Acicular structure formation under rolling contact fatigue of carburized SAE5120

Daisuke Takazaki[1], Masato Yuya[1], Takahide Umehara[1], Makoto Kosaka[1] and Kaori Kawano[1]

[1]*Nippon Steel Corporation, Chiba 293-8511, Japan*

The objective of this study is to gain mechanistic insight into the premature failure mode of bearing steels in rolling contact fatigue (RCF) in order to enhance the safety and reliability of the bearings with a particular focus on the formation mechanism of the acicular structure that is formed before White Etching Cracks (WECs) formation. A two-roller type contact fatigue test performed with a carburized SAE5120 successfully provides systematic sequences leading to the acicular structure formation at the range from 100 to 600 μm below the contact surface. The longitudinal directions of acicular structures are both almost parallel and perpendicular to the rolling direction. The depth and direction of the acicular structure formation are consistent with the peak depth and direction of the cyclic shear stress $\Delta\tau_{yz}$, which indicates that the driving force of the acicular structure formation is the cyclic shear stress. Also, the EBSD analysis shows that the acicular structures were observed along to the slip plane {110} and slip direction <111>. These observation results strongly indicate that the acicular structure is formed by the dislocation movement.

Keywords: *Rolling Contact Fatigue (RCF), Bearing, Carburization, White Etching Area*

1. Introduction

Formation of White Etching Cracks (WECs), which is associated with a microstructural alteration known as White Etching Area (WEA), is a premature failure mode observed in bearing steels used for wind turbine gearboxes, automotive transmissions and automotive compressors. WECs typically develop several hundred micrometers below the contact surface. Due to their detrimental effect on bearing lifetime, a number of research has been conducted to understand the mechanism of the WECs formation over the years [1-3]. It has been known that the formation of acicular structures, which is another mode of microstructural alternation in bearing steels induced by rolling contact fatigue (RCF), precedes the WECs formation [1]. However, the detailed mechanism of the acicular structure formation remains poorly understood. The objective of this study is to gain mechanistic insight into the premature failure mode of bearing steels under RCF in order to enhance the safety and reliability of bearings. In particular, this study focuses on the mechanism of the acicular structure formation.

2. Experimental procedure

2.1 Material

The material used for the test is a carburized SAE5120 (0.19 mass %C, 0.21 mass %Si, 0.85 mass %Mn, 0.85 mass %Cr). The material was normalized at 925 ℃ followed by air cooling. It was then machined into a round bar specimen with a diameter of 26 mm and subsequently carburized. The profile of the Vickers hardness and carbon content of the specimen are shown in Figure 1. The Vickers hardness and the carbon content at the surface of the specimen were 0.8 % and 780 HV respectively.

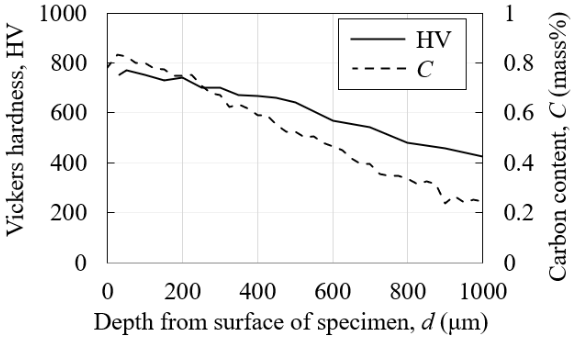

Figure 1 Profile of Vickers hardness and carbon content of the carburized SAE5120 specimen

2.2 Two-roller type RCF test

A two-roller type RCF test was conducted to investigate the mechanism of acicular structure formation. A schematic representation of the experimental setup is shown in Figure 2. A counter roller was pressed into contact with the specimen, and both were rotated at different circumferential speeds. During testing, an ATF-oil was flushed into the contact part. The testing conditions are shown in Table 1. After the test, acicular structures were observed on the cross-section of the specimen.

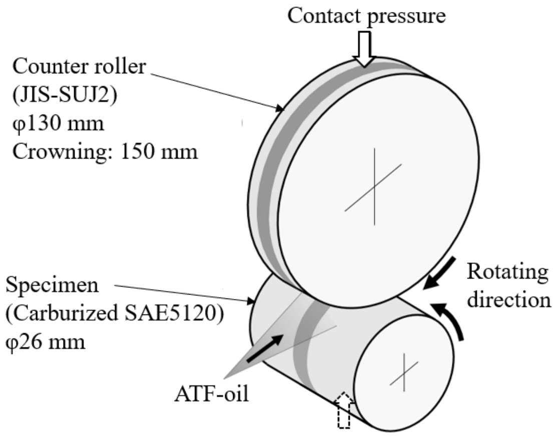

Figure 2 Testing method of two roller type RCF test

Table 1 Testing conditions

Contact stress	Number of cycles	Frequency	Circumferential speeds		Oil temp.
			Specimen	Counter roller	
2.6 GPa	5.0×10^7	1500 rpm	2.0 m/s	2.8 m/s	90 ℃

2.3 Calculation of shear stress

Shear stress below the contact surface was calculated by TED/CPA $^{4)}$ which is a numerical calculation method for counterformal rolling contact using a boundary element method. The geometry of the analysis model and coordinate systems are shown in Figure 3. The shear stress τ_{yz} at plane x = 0 was calculated under the contact stress of 2.6 GPa and the friction coefficient of 0.07.

