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Experimental investigation of ultrasonic assisted equal channel angular pressing process

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ABSTRACT

Improvement of equal channel angular pressing (ECAP) efficiency is an important challenge for industrialization of this technique. The reduction of pressing load and improvement of material mechanical properties are among the most challengeable subjects during this process. In this research, commercial pure aluminum has been ECAPed at room temperature using conventional and ultrasonic vibration techniques to investigate the influence of ultrasonic wave on the pressing load and mechanical characteristics of deformed samples. The results showed that the superimposing ultrasonic vibration on the ECAP process not only decreases the required punch load, but also improves the mechanical properties of the material as compared to the conventional condition. Interestingly, the ultrasonic vibration assisted process leads to about 16%, 10% and 12% increments at the yield strength, ultimate tensile strength and hardness value respectively and also, 9% reduction at the punch load. Furthermore, the dislocation density of the sample produced by ultrasonic assisted ECAP is about 35% more than the achieved conventional sample.

1. Introduction

Fabrication of ultrafine grain (UFG) and nanostructure (NS) materials by equal channel angular pressing (ECAP) method is one of the most considered techniques of severe plastic deformation (SPD). This method results in the enhancement of mechanical, superplasticity and the other properties of materials [1–3]. During this process, a cylinder or square shape work-piece is pressed through a die with two identical cross-sectional channels intersecting at a die channel with the outer corner angles of Φ and Ψ, respectively. Since there is no change at the dimensions of the sample after pressing, this process can be repeated for a number of times to achieve the desired characteristics [4,5]. ECAP is considered to be a friction sensitive process and studies have shown that the increment of the friction factor increases strongly the forming force. Also, there exists a critical friction factor in which, the dead metal zone is formed during the process. Thus decreasing the sliding friction between the work-piece and the die especially for the higher passes in the entrance channel would help to reduce the pressing load as well as increase the efficiency of the process [6,7]. Hence, it has been proposed to reduce the forming load by

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simultaneous application of ultrasonic vibration (UV) during the process [8–10].

In recent years, the attention for application of ultrasonic energy on the various metal forming processes has been considerably increased. The investigation by researchers has shown beneficial effects such as lower forming load, lower number of steps in the process, better surface finish, material softening and acoustoplastic effect [8–12]. The experimental study by Izumi et al. on the effect of superimposed ultrasonic vibration during compression test showed that the compressive flow stress is decreased by applying UV. In addition, the UV efficiency is related to the metal properties such as acoustic impedance, Young's modulus, melting point, work hardening and stacking fault energy [13]. Reduction in the both flow stress and forming force in the hot upsetting process via axial ultrasonic vibration technique has been reported by Hung et al. [14,15]. Also, the influence of UV on processes like hot upsetting cannot be justified only by the simple mechanism like frictional effect at the interface. In fact, it can be related to the ultrasonic energy absorption by the dislocations. Experimental and numerical investigations by Liu et al. revealed that upsetting method with ultrasonic vibration leads to fabrication of ultrafine grain structure at the pure copper cone tips [16,17]. The application of ultrasonic vibration on the cold forging process indicated that the service time of trimming knives is improved by about 100% at the cold rolling process due to the tool steel mechanical properties enhancement [18]. The study by Bunget and Ngaile confirmed that the extrusion process of difficult-to-lubricate materials can be carried out using UV. The results showed significant reduction at the extruded force and better surface property of final sample is achieved [19]. Investigation by Mousavi et al. on the ultrasonic vibration assisted extrusion process indicated that the magnitudes of forming load and flow stress are reduced significantly [20]. Jimma et al. explored the influence of ultrasonic vibration on the deep drawing process. The blank holder and the die were radially vibrated which led to the increment at the drawing ratio, better sheet deformation and protection against cracks and wrinkles [21]. The influence of ultrasonic waves on the strip drawing process studied by Siegert and Ulmer showed that the friction value is reduced and the surface quality of the samples are improved [22]. The studies by Hayashi et al. and Murakawa et al. demonstrated that improved drawing resistance, enhanced lubrication condition and wire breakage reduction can be obtained by imposing UV to the wire drawing process. Furthermore, the radial ultrasonic vibration is more effective than the axial one on the increment of critical rate by about 10 times [23,24]. Ashida and Aoyama surveyed experimentally and numerically the press forming process behavior via ultrasonic vibration and showed that this technique leads to the lower forming load, higher formability and lower crack formation as compared to the conventional one [25]. It can be concluded that diminution of the forming load, decrease of material flow stress, reduction of friction between the interface of the sample and the die, better surface quality of the processed sample, higher dimensional accuracy of the produced sample, rise at the material temperature during the process and the spring-back reduction in the sheet forming are the most advantages of ultrasonic vibration application in the metal forming processes.

