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ORIGINAL ARTICLE

Improvement of ECAP process by imposing ultrasonic vibrations

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Abstract In a few last decades, equal-channel angular pressing (ECAP) has been one of the most prominent procedures for fabrication of ultrafine-grained (UFG) structures among various severe plastic deformation (SPD) techniques. The objective of this paper is to experimentally investigate the influence of longitudinal ultrasonic vibrations on the ECAP process. A robust experimental ECAP system was designed and manufactured, in which the punch can be excited by ultrasonic vibrations. ECAP experiments were carried out with and without ultrasonic vibration on pure Al. The microstructure of the specimens formed with ultrasonic-assisted ECAP and conventional ECAP were studied. The results of this study showed that superimposing ultrasonic vibrations on the ECAP process could improve the grain refinement efficiency. The grains of the specimens after conventional ECAP process were refined to 45 μm, while by applying ultrasonic vibration with amplitudes of 2.5 and 5 μm, the grains were refined to 28.2 and 22 μm , respectively. Using higher vibration amplitudes caused more refinement of the grains. The homogeneity of the microstructure after four passes of ECAP was also improved by 26.7 % while using ultrasonic vibration with amplitude of 2.5 μm. Higher vibration amplitudes made a more homogenous structure. The yield strength and ultimate tensile strength of the specimens after one pass of ECAP were higher in comparison with the conventional ECAP.

Keywords ECAP · Ultrasonic vibrations · Homogeneity · Grain size

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1 Introduction

Although the mechanical and physical properties of all crystalline materials are determined by several factors, the average grain size of the material generally plays a very significant, and often a dominant, role. Thus, the strength of all polycrystalline materials is related to the grain size, d, through the Hall–Petch equation which states that the yield stress, σ_y, is given by:

$$\sigma_y = \sigma_0 + k_y d^{\frac{-1}{2}} \tag{1}$$

where σ_0 is called the friction stress and k_y is a constant [1]. It follows from Eq. (1) that the strength increases with a reduction in the grain size, and this has led to an ever-increasing interest in fabricating materials with extremely small grain sizes.

It has been known for some time that very high strains may lead to refinement of the microstructure of metals. In order to convert a coarse-grained solid into a material with ultrafine grains (UFG material), it is necessary both to impose an exceptionally high strain in order to introduce a high density of dislocations and also to see to it that these dislocations are subsequently re-arranged to form an array of grain boundaries [1]. One of the interesting groups of techniques that allow a decrease in the grain size of materials is based on severe plastic deformation (SPD). Methods considered as SPD ones are severe plastic torsion straining (SPTS), multiple forging (MF), and equal channel angular pressing (ECAP), known also as equal-channel angular extrusion (ECAE). All of those techniques were proved to be able to decrease grain size in a material to sub-micrometer level [2–4]. A most promising way of deformation for future use on industrial scale seems to be ECAP as it fulfils very important condition [1].

ECAP was developed and patented in Russia by Segal in 1977 [5, 6]. The basic objective at that time was to develop a metal forming process where high strains may be introduced into metal billets by simple shear. The most important characteristic of this method of deformation is the possibility of introducing very high strains into the material without change of its cross-section. Stability of dimensions of the processed billet allows repetitive pressing and, as a consequence, introduction of extremely high strains.

The process is the extrusion of a well-lubricated billet through a die. The die used for ECAP, shown in Fig. 1, consists of two channels of identical diameter intersecting each other at an angle of ϕ' and with an outer corner angle of ψ'.

The sample, which is put in the vertical channel, is pressed by the plunger of a pressing machine to the horizontal channel as shown in Fig. 1. During the deformation, the equivalent plastic strain/effective strain $\overline{\varepsilon}$' induced in the material, assuming frictionless conditions, can be estimated by Eq. (2) [7], which shows that the strain induced is mainly influenced by channel and outer corner angles.

$$\overline{\varepsilon} = \left[\frac{2\mathrm{cotg}\left(\frac{\phi}{2}+\frac{\psi}{2}\right)+\psi\mathrm{cosec}\left(\frac{\phi}{2}+\frac{\psi}{2}\right)}{\sqrt{3}}\right] \tag{2}$$

Friction between the surface of the sample and the die wall is unavoidable in practice. ECAP is actually a friction-sensitive process, and there have been several studies regarding the effect of friction on the deformation behavior during the process [8, 9]. Eivani [10] has shown that increasing the friction factor increases the forming force strongly, and also there exists a critical friction factor in which dead metal zone is formed during the forming process. Forming force in the ECAP process (F) using upper-bound analysis can be estimated by Eq. (3) [11]:

$$F = a^2\tau_0(1+m)[2\cot((\phi+\psi)/2)+\psi]+4ma\tau_0(l_i+l_0) \tag{3}$$

where ϕ, ψ, a, l_i, l_0, m, τ_0 are the channel angle, the corner angle, the width of the ECAP channel, the instant length of the sample in the entry channel, the instant length of the sample in the exit channel, the friction, and the shear strength, respectively. Equation (3) shows that the forming load in the ECAP process decreases with reducing friction factor; thus, it is crucial to decrease the sliding friction between the work-piece and the die especially in the entrance channel.

