Three-dimensional Imaging of Fatigue Cracks by Microtomography with Refractive Contrast Effect

Fatigue is a major cause of failure in structural components in many industrial fields. To suppress the undesirable failure and prolong the service life of products, the exploration of durable materials and process technologies is carried out, together with the development of testing procedures. X-ray computed tomography (CT) developed for medical diagnosis currently plays a key role in the nondestructive evaluation of materials. It utilizes X-ray attenuation passing through materials and offers three-dimensional (3D) information on the internal structure. Synchrotron radiation can feature another characteristic of the interaction between X-ray and materials, i.e., phase shift, as a sensitive index. It is well known that the effect of the phase shift appears as a refractive contrast on projection images, which remarkably enhances the edge of an object by setting a detector apart from the object.

The purpose of this study is to demonstrate the applicability of X-ray CT with the refractive contrast to the imaging of minute fatigue cracks in macroscopic engineering materials. Although the cracks are tiny in the initial stage and difficult to image using the conventional X-ray CT or fluoroscopy, 3D images, however, are successfully reconstructed by the micro-CT (μCT) technique with highly parallelized brilliant X-ray of SPring-8. In addition to this purpose, the effect of laser peening, an emerging surface processing technology, which is to retard fatigue crack growth, was examined by μCT [1].

Fatigue test samples were prepared from a cast aluminum alloy, JIS AC4CH [2]. A small drill hole of 0.3 mm diameter was made at the center of each sample to initiate a fatigue crack from the drill hole. A precrack with a length of 2.5 mm was introduced on the surface of every sample by rotating-bending fatigue loading. Laser peening was applied to some of the precracked samples to impart compressive residual stress on the surface [1]. All samples were then further subjected to fatigue loading of 1×10^5 cycles. Figure 1 shows the propagation behavior of the surface cracks on the unpeened reference and laser-peened samples. Each curve was shifted in a manner where the number of fatigue cycles at the crack length of 2.5 mm became the origin of the horizontal axis. Here, the crack length was measured on the surface with an optical microscope. The cracks rapidly propagated on the unpeened samples. In contrast, on the laser-peened samples, the cracks remained unpropagated during the additional 10^5 cycles.

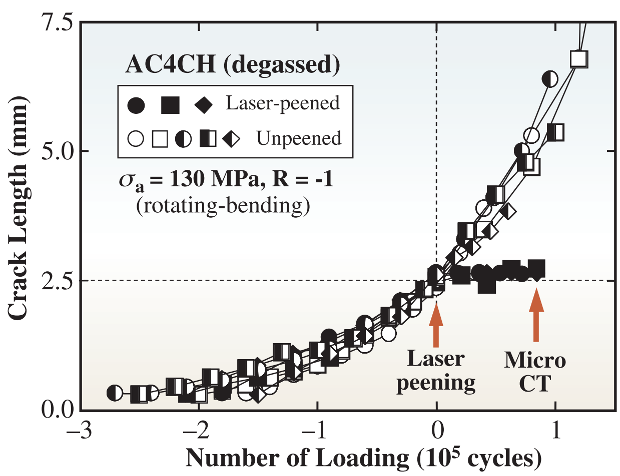

Fig. 1. Fatigue crack growth behavior.

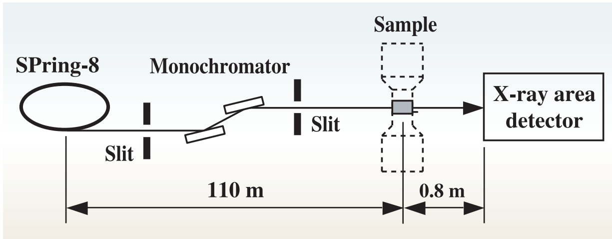

Fig. 2. Experimental setup of μCT imaging.

Imaging experiments with refractive contrast effect were performed at beamline **BL19B2**. The setup is schematically shown in Fig. 2 [1]. The X-ray energy was adjusted to 28 keV with a Si double-crystal monochromator. The distance between a bending magnet (X-ray source) and the sample was about 110 m. The area detector (cooled CCD camera) was set 0.8 m behind the sample to obtain a refractive contract effect, after the preliminary experiments in which the detector position was varied. Projection data of 1024 × 1024 was recorded every 0.5° from 0° to 180°. The effective pixel size of the detector was about 6 μm, considering the optical magnification of a relay lens after a converter. Slice images were reconstructed by a standard algorithm of filtered-back projection.

