Fatigue properties of age-hardened Al alloy 2017-T4 under ultrasonic loading

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Abstract Fatigue properties of age-hardened Al alloy 2017-T4 under ultrasonic loading frequency (20 kHz) were investigated and compared with the results under conventional loading of rotating bending (50 Hz). The growth of a crack retarded at about 500 μm in surface length under ultrasonic loading, while at about 20 μm under rotating bending. Although striations being a typical fracture mechanism were observed under conventional loading, most of fracture surface was covered with many facets under ultrasonic loading. These facets were also observed under rotating bending in nitrogen gas. The difference in growth mechanism depending on the loading frequency and the retardation of a crack growth under ultrasonic loading may be caused by the environment at the crack tip due to high crack growth rate under ultrasonic loading. © 2012 The Chinese Society of Theoretical and Applied Mechanics. [doi:10.1063/2.1203108]

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Long term service and applications of high strength Al alloys as materials of components of machines and structures are very effective to reduce environment load. For this purpose, reliability for fatigue strength in long life region should be secured. However, the alloys have no definite fatigue limit.1,2 Moreover, it is a time consuming task to examine the fatigue properties in long life region. In order to save the testing time, ultrasonic fatigue test is an attractive technology for evaluation of fatigue properties in long life region.3,4 However, the effect of high frequency on fatigue properties is not fully understood. Especially, effects of environment, microstructure and loading frequency on the properties are important factors to be clarified.5,6

In the present study, fatigue tests under ultrasonic loading frequency (20 kHz) and rotating bending (50 Hz) were carried out for an age-hardened Al alloy 2017-T4 (Al-Cu-Mg alloy), to investigate the effect of loading frequency on the growth behavior of a crack.

Material used was a drawn bar of an age-hardened Al alloy, 2017-T4. The chemical composition (mass %) of the alloy were 0.41Si, 0.32Fe, 3.87Cu, 0.7Mn, 0.62Mg, 0.04Cr, 0.03Zn, 0.04Ti and remainder Al. The mechanical properties were 0.2% proof stress of 303 MPa, tensile stress of 464 MPa and reduction of area of 43.7%. Mean grain size was about 18 μm.

Figure 1 shows the shape and dimensions of the specimens. The fatigue tests were carried out using a 20 kHz piezoelectricity actuated ultrasonic machine and rotating bending testing machine operated at 50 Hz repetition in ambient air. Moreover fatigue tests were also carried out under rotating bending in nitrogen (N₂: > 99.995%, O₂: < 5 mg/kg, H₂O: < 10 mg/kg) gas to investigate the effects of water vapor and oxygen gas in ambient air. In ultrasonic fatigue test, a pulse-pause test with times of 1 s and 5 s was performed to reduce the temperature rise under high frequency. The observation of fatigue damage was conducted under a scanning electron microscope (SEM). Surface crack length was measured along the circumferential direction on the surface under an optical microscope using the plastic replica technique. Fatigue tests were interrupted at certain numbers of cycles to make replica on the surface of specimens. The influence of repetitious

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process on the fatigue life was hardly recognized.

Figure 2 shows $S$–$N$ curves in both tests. Fatigue strength under ultrasonic loading is higher than that under rotating bending. Figure 3 shows crack growth curves. A crack initiated at the early stage of stress repetitions meaning that fatigue life may be evaluated by the growth life of a crack, especially smaller than about 1 mm under both tests. In the growth process of a crack, a marked retardation of a crack growth is confirmed at about 500 $\mu$m in length under ultrasonic loading and about 20 $\mu$m of the order of grain size under rotating bending at the stress tested.

Figure 4 shows the relation between crack growth rate and stress intensity factor range. Marked retardation of crack growth at around $\Delta K \approx 10$ MPa $m^{1/2}$ and $(2–3) \times 10^{-9}$ m/c is confirmed under ultrasonic loading, and the crack growth rate is lower under ultrasonic loading than that under rotating bending in wide life region. A crack propagated in a tensile mode macroscopically after the initiation of a shear mode crack under both tests. Figure 5 shows crack morphologies. A crack propagated in a tensile mode macroscopically after the initiation of a shear mode crack under both tests. That is, there is no obvious difference in the feature of a crack from the surface observation.

Fracture surfaces under both tests are shown in

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**Fig. 2.** $S$–$N$ curves.

**Fig. 3.** Crack growth curves.

**Fig. 4.** Crack growth rate against stress intensity factor range.

**Fig. 5.** Morphologies of surface cracking under different loading frequency.

**Fig. 6.** Under ultrasonic loading, many facets are observed at fracture surface yielded by the tensile mode crack and there are few striations which are a typical growth mechanism of a fatigue crack as shown in Fig. 6(b) under rotating bending. Figure 7 shows the cross section of facets. Results of ESBD indicates most of facets inclined about 45$^\circ$ to the tensile loading direction. Moreover wavy pattern is confirmed at the surface of a facet, suggesting that the facet is yielded by slip. Crystallographic plane is also observed by etch pit method. A shape of a pit is triangle, meaning that the facet is the slip plane. From the results mentioned above, the difference in the growth mechanism of a fatigue crack due to loading frequency may be explained from the environment at the crack tip due to the high crack growth rate under ultrasonic frequency. That is, the actual crack growth rate under ultrasonic loading is very high in comparison with that under the conventional loading frequency. Therefore the environment at the crack tip may be similar to the one in vacuum.

In order to examine the above inference, rotating bend-
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Fatigue tests are carried out in nitrogen gas where hardly contains oxygen and water vapor.

Figure 8 shows fracture surface tested under rotating bending in nitrogen gas. There are many facets and striations at the fracture surface, meaning that the growth mechanism is nearly the same as the one under ultrasonic loading. Therefore, the retardation of a crack growth under ultrasonic loading may be considered due to the change in fracture mechanism while the one under rotating bending be due to the barrier effect of a grain boundary to the growth.

Fatigue tests under ultrasonic loading frequency and rotating bending are carried out for a drawn bar of an age-hardened Al alloy 2017-T4, to investigate the effect of loading frequency on growth behavior of a fatigue crack. The growth of a crack retards at about 500 μm in length under ultrasonic loading, while at about 20 μm under rotating bending. Although striations are observed under rotating bending, fracture surfaces are covered with many facets under ultrasonic loading. These facets were also observed even in rotating bending in nitrogen gas. The difference in growth mechanism depending on the loading frequency was explained from the difference in environment at the crack tip.
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