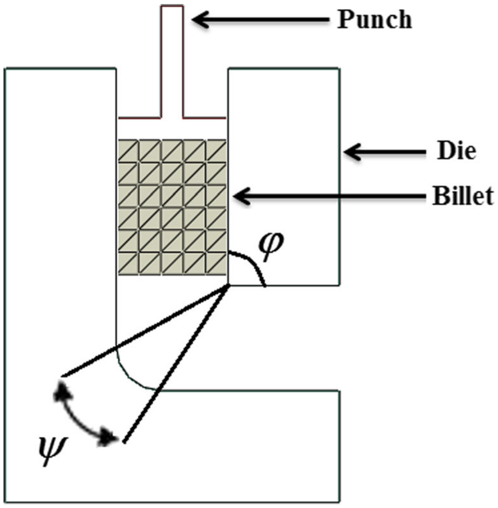


Fig. 1 Schematic of ECAP

ECAP method has undergone several constructive changes or modifications since its origin by focusing on reduction of contact friction and also by increasing the intensity of deformation during each pass. Improvements were obtained by changing channel and corner angles, movement of each ECAP die wall, and multiple successive channels within a single ECAP die [12].

In recent years, many researches have focused on ultrasonic-assisted metal forming processes. Applications of ultrasonic in metal working processes have been studied since early 1950s [13], beginning with the earliest studies of Blaha and Langenecker who researched the effects of ultrasonic excitation on metal plasticity [14].

Experiments conducted by researchers on imposing ultrasonic oscillations on metal forming processes have shown useful effects such as reduction in the forming load, reduction in the number of process steps, and improvement of surface finish [15–23].

Reduction in forming force is attributed to the reduction in flow stress of the work material and also changes in friction at the interface between the vibrating tool and work material. When ultrasonic vibrations are superimposed on a metal forming process, several measurements have shown that metal specimens exhibit significant temporary material softening [24–26]. The phenomenon of material softening effects was reported by Blaha and Langenecke [14]. This phenomenon is therefore often referred to as the Blaha effect, or volume effect, and is also known as the acousto-plastic effect [27, 28]. This acousto-plastic effect is described as a decrease in the flow stress during deformation at a constant strain rate and/or an increase in strain rate during plastic deformation under a constant stress.

This beneficial effect can also be attributed to another main mechanism other than the volume effect named surface effect. The surface effect deals with the changes in the interface

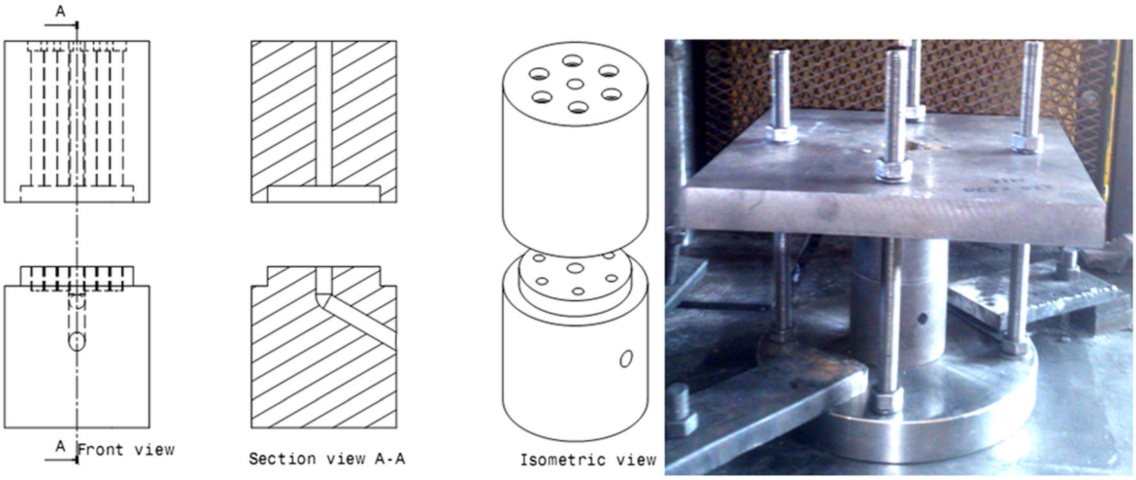


Fig. 2 Isometric and section view of the ECAP die

friction that involve a contact surface between the die and the specimen causing a reduction in forming forces [25].

