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Fatigue voids in structural Al-alloys under high-frequency cyclic loading

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Aluminum alloys are widely used for automotive and aerospace structural applications. Fatigue induced from various mechanical or aeromechanical sources can reach the very long life region ($>10^7$ cycles) due to high frequency vibrations. The required design lifetime of many engine, wheel, chassis, and body components often exceeds 10^9 (giga-range) cycles [1, 2]. In recent years there has been a development of interest in very long life fatigue between 10^7 and 10^{10} cycles for various high strength steels [2–6]. It is well known that many materials, including aluminum alloys, do not exhibit a conventional endurance limit in S-N curves between 10^6 and 10^7 cycles [7]. Fatigue failure could occur beyond 10^7 cycles. It is therefore important to realize the risk of using an arbitrary cut-off value of 10^6 (or 10^7) cycles to establish the fatigue limit. However, only limited studies of very long life fatigue and near threshold fatigue crack growth behavior of aluminum alloys have been performed due to testing time limitations with conventional equipment. A possibility for accelerated testing of specimens involves the use of high-frequency cyclic loading. The piezoelectric fatigue technique provides one practical means of generating very high cycle fatigue data [2–4, 7].

The formation, growth, and coalescence of interfacial voids in the static fracture process of metallic materials have been frequently observed and extensively investigated by numerous researchers [8–11]. In early studies, the significant effect of hydrostatic, bi- and tri-axial stress states on the evolution of voids in ductile fracture was established. Voids are also noticed in fatigue fracture in 2xxx-series aluminum alloys [12]. Al-alloys, such as 2024/T3, 7075/T6, and 6061/T6, contain numerous constituent particles of brittle phases dispersed in the ductile matrix, which play an important role in void formation [13]. Interfacial void formation usually occurs in the presence of second phase particles or inclusions. When ductile matrix materials are subjected to static or cyclic loads, ductile (fatigue) fracture may result from the nucleation, growth and coalescence of microscopic voids.

In this study, fatigue behavior of 7075/T6 and 6061/T6 aluminum alloys in the very long life regime (10^4–10^9 cycles) was investigated by using piezoelectric accelerated fatigue tests at 19.5 KHz. Moreover, the mechanism of fatigue crack initiation and propagation by void formation and growth has been identified using scanning electron microscopy (SEM).

Two aluminum alloys, 7075/T6 and 6061/T6, were selected for this study. The mechanical properties and the chemical composition are shown in Tables I and II, respectively.

Hourglass-shaped specimens designed to resonate longitudinally at 19.5 KHz were machined from 6061/T6 and 7075/T6 alloys, both supplied in the form of 20 mm diameter bar. All the specimens had a gauge length of 27.1 mm, a gauge diameter of 4.0 mm, a maximum section diameter of 12.0 mm, and a continuous radius of 25.0 mm. The total resonance lengths of the specimens calculated using an analytical method [14] are 67.0 mm for 6061/T6 alloy and 69.1 mm for 7075/T6 alloy. A diagram of the specimen is shown in Fig. 1. The specimen gauge surfaces were mechanically polished with emery paper before testing.

Fatigue testing was carried out in a piezoelectric resonance system operating at 19.5 KHz with zero mean stress ($R = -1$). The testing facility has been described in detail elsewhere [7, 14]. The vibration loading amplitude was controlled during the test. The specimens were cyclically loaded until failure or up to 10^9 cycles as run-out.

Fig. 2 shows the S-N curves for the 6061/T6 and 7075/T6 aluminum alloys in the very long life range of 10^4–10^9 cycles. The experimental results show that fatigue fracture can occur in both Al-alloys beyond 10^7 cycles. The fatigue strength at 10^7 cycles is 210 MPa for 7075/T6 Al-alloy, much better than the 140 MPa for 6061/T6 Al-alloy. Fatigue properties of 7075/T6 are superior to those of 6061/T6 alloy due to its superior tensile strength. Fractographic examination was performed using SEM. The crack initiation sites were

TABLE I Mechanical properties

Material	E (Gpa)	ρ (kg/m^3)	σ_T (MPa)	σ_Y (MPa)
7075/T6	72	2800	764	691
6061/T6	69	2800	478	310

TABLE II Chemical composition (wt%)

Material	Si	Cu	Fe	Mn	Mg	Cr	Zn
7075/T6	0.10	1.47	0.25	0.03	2.56	0.20	5.46
6061/T6	0.70	0.27	0.44	0.02	0.90	0.08	0.05

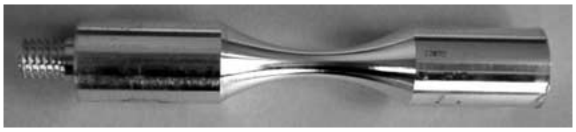

Figure 1 Shape of the test specimen.