Despite the significant merits of ultrasonic vibration application on the various metal forming processes, this technology has not been developed for severe plastic deformation methods, hence there is a little study in this field [8]. The equal channel angular pressing method equipped with ultrasonic vibration technique was investigated by Djavanroodi et al. and they verified that lower pressing force is required by using ultrasonic vibration. Also, the influence of vibration amplitude is more sizeable than frequency on the required force reduction [9]. Ahmadi and Farzin [10] investigated numerically the effect of superimposing ultrasonic vibration on the punch during the ECAP process. They showed that there is a reduction in the forming force and this force reduction depends on the vibration amplitude and the die velocity. Application of ultrasonic vibration on the tubular channel angular pressing studied by Faraji et al. indicated that the radial ultrasonic is the dominant factor as compared to the axial one on both the strain behavior and the pressing force [26]. Also, the results showed that vibration of the die is more significant than either mandrel or punch.

The authors have made a detailed finite element investigation on the effect of ultrasonic vibration during ECAP process [9]. In continuation of their previous studies, the purpose of this research is to investigate experimentally the influence of ultrasonic vibration application on the equal channel angular pressing process. Hence, the ECAP process has been experimentally equipped with ultrasonic vibration technique and its effects have been evaluated on forming load and mechanical properties of deformed billet.

2. Experimental procedure

Cylindrical shape commercial pure (CP) aluminum (Al1070) with the chemical composition listed in Table 1 was prepared with the length and diameter of 150 mm and 20 mm, respectively. To make sure that there is no non-homogeneity in the structure, all samples were annealed at 380 °C for half-an-hour before the ECAP process. ECAP die with the die channel angle of 90°, outer corner angle of 15°, channel diameter of 20 mm, the entrance and exit channels length of 200 mm and 230 mm was designed and manufactured as shown in Fig. 1. To perform the ECAP process, a hydraulic press with the capacity of 400 tons and ram speed of 2 mm/s were

Table 1 – The chemical composition of commercial pure aluminum used for this study.

Element	Al	Fe	Sn	Mg	V	Zn	Ti
Weight percent	99.737	0.127	0.043	0.030	0.012	0.009	0.002

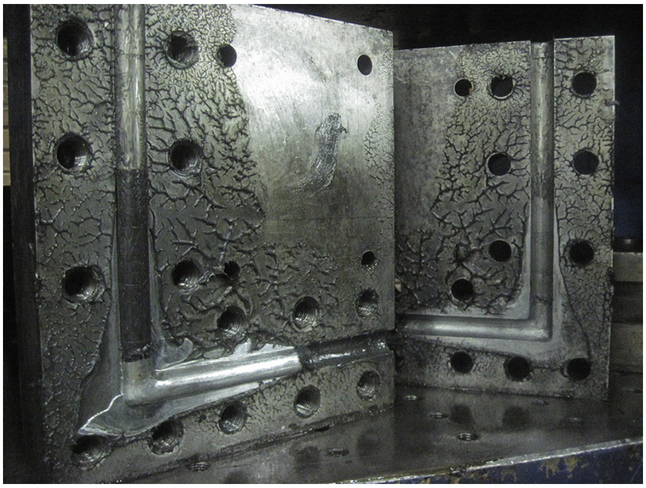

Fig. 1 – The equal channel angular pressing die.

utilized. Molybdenum disulfide (MoS_2) was used for lubrication between the billet and the die.

