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Change in Microstructure and Properties in the Rolling Contact Fatigue of Bearing Steel

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Abstract

Bearing steel has recently made rapid progress in maintaining high cleanliness and therefore, longevity. As a result, applications under high contact stress have been promoted and thus have generated the issue of the occurrence of microstructural changes. This study researched such behavior of microstructure to show the following: in rolling contact fatigue, plate microstructures, white etching bands and "striped" microstructures at the depth of the biggest shear stress have been found. The white etching bands have ferrite and the plate and "striped" microstructures have pseudo-pearlite structure. A remarkable decrease has been observed at the peak of X-ray analysis under microstructural changes which occur under fatigue in half value width. The above phenomena is presumably due to the concentration of shear strain and its accompanying heat. It is estimated that the reached temperature is around 300℃ overall and over 600℃ locally in the white etching bands area.

1. Introduction

Bearings are one of the main mechanical parts used in automobiles and manufacturing machines. Their required characteristic is rolling fatigue. Recently, lighter weight and lower fuel consumption of automobiles have become major issues due to the desire to protect the world's environment. There is a strong demand for improved bearing longevity. Since the existence of nonmetallic inclusion is the starting of rolling fatigue fracture of bearings, longevity was mainly tried by reducing nonmetallic inclusion through the lowering of oxygen.

However, with the rapid progress made in high cleanliness of bearing steel in recent years there has also been improved longevity. As bearings are being used under ever increasingly severe high contact stress, the peculiar microstructures shown in **Fig. 1** are generated by the process involved in rolling fatigue. The phenomenon occurs where this peculiar microstructure is the path for the propagation of crack. These peculiar microstructures are known as "dark etching regions", "white etching regions" or as the "butterfly" that is generated in the periphery of the nonmetallic inclusion. Many investigations have been made concerning these microstructures[1-4]. However, there are many points such as the cause relating to their


Fig. 1 Peculiar microstructure and crack 50μm

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creation and the relationship to the macro quality of the steel that have yet to be clarified.

The authors researched and analyzed the generation of the peculiar microstructure under the process of rolling fatigue of bearing steel and the change of the material quality that accompanied it.

2. Experimental Method

Carburized steel SCr420 and bearing steel SUJ2 were used as the specimens. **Table 1** shows their chemical compositions. Carburized steel was used because the analysis of the change in the microstructure is easy compared with SUJ2 whose microstructure includes spherical carbide. Oxygen amounts were 9 ppm and 6 ppm respectively for each. Carburized steel was carburized with a carbon potential of 0.8%, quenched and tempered under the conditions of 180°C for 2 hours. Hardness for the hardened layer was HV780; for the core, HV350. The effective hardness depth was 1.3 mm and the retained austenite amount was 30%. SUJ2 was quenched at 840°C for 30 minutes and tempered at 170° for 2 hours.

Next, a test piece with a diameter of 12 mm and length of 22 mm was used for the rolling fatigue test. The test was performed on a point contact type rolling fatigue testing machine. The diameter of the steel ball was 19.1 mm. The test was performed under the conditions of a weighted load in the radial direction. The maximum contact stress was 600 kgf/mm^2 and the stress load speed was 46,200 cpm. Turbine oil with a temperature of approximately 85°C was used as the lubricant.

For the analysis of fine carbide microstructures, an Auger electron spectroscope (AES), scanning electron microscope (SEM) and transmission electron microscope (TEM) were used. Microstructure appeared through electrolytic etching using the SPEED method[5].

A micro X-ray measuring apparatus was used for the measurements of residual stress, retained austenite amounts, and half-widths of the diffraction peaks of X-rays. An X-ray tube using Cr as the target was used. Diffraction peak of the ferrite (211) was used for the residual stress and the half-width measurements.

Table 1 Chemical compositions of specimens

(wt%) (*ppm)

	C	Si	Mn	P	S	Cr	Al	N	O
SCr420	0.19	0.24	0.85	0.006	0.010	1.14	0.046	0.020	9*
SUJ2	0.96	0.20	0.35	0.007	0.007	1.34	0.035	0.008	6*

3. Experimental Results and Considerations

3.1 Analysis of peculiar microstructures generating during the rolling fatigue process

Because analysis of changes in the microstructure is difficult due to the obstructions by spherical carbide in SUJ2, testing was first done using carburized steel. **Fig. 2** shows the cross section microstructure of the carburized steel and rolling contact track after 1.5×10^8 times rolling contact fatigue. In the original specimen there were substantially uniform high carbon martensite microstructure. After 1.5×10^8 times rolling contact fatigue, at a depth of approximately 0.15 mm from the rolling surface, a white band at an angle of approximately 20° in the direction of the weight movement and vertical stripes at an angle approximately 90° to the white band were formed. In this research, the white band is called white microstructures and the vertical stripes are called plate microstructures. Next, at a depth of approximately 0.25 mm, and at an angle of approximately 30° in the direction of weight load movement, one type of white microstructures called striped microstructures appeared.

