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Effect of equal-channel angular pressing and post-aging on impact toughness of Al-Li alloys

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ABSTRACT

Overcoming the toughness inadequacy of Al-Li alloys is in urgent need for developing new low-density and high-performance aerospace aluminum alloys. In this research, continuous equal-channel angular pressing (ECAP) and post-aging were developed to significantly enhance the impact toughness of 1420 Al-Li alloy. The effects of the processes on microstructure evolution, impact absorbed energy and fracture surfaces of 1420 alloy were investigated. The results demonstrated that the impact toughness of ultrafine-grained (UFG) 1420 alloy after 8 ECAP passes at 573 K reached up to 26.6 J/cm^2 at room temperature and increased sixfold compared with that of the coarse-grained sample, but the post-aging reduced the beneficial effect. The remarkable improvement after the warm ECAP was mainly due to the UFG microstructure, certain amount of dislocations, and the fine precipitates with uniform distribution, thereby making UFG 1420 alloys more attractive in aerospace applications.

1. Introduction

Lightweight materials have become more and more important in aerospace and automotive industry, owing to urgent demands for energy saving and environment protection. Aluminum-lithium alloys have lower density, higher strength and better stiffness than conventional aluminum alloys, thus being of great interest in structural applications. However, the poor toughness and ductility of aluminum-lithium alloys greatly impede their broader applications [1–3]. It is widely accepted that two main phases are present in Al-Mg-Li system: unequilibrium, coherent and ordered δ' precipitates (Al_3Li) and equilibrium cubic S_1 phase (Al_2MgLi). The δ'-Al_3Li phase contributes not only to the high values of elastic modulus, but also to low ductility and poor fracture toughness because of planar slip. While the S_1(Al_2MgLi) phase usually precipitates along the grain boundaries and subgrain boundaries [4,5]. Since the aerospace structures are often subjected to impact loading, improving impact toughness of Al-Li alloys is in urgent need.

One approach to overcome the poor toughness and ductility of alloys caused by strain localization is refinement of the grain size. There are several routes to improve the microstructure and mechanical properties of alloys. Severe plastic deformation (SPD) process, which is one of the most effective methods to provide ideal service properties and enhanced workability by greatly refining microstructure, has attracted much attention in the past several decades [6–8]. Equal-channel-angular pressing (ECAP), originally developed by Segal et al. (1981), is regarded as the most developed SPD processing technique at present [9]. An attracting feature of this technique is that it allows to produce bulk ultrafine-grained (UFG) structures without changing the initial shape of billets during processing, and it is applicable to nearly all commercial alloys [10–12]. During ECAP, a super plastic strain is imposed upon a polycrystalline sample by extruding the billet through a die constrained within a channel that is bent at an abrupt angle. Several experimental results have been reported on SPD processed Al-Li alloys. One of the distinctive characteristics of UFG Al-Li, especially Al-Mg-Li alloy is superplasticity [13–17]. As early as 2002, Fanil Musin et al. [15] reported that ECAP-processed 1421 Al exhibited the highest elongation of 1850% without failure appeared at a temperature of 400 °C and initial strain rate of 1.4×10^{-2} s^{-1}. Later, R.K. Islamgaliev et al. [14] also presented that an ECAP processed 1421 alloy had a superplastic elongation of ~ 1500% at 400 °C using an initial strain rate of 10^{-1} s^{-1}. However, other properties of UFG Al-Li alloy have not yet been sufficiently elucidated, such as impact toughness, corrosion resistance and so on.

Previous studies indicated that multi-pass ECAP can significantly raise the impact toughness of UFG Al-Si alloy to 18 times of the coarse-grained alloy [18–20]. A. Shokuhfar et al. [21] also demonstrated a unique combination of high strength and good impact toughness in 6061 alloy after heat treatment and followed ECAP process. At the same

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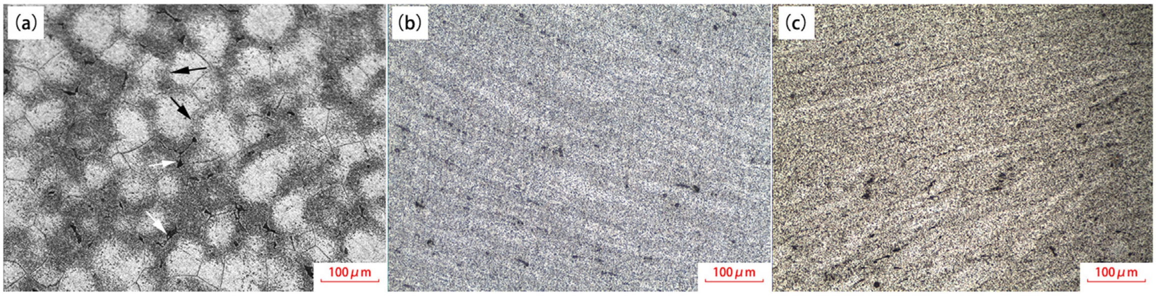

Fig. 1. Microstructure of 1420 alloys with different ECAP passes at 573 K: (a) as-cast; (b) 4 passes; (c) 8 passes.

time, P. Das et al. [22] reported that the impact toughness of the cryorolled 7075 alloy up to 70% thickness reduction have increased by 60% compared to the starting material. Besides aluminum alloys, I.P. Semenova et al. [23] found that the ultrafine-grained structure and high-angle misorientations processed by ECAP may contribute to the increase in the impact toughness for UFG Grade 5 Ti alloy. G. Purcek et al. [24] improved the impact toughness of Zn-40Al alloy by multi-pass ECAE due to the significant increase in ductility. Therefore, it would be interesting to check if UFG Al-Li alloys produced by ECAP have better toughness and ductility, and to further analyze the effect of microstructure evolution on their impact performance. Herein, the objective of the present work is to develop a high performance 1420 alloy and confirm the effect of ECAP process and post aging on the impact toughness of Al-Li alloy.

