Plastic deformation of 7075 Aluminium Alloy using Integrated Extrusion-Equal Channel Angular Pressing

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ARTICLE INFO

ABSTRACT

Grain refinement improves the mechanical properties and formability of metals and alloys. So far, several different grain refinement methods have been proposed and studied. Severe plastic deformation is one of the most promising and efficient methods. Therefore, in the present study the possibility of imposing a two-step severe plastic deformation (Extrusion and Equal channel angular pressing) on AA7075 alloy using a special designed die is investigated. Using this method, a very coarse grained microstructure with grain size of 94µm is refined to grain size of 7.5µm. Also, microstructural developments during severe deformation with and without preheating are investigated. Plastic strain distribution and temperature variation inside deformed samples are predicted by the use of thermal coupled displacement 3D finite element method. Results of FEM simulations clearly showes that the plastic strain distribution and temperature is non-uniform in sample and this introduces inhomogeneity in the resultant microstructure of sample at different regions.

1. Introduction

Processing of materials with high strength is one of the main demands of metals industry. In this respect, grain refinement is of great importance due to increase of strength and formability of material. Strength and fracture toughness increases with decreasing grain size in the final microstructure of materials [1]. One of the most promising approaches in this area is severe plastic deformation of initial course grained material [2-4]. As a consequence, primary coarse grained microstructure is refined by microstructure evolutions which depend on deformation conditions and material type. To date, very wide research has been conducted for developing the severe plastic deformation techniques as well as investigation on the effect of various parameters on resultant microstructural characteristics of material. Till

now, more than dozen different techniques have been introduced [5, 6]. Equal channel angular pressing is one of the most popular techniques. Fig.1 shows the schematic of this technique. As can be seen, ECAP die has two channels with square or circular cross-section. The channel is curved with sharp angle. In this figure, Φ indicates the channel angle and ψ is the outer curvature angle of intersected channels. In this method, applied strain is calculated by the following equation [7]:

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2c\left(\frac{\Phi + \Psi}{2}\right) + \Psi c\left(\frac{\Phi + \Psi}{2}\right)\right] \qquad (1)$$

One of the restrictions of ECAP is the need for removing ECAP sample after each step and reinserting inside channel again in order to achieve high strains. This is time-consuming and has its own problem. Therefore, a lot of

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effort has been done to eliminate this step and different processes are being developed in this area. Using a combination of SPD methods is an important approach in this field [8]. Therefore, in this study a new die was designed and fabricated. With this die, it is possible to impose two step severe plastic deformations on samples, comprising extrusion and equal channel angular pressing. The combination of ECAP with extrusion in a single die not only increases the amount of imposed plastic strain in a single pass deformation and decreases the cost of facilities, it also eliminates the need for preheating between passes required in the separate two step extrusion and ECAP at high temperature deformation. To date, most research conducted in ECAP field is on relatively soft FCC materials. For example, numerous studies concerning the application of ECAP on pure aluminum and Al-Mg solid solution alloys has been performed. In contrast, few reports on the ECAP of more complex alloys such as Al-Zn-Mg-Cu and 7000 series are available [9]. In practice, forming these alloys at room temperature is very difficult due to their limited formability [10]. Given the above expressions, the aim of the present study is to investigate the feasibility of the two-stage plastic deformation (Extrusion-ECAP) and the effect of preheating on microstructure evolutions of Al7075 alloy and mechanisms of fine grain formation during deformation.
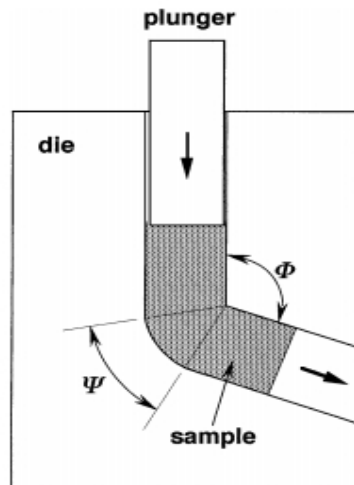

Fig 1. Schematic of ECAP process [11]