The ultrasonic vibration system designed for the experimental work during the ECAP process consists of three main parts including ultrasonic generator (power supply), ultrasonic transducer (piezoelectric converter and booster) and the horn. This system was designed in order to superimpose ultrasonic vibration to the aluminum billet during the ECAP process. Fig. 2 shows the schematic representation of ultrasonic vibration ECAP set-up used in this work.

For this study, a 3 kW variable frequency ultrasonic generator and a 20 kHz ultrasonic transducer were employed; see Fig. 3(a) and (b). In addition, a step horn was designed and manufactured to superimpose the ultrasonic vibration on the sample during the process as shown in Fig. 3c. The horn material is H13 hot work tool steel. D_1, D_2 and L_1 are the small diameter of the booster, the ECAP die channel diameter and one-fourth of the wave-length ($\lambda/4$), respectively. L_2 is calculated using the modal analysis and laser vibratometer, hence not only buckling effect is avoided during the process, but also the optimal UV energy efficiency is achieved since the set-up natural frequency would be the excitation frequency of 20 kHz. Furthermore, the step in the horn acts as a supported position at the vibratory node and also, increases the oscillation amplitude at the interface of the horn and sample. In fact, the horn was designed, so that it succeeds in achieving the natural frequency of the system with the desired excitation one. At this condition, the ultrasonic vibration is transferred to the sample with the maximum amplitude and the horn plays the role of the punch for applying the mechanical load to the aluminum billet. It should be noted that during the simultaneous application of vibration and pressure on the Al sample via the designed horn, the magnitude of vibration amplitude was measured at the interface of the horn and sample by the use of the laser vibratometer which was equal to approximately 2.5 μm. Table 2 lists the horn dimension manufactured for this study.

Fig. 4 shows the UV assisted ECAP process set-up for pressing CP aluminum billet. As can be seen, a fixture was

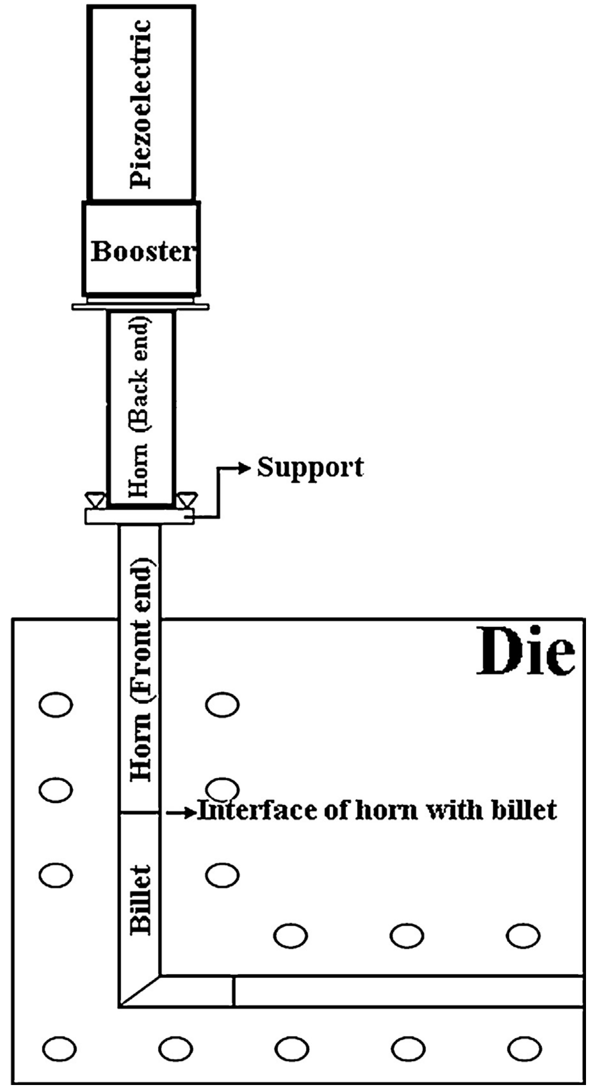

Fig. 2 – The schematic representation of ultrasonic vibration ECAP die set-up.

designed and manufactured to attach the horn to the upper moving ram of the press. It needs to say that the horn was installed at the vibratory node. Also, the piezoelectric and booster were connected to the horn via a screw. This setting insures the transfer of produced oscillatory energy to the booster and then to the horn and finally to the billet with the maximum amplitude.

