]. The virtual thickness $h$ is calculated from the average value of $\sqrt{\text{area}_{\text{max}}}$. We defined hazardous volume $V_{\text{RCF}}$ at the rolling contact fatigue tests as equation (1).

$$V_{\text{RCF}} = \pi a_c D_p$$

(1)

The pitch circle diameter $D_p$ was 38.5 mm. The contact width $a_c$, which was measured after the RCF test was 1 mm. We defined $d_s$ as the depth from the surface when the stress is 80% of maximum shear stress. The maximum shear stress was calculated based on the Hertzian contact theory and Sackfield & Hills formula [4,8]. From the calculation results, it was found that the maximum shear stress was 388.8 MPa and depth from the surface $d_s$ was 0.26 mm. From the results of calculations using Eq. (1), the hazardous volume was 31.4 mm$^3$. We evaluate the MCI of $A_{\text{track}}$ and $A_{\text{core}}$ as follows.

$$MCI_{\text{track}} = 25.9 \ [\mu m]$$

$$MCI_{\text{core}} = 27.4 \ [\mu m]$$

The difference between both MCI values is negligible. This result shows the distribution of inclusions in SUJ2 is distributed uniformly in a direction of TD and the inclusion size of $A_{\text{track}}$ is the same as in $A_{\text{core}}$.

4. Conclusions
We investigated effects of observation position of SUJ2 bar specimens on inclusions distribution. We measured Vickers hardness distribution, and observed the inclusions below the rolling track area and near the core area. After measuring the maximum inclusion size, we evaluated the distribution of inclusions with the statistics of extreme values and calculated the maximum inclusion size in a hazardous volume. The conclusions are as follows.

1) The Vickers hardness values distributed evenly.
2) The distribution of the maximum inclusion size in track area was similar to that in core area. The difference between both the maximum inclusion sizes was negligible. These results show the inclusions in SUJ2 are distributed uniformly and the maximum inclusion size of the track area is the same as in the core area.

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