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Fatigue crack propagation in ultrafine grained Al–Mg alloy

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Abstract

The fatigue crack growth rates in ultrafine grained (UFG) Al–7.5Mg were investigated and were compared to those observed in powder-metallurgy (P/M) Al–7Mg and ingot-metallurgy (I/M) Al–7Mg. Fatigue crack growth rates in UFG Al–7.5Mg are significantly higher than those of P/M Al–7Mg, which, in turn, are significantly higher than those of I/M Al–7Mg. The fatigue crack growth threshold is the lowest in the UFG Al–7.5Mg, followed by P/M Al–7Mg, and is the highest in I/M Al–7Mg. The higher fatigue crack growth rates and lower thresholds in UFG Al–7.5Mg may be attributed to the much smoother fracture surface morphology and lower roughness-induced crack closure and crack deflection.

Keywords: Fatigue crack growth; Fatigue crack growth threshold; Ultrafine grained material; Microstructure; Aluminum

1. Introduction

Nanocrystalline materials have received considerable attention recently due to the possibility of improved surface, electronic, optical, magnetic, and/or mechanical properties. Because of the difficulties in producing submicron materials in sufficiently large quantity and quality, many of the studies on nanocrystalline materials have been limited to thin films or very small samples. Mechanical properties of submicron materials have thus often been deduced indirectly from microindentation tests due to the limited amount of material available. With recent advances in nanocrystalline materials production techniques, such as ball-milling at cryogenic temperatures (cryomilling), large quantities of Al–Mg particulates with grain sizes of several nanometers can be successfully produced [1–5]. After subsequent elevated temperature powder compaction and extrusion, the grain size of the extrusion is still in an ultrafine grain range (100–1000 nm). Tensile properties, creep behavior, and fatigue crack growth have been investigated for ultrafine grained (UFG) Al–Mg alloys [1,2,6]. However, a direct comparison of the fatigue crack growth behavior of the very small grain size Al–Mg alloy with larger grain sized materials of similar composition has not been made.

In the present study, the fatigue crack growth rates and fatigue crack growth threshold stress intensity factor ranges (ΔK_{th}) of an UFG Al–7.5Mg alloy in ambient air were evaluated and were compared to those of larger grained powder metallurgy (P/M) Al–7Mg and ingot metallurgy (I/M) Al–7Mg alloy.

2. Experimental procedures

The ultrafine grained material used in this study was 101.6-mm-diameter Al–7.5Mg (wt%) extruded rod. Spray atomized Al–7.5Mg powders with a particle size less than 100 μm were mechanically ball milled in liquid nitrogen for 8 h. Details of the cryomilling processes can be found in Ref. [7]. The cryomilled powders were degassed at 317 °C in a 1.33×10^{-4} Pa vacuum, consolidated by hot isostatic pressing (HIP) at 317 °C and 200 MPa, and then extruded at 202 °C into an 101.6-mm-diameter rod with an extrusion ratio of 6.5:1.

For comparison purposes, larger grained Al–7Mg (wt%) fabricated by powder metallurgy (P/M) and ingot metallurgy (I/M) processes were obtained and were included in this investigation. A valid comparison among fatigue crack growth responses in UFG Al–7.5Mg and P/M and I/M Al–7Mg is expected as the UFG Al–7.5Mg and the P/M and I/M Al–7Mg fall into the same two phase equilibrium field,

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with the differences in the amount of precipitate at equilibrium no more than 7% based on phase diagram calculation. The P/M Al–7Mg was made first by producing inert gas atomized powders, followed by vacuum degassing and compaction at 440 °C, and extrusion at 410 °C. The extruded bar had a cross-section of 25.4 mm by 76.2 mm. The I/M Al–7Mg had a cross-section of 76 mm by 457 mm.

For fatigue crack growth studies, 5.08-mm-thick compact-tension (CT) fracture mechanics specimens with a width of 38.1 mm and oriented in the L–C direction (the crack plane is perpendicular to the extrusion direction and the crack growth direction is parallel to the circumferential direction) were machined from as-extruded UFG Al–7.5Mg rod. For P/M and I/M Al–7Mg, CT fatigue specimens were oriented in the T–L direction (the crack plane and the crack growth direction are parallel to the longitudinal direction). Side grooves with depths equal to 5% of the thickness were introduced on both sides of each fatigue specimen to enhance constraint. The stress-intensity factor range (ΔK) for the CT specimens was computed from Eq. (1) [8]

$$\Delta K = [\Delta P/(BW^{1/2})][(2 + a/W)(0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4]/(1 - a/W)^{3/2}, \quad (1)$$

where ΔP = applied load amplitude, B = specimen thickness, W = specimen width, and a = crack length. The fatigue crack growth experiments were conducted in accord with ASTM E 647 in ambient air (20 °C and 42% relative humidity) with a cyclic load frequency of 5 Hz, a sine waveform, and load ratios R ranging from 0.1 to 0.8 [9]. Fatigue crack length was continuously monitored using the compliance technique. Details of the fatigue crack growth test procedures can be found in Refs. [6,10]. After fatigue tests, the fatigue-fractured surfaces were studied by scanning electron microscopy (SEM). Profilometry was used to measure the fracture surface roughness of the post-fatigue specimens.