In this research, Al1070 billet has been ECAPed at the conventional (C-ECAP) and ultrasonic vibration (UV-ECAP) conditions up to one pass at room temperature. All other factors have been assumed to be constant for both conditions. The ultrasonic vibration with the frequency of 20 kHz and the amplitude of 2.5 μm has been employed [9]. After deformation, the effect of ultrasonic wave has been investigated on the required pressing force, tensile properties and hardness behavior of the ECAP sample. Tensile test was carried out according to the ASTM B557M with the nominal diameter, gage length, radius of filet and length of reduced section of 12.5 mm, 62.5 mm, 9 mm and 75 mm, respectively by means

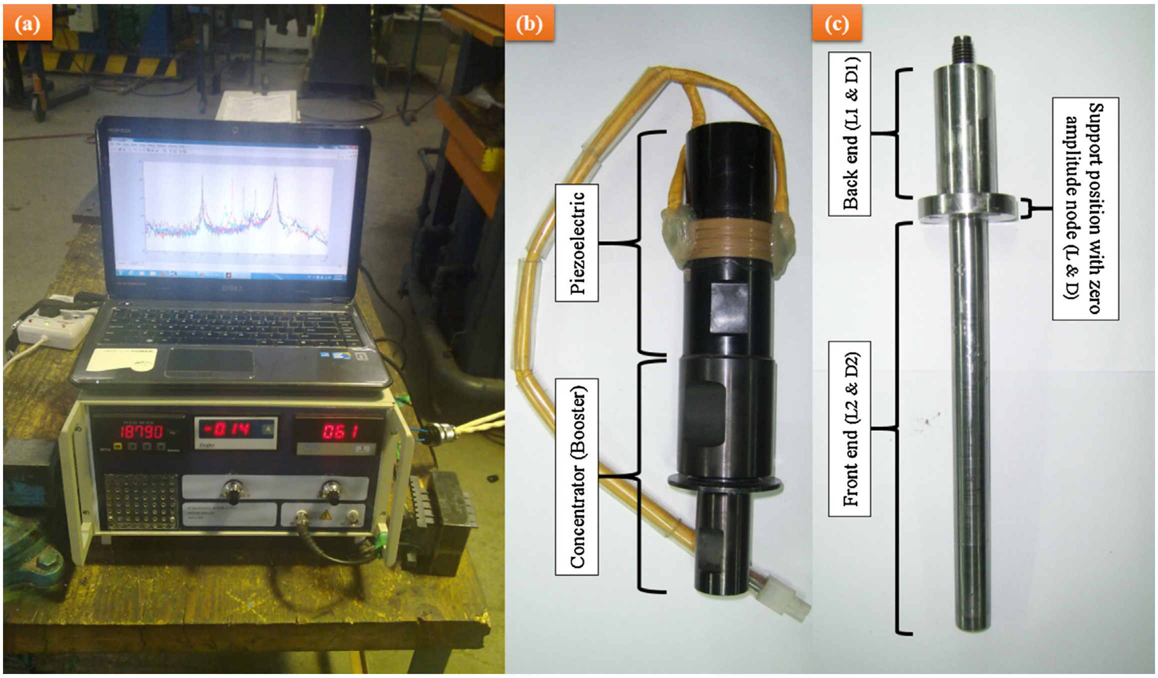

Fig. 3 – (a) The variable frequency ultrasonic generator with the power of 3 kW, (b) the 20 kHz piezoelectric transducer and (c) the H13 tool steel horn.

