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Effect of deformation structure on fatigue behavior of an Al-Mg-Sc alloy

Daria Zhemchuzhnikova and Rustam Kaibyshev
Belgorod State University, Pobeda 85, Belgorod, 308015, Russia
E-mail: zhemchuzhnikova@bsu.edu.ru

Abstract. Effect of initial grain size on fatigue behavior of an Al–6%Mg–0.35%Mn–0.2%Sc–0.08%Zr–0.07%Cr alloy was examined. The initial CG microstructure with an average grain size of ~ 22 μm was manufactured by casting followed by solution treatment at 360 °C for 12 h. To produce the UFG condition, the alloy was subjected to equal-channel angular pressing (ECAP) at 320 °C up to a total strain of ~ 14. Extensive grain refinement provided the formation of fully recrystallized structure with an average grain size of 700 nm. It was shown that the formation of UFG structure provided +60% increases in yield stress and +25% increases in fatigue strength. Fundamentals of this effect of microstructure on the static strength, fatigue resistance and fracture modes are discussed.

1. Introduction

Mechanical failure of structures and components is of serious concern in all industries including aerospace, aviation, warship and nuclear industries. It has been estimated than almost 50 - 90% of all service failures of metal parts are caused by fatigue [1, 2]. The fatigue failure process exploits the weakest links in the test material, which act as nucleation sites for crack origins [1]. Previous studies [3, 4] have shown that main metallurgical parameters affecting fracture toughness and developments in fracture mechanical testing are related to: (a) the distribution and resistance of particles to cleavage and decohesion; (b) the local strain concentration and precipitate-free zones; (c) the grain size. Therefore, to develop a material-based and reliable life prediction methodology, there is a need to investigate correlation between microstructural features and fatigue performance.

Aluminum alloys of the 5xxx series constitute a group of non heat-treatable alloys with medium strength, high ductility, excellent corrosion resistance and weldability. The formation of a fine grained structure using of severe plastic deformation methods leads to significant increase in their strength [5,6], however, these properties are not sufficient for structural alloys. Therefore, to establish the fatigue life assessments, it is important to know the effect of microstructure on the fatigue toughness and fracture modes.

The aim of the present paper is to report the effect of severe plastic deformation on the microstructure, mechanical properties and high cycle fatigue of Al-Mg-Sc-Zr alloy.

2. Experimental

The investigated alloy, denoted here as 1575C Al, with a chemical composition of Al–6%Mg–0.35%Mn–0.2%Sc–0.08%Zr–0.07%Cr (in wt.) was manufactured by semi-continuous casting using a water-cooled copper chilled mold with a rectangular shape of dimensions 160 mm × 40 mm. The ingot alloy was then homogenized at 633 K for 12 h and cut into plates. Half of these plates were processed by ECAP at 593 K for a total of 12 passes giving an imposed strain of ~ 14, using route B_{CZ} and a die with rectangular cross-section of 20 mm × 20 mm and channel inner angle of 90°.

All mechanical tests were carried out at room temperature in air. Tensile tests were carried out using an Instron 5882 testing apparatus with an initial strain rate of ~ 10^{-3} s^{-1}, using specimens with a gauge part 1.5 mm × 3 mm machined along the last pressing direction. Fatigue tests were performed using a servo-hydraulic testing machine Instron 8801. The dog-bone samples were cycled sinusoidally at a frequency of 25 Hz, using a minimum/maximum stress ratio R of 0.1. The longitudinal sections of the specimens were parallel to the central

axis of the ingot or pressing direction. Stress amplitude versus number of cycles to failure curves were plotted with the data from the above test.
The details of sample preparation for structural characterization methods by optical metallography (OM), transmission electron microscopy (TEM), electron backscattering diffraction (EBSD) analysis and were described in previous paper in details [7].

3. Results and discussion

The initial microstructure of 1575C Al before ECAP has been described in detail in a previous work [7]. Briefly, the microstructure of the cast material consisted of equiaxed grains with a mean size of 22 μm (Fig. 1a). The grains contained almost no sub-boundaries, and the density of free dislocations was measured to be as low as 3×10^{12} m^{-2} (Fig. 1b). A characteristic feature of this material was a continuous network of relatively coarse Al_6Mn particles arranged along the original grain boundaries, the nano-scale Al_3(Sc,Zr) dispersoids were uniformly distributed in the grain interior.
The ECAP resulted in the formation of almost uniform structure with an average grain size of ~ 0.7 μm and the recrystallized volume fraction more than 90% (Fig.1a'). The population of HABs and the average misorientation slightly changed compared to the initial state and are 84% and 35^{o}, respectively. Coherent Al3(Sc ,Zr) dispersoids with an average size of 10-15 nm and incoherent Al_6Mn precipitates of 30-35 nm and equiaxed shape are uniformly distributed within grain interiors. Most of grains contain high density of lattice dislocations ($\rho\sim4\times10^{14}$ m^{-2}) which are pinned by precipitates (Fig. 1b').

