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Notch fracture toughness of high-strength Al alloys

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ABSTRACT

In this study, the notch fracture toughness (*NFT*) of high-strength Al alloys was examined by a non-standardized procedure. The *NFT* is defined as the critical notch stress-intensity factor (*NSIF*) $K_{\rho,c}$, which is determined by using several methods of analysis and computing. A set of specimens with different notch root radii made from overaged 7xxx alloy forging was selected. The influence of the notch radius on the fracture toughness of the material was considered. It was found that the notch radius strongly affects the fracture behavior of forged 7xxx alloy in overaged condition. The notch fracture toughness was higher than the fracture toughness of a cracked specimen and increased linearly with notch radius. The critical notch radius was related to the spacing of intermetallic (IM) particles which promote an intergranular or transgranular fracture mechanism according to their size. It appeared that ductile transgranular fracture generated by the formation of dimples around dispersoids and matrix precipitates was predominant which indicates that intense strains are limited to a much smaller zone than the coarse IM particles spacing. This double mechanism is also operate for crack propagation of ductile fatigue. The nature and morphology of IM particles exert significant effects on the rate of fatigue crack growth and fracture toughness properties.

1. Introduction

High-strength Al–Zn–Mg–Cu alloys of the 7xxx series are very important light-weight structure materials and widely used in the military and aerospace industries [1]. Knowledge of the fracture characteristics of these alloys is an important factor in application under failure-safe design [2], taking into account that the fracture toughness in aluminum alloys is one of the main obstacles to using these materials in widespread ways [3]. Failure-safe design is based on valid plane-strain fracture toughness (K_{Ic}) values. The material property "K_{Ic}" characterizes the resistance of a material to fracture in the presence of a crack-like defect under a fracture opening mode, considered as the most dangerous. For conservative reasons, this property is measured with stress state near the crack front as plane strain and confined plasticity. If these conditions are valid, the K_{Ic} value represents a lower limiting value of fracture toughness, which leads to a very conservative design and estimation of failure stress and critical defect size for a material in service under similar stress state conditions [4]. The conditions to obtain a valid value are described in the ASTM Standard Test Method ASTM E1820-09e1 [5]. This standard is, however, an expensive and time-consuming method due to the necessity of using pre-cracked specimens. In addition, the fatigue pre-cracking must be done with utmost care for a valid test [6] and is not appropriate for very brittle materials. In order to prevent over conservatism inherent when using the crack-like concept, it is possible to determine the fracture resistance from the real defect radius using the Notch Fracture Mechanics (NFM) approach. On the other hand, it has been seen that fracture behavior depends on the notch severity [7,8]. As reported by Akourri et al. [8], the "notch" fracture toughness increases linearly with the square root of the notch radius ρ. The slope of the relationship between fracture toughness and notch radius is called the notch sensitivity and is an additional characteristic of a material.

By applying the Notch Fracture Mechanics and particularly the Volumetric Method, the notch sensitivity a 7xxx alloy was determined. The obtained values are compared using the solution given by Creager and Paris [9] and Classical Linear Fracture Mechanics. The alloy microstructure and fracture mechanisms reported earlier in our extensive studies [10–14] are also presented.

2. Characteristics of material

The used material is a commercial aluminum alloy: Al–7.30 Zn–2.26 Mg–1.55 Cu–0.29 Mn–0.18 Cr–0.13 Zr–0.015 Ti–0.007

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V–0.003 B–0.16 Fe–0.09 Si (mass%). Alloy plates (Ø 500 × 51 mm) are produced by a conventional industrial procedure involving casting, two-step homogenization, hot forging with 85% height reduction, solution treatment, water quenching and two-step artificial ageing (T73 treatment). Further details of the alloy production are given in the literature [15].

According to the process conditions, the alloy is unrecrystallized due to the addition of Cr, Mn and Zr, which formed dispersoids that could effectively pin grain boundaries to prevent the occurrence of recrystallization. The unrecrystallized grains were straight and highly elongated in the direction of the prevailing deformation, Fig. 1a. Intermetallic (IM) particles of different sizes can also be seen in the microstructure. Their nature and morphology were characterized in our previous studies [10–15] using light microscopy (LM) and scanning electron microscopy (SEM).

In general, two types of IM particles could be observed in these overaged plates. One type was coarse (>1 μm) particles formed during solidification and aligned with flow direction during the hot forging. The other type was smaller dispersoids, inter- and intragranular precipitates (<0.02–0.5 μm in diameter). The coarse IM particles present in an amount of 0.669 vol.% were identified essentially as (Cu,Fe,Mn)Al_3, Al_7Cu_2Fe and Mg_2Si phases. As discussed later in this article, these types of particles are brittle and act as the preferred site for crack initiation. Selective etching also revealed that there were particles of *S*-$CuMgAl_2$ and η-Mg(Zn,Cu,Al)$_2$ phases, in addition to the Fe- and Si-containing particles. The presence of these soluble phases in the microstructure of the forgings indicates that the applied regime of homogenization and solution treatment was ineffective.

