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The Effect of the Rate of Strain on the Thermal and Mechanical Properties of Al- 6030 Processed by ECAP

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KEYWORDS:

ECAP; Al-6030; Hardness; Strain rate; Thermal conductivity, Optimum properties

***Abstract*—The function of severe plastic deformation (SPD) rate during equal-channel angular pressing (ECAP) on the thermal and mechanical characteristics of the aluminum alloy 6030 are experimentally investigated. ECAP was carried out at room temperature onto refining grain size for Al- 6030 of square cross-section specimens. The tests show that, for decreasing the rate of strain from 0.016 to 0.0023 s^{-1}, the improvement in the hardness increases gradually until the highest value is reached at the rate of strain 0.004 $s^{-1}$and decreases after that gradually. The percentage improvement in the hardness is around 68 % at the rate of strain 0.004 s^{-1}. The ECAP process improves the yield strength of aluminum alloy 6030 by 222 % on average at the rate of strain 0.004 s^{-1}. Also, for decreasing the rate of strain from 0.016 to 0.0023 s^{-1} the thermal conductivity increases gradually to the maximum value 137.5 W/m° K at rate of strain 0.004 $s^{-1}$and decrease after that gradually. The ECAP process improves the thermal conductivity by 4.88 % for the rate of strain 0.004 s^{-1} as compared to the case without ECAP process. From the present experimental results, the optimum rate of strain is 0.004 s^{-1} to obtain the optimal thermal and mechanical properties of the aluminum alloy 6030 during the ECAP processing.**

I. INTRODUCTION

ULTRAFINE Grained (UFG) metals (Nanostructured metals or nanometals) own grain size that ranges between 0.1–1 µm compared to tens or hundreds micrometers of common metals. This structural variation influences many characteristics of UFG metals and have 2-4 times greater strength.

The forming techniques and the properties of nanostructured and UFG materials transformed by Severe Plastic Deformations (SPD) methods become the recent studies lately [1]. According to the techniques of SPD, Equal Channel Angular Pressing (ECAP) owns the usefulness of great samples production [2] and has the ability to commercialize [3]. It was proposed by Segal et al. [4] and later developed by Valiev et al. [5, 6] for achieving ductility In this method, as illustrated in Fig. 1, a billet may be pressured by a die that has two angles channel angle φ and an outer arc of curvature ψ. An equivalent strain of 1 is obtained [1]. A major advantage achieved in equal-channel angular extrusion (ECAE) is the unchanged cross-area of the extruded material .This means that the material might have a chance to be malformed to obtain a high total strain [7, 8]. In addition, it is

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utilized as high strength and smart metal materials and super plastic materials. Two unrivaled features for UFG materials generated all toward ECAP are high quality and the possibility of super plasticity at low temperatures that has higher rate of strains. [9, 10]. In applications, the Nonmaterial are promising to develop the microelectronics, informatics, and micro electro-mechanics systems [1, 8, and 9]. The internal combustion engine and the high strength threaded parts are utilized in the applications. Another demand near execution may be restorative implants made from UFG CP titanium. [11]. Different demands will absolutely follow for light weight and high strength so valued in the automotive and aerospace industries [12, 13].

Plastic deformation is by shear in a fluffy layer at the intersection plane of the channel passages. This shear with rotation transforms the material rectangular vertical volume as Indicated in Fig. 1

The equivalent plastic strain ε_N in this case is about 1.15 [4, 14]. It is estimated by the equation:

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

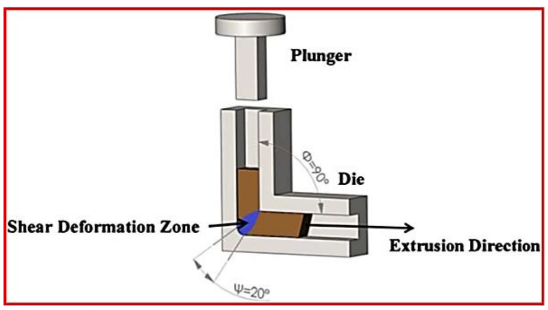

Fig.1 The image of the ECAP dies processing

Where N is the number of passes, since the strain required for changing the microstructure is 4–8 passes, the billet must be pressured through the die. It permits for billet rotation around its axis among every pass of ECAP die (Fig. 2). The 3 options are called A (no rotation), C (180° rotation), and BC (90° rotation in the same direction).