2. Experimental procedure

Chemical composition of Al7075 alloy is shown in Table 1. At first, cylindrical samples with 40mm height and 14mm diameter are machined from as received plate. Samples solution treated at 480 ˚C for half an hour and quenched at water to form super saturated solid solution at room temperature. One of the samples were pressed into the die right after quenching and the other one after 15 minutes heating at 300 ˚C. Die used in this study was made of H12 tool steel. Fig. 2 shows the schematic representation of steel made die. A mixture of graphite and oil was used as lubricant. After deformation, samples were bisected by the symmetry and then microscopic studies were performed on it. ABAQUS 6.7 software was used to investigate deformation process and strain and temperature distributions inside sample. Johnson – Cook model was used to predict the flow behavior of material. In this model the metal flow stress is obtained from the following equation [12]:

$$\sigma = (A + B\varepsilon^n).\left[1 + C\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right].\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right] \quad (2)$$

In this equation ε is strain, $\dot{\varepsilon}$ is strain rate, T is sample temperature, T_m is melting temperature of alloy, T_r is reference temperature, $\dot{\varepsilon}_0$ is reference strain rate and A ، B ، C، n and m are coefficients of material. The coefficients of the Al7075 alloy are shown in Table. 2 and thermo-physical properties of the alloy are shown in Table. 3.

Table 1. Chemical composition of alloy used in this research (%Wt.)

Zn	Mg	Cu	Mn	Si
5.4	2.6	1.3	0.2	0.32

Table 2. Coefficients related to flow properties of Al7075 alloy [13].

m	n	C	B (MPa)	A (MPa)
0.772	0.39	0.968	303.58	53.68

Table 3. Physical and thermal properties of material [14]

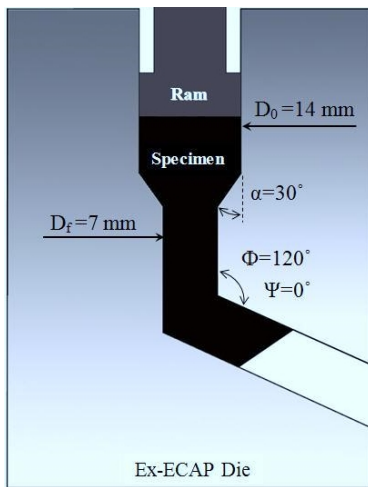| Thermal (W/m K) conductivity	Density (kg/m^3)	J/kg) Heat (K capacity
155	2810	960

Fig 2. Schematic representation of Ex-ECAP process.

3. Results and discussions

3.1. Strain distribution in deformed sample

Distributions of the applied strain in the samples with different preheating temperature are shown in Fig. 3. As can be seen, in both temperatures, strain distribution in the sample is non-uniform. Imposed strain in the regions close to the surface of sample is higher than central regions. This is caused by friction between the inner surface of the die and the surface of samples. As a result, some additional shear strain is applied to the area near the surface. It is observed that the strain distribution is similar in both samples. Therefore, strain distribution in deformed samples does not depend on the preheating temperature. In Fig. 4 the variation of the applied strain on the central axis of the sample (from top to bottom) is shown. Variations of applied strain and the strain measured in the central region of the sample is similar in both preheat temperature. Sample can be divided into four different regions based on strain variations at centerline. Before extrusion zone (zone I in Figure 4), which does not experience any deformation, Extrusion zone (zone II in Figure 4), where imposed strain on sample increases from top to bottom, after extrusion zone (zone III in Figure 4), which experiences extrusion only and finally after ECAP area that is experiencing both extrusion and ECAP and maximum strain applied on these area reaches to 2.
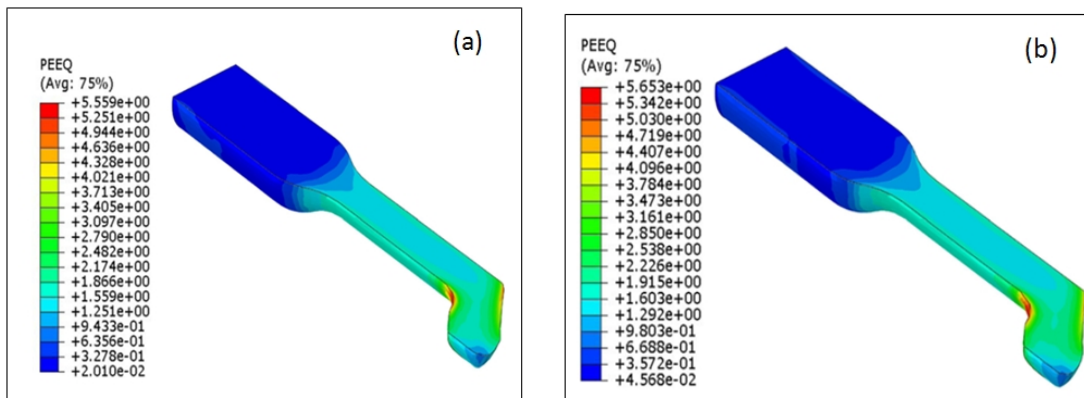

