ULTRASONIC FATIGUE IN POLYCRYSTALLINE ALUMINUM

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ABSTRACT Ultrasonic fatigue tests at 20 kHz in the range of 10^7 to 10^{11} cycles and measurements of strain amplitude dependence of resonant frequency were carried out on polycrystalline aluminum. S-N curves decreased in 10^9 or more cycles. It was found that there is a critical strain (ε_c) below which slip bands were not formed on a specimen surface. The ε_c is believed to be a fatigue limit based on dislocation motion and generation, although the fatigue limit in practical meaning is defined whether or not specimens are fractured. Transmission electron microscopic observations of dislocation substructures in fatigued specimens showed that dislocation free zones were formed along the grain boundaries. It is considered that such zones prevent the accumulation of strain between grains.

Keywords: *ultrasonic fatigue, aluminum, fatigue limit, dislocation substructure, dislocation-free zone (DFZ)*

1. INTRODUCTION

Ultrasonic fatigue can be used to perform a fatigue test at high frequency, for example, in the range of 10 to 100 kHz [1-4]. By this method, resonant vibration is generated in a specimen by piezoelectric [1-3] or magnetostrictive [4] elements. This vibration deforms the specimen in a tension-compression mode. There are two primary advantages to use the ultrasonic fatigue testing machine: firstly, fatigue tests up to 10^7 cycles, which is the largest number in a conventional fatigue test, are accomplished in a short time, e.g., about 8 minutes in the case of a 20 kHz frequency; secondly, the technique is suitable to investigate fatigue limit phenomena, that is, high cycle fatigue, e.g., $10^8 \sim 10^{10}$ cycles, at low strain amplitude. The fatigue limit in practical meaning is defined as the minimum stress at which fatigue failure occurs. However, fatigue damages such as dislocation substructures, slip bands and microcracks can be formed below the practical fatigue limit, which implies that fatigue failure may occur as a result of accumulation of such damages after prolonged cycling. Actually, stress versus number of cycles to failure (S-N) curves in ultrasonic fatigue tests reported by Xiangen et al. [5] continued decreasing up to 10^{10} cycles.

In the present study, fatigue tests of aluminum in the range of 10^6 to 10^{11} cycles were carried out and an attempt was made to understand fatigue limit phenomena.

2. EXPERIMENTAL PROCEDURES

The ultrasonic fatigue testing machine used is schematically illustrated in Fig. 1. Four piezoelectric elements are used for driving, to which alternating current of about 20 kHz in frequency is applied and vibration is generated. The vibration is amplified and transferred to a specimen by a horn. Sizes of a half dumbbell shaped specimen is shown in Fig. 2. The specimen is resonantly vibrated in a longitudinal direction, leading to push-pull fatigue with the maximum strain at a distance one quarter of the wave length (λ) from the free end of the specimen. Displacement amplitude at the free end of the specimen (U_0) was measured by a scale in an optical microscope. The vibration is monitored by the other two piezoelectric elements for detecting (Fig.1). Applied voltage (V_a) and pickup voltage (V_p) from the driving and detecting elements, respectively, and resonant frequency (f_r) are recorded.

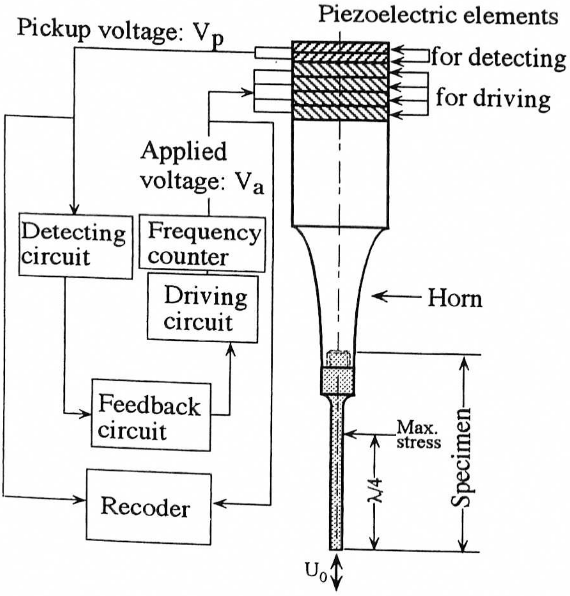

Fig.1 Schematic illustration of the ultrasonic fatigue machine.

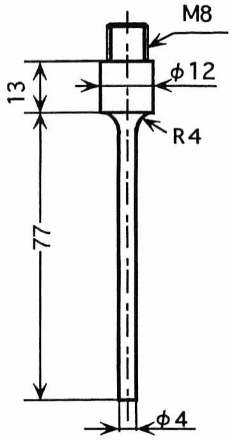

Fig. 2 Shape and sizes of the specimen.

