Development of Fatigue Testing System for in-situ Observation by an Atomic Force Microscope and Small Fatigue Crack Growth Behavior in $\alpha$-Brass

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A small in-plane bending fatigue testing machine for in-situ observation of small fatigue crack growth behavior by means of an atomic force microscope (AFM) was successfully developed. The multiple layer piezoelectric ceramics were adopted as an actuator in order to miniaturize the fatigue loading facility operating on the stage of an AFM. Small fatigue crack growth test under constant amplitude loading was then carried out on $\alpha$-brass and successive observation of small fatigue crack growth behavior was performed by the AFM. The fatigue crack tended to grow along one slip direction with the highest Schmid factor, as the crack driving force of a small crack was not large enough to operate other slip directions with lower Schmid factors simultaneously. Frequent crack branching and deflection behavior were also observed during crack growth. It was considered that the constraint of slip deformation due to the cyclic strain hardening was mainly responsible for crack branching and deflection behavior. The intervals of branching or deflection were affected by the difference of mobility among slip planes.

Key Words: Atomic Force Microscope, In-Situ Observation, Small Fatigue Crack, Crack Growth Behavior, Cross Slip, $\alpha$-Brass

1. Introduction

Since fatigue crack growth owing to fatigue damage at the crack tip region is considered to be an intrinsically localized phenomenon, microscopic observation is an effective technique to elucidate the fatigue crack growth mechanism. Most direct observations of fatigue crack growth behavior have been made using an optical microscope and/or a scanning electron microscope (SEM), and many valuable findings on the crack growth mechanism have been obtained(1)–(3). In those researches, however, the individual slip lines around the crack tip, which brought about crack extension, were hardly observed as the resolution of microscopes was limited(4)–(8). In-situ observation around growing fatigue crack tip, however, must be done in order to figure out the fatigue crack growth behavior in a grain oriented 3% silicon iron by an AFM and could have identified the forward slip deformation around the crack tip during the loading half cycle as well as the reverse one during the unloading half cycle as individual slip lines, and successfully proposed fatigue crack growth model based on AFM microscopy(4)–(6).

AFM observation is usually performed using very small samples or plastic replicas taken from large specimen surface because the sample size which can be installed into the stage of an AFM is limited(4)–(8). In-situ observation around growing fatigue crack tip, however, must be done in order to figure out the fatigue crack...
growth mechanism as the fatigue damage localized at the crack tip is accumulated cycle by cycle. For example, Ko-
mair et al. performed in-situ observation of stress corro-
sion cracking by an AFM and indicated the importance 
of microscopic in-situ observation to elucidate the time-
dependent crack growth mechanism\(^{(9)}\), \(^{(10)}\). However, in-
situ observation of growing fatigue crack by an AFM has 
been hardly carried out.

The authors have successfully developed a specially 
designed small in-plane bending fatigue testing machine 
integrated with the stage of an AFM and the in-situ obser-
vation system of small fatigue crack growth by an AFM. 
In this study, fatigue crack growth behavior under low 
growth rate region in \(\alpha\)-brass was observed.

2. Development of in-situ Observation System

The AFM (Veeco Instruments, Dimension 3100), 
controlled by the Nanoscope IIIa system (Veeco Instru-
ments), has the relatively large specimen stage with the 
diameter of 200 mm. A small in-plane electro-servo bend-
ing fatigue testing machine has been newly designed and 
installed to the stage of the AFM as schematically shown 
in Fig. 1. It is possible to set the fatigue crack tip in the 
center of field of the AFM with high accuracy by moving 
the specimen stage using the electronic controlled step-
ning motors. The multiple layer piezoelectric ceramics 
were adopted as an actuator in order to miniaturize the 
fatigue loading facility operating on the stage of an AFM. 
Although the maximum displacement of the actuator was 
limited to 170 \(\mu\)m, the displacement was amplified by 5 
times using the cantilever arm through which bending mo-
moment was applied to the specimen. Figure 2 indicates a 
detail of the mounted specimen. A roller was introduced just 
under the specimen in order to amplify the load enough 
for fatigue crack initiation and propagation. Strain gauges 
were attached on the cantilever arm to detect the load of 
the specimen, and load controlled fatigue test could be 
conducted by a closed-loop feedback system. A microme-
ter was also equipped with the testing machine to give the 
desired displacement to the specimen or to hold the load 
at the arbitrary stage of the fatigue loading.

