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Assessment of Actual Complicated Fatigue Crack Propagation via 3D Image-based Numerical Simulation

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3D fatigue crack opening and propagation behaviors in an Al-Mg-Si alloy have been investigated in this study by using a combined methodology of an in-situ 3D crack visualization via the synchrotron X-ray microcomputed tomography (CT) and image-based numerical simulation which takes into account real crack morphology. The synchrotron X-ray CT provides a unique possibility to approach 3D crack behaviors. A numerical simulation based on a real crack morphology can provide 3D information on local-scale deformation behaviors and crack evolution behaviors which have not been obtained by the conventional simplified models. The details of a crack with non-planar torturous crack morphology have been observed and many essential features of the crack and its opening/propagation inside the material have been identified. Typical example would be the complex deformation behaviors in the region where two crack segments lying on different horizontal planes overlap each other, and the influence of complicated crack front line on local crack driving forces. We recognized that two overlapping crack segments affected significantly the local fatigue crack opening and propagation behaviors each other. The region next to overlapping was influenced to a relatively large extent through shielding the near-tip stress/strain fields thereby reducing the local crack driving forces. And we believe that the extent of the influence of overlapping crack segments on the next region will increase as the overlapping crack segments propagate further.

Keywords: *Synchrotron X-ray CT; image-based numerical simulation; 3D fatigue crack image.*

1. Introduction

Recently, synchrotron X-ray CT has been applied to the study of three-dimensional fatigue crack propagation behaviors, which has the unique potential to provide the internal information of the fatigue test specimen [1-5]. Some new features of three-dimensional fatigue crack propagation behaviors have been revealed. The typical example would be the partially overlapped crack segments along the loading direction in an Al-Mg-Si alloy in a fatigue test, by using a combined methodology of in-situ three-dimensional visualization via synchrotron X-ray CT and a image-based numerical simulation method [6]. Qian has reported that the near-tip plastic deformations of the cracks in the region next to overlapping were reduced significantly and the mode of the local loading on crack tip transferred from pure mode I to mode I-II. This indicated that the neighboring cracks of the overlapping region were reduced significantly on crack driving forces and their propagation direction would deviate from the global mode I crack growth direction due to the load shielding effect. But how the loading shielding effect works on the reduction of crack driving forces has not been reported yet. In the present paper, a combined methodology of in-situ three-dimensional visualization via synchrotron X-ray CT and a image-based numerical simulation method was applied to investigate the mechanisms of the abovementioned load shielding effect.

2. Experimental Method

The selected material is a cast Al-Mg-Si alloy (Mg: 0.43%, Si: 0.29%, Mg_2Si: 0.68%), which was haet-treated on a T6 condition. The synchrotron X-ray micro-computed tomographic scanning was performed at the third generation synchrotron radiation facility, Spring-8, in Japan. To perform the

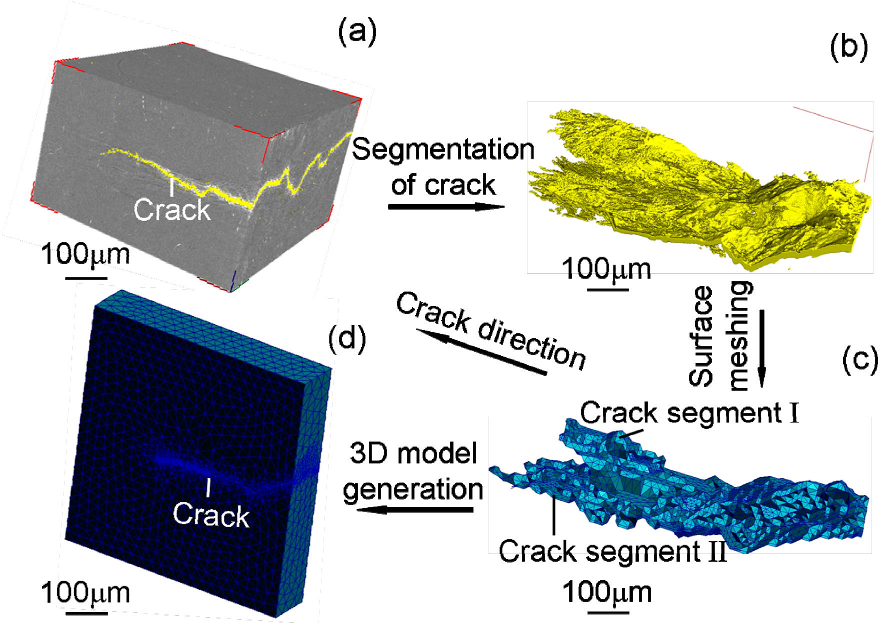

Fig.1 Schematic explanation of the process of creating image-based crack model. (a) volume rendering of the specimen at maximum load after fatigue, (b) crack image segmented from the specimen volume rendering in (a), (c) crack surface mesh extracted from the crack image in (b), (d) 3-D crack model

high-resolution micro-tomographic imaging, a parallepiped parallepiped single-edge fatigue sample 0.6mm×0.6mm×12mm in size, was extracted in the crack tip from a three-point bending specimen with a fatigue pre-crack, to fit the field of view. Other details of the XMCT imaging are available elsewhere [7].

