PREDICTION OF FATIGUE CRACK INITIATION LIFE WITH ATOMIC-FORCE MICROSCOPY

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ABSTRACT

Slip-band formation and fatigue crack-initiation processes in α-brass were observed by means of atomic force microscopy (AFM), and the effects of the grain size, the stress amplitude, and the mean stress were discussed. In a fine grain material, fatigue cracks were initiated only from the slip-bands. In a coarse grain material, however, they were initiated either from the slip-bands or the grain boundaries. The depth of an intrusion drastically increased with its outgrowth to a crack, and with coalescence of cracks, the width of cracks increased rapidly.

The depth of an intrusion increased with the number of loading cycles, and when the depth reaches a critical value, a transgranular crack was initiated from the intrusion. The critical value was given as a function of the slip-band angle relative to the stress axis. From the AFM observations, it was found that the critical value of the slip distance was independent of the slip-band angle relative to the stress axis, the stress amplitude, the mean stress, and the grain-size.

1. INTRODUCTION

It is well known that the fatigue process of metallic materials without macroscopic defects can be divided into initiation and growth processes of cracks and final unstable fracture. Among these processes, various studies have been conducted on the crack-growth behavior, and that can be quantitatively analyzed based on the fracture mechanics [1]. The initiation condition of fatigue micro-cracks, however, still has not clarified enough, because no method for successive, direct and quantitative observation of the process had been devised. The study on fatigue crack initiation is especially important for fatigue damage evaluation of micro-machine components because most of fatigue life of these components is occupied by the crack initiation life [2].

For components without significant internal defects, free surface is normally the site for fatigue crack initiation, then microscopic observation is the most useful method to clarify the mechanisms of fatigue processes in materials, and the progress of metal fatigue study has strongly depended on the development of new microscopic observation methods.

With conventional microscopes, such as optical microscopes (OM), transmission electron microscopes (TEM), and scanning electron microscopes (SEM), however, successive, quantitative three-dimensional observations of the crack nucleation portion in the specimen surface could not be conducted. In most of these studies, the crack-initiation mechanisms were discussed qualitatively.

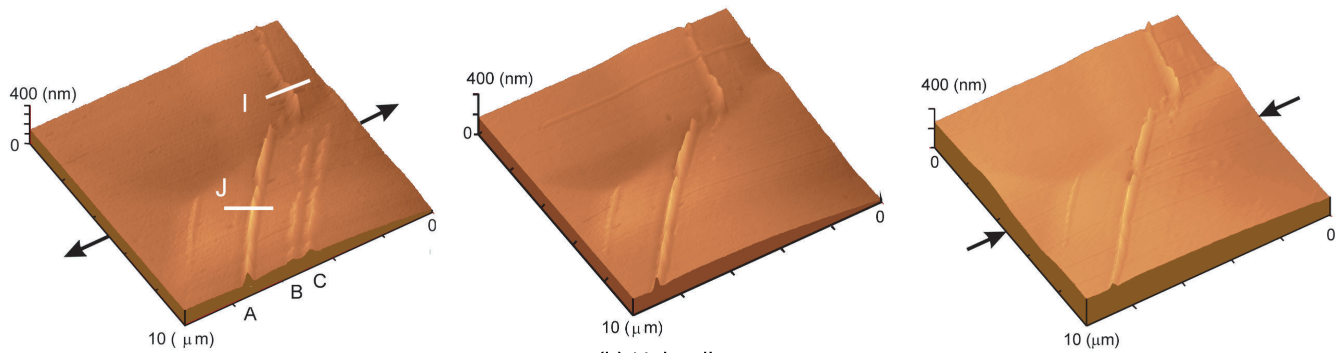
Since the surface morphology of materials can be observed with atomic-scale resolution, the scanning atomic force microscopy (AFM) is a powerful technique to study mechanisms of fatigue and fracture of solid materials. Nakai and his coworkers studied fatigue slip-bands, fatigue crack-initiation, and the growth behavior of micro-cracks in a structural steel [3], and α-brass [4]-[6].

In the present paper, slip-band formation and fatigue crack-initiation processes in α-brass were observed by means of AFM, and the conditions for the crack-initiation was discussed.

2. EXPERIMENTAL PROCEDURE

The material for the present study was 70-30 brass (α-brass). The chemical composition, mechanical properties, and dimensions and shape of specimen were given elsewhere [4]-[6]. After the specimens were made by the electric-discharge machining, they were heat treated at 320 °C for 180 s (Material A), or at 850 °C for 3600 s (Material B). The grain sizes of Material A and B were 20 μm and 1,100 μm, respectively. Before fatigue tests, surface of the specimens were electrochemically polished. The fatigue tests were carried out in a computer-controlled electro-dynamic vibrator operated at a frequency of 30 Hz under fully reversed cyclic plane bending moment ($R = -1$), or pulsating bending moment ($R = 0$).