Up to now, limited reports have been published on the experimental and numerical analyses of ultrasonic vibration in metal forming processes. Finite element modelling (FEM) and experimental works by Hung et al. [29] on the ring compression test using ultrasonic vibration showed that this technique can effectively reduce the material flow stress and increase the interfacial friction.

Studies by Mousavi et al. [30] on the influence of ultrasonic vibration during extrusion process demonstrated that the extrusion force and the material flow stress are decreased by applying ultrasonic vibration if the extrusion speed is below a critical rate.

Explorations of Bunget et al. [31] pointed out that there is a good potential for using ultrasonic vibration (UV) as a tool to extrude difficult-to-lubricate materials during the micro-extrusion process.

Hung et al. [32] evaluated the effect of ultrasonic vibration on the friction factor using double cup extrusion tests (DCET). The results demonstrated that the evaluation of the interface friction factor using DCET is sensitive, and the sensitivity of the friction factor is higher when area reduction ratio of extrusion is small.

Hayashi et al. reported [33] that the ultrasonic-assisted wire drawing process causes better drawing resistance, improvement of lubrication state, and reduction of wire breakage and also leads to handling of drawing of difficult-to-draw materials.

Influence of radially and axially ultrasonic vibration on the wire drawing process (RVD and AVD) by Murakawa and Jin [34] revealed that the RVD at a certain critical speed is about ten times more effective than AVD.

Suh et al. [35, 36] found that ultrasonic cold forging technology causes improvement in the mechanical properties of tool steel.

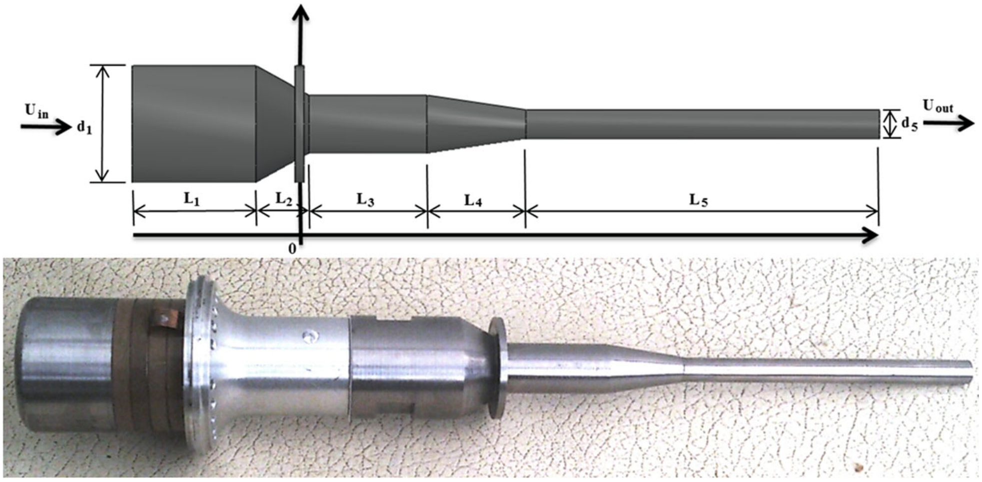


Fig. 3 A five-section horn with its flange at the nodal point and its connected transducer

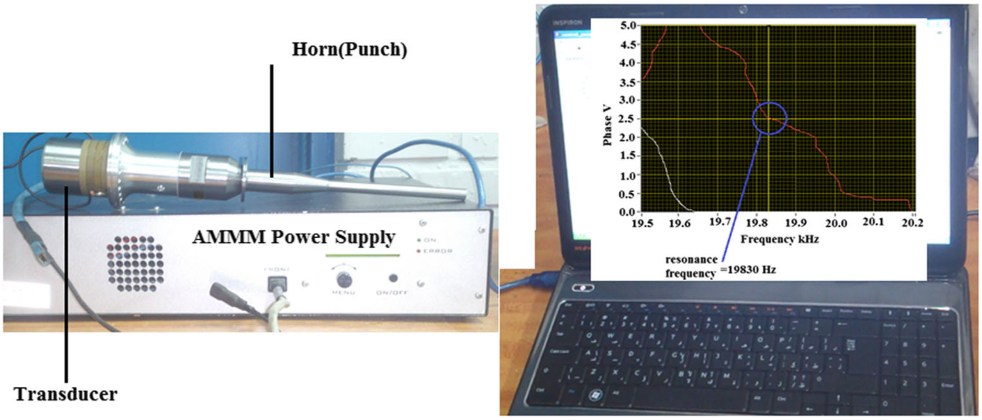


Fig. 4 Test of the vibrational components with scanning graph of phase against frequency in unloaded condition

Huang et al. [37] investigated the influence of ultrasonic vibrations on micro-deep drawing process and showed that by applying ultrasonic vibrations following a micro-deep drawing process, the LDR increased depending on the foil thickness and the oscillation amplitude.