Fig 3. Strain distribution inside sample at different preheat temperatures. a) 13 ˚C, b) 300 ˚C.
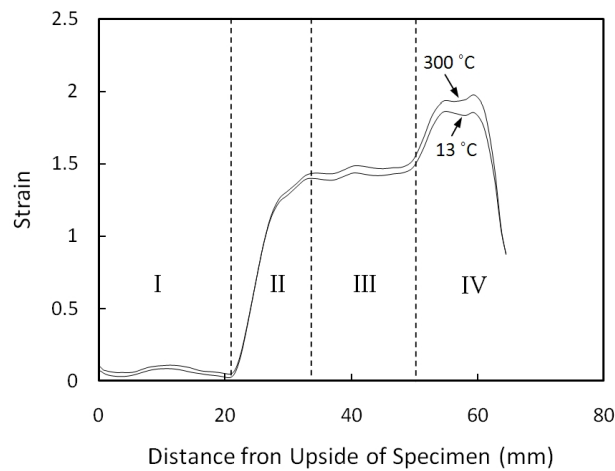
Fig 4. Equivalent strain distribution on centerline of sample at different preheat temperatures.

3.2. Temperature distribution in deformed samples

Fig. 5 shows the temperature distribution in the sample after deformation with different preheat temperatures (13°C and 300°C). Temperature distribution in the sample is Non-uniform similar to the distribution of the applied strain. Highest temperature in cold deformed sample is at after-extrusion-part of sample. While, in sample preheated at 300 °C, maximum temperature is at upper side of after-extrusion-part of sample (region III) and central region of after-ECAP-part of sample (region IV). In both cases the temperature rise is seen in the region I of the sample which is in contact with the ram. The increase in temperature is due to the heat generation from the friction between the samples and die walls. Fig. 6 shows temperature variation in centerline of sample preheated at 300 °C and sample deformed at room temperature. At preheat temperature of 300 °C, maximum and minimum temperatures inside sample are 117 and 107.5 °C, respectively. In this condition, temperature difference between sample and die is high (sample at temperature of 300 °C is inserted inside the die with temperature of 13 °C). So Heat transfer rate from the sample is very high, especially at high pressure that deformation heat cannot compensate the heat flow from sample to die. In this condition, the temperature in all parts of the sample is lower than preheat temperature. Low temperature difference between various parts of the central axis and in other words the high uniformity of the temperature on the central axis of sample shows that the amount of heat generated during deformation is lower than heat transformation from sample to die. At cold deformed sample, maximum and minimum temperature inside sample is 82 and 75 degrees centigrade respectively. At cold deformation, initial temperature of sample and die is the same (13°C) and no heat transfer occurs at first. Temperature of sample increases due to heat generation during deformation. Heat transfer between sample and die increases with increasing sample temperature. However, due to the low temperature difference between the sample and the die during deformation process, the amount of transformed heat is lower than preheat temperature of 300 °C. Therefore, temperature of sample at cold work condition increases in contrast to that of sample deformed at high temperature.
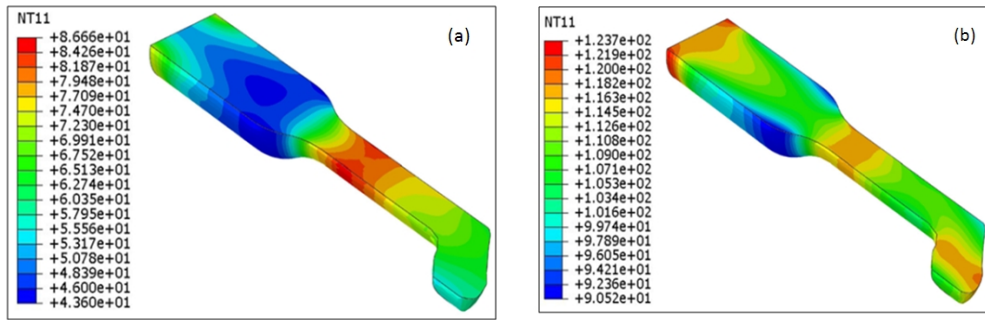
Fig 5. Temperature distribution at different regions of sample right after completion of deformation process
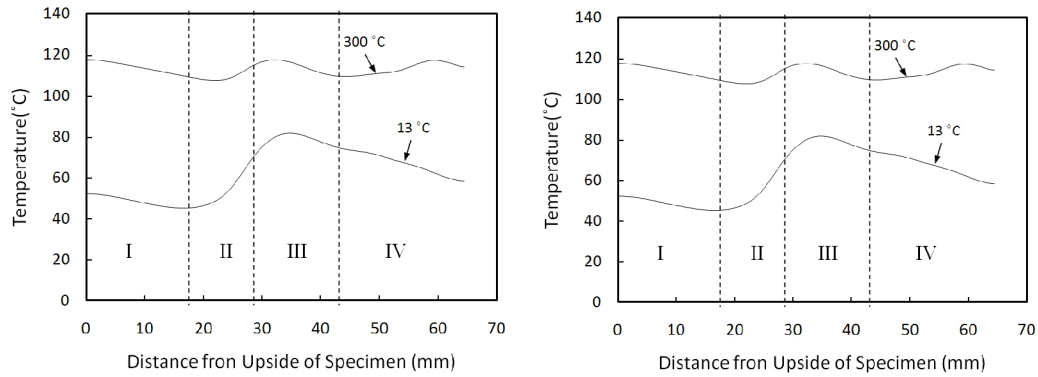a) cold worked and b) deformed at preheat of 300 ˚C.