As can be seen from Fig. 1b and c, the microstructure of homogenized ingots was heterogeneous and contained, besides densely distributed precipitates, coarse IM particles situated at grain and dendrite arm boundaries. The energy-dispersive spectroscopy (EDS) analysis performed in previously [15] revealed that most of these particles were insoluble Fe-containing phases. The Mg_2Si phase, the dissolution of which proceeded slowly during homogenization, was present in a lesser amount, possibly due to the very low Si content in this alloy. However, the alloy contains relatively high solute levels, which contribute to the formation of soluble IM phases containing Al, Zn, Mg and Cu. It appeared that excess amounts of these phases, identified as η-Mg(Zn,Cu,Al)$_2$ and *S*-$CuMgAl_2$, were not removed during the dissolution process. As a consequence, the amount of fine hardening precipitates developed during the ageing stage decreased, which might be reflected in a lower yield stress level. On the other hand, the cracks initiated at either the η- or *S*-phase particles in this alloy are negligible [11,13,14]. Furthermore, as will be discussed in the next section, these particles contribute beneficially to the fatigue life.

This alloy provides high strength in the T6 temper, but is susceptible to fracture and stress-corrosion cracking (SCC). The fracture and SCC resistance can be improved by T73 treatment. However, the strength is considerably sacrificed due to severe overageing. To increase both the strength and fracture resistance simultaneously, the size of the alloy parts must be enlarged. Thus, a good combination of strength, fracture toughness and SCC resistance of thicker products can be obtained by the T73 treatment. The tensile (yield strength, σ_y, ultimate tensile strength, σ_{UTS}, and total elongation, *A*) and fracture toughness (critical *J*-integral, J_{Ic}, and plane-strain fracture toughness, K_{Ic}) properties of alloy plates in the radial-longitudinal (RL) orientation are presented in Table 1. The methods used to determine these mechanical properties at room temperature according to ASTM Standards are described in details elsewhere [12,14,15]. The validity of the K_{Ic} fracture mechanics parameter was verified using adequate methods as described previously [12,14].

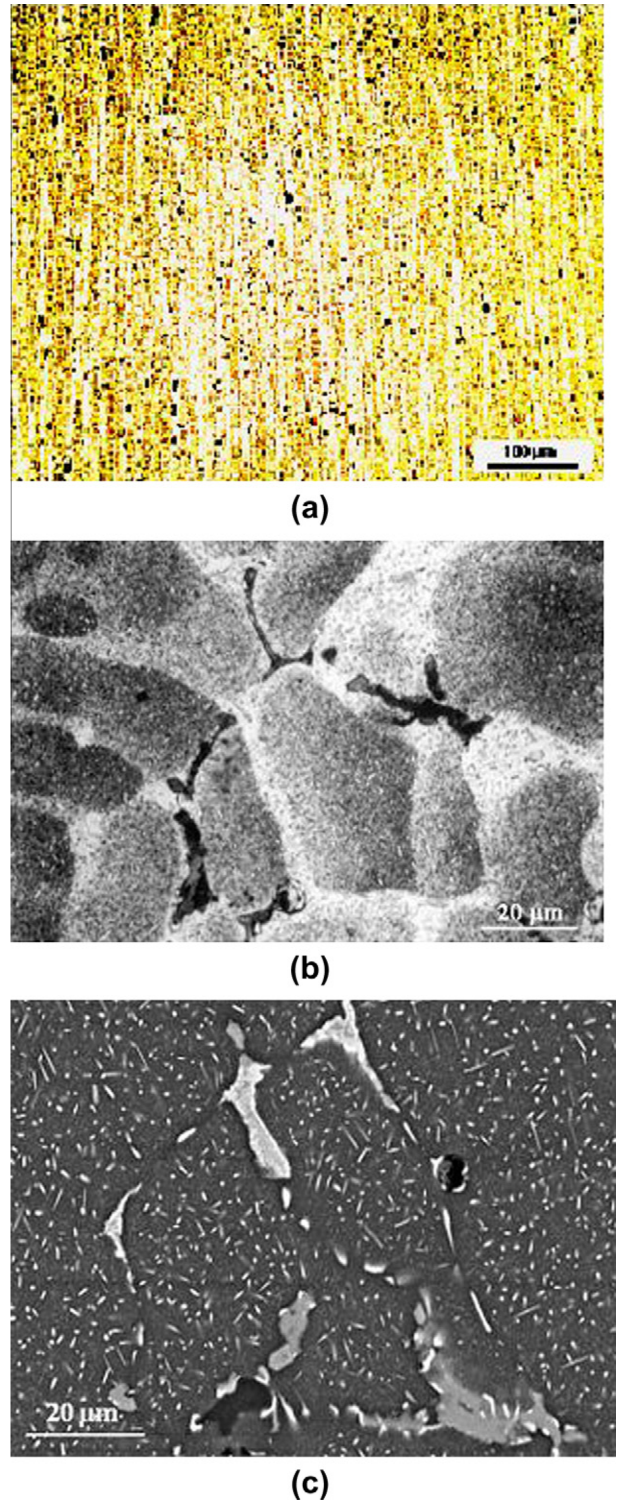

Fig. 1. Microstructures of (a) hot-forged plate and (b and c) homogenized ingot. (a and b) LM micrographs, (c) SEM back scattered image showing the nature of the IM particles.

3. Determination of the notch fracture toughness

In this work, single-edge-notched-bend (SENB) specimens with thickness $B = 10$ mm, width $W = 20$ mm and length $L = 140$ mm were machined in the RL orientation. Different U-notch root radii ($\rho = 0.15$, 0.30, 0.50, 0.80, and 1.0 mm) made by electro erosion were introduced. The notch depth was $a = 10$ mm.