Influence of ultrasonic vibrations on tube spinning process was studied by Rasoli [38]. Experimental results showed that low power longitudinal ultrasonic vibrations can improve the inner surface quality of annealed 6061 aluminum samples. In addition, high-power ultrasonic vibrations can affect forming forces.

Investigation of the effects of applying ultrasonic vibration on micro-upsetting along with the influence of the size effect and grain size was conducted by Hung and et al. [39]. Applying ultrasonic vibration in micro-upsetting effectively reduced the flow stress. This reduction for specimens with smaller grain sizes under the same scaling factor exhibited minimal deviation.

Finite element modelling by Ahmadi and Djavanroodi [40, 41] on ECAP process using ultrasonic vibration clarified that forming force is reduced by increasing vibration amplitude, vibration frequency, friction factor, billet length, and die channel angle. Also, the proposed FEM model by Ahmadi was more realistic [41].

The effects of ultrasonic vibrations on microstructural properties have also been reported [42–47].

Rasooli et al. [42] investigated the effect of ultrasonic vibrations on the microstructure and hardness of aluminium alloy 2024 specimens after tube spinning process. Improvement of metallurgical and mechanical properties of deformed

Fig. 5 Test equipment installed on a hydraulic press

Fig. 6 Aluminum specimens after one pass of ECAP process

parts, such as precipitate morphology and surface and through-thickness hardness profiles, was reported in this work.

Investigations of Liu et al. [43, 47] indicated that ultrasonic wave during the upsetting process leads to fabrication of UFG structure of pure copper cone tips.

Liu et al. mentioned that the major mechanism in reducing the grain size by ultrasonic excitation is further movement of dislocations [46].

Employment of ultrasonic vibration in tubular channel angular pressing (TCAP) process by Faraji and et al. [45] led to enhancement of effective strain magnitude and strain distribution uniformity. Also, lower pressing force was needed by utilizing a UV technique in TCAP process.

Based on the abovementioned researches about the ultrasonic and severe plastic deformation, this investigation aims to combine the effect of ultrasonic vibration and plastic deformation to obtain finer grain materials. In other words, ultrasonic vibration is applied on ECAP process to investigate the deformation behavior in the presence of ultrasonic vibration. Effects of ultrasonic excitation on ECAP process of pure Al are studied. For this purpose, an ECAP system is designed and manufactured, in which the punch can be excited by ultrasonic vibrations. In the experiments, the punch, vibrating at a frequency of 20 kHz, moves into the entry channel at a constant velocity of 3 mm/s. Effects of ultrasonic vibrations on the material properties, grain size, and microstructure homogeneity after four passes of ECAP process of pure Al are investigated.

2 Ultrasonic system design

2.1 Conceptual design of experimental system

Ultrasound waves are mechanical vibrations in a solid or fluid, at a frequency higher than the range audible to humans—the lowest ultrasonic frequency is 20 kHz. Oscillatory metal working is said to occur if cyclic motion or stress is applied to the die or the work-piece during the forming process. In this paper, longitudinal ultrasonic vibrations are superimposed to the billet. For this purpose, the punch is vibrated at a frequency of 20 kHz and simultaneously is advanced in the entry channel to form the billet.

ECAP die was designed and manufactured from the tool steel X153CrMoV12 and then hardened to 55 HRC. The die channel angle of φ was 120° and outer corner angle of ψ was 20°. Contrary to the most ECAP dies in the literature, our die is integrated in the deformation zone. Figure 2 shows the design of the ECAP die.

2.2 Vibrational analysis of the system

The development and application of high-power ultrasonic in forming processes require the use of specifically designed ultrasonic components to correctly transmit energy from the transducer to the tool and die interface. Typical high-power transducers consist of a piezoelectric or magnetostrictive element of transduction and a solid acoustic horn acting as an amplifier. The natural frequency of the horn, which is also the same as the punch in this work, needs to be 20 kHz.