3. Experimental Procedure

The material employed is \(\alpha\)-brass (JIS CP2600-O), 
which was annealed at 993 K for 1 hour in salt-bath. The 
chemical composition and mechanical properties of mate-
rial are shown in Tables 1 and 2, respectively. Figure 3 
shows the microstructure of this material. Twin bound-
aries were observed in the \(\alpha\)-phase grain. The grains were 
enlarged by the annealing process in order to minimize the 
effect of grain boundaries on fatigue crack growth behav-
ior. The average grain diameter was about 205 \(\mu\)m. The di-
mension and configuration of specimen is shown in Fig. 4, 
at the center of which a notch was formed by electro-

![Fig. 1 Configuration of fatigue test machine for in-plane bending](image1)

![Fig. 2 Detail of specimen mount](image2)

| Table 1 Chemical composition of material (mass %) |
| Cu | Pb | Fe | Zn |
|---|---|---|---|
| 68.8 | 0.004 | 0.002 | Bal. |

| Table 2 Mechanical properties of material |
|---|---|---|---|---|
| 0.2% proof stress \(\sigma_{0.2}\) [MPa] | Tensile strength \(\sigma_b\) [MPa] | Elongation \(\delta\) [%] | Reduction in area \(\phi\) [%] | Grain size [\(\mu\)m] |
| 105 | 290 | 74.3 | 78.8 | 205 |
discharging as the starter of fatigue crack. The diameter of curvature was 0.18 mm where the stress concentration factor was 3.7. The specimen was finally electro-polished in order to remove the residual stress.

A fatigue crack growth test was carried out using a sinusoidal wave at a frequency, $f = 10$ Hz. The maximum stress, $\sigma_{\text{max}}$, was 130 MPa, where the stress ratio, $R$, was 0.05.

4. Experimental Results and Discussions

4.1 Crack growth behavior

Figure 5 shows the macroscopic fatigue crack growth path observed by an optical microscope at the number of load cycles, $N = 1.3 \times 10^6$. The specimen surface was etched to enhance grain boundaries. Fatigue crack initiated in the grain located at the notch root, and propagated transgranularly. When the crack tip located within the rectangular region “A”, the detailed observation around the crack tip was performed by the AFM. Figure 6 shows the AFM image of fatigue crack growth path obtained at $N = 4.0 \times 10^5$, where static load of 100 MPa was applied. The crack front was located about 90 $\mu$m from the notch. However crack tip opening was unclear because the crack opening displacement near the crack tip was too small to identify by the AFM with the limited horizontal resolution.

In Fig. 6, there found exist two preferential slip lines on the specimen surface, namely slip lines A and B having the slip direction of 72 and $-50$ degree to the direction perpendicular to the loading axis, respectively. These slip lines were recognized through the whole area of the grain as cross stripes shown by white arrows in the figure, indicating those slip lines were formed by load cycling irrelevantly to the high stress filed around the crack tip. It is considered that some slip planes recognized as cross stripes in the grain are especially active ones in the slip systems A and B. Although the angle between slip plane and specimen surface is unclear, Schmid factor of each slip plane should be different. Therefore, it can be thought that there is difference in resistance to slip in both slip planes A and B. Since the slip direction of the slip line B on the specimen surface is near to the maximum resolved shear stress direction, it is considered that the slip plane B is easier to be activated than slip plane A. Consequently, many slip lines lying in the slip plane B were observed on the specimen surface, while few in the slip direction A, implying Schmid factor of slip plane B is larger.
than that of A.