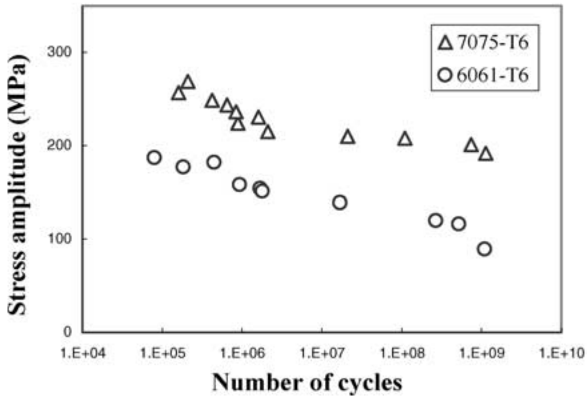

Figure 2 2 S-N curves of 7075/T6 and 6061/T6 Al-alloys.

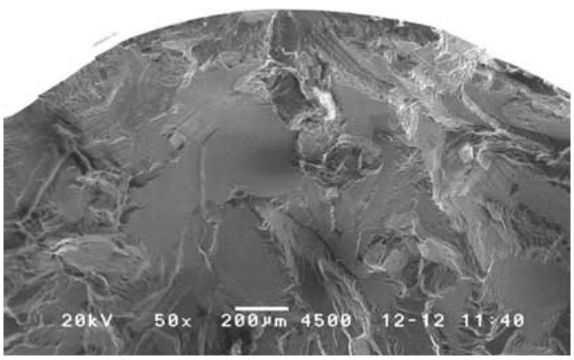

Figure 3 SEM micrograph of the fatigue fracture surface of 6061/T6 alloy.

found almost always on the surface, unlike with high strength steels, where subsurface crack initiation was dominant in the long-life regime [2–7].

The fracture surfaces of tested specimens were investigated by SEM. Fig. 3 shows a typical high cycle fatigue fracture surface of a 6061/T6 specimen. Localized inhomogeneous planar slip deformation of the crack surface was visible. A translamellar cleavage fracture mode was observed in the alloy. Subsurface facets produced micro-voids and initiated fracture in the fatigue process. A population of micro-voids on the fracture surface was formed during crack initiation and early growth (Fig. 4a and b). The expanding voids coalesce to form drawing lines in the cleavage facets. The line-type voids then act as macro-cracks. Fatigue failure starts with the formation, growth, and coalescence of interfacial voids and ends with the propagation of macro-cracks initiated at the base of the voids.

Again, the fracture surfaces of 7075/T6 alloy (Fig. 5) have a facetted appearance, although the facets are smaller than those in 6061/T6 alloy, and significant interfacial void is observed in the fatigue crack growth process (Fig. 6). Fatigue crack growth was initially

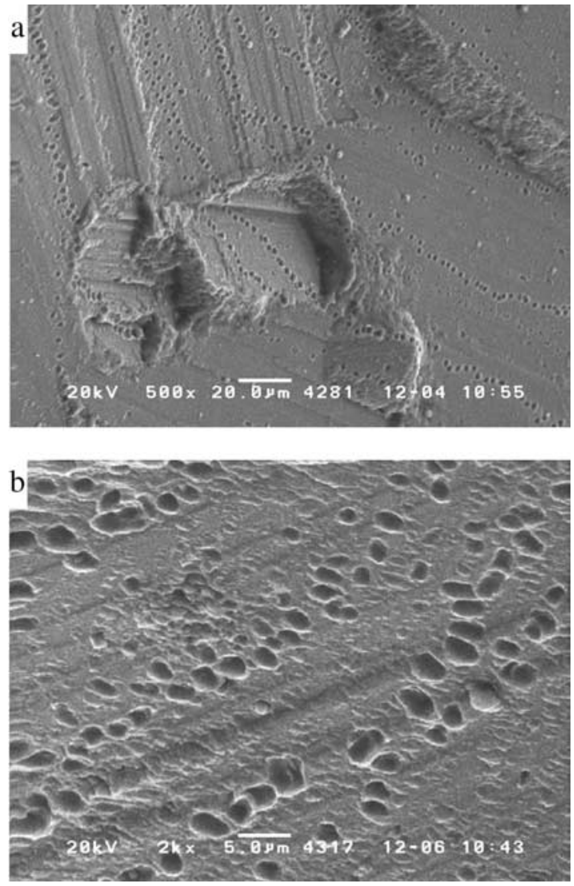

Figure 4 SEM micrographs showing a drawing line distribution of fatigue voids in 6061/T6 aluminum alloy: (a) at low magnification and (b) at high magnification.

