Size Effect in Equal Channel Angular Pressing (ECAP) Process

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ABSTRACT

The influence of the sample size (diameter while keeping the length constant) in equal channel angular pressing (ECAP) of pure aluminum is examined using finite element method (FEM) and experiment. Aluminum rods with different sizes were processed via ECAP and the effect of the sample size on the strain homogeneity, process load, and the ratio of the friction to the total force was evaluated. The results showed that there is no distinct trend in variation of the strain homogeneity when the sample diameter is changed although largest diameter sample exhibits the best strain homogeneity. It was apparent that an increase in the sample diameter caused an increase in the total required load. A decrease in the sample size led to a significant increase in the ratio of the friction to the total force. On the other hand, the friction force is more sensitive than the deformation force to the sample size. More precisely, the friction to total load ratio may be related to the ratio of the sample length to the sample diameter (l/d). In a constant sample length, friction to total load ratio amplifies significantly with a decrease in the sample diameter. The present study showed some limitation for the scaling up of the ECAP process for the industrial application especially with increase in the sample length. It may be concluded that the ECAP processing is not suitable method for producing of long UFG materials.

1. Introduction

Equal-channel angular pressing (ECAP) is identified as a deformation method in which the materials are subjected to simple shear [1]. Generally, the ECAP procedure is done at almost low homologous temperatures in a manner similar to a cold-working process [2]. It is now well-established that ECAP is used for producing significant grain refinement in metals while maintaining constant the cross-sectional area of the sample. It has been shown that nanostructured grains lead to higher strength at ambient temperature and may cause super plasticity at higher temperatures [3, 4]. Also, in general, very small grains in nanostructured range make a possibility to achieve extremely high tensile ductility at high temperatures [5, 6]. The ECAP process could produce ultrafine-grained (UFG) structures due to the repeatability of the process similar to other important severe plastic deformation processes, such as high pressure torsion (HPT) [7] and accumulative roll-bonding (ARB) [8]. No change in the cross section of the billet takes place after the SPD processing [9].

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In the description of ECAP, simple shear plays a dominant role in the deformation [10]. As shown in Fig. 1, an initial billet is pressed into the entrance of die channel and exited in the perpendicular way of that, through the die exit channel. Friction between die wall and work-piece has significant effects on the ECAP parameters. The process force during ECAP strongly depends on the friction force [3]. Also, plastic strain and strain homogeneity are affected by it. In addition, a reduction in the friction coefficient may reduce the corner gap size and make the material flow fit better the die outer corner [11]. However, recently, some efforts such as using ultrasonic force and pressurized lubrication between die and work-piece have been made to reduce the process force. Finite element (FE) method as the most important numerical method can be used to explain the deformation process during the ECAP process [12]. Most of the previous studies on the ECAP process using FE were in 2D strain condition [12], die design for homogeneous plastic deformation [13], the right selection of ECAP die channel [14, 15], analysis of strain rate sensitive metals [16], texture evolution [17], modified ECAP processing [18], bending behavior [19] and the die corner gap formation [20]. However, there are a few works on 3D FEM simulation of the ECAP process. Suo et al. [21] and Basavaraj et al. [22] have recently made a 3D analysis to examine the homogeneity during the ECAP. The distribution of strain in the cross-section of the pure Al and CP-Ti samples using a 3D FE simulation were examined by Xu et al. [23] and Jiang et al. [24], respectively.

In the ECAP process, as shown in Fig. 1, the die was constructed by two channels of equal cross sectional area intersected at an angle of φ and with a curvature angle of ψ. A major concern in ECAP is the possibility of scaling up and down for industrial applications. The effect of the sample size on the process plays an important role on the input parameters such as force and output parameters such as strain distribution, microstructure homogeneity, and mechanical properties. A few works have been done to examine the effect of the sample size during ECAP processing. Results of experimental work done by Horita et al. demonstrate that grain refinement processed by ECAP and the subsequent mechanical properties are independent of the sample size [25]. They considered different sample diameters in the range of 6 to 40 mm. Most of the previous works on equal channel angular pressing (ECAP) only focused on a particular sample size, and very few investigations on the sample size effect have been reported. The published works about the impact of the sample size examined the effect of the sample diameter in different lengths while this may not fully illustrate the effect of the sample size. In all the previous works, the lengths of the samples were not taken constant when the diameter has been changed [26, 27]. This may not fully demonstrate the effect of the sample diameter. The current study investigates the effect of the sample diameter in an identical length on plastic deformation behavior, process load, strain level and homogeneity and the friction force using 3D FE modeling and experimental verifications.