The right side of Fig. 2 shows the distribution in the depth direction directly below the rolling contact surface of the shear stress τ_{st}. τ_{st} is the shear stress working in the direction 45° to the rolling surface. At the depth of the maximum shear stress, the changes in microstructure are the most remarkable. From this fact, the formation of the peculiar microstructure can be considered to be caused by the concentration of strain and the accompanying heat that is generated.

Fig. 2 is a photograph of the radial cross section (C cross section) of the test piece. These are flat surfaces parallel to the roller surface. In other words, **Fig. 3** shows the Z cross section for the depths viewed from the surface. The hatched zone in the test piece shown at the right side of Fig. 3 is the observed surface. Looking at Fig. 3, you can see that peculiar microstructures have vertical bands in the direction of the weight movement at each depth and that

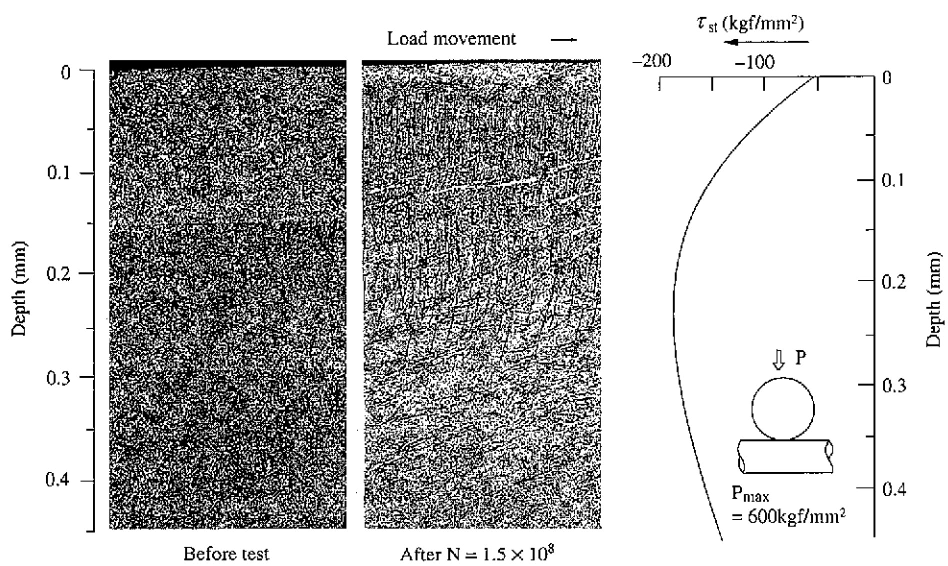

Fig. 2 Relationship between the changes in microstructure during the rolling contact fatigue process and the distribution of shear stress

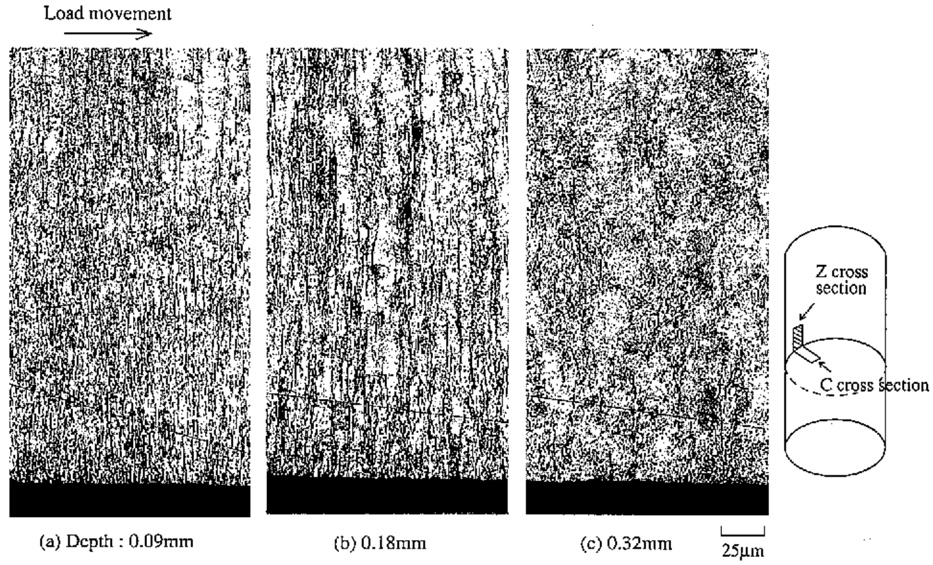

Fig. 3 Microstructures at the rolled surface directly below the rolling surface and the planar surface (Z cross section)