Fig. 7 Orientation at the start of the second ECAP process

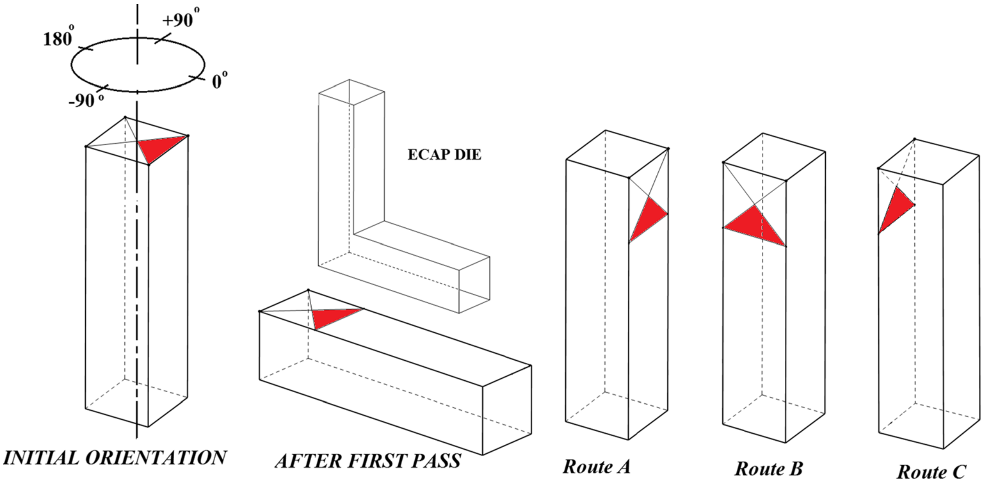


Table 1 Comparison for yield stress and ultimate strength of industrial pure aluminum

	Yield strength (MPa)	Ultimate strength (MPa)
Original	28.7	65.2
After one pass conventional	34.5	76.65
After one pass with ultrasonic vibration amplitude 2.5 μm	38.9	80.1
After one pass with ultrasonic vibration amplitude 5 μm	41.5	82.4

The material used for the punch was Ti–6Al–4 V. According to the principles of horn designing discussed in [40], the horn with a five-section configuration [48] was designed using the FE software Abaqus. L1 to L5 in Fig. 3 show the five-section configuration of the horn.

Figure 3 also shows the shape of the designed horn and connected transducer. The tuned horn has a flange to be used as a mounting mean and fix the horn to the test machine at a vibration node. This ensures that the mounting rig does not affect the vibrating characteristics of the horn or transducer.

2.3 Vibrational test of the system

In this investigation, an AMMM power supply was used. According to AMMM power supply manual [49], the vibration system can be electrically simulated. To work at real resonance condition, the whole system assembly is simulated as electrical elements (resistor, capacitor, and inductor) loaded on the power supply output terminal and the output power supply compensating capacitors are appropriately adjusted to gain a pure resistive load. This electrical system has the capability of refreshing instantaneous resonance frequency with the rate of 100 times per second and self-adjustment of the frequency with the same rate. Figure 4 shows the vibrational components of the experimental system. In this figure, the scanning graph shows that the resonance frequency is approximately 19.83 kHz which is in conformity with +2.5 (zero phase angle between voltage and current to the transducer according to AMMM suggestion).

3 Experimental procedure

3.1 Ultrasonic-assisted ECAP setup

Figure 5 demonstrates the experimental setup used for ultrasonic-assisted ECAP. As already mentioned, vibrational energy was provided by a computer-controlled AMMM power supply designed by MPI Corporation.

The transducer needs to be cooled during the process. Therefore, an air pump was used to blow air on the surface of the piezoelectrics.

The sample material was an industrial pure aluminium rod, 9.9 mm in diameter and 60 mm in height. Experiments were performed at room temperature. After one ECAP pass, all of the samples were annealed at 380 °C for 1 h and then cooled in air to room temperature to eliminate internal stresses generated during the process. By this procedure, a uniform refinement of grains was obtained. Figure 6 shows the specimens after one pass of ECAP process.

3.2 Process parameters

During ECAP process, direction and number of passes through the channels are very important for microstructure refinement. Figure 7 illustrates billet orientations of multiple-pass ECAP processing for the routes of A, B_C, and C.

The effect of different routes on deformation homogeneity was discussed in [50]. Among the conventional routes A, B_C, and C, the route B_C is the best for achieving ultrafine-grained material with a more homogenous microstructure [51].

Therefore, in order to investigate homogeneity of microstructure, four passes with route B_C were chosen in the experiments. For the experimental ultrasonic condition, the press punch (ram) was vibrated with a vibration amplitude of 2.5 μm at 20 kHz. The value of vibration amplitude was restricted by the power of ultrasonic generator. In this work, using vibration amplitudes more than 5 μm needed a higher-power ultrasonic generator. The process was performed at a minimum possible ram speed of the press, i.e., 3 mm/s, and MoS_2 was used as lubricant.

