This paper is part of the Proceedings of the 2nd International Conference on
High Performance and Optimum Design of Structures and Materials (HPSM 2016)
www.witconferences.com

Effect of friction on material behaviour in non-equal channel multi angular extrusion (NECMAE)

M. S. El-Asfoury[1], M. N. A. Nasr[1,2] & A. Abdel-Moneim[1]
[1]Department of Materials Science and Engineering,
Egypt-Japan University of Science and Technology, Egypt
[2]Department of Mechanical Engineering, Faculty of Engineering,
Alexandria University, Egypt

Abstract

The current work investigates the effect of friction on material mechanical behaviour during a new severe plastic deformation (SPD) process, named: "non-equal channel multi angular extrusion (NECMAE)". This is done with the aid of finite element modelling, where a two-dimensional thermo-mechanical plane strain model was built using the commercial software ABAQUS/Explicit. NECMAE was developed by the current authors in order to improve the degree of homogeneity and impose higher strains into the workpiece. The NECMAE die has three channels; the first two represent a standard ECAP process, while the third one experiences a reduction in cross-sectional area. Different percentages of area reduction (10%, 30% and 50%) were examined. The simple Coulomb friction model was used, where different values were assigned to the friction coefficient (0, 0.1 and 0.2). The workpiece material is pure aluminium. The model was validated by comparing the predicted average strain values to available data in the literature. The coefficient of friction was found to affect the corner gap size, as friction tends to increase the sticking possibility of the workpiece to the die. Also, cases with higher coefficient of friction were found to have higher and more uniform plastic deformation.
Keywords: non-equal channel angular extrusion (NECAE), multi-pass, severe plastic deformation (SPD), back pressure, finite element modelling (FEM).

1 Introduction

Simple shear was transformed to potentially industrial technology after invention of equal channel angular extrusion, when severe deformation of massive billets became possible. Equal channel angular extrusion (ECAE) is the most interesting process for modifying micro structure in producing ultrafine grained (UFG) materials, and was invented by Segal [1]. ECAE leads to significant improvement of mechanical and physical properties that defines many possible applications. The process shows many progress in: grain refinement to nano-scale; refinement of second phases and particles; healing of voids, pores and other volume defects; enhanced diffusivity; control of textures; geometrical control of structural elements; consolidation and bonding of particulate materials; phase transformation; enhanced super plasticity [2]. In the process, workpiece pressed into a die of two channels which intersecting at an angle φ. This procedure abundant imposing very large plastic strains on the workpiece, without changing its cross-sectional dimensions, as schematically shown in Fig. 1. In Fig. 1(a). Severe plastic deformation occurs as the material changes its direction (shear deformation) between the two channels. Although good levels of grain refinement could be achieved via a single-path ECAE process, several paths are typically required in order to achieve the desired levels of refinement/properties [3, 4].

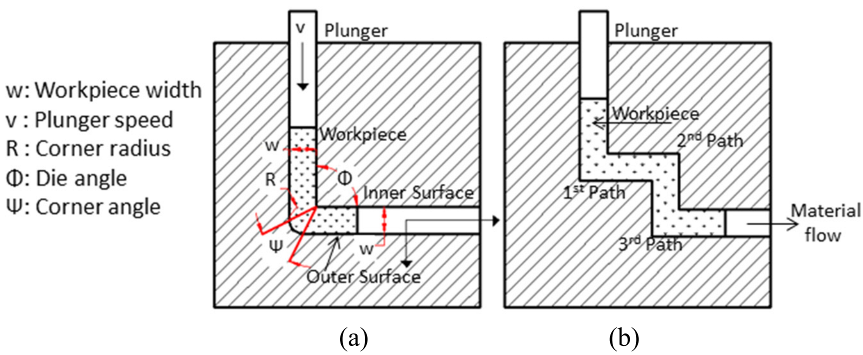

Figure 1: Schematic illustration of (a) single path ECAE, (b) multi-path ECAP process.

Originally, ECAE was designated for material processing by intensive and uniform simple shear. However, the considered solutions show that actual stress/strain states can be more complicated and different from the ideal deformation model [5]. This consideration came from the limited awareness of the most important parameters, which are contact friction, the geometry of channels and tool design. Effects of back pressure and material characteristics are also significant. Depending on friction, plastic zone can be ranged from localized shear to an enlarged central fan and may include a free surface, dead metal zone and area of non-uniform strains.