Fig 6. Temperature distribution at different regions of sample on centerline after deformation
with different preheat temperature.

3.3. Microstructural events during plastic deformation

Initial microstructure of AA7075 alloy is represented in Fig. 7. As can be seen, starting material consisted of coarse α grain, and dispersed Mg_2Si and $FeAl_3$ inclusions. Also, the grain size distribution is represented in this figure. The mean grain size of α phase is about 94μm. Fig. 8 shows the microstructure of processed sample at 300ºC.it is clear that the microstructure of extruded region (region III) is composed of equiaxed α phase. In contrast, grains are elongated in shear direction at ECAPed region (region IV). These equiaxed and elongated grains are formed as the result of dynamic recrystallization in these regions. Microstructure after extrusion (Fig. 8(a)) is more uniform than developed microstructure after extrusion and equal channel angular pressing (Fig. 8 (b)).
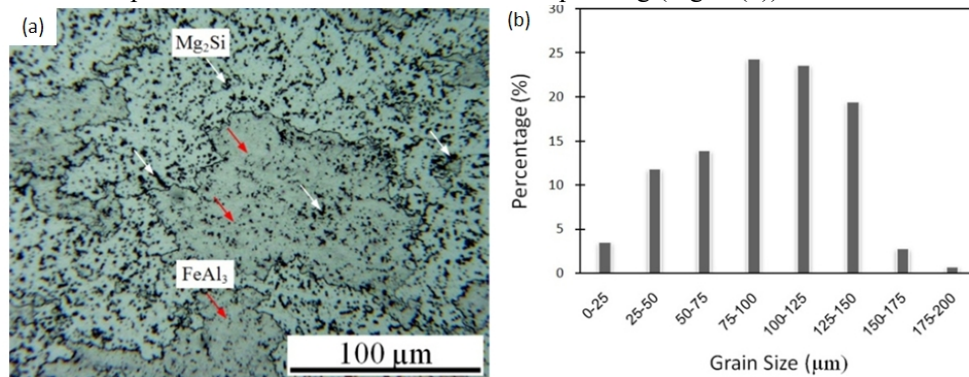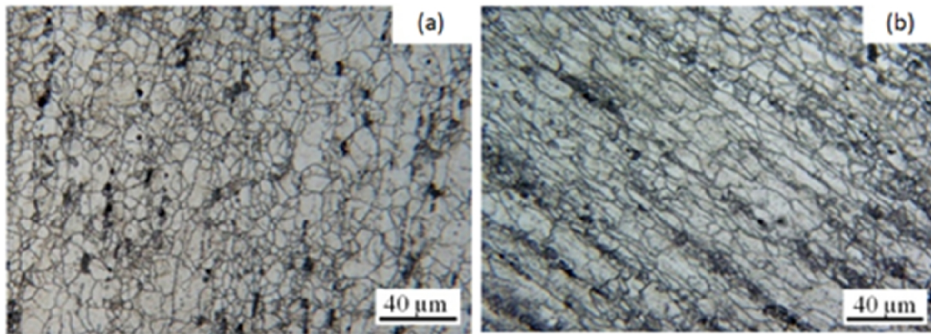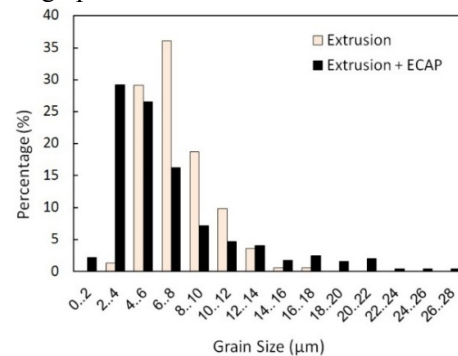

