Observation of rolling contact fatigue cracks by laminography using ultra-bright synchrotron radiation

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Abstract

Micro computed laminography imaging using ultra-bright synchrotron radiation (SRCL) was applied to the observation of flaking defects under rolling contact fatigue (RCF) of a high strength steel. Specially fabricated inclusion rich steel plate specimens were employed for the experiments. RCF fatigue tests were carried out near the measurement hatch of SRCL for successive observation of crack initiation and growth behaviors. Specimens before and after the initiation of flaking were observed by SRCL, and the flaking defects and cracks under the surface were successfully detected. The shape and location of RCF crack obtained by SRCL imaging were almost coincident with those obtained by SEM, and detail process of crack initiation and flaking in RCF process can be discussed.

Keywords: Rolling contact fatigue; laminography; ultra-bright synchrotron radiation; 3D imaging

1. Introduction

In rolling contact fatigue (RCF), cracks are usually initiated from inclusions under the surface, and they propagate to form a flaking (Murakami (1988), Goshima (1988)). Although non-metallic inclusions are known to have a detrimental effect on fatigue performance of high strength steels, commercial production of steels with very high cleanliness is unrealistic because of high-cost. Then, it is plausible to control the concentration and size of inclusion to obtain better performance of steels. Especially in bearing steels, inclusions have complex shapes and are often lined up, thus forming so-called stringers, and the effects of shape and distribution of inclusions on RCF should be taken into account. The phenomena under the surface cannot be observed by conventional microscopes, such as optical microscope and scanning electron microscope, and it is difficult to observe the fracture surface of
flaking because flaking area is damaged by rolling steel ball after its emergence. Therefore, the effect of the configurations of inclusions has not been systematically investigated yet.

To discuss the mechanism of RCF crack initiation under contact surface, Grabulov and Zandbergen et al. (2007) investigated the crack initiation around inclusions by dual beam (scanning electron microscopy (SEM)/focus ion beam (FIB)) technique. Since this method is destructive, the crack propagation behavior is difficult to observe, then the synchrotron radiation micro computed tomography imaging (SRCT) has been applied as nondestructive inspection (Gondrom, et al. (1999)). Stiénon et al. (2009, 2010) calculated the stress field around the non-metallic inclusions in bearing steels under RCF tests using 3D shapes obtained by SRCT, which was conducted at European synchrotron radiation facility, ESRF. The authors applied SRCT imaging to the observation of sample with flaking damage and RCF cracks (Shiozawa et al. (2012), Makino et al. (2012)). In their studies, samples were cut from a normal size RCF specimen to include the damage, and the 3D imaging of damage before flaking provided the useful information about RCF crack initiation and propagation process. To investigate the effect of the shape of inclusions on the crack initiation, the artificial defects, which simulate a stringer shaped inclusion, were introduced in the specimen, and the crack initiation and propagation from the artificial defects were observed. In SRCT imaging of successive observations in RCF process, sizes of sample has to be small enough to allow transmission of X-ray, and the size of cross-section must smaller than 500 μm × 500 μm. Our previous study, however, showed that the mechanism of RCF in small sample is different from that in bulk sample. Then, the synchrotron radiation computed laminography (SRCL) is applied, which allows high-resolution non-destructive imaging for thin plates. This method provides a unique means to observe 3D shape of micro-structures and cracks in thin plate.

In this study, SRCL imaging is applied to the observation of inclusions and RCF crack in a bearing steel. A compact RCF testing machine, which enables RCF tests and SRCL observation alternatively, was developed, and the crack initiation and propagation behaviors are discussed.

2. Material and experimental procedure

2.1. Material

The material for the present study is a bearing steel (modified JIS SUJ2), whose chemical composition (in mass %) is as follows: 1.00C, 0.35Si, 0.47Mn, 0.006P, 0.017S, 1.50Cr, and balance Fe. The material has intentionally contains high concentration of sulfur for the observation of crack initiation from MnS inclusion. It was forged from ingot with diameter of 65 mm, and inclusions are intergranular with a preferential alignment along the forging direction. After the spheroidizing annealing, specimens were cut from the forged bar, where the transverse cross section of the bar corresponds to the contact surface of specimen. The specimen was quenching at 1103 K for 0.5 h and tempered at 453 K for 2 h. The dimension of the specimen for SRCL imaging is 10 mm in width, 24 mm in length and 0.4, 0.5, or 1 mm in thickness. The thickness of the specimen was determined to allow transmitted X-ray with enough intensity for CT imaging. The
plates with thickness of 0.4 or 0.5 mm are for beam line BL19, and that of 1.0 mm are for beam line BL46XU.