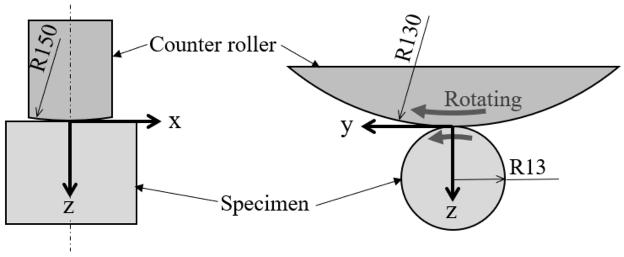

Figure 3 Stress calculation model of two-roller type RCF test (dimensions are in mm)

3. Results and discussions

Figure 4 shows the acicular structures formed below the contact surface of the specimen. These acicular structures were observed at a depth ranging from 100 to 600 μm below the contact surface. Remarkably, the longitudinal directions of these acicular structures were found to be both nearly parallel and perpendicular to the rolling direction. Another important point shown in Figure 3 is that the acicular structures do not propagate beyond the primary austenite grain boundary.

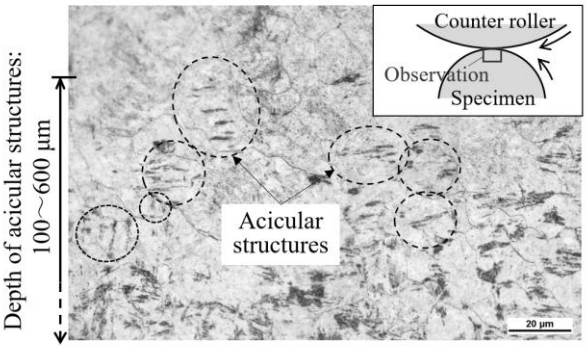

Figure 4 Acicular structures observed in circumferential cross-section of tested specimen

Figure 5 shows the distribution of the cyclic shear stress, $\Delta\tau_{yz}$, with a maximum peak observed at 240 μm below the contact surface under this testing condition. The depth of the acicular structure formation was found to be consistent with the peak depth of the cyclic shear stress. In addition, the longitudinal directions of the acicular structures are also consistent with the direction of the cyclic shear stress $\Delta\tau_{yz}$, indicating that the driving force for the acicular structure formation was the cyclic shear stress.

Figure 6 shows a SEM image of acicular structure, IPF map and EBSD analysis of the crystal orientation near the acicular structure. The acicular structures were formed along the martensite block. Additionally, the acicular structure was observed along the slip plane {110} and slip direction <111>.

The results obtained in this study indicate that the acicular structure was formed by dislocation slip driven by the cyclic shear stress $\Delta\tau_{yz}$. It is believed that the acicular structure forms within a martensite block when the directions of the martensite block, slip planes, and slip directions are aligned.

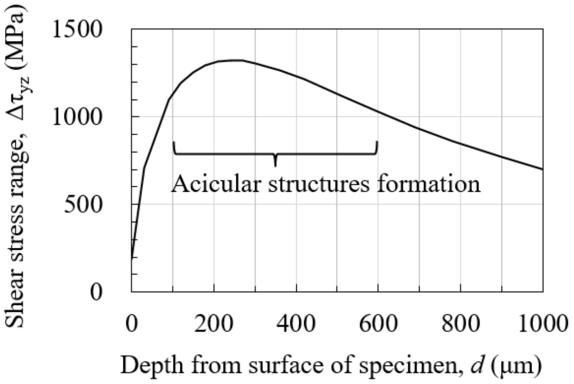

Figure 5 Shear stress range calculated by stress analysis

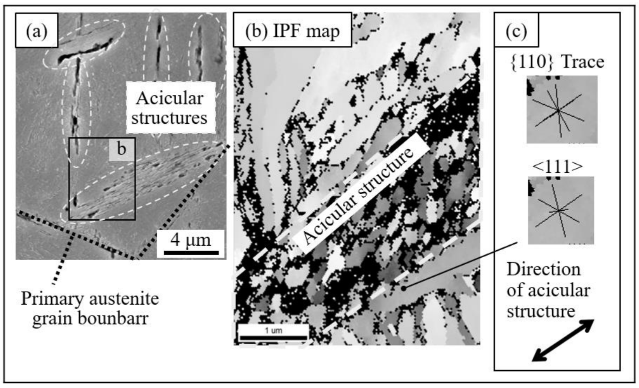

Figure 6 EBSD analysis of acicular structure ((a)SEM image, (b) IPF map at "b", (c) Crystal orientation analysis near an acicular structure.

4. Conclusions

A two-roller type RCF test was carried out in order to consider the mechanism of the acicular structure formation. The results showed the relationship between the acicular structures, shear stress and crystal orientation, indicating that the acicular structures formation is caused by the dislocation movement.

References

1) H. Harada, T. Mikami, M. Shibata, D. Sokai, A. Yamamoto and H. Tsubakino: ISIJ Int. **45** (2005) 1897-1902.
2) M. -H. Evans, L. Wang and R. J. K. Wood: Journal of Eng. Tribo. **228** (2014) 1047-1062.
3) S. W. Ooi, A. Gola, R. H. Vegter, P. Yan and K. Stadler: Mater. Sci. and Tech., **33** (2017) 1657-1666.
4) K. Kakoi and T. Obara: JSME International Journal Series A. **36** (1993) 57-62.