Characterization of fatigue crack initiation in $\alpha$-brass by means of AFM and EBSP

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Abstract: Slip-band formation and crack-initiation processes in $\alpha$-brass under cyclic shear stress were examined by means of atomic force microscopy (AFM), and the slip-direction was identified with electron back scattering pattern method (EBSP). From AFM observations, it was found that slip-bands were not always formed along the maximum resolved shear stress directions, and slip-systems could be activated in the direction whose angles from the surface were larger than 22°. The depth of an intrusion increased linearly with the logarithm of the number of cycles, and the increasing rate of the intrusion depth drastically increased with crack initiation. By combining the intrusion depth and the slip direction, those were measured with AFM and EBSP, respectively, the value of slip distance could be evaluated, and the critical values of the slip distance for the initiation of transgranular crack was found to be constant for all crack initiation sites, while the intrusion depth was not constant. The critical value of the slip distance for cyclic shear stress (torsion) was identical for cyclic normal stress (bending). A unique relationship between shear stress amplitude in the actual slip direction and number of cycles to failure was obtained for cyclic torsion and bending loadings.

Key words: Fatigue, Crack initiation, Cyclic shear stress, AFM, EBSP, Nanotechnology, Maximum shear stress theory

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 study on fatigue crack initiation is especially important for fatigue damage evaluation of micro-machine components because the fatigue life of these components is almost the crack initiation life [2, 3]. 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.

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, transmission electron microscopes (TEM), and scanning electron microscopes (SEM), however, successive, quantitative three-dimensional observations of the crack nucleation site in the specimen surface could not be conducted. Then, 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 the mechanisms of fatigue and fracture of solid materials. Nakai and his co-workers studied fatigue slip-bands, fatigue crack-initiation, and the growth behavior of micro-cracks in a structural steel [4], and $\alpha$-brass [5-8]. They reported for fine grain $\alpha$-brass that fatigue cracks were initiated only from the slip-bands. In a coarse grain $\alpha$-brass, however, they were initiated either from the slip-bands or the grain boundaries. The depth of an intrusion drastically increased with crack initiation, 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 and geometrical consideration, 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, and the grain-size. For crack-initiations from grain boundaries, however, the value of the grain boundary depth at the crack initiation was not a unique function of the grain boundary angle relative to the stress axis. In the present paper, slip-band formation and crack initiation processes in $\alpha$-brass under cyclic shear stress were examined by means of atomic force microscopy (AFM), and the slip-direction was identified with electron back scattering pattern method (EBSP) to elucidate fatigue crack initiation condition.
2. THEORY

Condition for the transgranular fatigue crack initiation can be analyzed by a geometrical model proposed by Tanaka and Nakai [9,10], which explains the relation between the surface-step and the slip-direction. The surface-step, \( d \), induced by a slip is

\[
d = s \sin \beta \cos \alpha'
\]  

(1)

where the value of \( s \) is the slip distance in the slip-direction, the value of \( \alpha' \) is the angle between the normal of 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 \( \beta \) is the angle between the slip-direction and the slip-traces on the surface (see Fig. 1). Although fatigue slip bands are not steps like Fig. 1, but they are intrusion and intrusions, Eq. (1) can be applied to fatigue slip bands because they are consequences of each step generated at each cycle.

A slip usually takes place along slip plane where the resolved shear stress exceeds the frictional stress of dislocation motion. For isotropic homogeneous material under uniaxial normal stress, lots of planes can be the maximum resolved shear stress plane whose normal has the angle of 45° from the loading axis as shown in Fig. 2 (a). Then, in polycrystalline materials, there are many grains whose slip plane is very close to the maximum resolved shear stress plane, and cracks are considered to be initiated from slip bands, which had slip systems in the maximum resolved shear stress direction [9,10].

For slip-bands, where the resolved shear stress along the slip-direction takes the maximum value, the following relationship should be satisfied.

\[
\cos \beta = \cos \alpha
\]  

(2)

\[
\cot^2 \alpha + \tan^2 \alpha' = 1
\]  

(3)

where the value of \( \alpha \) is the angle between the loading-axis and the trace of the slip-band on the surface. The value of slip distance can be calculated from the measured values of the depth of intrusion, \( d \), and slip band angle, \( \alpha' \), by substituting these values into Esq. (2), (3), and Eq. (1).

The relation between the slip distance and the number of cycles in uniaxial loading (bending) fatigue test is shown in Fig. 3, where open marks indicate data before the crack initiation, and solid marks show data after the crack initiation. The values of \( \alpha \) are also indicated in the figure. The slope of the line is changed with crack initiation, and cracks are initiated from slip bands when the slip distance reached a critical value. This critical value is 380 nm independent of stress amplitude.

The value was also found to be independent of stress ratio and grain size [7,8].