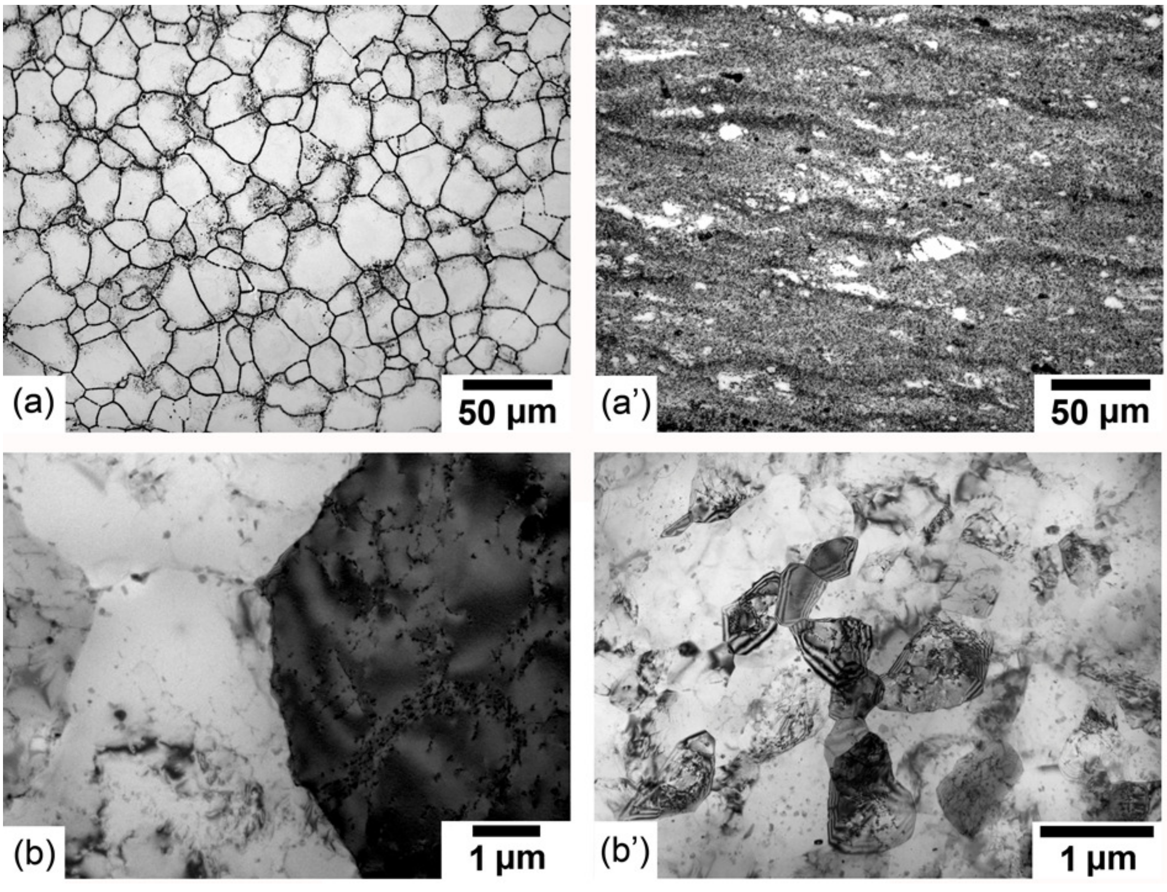

Fig. 1. Microstructures of the 1575C Al before (a, b) and after ECAP (a', b').

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Mechanical properties of the 1575C alloy in initial state and after ECAP are summarized in Table 1. It is seen that extensive grain refinement leads to a significant increase in yield stress (+65%) and total elongation (+80%). The growth of ultimate tensile stress is less (+20%) (Table 1). Therefore, the formation of recrystallized structure in the 1575C provides the enhancement of tensile strength.