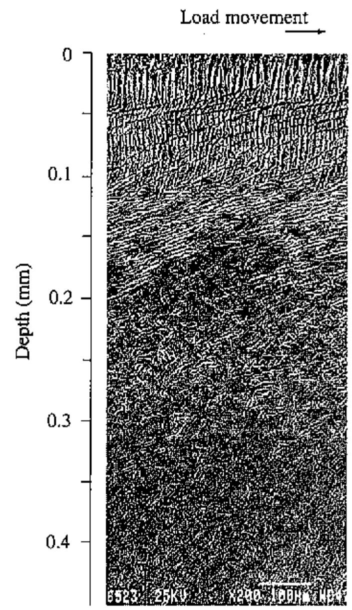

Fig. 4 SEM microstructure directly below the rolling surface that appeared by electrolytic etching (rolling contact fatigue cycles $N = 1.5 \times 10^6$)

each of them is a three-dimensional plate.

Fig. 4 is an SEM photograph where electrolytic etching was performed using the SPEED method on the cross section directly below the rolling contact surface in the same way as in Fig. 2. Minute precipitants were found in either the plate microstructures, stripe microstructures or near the white microstructures. **Fig. 5** shows an expanded photograph of the plate microstructures as one example. These consisted of concave and convex microstructures, and the authors observed minute precipitation at the convex areas. Fe and C were detected in the AES analysis. The convex areas had more amounts of C than did the concave areas and these precipitants were considered carbides.

Fig. 6 is the observed results with TEM using the extraction replica method for the precipitants of the region in Fig. 5. The results of the electron diffraction analysis could be indexed through

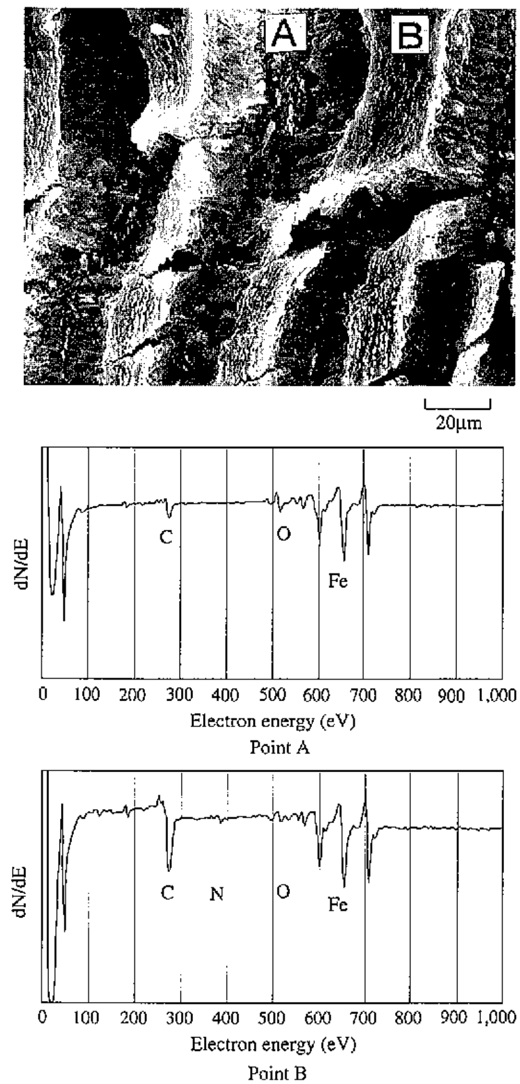

Fig. 5 AES spectrum of the peculiar microstructure at a depth of 0.08 mm directly below the rolling surface

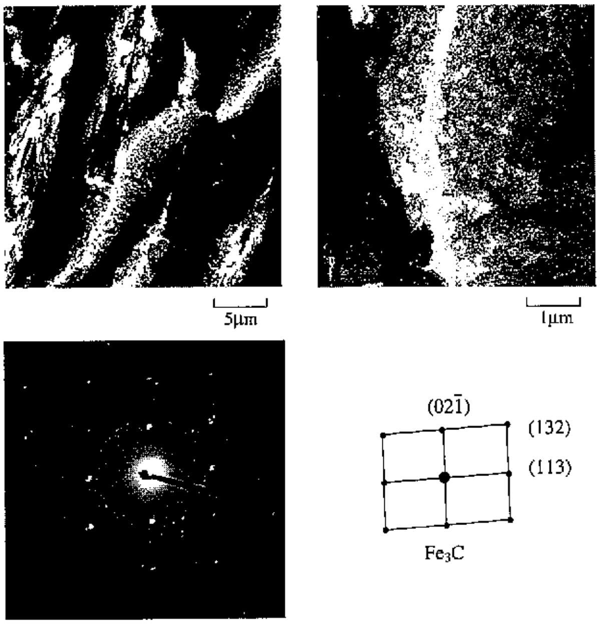

Fig. 6 TEM photograph and the electron diffraction pattern of the minute precipitation in the peculiar microstructure