Since it was very difficult to identify in advance where fatigue cracks would be initiated, replicas of the specimen surface were taken at the predetermined number of fatigue cycles.



(a) Maximun stress (b) Unloading (c) Mininum stress

Figure 1: AFM images of slip-bands ($\sigma_a = 240$ MPa, $N = 5.2 \times 10^3$, Material A).

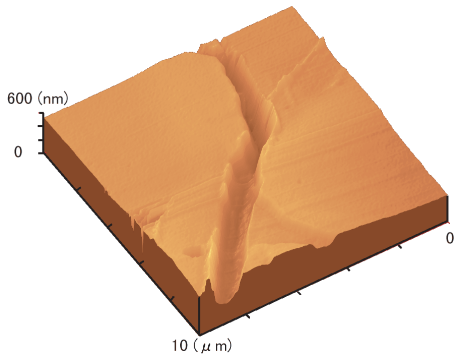


Figure 2: AFM images of slip-bands ($\sigma_a = 240$ MPa, $N = 1.2 \times 10^5$, Material A).

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Motion of Slip-bands during One Fatigue Cycle

Surface of a fatigued α-brass specimen was observed at the maximum stress, the unloading state, and the minimum stress at the same number of cycles. AFM images of slip-bands are shown in Fig. 1, where arrows indicate the loading direction.

Positions I and J in Fig. 1 (a) were considered to be in different grains because the slip directions were different from each other. Slip-band A, which is shown in Fig. 1 (a), can be observed under any stress level. Slip-bands B and C (Fig.1 (a)), however, can be observed only under tension stress, and these slip-bands did not appear with a different number of cycles. Slip-bands those appeared only under compression stress and was not observed under tension stress also existed. Therefore, slip-bands, which appear only under tension stress or under compression stress, were observed only in the initial stage of the fatigue process. It is considered that these slip-bands were formed by monotonic deformation. These kinds of slip-bands, however, disappeared shortly, and they were observed only when the maximum stress exceeded the yield strength.

Up to $N = 1.5 \times 10^4$ cycles, slip-bands were relatively unchanged in appearance, i.e., Slip-band J was blocked by a grain boundary. At $N = 6.0 \times 10^4$ cycles, Slip-band J passed through the grain boundary and Slip-band I. This passage through the grain boundary and slip-band was considered to be a premonitory sign of crack-initiation. At $N = 1.2 \times 10^5$ cycles, a fatigue crack nucleation was found under tension stress by its large opening compared to slip-bands (see Fig. 2). Under unloading state, however, it was hardly distinguished between slip-bands and cracks from AFM images. In AFM images obtained under compression stress, cracks showed slightly different appearance from slip-bands. Mode II and/or Mode III deformation may be responsible for that difference.

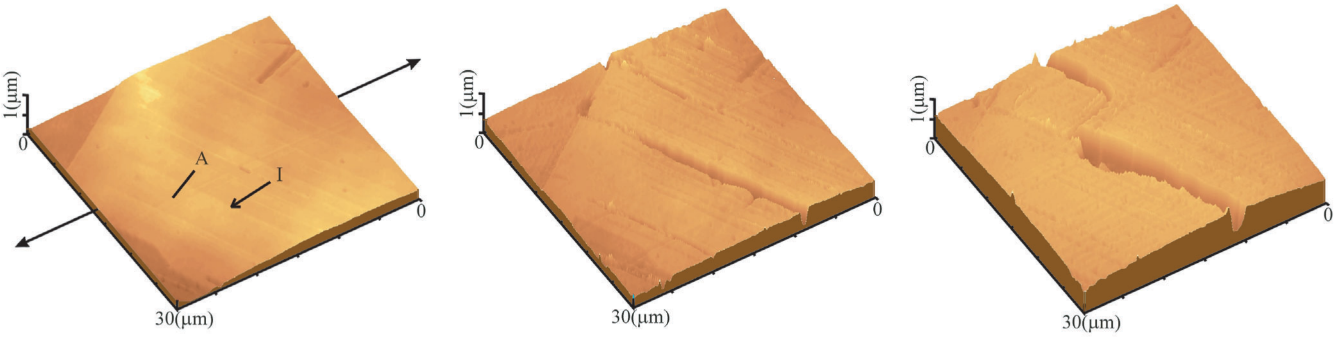
3.2 Crack initiation

3.2.1 Transgranular Cracking

In this section, the conditions for the crack-initiation in α-brass will be discussed as a function of slip-band angle relative to the stress axis, stress amplitude, mean stress, and grain size. In α-brass, fatigue cracks were initiated either from slip bands or along grain boundaries.