For corresponding very large strains, continuous stable flow is exchanged by localized discontinuous flow inside shear bands observed at different structural levels. In many cases, friction in channels is different because of different processing conditions. Lubricated billets are inserted directly into inlet channel. However, following extrusion, a lubrication layer may be destroyed and localized shear on uncovered clean surfaces that causes provoking to tool. In evaluating this effect, it is worth to consider the limiting case of zero friction.

The average equivalent strain (εN) generated in the workpiece during an ECAP process was first calculated analytically by Iwahashi *et al.* [5], as given by Eq. (1):

$$\varepsilon\_N=N/(\sqrt{3})\ [2\cot\ (\emptyset/2+\psi/2)+\psi.\mathrm{cosec}(\emptyset/2+\psi/2)] \quad (1)$$

where (N) is the number of paths, (φ) is the die angle and (ψ) is the corner angle.

After that, Dobatkin [6] and Eivani and Karimi Taheri [7] have introduced a modified form of Iwahashi's work to calculate the equivalent strain, as given by Eq. (2).

$$\varepsilon\_N=N/\sqrt{3}[2\cot\ (\emptyset/2+\psi/2)+\psi] \quad (2)$$

According to these equations, the equivalent plastic strain depends on both angles φ and ψ. So, just die geometry was considered with many assumptions. The assumptions include simple shear, uniform plastic flow, complete filling of die corner and frictionless between die surfaces and workpiece. The analytical approach provided homogenous value of strain in the whole workpiece and ignored the effect of friction and temperature dropped out on the strain gradients.

It is important to note that, a single-pass ECAE process typically results in non-uniform plastic deformation, where the degree of inhomogeneity is directly related to how the plastic shear zone is deformed. Also, the strain-rate distribution is an important parameter. Due to the geometrical constraints applied to the workpiece, the workpiece experiences higher strains and strain-rates at the inner corner compared to the outer corner especially in the strain hardening and rate insensitive materials. The outer part of the workpiece, which receives lower deformation and therefore softer than the inner part within the deforming zone, can flow faster to the exit channel and the corner gap is formed and it produces inhomogeneous deformation. This is basically what results in the non-uniformity experienced by the workpiece. Accordingly, multi-pass ECAP processing was found to be essential to achieve a better degree of uniformity, by accumulating strains over multiple passes where the inner and outer surfaces are interchanged. However, the effect of strain hardening, especially with friction condition and multi-channel geometry is not properly evaluated. A typical multi-path ECAP die is shown in Fig. 1(b).

A modified version of the ECAP process, namely non-equal channel angular pressing (NECAP), was then introduced. A flow line function was provided by Hasani *et al.* [8] that describes the deformation behaviour in the NECAP process. NECAP is basically a combination the ECAP process with the extrusion principle in a single step, and is achieved by using two non-equal channels (channel-1 and channel-2 in Fig. 1(a). Despite the success in obtaining significant large strains in one NECAP path, grains became more elongated and benefits of unchanging dimensions vanished. In addition, no information is currently available on the level of homogeneity that may be achieved in billets processed by the NECAP process.

Strain uniformity can be an important issue when ECAE processed materials are used to produce mechanical components. In our recent paper [9] a new non-equal channel multi angular extrusion (NECMAE) process is introduced and analysed, with the aid of finite element modelling (FEM). The process involves two stages; the first stage is a standard ECAP process, while the second stage has different reduction ratios. Three levels of reduction have been examined, where the workpiece width is reduced by 10%, 30% and 50% compared to the initial width. In this work, FEA have been exposed and discussed in term of the effect of different friction coefficient in existence of temperature (150°) on the deformation behaviour. Special focus is given to the homogeneity of plastic deformation across the workpiece width, as well as the magnitude of induced plastic strains. Fig. 3 shows the different studied cases.

2 Finite element modelling (FEM)

2.1 General description

A set of two-dimensional plane-strain finite element (FE) models was built, using the commercial software ABAQUS/Explicit. Fig. 2 shows a schematic of the built model; a detailed description of the model was previously presented in [9]. Lagrangian formulation, with continuous remeshing, was used in order model the effects of friction on material behaviour in non-equal channel multi angular extrusion (NECMAE). In the current study, the simple Coulomb friction model was used, and three different values were assigned to the coefficient of friction

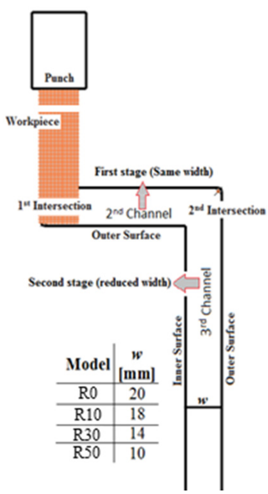

Figure 2: Schematic of the FE model.