2.2. Rolling contact fatigue test

To conduct rolling contact fatigue test for thin plate nearby the experimental hatch of beam lines of the synchrotron radiation facility, SPring-8, a special testing machine was developed. The schematic illustration of the new RCF testing machine is shown in Fig. 1. The developed testing machine is ball-on-disk type contact tester. In this testing machine, reciprocal sliding motion is generated by a liner guide and an eccentric cam, and then the steel ball rolls on the specimen linearly and reciprocally, unlike the Mori type rolling contact fatigue testing machine in which rolling is in a single direction. For observations of the crack initiation and propagation behaviors, fatigue tests were interrupted to conduct SRCL imaging. In this developed testing machine, a sample can be attached and removed easily. The size of the bearing steel ball was 6 mm in diameter. The sliding distance of this testing machine was 3 mm.

Since RCF crack initiation cannot be identified from the surface, crack depth measurement instrument (RMG 4015, KARL Deutsch) was employed to detect the sign of crack initiation for efficient measurement of SRCL. This instrument employs the electrical potential method with alternating current (Nakai and Wei (1989)). The principle of this method is based on the measurement of electrical resistance between two points in a sample. The change of electrical resistance, however, depends not only on depth but also morphology of crack. The employed instrument calculates the crack depth by assuming that its face is perpendicular to the free surface. Although the morphology of RCF cracks is complex, and the crack depth measured by this instrument is not actual but apparent value, the change of output of this instrument, which is displayed as “crack depth”, is considered to correspond to the change of morphology (or initiation) of RCF crack. Therefore, RCF crack initiation and propagation under the surface may be able to be detected.

2.3. Measurement setup

The measurement of SRCL imaging was carried out at BL19B2 and BL46XU beam lines of Spring-8, which is the brightest synchrotron radiation facility in Japan. The source of X-ray beam at BL19B2 and BL46XU are bending magnet and anerator, respectively. The brightness of BL46XU is higher than that of BL19B2. Figure 2 shows SRCL imaging apparatus. The axis inclination angle for the laminography, $\phi$, was 30°, and a monochromatic X-ray beam with 37 keV was employed. In the present study, the effective voxel sizes in the reconstructed 3D image were 0.74 $\mu$m and 1.48 $\mu$m for the measurements in beam lines BL46XU and BL19B2, respectively. For 3D reconstruction, a set of 720 radiographs of a specimen were recorded over 360° rotations, where each rotation angle was 0.5°. The exposure time was 6 s and 0.5 s for the measurements at BL19B2 and BL46XU, respectively. To utilize the phase contrast
effect, the X-ray area detector was set by 0.35 m behind the sample for either beam lines. Once reconstructed, the 3D images have been visualized using software, Image-J and Amira. For 3D damage (inclusions and crack) representation, a simple gray value threshold was used to segment damage, where gray value threshold between matrix and air was employed to produce binarized 3D images.

3. Experimental results

S-N curve for the specimen with thickness of 0.5 mm is shown in Fig. 3, where solid marks indicate the results of specimens whose rolling contact surface was polished but the back surface was left as machining. Open marks indicate the results of the specimens in which both surfaces were polished. The fatigue life for the latter specimens is longer than that for the former.

To investigate the applicability of SRCL to the observation of RCF cracks, 0.4 mm thick specimen with flaking was observed. SRCL images are shown in Fig. 4, which was measured in beam line BL19B2. Figure 4 (a) indicates the cross-section parallel to the contact surface and 0.14 mm deep from the surface, and Figure 4 (b) shows the lateral-sectional image along A-B line in Fig. 4 (a). The RCF cracks under the surface can be detected. To confirm the shape of these cracks, the side of specimen was machined, and 2D shapes of the cracks were observed with scanning electron microscope (SEM). Figure 5 shows a comparison between SRCL imaging and SEM observations at the same site. The shape and location of cracks obtained by SEM almost coincided with that by SRCL imaging. It proves that the RCF cracks in planar specimen could be identified by SRCL using BL46XU beam line.

