Fatigue properties of an 1421 aluminum alloy processed by ECAE

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Abstract. Fatigue properties and fatigue crack growth rate were examined in an Al-Mg-Li-Sc-Zr allow subjected to equal channel angular extrusion (ECAE) with rectangular shape of channels up to a total strain of ~4 at a temperature of 325°C followed by solution treatment with subsequent oil quenching with aging. After this processing the fraction recrystallized was ~80pct; the deformed microstructure remains essentially unchanged under solution treatment due to high density of Al_3Sc coherent dispersoids playing a role of effective pinning agents. It was shown that the fatigue limit of this material attained a value of ~185 MPa. Thermomechanical processing provided a decrease in fatigue crack propagation growth rate and an increase in the stress intensity factor, K_{1c}, in comparison with extruded bar. However, characteristics of crack propagation resistance did not attain values suitable for application of this alloy for critical aircraft components.

1. Introduction

Al-Li-Mg alloys are considered as advanced materials for airplanes due to excellent combination of low density and sufficient strength [1, 2]. However, crack propagation resistance of these alloys is not enough for commercial application for critical components of aircrafts. Nowadays, extensive work with Al-Li-Mg alloys is carried out to increase their values of the stress intensity factor, K_{1c}, and fatigue crack growth rate up to those obtained for the AA2524 aluminum alloy. Two approaches are used to improve crack propagation resistance of the Al-Li-Mg alloys. First approach is associated with optimization of chemical and phase composition of these alloys. Second path is in the development of thermomechanical processing (TMP) route which provides the manufacturing of semi-finished products with recrystallized structure. Authors [1] assumed that the formation of recrystallized grains can improve crack propagation resistance of Al-Li-Mg alloys in contrast to aluminum alloys belonging to the other systems. However, conventional TMP consisting of cold or warm rolling and final recrystallisation annealing could not be applied to the Al-Li-Mg alloys because of poor workability of these alloys at low temperatures that led to a premature fracture under working conditions. At the same time, recrystallization structure can be easily produced in Al-Li-Mg alloys by equal-channel angular extrusion (ECAE) at a temperature of ~300°C [3-5].The aim of the present study is to examine fatigue resistance of an Al-Li-Mg alloy with recrystallized structure. This alloy was subjected to standard heat treatment consisting of solution treatment followed by oil quenching and subsequent aging after ECAE.

2. Experimental

The experiments were conducted using the 1421 Al with a chemical composition of Al-5.1%Mg-2.1%Li-0.17%Sc-0.08%Zr (in weight pct). Details of manufacturing process and procedure of ECAE and techniques used for structural characterization as well were reported in previous works [3-5] in detail. The ECAE with rectangular shape of channels was carried out using route B_{cz} [5] at a temperature of 325°C up to a total strain of ~4. Thin foils were examined by using a Jeol-2010 TEM with a double-tilt stage and equipped with energy dispersive spectrum analysis (EDS) produced by Oxford Instruments, Ltd at an accelerating potential of 200 kV. The specimen surface was observed by scanning electron microscopy (SEM) Quanta 200 3D. Fatigue life characterization in terms of normal stress (S-N curve characterization) and measurement of fatigue crack growth rates were performed using a 100 kN servohydraulic Instron8801 testing machine under load control condition. Completely reversible push-pull (stress ratio, R=-1) sinusoidal load cycles at a frequency of 25 Hz were used for all the tests. Compact tension (CT) specimens 20 mm thick were cut in accordance with ASTM Standard E399-06. The specimens were loaded using a sinusoidal cycle with a frequency of 5 Hz and an asymmetry coefficient R = 0.1. The fatigue crack growth rate as a function of the stress-intensity factor range, ΔK, was obtained in accordance with ASTM standard E647-08.

3. Results and discussion

ECAE followed by the heat treatment results in the formation of recrystallized structure with volume fraction of recrystallized grains of ~80pct. (Fig. 1a); average size of recrystallized grains is ~2 μm, portion of high-angle boundaries (HAGB) is ~79pct., average misorientation is 30.7°. Average density of lattice dislocation within recrystalized grains is $\rho \sim 5\times10^{14}$ m^{-2}. Particles of S_1-phase with an average size of 0.4 μm are observed at grain boundaries and even within grain interiors (Fig.1b). Their volume fraction attends ~16 pct. There is a weak evidence for the formation of the δ' – phase dispersoids (Fig.1b); their volume fraction is negligible.