To observe the propagation of a three-dimensional fatigue crack in-situ inside the Al-alloy, tomographic scanning was performed every 30000 fatigue cycles at maximum load and was carried out on six load levels after fatigue cycles. The applied fatigue load was in the range of 5MPa-50MPa, with a frequency of 10Hz. Fig. 1 shows a crack extracted from a rendered volume that was taken at the maximum load after 120000 load cycles.

3. Image-based Numerical Simulation Method

The flow chart of the procedure to create models is schematically shown in Figure 1. After segmenting the partial crack volume containing two overlapping crack segments which was the region of interested in the study, the polygonal crack surface mesh was extracted by tracing iso-gray-value surfaces through the trilinear interpolation. Then the crack surface mesh and the

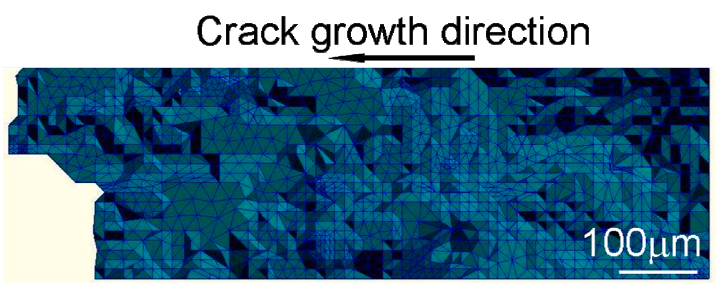

Fig.2 Top view of the crack surface mesh of model 2.

surface mesh of a specimen were combined to create the original three-dimensional model (model 1). The height and length along the crack propagation direction in the models are identical with those of the sample used for the tomographic scanning. The widths of the model are 0.1mm. The applied fatigue load ranged between 5～50MPa, which is equal to the experimental fatigue load. The material characteristics for the model are those of the experimental material. A commercial finite element program ANSYS was used for the simulation and no attempt was made to simulate crack propagation at the moment.

4. Results

4.1 Interaction of overlapped crack segments

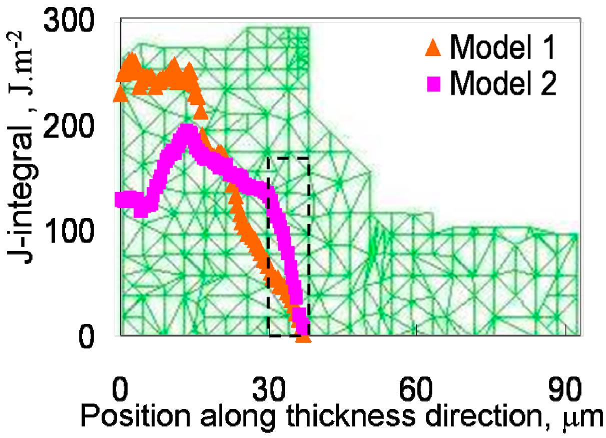

Fig. 3 Variation of J-integral of segment I in model 1 and 2

The three-dimensional view of the fatigue crack volume rendering at the maximum load after 120000 fatigue cycles was performed in Figure.1(b). From Qian's report [6], it has been known that the local crack driving forces in both the overlapping region and the region next to overlapping were reduced significantly due to the load shielding effect. But the mechanisms of the load shielding effect are not completely understood yet. From the previous literatures studying on the bifurcated cracks [8-13], we know that the load shielding effect exist between the two branches of the bifurcated cracks either. The load shielding effect will increase with the decrease of the gap and the angle between the two crack branches. A little difference of the length between the two branches will cause the arrest of the shorter crack branch. But the conventional two-dimensional studies on bifurcated cracks were based on an assumption that the crack branches were through-thickness, while the three-dimensional crack presented in the paper has two partially overlapped crack segments. Therefore, besides the same load shielding mechanism with two-dimensional through-thickness bifurcated cracks, there must be some else load shielding mechanisms for the three-dimensional partially overlapped crack segments. One is the constraint of the surrounding ligaments. From figure.1(b), we found that the two

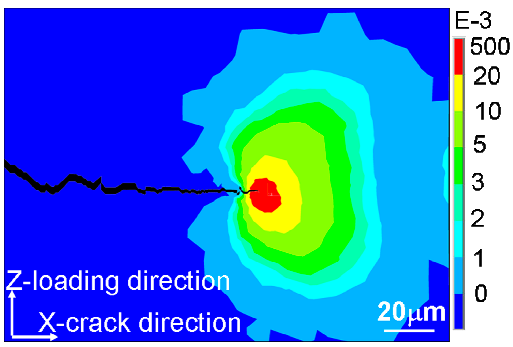

Fig.4 Contours of equivalent plastic strain on x-z slices in overlapping region.