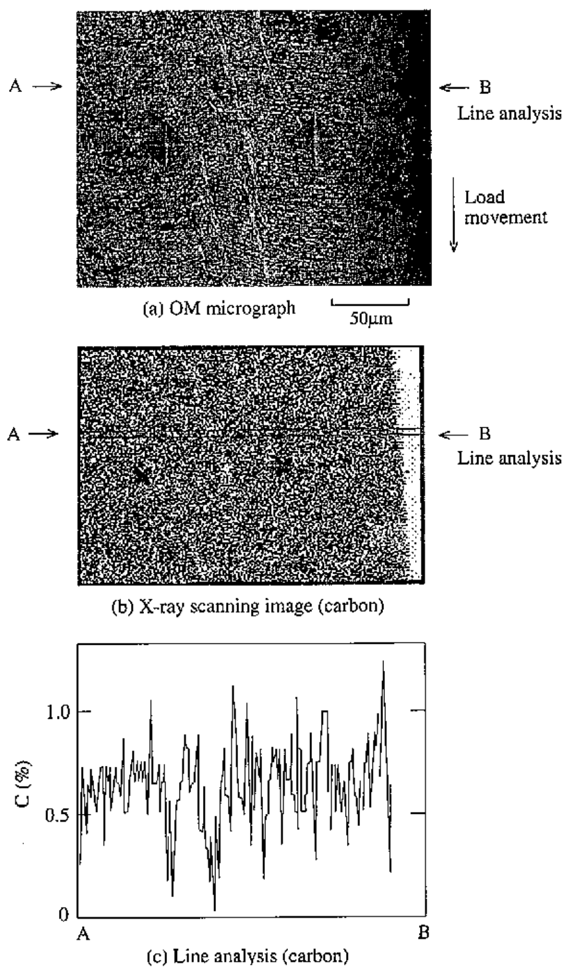

Fig. 7 Analysis of the distribution of carbon density near the white microstructures by EPMA

Fe_3C. In other words, these minute microstructures were cementites. From the above, it can be said that plate microstructures and striped microstructures are a pseudo-pearlite phase that accompanies the precipitation of cementite. Also, there is the suggestion of heat generation above 300°C directly below the rolling contact surface from the precipitation of cementite as in Fig. 6.

Next, the causes of white microstructures were investigated. The photograph of **Fig. 7** (a) is the observed with an optical microscope; and (b) is the result of investigation of the distribution of C using EPMA on the area of (a). The areas marked × in the photograph of (b) correspond to the depression traces of the Vickers hardness meter in the photograph of (a). There were three large white microstructures and there was a decrease in C concentration at the white microstructures. It is shown in (c) the line analysis result of C concentration along the A-B line in the photograph of (a). While in the matrix, the C amount was 0.8%, it had decreased to below 0.1% in the white microstructures.

Fig. 8 is the result of the investigation of the hardness near the white microstructures. The hardness of the A-B line in the above photograph is shown in the figure below. The hardness of the matrix was approximately 750 in HV while the hardness of the white microstructures had softened to approximately 600. In view of the above, the white microstructures were considered the ferrite phase generated by the removed carbon. Considering that white microstructures were ferrite, it's hardness was too high. It is considered that it is caused by hardening due to the strain concentration.