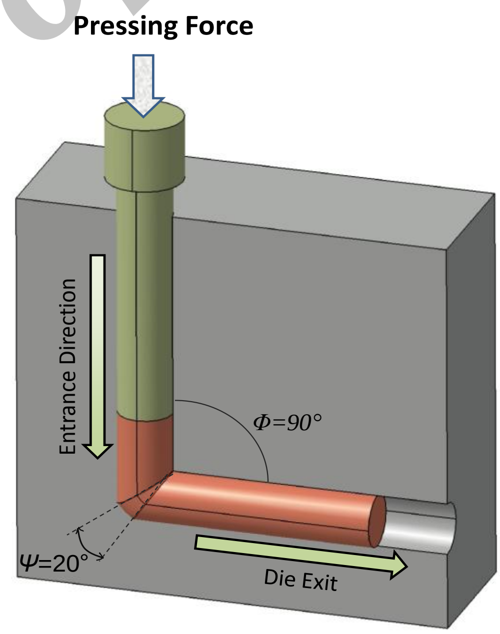

Fig. 1. Schematic of the ECAP process

2. FE and experimental procedure

There are three possible methods in two-dimensional ECAP process for approximation including plane stress, plane strain, and axisymmetric. Plane stress method can be used in the case of very small thicknesses. Also, 2D plane strain process can be used in the case of very large thickness of the work-piece. Due to the discrepancy in the work-piece geometry, none of plane strain and the plane stress conditions is suitable for the cylindrical work-piece used in ECAP. In this study, the ECAP processing of cylindrical billets with different diameters of 10, 15, 20, 25 and 30 mm with identical length of 100 mm have been analyzed using the 3D FE simulations carried out by ABAQUS/explicit FE code. The values of φ and ψ angles are considered to be equal to 90° and 20°, respectively. The material properties of the specimen used in the FE analysis are described in Table 1. The stress-strain curve of the used materials shown in Fig. 2 was determined from tensile test at room temperature at the strain rate of 5x10-4. The frictional behavior was modeled by the standard Coulomb friction model. Each sample deformation has been simulated in two states of frictionless and penalty friction with the coefficient of friction of 0.05 [28, 29]. The die and punch were modeled as rigid bodies. Adaptive meshing was used for all the simulations to prevent excessive mesh distortion during large deformations. The chemical composition of the used aluminum was Al (bulk), Si (0.13 % wt.), Fe (0.32% wt.), Cu (0.16% wt.), Pb (0.19% wt.), Sn (0.01 % wt.). An ECAP die was fabricated from H13 tool steel and hardened to 50 HRC. An aluminum rod with 10 mm diameter was machined from an as-cast billet and annealed at 315 °C for three hrs to achieve an equiaxed homogeneous microstructure. The sample was ECAP processed at room temperature at 5 mm punch speed using a 30 ton Instron press through a single pass. The MoS_2 lubricant was applied to the die and work-piece interface to reduce the friction.

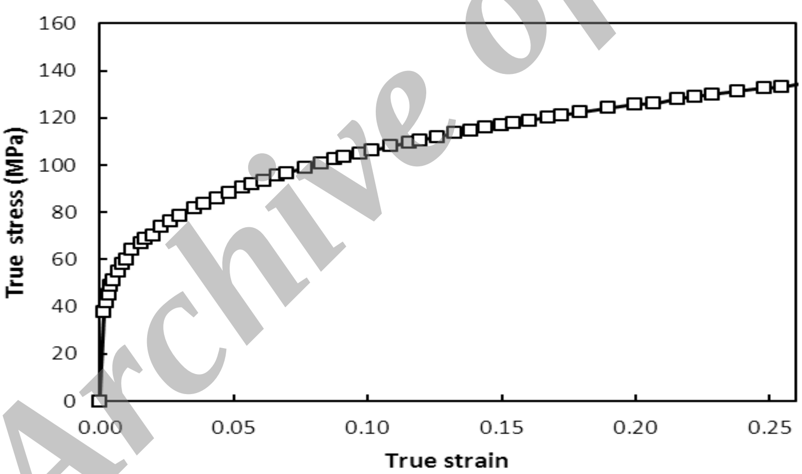

Fig. 2. Stress-strain curve of the used material

Table 1. Mechanical and physical properties of the used material

Parameter	Value
Young modulus (GPa)	70
Yield strength (MPa)	54
Poisson's ratio	0.33
Density (Kg/m^3)	2700

3. Results and discussions

Fig. 3 (a) - (e) shows the equivalent plastic strain contours of frictional ECAP processed samples with different diameters of 30, 25, 20, 15 and 10 mm, respectively. Clearly, the level of strain in the upper surface of all samples is higher than that in the lower surface. However, the distribution of the strain is almost different in different samples as reported in previous references like [30]. The right-hand side contours of the cross sections of different frictional ECAPed samples show that the reduction in the sample diameter may lead to smooth reduction in the strain from the upper to the lower surface of the samples. Comparison between two equivalent plastic strain contours of frictional (Fig. 3(a)-(e)) and frictionless states (Fig. 3(f)-(j)) showed that the level of strain in the upper portion of the frictional state samples is higher than that of the frictionless state counterparts. Also, this difference in small diameter samples is almost more distinguishable than that in larger diameter samples.