Figure 2b shows the stress–cycles to failure (N) curves for both states of the 1575C Al. As can be seen, the stress-fatigue life curves continuously reduce with increasing number of cycles and the fatigue limit is not well observed, which is typical for aluminum alloys [8,9]. Therefore, the fatigue limit based on 10^7 cycles was measured and accepted as a measure of high cycle fatigue life [8]. The fine grained material which was processed by ECAP exhibits a higher fatigue resistance than the initial alloy over the whole range of fatigue lives investigated (Fig. 2). At the same time the so-called fatigue ratio not changed (Table 1) [10].

The experimental values of the fatigue strength on 10^7 cycles of the alloys before and after ECAP are approximately 155 MPa and ~195 MPa, respectively (Table 1). Thus, the fatigue strength increase was 25% due to grain refinement (Table 1). As reported in previous studies [9,10,12], the increase in fatigue life after ECAP has been explained as the result of decreased damage nucleation thanks to the reduction in grain size and a reduction in the number of dislocations in slip bands.

Table 1. Mechanical properties of the 1575C Al alloy in initial state and after ECAP: the yield stress ($\sigma_{0.2}$), ultimate tensile strength (σ_B), the total elongation-to-failure (δ) and the fatigue strength (σ_f)

State	$\sigma_{0.2}$, MPa	σ_u, MPa	δ, %	σ_f*, MPa	Fatigue ratio σ_f*/ σ_u
Initial state	225	360	12	155	0.43
After ECAP	365	440	22	195	0.44

*maximum fatigue stress on the basis of 10^7 cycles

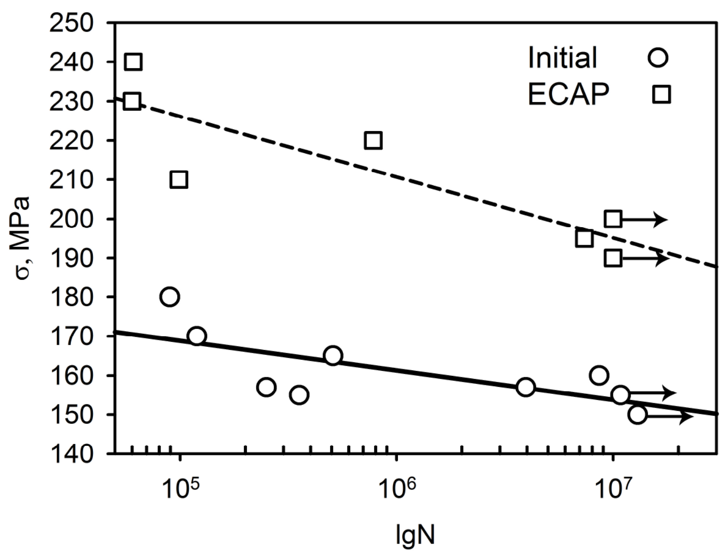

Fig 2. Stress amplitude vs. number of cycles to failure for the 1575C alloy before and after ECAP. Arrows indicate samples that did not fracture.