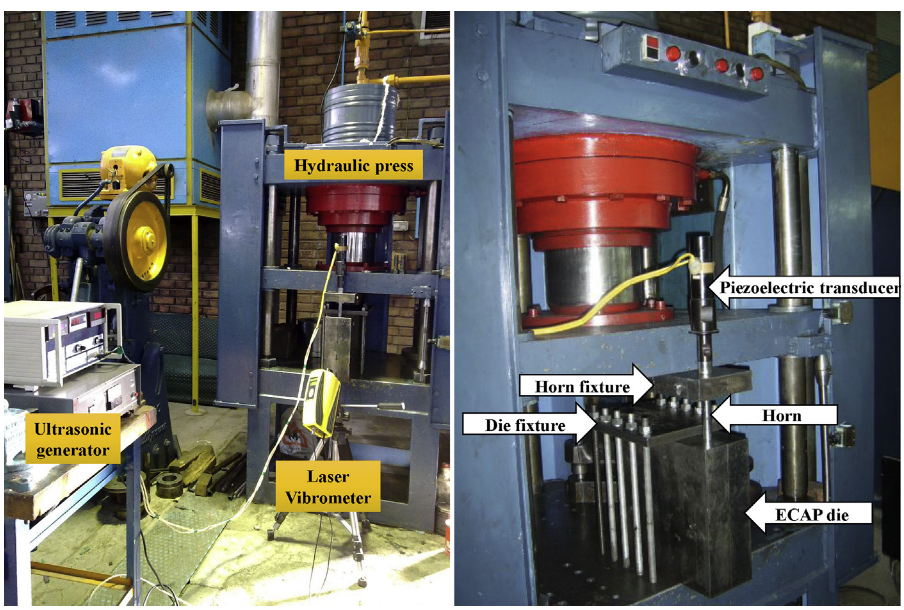

Fig. 4 – The ultrasonic assisted ECAP process set-up.

of INSTRON 5984 universal testing machine. Additionally, Vickers microhardness (HV) measurements were performed at least four times for each reported location to ensure the accuracy of the results. This test was done in accordance with the ASTM E92 with a load and dwell time of 100 gf and 15 s, respectively.

Table 2 – The manufactured horn dimension.

Name	D	D_1	D_2	L	L_1	L_2
Dimension (mm)	51	31	20	10	66.4	206

3. Results and discussion

The required pressing load for the first pass ECAP process under the two conditions (conventional and ultrasonic assisted ECAP) has been measured and compared. The magnitudes of frequency and amplitude for the vibration

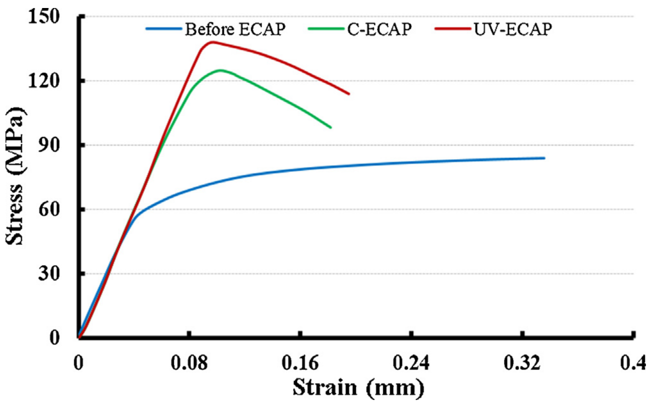

Fig. 5 – The stress–strain curves of commercial pure aluminum before and after the first pass ECAP process for the conventional and ultrasonic vibration conditions.

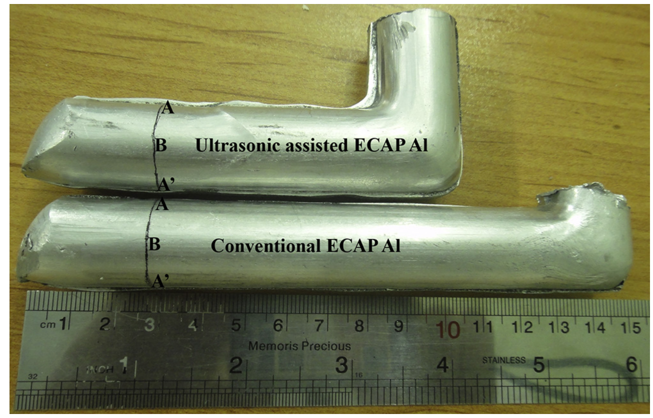

Fig. 6 – The location of Vickers hardness test at the ECAP CP aluminum for the both conventional and ultrasonic vibration conditions.