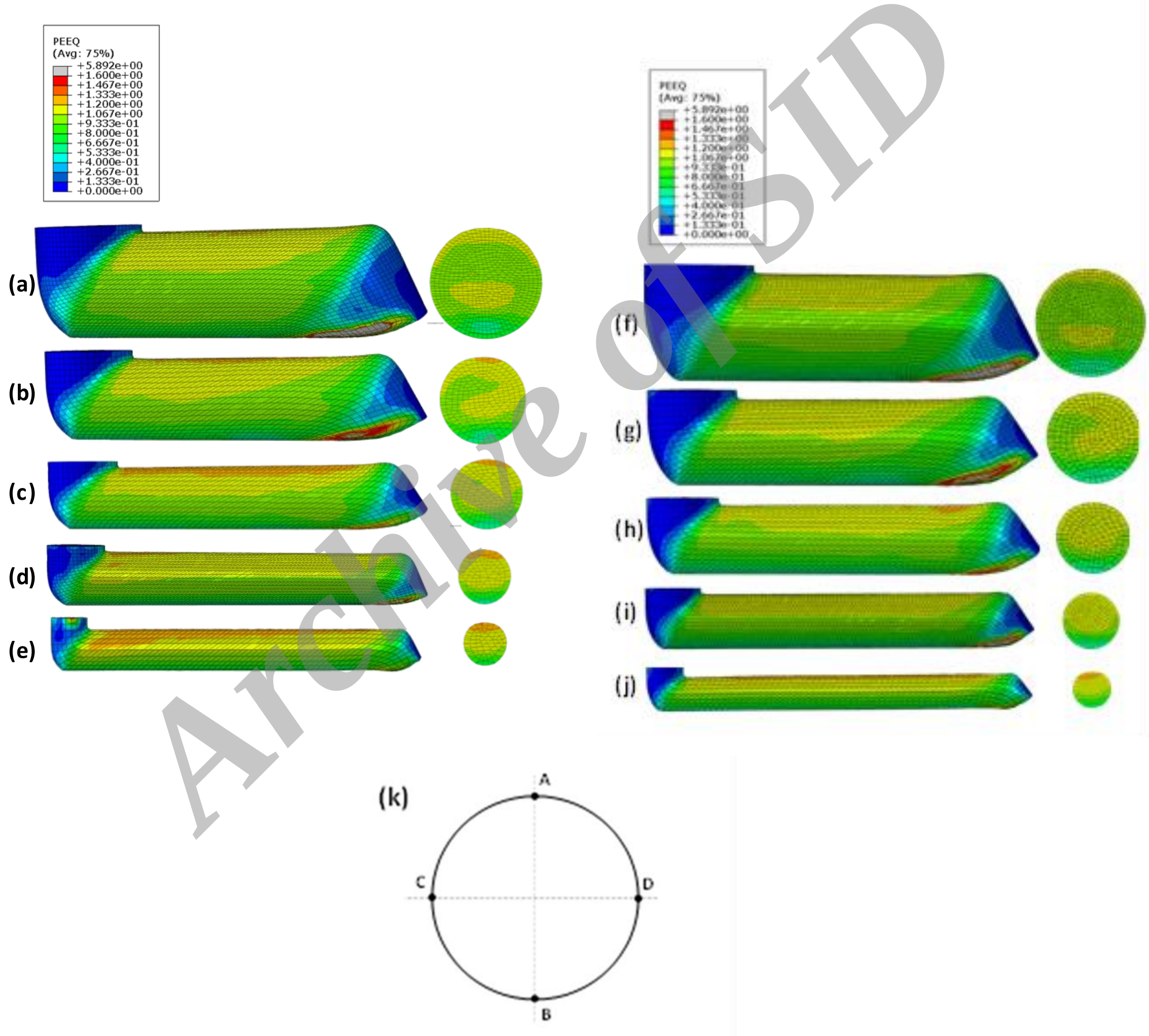

Fig. 3. Equivalent plastic strain contours in ECAP processed samples with different diameters in **(a)-(e)** frictional and (f)-(j) frictionless state.