The fatigue crack was found to grow along these slip planes A and B in a zigzag manner as a result of successive crack branching and deflection. It is found that the frequency of the crack branching and deflection is not uniform. The fatigue crack was observed to deflect at short intervals near the current fatigue crack tip. On the other hand, in the right-hand side of Fig.6, the interval of deflection is relatively large, indicating that the crack deflection behavior is depending on the crystallographic conditions. In order to clarify the detailed mechanism of crack deflection, crack growth behavior in the areas indicated by square region “α” and “β” was successively observed.

4.2 Microscopic crack growth behavior in region “α”

Figure 7 shows the example of successive AFM images in square region “α” of Fig.6 taken at the number of load cycles, \( N = 3.47 \times 10^{5} \) to \( 3.60 \times 10^{5} \), where the sampling interval was 1000 to 5000 cycles. Static load of 100 MPa was applied to make slip lines clear during observation. In the right-hand figures of Fig.7 (a) – (g), the fatigue crack path and slip lines are traced by solid line and dashed lines, respectively. In Fig.7 (a), the crack grew along slip plane A, and then deflected and propagated along slip plane B, whose Schmid factor is larger than that of A as mentioned above. Since the crack driving force is too small in the low growth rate region to activate both slip planes A and B, crack tends to grow along one slip plane, especially slip plane B with larger Schmid factor. In this case, slip line B1 can be recognized in front of the crack tip and the front of slip locates at the point 1. After load cycling of 2000 cycles (Fig.7 (b)), the front of slip line B1 (point 1) was same with Fig.7 (a), indicating crack was arrested during 2000 cycles. It is considered that the slip deformation along the slip plane B would have been constrained because the repeated operation of the same slip plane corresponding to the crack growth direction induced dislocations to pile up in front of the crack tip. However, a new slip line A1 emanated from the location about 3.5 \( \mu \)m behind the crack tip during the load cycling, and then the slip line B2 was observed to occur at the tip of slip A1. Since the fatigue crack tip lies on the slip line B1 at this point, the cross slip which consisted of slip A1 and B2 was thought to occur near the arrested crack tip.

After load cycling of 3000 cycles (Fig.7 (c)), crack emanated from the branching point 1 just behind the arrested crack tip and grew along the slip plane A1. In Fig.7 (d), which was sampled after 1000 load cycles, crack deflected at the kinking point 1, and subsequently propagated along the slip plane B2 through the slip deformation. The front of slip line B2 located at the point 2 and maintained after the load cycling of 1000 cycles (Fig.7 (e)). Therefore, the slip deformation along slip plane B2 was thought to be constrained by strain hardening in front of the crack tip. As a result, fatigue crack arrest occurred after some crack growth, and other slip system (slip A2), the direction of which is different from that of the now constrained slip, began to operate behind the arrested crack tip. The slip line B3 occurred at the tip of slip line A2 and a new cross slip was observed. After load cycling of 5000 cycles (Fig.7 (f)), fatigue crack grew along the slip plane A2, resulting in crack branching such as the branching point 2. In Fig.7 (g), which was sampled after 1000 load cycles, fatigue crack deflected at the kinking point 2 and then grew along the slip line B3, which was formed as a cross slip when the fatigue crack arrested on the slip plane B2 as shown in Fig.7 (e).

It was confirmed from the successive observation that the crack predominantly grew along slip plane B, which was easier to be activated than slip plane A. However, crack would be arrested because the repeated operation of the same slip plane induced dislocations to pile up in front of the crack tip. Then slip plane A was activated just behind the arrested crack tip and the cross slip occurred at the tip of slip A, and crack grew along cross slip with crack branching and deflection.