Polycrystalline pure aluminum rods with 12 mm in diameter were turned and mechanically polished, then annealed at 473, 623 and 773 K for 3.6 ks in argon atmosphere and air cooled to room temperature. These treatments resulted in mean grain sizes of about 20, 25 and 60 μm in diameter, respectively. The gauge part of the specimen was electropolished before fatigue testing.

Tensile tests were carried out using specimens prepared from the same rod and annealed at the above mentioned conditions. Sizes of the gauge part were $5^{w} \times 10^{L} \times 2^{t}$ (mm).

Slip bands on the fatigued specimens were examined by a scanning electron microscope (SEM). Thin foil specimens for a transmission electron microscopic (TEM) observations were prepared from discs cut perpendicular to the longitudinal axis of the specimen.

3. RESULTS AND DISCUSSION

Since stress nor strain are not directly measured, they are calculated from the displacement U_0 [6]. Using the calculated stress values, S-N curves for the specimens are represented as shown in Fig. 3. Solid marks in the figure indicate that the specimens were fractured, while open marks means that the slip bands were formed on the specimen surfaces although they were not fractured. The curves decreased even in 10^9 cycles, although solid and broken lines were drawn only on the solid marks. The numbers of cycles for open marks have not any meaning but indicate stress levels at which fatigue damages are induced in the specimens without fatigue fracture. The largest number of cycles in this study is 10^{11} cycles for 623 K annealed specimen. Slip bands were observed by SEM on the surface of this specimen. However, it maybe doubtful that the slip bands were formed in the early stage of fatigue and did not act in the latter stage. Thus, slip bands were removed by electropolishing and the specimen was fatigued for additional 10^7 cycles at the same stress amplitude. The slip bands were observed again, that is, the slip bands were active, which means that fatigue fracture may occur in prolonged cycling. However, it seems to be time-consuming to carry out fatigue tests beyond 10^{11} cycles in order to confirm the fatigue limit.

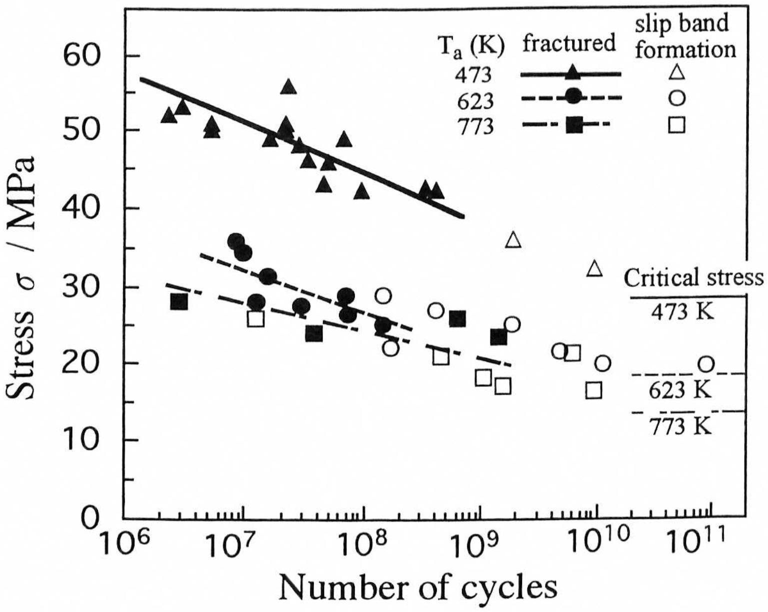

Fig. 3 S-N curves for the specimen annealed at 473, 623 and 773 K.

Thus, dependence of resonant frequency (f_r) on strain amplitude was measured using one specimen for each annealing condition. In general, f_r decreases with increasing ε as shown in Fig. 4. There can be seen inflection points in the curves, which are indicated by the arrows. In the previous paper [7], we reported the strain amplitude dependence of internal friction (Q^{-1}) and there existed critical strain amplitude (ε_c) below which fatigue deformation did not occur. The inflection points in Fig. 4 are considered to correspond to ε_c. Specimens annealed at 773 K were fatigued for 10^9 cycles at $\varepsilon=1.6\times10^{-4}$ and 2.1×10^{-4} which correspond to strain amplitude above and below ε_c, respectively, and examined by SEM. Surfaces of the specimens are shown in Fig. 5. There are no slip lines on the specimen fatigued below ε_c, (a), while many slip bands (bright contrast) can be seen on the specimen fatigued above ε_c, (b). It is considered that ε_c corresponds to the critical strain whether or not dislocation motion in long distance and generation can be occurred. The specimen