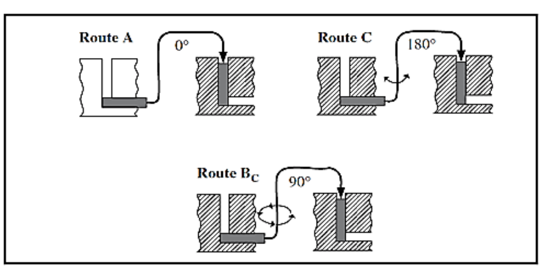

Fig.2 Three basic options for billet rotation between consecutive passes through ECAP die

It is shown that 4 processing routes are utilized for ECAP [15, 16]. Few researchers have concluded that route BC (where the billet is rotated 90° clockwise or anti-clockwise) is efficient route to produce UFG material [17], while others suggested that route A is more effective [18]. The non-presence of the strain hardening will be an alternate essential trademark of the materials' deformation behavior [19]. In addition, when decreasing hardness or strength during ECAP, the number of passes increases [10, 20, and 21].

The aim of this study is improving the thermal and mechanical properties of the aluminum alloy 6030 by using (ECAP). ECAP was carried out at room temperature onto refining grain size for Al- 6030 of square cross-section specimens. The effects of rate of strain on the thermal and mechanical properties of Al- 6030 after ECAP processing were investigated to get the optimum rate of strain for ECAP processing.

II. EXPERIMENTAL PROCEDURE

The experiments were concluded by utilizing aluminum alloy of composition given in Table 1. The chemical analysis of the used alloy was done by spark analysis in Helwan Company for Engineering Industries, Helwan-Egypt. Aluminum and its alloys are utilized in many fields such as building, automobile, aircraft, electrical engineering, and packaging due to their characteristics. The advantageous characteristics aluminum alloy 6030 are low density, high thermal conductivity, high electrical conductivity, suitability for surface treatments, corrosion resistance, diversity of aluminum alloys and semi-products, particular strength, functional advantages of extruded and cast semi-products, weld ability, formability ,and ease of recycling.

TABLE 1
CHEMICAL COMPOSITION OF THE MATERIALS USED IN THIS WORK

Component	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Al**
b wt %	0.428	0.04	0.0568	0.28	0.0512	balance

The specimens of aluminum alloy 6030 used in the present experimental work are in the form of extruded rods 15 × 7 cm and was cut into billets of length of 60 mm and 14 mm x 14 mm has been processed by ECAP.

The ECAP process are done at room temperature with different speeds of 1, 0.5, 0.25, 0.2 and 0.15 mm s^{-1} (corresponding to initial rate of strains of 0.016, 0.008, 0.004, 0.003 and 0.0023 s^{-1} respectively) and at a split die having an internal channel with an angle of $\varphi = 90°$ and an outer angle of curvature of $\psi = 20°$.

All extrusions (ECAP) were performed by using an Instron 8505 machine of 120 ton and 100 ton static and dynamic loading capacities respectively. The die and sub-press equipment (punch and clamps) were made of tool steel and the extruded belt shown in (Fig. 3). Molybdenum disulfide (MoS_2) and Teflon were used as lubricants between inner die surface and the surface of the extruded billet.

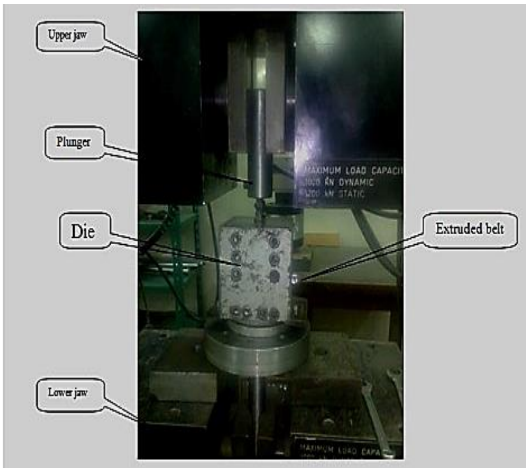

Fig.3 The die of the ECAP processing mounting in Instron machine

The exit billets were divided perpendicular to their longitudinal axes by a wire cutting machine and then mounted and pressed as shown in Fig. 4. The Vickers hardness was measured using SHIMADZU micro hardness testing machine at load of 300 g. The test (I) according to ISO 6507-1 (Metallic materials-Vickers Hardness Test), A series of individual measurements was recorded on each polished section whereby the Vickers indenter was moved over the surface and measurements of the Vickers hardness (Hv) were recorded in a regular grid pattern with spacing between each separate measurement of 3 mm.

