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Influence of precipitates on low-cycle fatigue and crack growth behavior in an ultrafine-grained aluminum alloy

K. Hockauf [a,*], M.F.-X. Wagner [b], T. Halle [c], T. Niendorf [d,1], M. Hockauf [b,2], T. Lampke [a]

[a] Chair of Surface Technology and Functional Materials, Institute of Materials Science and Engineering, Technische Universität Chemnitz, 09107 Chemnitz, Germany

[b] Chair of Materials Engineering, Institute of Materials Science and Engineering, Technische Universität Chemnitz, 09107 Chemnitz, Germany

[c] Chair of Metallic Materials, Institute of Materials and Joining Technology, Otto von Guericke University Magdeburg, 39106 Magdeburg, Germany

[d] Lehrstuhl für Werkstoffkunde (Materials Science), University of Paderborn, Pohlweg 47-49, 33098 Paderborn, Germany

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Abstract

The strain-controlled fatigue and near-threshold fatigue crack growth behavior of an ultrafine-grained (UFG), age-hardening aluminum alloy after severe plastic deformation by equal-channel angular pressing (ECAP) are discussed. The main question addressed is how different precipitate morphologies affect low-cycle fatigue (LCF) and fatigue crack growth. An AlMg0.5Si0.4 alloy is subjected to two and eight passes of ECAP to obtain different degrees of grain refinement and fragmentation of the initially semi-coherent precipitates. Furthermore, a thermally recovered condition with newly formed, small coherent precipitates, which is obtained by aging after two ECAP passes, is considered. Strain-controlled fatigue tests and ΔK-controlled crack growth measurements are conducted and microstructural evolution during cycling and fracture surfaces are carefully analyzed using scanning and transmission electron microscopy. Most importantly, the results of this study show that newly formed, coherent precipitates in the thermally recovered condition directly contribute to a more planar slip behavior, to slip localization and to early failure during LCF loading. It is clearly demonstrated that precipitate morphology also affects fatigue crack propagation, and that this is closely related to slip reversibility, even in the UFG regime.

Keywords: Severe plastic deformation; Ultrafine-grained materials; Aluminum alloys; Fatigue; Fatigue crack propagation

1. Introduction

Ultrafine-grained (UFG) materials are of high scientific interest due to their outstanding properties [1,2]. Equal-channel angular pressing (ECAP) has emerged as one of the most frequently used methods of severe plastic deformation (SPD). Grain refinement by SPD methods is realized by large strains that are imposed on initially conventionally grained (CG) microstructures. Upon repetitive straining, the accumulation of defects in dense dislocation walls gradually leads to the formation of cells and subgrains, and to a fragmentation of the initial microstructure into the submicron range [3–5]. Extensive work has been carried out characterizing the microstructural evolution of various pure metals and alloys as a function of the applied equivalent strain, processing route, temperature and hydrostatic pressure during SPD, and on relating different deformation processes to the resulting mechanical properties, such as hardness, strength and ductility [6–10]. Focusing on potential future applications of UFG

* Corresponding author. Tel.: +49 37153136812.
E-mail address: kristin.hockauf@mb.tu-chemnitz.de (K. Hockauf).
[1] Current address: Institute for Materials Engineering, Technische Universität Bergakademie Freiberg, Gustav-Zeuner-Str. 5, 09599 Freiberg, Germany.
[2] Current address: CEWUS – "Materials Engineering and Surface Technology", Neefestr. 80A, 09119 Chemnitz, Germany.

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materials, such as load-bearing structural components, fatigue and crack growth play an important role, and research in this area has recently received considerable attention.

Under stress control, the increased strength of UFG materials generally leads to an improvement in high-cycle fatigue (HCF) performance [11–16]. However, these severely predeformed conditions suffer from a lack of strain-hardening capability and testing in the strain-controlled low-cycle fatigue (LCF) regime reveals microstructural instability, cyclic softening and consequently a significantly reduced fatigue life. In high-purity metals subjected to strain-controlled fatigue, cyclic softening can be accompanied by dynamic recrystallization and grain growth; in alloys and metals of commercial purity, recovery processes can be observed [14–20]. Furthermore, localization of plastic deformation in shear bands is discussed as a relevant microstructural mechanism that accounts for cyclic softening. A review on these aspects is given in Ref. [15]. The fatigue crack propagation behavior in UFG materials is similarly deteriorated: a decreased fatigue threshold ΔK_{th} and increased crack propagation rates for the microstructure-dependent near-threshold regime are clearly related to the reduced grain size [11,21–25].