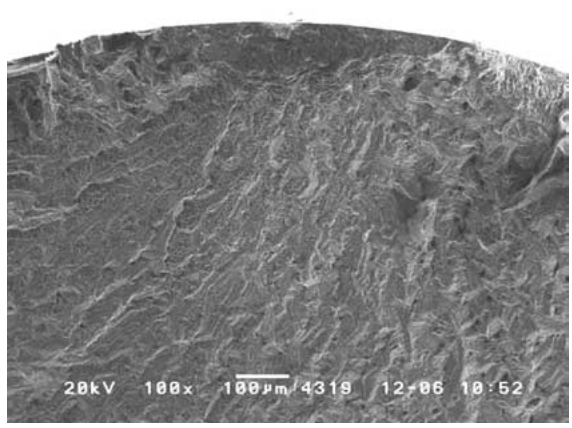

Figure 5 SEM micrograph of the fatigue fracture surface of 7075/T6 alloy.

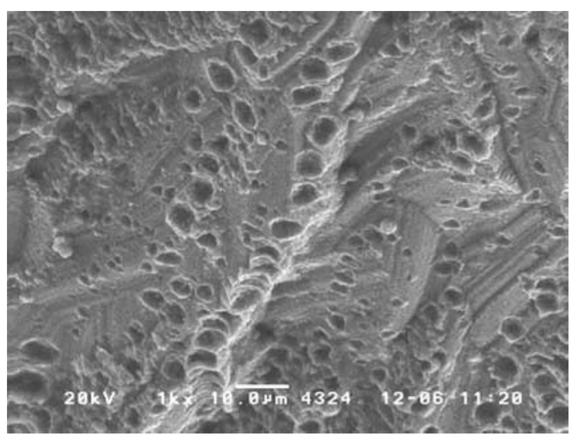

Figure 6 SEM micrograph showing fatigue voids in 7075/T6 alloy.

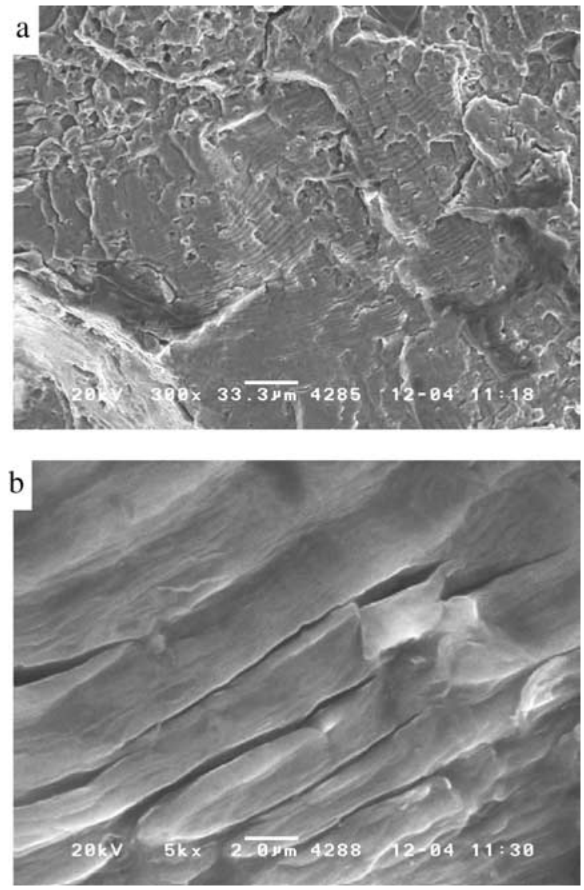

Figure 7 SEM micrographs showing fatigue brittle striations in 6061/T6 aluminum alloy: (a) at low magnification and (b) at high magnification.

transgranular, followed by a mixed transgranular-intergranular fracture. The mixed fracture surface exhibits flat cleavage areas with a population of micro-voids. The voids coalesce to form void lines randomly distributed through the alloy microstructure. The void lines can be considered as macroscopic cracks.

It is observed that significant interfacial voids occur in the two Al-alloys in the early fatigue crack growth process. At high crack growth rate, limited fatigue voids are noticed (Fig. 7), instead, brittle striations are well defined. A recent study [15] has shown that the appearance of voids modifies the instantaneous macroscopic response of 7055 Al-alloy. With continued cyclic deformation, the initiation of a population of voids, coupled with their growth and coalescence, as a result of strain localization between expanding voids, facilitates small increments of crack-tip extension. Fatigue failure in Al-alloys might be ascribed to: the formation of a number of fatigue voids; their growth and coalescence through the microstructure; and eventual formation of macroscopic cracks.

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