condition are 20 kHz and 2.5 μm, respectively. The results show that the required force value for the conventional and ultrasonic vibration conditions are about 162.5 kN and 147.7 kN, respectively. It means that about 9% reduction at the required ECAP load is achieved by the use of ultrasonic wave; hence this technique has a significant effect on the required pressing force. The main reason for this decrease can be attributed to the friction force reduction because the actual contact surface between the die and sample is reduced using this technique as compared to the conventional process.

The measured tensile behavior of the CP aluminum before and after the first pass ECAP process at the conventional and vibration methods is shown in Fig. 5. About 118% and 154% enhancements at the yield strength and also, approximate 49% and 64% improvements at the ultimate tensile strength have been attained after the first ECAP pass for the conventional and ultrasonic vibration situations, respectively as compared to the as-received condition. Although there is a considerable enhancement at the mechanical properties of samples after the ECAP process for the both conditions, the UV technique has higher influence than the conventional circumstance on the strength growth. It is worth to note that ultrasonic assisted ECAP process leads to about 16% and 10% improvements at the yield and the ultimate tensile strengths in comparison with the conventional ECAP. In addition, taking into consideration the slope corresponding to the elastic stage in tensile curves and also the experimental error, the elongations to failure of the conventional ECAP and UV-ECAP aluminum samples are approximately unchanged.

Furthermore, Vickers hardness measurements have been performed on the CP Al billets before and after the first pass process using the conventional and vibration conditions. These tests have been carried out at the cross-sectional surface with the distance of 30 mm from the head part of the ECAP sample on the vertical and horizontal lines as shown in Fig. 6. The vertical and horizontal lines have been marked by AA′ and BB′, respectively. Furthermore, the results have been represented in Fig. 7.

As a first finding, the magnitude of hardness increases intensely by application of ECAP process irrespective of the conventional or vibration method. It can be said that there are about 108% and 133% improvements at the average hardness value of ECAP Al for the conventional and ultrasonic vibration conditions, respectively as compared to the annealed condition. This means that the ultrasonic assisted ECAP process leads to higher hardness behavior than the conventional method (approximate 12%). In addition, the hardness distribution is the same for the both techniques at the horizontal line (BB′). Furthermore, the magnitude of HV reduces gradually at the cross-section from the top to the bottom for the both methods. There are about 20% and 13% differences between

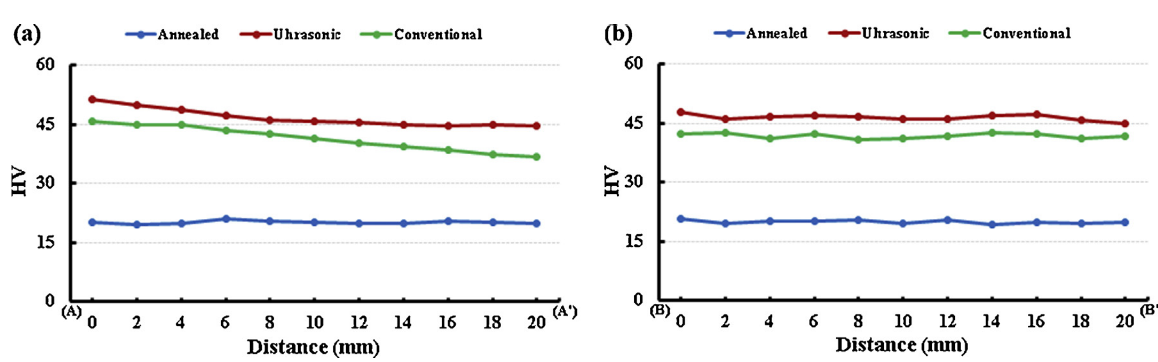

Fig. 7 – The Vickers hardness magnitudes for the both conventional and ultrasonic vibration ECAP aluminum along the (a) vertical and (b) horizontal directions.

the upmost and the lowest regions of ECAP CP Al from the hardness value point of view for the conventional and vibration conditions. This indicates that ECAP process of aluminum billet with the application of UV technique causes more uniform hardness homogeneity and hence, the better isotropic material than the conventional situation.