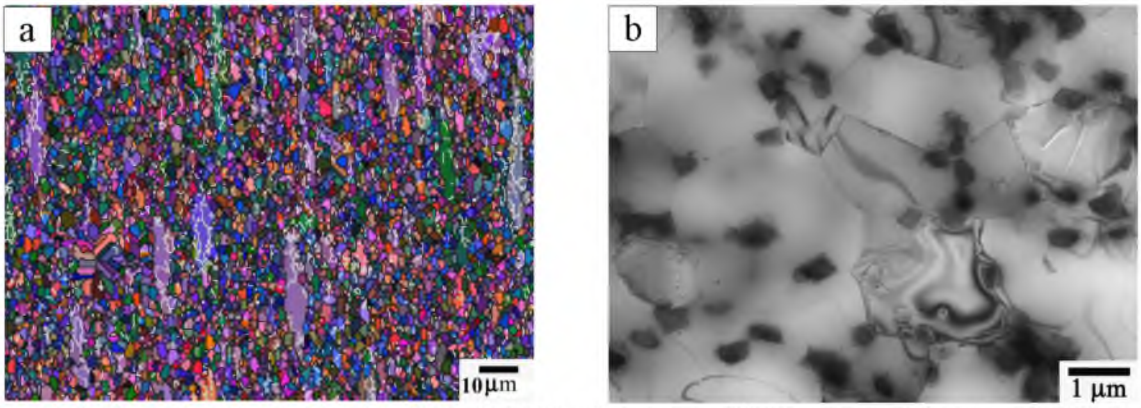

Figure 1. Typical microstructures of the 1421Al subjected to ECAE with ε~4 followed by T6 heat treatment.

The S-N plot characterizing the fatigue life under testing with constant load amplitude is shown in figure 2. The S-N curve does not show any deflection points and apparent knee as well. The fatigue behaviors of the 1421 alloy in low cycle fatigue (LCF) and high cycle fatigue (HCF) range are almost the same. Linear dependence of S vs N remains virtually unchanged with transition from region of LCF to region of HCF. Therefore, the fatigue limit, σ_f, could not be defined. At 10^7 cycles, the fatigue strength was determined as 185 MPa. This value is relatively high for aluminum alloys.

In order to explain the usual fatigue behavior of the 1421 Al with recrystallized structure the fatigue crack growth rate (da/dN) on the stress intensity range, ΔK, was obtained (figure 3). Only two stages can be defined in figure 3. At stage I (ΔK ≤ 6 MPa×√m), any small increase in the ΔK value leads to dramatic increase in the fatigue crack growth rate. As a result, this rate attains a relatively high value of 0.1 μm/cycle even at ΔK ~6 MPa×√m. At higher values of stress intensity range, ΔK, a well-defined stage II is observed (figure 3). A fatigue growth rate of 0.65 μm/cycle is attained at ΔK ~14 MPa×√m. At ΔK ~ 15 MPa×m$^{1/2}$, fracture occurs rapidly; no transition to stage III was detected. The stress intensity factor of K_{1c} = 22.7 MPa×√m is evaluated for the present samples. It is worth noting that characteristics of crack propagation resistance of the present 1421 Al with recrystallized structure and those of the early version of this alloy (1420Al) with unrecrystallized structure are almost the same despite the fact that yield stress of the 1421 alloy was high than that of the 1420 alloy by a factor of 1.5 [1].

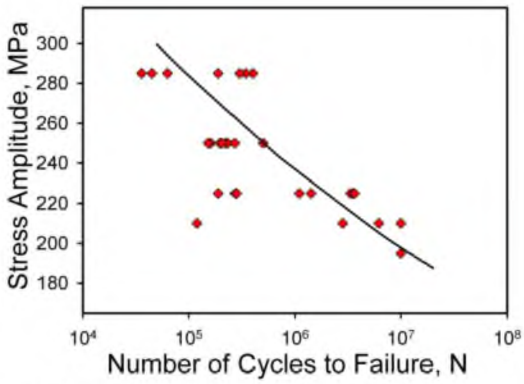

Figure 2. S-N curve for ECAE 1421 alloy.

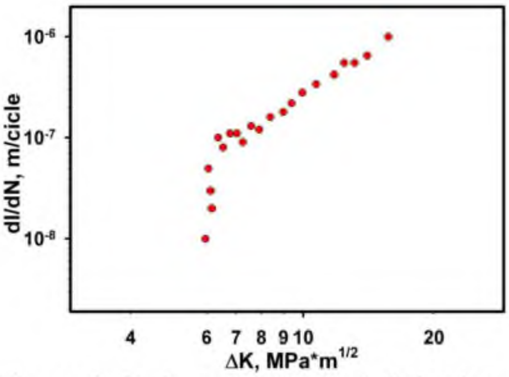

Figure 3. Fatigue crack growth behavior of 1421 alloy.

