Observation of fatigue crack propagation in laser-peened aluminum alloy by computed tomography with synchrotron radiation

Fatigue is a major cause of reduced structural integrity, and fatigue fracture usually starts from the surface of components. Therefore, various technologies have been developed to enhance surface properties, and laser peening is an emerging technology that effectively prolongs the fatigue life of structures [1]. However, it is not thoroughly understood how these technologies work on resisting fatigue because of the difficulty in directly observing fatigue cracks propagating inside opaque materials. To overcome this situation, we have made an ambitious challenge to visualize fatigue cracks inside materials and their propagation by computed tomography (CT) with synchrotron radiation [2]. Even if we utilized CT, we could not expect a clear image of fatigue cracks since they are almost closed without external loading. After attempting to open a fatigue crack with a newly devised specimen holder to obtain a clearer image without obstructing X-ray paths, we performed imaging experiments of fatigue cracks developing inside materials.

The holder was introduced on a rotation stage at beamline **BL19B2**, as shown in Fig. 1. The holder keeps a fatigue specimen and controls the tension load on it to slightly open the fatigue crack, which could enhance the contrast of the crack image. The specimen is pulled using a driving nut on a tension bolt at the top of the holder without torsion on the specimen. The load is measured with a compact load cell placed between the tension bolt and the specimen. The reacting compression load is supported by a thin pipe of polycarbonate, which is almost transparent for high energy X-ray. The holder is equipped with a dummy pipe under the specimen, which is used to compensate for the slight absorption by the pipe by substituting the background collected through the dummy pipe. While the holder or supporting pipe is outside the reconstructed area, the quality of the images is not affected because of the concentric arrangement of the supporting pipe with the axis of the rotating motion.

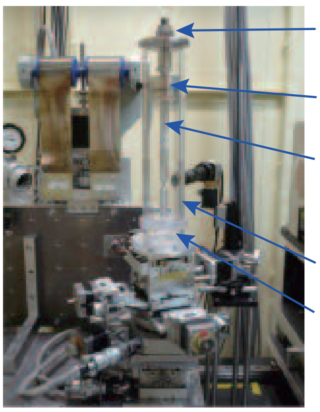


Fig. 1. Specimen holder on a rotation stage at BL19B2 for CT experiment.

Figure 2 shows the reconstructed image of a fatigue crack in a specimen of AC4CH cast aluminum alloy under different tension loads of 0 and 40 MPa. White shadows are the 2D expressions of the 3D image of the fatigue crack projected onto a plane perpendicular to the axis of the specimen. The imaging conditions are almost the same as in the previous study [2]: White X-ray from a bending magnet was monochromatized by a silicon double-crystal and the energy was adjusted to 28 keV. The distance between the specimen and an X-ray area detector was set to 0.8 m to incorporate the phase contrast effect into the image. A series of 2D slice images were reconstructed by convolution back projection algorithm, and the 3D image was retrieved by stacking the 2D slice images sequentially. The fatigue crack developed from a small drilled hole that is intentionally made to control the crack initiation position. The image of 40 MPa tension load is clearer than that of 0 MPa, suggesting the crack opening as expected and the enhancement of the image due to phase and/or absorption contrast. The crack image would not change in shape or size even with increasing the tension load onto the specimen beyond 40 MPa, and the crack length on the surface deduced from the image agreed well with the surface observation. These results imply that the crack front could be most likely determined by controlling the tension load.

It is self-evident that defects inside the material could not be detected by external observation such as replication method or optical microscopy. Actually, we could not identify the defects through external observation; however, CT revealed an internal defect as indicated by the arrow in Fig. 3 [3]. It happened that the defect existed just below the surface. The fatigue crack is clearly visualized as well, showing the propagation from the defect with the increase in the number of fatigue loading cycles of 160 MPa stress amplitude. Figure 4 is a replica of the surface covering the position of the internal defect, which of course

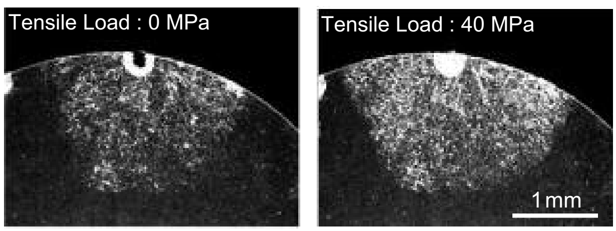


Fig. 2. Images of a fatigue crack under different axial tensile loads.