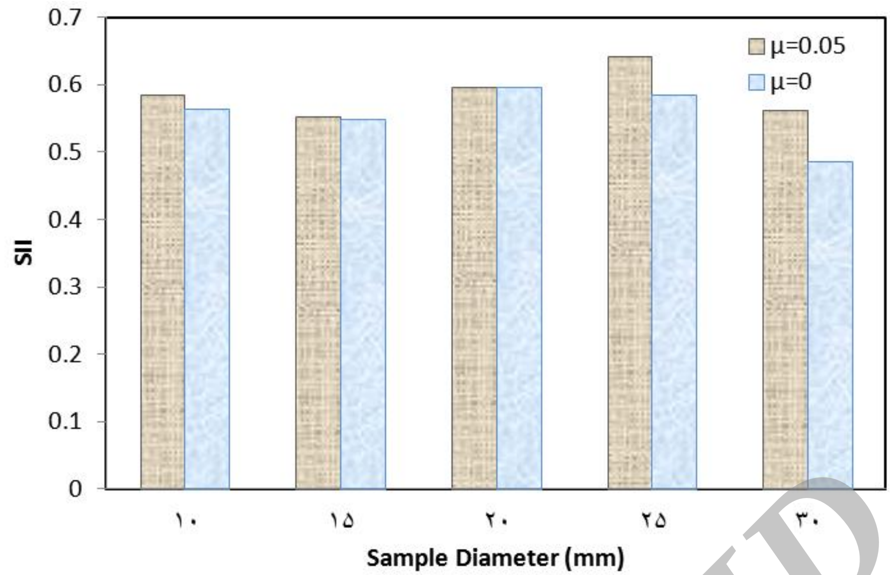

Fig. 4. SII versus sample diameter in two states of frictionless and friction coefficient of 0.05

Strain homogeneity in the ECAP process is mainly dependent on the deformation zone characteristics [31]. The strain distributions were measured along the transverse direction (AB in Fig. 3 (k)). Strain inhomogeneity index (SII) is defined to investigate the effect of the sample size on the strain homogeneity through the ECAP processed samples quantitatively that is [32]:

$$SII = \frac{\varepsilon_{\max.} - \varepsilon_{\min.}}{\varepsilon_{ave.}} \qquad [1]$$

Where denote the maximum, minimum and average plastic strain along the transverse direction (AB direction in Fig. 3(k)), respectively. It worth mentioning that lower SII means that there is a better strain homogeneity in the sample. The SII of different size ECAP processed samples along the transverse direction was calculated using Eq. (1) and used as criterion for the homogeneity of the samples. Fig. 4 shows the SII in the deformed work-pieces in frictional (μ = 0.05) and frictionless (μ = 0) states. As can be seen in this figure, there is no distinct trend when the sample diameter is changed although the largest diameter sample exhibits the best strain homogeneity or the lowest SII. It could also be observed that better strain homogeneity exists in the frictionless state compared to the frictional state for almost all sample sizes. Only for the sample with 20 mm diameter, the same homogeneity was observed for both frictional and frictionless states. Fig. 5 shows the punch load versus punch displacement curve of the frictional ECAP processing of the various samples with different sizes. In all the curves, the amount of force dramatically increased and then decreased gradually. Each curve reached a pick point used as a maximum force which is the sum of deformation and friction forces. Friction force depends on friction coefficient, contact area, and normal stress interacted between work piece and die wall [33]. In the ECAP processing, effective area to determine the friction force is the area before the shear zone. When the plunger proceeds, the effective contact area is gradually reduced, leading to the reduction of the friction force. Generally, reduction of the force in all sample sizes is related to different frictional force before and after the shear zone [33, 34] and may also be related to elastic recovery [29]. However, in frictional ECAP processing, the major reason for load decrease is friction effect. Fig. 6 shows the load versus punch displacement in frictionless ECAP processing of the samples with different diameters. As can be seen, the punch force is increased dramatically, but then it remains almost constant (a bit reduce) unlike the curve of Fig. 5. This may be attributed to the notion that reduction in the punch force after the first pick in frictional ECAP processing is related to both elastic recovery and different in the frictional force before and after shear zone while, in the frictionless counterpart, it is related to only elastic recovery [29].

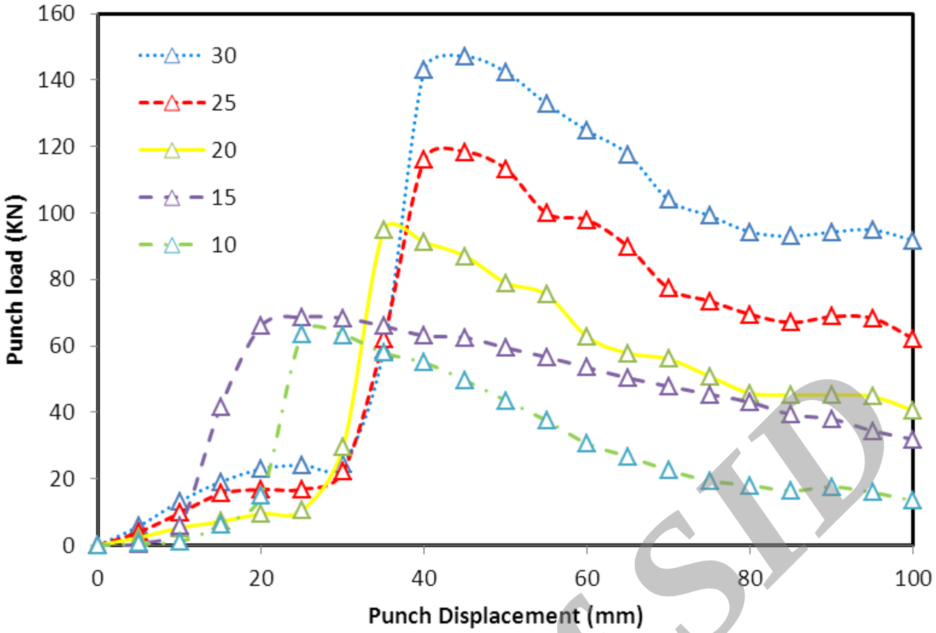

Fig. 5. The load versus punch displacement in different sample sizes in frictional ECAP processing