3.2 Changes of the microstructure and material quality in the rolling fatigue process over time

Changes in the microstructure and material quality over time

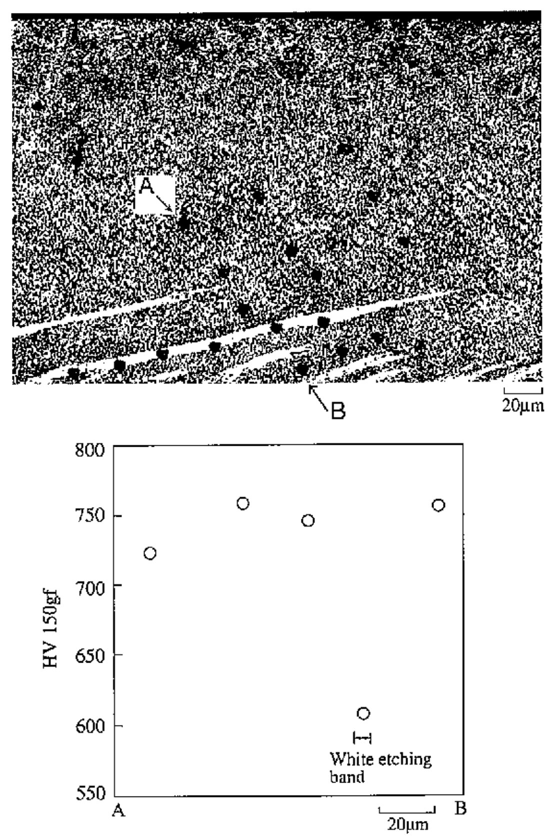

Fig. 8 Hardness distribution near the white microstructures

were investigated using SUJ2. **Fig. 9** shows the microstructure directly below the rolling surface before the rolling fatigue test and at each stage during the rolling fatigue test. After 10^6 times rolling contact fatigue, microstructure were slightly blackened. Except for that point, there was no great difference in the microstructure between before the rolling contact fatigue test and after 10^6 times rolling contact fatigue. After 10^7 times rolling contact fatigue, a plate microstructure at an angle of approximately 90° to the direction of the movement of the weight up to a depth of 0.1 mm and a stripe microstructure at an angle of approximately 30° with a depth of 0.2 mm appeared. Also, after 10^8 times rolling contact fatigue, plate microstructures further deepened and stripe microstructures up to a depth of 0.2 mm advanced to white microstructures and were inclined approximately 20°. Also, at a position deeper around 0.3 mm, stripe microstructures appeared at a depth of 0.2 mm after 10^7 times rolling contact fatigue.

From the above, it is considered that the concentrated sheer strain and the accompanying heat that is generated created the stripe microstructures which is the pseudo-pearlite phase, then carbon is dispersed and white microstructure are formed by the progression of ferrite bands. Also, the microstructure after 10^8 times rolling contact fatigue showed the same microstructure as the carburized steel shown previously. There was no difference to the microstructural changes with the carburized steel and the bearing steel SUJ2.

Next, the macro material quality changes over time were investigated using SUJ2. **Fig. 10** shows the hardness distribution that was measured at the C cross section of the test piece. The hardness before the test was substantially the same in the depth direction and approximately 800 in HV. When a rolling fatigue test was performed, at a depth of 0.2 mm where shear stress was at its greatest, it became hard once after 10^6 times rolling contact fatigue and later decreased. Increase in hardness to 10^6 times was inferred to be caused by the decomposition of austenite and precipitation hardening due to the minute carbide precipitations.

Fig. 11 shows the result of the measuring the half-widths of the X-ray diffraction peaks corresponding to the density of the dislocation as an index to net hardness. The change of the half-width over time was also most notable at a depth of approximately 0.2 mm from the rolling surface but it decreased uniformly in the fatiguing process differing from the hardness. In this way, the half-width is expected to correspond to net hardness, but the changes over time in half-widths were slightly different from hardness. Since the influence of residual stress is included in hardness, it is presumed that the net material quality characteristics are represented

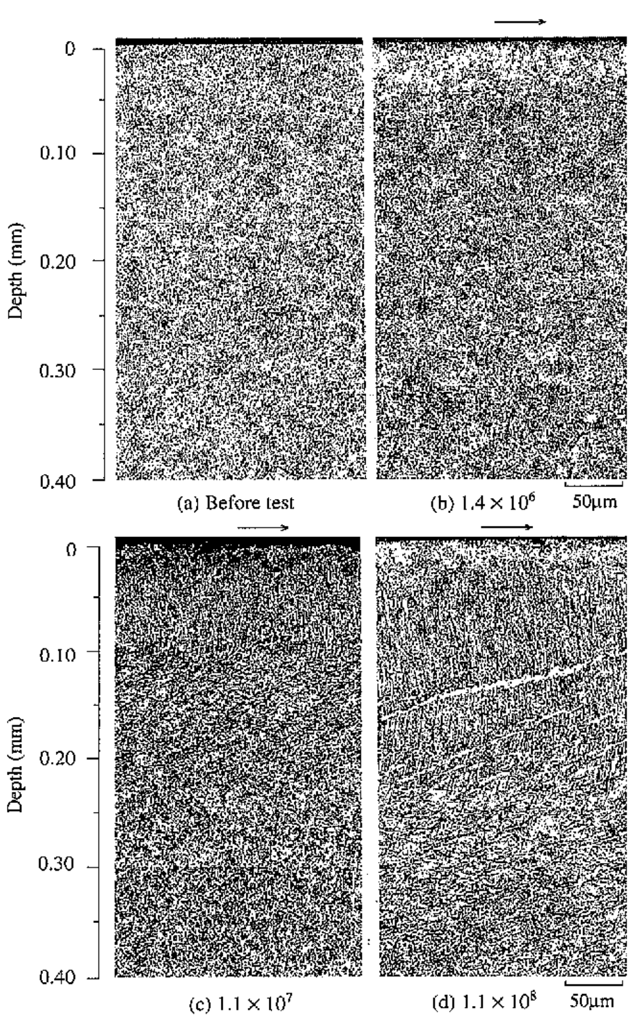

Fig. 9 Relationship of the number of cycles and the microstructure directly below the rolling surface

