Materials Science & Engineering A 733 (2018) 71–79

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effects of crack orientation on the fatigue crack growth rate and fracture toughness of AA6063 alloy deformed by ECAP

Mohammad Ali Kazemi, Rahman Seifi*

Department of Mechanical Engineering, Faculty of Engineering, Bu-Ali Sina University, P.O.C 65175-4161 Hamedan, Iran

ARTICLE INFO

Keywords:
ECAP
Fracture toughness
Fatigue crack growth
Crack orientation

ABSTRACT

In this study, effects of crack plane orientation on the fatigue crack growth rate and fracture toughness of 6063 aluminum alloy deformed by equal channel angular pressing (ECAP) were investigated. The ECAP process continued up to five passes without failure. Grain refinement was obvious after five passes of the ECAP process. Textural studies showed aligning the grains in known directions. After four passes, yield and ultimate strengths increase respectively from 90 MPa and 209 MPa to 300MPa and 375 MPa and also reduction in elongation was observed. The roughness decreased after the process. The fatigue crack growth rate was investigated at different load ranges with the same load ratio for different orientations. The crack growth rate increased after one pass of the ECAP process. After five passes, the AA6063 shows a lower crack growth rate in compared with as-received material. The fracture toughness of mode I and mixed-mode for different orientations were measured. The results showed that the orientation has a significant effect on the fatigue crack growth and fracture toughness of the ECAPed samples. The fracture surfaces were studied using scanning electron microscope (SEM) and refined equiaxed dimples were observed after the ECAP process.

1. Introduction

The average grain size plays a crucial role in the mechanical properties of a material. Different methods of severe plastic deformations (SPD) were used to produce ultrafine grained (UFG) materials with improved properties such as strength, hardness, fatigue life and fracture toughness. The ECAP method is the common and simple process between the SPD processes. The ECAP process has wide applications for different metallic alloys. This process increased the strength of the material by imposing high strains to introduce the high density of dislocations [1]. The cross-section area of the specimen has no significant changes after the ECAP process. Different routes are available for samples to pass through intersecting channels such as A, B and C routes [2]. The route A is the most widely used route. In this route as can be seen in Fig. 1, the specimen has no rotation according to previous pass. The UFG materials has wide applications in energy (oil-gas), biomedical, aerospace, sports, etc. [3]. Many researchers have studied mechanical properties and microstructures of this materials such as aluminum [4–6] and Mg alloys [7,8].

Horita et al. [9] studied the effects of the ECAP process on the mechanical properties of the aluminum alloys. They found that the strength increased after the ECAP process, however elongation to failure showed a large decrease after the first pass. The dislocation movement plays an important role in the mechanical properties changes after this process.

The fatigue behavior of severely deformed metals was investigated by Vinogradov and Hashimoto [10]. The results showed that the grain boundaries have important effects on both low and high cycle fatigue behaviors of these materials. The SPD materials have shorter low cycle fatigue(LCF) lives in compared with coarse-grained solids because of large decrease in ductility during the process. However, the high cycle fatigue (HCF) lives increased after the SPD process. The shear banding and crack nucleation strongly depends on the material and type of the SPD process. An optimum balance between strength and ductility leads to better fatigue properties [11]. The effects of the ECAP process with subsequent thermal mechanical treatments on the HCF strength of titanium were investigated by Semenova et al. [12]. They found that Low-temperature annealing of samples increased the endurance limit, strength and ductility. Namdar and Jahromi [13] studied the effects of the ECAP on the fatigue behavior of AA2011 alloy. The experimental results revealed that the HCF enhanced by increasing the strength of the material [14].

While the enhancement of tensile strength due to the grain refinement is sensible, the fatigue strength of the UFG materials is not improved in the same manner. The effect of the grain refinement, texture and chemical composition of the material on the fatigue behavior of

* Corresponding author.
E-mail address: rseifi@basu.ac.ir (R. Seifi).

https://doi.org/10.1016/j.msea.2018.07.042
Received 30 May 2018; Received in revised form 7 July 2018; Accepted 12 July 2018
0921-5093/

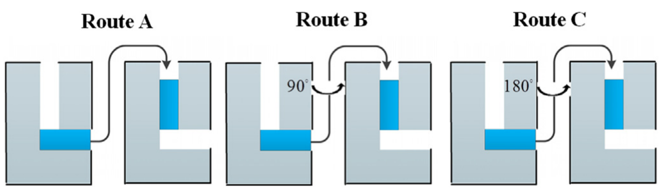

Fig. 1. Fundamental routes used in ECAP process.

metallic alloys makes it difficult to investigate the influence of only one of these parameters on the fatigue performance. The chemical composition plays crucial role in the fatigue behavior of light alloys [15]. Cavaliere [16] studied the fatigue characteristics of pure metal (Al, Ti, Ni and Cu) produced by the ECAP process. The experimental results showed that the fatigue crack growth rate increased in the pure UFG metals in compared with CG (coarse grained) ones. The fatigue tests revealed that the ECAPed material is less sensitive to the crack initiation due to decreasing the average grain size. Vinogradov et al. [17] investigated the effect of the ECAP process on the fatigue crack growth in copper samples. They found that for small values of ΔK_I (stress intensity factor range for mode I), the crack propagation rates for ECAPed copper is higher than that of the CG copper. The growth rate is the same for the UFG and CG materials at higher ΔK_I regime. Fatigue crack initiation life for fine grain brass H62 was investigated by Zheng et al. [18]. They found that the finer grains create higher strength in the brass and cause intergranular cracking under the fatigue loadings. Effects of the ECAP process on the fracture toughness of the materials are studied by Seifi and Kazemi [5] for AA6063, Yu et al. [19] for AZ31 and Rahmatabadi et al. [20] for pure AA1050.