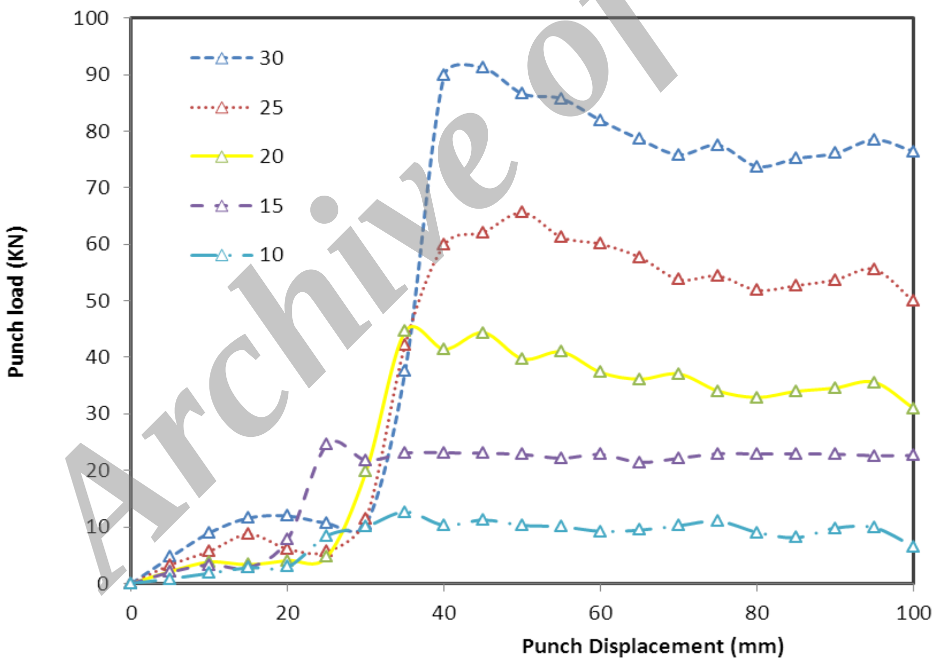

Fig. 6. The load versus punch displacement in different sample sizes in frictionless ECAP processing.

Fig. 7 indicates the maximum processing force versus the sample sizes in both frictional and frictionless states. It is apparent that an increase in the sample diameter caused an increase in the total required load. Total force is the sum of the deformation and frictional forces. Deformation force is almost the same for both frictional and frictionless ECAP processing of an identical sample. But, the friction force could be different for two states. An important point in Fig. 7 is related to the ratio of the total to the friction force. A reduction in the sample size leads to a significant increase in the share of the ratio of the friction to the total force as shown in Fig. 8. This is due to the fact that an increase in the sample diameter resulted in a decrease in the surface to volume ratio of the sample, and the friction force is influenced by the contact area. The friction force is more sensitive than the deformation force to the sample size. In Fig. 8, the ratio of the friction to the total force is raised by decreasing in the sample diameter. It means that the friction force is more efficient in ECAP processing of small diameter samples rather than large diameter samples. More precisely, the fraction of the friction load to the total load may be related to the fraction of sample length to the sample diameter (l/d). In a constant sample length, friction load/total load is significantly amplified with a decrease in the sample diameter. This may limit the scale up in ECAP processing especially when the sample length is increased. It may be concluded that the ECAP processing is not a suitable method for producing of long (large l/d ratio) UFG materials. Other related techniques such as ECAP-Conform [35], ECAP with subsequent rolling [36] could be more suitable for processing long length UFG materials.