3. Results and discussion

3.1. Microstructure and tensile properties

The average grain size of the as-cryomilled Al–7.5Mg powders was estimated to be about 25 nm by the X-ray diffraction technique. Following elevated temperature degassing, HIP, and extrusion, even though the grains have coarsened considerably, the average grain size of UFG Al–7.5Mg is still very fine and is about 0.25 μm. Fig. 1a shows a TEM micrograph of this UFG Al–7.5Mg. No intergranular or intragranular precipitates were observed. The excess Mg was in supersaturated solid solution. The selected area diffraction (SAD) ring pattern, as shown in Fig. 1a, is typical for a very fine grained alloy. Fig. 1b shows a TEM micrograph of P/M Al–7Mg. The average grain size in P/M Al–7Mg is about 2 μm. There are numerous fine Al_3Mg_2 precipitates in the grain interior, but not at the grain boundaries. Fig. 1c shows an optical micrograph of I/M Al–7Mg. Large Al_3Mg_2 precipitates are present both at the grain boundaries and in the grain interior. The average grain size in I/M Al–7Mg, as shown in Fig. 1c, is about 100 μm, which is about 50 times larger than that in P/M Al–7Mg (Fig. 1b), and is over two orders-of-magnitude larger than that in the UFG Al–7.5Mg (Fig. 1a).

Tensile properties in the longitudinal direction (parallel to the extrusion direction) of UFG Al–7.5Mg are tabulated in Table 1, together with those of P/M Al–7Mg and I/M Al–7Mg. As shown in Table 1, the yield strength of UFG Al–7.5Mg is more than twice that of P/M Al–7Mg, and is about four times more than that of I/M Al–7Mg. The effect of grain size on yield strength is further illustrated in Fig. 2. As shown in Fig. 2, the yield strengths of the three Al–Mg alloys follow a Hall–Petch relation and are linearly proportional to $d^{-1/2}$, where d is the average grain size. The Hall–Petch slope in Fig. 2 is 0.223 MPa $\sqrt{\text{m}}$. This observation indicates that the flow stress of these materials is primarily related to the grain size, and only secondarily related to the precipitates. The tensile elongation of the UFG Al–7.5Mg, however, is significantly lower than those of both P/M Al–7Mg and I/M Al–7Mg.

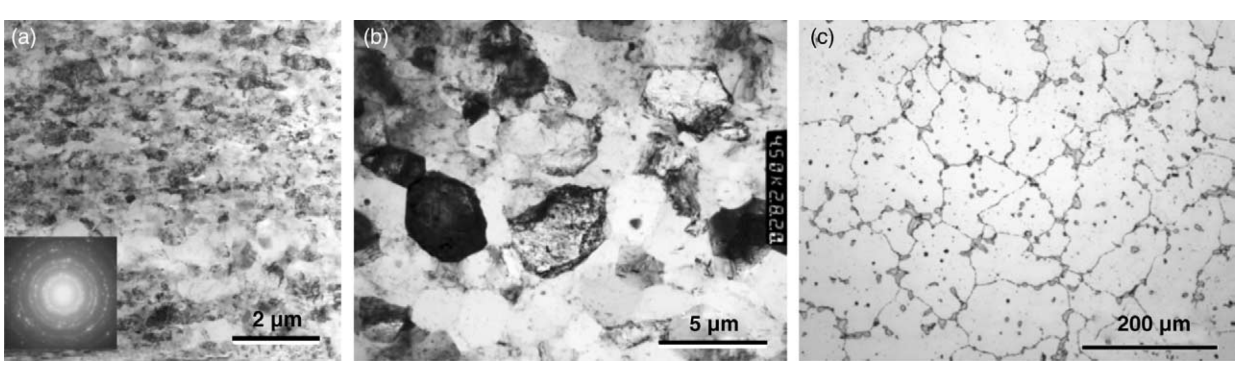

Fig. 1. (a) TEM micrograph of UFG Al–7.5Mg. (b) TEM micrograph of P/M Al–7Mg. (c) Optical micrograph of I/M Al–7Mg.