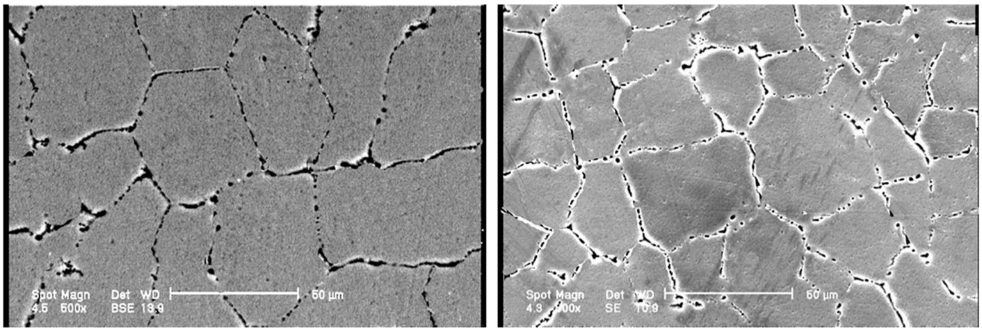


Fig. 8 Microstructures of conventional (*left*) and ultrasonic (*right*) ECAPed pure Al

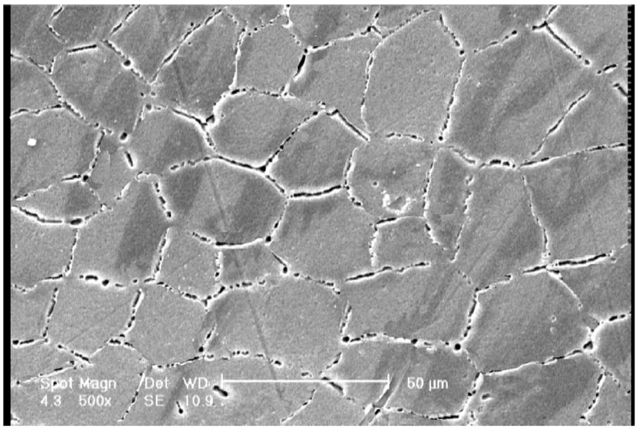


Fig. 9 Microstructure observations for ultrasonic ECAPed pure Al with ampliuted of 5 µm

4 Results and discussion

The main objective of this section is to investigate the effects of ultrasonic vibrations on the mechanical properties of material, grain size, and distribution of the grains after the ECAP process.

Although maximum punch force after superimposing ultrasonic vibration is a very important parameter in the experiments, it was omitted from this paper. However, as expected, the forming force was reduced by applying ultrasonic vibration to the punch as elaborated in [40].

4.1 Influence of ultrasonic vibrations on the mechanical properties of a material

The mechanical properties of a material in both original and after ECAP states were tested by a universal testing machine (Santam Machine, 5 kN). In the present work, the yield stress was defined as $\sigma_{0.2}$. Changes of yield stress and ultimate strength after one pass of ECAP are shown in Table 1. It should be noted that the experiments were repeated for four times, and the average of the results was presented.

From Table 1, increase of yield stress after one pass of ECAP with and without superimposing ultrasonic vibration is about 20.2 and 35.5 %, respectively, and for the ultimate strength at about 17.56 and 22.85 %, respectively. Higher vibration amplitude increases the yield strength and ultimate strength by 44.5 and 26.3 %, respectively. It can be seen that superimposing ultrasonic vibration yields more efficiency of the ECAP process.

4.2 Effects of ultrasonic vibrations on grain size

In order to investigate the effect of ultrasonic vibration on grain size, two samples were subjected to ECAP process. One of the processes was performed with superimposing ultrasonic vibrations and one of them without any ultrasonic vibration. The ultrasonic amplitude was 2.5, respectively. The microstructures of the material were tested by SEM. The microstructures of the deformed specimens are illustrated in Fig. 8.

In order to have a qualitative comparison, the SEM for both samples was made from the same position. As can be seen in Fig. 8, the right sample, i.e., with ultrasonic vibrations, has finer grains as compared with the left sample. It means that the ultrasonic vibrations could make the samples' plastic deformation more severe and assist in improving grain refinement efficiency.

A very common method of measuring grain size is to compare the grains at a fixed magnification according to the American Society for Testing and Materials (ASTM) grain size charts [52]. The ASTM grain size number n is related to N, the number of grains per square inch at a magnification of× 100 by the relationship $N=2^{n-1}$.