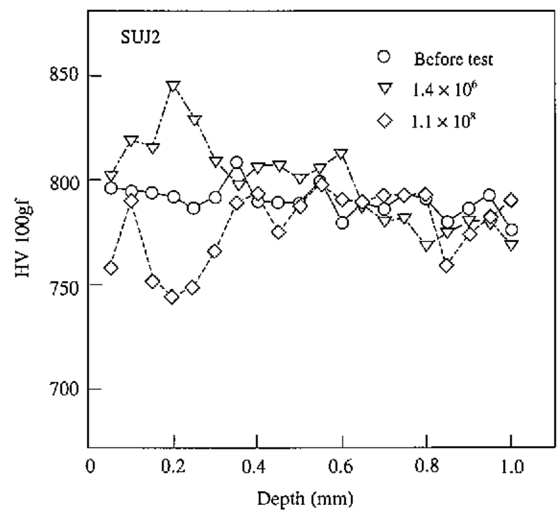

Fig. 10 Changes in hardness distribution during the rolling fatigue process

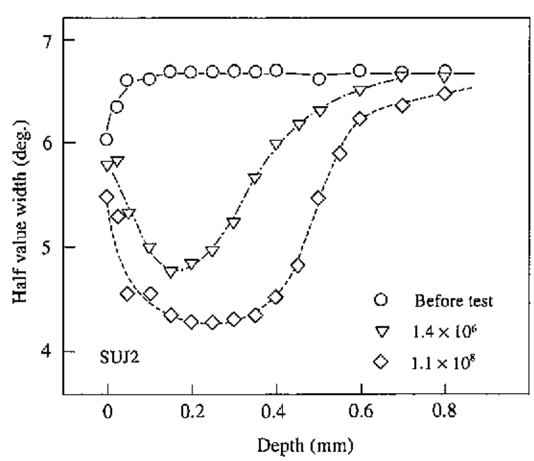

Fig. 11 Changes in distribution of half width of the X-ray diffraction peak during rolling contact fatigue process

in half-widths rather than hardness.

Fig. 12 shows the distribution in the depth direction of residual stress and retained austenite amounts. In the rolling fatigue process, at a depth of 0.2 mm where shear stress is greatest, a great compression of the residual stress occurs. Also, a decrease in the amount of retained austenite is notable at the same position. However, the amount of retained austenite in SUJ2 before testing was low at a level of 4%.

3.3 Presumption of heat generated at the rolling fatigue process

As an index of the half width shown in Fig. 11, to what degree the temperature rose during the rolling fatigue process was studied. **Fig. 13** shows the half-widths of the X-ray analysis peaks of tempered specimens, which were maintained at each tempering temperature for 0.5 hours corresponding to the repetitions of 10^6 times and for 40 hours corresponding to 10^8 times, by the temperature. The circles represent maintaining for 0.5 hours. Along with the rise of the tempering temperature there was a flat decrease in half-width. However, at maintaining for 40 hours, there was a decrease of 0.5 to 1 degree compared to that of the 0.5 hours even at the same tempering temperature. From Fig. 13 and 11 the ultimate temperature at each position in the depth direction was estimated. For example, the half-width was 4.3 degrees at a depth of 0.2 mm for material that was rolling contact fatigued 10^8 times. The half-width