The proposed Taylor relationship (Eq. (1)) has been used to compare the dislocation density of sample before and after the ECAP process for the conventional and the ultrasonic assisted conditions [27–29]. It must be point out that, this equation is based on the experimentally obtained value of the yield strength and it is not an independent explanation for the improved strength of the material. The average total dislocation density (ρ_{tot}) has been estimated by means of the proposed Taylor equation by the substitute of σ_i as the material strength resisting the dislocation glide with the yield strength (σ_{YS}). In addition, M, α, G and b are Taylor factor, non-dimensional constant, shear modulus and burger's vector, respectively. The magnitude of M is supposed to be equal to 3.06 for a polycrystalline FCC material of random orientation and the values of α, G and b are 0.3, 26.1 GPa and 0.286 nm for the pure aluminum, respectively.

$$\rho_{tot} = \left(\frac{\sigma_i}{M\alpha Gb}\right)^2 \tag{1}$$

The estimated magnitude of the total dislocation density for the as-received condition and also, the conventional and ultrasonic assisted equal channel angular pressed aluminum after the first pass are $0.59 \times 10^{14}\,m^{-2}$, $2.78 \times 10^{14}\,m^{-2}$ and $3.77 \times 10^{14}\,m^{-2}$, respectively. So, about 35% increment at the dislocation density is achieved for the UV-ECAP billet in comparison with the conventional process. Hence, it can be said that the ultrasonic vibration leads to the more creation and multiplication of dislocations. These dislocations then tangle with each other and the dislocation walls take place. Afterwards, the generated dislocations walls transform into low angle grain boundaries (LAGBs), and finally high angle grain boundaries (HAGBs) will be produced. The same behavior has been already reported by Hung and Lin on ultrasonic assisted upsetting [30].

It seems that material resistance to dislocation movement increases by employment of the ultrasonic energy and therefore, aluminum sample with higher dislocation density is obtained by application of ultrasonic vibration technique in comparison with the conventional ECAP process. In other words, the ultrasonic energy is an additional source for production of dislocation and assists the ECAP process which intern increase the dislocation density, i.e. the effect of ultrasonic energy on deformation is cumulative.

4. Conclusion

The influence of ultrasonic vibration on the required pressing force and mechanical properties of commercial pure aluminum during equal channel angular pressing as a one of the main severe plastic deformation processes has been experimentally investigated. For this aim, ECAP die has been designed and manufactured with the die channel and outer corner angles of 90° and 15° and also, channel diameter of 20 mm. In addition, ultrasonic vibration set-up was designed and implemented with the frequency and amplitude of 20 kHz and 2.5 μm, respectively. The results showed that the ultrasonic vibration assisted ECAP process requires 9% less pressing load than the conventional condition for fabrication of Al sample. Also for the case of UV assisted ECAP billet; improvement of about 16%, 10% and 12% have been achieved for yield strength, ultimate tensile strength and hardness values, respectively as compared to the conventional ECAP process. In addition, elongations to failure of the conventional ECAP and UV-ECAP aluminum samples are approximately unchanged. It can be concluded that the required pressing load reduction is related to the frictional force decrease because of actual contact diminution between the die and sample. Also, ECAP process of aluminum billet with the application of UV technique causes more uniform hardness homogeneity and hence, the better isotropic material than the conventional situation. Moreover, the higher mechanical properties of the sample produced by ultrasonic vibration assisted ECAP are attributed to the dislocation density increment from $2.78 \times 10^{14}\,m^{-2}$ to $3.32 \times 10^{14}\,m^{-2}$. So, it is believed that ultrasonic vibration has a double effect on the ECAP process. It not only leads to the fabrication of material with lower required pressing load, but also results in more homogenous aluminum sample with the higher mechanical properties in comparison with the conventional ECAP process.

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