3. EXPERIMENTAL PROCEDURE

The material for the present study was 70-30 brass (\( \alpha \)-brass). The chemical composition and mechanical properties of the material are shown in Tables 1 and 2, respectively. After the specimens were made by an electric-discharge machining, they were heat treated at...
320 °C for 180 s. After the heat treatment, the grain size of the material was 20 µm. Before fatigue tests, surface of the specimens were electro-chemically polished.

As shown in Fig. 4, the specimen has a minimum cross-section of width 8 mm, and a thickness of 3 mm. The cyclic torsion fatigue tests were carried out in a resonance type fatigue-testing machine (Shimadzu TB-10) operated at a frequency of 33.3 Hz under fully reversed cyclic torsion.

Denoting by \( W \) and \( t \), respectively, the width (8 mm) and the thickness (3 mm) of the specimen, and by \( T \) the torque applied to the specimen, the maximum shear stress occurs along the center line of the wider face of specimen, and is given by the formula

\[
\tau = \frac{T}{kWt}
\]  

The value of \( k \) is 2.62 for \( W/t = 8/3 \) [11].

To conduct a quantitative analysis of the development of fatigue slip-bands, the scanning atomic force microscopy (AFM) was employed for the present study. The scanning area for the observations was 30 µm \( \times \) 30 µm. 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. With resonance type testing machine, static loading was not easy, then the AFM images were taken at the unloading state.

The replica films were coated by gold (Au) before observation. Although the height of the surface in the replica film was reversed from the specimen surface, the height of the replica film in the AFM images was reversed by an image processing technique.

Fig. 5. AFM images (\( \tau_a = 140 \) MPa, Scanning area 30 µm \( \times \) 30 µm, vertical scanning range 1 µm).

![AFM images](image)

![Change of surface geometry with stress cycles.](image)

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Crack initiation process

An example of AFM image of transgranular cracking process under cyclic shear stress (torsion) is shown in Fig. 5, and the change of geometry of cross section A, which is indicated in Fig. 5 (a), is shown in Fig. 6. In bending tests, the observations were conducted under maximum tension stress, and it was very easy to identify the crack initiation. In torsion tests, however, it was very difficult to observe under loading condition, therefore, these figures were taken under unloading condition. In this case, fatigue crack initiation is not easy to identify from these observations.

Change of the depth of intrusion is shown in Fig. 7.
as a function of the number of the fatigue cycles, \( N \). The depth of intrusion increases linearly with logarithms of number of cycles, and the increasing rate of the depth of the intrusion drastically increased at \( N = 3.5 \times 10^5 \) cycles. This change of the slope may come from crack initiation [7,8].

4.2. Crack initiation condition

In the theory for uniaxial stress, fatigue cracks were considered to be initiated from slip bands, which had slip systems in the maximum resolved shear stress direction. In torsion loading, however, only two sets of planes can be the maximum shear stress planes as shown in Fig. 2 (b), and the actual slip bands had slight angle from the maximum resolved shear stress direction as shown in Fig. 8. Then the slip distance cannot be calculated through the measurement of the slip depth by assuming that the slip plane is coincident with the maximum shear stress plane. Therefore, the direction of slip plane and the slip direction were experimentally measured by the electron back scattering pattern (EBSP) method. An example of the crystal orientation obtained by the EBSP methods is shown in Fig. 9, where each color indicates a specific orientation.

For the case of face-centered cubic (FCC) crystals, slip occurs most often on \{111\} planes and in \langle 110 \rangle directions. In all, there are 12 slip systems (four \{111\} planes and three \langle 110 \rangle slip directions for each \{111\} plane). With the EBSP method, one of \{111\} planes and one of \langle 110 \rangle slip direction can be identified. Other planes and directions can be determined from the geometrical relationships for FCC crystal. Since a slip line on surface is an intersection line of slip plane and surface plane, the actual slip plane can be identified from EBSP method and the actual slip line observed by microscopy.

Slip direction, however, cannot be specified from the methods mentioned above, then Schmid factor of the actual slip direction should be considered. The most reasonable assumption may be that Schmid factor of the actual slip direction is larger than that of other slip directions. Figure 10 shows examples of slip distance estimated by the assumption. Open marks show data before crack initiation, solid marks indicate those after crack initiation, and the value of \( \lambda_1 \) is the angle between the surface and the slip direction determined by the maximum Schmid factor criterion. For \( \lambda_1 = 22^\circ \) (Fig. 7 (a)), the slip distance at crack initiation is 380 nm, which is identical to that obtained for bending tests. For \( \lambda_1 = 4^\circ \) (Fig. 7 (b)), and \( \lambda_1 = 8^\circ \) (Fig. 7 (c)), the distance is about 3 \( \mu \)m and 1 \( \mu \)m, respectively. Surface observations of slip bands with AFM, however, did not support such large discrepancy across the slip line. Generally, for the values of \( \lambda_1 \) smaller than 22\(^\circ\), the estimated slip distance was unrealistically large. In the observations of slip bands formed under uniaxial stress fatigue, the value of \( \lambda_1 \) smaller than 18\(^\circ\) was not appeared [7,8], then the slip system may not be activated if it is almost parallel to the surface.