One possible enhancement of fatigue performance associated with a bimodal grain size distribution, for example realized by localized grain growth during post-ECAP annealing, has been discussed theoretically in Ref. [11]. To the authors' knowledge, no data has been published on crack growth in bimodal, partially-UFG microstructures yet, besides our own previous study [26].[3] In contrast, several attempts were made to deal with the issue of reduced LCF life by increasing the strain-hardening capability and ductility of as-processed UFG materials. In most cases, the method of choice was a short annealing treatment after SPD. In Refs. [14,15,17,28,29] it was demonstrated that this strategy is effective for pure metals (Al, Cu) as well as their alloys. However, such annealing treatments are usually accompanied by a loss in strength and thus an expected reduction in HCF life when compared to the as-processed conditions. For age-hardening aluminum alloys, Kim et al. [30–32] reported on a successful strategy to simultaneously improve the ductility of ECAP processed conditions while conserving their strength: this they realized by shifting the cold-working treatment in between the solution annealing and the artificial aging step. During aging, very fine precipitates are formed from numerous nucleation sites in the severely predeformed matrix; these precipitates contribute to an increase of strength, while moderate processes of thermal recovery enable a simultaneous improvement in ductility.

Strain-controlled fatigue and crack propagation in age-hardening alloys are controlled by complex microstructural mechanisms: the type of coherency (coherent, semi-coherent or incoherent) of the strengthening precipitates strongly affects the homogeneity of slip, which directly affects all fatigue regimes where (microscopic, cyclic) yielding occurs. While these effects are well understood in CG aluminum alloys [33–38], there is a need for systematic studies that extend the current knowledge to the UFG regime. In this paper we present a thorough investigation on the influence of prominent microstructural features on the LCF and crack growth behavior of an aluminum alloy that was processed by ECAP. The conditions under investigation differ in terms of average grain sizes and grain size distributions as well as post-ECAP aging treatments. The influence of grain size, grain boundary misorientation and the degree of the microstructural non-equilibrium condition is studied; special attention is paid to the altered precipitate morphologies and their influence on the fatigue damage processes. We discuss how precipitate morphology affects fatigue crack propagation, and we show that this is closely related to a classical model for slip reversibility in fatigue crack growth [39] that can be extended to the regime of ultrafine grain sizes.

2. Experimental

The age-hardening alloy AA6060 (AlMg0.5Si0.4) of commercial purity was used in this study. For ECAP processing, a friction-optimized tool in laboratory scale (15×15 mm^2 cross-section) with sliding walls and a bottom slider was used. The intersection angle of the inlet and outlet channels in this tool is 90°, which results in an equivalent plastic strain of 1.15 per pass [40]. Starting with the initial material in a peak-aged condition (CG T6), two (E2) and eight (E8) pressings were performed at room temperature, following route E. This processing route consists of the rotation scheme 180°/90°/180°/90°..., and was selected because it is effective for a fast microstructural refinement and profitable product yield [41]. In all passes, a back pressure of 70 MPa was applied to ensure a homogeneous deformation and to prevent the material from cracking [42,43].

The thermally recovered condition (E2opt) was processed starting with solution annealing and quenching. After two ECAP passes, the material was aged at 170 °C for 18 min, leading to peak hardness. The annealing parameters were selected based on a previous study on the post-ECAP aging kinetics of this alloy [44], where this particular aging sequence (associated with both recovery and precipitation) was shown to result in an optimum combination of strength and ductility. The thermomechanical treatments of the different materials studied here, and the resulting mechanical properties as determined from quasi-static tensile tests, are summarized in Table 1. We note that

[3] Our interpretation of "bimodal" differs from the majority of literature on UFG materials, where "bimodal" is used for structures that exhibit areas of truly large, recrystallized grains in an ultrafine-grained matrix, as for example shown in Ref. [27]. In contrast, the bimodal conditions in our study are characterized by an intermediate state of grain refinement, where the presence of larger grains is not related to localized grain growth or recrystallization, but to inhomogeneously distributed refined grains, caused by the selected ECAP route and the low number of passes.