Journal of Engineering and Applied Sciences 12 (8): 2143-2147, 2017
ISSN: 1816-949X

Effect of Equal Channel Angular Pressing on Yield Stress and Fatigue Properties of Al 6063 Alloy

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Abstract: The present research investigates the effect of Severe Plastic Deformation (SPD) on the mechanical properties (yield and tensile strength) of Al 6063 alloy along with its fatigue behavior. The severe plastic deformation was carried out by using Equal Channel Angular Pressing (ECAP) technique. This technique was used to refine grains into ultrafine grain size of the metal alloy without changing the cross-sectional dimensions of the work piece. Prior to the ECAP deformation process the material was annealed for 2 h at 415°C. The Al 6063 alloy specimens with 12×12 mm cross section and 100 mm length were machined from these annealed bars. They were pressed at room temperature with a speed rate of 10 mm/min through 120° die channel angle using a 100 KN hydraulic press machine. Molybdenum disulfide was used as lubricant for reducing friction between the work piece and ECAP die. The tensile tests were conducted before and after ECAP at room temperature with a fixed cross head displacement rate 1 mm/min using a hydraulic machine. The Fatigue life was tested under axial loading tension-compression with stress ratio R = -1. The results showed a significant improvement in mechanical properties of Al 6063 alloy after ECAP technique. Furthermore, the improvement of the fatigue life in the high-cycle fatigue region was substantial compared with low-cycle fatigue region.

Key words: Al 6063 alloy, ECAP, mechanical properties, tensile test, fatigue

INTRODUCTION

Aluminum alloys are widely used in many applications fields such as aerospace in our transportation sector, electrical power generators, railings, rail road, irrigation pipes, drill pipes and big structures due to the light weight, low cost and there are a lot of advantages obtained by aluminum application whereby the researchers have pointed to the potential use of it (Placido *et al*., 2005). The fatigue behavior of aluminum alloy is attract attention of researchers because these applications are subjected to cyclic loading (Zhao and Jiang, 2008) so fatigue failure is the most common and represents 90% of the causes of mechanical failure which is phenomenon of failure of structure under fluctuating loads at a value of stress is lower than the yielding stress (Mishra *et al*., 2016; Walton *et al*., 1986). Economic and human cost as result of fatigue failure, it causes loss durability and the system reliability. Therefore, many of scientists and engineers strive for improving mechanical properties of materials and structures against fatigue. With a variation in the understanding of behavior by researchers, so they employed different techniques to overcome the problem of sudden failure and make service life of the materials as long as possible. A Severe Plastic Deformation (SPD) approach use to improve the fatigue life and performance of structures is exploiting materials (Estrin and Vinogradov, 2010; Farshidi *et al*., 2013a, b; Liu *et al*., 2014). Severe Plastic Deformation (SPD) is a public idiom indicates to processes of metalworking techniques involving imposition of ultra-large strain into the material structure with keeping of the same geometry of the material Mechanism of SPD approach is large strains typically including a high shear or complicated stress state. SPD has provided new opportunities in investigations to enhance and raise materials properties like high strength and ductility. Therefore, the interest has been changed towards the using of SPD methods to create durable metals for applications require more strength with lightweight (Toth and Gu, 2014;

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Valiev *et al*., 2006; Wang *et al*., 2012). The most commonly used SPD method and attractive is the Equal Channel Angular Press (ECAP) technique. ECAP technique consisted of two identical circular channels linked through the junction at a specific angle. ECAP is an efficient method for material processing to get rid of porosity and reduce impurities at a low cost (Jafarlou *et al*., 2016; Langdon, 2007). Many researchers have focused on the enhancement in the physical and a mechanical property of aluminum alloys is induced by SPD is currently of great attention (Cabibbo, 2012; Shaeri *et al*., 2013, 2015). Toth and Gu (2014) showed the effect of SPD on the yield strength and provides best S-N fatigue resistance whereby it delay the initiation and propagation of crack. Hamada *et al*. (2011) reported very significant improvement (43-80%) in the bending fatigue resistances but severe plastic deformation generates residual stresses in the material and therefore corrosion fatigue performance of material will be impaired. Preliminary studies explain the fatigue behavior indicated that the fatigue mechanism is sensitive to plastic deformation. However, there isn't further investigation about the effect of ECAP on axial fatigue.

The objective of this research was to investigate effect ECAP technique to enhance the mechanical properties, axial fatigue strength and increase fatigue life of 6063 AL for use it as alternative material in components of heavy structures where it is characterized by lightweight that avoids stresses of extra weight and to avoid early failure for shafts in applications of power plant, aerospace and automotive. The tensile strength, fatigue strength especially axial fatigue sensitivity of the SPD processed AL were measured and compared with Al6063 before SPD.