Fig7. Initial microstructure (a) and grain size distribution (b) of Al7075 alloy.
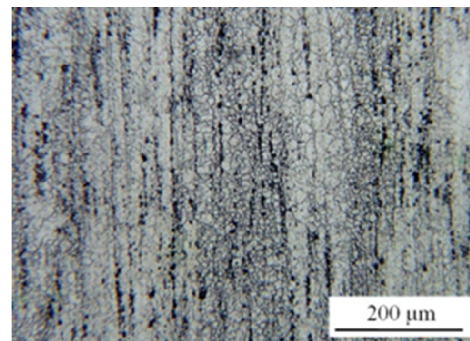
Fig 8. Microstructure of Al7075 alloy a) after extrusion and b) after extrusion and ECAP with preheating temperature of 300 ˚C.

The resultant microstructure after ECAP is in the form of shear bands introduced in the extruded microstructure so that imposed strain is more severe in regions around these shear bands. Consequently, as it is apparent from Fig. 8 (b), deformed microstructure is consisted of fine and coarse grains. Grain size distribution of α phase after extrusion and two step integrated extrusion-ECAP is shown in Fig. 9. Mean grain size after extrusion is about 7.5µm and after integrated extrusion-ECAP is about 7µm. In addition, grain size distribution after extrusion is more uniform than after integrated extrusion-ECAP process. Resultant microstructure of solution annealed AA7075 alloy after extrusion at ambient temperature is represented in Fig. 10. As can be seen, microstructure is mainly consisted of elongated grains, although some fine equiaxed grains are observed as well. These fine grains can be produced by dynamic recrystallization. In addition, high density of dislocations is introduced in deformed microstructure specially near initial grain boundaries due to imposing severe plastic deformation (ε=1.4) and low stacking fault energy of AA7075 alloy. High density of dislocations with local temperature rise triggers dynamic recrystallization in these regions. Fig. 11 shows the Ex-ECAPed region of sample deformed at ambient temperature. As can be seen, imposing two step deformations were not successful due to low workability of this alloy. Severe cracks, aligned in the shear stress direction, were observed in the Ex-ECAPed part of sample after deformation. Optical micrograph of this region is also represented in Fig. 11(b). Material flow at this region is clear in optical micrograph.

Fig 9. Grain size distributions of sample deformed with preheat of 300 ˚C.

Fig 10. Microstructure of Al7075 alloy after extrusion at ambient temperature.
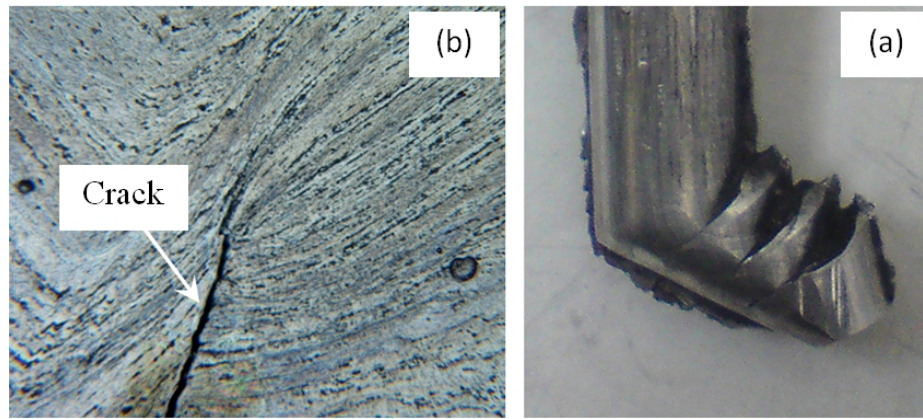
Fig 11. Picture of cracks initiated from top surface of sample after extrusion and ECAP (a), and optical micrograph of Ex-ECAPed region.