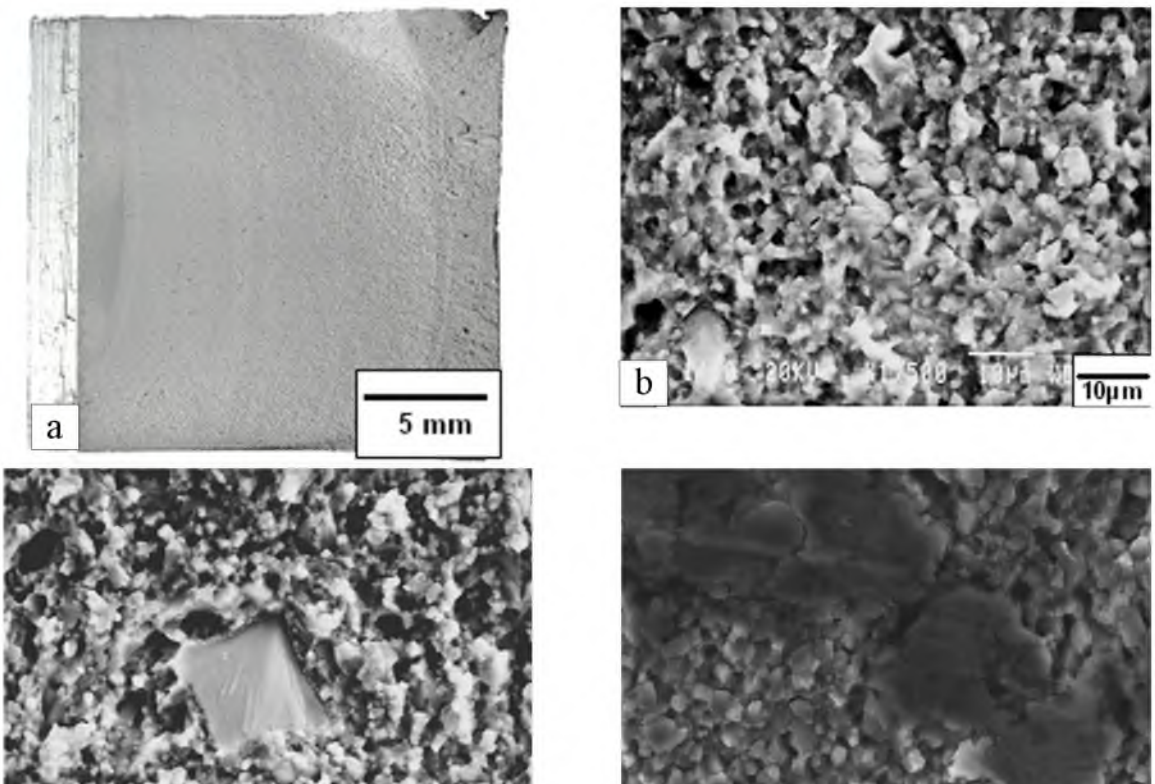

Figure 5. Optical micrograph (a); SEM fractographs (b, c, d).

Typical views of fracture surface of the flat rectangular sample with the edge crack are given in figure 4. Concentric lines, which are peculiar for fatigue failure can be observed on the sample fracture (figure 4a). The intergranular type of fatigue crack propagation with same separate sections of plastic fracture is seen in figure 4b. Crack nucleation appears also on the large particles of the primary phase $Al_3(Sc,Zr)$ on the samples after ECAE up to the strain of 4 (figure 4c). The fracture observations also suggest that the crack splitting frequently occurs in the material after ECAP that increases its service properties.

With low values of $\Delta K \sim 6$ MPa×m^{½} the fracture morphology shows the intergranular character of material failure. That is indicated by the facet fracture with the facet size close to the grain size (figure 4a). Data in figure 4 clearly show that the fatigue crack gradually ceases to be sensitive to the grain boundaries. This is confirmed by the non structure-sensitive character of its spreading in relation to the grain size at the stage of linear growth (figure 3)

The results of the given research show that intergranular failure that is characterized by the low sinuosity of the fatigue crack of the samples occurs with low values of the stress intensity factor range (figure 4a). This causes lower resistance to the fatigue crack growth. With the high values of the stress intensity factor range the mixed type of failure occurs. The transition from intergranular to transgranular fatigue failure occurs at scarce non-recrystallized areas (figure 4d). Nevertheless, the intergranular failure is the dominant mechanism. Rough primary particles also cause brittle fracture (figure 4c).

4. Conclusions

The development of ultrafine grained microstructure by ECAE does not lead to significant improvement of the fatigue properties for the 1421 aluminum alloy as compared to relatively coarse grained microstructure evolved after conventional hot extrusion. The S-N curve does not show any deflection points and noticeable knees. Behavior of the 1421 alloy in LCF range and HCF range is almost the same. The stage III of unstable crack propagation can hardly be revealed on the relationship between the fatigue crack growth rate and the stress intensity range.

References

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