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The effects of heat treatment on very high cycle fatigue behavior in hot-rolled WE43 magnesium

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ABSTRACT

The role of crack initiation and short crack growth on fatigue life in the very high cycle fatigue regime (VHCF) is investigated for three heat treatments of the wrought magnesium alloy WE43. As-received (T5) WE43 with a relatively fine grain size was solution treated and aged to produce precipitation strengthened coarse-grained microstructures in the underaged and peak-aged (T6) conditions. Ultrasonic axial fatigue tests with a cyclic frequency of 20 kHz were conducted using smooth specimens. Heat treatment was shown to have a strong effect on fatigue strength, with the fine-grained, strain-hardened T5 condition exhibiting much higher values than the coarse-grained conditions. No significant difference in fatigue strength was observed between the underaged and peak-aged microstructures of equivalent grain size. Crack initiation and short crack growth behaviors in each condition were investigated to determine if one of these behaviors dominated the VHCF lives. It was found that average short crack growth rates for the three conditions were similar and had no clear dependence on microstructural condition. Crack initiation was shown to occur through cyclic slip deformation in particularly large and favorably oriented grains in each condition. Subsurface crack initiation was observed at low stresses and high lifetimes in the coarse-grained conditions, but not in the fine grained T5 condition. Crack growth rates in vacuum were investigated using a unique combination of ultrasonic fatigue instrumentation and scanning electron microscopy (UFSEM) in order to simulate subsurface crack propagation. Environment was shown to have a significant effect on crack growth rate, with rates in vacuum nearly two orders of magnitude lower than in laboratory air.

1. Introduction

Magnesium alloys are increasingly being considered in structural applications due to their excellent properties, such as low density and high specific strength. These lightweight alloys are particularly attractive in applications where reductions in weight can result in significant improvements to fuel efficiency [1]. However, the fatigue behavior in magnesium alloys has not been investigated as fully as in other structural alloy systems, and the roles of microstructure on fatigue mechanisms are not yet well understood, especially in the VHCF regime, where local microstructure controls crack initiation and early propagation behavior. Ultrasonic fatigue provides a practical method for the study of fatigue behavior in the VHCF regime, and therefore provides a method for the investigation of fatigue mechanisms on the microstructural scale. Progress in the use of the ultrasonic technique for understanding fatigue behavior has been reviewed by Bathias [2], Stanzl-Tschegg [3], and Mayer [4].

The fatigue response of an alloy is comprised of different behavioral regimes, including crack initiation, short crack growth, and long crack growth behaviors, which together determine the total fatigue life of a structure. Fatigue life in the VHCF regime is dominated by crack initiation and microstructurally small crack growth, and variation in these behaviors can have a significant effect on total component lifetime [5]. Even at nominally elastic strain levels, cyclic damage can accumulate and lead to crack initiation and failure beyond the HCF regime, i.e., 10^7 cycles, which is often considered a fatigue limit for many non-ferrous materials [6–8]. For magnesium alloys in general, fatigue lifetime data beyond 10^7 cycles is sparse. Ultrasonic testing methods allow for the investigation of fatigue behavior in the VHCF regime much more rapidly than is possible with conventional servo-hydraulic testing methods.

When the crack length is on the order of the microstructural length scale, accurate prediction of fatigue life requires an understanding of the micro-scale mechanistic responses to cyclic stress

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during initiation and small scale crack growth. Furthermore, crack initiation mechanisms are dependent on fatigue regime, with different initiation mechanisms and their microstructural dependences operating in low cycle fatigue and in the VHCF regime. In the VHCF regime, it has been suggested that, while the strain level is too low to develop persistent slip bands (PSBs), a small fraction of grains exhibit microstructurally irreversible slip [8]. This irreversible slip then accumulates at favorable microstructural locations at the surface, resulting in localized surface roughening and eventual crack initiation [9]. As strain accumulates more rapidly at specific microstructural configurations or features, these mechanisms and microstructural features must be studied in order to understand initiation behavior in magnesium alloys. In the VHCF regime, researchers have observed a variety of crack initiation mechanisms. Studies have shown in a range of alloys that stress-life (S–N) plots exhibit two distinct regions with two apparent asymptotes, an apparent HCF fatigue limit at moderate stresses and a VHCF fatigue limit at lower stresses. These distinct regions occur as a result of a competition between two failure modes, with one failure mode active at lower lifetimes, and a second failure mode creating a secondary fatigue limit at higher lifetimes [10–13]. In a study of fatigue in high strength low alloy steels, Wang et al. observed that failures in the gigacycle regime were dominated by subsurface crack initiation at inclusions, while failures below 10^7 cycles were dominated by surface initiation [12]. Similar results in a beta titanium alloy were observed by Chandran and Jha, who further linked the variation in fatigue life to environmental effects accelerating crack initiation and growth at surface initiation sites [13]. In materials where inclusions or pores do not cause initiation, initiation tends to occur at microstructural sites where the accumulation of irreversible slip is favored. Szczepanski et al. observed crack initiation in Ti-6246 at surface locations featuring larger than average primary alpha, α_p, grains, which occurred by cyclic strain localization on basal and prismatic planes [14]. Fractography of crack initiation sites revealed the presence of many facets with orientations favorable for slip. Huang et al. found that in gigacycle fatigue of a bearing steel, subsurface crack initiation occurred at large, single grains [15]. They further observed that, for subsurface initiation sites, 90% of the total lifetime was devoted to initiation of the crack. In a study of VHCF of polycrystalline copper, Stanzl-Tschegg and Schönbauer observed strain localization and PSB formation below the conventional "PSB threshold" along with the formation of numerous non-propagating small cracks [16]. They observed that an approximate 100% increase in strain amplitude was necessary for the formation of a propagating crack, indicating that sub-PSB threshold crack growth may not be possible in some materials.

