Fatigue 2010

Observation of crack propagation under torsion fatigue tests by synchrotron radiation μCT imaging

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Received 27 February 2010; revised 9 March 2010; accepted 15 March 2010

Abstract

In the present study, synchrotron radiation micro computed tomography (SR μCT) imaging of SPring-8 was applied to the observation of the torsion fatigue crack propagation behavior. The transition of crack propagation from Mode II to I occurs under torsion fatigue. The conventional technique, such as optical microscope and scanning microscope, cannot give us the crack growth behavior under the surface. Therefore, the transition of crack propagation could not be discussed in detail. The compact torsion fatigue-testing machine was developed for fatigue testing at SPring-8, and the torsion fatigue tests and measurements of SR micro-CT were carried out alternately. The shape of torsion fatigue cracks could be evaluated quantitatively and nondestructively. Transition of crack propagation from Mode II to Mode I under the surface could be observed. The condition of transition of crack propagation was discussed by using three-dimensional shape of cracks.

Keywords: Micro Computed Tomography Imaging, Synchrotron Radiation, Torsion Fatigue, Crack Propagation Behavior, Ti-6Al-4V;

1. Introduction

Recently the behavior of fatigue cracks under mixed mode loading has been studied by several researchers [1,2]. The crack propagation behavior under torsion fatigue is complex, such as the transition of crack propagation from Mode II to I. The crack propagation behavior during fatigue is usually studied through the observation of cracks on the surface with direct or indirect method. However, it is not easy to evaluate the behavior of cracks, simply by the conventional technique, such as the replication technique. It give us only the information at the surface. Therefore, the transition condition of crack propagation could not be discussed in detail. The micro computed tomography (μCT) with synchrotron radiation could make possible to monitor the shape of cracks inside the material continuously or intermittently.

The authors have been applied μCT with synchrotron radiation of SPring-8 to the three-dimensional measurement of inclusion and cracks in steels and fretting fatigue cracks [3-6]. In the present study, the behavior of fatigue cracks from the initiation to the fracture was observed and the condition of transition of crack propagation

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doi:10.1016/j.proeng.2010.03.153
mode was discussed by using three-dimensional shape of cracks. A compact torsion fatigue testing machine was developed to facilitate the experiments at SPring-8.

2. Experimental procedure

2.1. Torsion fatigue-testing machine

It is convenient that a fatigue-testing machine can be set on a sample stage in an experimental hatch of a beam-line for observation of fatigue propagation behavior. It is not feasible to evaluate microscopic fatigue propagation behavior of specimens of a standard size, because of the overweight of the machine for the sample stage. A compact fatigue-testing machine, which can be set nearby the experimental hatch, is developed.

The newly developed torsion fatigue-testing machine is shown in Fig. 1. The dimension and mass of the machine are approximately 500mm × 200mm × 200mm, and 10kg respectively. The machine is transportable and can be placed on a desk. The torque is applied by a direct drive motor. The capacity of the motor is 5.0Nm. The rotary type motor directly transfers the torque to the specimen, so that the fatigue-testing machine does not require load transfer mechanism, then downsizing of machine and greater precision torque control are possible. In this experiments, fully reversed cyclic torsion load ($R = -1$) with a frequency of 10 Hz was applied to the specimen.

![Fig. 1 Newly-developed torsion fatigue testing machine (a) Photograph. (b)Schematic diagram of torsion fatigue testing machine.](image)

2.2. Material and specimen

The material for this study was a titanium alloy, (JIS Ti-6Al-4V). The chemical composition of this titanium alloy is as follows: 0.01C, 3.96V, 6.23Al, 0.14O, 0.01N, 0.15Fe, and balance Ti (in mass%). The 0.2% proof stress is 868 MPa, the tensile strength was 995 MPa, and the elongation is 18%. The shape and dimensions of the specimen are shown in Fig. 2. Figure. 3 shows the microstructures of Ti-6Al-4V used in the present study. The microstructures is equiaxial and the average grain size is 8μm.
2.3. Measurement method

X-ray imaging was carried out at BL19B2 beam line of SPring-8, which is the large synchrotron radiation facility in Japan. X-ray energy was adjusted to 35keV with silicon double-crystal monochromator. The distance between a bending magnet (X-ray source) and the specimen was about 100m. The projection image of penetrated X-ray was observed by an X-ray area detector. The detector was composed of a beam monitor (Hamamatsu Photonics AA50) and cooled CCD camera (Hamamatsu Photonics C4880 41S). Transmitted X-ray is converted to visible light through a thin phosphor screen and projected to the CCD camera by an optical relay-lens. Series of projection images of the specimen were obtained every 0.3° from 0° to 180° by rotating the specimen. To utilize the phase contrast effect, the X-ray area detector was set by 0.7 and 0.4m behind the sample. Slice images were reconstructed from the series of projection images by filtered-back projection algorithm. It provides a 3D image with a greyscale color map that is proportional to the local X-ray attenuation coefficient.

3. Experimental results and discussion

Figure 4 shows a kinked and branched crack under $\tau_{w}=450$ MPa. The torsion crack initiated and propagated in the direction parallel to the specimen axis by Mode II. The branching or kinking angles are smaller than the angle of the maximum principal stress. After the branch of the crack, the direction of crack propagation changed from initial branching angle to the specimen axis with crack extension.