A compression test defines the materials behavior under crushing loads. The specimen is pressured and compaction is recorded. Compressive strains are estimated and plotted as a stress-strain diagram that is utilized for determining elastic limit, proportional limit, yield point, yield strength and, for some materials, compressive strength.

Fig.4 The extruded sample after pressing

It is a beneficial procedure to estimate the plastic flow manner and the limits of ductile fracture of a material. Estimating the flow of plastic manner needs frictionless (homogenous compression) test conditions, but the limits of estimating flexible fracture take the characteristics of the rumble formation and barred stress and strain conditions at the equator of the barreled surface while compressive is achieved with friction. The testing of axial compression is beneficial to measure elastic and compressive fracture characteristics of low-ductility materials. In any case, using samples that have large L/D ratios should be neglected for prohibiting the shearing and buckling deformation [22]. The compression properties were defined by the standard tests that were cut from their axis in parallel to the compressing direction pushed through ECAP. The dimension of the tested specimens was 18 mm × 10 mm (length × diameter).

The method of measuring thermal conductivity has done by the thermal constant analyzer, Hot Disk TPS 2500 S, Meets ISO Standard 22007-2.

III. RESULTS AND DISCUSSION

A. Hardness

The hardness increases with ECAP after one pass as mentioned in [23, 24, and 25]. Hardness distributions on the cross-sectional plane for Al 6030 before and after a single pass of ECAP are plotted in Fig.5. The x-axis in the figure represents the site of individual hardness point on a cross-sectional plane perpendicular to its extruded axis with respect to the midpoint of the section. It can be observed that the difference of the hardness values along the cross-section of the sample after ECAP (one pass) is minimal. The values are not affected by the pressing rate.. This indicates a more homogeneous microstructure of the sample through the cross-section after ECAP.

Measurements exhibit a homogeneous hardness distribution throughout the completely cross-sectional sample plane before ECAP with an average hardness value of ~58. After a single pass of ECAP as shown in Fig. 5, the variation of Vickers hardness on Al-6030 at different rate of strains or compression speed was 1, 0.5, 0.25, 0.2, and 0.15 mm s^{-1} (corresponding to initial rate of strains of 0.016, 0.008, 0.004, 0.003 and 0.0023 s^{-1}). The results show that the percentage improvements in the hardness are around 9%, 33.5%, 68%, 53% ,and 33% for the rate of strain 0.016, 0.008, 0.004, 0.003 and 0.0.0023 s^{-1} respectively. As shown in Figure (5) the hardness increases gradually with decreasing the rate of strain until a maximum value at a rate of strain of 0.004 s^{-1} and decreases after that gradually with decreasing the rate of strain. The results show that the optimum rate of strain is 0.004 s^{1}. This result is in good agreement with grain diameter measurements and interpretation [25, 26].

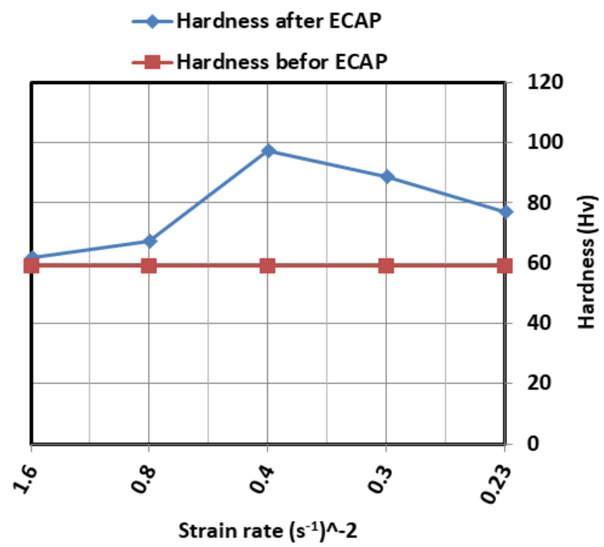

Fig.5 The effect of rate on hardness for Al-alloy (6030)

B. Strength

The true stress-strain curves of aluminum alloy 6030 before and after ECAP with rates of strain 0.016, 0.008, 0.004, 0.003, and 0.0023 s^{-1} are shown in Fig. 6 and 7. The stress-strain curves in elastic zone are represented in Fig. 7. The yield strength of Aluminum alloy 6030 before ECAP (as-received material) reached 100 MPa. Also, the yield strength of Aluminum alloy 6030 after ECAP process increased to 201, 217, 222, 216, and 200 MPa for a rate of strain 0.016, 0.008, 0.004, 0.003, and 0.0023 s^{-1}, respectively. The results show that after one pass of the extruded billet the strength increases by approximately 2.22 times after ECAP at the strain rate 0.004 s^{-1} due to the effect of UFG of Al alloy.