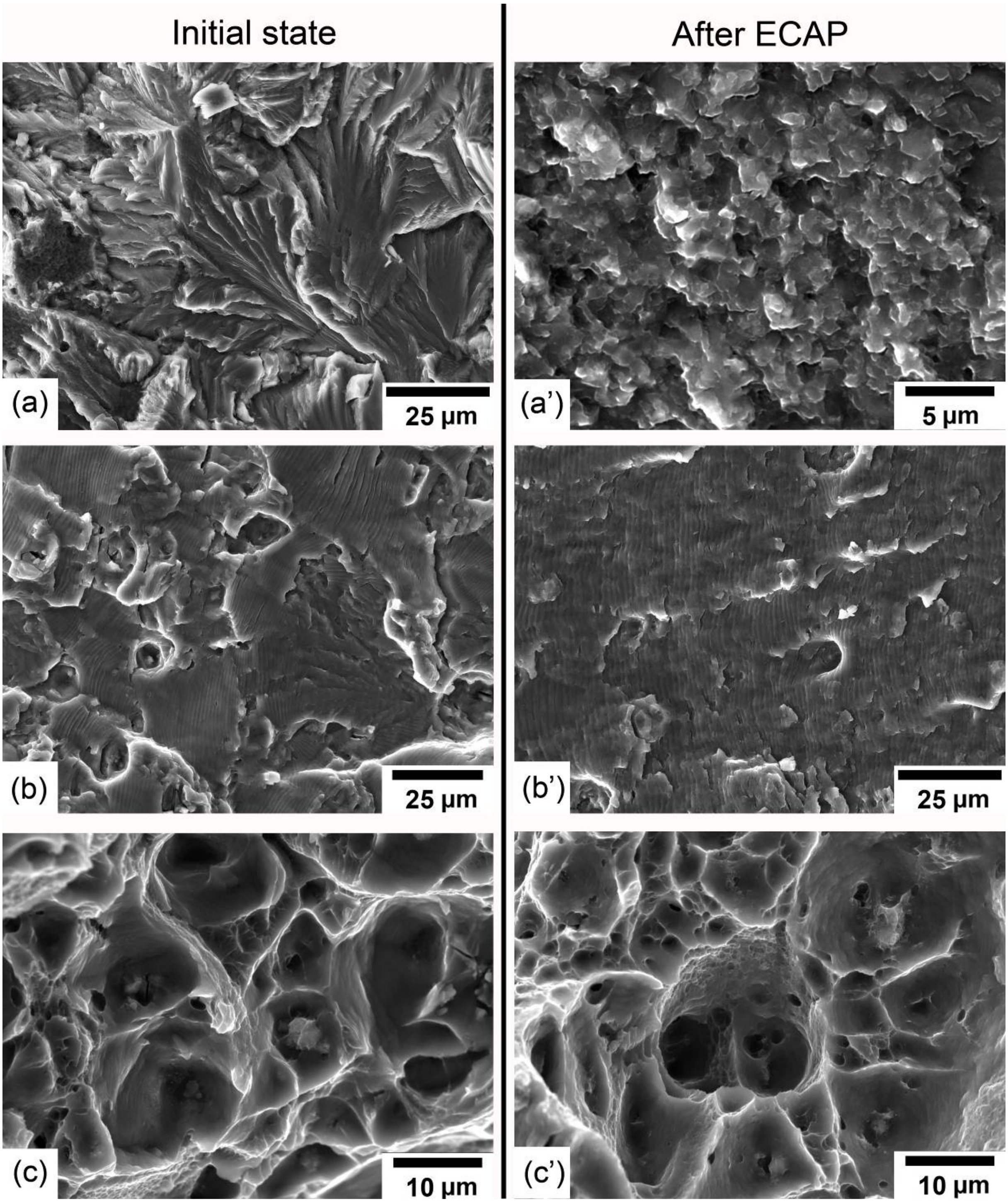

Fig. 3. The typical stage of fatigue failure of the specimens fractured after 10^7 cycles for the 1575C alloy: (a, a') stage I; (b, b') stage II; (c, c') stage III.

SEM fractographs of the fracture surfaces of the alloy in the initial condition and after ECAP are shown in Fig. 3. The typical stage of fatigue failure can observe: stage I, during which the microcracks are initiated, stage II of fatigue macrocrack propagation and stage III, where the static fracture modes are occurs [13].

Numerous microcracks start to propagate from the initial alloy specimen surface by a transgranular cleavage-like mechanism. Well-defined areas of stair-step fracture surfaces are observed (Fig. 3a) [14,15]. Numerous fatigue fracture surfaces are faceted and do not exhibit fatigue striations. The crack growth is temporally arrested within grains (Fig.3a). In contrast, the transgranular ductile fracture gives the main contribution to crack propagation in the fine-grained alloy (Fig.3a'), the fracture surface of this alloy is smoother. The small sizes of the dimples reflect a relatively large resistance to crack nucleation and propagation (Fig.3a').
Fracture during stage II occurs by a classical crack-tip blunting mechanism that gives rise to striations formation accompanied by secondary cracks opening [14]. These striations propagate on multiple plateaus that are at different heights with respect to one another. The grain size of alloy did not reveal any influence on the striation spacing (Fig.3b & b'). The fracture surface of the initial alloy also shows the dimpled ductile fracture with the particles of secondary phases observed on the bottom of dimples (Fig.3b). These dimples are present at the surface of fine-grained alloy too, but their volume fraction is significantly less (Fig.3b').
Final fracture (stage III) of both initial and after ECAP alloys occurs by the ductile mode, well-defined deep dimples that are equiaxed in shape with second phase particles located at their bottom were observed (Fig.3c & c').

4. Summary
In this paper, the mechanical properties including the high cycle fatigue behavior and fracture modes of Al–6%Mg–0.35%Mn–0.2%Sc–0.08%Zr (in wt. %) alloy in the initial condition and after ECAP were examined. The ECAP resulted in fully recrystallized structure with an average grain size of ~ 0.7 μm and enhancement of static strength and fatigue resistance. At ambient temperature, the extensive grain refinement provides +65% and +80% increases in YS and ductility, respectively, +25% increases in UTS. The fatigue strength at 10^7 cycles of the initial alloy increase is 25% due to ECAP.

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