2. Experimental procedures

A commercial 1420 Al-Li alloy was used for the present research, having a chemical composition of 5.5% Mg, 2.1% Li, 0.12% Zr, 0.2% Si and the balance of Al. The as-cast alloy was solution heat-treated (SHT) at 723 K for 7 h and then water quenched at room temperature. ECAP processing was continuously performed by a rotational die ECAP (RD-ECAP) setup, in which the billet does not need to be removed from the die and reinserted for the next pass [19]. Billet with dimension of 20 mm × 20 mm × 45 mm was inserted in the die, preheated at 573 K for 20 min together, and then continuously ECAP-processed for 4–12 passes. The processing speed was $0.1\ \mathrm{mm\ s^{-1}}$. Molybdenum disulphide and graphite were used as lubricants. The effective strain (ε) per pass was about 1.15. Subsequently, the ECAPed billets were removed from the die and quickly cooled in water. For some of the samples, deformation temperature from 473 K to 623 K was chosen to investigate the effect of ECAP temperature on the impact toughness. To illustrate the influence of aging hardening, samples were cut from near to the center of the ECAPed material, thereafter were conducted aging treatment at 393 K. The measurement of Vickers Micro-hardness vs. different aging time was carried out to determine the peak aging hardening time, that is 24 h.

Charpy impact testing samples were made from the ECAP billets by machining in the longitudinal direction. The size of the testing samples was the dimension of 3 mm × 4 mm × 34 mm. A standard instrumented impact tester (XJ-300A, China) was applied for measuring the absorbed energy of the samples during impact testing [18–20]. The measured value of impact toughness for each condition was the average of at least three samples. The preliminary tests on the absorbed energy showed that the optimum ECAP pass was no more than 8 for the alloy pressed at 573 K. Thereafter, the fracture surfaces of the broken samples after impact testing were examined by scanning electron microscope (SEM, Hitachi-S3400N).

Microstructure characterizations of the samples were carried out by an optical microscopy (OM, Olympus BX51). Before OM observation, the samples were polished and etched with a 0.5% HF solution. X-ray diffraction (XRD, D8 Advance) and energy dispersive spectroscope (EDS) were used to analyze the phase constitutes. A transmission electron microcopy (TEM, FEI Tecnai G2 T20) was used to observe the ultrafine-grained microstructure and phases in the 1420 alloy. The samples were mechanically thinned to 60 ~ 100 μm, and then twin jet polished with a solution of 6% perchloric acid and 94% ethanol. The operating voltage was 200 kV. The grain size distribution was further characterised using high resolution electron back scattered diffraction (EBSD) analysis with an FEG-SEM (Philips XL30 FEG) at an operation voltage of 25 kV. The EBSD maps were analysed using TSL-EDAX OIM analysis software, and the map step size of 0.5 μm was set.

3. Results

3.1. Microstructure characterization

Figs. 1, 2 illustrate optical micrographs and XRD patterns of 1420 alloy with different ECAP passes. As showed in Fig. 1a, the average grain size of the initial as-cast state is ~ 80 μm. Fig. 3 further shows EDS point scans of as-cast 1420 alloy. According to XRD and EDS, the as-cast alloy are mainly composed of the dendrites of aluminum matrix, a small amount of large black phases mixture of Mg_2Si at the grain boundaries (marked with white arrows in Fig. 1a and “point A” in Fig. 3a, with the EDS analysis in Fig. 3c), and some other little intermetallic compound particles consisting of Mg nearby the boundaries (marked with black arrows in Fig. 1a and “point B” in Fig. 3b, with the EDS analysis in Fig. 3d). Since Li element is too light to be detected by EDS, the additional grain boundary precipitates may be identified as another possible precipitate in Al-Mg-Li alloy combined with XRD patterns of the as-cast alloy, that is the S(Al_2MgLi) phases [25–27]. After pressing by ECAP for 4 and 8 passes at 573 K, no dendrite structure is left in the alloy, and the primary microstructure has changed into bands along the extrusion direction due to the plastic flow of the matrix as shown in Fig. 1b and c. The intermetallic phases have been broken, and their distribution

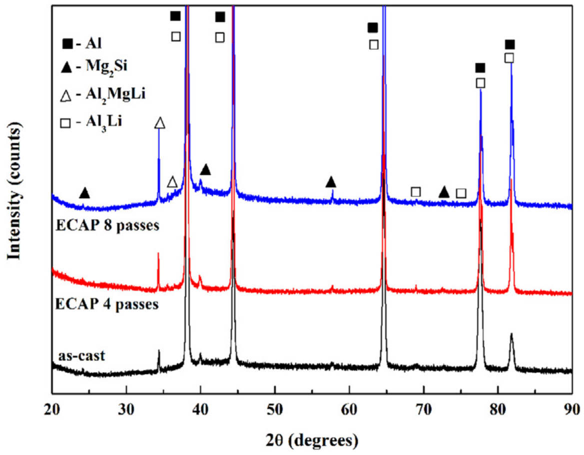

Fig. 2. XRD patterns of 1420 alloys with different ECAP passes at 573 K.