In the consideration of slip motion, image force does not act on the dislocation motion in the parallel direction of surface, but in the normal direction of the surface that operates to enhance the dislocation motion, \( i.e. \), dislocations can move normal to the surface by smaller force than in the parallel direction. The oxidation of newly created surface may be another factor to control the direction of dislocation motion. When the slip direction is parallel to the surface, there is no slip step, and fresh surface is not formed. Then reversible motion of slip plane is possible in reversed cyclic loading. On the other hand, by the absorption of oxygen atoms on the fresh surface, slip motion cannot occur in the same plane between tension going part and compression going part of the fatigue cycle, and intrusions and extrusions can easy to be formed.

By assuming for \( \lambda_1 \) smaller than 22\(^\circ\) that the slip direction should be the secondly large Schmid factor direction, the estimated slip distance is shown in Fig. 8. The estimated slip distance at the crack initiation is 380 nm
independent of the slip bands angle, and this value is identical to that for bending fatigue tests.

4.3. S-N curve

One of the most difficult tasks in fatigue is to translate the information gathered on the uniaxial fatigue to applications involving complex states of cyclic stress. The multiaxial approaches have been based on the following three criteria: (i) maximum principal stress, (ii) shearing energy (von Mises yield condition), and (iii) maximum shear stress (Tresca yield condition). If the fatigue damage of metallic materials come from slip motion of dislocations and it is controlled by the shear stress on the slip plane, the fatigue strength should be given as a unique function of cyclic shear stress amplitude. Experimental results on multiaxial fatigue, however, does not always support the maximum shear stress (Tresca) criterion. Nisitani and his co-workers reported that the ratio of fatigue limits of torsion and bending is larger for isotropic steels (0.68) than that for anisotropic steels with lamellar structure (0.58) [12-14]. They also reported that the ratio is much larger (0.77) for steels with small defects [15]. They discussed the difference of crack initiation site and strain concentration in ferrite grain in the materials, but it is still unsolved why the maximum shear stress criterion is not applied even for homogeneous isotropic material. Kitamura and his co-workers pointed out that the maximum shear stress evaluated by the formulae for the homogeneous isotropic materials cannot explain the local shear stress of polycrystalline metals, and they calculated the local shear stress in each grain by FEM analysis for anisotropic body [16]. The observation of slip direction in the present study, however, does not support such maximum shear stress criterion, but the
slip direction should be considered.

S-N curves of the present material for bending and torsion fatigue are shown in Fig. 12 by circular marks, where the value of \( \tau \) is the amplitude of maximum shear stress evaluated by the formula for homogeneous isotopic materials. The relation for torsion fatigue does not agree with that for bending fatigue, and fatigue strength is not controlled by the maximum shear stress amplitude. Open triangular marks show the relation for the torsion fatigue where the shear stress amplitude is that in the actual slip direction that was evaluated in last section, where the average value of Schmid factor was employed. By taking the assumption, the relation for torsion is almost identical to that for bending.

Actually, the fatigue life is the sum of crack initiation life and propagation life, and in most metals, the latter is more dominant than the former. In most cases, the fatigue crack propagation rate is controlled by the mode I component of the stress intensity factor, and fatigue life may be controlled by the maximum principal stress. Then the ratio of shear stress amplitude of cyclic uniaxial stress amplitude and the cyclic shear stress amplitude for the same fatigue crack propagation life may be 1:0.5. On the other hand, the ratio was 1:0.55 for crack initiation life by assuming that slip occurred in the secondly large Schmid factor direction. In the present material, the ratio is almost the same for crack propagation life and crack initiation life, then as a result, the consideration only for crack initiation can be explain the fatigue life of cyclic uniaxial stress and cyclic shear stress.

Short crack propagation life is more important for fatigue life analysis. Then the crack propagation law of short cracks under mixed mode should also be considered [17].

5. CONCLUSIONS

Slip-band formation and crack-initiation processes in \( \alpha \)-brass under cyclic shear stress were examined by means of atomic force microscopy (AFM), and the slip-direction was identified with electron back scattering pattern method (EBSP) to elucidate fatigue crack initiation condition. The following results were obtained.

(1) For transgranular cracking, the increasing rate of intrusion depth and slip distance drastically increased with crack initiation.

(2) When the slip distance reached a critical value, fatigue cracks were initiated from the intrusion. The critical value for torsion fatigue is identical to that for bending fatigue.

(3) Slip system, which is almost parallel to the surface, cannot be activated even if Schmid factor of the slip system is largest in that direction. In this case, slip system with secondary large Schmid factor may be activated.

(4) To employ the shear stress in the actual slip-direction, the relation between shear stress and fatigue life for torsion is almost identical to that for bending.

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REFERENCES