Another example of transgranular cracking process is shown in Fig. 3. It is clear from AFM images that two parallel fatigue cracks were initiated at $N = 9.1 \times 10^4$ cycles (Fig. 3 (b)), and they were coalesced at $N = 4.5 \times 10^5$ cycles (Fig. 3 (c)). The change of the geometry of Intrusion I at cross section A, which is indicated in Fig. 3 (a), is shown in Fig. 4. With crack-initiation at $N = 9.1 \times 10^4$ cycles, the depth of the intrusion increased rapidly, and with coalescence of cracks at $N = 4.5 \times 10^5$ cycles, the width of the cracks (intrusion) increased rapidly. Change of the depth of Intrusion I is shown in Fig. 5 as a function of the number of the fatigue cycles, N. Even though the measured value was not actual depth after crack initiation, the depth of the intrusion drastically increased with its outgrowth to a crack at $N = 9.1 \times 10^4$ cycles.

From surface observation, cracks much shorter than the grain-size were not found. Even just after the initiation, a crack prevailed whole grain, and Stage I crack growth was not observed. In the thickness direction, however, the depth of intrusion changed continuously before and after crack initiation, i.e., no jumping in the depth of intrusion was observed. It may indicates that Stage I crack growth, which is a fatigue crack growth along a slip-band, occurred in the thickness direction.



(a) $N = 5.9 \times 10^2$ cycles (b) $N = 9.1 \times 10^4$ cycles (c) $N = 4.5 \times 10^5$ cycles

Figure 3: AFM images of transgranular cracking ($\sigma_a = 173$ MPa, Material A).

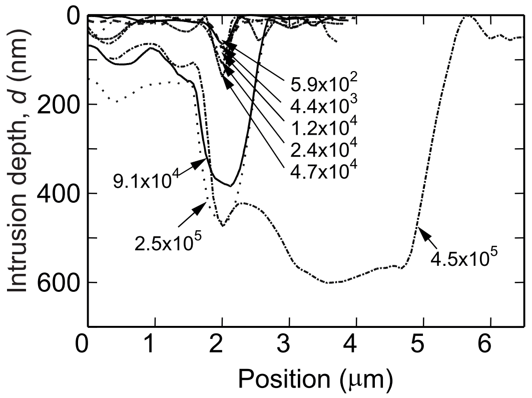


Figure 4: Change of intrusion geometry in fatigue (Material A).

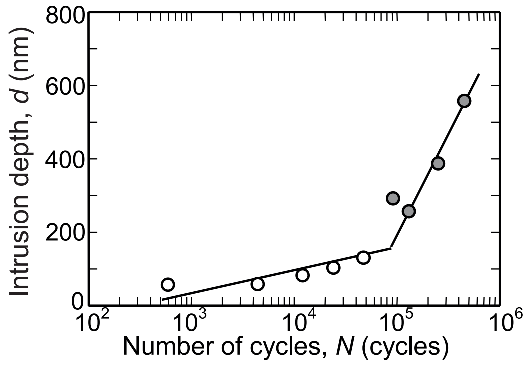


Figure 5: Change of intrusion depth in fatigue (Material A).

3.2.2 Intergranular Cracking

An example of the intergranular cracking is shown in Fig. 6. Slip-bands were formed in a grain on the right side of a grain-boundary, and they were parallel to the grain-boundary. Both intrusions and extrusions were observed in the grain. In the grain on the left size of the grain boundary, slip-bands are not observed. A fatigue crack was initiated from the grain-boundary at $N = 4.6 \times 10^4$. An intergranular crack was considered to have been initiated along grain-boundaries between grains with high Schmidt factor slip system and with low Schmidt factor slip system. The depth of the grain boundary, d, also increased with the number of cycles, N, and the crack-initiation could be easily identified from the change of the slope of the $\log N - d$ relationship.

3.2.3 Model

Condition for the transgranular crack initiation can be analyzed by a geometrical model proposed by Tanaka and Nakai [7][8], which explains the relation between the surface-step and the slip-direction. The surface-step, d, induced by the slip is

$$d = s \cdot \sin\beta \cdot \cos\alpha', \tag{1}$$

where the value of s is the slip distance in the slip-direction, the value of α' is the angle between the normal to the surface and the trace of the slip-band on the plane that is perpendicular to the surface and parallel to the loading-axis, and the value of β is the angle between the slip-direction and the slip-traces on the surface. Cracks are considered to have been initiated from slip bands, which had slip system in the maximum resolved shear stress [7][8]. For slip-bands, where the resolved shear stress along the slip-direction takes the maximum value, the following relationship should be satisfied.

$$\cos\beta = \sqrt{2}\cos\alpha, \tag{2}$$

$$\cot^2\alpha + \tan^2\alpha' = 1. \tag{3}$$

The relation between d and s can be derived as a function of α by substituting Eqs (2) and (3) into Eq. (1).