Figures 5 and 6 show the cross sectional images at every 54µm from surface to 214 and 322µm in depth, respectively. These images indicate the map of X-ray attenuation coefficient. Cracks are obtained as black line in the absorption contrast image. The effect of phase contrast generates distinct white and black lines at interface of structure, so that the cracks are obtained as white and black lines or the white line, though the crack opening distance smaller than pixel size of detector.
In the tomographic images, the position of the crack tip can be determined via simple visual inspection using image-editing software when the contrast of crack image is high. Otherwise, it should be determined manually. Plug-in for the software of Image J allows for retrieving the coordinates of the pixel that is manually selected as the crack tip at each slice through the sample thickness. Figure 7 shows shapes and dimensions of torsion cracks obtained from the μCT images. Closed circles indicate the crack tips propagated by Mode II, and open circles indicate the branched crack tips. The crack growth in the depth direction can be identified from $1.53 \times 10^5$ cycles to
1.64×10^5 cycles. The growth of the branched crack started after the crack depth increased up to the 320μm. And then, the branched crack length increased with increasing in number of cycles, and the crack resumed the propagation in the depth direction.

Figure 8 shows crack propagation curve. The crack lengths on the surface of the specimen was observed by the optical microscope and CT imaging, and crack depth was measured by μCT image. Closed squares indicate the length of Mode II crack on the surface, and open squares indicate the length of branched crack on the surface. The torsion crack was detected at the surface by optical microscope at 9.30×10^4 cycles. On the other hand, the crack could not be detected by μCT image until 1.53×10^5 cycles. It is considered that the crack from N=9.30×10^4 cycles to 1.50×10^5 cycles is Stage I crack, so that the crack is not enough scale to be detected by the detector. The crack depth increased with increasing in the number of cycles from 1.53×10^5 cycles to 1.60×10^5 cycles, though the crack rarely propagated at the surface. The abrasion powders had been observed from 1.53×10^5 cycles, as shown in Fig. 4. The non-propagation of Mode II crack is related to the crack tip shielding [7,8]. The crack tip shielding, which is believed to arise due to both the development frictional resistance to a relative shear displacement of the fatigue surface asperities and mechanical interlock of fracture surface asperities. The growth of branched crack started at 1.68×10^5 cycles, and was followed by the resuming of the propagation in the depth direction.

![Fig. 7 Internal shape of cracks by measured by slices of μCT images.](image1)

![Fig. 8 Crack growth curves](image2)
Figure 9 shows the changes of aspect ratio of cracks, which is defined as the ratio of total crack length at the surface to the crack depth. The aspect ratio changed from 0.4 to 0.6. The stress intensity factor ranges, $\Delta K_I$, $\Delta K_{II}$, and $\Delta K_{III}$ are plotted against the crack length and the crack depth in Fig. 10, where $\Delta K_{II(A)}$ and $\Delta K_{II}$ are the stress intensity factors at the crack tip at the surface of specimen, and $\Delta K_{II(B)}$ and $\Delta K_{III}$ are the stress intensity factors at the depth of crack tip. The stress intensity factor range, $\Delta K_{II}$ and $\Delta K_{III}$ were calculated by using Kaissir and Sih’s equation \(^{(9)}\) based on the crack shape projected to the plane parallel to the specimen axis, and $\Delta K_{II(A)}$ and $\Delta K_{II(B)}$ were calculated by using Irwin’s equation \(^{(10),(11)}\) based on the crack shape projected to the principal plane of stress. The shear stress distribution was assumed to be constant in the depth direction for simple evaluation of the stress intensity factor. $\Delta K_{II}$ increase with increasing the crack depth even if the non-propagation of the crack at the surface. After the crack branch, tendency of $\Delta K_{II}$ changes from increase to decrease as the crack length at the surface increase. On the other hand, $\Delta K_I$ increases with increasing crack length. It is presumed that the crack branching (Mode I crack) is the results of the change of aspect ratio of cracks, and accordingly dominant mode transition from Mode II to I.
4. Conclusions

Imagining to evaluate the torsion fatigue crack propagation property in Ti alloy Ti-6Al-4V were performed by the μCT with the synchrotron radiation of SPring-8. The results obtained are as follows

1. A compact torsion fatigue testing machine was developed. It is possible to generate high torque up to 5Nm, and carry out at loading frequency of 20 Hz.
2. The fatigue crack propagation behavior under reversed torsion was evaluated by the μCT technique. The crack propagation in the depth direction and propagation behavior of branched cracks and kinked cracks could be observed.
3. The stress intensity factor ranges were calculated by using the three-dimensional crack shape. When the transition of crack propagation occurred, tendency of ΔKII changed from increase to decrease as the crack length at the surface increases. It is presumed that the crack branching is the results of the change of aspect ratio of cracks, and accordingly dominant mode transition from Mode II to Mode I.

Acknowledgements

The synchrotron radiation experiments were performed at BL19B2 in SPring-8 with the approval of the Japan Synchrotron Radiation Research Institute (JASRI) under proposal numbers of 2008A1922 and 2009B1895. The authors are grateful for his technical support of Dr. Kentaro Kajiwara (JASRI).

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