MATERIALS AND METHODS

Experimental materials and specimens preparation: The chemical composition of Al6063 alloy used in the ECAP experiments shown in Table 1 and the mechanical properties shown in Table 2.

The Al 6063 specimens were obtained from 12×12 mm bar. The bar was cut into many pieces each one 100 mm length and then it were annealed at 415°C for 2 h. Specimens was machined to manufacture tensile and fatigue test samples according ASTM standards E8M and E466. Same the number of specimens were processed by equal channel angular pressing ECAP with channel angle of ECAP die is 120° as well as a corner angle is 20° as shown in Fig. 1 the channel of die is well lubricated with molybdenum disulfide-based solid lubricant (MoS2), a pressing speed of 10 mm/min. The die was designed to give an accumulated equivalent strain of 0.7 on each pressing according to Eq. 1 (Kim *et al*., 2006; Serban *et al*., 2012). The processed specimens by ECAP were machined into the same size of normal samples:

Table 1: Chemical composition of tested 6063 Al in wt%

Elements	Cu	Fe	Mg	Mn	Si	Ti	Zn	Cr	Al
wt.%	<0.01	0.19	0.51	0.04	0.46	0.008	<0.01	<0.01	Balance

Table 2: Comparison the yield and ultimate stress of 6063 Al before and after ECAP

Variables	σ_y (MPa)	σ_{UTS} (Mpa)
Before ECAP	122	195
After ECAP	191	232

Fig. 1: Equal channel angular pressing (ECAP) mold

$$\varepsilon = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\phi}{2}+\frac{\varphi}{2}\right)\varphi\operatorname{cosec}\left(\frac{\phi}{2}+\frac{\varphi}{2}\right)\right] \quad (1)$$

Where:

ε = Accumulated equivalent strain

ϕ = The channel angle

φ = The corner angle

Tensile test and fatigue test: Two different types of samples were machined to make samples of tensile test according to ASM 8M where gauge length of cylindrical specimens is 24 mm and diameter 4 mm. Three specimens of the cast material and three specimens of the material after ECAP. The tensile tests were carried out at room temperature in lab air.

Second type of samples is 22.05 mm of gauge length of cylindrical specimens and minimum diameter in the middle of gauge length is 5.8 mm that was manufactured for fatigue test according to ASTM E466. Fatigue test implemented under axial loading tension-compression with stress ration R = -1. Instron 8874 machine was used to execute the test with frequency 20 HZ (Murashkin *et al*., 2015; Jimenez *et al*., 2007). The tests were performed at room temperature in lab air. Establishing S-N curve based on recommendations by

ASTM E606. Changing of stress amplitude according to the following percentages of the yield stress of cast material was obtained from tensile test for cast aluminum are 92, 85, 77 and 69% for ECAPed aluminum are 99, 92, 85 and 78%.

RESULTS AND DISCUSSION

The heat treatment before equal channel angular process has significant effect to develop homogeneous of grain structure and increase ductility which keep the specimen from crack during severe plastic deformation (Chen *et al*., 2008).

The mechanical properties, deformation properties and strength are increased by ECAP. The results of tensile tests as shown in Fig. 2 for specimens of material processed by ECAP has a tensile property higher than specimens without SPD treatment as clear in stress-strain curves. Table 2 shows comparison for 6063 Al before and after processing of ECAP. The percentage of improvement in the properties of materials by SPE is based on the details of process. ECAP technique provides the structure of material by a favorable combination of ductility and strength.

The improvement of fatigue resistance is presumed to be due to a reduction in the grain refinement of the Al.6063 alloy. The fatigue life with endurance limit are got significant enhancement by ECAP processing in middle and high cycle fatigue regime as observed from S-N curves in Fig. 3. The equation of power law curves is:

$$y = aX^{b} \tag{2}$$

Equation 3 represents relation between load and fatigue life. This relation is applicable when the work based on stress approach for fatigue design and analysis and the S-N curve for cast aluminum alloy can be fitted by power law:

$$\sigma_a = 161.18N^{-0.045} \tag{3}$$

Where:

σ_a = Stress amplitude
N = The number of cycles to failure

All the samples were tested at stress amplitude <80 MP. Equation 4 is based only on the data corresponding to the broken specimens. The endurance limit is 80 MP based on 10^7 cycles. So, stress amplitude of the samples <75 MP because the failure occurs before thetests reach 10^7. Endurance limit for The S-N curve of the material treated by ECAP σ_a is 90 MP at 10^7 according to power law Eq. 4 as:

$$\sigma_a = 221.21N_f^{-0.058} \tag{4}$$

So, the processed samples were tested at stress amplitude more than 90 MP. There is a clear improvement in fatigue life of 6063 aluminum alloy processed by ECAP in medium and high-cycle fatigue region where severe plastic deformation creates change in grain structure, consequently the fine grains provide more grain borders and minimize the amount of irreversible slip so this prevent the occurring of early crack initiation. There isn't benefit of ECAP as regards the low cycle fatigue strength.