Figure 7 shows the depth of intrusions for various numbers of cycles as a function of the intrusion angle relative to the stress-axis. In the figure, data from the same intrusion fall on the same angle. Open marks indicate data before the crack initiation, and solid marks show data after the crack initiation. The solid-line in Fig. 7 shows the relationship given from Eq. (1) for the value of $s = 380$ nm. For the transgranular cracking, which are shown in Fig. 7, data before the crack initiation fall below the solid line, and data after the crack initiation locate above the solid line. It indicates that there was a critical value of accumulated slip-distance, s. The critical value of s was 380 nm, independent of the stress amplitude, the mean stress, and the grain-size. When the accumulated slip distance of an

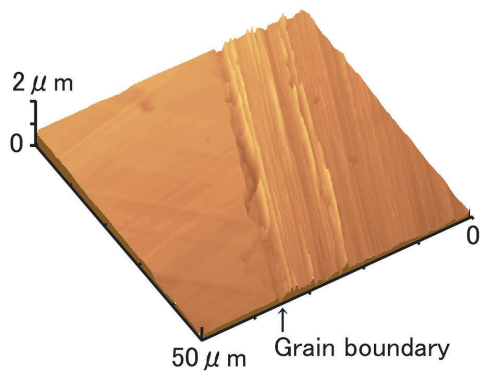
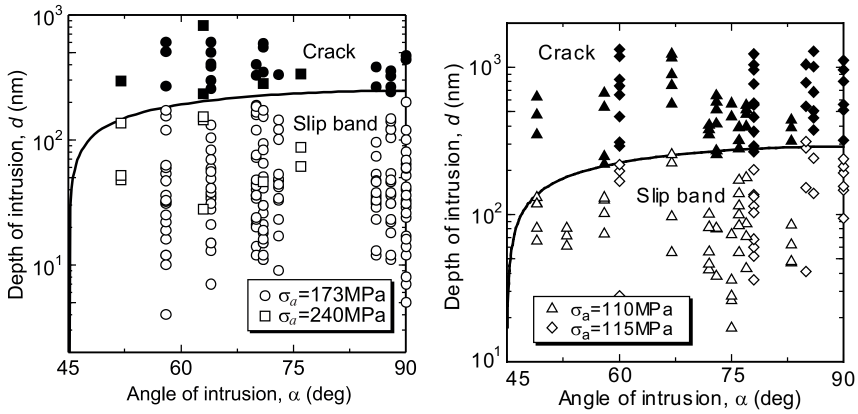


Figure 6: Intergranular fatigue crack initiation (Material B).



(a) Material A

(b) Material B

Figure 7: Transgranular fatigue crack initiation condition.

intrusion in a slip-band grew up to the critical value, a cracks was initiated from the intrusion.

These results indicate that the transgranular crack initiation is controlled by the damage accumulation due to the dislocation substructures rather than the stress concentration induced by the intrusion.

It is easy to predict when the depth reaches the critical value because the intrusion depth increased linearly with the logarithm of the number of cycles as shown in Fig. 5. Therefore, the location and remaining life of fatigue crack initiation can be predicted by measuring the intrusion depth few times before crack initiation.

Contrary to the transgranular cracking, the grain boundary depth at the intergranular crack initiation was not a unique function of the grain boundary angle relative to the stress axis. Other mechanism for the intergranular crack initiation should be considered, which may include the incompatibilities of deformation between two adjacent grains.

4. CONCLUSIONS

The fatigue slip-band formation and fatigue crack-initiation process in 70-30 brass were observed by means of AFM, and the following results were obtained.

(1) The depth of an intrusion drastically increased with its outgrowth to a crack, and with coalescence of cracks, the width of cracks increased rapidly.

(2) For the transgranular crack initiation, the intrusion depth at the crack initiation depended on the slip-band angle relative to the stress axis. At crack initiation, the slip distance in the slip direction, however, was constant independent of the slip-band angle, the stress amplitude, the mean stress, and the grain size.

(3) Intergranular cracks were formed along grain-boundaries between highly deformed grains and grains without activating slip systems. For the intergranular crack initiation, the value of the intrusion depth (the grain boundary depth) at the crack initiation was not a unique function of the grain boundary angle relative to the stress axis.

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