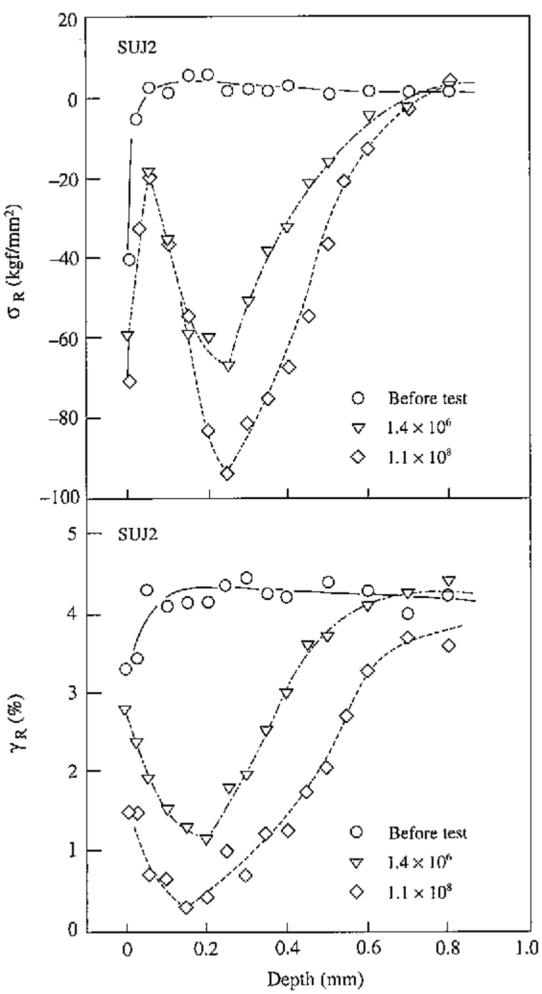

Fig. 12 Changes in distribution of residual stress and retained austenite amounts during rolling contact fatigue process

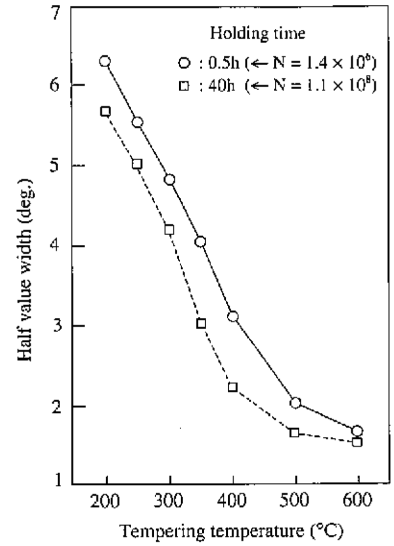

Fig. 13 Relationship of the tempering temperature and the half width of the x-ray diffraction peak of SUJ2

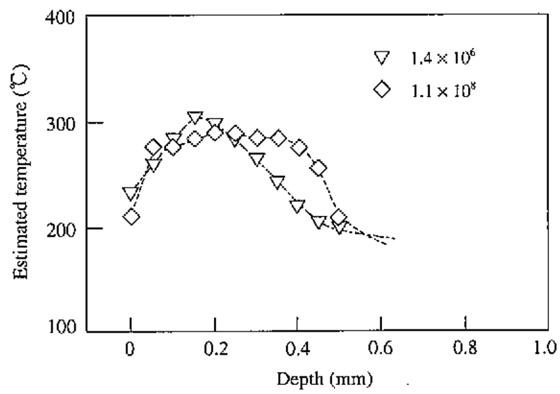

Fig. 14 Temperature distribution directly below the rolling contact surface estimated by the half width

that was 4.3 degrees at tempering with maintaining for 40 hours corresponding to 10^8 times was when the tempering temperature was 300°C from Fig. 13. Therefore, the ultimate temperature in this case was estimated to be 300°C.

In the manner above, the ultimate temperature was estimated from the equivalent temperature by tempering for the same half width. The result was that the macro temperature distribution is as shown in **Fig. 14** and the temperature rose to the level of 300°C at the depth of 0.2 mm where shear stress is at its maximum. Also, this is an estimation of the ultimate temperature at the macro region and it means that the local temperature rose to more than 300°C. This matches the situation with the experiment in which peculiar microstructure accompanied the precipitation of cementite.

Next, to what degree did the temperature rise locally in the region generating the white microstructures was studied. **Fig. 15** shows a comparison of peculiar microstructures at a depth of 0.25 mm directly below the rolling surface in the rolling fatigue process and the microstructure of tempered specimens under varying temperatures and times. In the rolling fatigue process, stripe microstructures appeared after 10^7 times rolling contact fatigue and when contact fatigued 10^8 times, white microstructures were developed. However, maintaining for 4 hours corresponding to contact fatigue