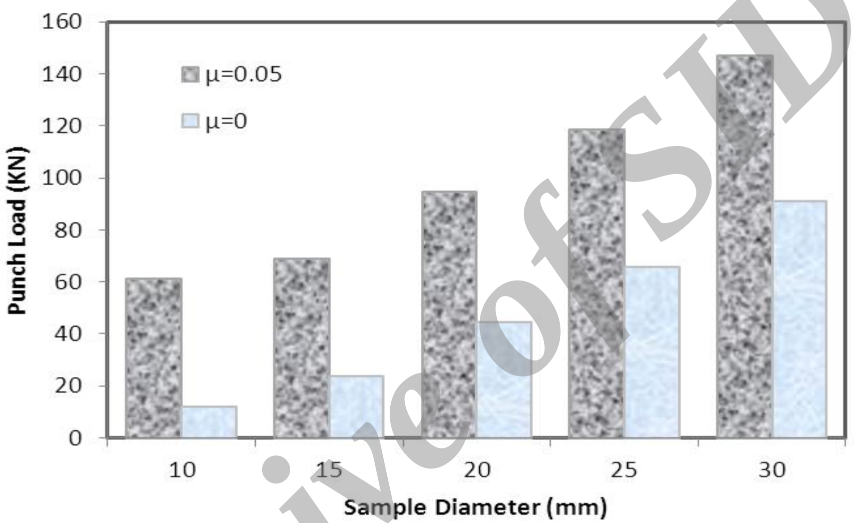

Fig. 7. Maximum forces in different sample sizes in both frictional and frictionless states

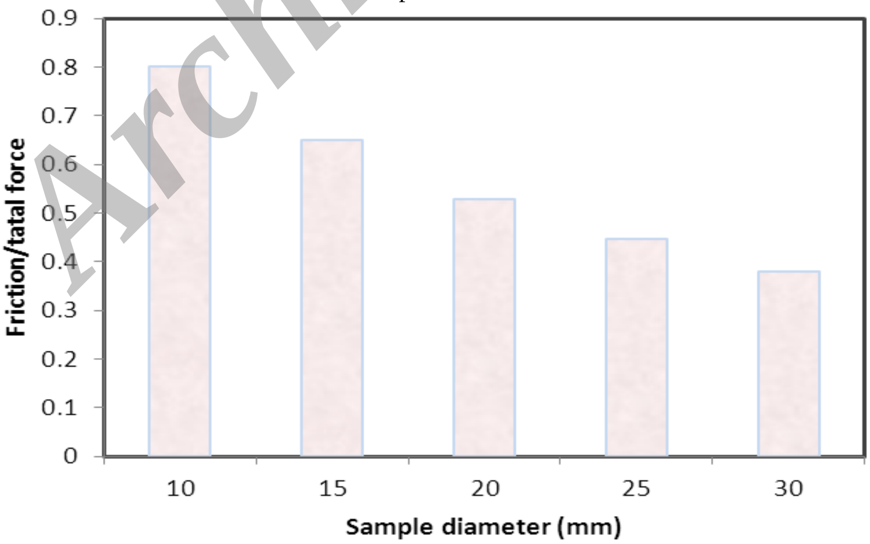

Fig. 8. Ratio of friction to the total force in all sample sizes

Fig. 9. ECAPed aluminum billet during the process

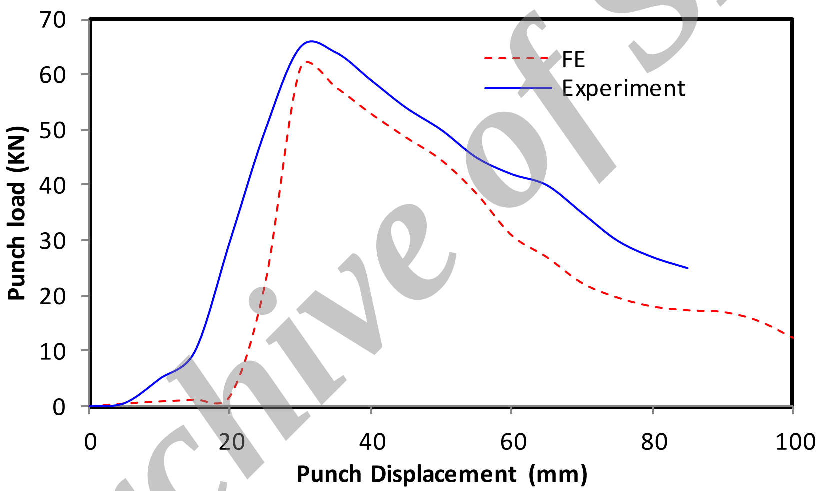

Fig. 10. The force-displacement curves in ECAP processing of 10 mm diameter billet resulted from experiment and FE

An experimental test was carried out for verification of the FE results. Fig. 9 shows the ECAPed aluminum billet with 10 mm diameter during the processing. Fig. 10 shows the force - displacement curves resulted from the experiment and FE. The maximum load resulted from experiments is slightly higher than that obtained from FE. This may be attributed to the prediction in the friction coefficient. However, this figure shows a very good agreement between the data resulted from experiment and FE. The maximum error is about 6.5 % which is an excellent value in engineering matters.