Reconstructed slice images at the elevation of the drill holes are shown in Fig. 3. The drill hole is distorted around the surface of the laser-peened sample, which suggests that a fairly large plastic deformation was induced on the surface by laser

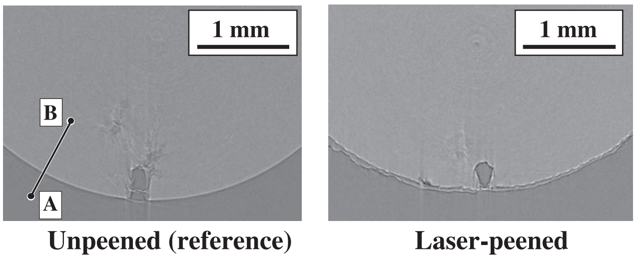

Fig. 3. Reconstructed slice images.

peening. The contrast in the images probably due to crack opening was observed near the drill hole inside the samples. The borders between the objects and surrounding air are enhanced with a pair of fine stripes in black and white. The attenuation coefficient along the line AB in the reference sample is shown in Fig. 4. Edge enhancement by refractive contrast is evident at the border of the object in the reconstructed images.

Three-dimensional images of fatigue cracks were made by extracting the crack image in each slice and then stacking them sequentially. Figure 5 shows the crack images in the unpeened reference and the laser-peened samples [1]. The shadows depicted in white might correspond to the opening of the fatigue cracks. The upper images are those viewed from the direction of the sample axis, while the lower images are those viewed from the direction perpendicular to the axis. The initial drill holes can be identified at the center of the shadows. These images well agree with the surface observation by optical microscopy and suggest that the crack growth is impeded in the case of the laser-peened sample not only on the surface direction but also toward the inside, which could not be realized without the highly parallelized brilliant

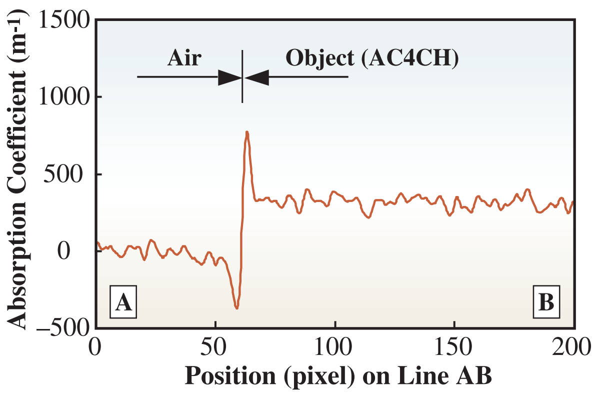

Fig. 4. Attenuation coefficient along line AB in Fig. 3.

X-ray of SPring-8. Further evaluation should be performed, taking into account the refractive contrast effect on the reconstructed images quantitatively.

The edge enhancement of the objects due to refractive contrast was observed in the images reconstructed by X-ray μCT with the highly collimated brilliant X-ray of SPring-8, which enabled us to visualize fatigue cracks nondestructively in an engineering material, AC4CH cast aluminum alloy. The effect of laser peening, which is to retard the propagation of precracks toward the inside as well as on the surface direction, was confirmed by μCT imaging. The results agree well with the precise observation on the surface using an optical microscope. By using the μCT technique in SPring-8, the nondestructive observation of crack growth is feasible in parallel with the measurement of residual stress redistribution. This provides indispensable information for optimizing residual stress distribution and process parameters, considering actual loading conditions.

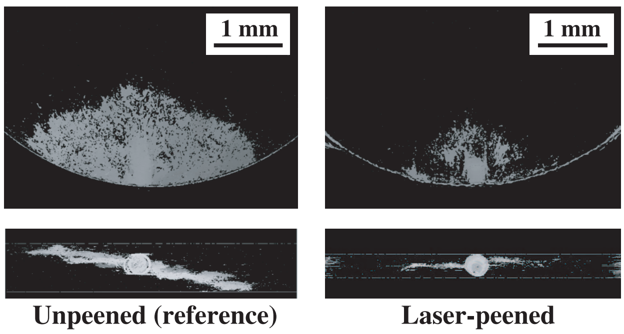

Fig. 5. Three-dimensional images of fatigue cracks.

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