This increase in the yield strength is expected as the grain size was refined through the shearing of the sample. This refinement of grains acts as a strengthening mechanism as the free path of dislocations become shorter [27]. More load is needed to overcome the resistance of dislocation motion through the grain boundaries. The strengthening mechanisms are constant in all rates. The results show that the optimum stain rate is 0.004 s^{-1}.

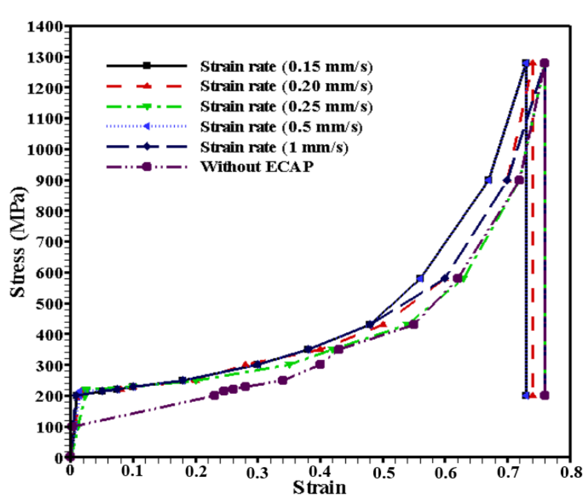

Fig.6 The true stress strain curve before and after ECAP

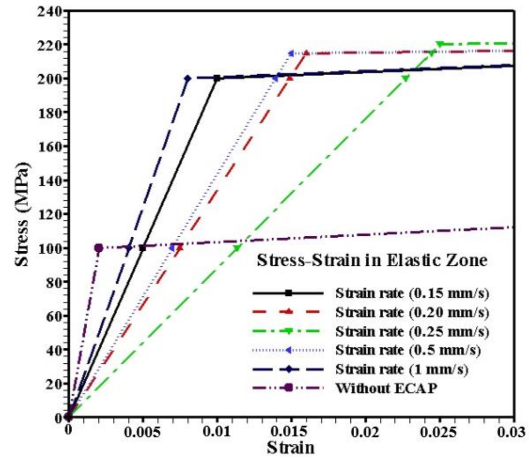

Fig.7 The true stress strain curve through the elastic zone before and after ECAP

C. Thermal conductivity

Fig. 8 shows the thermal conductivity of the aluminum alloy 6030 before and after ECAP process. As shown in this figure, the value of thermal conductivity for the aluminum alloy 6030 after ECAP process was recorded 87.1, 127.6, 137.5, 114, and 100.17 W/m K for the rate of strain 0.016, 0.008, 0.004, 0.003, and 0.0023 s^{-1} respectively. Without ECAP process, its value was about 131.2 W/m k. These results show that after ECAP process, its value increases gradually to the maximum value at a rate of strain of 0.004 s^{-1} and decreases after that gradually with decreasing the rate of strain. In addition, the results show that the ECAP process decreases the thermal conductivity by 33.64%, 2.67%, 13.04%, and 20.89% for the rate of strain 0.016, 0.008, 0.003, and 0.0.0023 s^{-1} respectively as compared to the case without ECAP process. At the rate of strain 0.004 s^{-1}, the ECAP process improves the thermal conductivity by 4.88 % as compared to the case without ECAP process.

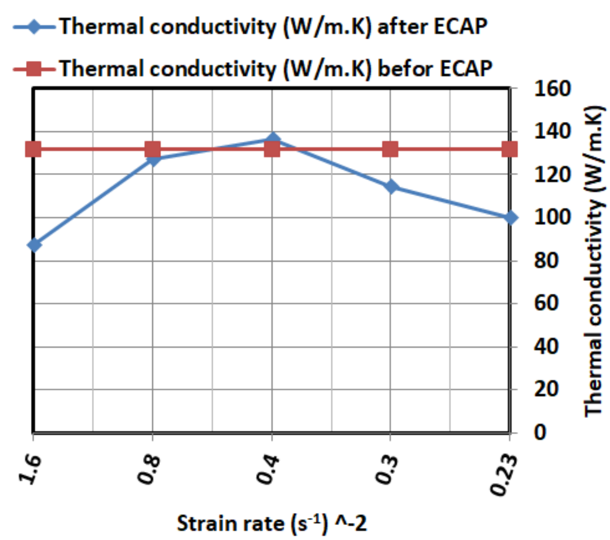

Fig.8 Thermal conductivity on AL-6030 before and after ECAP at different rate of strains