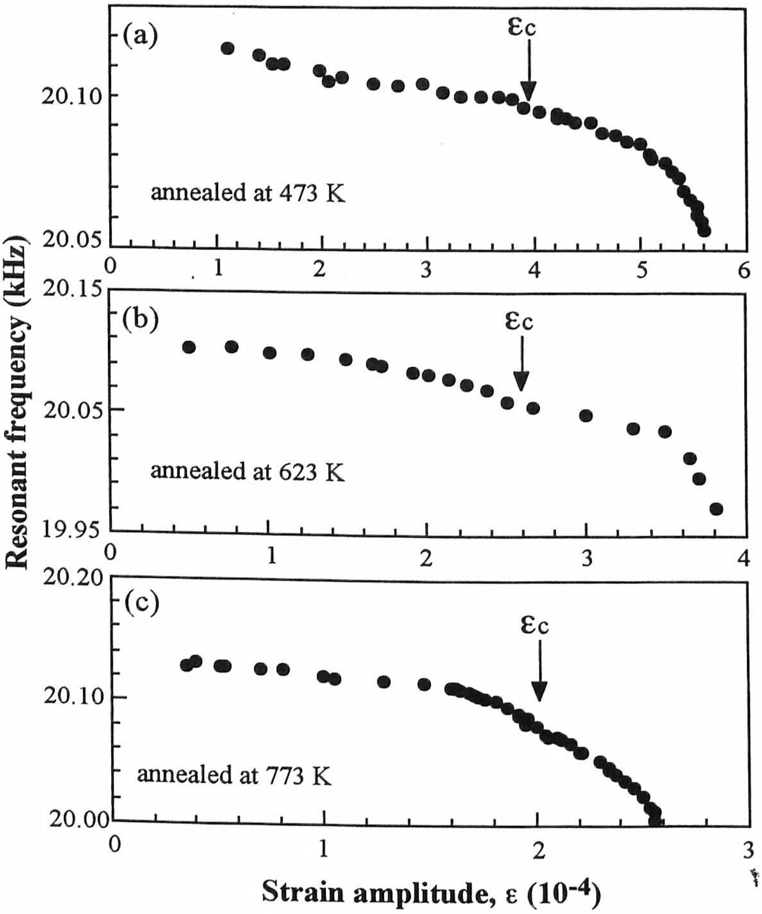

Fig. 4 Strain amplitude dependence of resonant frequency in specimens annealed at 473 (a), 623 (b) and 773 K (c).

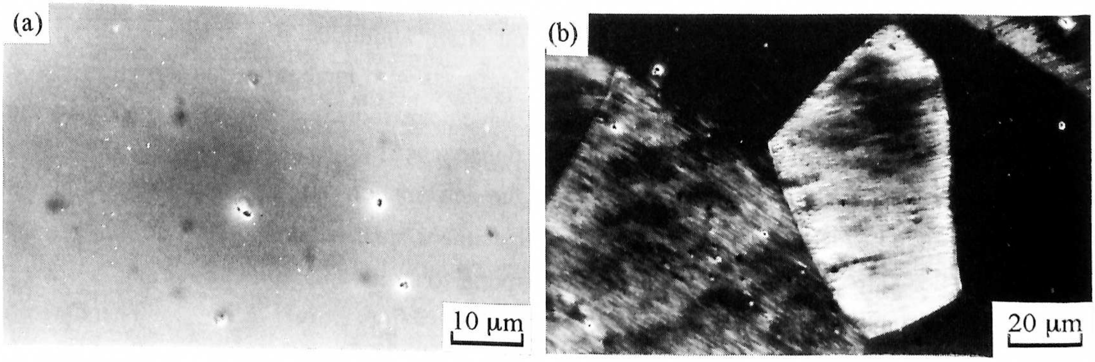

Fig. 5 Slip bands on the specimens fatigued for 10^9 cycles at $\varepsilon=1.6\times10^{-4}$: (a) and 2.1×10^{-4}: (b).

used here is polycrystalline, therefore, it should be expressed in more accurate that motion and generation of dislocations start in most grains above the ε_c. Internal friction is increased by dislocation motion, which results in increasing specimen temperature. The length of the specimen is increased by thermal expansion, which decreases f_r. Values of ε_c in the specimens annealed at 473, 623 and 773 K are about 4.0, 2.6 and 2.0×10^{-4}, respectively, stresses corresponding to these ε_c are about 28, 18 and 14 MPa, respectively, which are indicated in Fig. 3. S-N curves of the specimens annealed at each temperature are believed to approach asymptotically to these stresses.