4.3 Microscopic crack growth behavior in region “β”

Figure 8 shows the examples of successive AFM images in square region “β” of Fig.6 taken at the number of load cycles, \( N = 3.74 \times 10^{5} \) to \( 4.0 \times 10^{5} \), where the sampling interval was 2000 to 7000 cycles. In Fig.8 (a), the crack was growing along the slip plane B3 shown in Fig.7 (g). In this case, the slip line B4 is recognized near the crack tip. However, this slip line was formed in the same manner as the other slip lines shown by white arrows in Figs.6 and 8(a), namely formed by cyclic loading irrespective of the high stress field around the crack tip. After load cycling of 3000 cycles (Fig.8 (b)), the location of the top of slip line B3 (point 3) was preserved, indicating the fatigue crack was arrested due to the strain hardening. In Fig.8 (b), the slip plane B3 was activated from the crack tip toward the slip plane B1. In Fig.8 (c), which was sampled after 4000 load cycles, crack grew along the slip plane A3 and deflected toward the slip plane B5. Cross slips and crack branching behind the crack tip shown in Fig.7 were not recognized in Fig.8, indicating the crack shown in Fig.8 propagated irrelevantly to cross slips. Successive observation between Fig.8 (b) and (c) shows that the slip line A3 was activated beyond the slip line B4, which was considered to be easier to be activated than slip plane B5. It is thought that the activation of slip B4, which was considerably close to the slip line B3, was restricted by the stress field induced by the piled-up dislocations on the slip plane B3, and resulted in the crack growth along slip plane A3 beyond the slip plane B4.

Crack growth and deflection behavior without cross slips were also observed in the successive images of Fig.8 (d) to (g). In Fig.8, the fatigue crack was found.
Fig. 7 AFM images of fatigue crack growth process in region “α”

4.4 Fatigue crack growth model

As shown in the previous sections, two kinds of representative fatigue crack growth behavior were observed. First, crack growth with cross slips and crack branching behind the crack tip, which resulted in the relatively long interval of crack deflection. Secondly, crack growth
without cross slips, where crack deflection took place frequently. As indicated by white arrows in Fig. 6, the cross-stripe pattern was observed due to slip deformation on the slip planes A and B, which were activated by cyclic loading irrespective to the high stress field at the crack tip. It implies that the slip systems denoted as A and B have some particular slip planes easier to be activated, and resulted in the cross stripes in the grain by cyclic loading. The distribution of particular slip planes with high activity and resulting cross stripes are schematically illustrated.
Schematic illustration of slip planes and crack growth path

Crack growth with cross slip

Crack growth without cross slip

Fig. 9 Schematic illustration of fatigue crack growth

5. Conclusions

A small in-plane bending fatigue testing machine for in-situ observation of small fatigue crack growth behavior by means of an AFM was successfully developed. Fatigue crack test in low growth rate region was carried out using α-brass. Growth behavior of the fatigue crack was observed successively in detail. The conclusions obtained in this study are as follows.

(1) A small in-plane bending fatigue testing machine which can be operated on the specimen stage of the AFM has been newly designed.

(2) Detailed AFM observation revealed that two preferred slip systems with slightly different Schmid factors dominated fatigue crack growth behavior. In the low growth rate region, the fatigue crack tended to grow along one preferred slip plane with higher Schmid factor, while another slip plane with lower Schmid factor simultaneously.

(3) Crack growth along only one preferred slip plane in the grain brought about cyclic strain hardening on that plane, as the same slip plane operated repeatedly at the crack tip. The cyclic strain hardening at the crack tip resulted in crack arrest and following crack branching or deflection toward another preferred slip plane. The fatigue crack grew in a microscopically zigzag manner as a result of successive crack branching and deflection.

(4) Two slip systems in the grain dominating crack growth behavior had some particular slip planes easier to be activated. If the particular slip plane with high activity...
existed near the arrested fatigue crack tip, large slip deformation took place at that plane and induced a cross slip toward another slip system. Consequently, fatigue crack grew along the cross slip with a relatively large deflection interval.

(5) When there is no slip plane having high activity near the arrested fatigue crack tip, a cross slip can not operate. In this case, crack deflection took place in a short interval.

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