IV. CONCLUSION

The pressing of Equal Channel Angular is able to produce bulk samples of ultrafine-grained materials and thus achieving advanced properties. The method is very attractive because of its potential for scaling-up in industrial applications. Investigations were carried out in this work to show the effect of the rate of strain of ECAP process on the mechanical and thermal characteristics of the aluminum alloy 6030. The following points can be concluded:

- The decreasing in rate of strain from 0.016 to 0.0023 s^{-1}, improve in the hardness increases gradually until the maximum value at rate of strain 0.004 s^{-1} and decrease after that gradually with decreasing the rate of strain.
- The percentage improvements in the hardness are around 68 % at the rate of strain 0.004 s-1.
- The ECAP process improves the yield strength of aluminum alloy 6030 by 222 % in average at the rate of strain 0.004 s-1.
- The decreasing in rate of strain from 0.016 to 0.0023 s-1 increases gradually the thermal conductivity to the maximum valve 137.5 W/m K at the rate of strain 0.004 s-1 and decreases after that gradually.
- The ECAP process improves the thermal conductivity by 4.88 % for the rate of strain 0.004 s-1 as compared to the case without ECAP process.
- The optimum strain rate is 0.004 s-1 to obtain better mechanical and thermal properties of the aluminum alloy 6030 during the ECAP processing.

AUTHORS CONTRIBUTION

Item	Dr. Maher Rashad	Dr. Nader Nabil	Dr. Abd Elnaby Kabeel
Conception or design of the work	100%		
Data collection and tools	100%		
Data analysis and interpretation	50%	30%	20%
Investigation	60%	40%	
Methodology	60%	40%	
Project administration	60%	40%	
Resources	50%	30%	20%
Supervision	50%	30%	20%
Drafting the article	50%	30%	20%
Critical revision of the article	50%	30%	20%
Final approval of the version to be published	50%	30%	20%

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Title Arabic:

تأثير معدل الانفعال على الخواص الحرارية والميكانيكية لسبيكة Al- 6030 بعد الكبس الزاوى ECAP

Arabic Abstract:

تمت دراسة معدل التشوه الشديد فى المدى اللدن (SPD) أثناء الضغط الزاوي ذات القنوات المتساوية (ECAP) على الخصائص الحرارية والميكانيكية لسبائك الألومنيوم ٦٠٣٠ عمليا. تم إجراء كبس زاوى ECAP في درجة حرارة الغرفة لتغير وتنعيم حجم حبيبات سبيكة الالومنيوم Al- 6030 لعينات المقطع العرضي المربعة. تم دراسة تأثير معدل الانفعال على الخصائص الحرارية والميكانيكية لـ سبيكة الالومنيوم Al- 6030 بعد تعرضها لكبس زاوى ECAP. أظهرت الاختبارات أن خفض معدل الانفعال من ٠.٠١٦ s^{-1} إلى ٠.٠٠٢٣ s^{-1} يزداد التحسن في الصلادة تدريجياً حتى يتم الوصول إلى أعلى قيمة عند معدل الانفعال ٠.٠٠٤ s^{-1} وتنخفض بعد ذلك تدريجياً. نسبة التحسن في الصلابة حوالي ٦٨٪ بمعدل الانفعال ٠.٠٠٤ s^{-1}. تعمل عملية ECAP على تحسين مقاومة الخضوع لسبائك الألومنيوم ٦٠٣٠ بنسبة ٢٢٢٪ في المتوسط بمعدل انفعال ٠.٠٠٤ s^{-1}. أيضًا بتقليل معدل الانفعال من ٠.٠١٦ إلى ٠.٠٠٢٣ s^{-1} ، تزداد الموصلية الحرارية تدريجياً إلى القيمة القصوى ١٣٧.٥ $W/m° K$ بمعدل الانفعال ٠.٠٠٤ s^{-1} وتنخفض بعد ذلك تدريجياً. تعمل عملية ECAP على تحسين التوصيل الحراري بنسبة ٤.٨٨٪ لمعدل الانفعال ٠.٠٠٤ s^{-1} مقارنة بالحالة بدون عملية ECAP. من النتائج التجريبية الحالية ، فإن معدل الانفعال الأمثل هو ٠.٠٠٤ s^{-1} للحصول على الخصائص الحرارية والميكانيكية المثلى لسبائك الألومنيوم ٦٠٣٠ أثناء اجراء عملية الكبس الزاوى ECAP.