4. Conclusion

Influence of the sample size in equal channel angular pressing (ECAP) of pure aluminum was investigated using finite element method (FEM). Aluminum rods with different sizes were processed via ECAP and the effect of the sample size on the strain homogeneity, process load, and the ratio of total to the friction force was evaluated. The results showed that there is no distinct trend in variation of the strain homogeneity when the sample diameter is changed, although the largest diameter sample exhibits the best strain homogeneity. It was also observed that better strain homogeneity exists in the frictionless state compared to the frictional state for all sample sizes. It was apparent that an increase in the sample diameter caused an increase in the total required load. A decrease in the sample size led to a significant increase in the ratio of the friction to the total force. On the other hand, the friction force is more sensitive than the deformation force to the sample size. More precisely, the fraction of the total load to friction load may be related to the fraction of the sample length to the sample diameter (l/d). In a constant sample length, total load/friction load is significantly amplified with a decrease in the sample diameter. Experimental results showed a very good agreement with the FE results. It may be concluded that ECAP processing is not a suitable method for producing long UFG materials.

References

1. V. Segal, V. Reznikov, A. Drobyshevskii and V. Kopylov, Plastic working of metals by simple shear, Russ. Met, No. 1, 1981, pp. 99-105.
2. S. L. Semiatin, P. B. Berbon and T. G. Langdon, Deformation heating and its effect on grain size evolution during equal channel angular extrusion, Scripta Materialia, Vol. 44, No. 1, 2001, pp. 135-140.
3. Z. Horita, M. Furukawa, M. Nemoto, A. J. Barnes and T. G. Langdon, Superplastic forming at high strain rates after severe plastic deformation, Acta Materialia, Vol. 48, No. 14, 2000, pp. 3633-3640.
4. S. Komura, P. B. Berbon, M. Furukawa, Z. Horita, M. Nemoto and T. G. Langdon, High strain rate superplasticity in an Al-Mg alloy containing scandium, Scripta Materialia, Vol. 38, No. 12, 1998, pp. 1851-1856.
5. Y. Iwahashi, Z. Horita, M. Nemoto and T. G. Langdon, An investigation of microstructural evolution during equal-channel angular pressing, Acta Materialia, Vol. 45, No. 11, 1997, pp. 4733-4741.
6. Y. Iwahashi, Z. Horita, M. Nemoto and T. G. Langdon, The process of grain refinement in equal-channel angular pressing, Acta Materialia, Vol. 46, No. 9,1998, pp. 3317-3331.
7. C. Xu, Z. Horita and T. G. Langdon, The evolution of homogeneity in processing by high-pressure torsion, Acta Materialia, Vol. 55, No. 1, 2007, pp. 203-212.
8. Y. Saito, H. Utsunomiya, N. Tsuji and T. Sakai, Novel ultra-high straining process for bulk materials—development of the accumulative roll-bonding (ARB) process, Acta Materialia, Vol. 47, No. 2, 1999, pp. 579-583.
9. K. Oh-ishi, A. P. Zhilyaev and T. R. McNelley, Effect of strain path on evolution of deformation bands during ECAP of pure aluminum, Materials Science and Engineering: A, Vol. 410–411, No. 0, 2005, pp. 183-187.
10. P. Zhilyaev, D. L. Swisher, K. Oh-ishi, T. G. Langdon and T. R. McNelley, Microtexture and microstructure evolution during processing of pure aluminum by repetitive ECAP, Materials Science and Engineering: A, Vol. 429, No. 1–2, 2006, pp. 137-148.
11. E. Cerri, P. P. De Marco and P. Leo, FEM and metallurgical analysis of modified 6082 aluminium alloys processed by multipass ECAP: Influence of material properties and different process settings on induced plastic strain, Journal of Materials Processing Technology, Vol. 209, No. 3, 2009, pp. 1550-1564.
12. H. S. Kim, M. H. Seo and S. I. Hong, Plastic deformation analysis of metals during equal channel angular pressing, Journal of Materials Processing Technology, Vol. 113, No. 1–3, 2001, pp. 622-626.
13. S. C. Yoon, P. Quang, S. I. Hong and H. S. Kim, Die design for homogeneous plastic deformation during equal channel angular pressing, Journal of Materials Processing Technology, Vol. 187–188, 2007, pp. 46-50.
14. J.-H. Han, H.-J. Chang, K.-K. Jee and K. H. Oh, Effects of die geometry on variation of the deformation rate in equal channel angular pressing, Metals and Materials International, Vol. 15, No. 3,2009, pp. 439-445.
15. C. Luis Pérez, On the correct selection of the channel die in ECAP processes, Scripta Materialia, Vol. 50, No. 3, 2004, pp. 387-393.
16. H. S. Kim, M. H. Seo and S. I. Hong, Finite element analysis of equal channel angular pressing of strain rate sensitive metals, Journal of Materials Processing Technology, Vol. 130–131, 2002, pp. 497-503.
17. G. Deng, C. Lu, L. Su, X. Liu and A. Tieu, Modeling texture evolution during ECAP of copper single crystal by crystal plasticity FEM, Materials Science and Engineering: A, Vol. 534, 2012, pp. 68-74.