There are a few studies conducted in field of the effect of the crack plane orientation on the fatigue and fracture behavior of the UFG materials. Hohenwarter and Pippan [21] studied the fracture toughness of the ECAP-deformed iron and effects of the crack plane orientation on the fracture toughness. They examined the fracture toughness in different orientations and measured the critical fracture toughness, K_{IC} and critical J integral, J_{IC}. The results showed that the crack plane orientation has a significant effect on the fracture toughness. Hohenwarter and Pippan [22] investigated the fracture toughness of nanopolycrystalline metals produced by the SPD process. They studied the recent results about the fracture properties of different UFG (d < 1 µm) and nanocrystalline (d < 100 nm) metals.

In this study, the effects of the crack plane orientation on the fatigue crack growth of AA6063 aluminum alloy fabricated by the ECAP process have been investigated experimentally. The results were compared with the fatigue and fracture properties of the CG as-received alloy. The microstructure, texture and strength of the ECAPed aluminum were evaluated. The SEM images were taken from fracture surfaces of the samples (ECAPed and CG) to determine the behaviors.

2. Experimental work

We used 6063 aluminum alloy (AA6063) for preparing the sample tests. The chemical composition of AA6063 is given in Table 1. The as-received specimens were annealed at 420 °C for 3 h before ECAP process to achieve better deformability and reduce friction due to the decrease of dislocation density [23].

MoS_2 lubricant was used to decrease the friction. Specimens with dimensions of 12 × 12 × 110 mm (Fig. 3a) in form of billets were machined from aluminum rods with 20 mm diameter. A two pieces split die was used for the ECAP process as depicted schematically in Fig. 2.

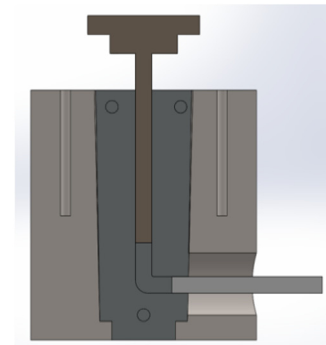

Fig. 2. The cross section of the assembled die.

The die material was H13 tool steel. This type of the die is suitable for reducing the time of the process, because it doesn't have bolts. The channels intersecting angle is $\Phi = 90^\circ$ and outer corner angle is $\Psi = 22^\circ$. In order to achieve better grain refinements and mechanical properties, rout A was selected for conducting the ECAP process based on recommendation in [24].

The ECAP process applied to billets up to five passes at 200 °C. The pressing speed of 0.5 mm/s was applied to specimens during the process. Equivalent strain is approximately 1.05 in every pass based on Eq. (1) which presents equivalent strain, ε_N after N passes of the ECAP process [1]. The strains that imposed on the sample are large simple shear [25].

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\Phi+\Psi}{2}\right) + \Psi\ \mathrm{cosec}\left(\frac{\Phi+\Psi}{2}\right)\right] \quad (1)$$

The specimens for tensile tests, Compact Tension (CT) and mixed-mode samples in different orientations were machined from ECAPed billets. A billet after one pass is shown in Fig. 3. The cross-sectional shape of the billet after extrusion was square.

The tensile tests were carried out by using a zwick/roell universal testing machine according to ASTM E8 standard [26]. The tensile specimens were machined from the center of the billets as depicted in Fig. 3(c) with dimensions as follows: gauge length = 45 mm, radius of fillets = 8 mm and diameter = 9 mm. Three tests were performed for each condition. The strain rate and crosshead speed applied on the samples are $3.7 \times 10^{-4} s^{-1}$ and 1 mm/min, respectively. The microstructure, texture and fracture surface studied by using scanning electron microscope (SEM), atomic force microscope (AFM) and x-ray diffraction (XRD).

The standard CT specimens were made from as-received and the ECAPed materials in different orientations according to ASTM E647 [27] for fatigue crack growth and fracture toughness measurements based on ASTM E1820 standard [28]. As depicted in Fig. 4, different types of the CT samples were made and noted as L, M and N. In L type, the crack surface is normal to normal direction (ND) and will grew in extrusion direction (ED), while in M and N types, the crack is normal to the ED. The growth direction of the cracks in M and N types are in the ND and transverse direction (TD), respectively.

The width and thickness of the CT specimens were considered as $W = 10mm$ and $B = 3mm$, respectively. The electric discharge machining (EDM) method was used to create sharp notches in the samples. In order to conduct the fatigue cyclic loading, the servo-hydraulic test

Table 1
Chemical composition (wt%) of AA6063.

Al	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	Co	Bi
Base	0.44	0.93	3.50	0.59	1.02	0.03	0.005	0.38	0.04	0.10	0.005	0.004