To examine the initiation and propagation behavior of RCF cracks, fatigue tests were interrupted at several loading cycles. The change of apparent crack depth measured by the potential method is shown in Fig. 6, where not the values but the change of them is significant. Figure 6 indicates that the measured value of the apparent crack depth increases with increasing loading cycles after $N=1.0 \times 10^6$ cycles. It means that the apparent crack depth measured by the potential method provides some information about appropriate time to SRCL imaging. Figure 7 shows the SRCL images obtained by beam line BL19B2. SRCL image shown in Fig. 7(a) was obtained at $N=2.0 \times 10^5$ cycles when no crack was detected by the potential method, and that in Fig. 7(b) was obtained at $N=3.0 \times 10^5$ cycles when measured apparent crack depth increased, but before flaking. Figure 7(c) shows an image after flaking ($N=9.0 \times 10^5$ cycles). In Fig. 7, the shapes of cracks in cross-section are also presented at the bottom of each figure. Figure 7(a) shows that a vertical crack is formed from the back surface, and it propagated parallel to the sliding direction. In this case, the apparent crack depth measured by the potential method did not increase. In Fig. 7(b), the inclined cracks are formed under the surface and locates upper half of the specimen. Since these inclined cracks were rarely connected to the vertical cracks from back surface, they must not be formed from the vertical cracks. In Fig. 7(c), cracks exist between inclined cracks, and these cracks grow to form flaking. Since the vertical cracks were first formed at back surface, they may affect the initiation and propagation of inclined crack near the rolling contact surface.

To prevent the crack initiation at the back surface, it was also polished to reduce surface roughness. The fatigue life of this specimen (thickness: 0.5 mm) was extended at the same contact stress, but cracks were also initiated at the back surface before flaking. The crack initiation from the back surface may have taken place by the cyclic tension stress at the back surface, which was induced by cyclic contact loading. To reduce the cyclic tensile stress at
Since brighter X-ray source is required for the specimen with the thickness of 1.0 mm, SRCL is carried out in another beam line BL46XU with higher brightness. Figure 8 shows the SRCL images obtained by beam line BL46XU for 1.0 mm thick specimen with flaking, where a crack can be detected under the surface.

Successive SRCL imaging and RCF test were carried out. SRCL images obtained by this test are shown in Fig. 9, where (a) is at \( N = 3.0 \times 10^6 \) cycles, (b) is at \( N = 5.0 \times 10^6 \) cycles. Cracks initiated from inclusions can be observed by
the SRCL imaging. These cracks propagate in a direction perpendicular to the contact surface, e.g., a vertical crack extended with loading cycles as indicated by dashed line in Fig. 9. Vertical cracks, those are formed along an artificial hole, which simulates stringer shaped inclusion, were also observed in our previous observations (Shiozawa et al, 2012). These results indicate that the vertical cracks affect the initiation and growth behaviour of the parallel cracks, which derive by shearing stress and grow to the flaking (Makino et. al. (2012)). Because of the time limitation to use the beam line, further observations could not be conducted for this specimen, but important information about RCF crack initiation and propagation behaviours have been obtained, and we shall discuss about the influence of vertical crack and 3D shape of inclusion on the RCF quantitatively in near future.

4. Conclusion

Synchrotron radiation computed laminography (SRCL) was applied to the observation of rolling contact fatigue cracks in high strength steel, and the following results were obtained

(1) To observe RCF crack and inclusions in a plate specimen, SRCL imaging was carried out at BL19B2 and BL46XU beam lines of SPring-8, which is the brightest synchrotron radiation facility in Japan. Cracks, which existed under the contact surface, could be detected with high resolution.

(2) For plate specimen with thickness of 0.5 mm, cracks were initiated at the back side of the contact surface, which affected the RCF crack initiation and propagation behaviors. The crack initiation at the back surface could be prevented by using specimen with thickness of 1.0mm.

(3) RCF test by a newly developed compact RCF testing machine and SRCL imaging were carried out successively to observe the crack initiation and propagation behaviors. In the experiments, vertical cracks along inclusion were observed, and these cracks were considered to be formed in the early stage of RCF life, and they affected the crack propagation behavior of the RCF.

(4) SRCL imaging is a powerful technique for elucidating the crack initiation and propagation behaviors of RCF.

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References