The cyclic deformation response of Al6063 aluminum alloy rocessed by ECAP is similar to the cast alloy

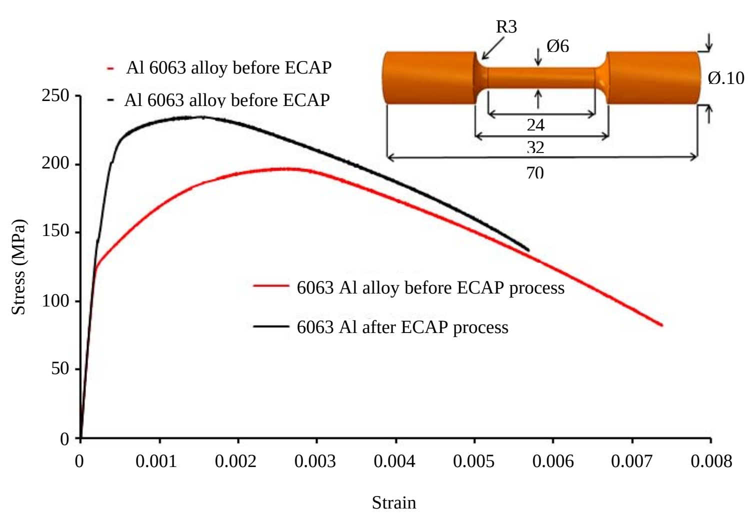

Fig. 2: Stress-strain curve of Al 6063 alloy before and after ECAP

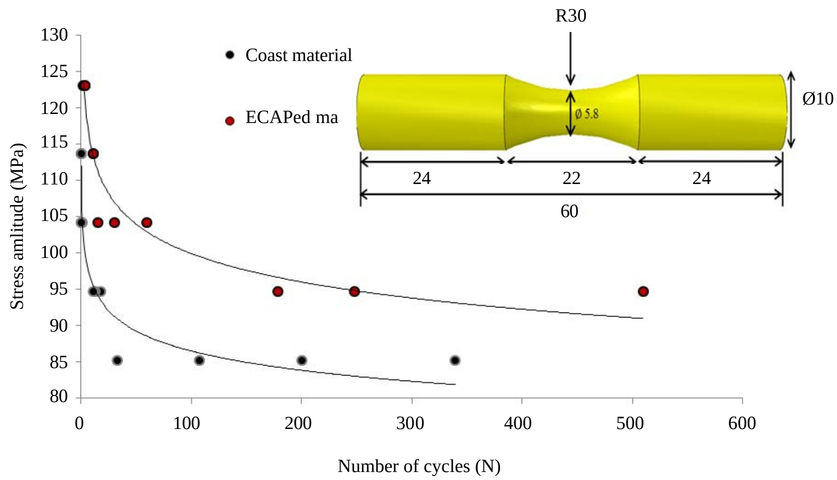

Fig. 3: S-N curves of cast and processed aluminum by ECAP

response where the magnitude and range of strain amplitude is increasing with increase of stress amplitude.

CONCLUSION

Al6063 alloy processed by equal channel angular pressing ECAP with channel angle of ECAP die is 120° as well as a corner angle is 20° after annealing material at 415°C for 2 h to improve yield stress, ultimate stress, hardness and fatigue life of aluminum alloy. The ECAP process enhances the tensile properties of the cast material especially, the yield stress has developed from 120-191 MP and the ultimate stress from 196-232 MP. The fatigue life of cast material and SPD processed Al6063 alloy are successfully characterized and it is improved after SPD processing as clear form S-N curves. The maximum increase fatigue life is about 123% which happen at 40 MPa of stress level. The fatigue strength 80 MPa is an endurance limit based on 107 cycles for cast material but it is 90 MPa for the alloy processed by SPD. There isn't substantially improved for the fatigue lifetime in the low-cycle fatigue region.

ACKNOWLEDGEMENT

Special thanks to University of Malaysia Putra financial support through Research Grant No. 9463100.

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