Many studies of crack initiation in magnesium alloys have focused on the low and high cycle fatigue regimes, and information on crack initiation mechanisms in the VHCF regime is generally lacking. In a study of very high cycle fatigue of extruded AZ80, Shiozawa et al. observed crack initiation along twin boundaries [17]. Fractographic analysis of the initiation site revealed facet-like regions oriented favorably for slip. Xu et al. observed both surface and near-surface initiation during VHCF of a Mg–Zn–Y–Zr alloy [18]. Oxide films were present at each initiation site, but absent elsewhere on the fracture surface. In the high cycle fatigue regime, observed crack initiation mechanisms include cyclic slip deformation active near grain boundaries and in grain interiors [5,19], and at twin boundaries [20], as well as stress concentration around inclusions in many cases[21–25]. In low cycle fatigue, researchers have found crack initiation modes to be dependent on the magnitude of cyclic loading, with cracks initiating both along grain boundaries and at twin tips [26].

Microstructure continues to play a critical role in fatigue behavior as a crack transitions from initiation to short crack growth. During microstructurally short crack growth, interactions between microstructure and the propagating crack can be influential in determining crack growth behavior. Short crack growth behaviors in magnesium alloys have been shown to be strongly affected by microstructural features, including precipitates or inclusions [27], grain size variation [28], and texture [29,30]. Furthermore, with the limited number of deformation systems active at room temperature, crack propagation in magnesium alloys has been observed to occur both transgranularly along specific crystallographic planes [31,32] and intergranularly [27,33]. With the growing interest in magnesium alloys, studies of fatigue in wrought magnesium alloys are increasing, but the number of alloy systems that have been studied are limited and fatigue responses vary widely across different alloy systems.

In the present study, fatigue lifetimes (S–N response), microstructurally small crack growth, and fatigue crack initiation behavior of commercial hot-rolled WE43 magnesium alloy are examined using ultrasonic fatigue testing techniques and scanning electron microscopy. The VCHF behavior in three microstructural conditions of the alloy was investigated and discussed in terms of short crack growth behavior and crack initiation mechanisms.

2. Materials and methods

2.1. Material

Magnesium alloy WE43 was prepared by Magnesium Elektron Ltd. The alloy was provided as hot-rolled plate in the T5 condition. The composition (wt%) of the alloy is 3.74Y, 2.10Nd, 0.52Gd, 0.45Zr, 0.016Zn, and Mg (balance). WE43 is primarily strengthened through the development of rare-earth-containing precipitates. The as-received material had been hot rolled and then aged for 48 h at 204 °C, a condition that is referred to in this paper as T5. Further heat treatment was conducted in our laboratory to produce underaged and peak-aged (T6) microstructures. Solution treatment of the as-received alloy was conducted at 525 °C for 8 h. Aging at 250 °C for 4 h and 16 h was used to produced the underaged and peak-aged conditions. Grain size was measured by standard methods using electron backscatter diffraction (EBSD) mapping (Fig. 1) in a Tescan Mira3 scanning electron microscope (SEM) along with EDAX OIM Data Analysis software. The 525 °C/8 h solution treatment increased the average grain size from 13 μm to approximately 113 μm, as detailed in Table 1. In each condition, fine β' precipitates are present in the matrix, while coarser β_1 and β_1/β precipitates are found respectively in the underaged and T6 conditions as plate-like structures along prismatic planes [34]. An investigation of tensile behavior in WE43 performed by Githens revealed notable differences in the mechanical properties of the three conditions (Table 1), with the T5 condition exhibiting yield and tensile strengths significantly higher than those of either the underaged or T6 conditions [35]. In these tests, the tensile loading direction was parallel to the rolling direction, which was the same orientation used in all fatigue tests.

The crystallographic texture produced by each treatment was investigated using EBSD (Fig. 2). Each of the three conditions featured a medium strength basal texture, with 2.90, 4.10, and 3.35 multiples of random distribution (m.r.d.) observed in the T5, underaged, and T6 conditions respectively, as expected in hot-rolled magnesium [36]. Basal poles were aligned perpendicular to the rolling plane, i.e. parallel to the normal direction (ND) of the plate.

In order to investigate the matrix strength of the heat treatments of WE43 without the effect of grain boundaries, hardness testing was conducted using a Hysitron Triboindenter. Nanohardness indents of approximately 1 μm in width were produced using