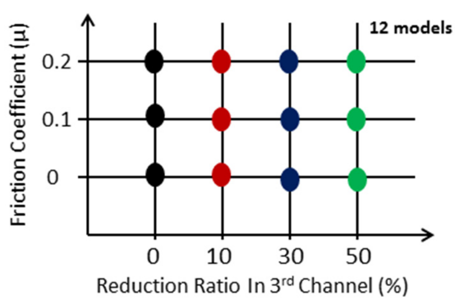

Figure 3: Test matrix.

www.witpress.com, ISSN 1743-3509 (on-line)

(μ); namely 0, 0.1 and 0.2. This was evaluated for four different NECMAE dies; each with a different % reduction of area for the second stage. The four dies had 0%, 10%, 30% and 50% reduction of area; i.e., the first die represented a conventional multi-pass ECAE. For convenience, from now on the four models are referred to as R0, R10, R30 and R50, respectively. The workpiece material was pure aluminium in all cases. The current test matrix is shown in Fig. 3. An initial temperature of 150°C was applied to the workpiece, and the die temperature was held constant at 150°C throughout the analysis. A punch speed of 1 mm/s was used, while the die was totally fixed in space.

2.2 Mesh controls

The workpiece was meshed with 4-node linear plane strain elements. The automatic adaptive remeshing technique available in ABAQUS/Explicit, under the option "arbitrary-Lagrangian-Eulerian (ALE)", was used in order to avoid large element distortion during the simulation. The remeshing frequency was set as 20, with two sweeps per increment.

2.3 Model validation

The current model was validated by comparing the predicted equivalent plastic strain (PEEQ) to the analytical values obtained from Equations (1) and (2). This was done at different corner angles (ψ), covering the range from 0° to 90°, as shown in Fig. 4. In addition, the current results were compared to the FE results of Balasundar *et al*. [10], which were obtained under the same current conditions. More details could be found in [9].

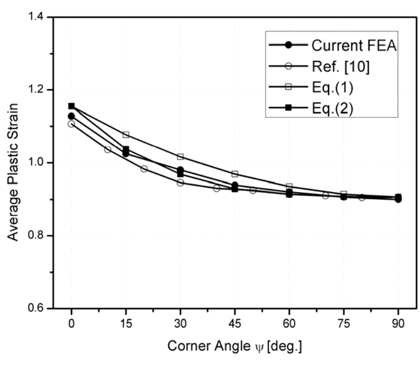

Figure 4: Model validation (PEEQ distribution).

3 Results and discussion

3.1 Corner gap angle (α)

Fig. 5 presents the effect of coefficient of friction (μ) on corner gap angle (α) of the first stage, as an example. In order to isolate the friction effects from area reduction and back pressure effects, the first stage corner gap angle was also examined before the material enters the second stage; i.e., for a one-stage ECAP process. As shown, the gap angle decreased with the increase of friction (μ). This is because, as μ increases, the outer surface of the deforming workpiece has a higher tendency to stick to the outer surface of the die. The same trend was found after the material entered the second deformation stage; however, the effect of μ became less evident. At the same time, the NECMAE first stage gap corner angle was significantly lower than that of the NECAP process. The reason for having less obvious effects for μ, as well as for having smaller gap angles, for the NECMAE process is actually attributed to the back pressure effects, arising from the reduction in area of the second stage. For the NECMAE second stage, μ had similar effects.

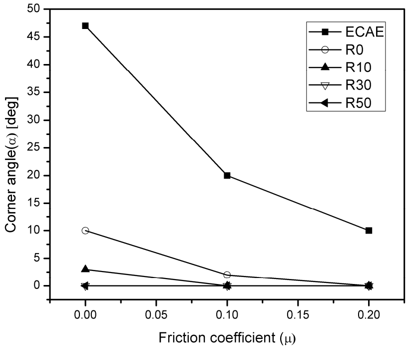

Figure 5: Effect of friction on corner gap angle (α) of the first stage.