Fig. 10 Micro hardness tester and location of the sample used for hardness

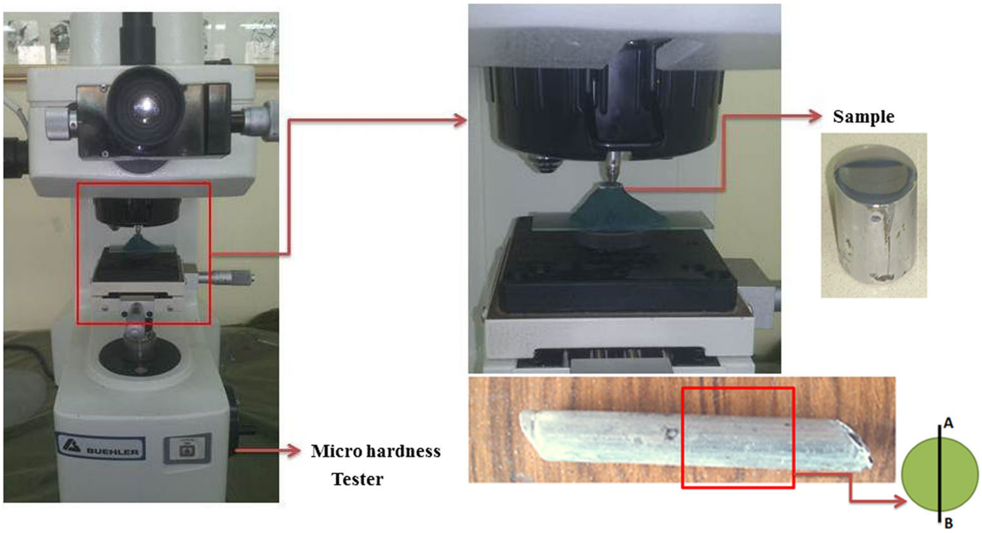
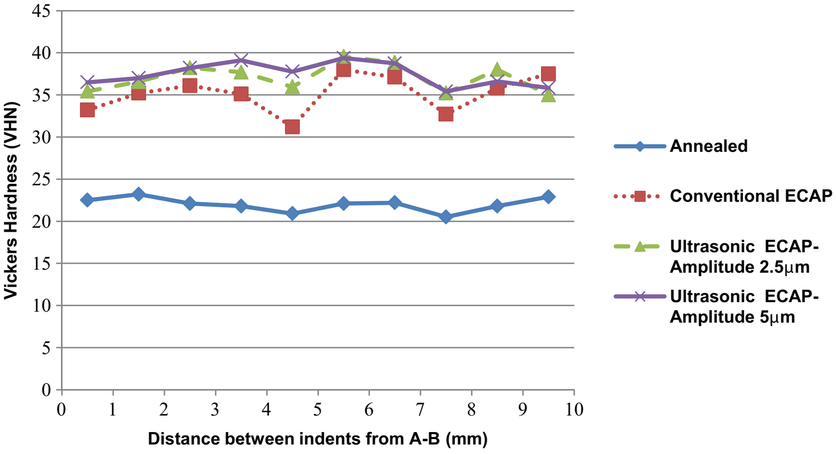


Fig. 11 Micro hardness profiles in the flow plane of annealed and four passes of ECAP



The ASTM grain size number for Al after one pass of ECAP and annealing is 3+. According to ASM Metals Handbook [53], this ASTM number is equal to an average grain diameter of about 109 μm. After ECAP process, the ASTM grain size numbers for Al are 6^{-} and 7^{+} for conventional and ultrasonic-assisted ECAP, respectively. It means that the average grain diameter of Al specimen is 45 μm after conventional ECAP and is 28.2 μm after ultrasonic-assisted ECAP. It can be concluded that superimposing ultrasonic vibration increases the refinement efficiency of the ECAP process by 37.3 %.

When ultrasonic wave transmits in the solid, it can disturb the particles of a body from equilibrium, which gives rise to internal forces that tend to return these particles to equilibrium [46]. The stresses associated with the propagation of ultrasonic wave are the basic cause of the numerous mechanical effects attributable to improving the material microstructure [54].

According to [55, 56], the stress produced by an ultrasonic wave may be calculated as follows:

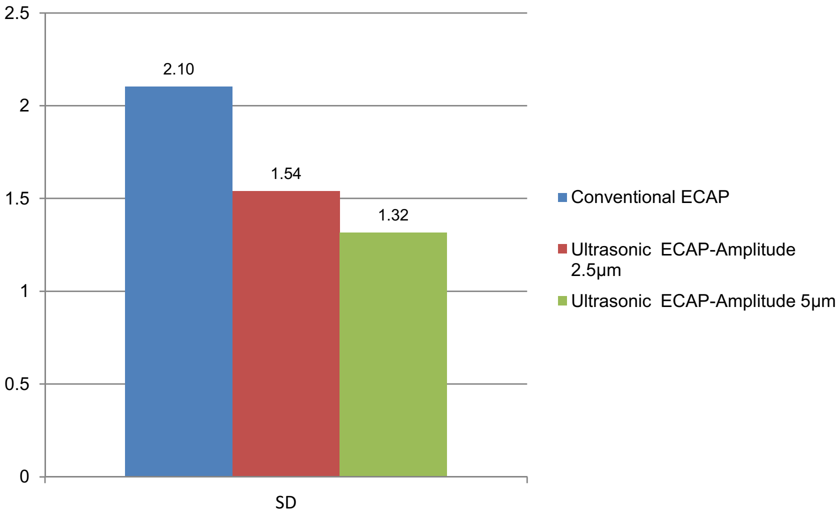
$$S = \xi \rho \omega c \tag{4}$$

where ξ is the particle displacement, ρ is the density, ω is the angular frequency and c is the wave velocity in the sample.

In this study, $\xi = 2.5$ μm, $\rho = 2700$ kg/m^3, $\omega = 2\pi f = 125,600$ Hz, and $c = 5055$ m/s, and hence the stress produced by ultrasonic vibration is 4.3 MPa. In this study, since the amplitude of vibration was small, the superimposed stress was also small. However, this stress can affect the plastic deformation and grain size by producing larger strains. By applying larger amplitude of vibration, the stress produced by travelling ultrasonic vibration through the sample increases, and consequently finer grains can be obtained. Figure 9 shows the microstructures of the deformed specimen for an amplitude of 5 μm, which is twice as much as of the previous test.

By comparing Figs. 8 and 9, it can be easily seen that by increasing the amplitude of the vibrations, finer grains can be attained. The ASTM number for the process with vibration amplitude of 5 μm is 8^{-}. The average grain diameter is about 23.2 μm. Applying the vibration amplitude of 5 μm increases the efficiency of the process by 48.4 %. It means that in comparison with the lower amplitude of 2.5 μm, the grain size decreases by 11.1 %.

Fig. 12 Standard deviation values of Vickers hardness after conventional and ultrasonic-assisted ECAP



4.3 Effects of ultrasonic vibrations on the homogeneity of the microstructure

Numerous investigations of ECAP have shown that it is necessary to process materials by ECAP by multiple passes in order to achieve satisfactory ultrafine-grained microstructures. Thus, homogeneity as a function of the number of passes is an important parameter in ECAP processing. Homogeneity may be examined experimentally by plotting micro hardness distributions on various cross-sectional planes [57].

Micro hardness profiles were taken along the flow plane by using micro hardness tester BUEHLER. After ECAP, sample for hardness measurements was prepared through the following two steps (shown in Fig. 10): First, 10 mm ECAPed rod was sliced at the centre of the sample in the transverse plane; next, the sliced piece was polished and used for hardness measurements. Hardness profile was taken across the width, A–B, with a distance of 1 mm between the indents. Hardness measurements were carried out with a load of 25 gf and dwell time of 5 s.

Figure 11 shows the micro hardness profile in the cross-section of the sample of Fig. 10 for conventional ECAP, ultrasonic-assisted ECAP, and annealed sample.

In order to have a more sensible evaluation of Fig. 11, the standard deviations of the micro hardness for conventional and ultrasonic-assisted ECAP are shown in Fig. 12.

As can be seen in Fig. 12, the standard deviation of the Vickers hardness in the cross-section of the sample is lower for ultrasonic-assisted ECAP. It means that superimposing ultrasonic vibration causes more homogeneity of the microstructure. Furthermore, using larger vibration amplitude values causes a more homogenous structure. The homogeneity of the microstructure was improved by 26.7 and 37.1 % using vibration amplitude of 2.5 and 5 μm, respectively.

5 Conclusions

In this study, the influence of longitudinal ultrasonic vibrations on the ECAP process has been investigated. A robust experimental ECAP system, in which the punch can be excited by ultrasonic vibration, was designed and manufactured. Experiments were carried with and without ultrasonic vibrations. Pure Al was chosen as the work-piece material. Conclusions made are as follows:

- From the SEM, it can be concluded that finer grains can be obtained by ultrasonic vibrations due to superimposed stress which produces larger strain in the plastic deformation. Superimposing ultrasonic vibration with the amplitude of 2.5 μm increases the efficiency of the ECAP process by 25.8 %.
- Using higher vibration amplitudes caused more refinement of the grains.
- In ECAP process with ultrasonic vibrations, the material properties such as yield stress and ultimate tensile strength of the specimens increased more in comparison with the conventional ECAP.
- Homogeneity of the microstructure was improved after using ultrasonic vibration. More homogenous structure can be obtained by using higher vibration amplitudes.

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