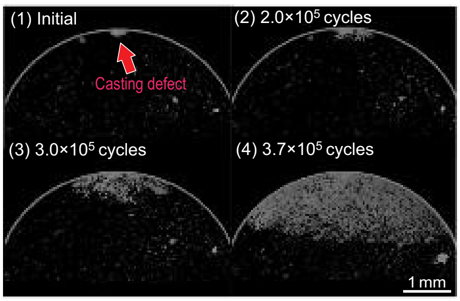


Fig. 3. Propagation of a fatigue crack from a defect beneath the surface.

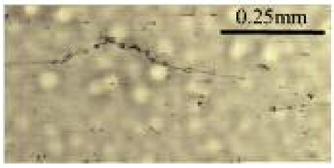


Fig. 4. Replica of the fatigue crack appearing on a surface at 1.5×10^5 loading cycles.

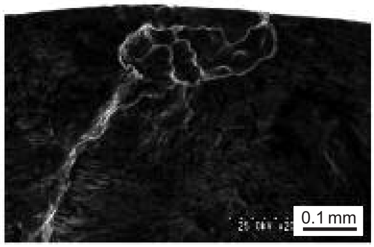
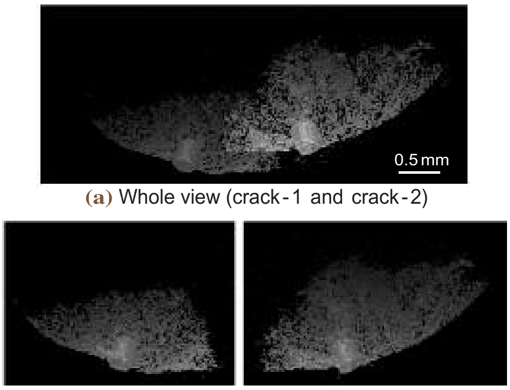


Fig. 5. SEM image of the defect on the fracture surface.

could not be observed on the replica. Figure 5 is a SEM image of the fractured surface of the specimen, showing a casting defect near the surface, which agreed with the results in Fig. 3. The inside defect and fatigue crack developing from the defect were successfully observed [3], which is the world's first 3D imaging of a fatigue crack developing from an inside defect, to the best of our knowledge.

The experiment was extended to evaluate the interference between two fatigue cracks closely located on a specimen. The two cracks were generated and propagated by fatigue loading with a stress amplitude of 120 MPa from two drilled holes separated by 0.5 mm axially and 30° azimuthally. Laser peening was applied to the specimen just before the overlapping of the two cracks. Then, additional 10^5 fatigue cycles were loaded to the specimen with a stress amplitude of 220 MPa because at a lower stress amplitude the cracks would not sufficiently propagate on the specimen toughened by laser peening within the available time of the experiment. The reconstructed 3D image of the cracks is shown in Fig. 6. Here, the surface of the specimen was deleted from the image. Figure 6(a) shows the entire view of the two cracks in a manner where the axis of the specimen is tilted by 30°. It is found that the drilled holes are distorted in shape to some extent, suggesting that the surface layer of the specimen deformed plastically by laser peening. The shape of the cracks is different from semi-ellipsoidal probably because of the interference between cracks and/or residual stress induced by laser peening. The two cracks can be divided virtually as shown in Figs. 6(b) and 6(c), which allows us to evaluate each crack separately and precisely. Such treatment would be hardly conceivable without utilizing the benefit of CT.

Computed tomography (CT) was performed for cast aluminum alloy AC4CH specimens at BL19B2. Taking advantage of highly parallelized synchrotron radiation, fatigue cracks and the propagation inside the specimens were successfully visualized by incorporating the edge enhancement arising from phase contrast. The results are summarized as follows: (i) The crack front was identified by introducing a newly devised holder and controlling the tension load on the specimen. (ii) The growth of a fatigue crack from an internal defect was visualized, which could not be attained without CT and is greatly expected to elucidate the mechanism of giga-cycle or ultrahigh-cycle fatigue, since the internal fracture is the major cause of the failure in the giga-cycle regime. (iii) The 3D shape of fatigue cracks was determined, which contributes to the verification and advancement of fracture mechanics, especially on FEM analysis.



(a) Whole view (crack-1 and crack-2)

(b) Crack-1 (c) Crack-2

Fig. 6. Three-dimensional images of fatigue cracks on a laser-peened specimen.

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References

[1] Y. Sano *et al*.: Mat. Sci. Eng. A **417** (2006) 334.
[2] Y. Sano and K. Masaki: SPring-8 Research Frontiers 2006, p.151.
[3] *K. Masaki, Y. Sano, Y. Ochi, K. Akita and K. Kajiwara: J. Sol. Mech. Mat. Eng.* ***2*** *(2008) 1104.*