Dislocation substructures formed in the specimens resemble those formed by fatigue deformation at conventional frequency. Figure 6 shows dislocation cell structure formed in the specimen annealed at 623 K and fatigued at a stress amplitude of about 23 MPa for 10^{11} cycles. In the specimens annealed at 473 K, similar structures were observed. However, dislocation substructures in the specimens annealed at 773 K seem to be different from Fig. 6. An example is shown in Fig. 7. The specimen was fatigued at about 24 MPa for 10^{10} cycles. Dislocation density is higher than that in Fig. 6. Moreover, there can be seen a zone with very low dislocation density along a grain boundary. Such a zone was reported by Winter et al. [8] in polycrystalline copper and named "dislocation free zone (DFZ)". DFZ in mild steel was also reported [9], but it has been found out in aluminum for the first time. In the specimen annealed at 623 K, DFZ was rarely observed although the zone was not so clear. Not all the grain boundaries are accompanied by DFZ, and in many cases, DFZ is formed only one side of the grain boundary (see Fig. 7).

Fig. 6 Dislocation substructure observed in the specimen annealed at 623 K and fatigued at 23 MPa for 10^{11} cycles.

Fig. 7 Dislocation substructure observed in the specimen annealed at 773 K and fatigued at 24 MPa for 10^{10} cycles.

Proof stresses obtained from tensile tests for the specimens annealed at 473, 623 and 773 K were 88, 49 and 17 MPa, respectively. The S-N curves in Fig. 3 for the specimen annealed at 473 and 623 K are drawn below each proof stress, while the curve for the 773 K annealed specimen is higher than the proof stress. Therefore, the dislocation density in 773 K annealed specimen is high compared with the other specimens. It is worth to notice that the 773 K annealed specimens resist fatigue fracture up to 10^9 or more cycles even though the applied stress is higher than the prof stress.

It is well known that the distance of shuttling motion of dislocations during fatigue deformation is a few micron meters, which was confirmed by in situ fatigue in TEM [10, 11]. However, an elemental process of fatigue deformation is an accumulation of irreversible components in dislocation motions, which causes a long range stress field in a grain. As mentioned above, the mean grain size of the 773 K annealed specimen is large, and DFZs tended to be formed in larger grains in the specimen. In such large grains, accumulated strain at grain boundaries are large. It can be seen that the contrast of a third left part of DFZ shown in Fig. 7 is dark. Tilting experiment showed that there is disorientation between DFZ and the grain interior. It is considered that DFZ accommodates strain between grains by this disorientation.

4. SUMMARY

It is considered that the ε_c is concerned with a microscopic yield, therefore, it is a fatigue limit based on dislocation motion and generation, and the S-N curve asymptotically approaches to the stress corresponding to the ε_c. DFZ is a significant feature in dislocation substructures when the specimen is fatigued above macroscopic yield stress, and it is considered that the DFZs prevent the accumulation of damages along grain boundaries.

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FATIGUE CRACK GROWTH PROPERTIES OF Al-Si-Mg BASE CAST ALUMINUM ALLOYS

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ABSTRACT The fatigue crack growth behavior of an Al-Si-Mg base cast alloy has been investigated with special reference to the effect of solidification structure and aging condition. Fatigue crack growth tests have been performed under the constant load amplitude condition at a stress ratio of R=0.1 using a CT specimen. Crack closure was also investigated during the test. The aging condition influenced the da/dN-ΔK relationship little . However, significant difference was observed for crack closure levels. This suggests that intrinsic fatigue crack growth rates were influenced by aging conditions. Refining and spheroidizing of eutectic Si particles reduced the fatigue crack growth rates over a wide range of ΔK.

keywords: *fatigue crack growth, Ai-Si-Mg base cast aluminum alloy, solidification structure, age hardening, eutectic Si particles*

1. INTRODUCTION

The call for improved economy in connection with high reliability is the overriding requirement for the development of transportation machine. It is demanded that the structure should have a long life and low weight. Efforts are presently concentrated on a substantial reduction of the manufacturing costs for components and assemblies which completes the manifold demands.

Cast aluminum alloys have satisfied these requirements because of its high specific strength and low cost. But the more extensive use of cast aluminum alloys has been hindered mainly by the lower strength in comparison with forging alloys [1]. And very few researches have been done so far on not only tensile properties but fatigue properties. As well as the S-N curves, evaluation of fatigue crack growth properties is important to improve the reliability of cast Al alloy. In general, the microstructure of material has great influences on fatigue properties [2]. Therefore, the fatigue crack growth properties of the cast aluminum alloy should be investigated with special reference to the effects of solidification structure.

In the present study, fatigue crack growth tests are performed on the sand cast Al-Si-Mg base alloys with the solidified structures controlled by changing aging conditions and morphology of eutectic Si. The sand cast alloys were hot isostatic pressing treated (HIPed) to eliminate the influence of casting defects. This will be beneficial to highlight the effect of microstructure on the