4. Conclusions

1) Results of finite element simulation showed that strain and temperature distributions in deformed sample is not uniform. Therefore, this is one of important factors that influences the microstructural uniformity inside deformed sample.

2) At preheat temperature of 300 ˚C; both deformation steps (extrusion and ECAP) are feasible. By contrast, at cold work condition deformation by ECAP is not feasible due to low formability of material. Cracks are initiated from top side of sample and propagated parallel to shear plane.

3) As a consequence of plastic deformation with preheat of 300 ˚C; initial microstructure with grain size of 95 µm is refined to grain size of 7.5 µm.

4) Microstructure after extrusion with preheat temperature of 300 ˚C is more uniform than obtained microstructure after extrusion and ECAP due to more uniform distribution of plastic strain.

References

[1] A.K. Giumelli, M. Militzer, "Analysis of the Austenite Grain Size Distribution in Plain Carbon Steels", ISIJ Int., Vol. 39, 1999, pp. 271–280.

[2] R.Z. Valiev, Y. Estrin, Z. Horita, T.G. Langdon, M. J. Zehetbauer, Y. T. Zhu,"Producing bulk ultrafine-grained materials by severe plastic deformation ", JOM., Aprill 2006, pp. 33-39.

[3] T.C. Lowe, R.Z. Valiev, "The use of severe plastic deformation techniques in grain refinement", JOM., October 2004, pp. 64-77.

[4] Z. Horita, M. Furukawa, M. Nemoto, T.G. Langdon, "Development of fine grained structures using severe plastic deformation", Mater. Sci. Technol., Vol. 16, 2000, pp. 1239-1245.

[5] R.Z. Valiev, T.G. Langdon, "Principles of equal-channel angular pressing as a processing tool for grain refinement ", Prog Mater. Sci., Vol. 51, 2006, pp. 881–981.

[6] Azushima, R. Kopp, A. Korhonen, D.Y. Yang, F. Micari, G.D. Lahoti, P. Groche, J. Yanagimoto, N. Tsuji, A. Rosochowski, A. Yanagida," Severe plastic deformation (SPD) processes for metals", CIRP Ann-Manuf. Techn., Vol. 57, 2008, pp. 716–735.

[7] M. Furukawa, Z. Horita, M. Nemoto, T.G. Langdon, "Processing of metals by equal-channel angular pressing", J. Mater. Sci., Vol. 36, 2001, pp. 2835-2843.

[8] D. Nagarajan, U. Chakkingal, P. Venugopal," Influence of cold extrusion on the microstructure and mechanical properties of an aluminium alloy previously subjected to equal channel angular pressing ", J. Mater. Proc. Technol., Vol. 182, 2006, pp. 363–8.

[9] Z.C. Duan, N.Q. Chinh, C. Xu, T. G.Langdon, "Developing Processing Routes for the Equal-Channel Angular Pressing of Age-Hardenable Aluminum Alloys", Metall Mater. Trans. A., Vol. 41, 2010, pp. 802-809.

[10] N.Q.Chinh, J. Gubicza, T. Czeppe, J. Lendvai, C. Xu, R.Z.Valiev, T.G.langdon, "Developing a strategy for the processing of age-hardenable alloys by ECAP at room temperature", Mater. Sci. Eng. A., Vol. 516, 2009, pp. 248-252.

[11] M. Furukawa, Z. Horita, M. Nemoto, T. G. Langdon, "Processing of metals by equal-channel angular pressing", J. Mater. Sci., 36, 2001, 2835-2843.

[12] Q.X. Pei, C. Lu, M.W. Fu, "Coupled Thermo-Mechanical Analysis of Severe Plastic Deformation for Producing Bulk Nanostructured Materials", Adv. Eng. Mater., Vol. 6, 2004, pp. 933-936.

[13] Y. Yang, Y. Zeng, Z.W. Gao," Numerical and experimental studies of self-organization of shear bands in 7075 aluminium alloy", Mater. Sci. Eng. A., Vol. 496, 2008, pp. 291-302.

[14] Y. Yang, D.H. Li, H.G. Zheng, X.M. Li, F. Jiang,"Self-organization behaviors of shear bands in 7075 T73 and annealed aluminum alloy", Mater. Sci. Eng. A., Vol. 527, 2009, pp. 344-354.