crack segments were surrounded by the ligaments on the boundaries of the overlapping region. It is obvious that the surrounding ligaments will reduce the local crack driving forces significantly. In order to investigate the extent of the reduction, another model (model 2) was used in the present study, in which the crack segment II in model 1 was deleted (Figure.2). Figure.3 shows the variation of the J-integrals along the thickness direction in model 1 and 2. It was found that the surrounding ligaments could only reduce the J-integral significantly in an relatively small scale (about 7μm). In the middle of overlapping region, the influence of the surrounding ligaments is negligible and there might be some other loading shielding mechanisms beside the two aforementioned. Figure.4 shows the contours of the equivalent plastic strain in a X-Y slice in the middle of the overlapping region. The two crack segments have the similar length along the global crack growth direction. The J-integral was calculated for the longer crack segment and then was converted into the stress intensity factor K_I, which has a value of 3.1Mpa√m. Assuming the crack in figure.4 was a through-thickness bifurcated crack, the angle between the two crack branches is 130, the initial lengths of the branches b_0 and c_0 are 15.8μm and 10.9μm, the exponent in Paris law equation m is 3.214, the crack length before bifurcation a_0 is 269μm, the current crack length of the longer segment b is 55.5μm. The equivalent stress intensity factor K_b was calculated based on the results in the reference paper [13], which is 5.01 Mpa√m. It is much different from the real local crack driving force K_I (3.1Mpa√m). Since the constraint of the surrounding ligaments is negligible, the large difference must be caused by some other load shielding mechanisms. From figure.4, we have found that large plastic deformation occurred in the overlapping region far behind the crack tip, which would consume a large amount of energy and reduce the local crack driving forces. While for a two-dimensional through-thickness bifurcated crack, no large plastic deformation occurs far behind the crack tip. We believe that the large plastic deformation in the overlapping region behind crack tip is significant to reduce of the local crack driving force K_I in overlapping region and the region next to overlapping.

4.2 Influence of mode III displacement in overlapping region

In order to completely understand the load shielding mechanism caused by the large plastic deformation behind crack tip, the other stress/strain components were investigated. It was found that the shear deformation along the loading direction and the thickness direction is much larger than the shear deformations along the other directions. If viewing at a cross-section normal to the global crack growth direction in the overlapping region, we would see two non-planar edge cracks propagating along the opposite directions. It has been reported that when the two non-planar edge cracks overlapped along the loading direction, large shear deformations along the loading direction and the original crack path direction would occur [14]. So did the three-dimensional partially overlapped crack segments. Figure.5 shows the contours of the displacement along the thickness direction on the

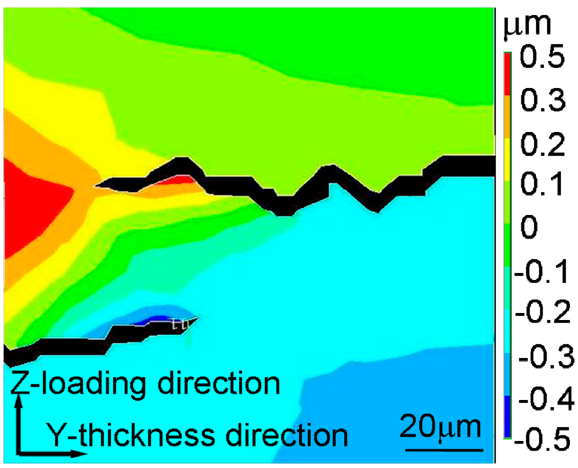

Fig.5 Contours of the displacement along the thickness direction on the cross-section normal to the global crack growth direction in the overlapping region

cross-section normal to the global crack growth direction in the overlapping region. We found that the displacements along the thickness direction were along the opposite direction for points close to the upper crack and the lower crack respectively, which implied the large shear deformation in this region.

Besides the energy consumed by the plastic dissipation in overlapping region, the fatigue crack closure caused by the mode III displacement (along the thickness direction) might be another load shielding mechanism. Since large mode III displacements existed in overlapping region, they might cause the premature contact of the mated crack faces when the crack plane was tortous along the thickness direction, which was called crack closure. The crack closure will shield the applied loading transferred on crack tip.

5. Conclusion

Therefore, we can conclude based on the above analyses that the large shear deformation along the loading direction and the thickness direction is an important load shielding mechanism for the overlapped crack segments. And its influence extends to the region next to overlapping. As the fatigue crack propagates further, we can imagine that the influence of the overlapped crack segments would be larger and larger. Another potential load shielding mechanism is the fatigue crack closure caused by the mode III displacement in overlapping region. All of these are the extra load shielding mechanisms compared with the two-dimensional through-thickness bifurcated cracks. As a result, the local crack growth resistance in overlapping region is much higher than a single mode I crack.

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