18. V. Nagasekhar and H. S. Kim, Analysis of T-shaped equal channel angular pressing using the finite element method, Metals and Materials International, Vol. 14, No. 5, 2008, pp. 565-568.
19. S. Yoon, A. Nagasekhar and H. Kim, Finite element analysis of the bending behavior of a workpiece in equal channel angular pressing, Metals and Materials International, Vol. 15, No. 2, 2009, pp. 215-219.
20. H. S. Kim, M. H. Seo and S. I. Hong, On the die corner gap formation in equal channel angular pressing, Materials Science and Engineering: A, Vol. 291, No. 1–2, 2000, pp. 86-90.
21. T. Suo, Y. Li, Y. Guo and Y. Liu, The simulation of deformation distribution during ECAP using 3D finite element method, Materials Science and Engineering: A, Vol. 432, No. 1, 2006, pp. 269-274.
22. V. P. Basavaraj, U. Chakkingal, T. P. Kumar, Study of inner corner influence in equal Channel Angular Pressing using 3D finite element simulation, Transactions of the Indian Institute of Metals, Vol. 61, 2008, pp. 125-129.
23. S. Xu, G. Zhao, Y. Luan and Y. Guan, Numerical studies on processing routes and deformation mechanism of multi-pass equal channel angular pressing processes, Journal of Materials Processing Technology, Vol. 176, No. 1–3, 2006, pp. 251-259.
24. H. Jiang, Z. Fan and C. Xie, 3D finite element simulation of deformation behavior of CP-Ti and working load during multi-pass equal channel angular extrusion, Materials Science and Engineering: A, Vol. 485, No. 1, 2008, pp. 409-414.
25. Z. Horita, T. Fujinami and T. G. Langdon, The potential for scaling ECAP: effect of sample size on grain refinement and mechanical properties, Materials Science and Engineering: A, Vol. 318, No. 1–2, 2001, pp. 34-41.
26. G. Y. Deng, C. Lu, L. H. Su, A. K. Tieu, H. L. Yu and X. H. Liu, Investigation of sample size effect on the deformation heterogeneity and texture development during equal channel angular pressing, Computational Materials Science, Vol. 74, 2013, pp. 75-85.
27. P. K. Chaudhury, B. Cherukuri and R. Srinivasan, Scaling up of equal-channel angular pressing and its effect on mechanical properties, microstructure, and hot workability of AA 6061, Materials Science and Engineering: A, Vol. 410, 2005, pp. 316-318.
28. G. Faraji, M. M. Mashhadi, S.-H. Joo and H. S. Kim, The role of friction in tubular channel angular pressing, Rev. Adv. Mater. Sci, Vol. 31, 2012, pp. 12-18.
29. V. Nagasekhar, S. C. Yoon, Y. Tick-Hon and H. S. Kim, An experimental verification of the finite element modelling of equal channel angular pressing, Computational Materials Science, Vol. 46, No. 2, 2009, pp. 347-351.
30. N. E. Mahallawy, F. A. Shehata, M. A. E. Hameed, M. I. A. E. Aal and H. S. Kim, 3D FEM simulations for the homogeneity of plastic deformation in Al–Cu alloys during ECAP, Materials Science and Engineering: A, Vol. 527, No. 6, 2010, pp. 1404-1410.
31. P. B. Prangnell, C. Harris and S. M. Roberts, Finite element modelling of equal channel angular extrusion, Scripta Materialia, Vol. 37, No. 7, 1997, pp. 983-989.
32. S. Li, I. J. Beyerlein, C. T. Necker, D. J. Alexander and M. Bourke, Heterogeneity of deformation texture in equal channel angular extrusion of copper, Acta Materialia, Vol. 52, No. 16, 2004, pp. 4859-4875.
33. G. Faraji, M. M. Mashhadi and H.S. Kim, Deformation Behavior in Tubular Channel Angular Pressing (TCAP) Using Triangular and Semicircular Channels, Materials Transactions, Vol. 53, No. 01, 2012, pp. 8-12.
34. G. Faraji, M. Mashhadi, A. Dizadji and M. Hamdi, A numerical and experimental study on tubular channel angular pressing (TCAP) process, Journal of mechanical science and technology, Vol. 26, No. 11, 2012, pp. 3463-3468.
35. G. J. Raab, R. Z. Valiev, T. C. Lowe and Y. T. Zhu, Continuous processing of ultrafine grained Al by ECAP–Conform, Materials Science and Engineering: A, Vol. 382, No. 1–2, 2004, pp. 30-34.
36. N. D. Stepanov, A. V. Kuznetsov, G. A. Salishchev, G. I. Raab, R. Z. Valiev, Effect of coldro and ling on microstructure and mechanical properties of copper subjected to ECAP withvarious numbers of passes, Materials Science and Engineering: A, Vol. 554, 2012, pp. 105- 115.