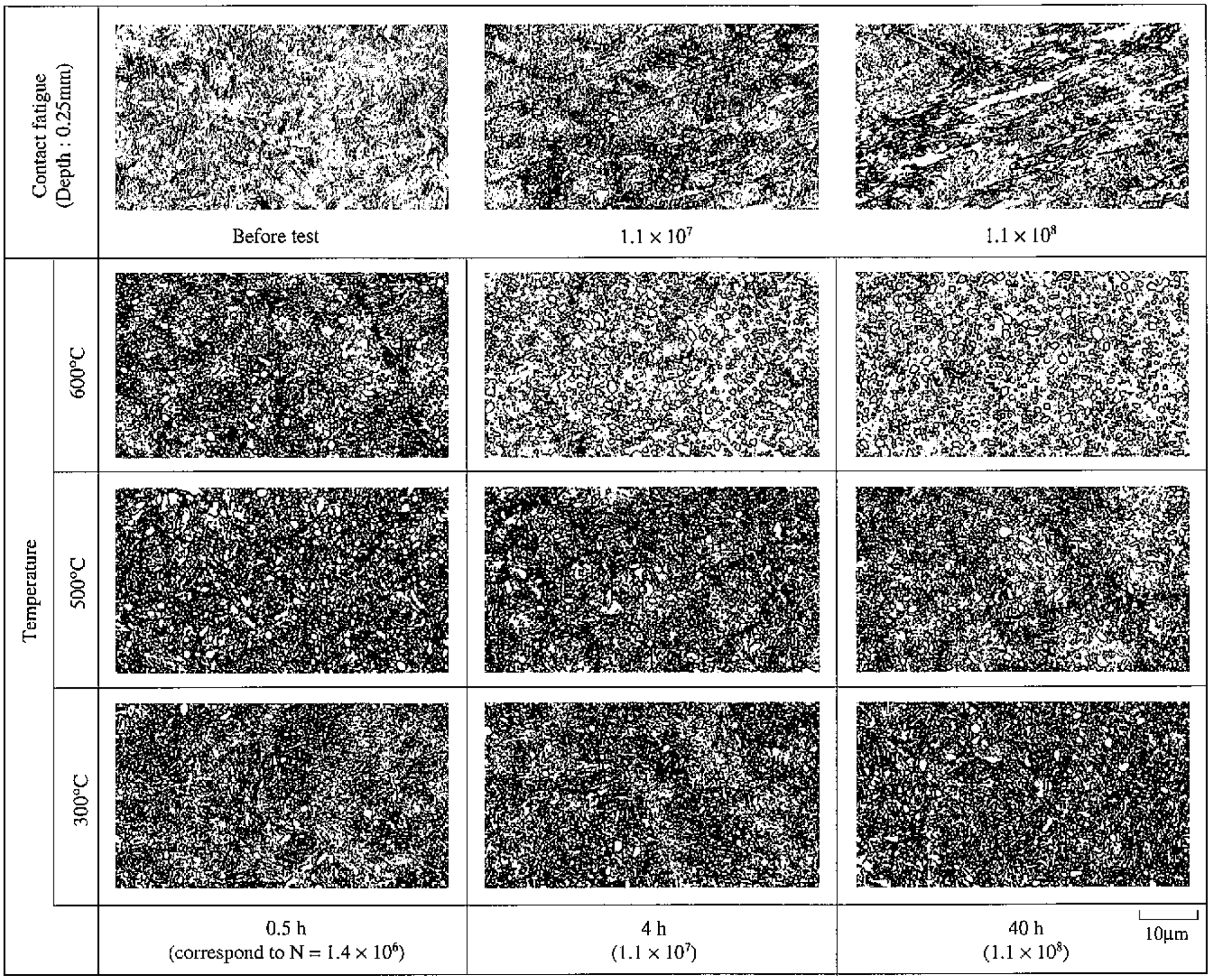

Fig. 15 Comparison of changes in the microstructure during the rolling contact fatigue process and tempering process

of 10^7 times at 300°C and even for 40 hours corresponding to contact fatigue of 10^8 times, there was substantially no change in the microstructure. The temperature was raised to 600°C and maintained for 40 hours where a white ferrite phase became clear. From the above, the macro ultimate temperature is approximately 300°C as shown before, but when the temperature rose to above 600°C locally, it is considered that white microstructures were formed.

4. Conclusion

The following points have been clarified by investigating and analyzing the changes in material quality that accompany the generation of peculiar microstructures in the rolling contact fatigue process of steel used for bearings.

1) In the rolling contact fatigue process, at the depth where shear stress directly below the rolling surface is at its maximum, plate microstructures at approximately 90° to the direction of the movement of the weight and white microstructures and stripe microstructures at approximately a 30° are generated. The white microstructures are ferrite and the plate microstructures and stripe microstructures are a pseudo-pearlite accompanying the cementite. Stripe microstructures shift to white microstructures with the rolling contact fatigue process.
2) There was a notable decrease in the half-width of the X-ray diffraction peak equivalent to the net hardness at the fatigue process at a depth where shear stress was at its maximum.
3) It is inferred that microstructures with the above fatigue process and the changes in the material quality occur with the concentration of shear strain and the heat which is generated. It is inferred that the ultimate temperature was at the level of 300°C in the macro and that the temperature is more than 600°C locally in the region in which white microstructures are formed.

The environment in which bearings are used is increasingly severe with high contact stress and environments which contain foreign matter (dirt, etc.) and high temperature environments, so it is predicted that there will be even more influences on the changes in microstructures which affect the longevity of rolling fatigue. In the future, it will be important to make efforts for high longevity with an focus on changes in microstructure.

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