3.2 Equivalent plastic strain (PEEQ)

Fig. 6 shows the effect of μ on PEEQ distribution in the first stage before the workpiece material enters the second stage; i.e., for a standard ECAP process. As shown, in general, higher μ values resulted in higher PEEQ magnitudes. At the

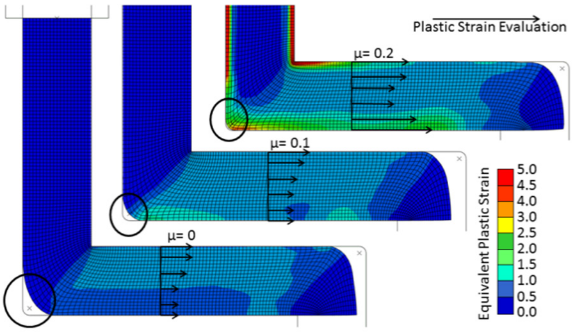

Figure 6: Effect of friction on PEEQ in the first stage, before material entering second stage.

same time, μ affected the degree of homogeneity of plastic deformation. As μ increased from 0 to 0.1, better homogeneity was achieved; i.e., less difference in PEEQ magnitude across the workpiece width. However, further increase in μ resulted in an opposite behaviour (more inhomogeneity compared to μ = 0.1). A proper explanation is still missing. We can try sending it like this, just because of time.

Fig. 7 presents the PEEQ distribution across the workpiece width. As shown in Fig. 7(a), the first two values of friction (μ = 0 and μ = 0.1) exhibit almost the same trend, with higher PEEQ magnitudes for higher friction. The plastic strain produced at the first intersection is slightly smaller at the outer surface, compared to the inner surface. In case of μ = 0.2, strain distribution became significantly inhomogeneous, where significant differences in the sub-surface layers of the workpiece are observed. Accordingly, the magnitude of maximum strain does not reflect the actual average strain imposed on the workpiece. The increase in the magnitude of plastic strain with friction is actually attributed to two reasons; 1) the drop in corner gap angle explained earlier, which imposes higher resistance to material flow, and 2) the higher shear stresses and strains imposed on the surface layers, due to higher frictional effects. In other words, the magnitude of maximum plastic strain and degree of homogeneity across the workpiece width were found to increase with friction. At the same time, smaller corner gap angles were generated with higher friction.

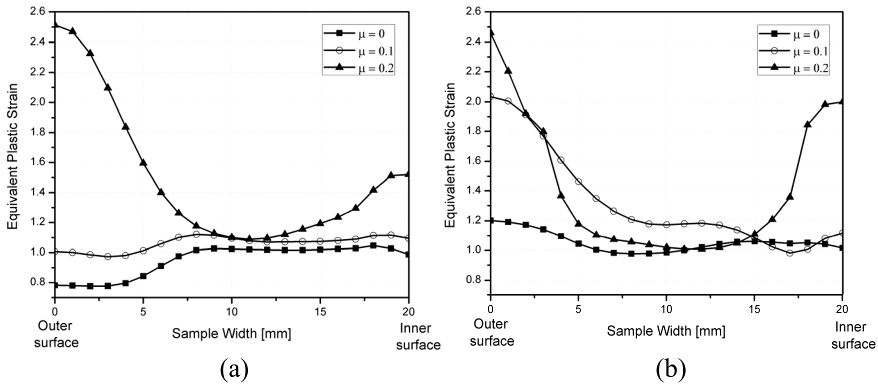

Figure 7: PEEQ distribution in 2nd channel (for non-reduction model (R0) after (a) first stage (before entering the second stage), (b) second stage after entering the second stage).

After the second intersection, the workpiece experienced higher magnitudes of plastic deformation, as shown in Fig. 7(b). It is obvious that better degree of homogeneity was achieved for the frictionless case. Even when μ = 0.2, the strain became homogeneous except in the outer sub-surface layer of the workpiece. Due to the back pressure provided by the second intersection, the strain on the outer surface continues to increase until satisfied and fill up the third channel, with progress the upper layer acquired almost same strain value and uniform behaviour generate in the core. Such behaviour indicates that high friction values disintegrate the effect of multi stage processing. It was related to less deformed layer in the lower part of the sample during a passage during second intersection, due to less deformation zone in vicinity of the rounded outer corner. Until this moment the behaviour recorded for μ=0 is optimum and satisfied the workpiece from appropriate strain and homogeneity point of view.

So to get high strain with the aid of friction, extrusion ratio and keeping the homogeneity is the target of our die design (balancing between acceptable friction value with approbate reduction ratio to get high uniformity). The effect of friction on the deformation behaviour of different reduction cases was simulated and shown in Fig. 8 (at second channel's steady state and after workpiece passed 2nd intersection). In case of frictionless (Fig. 8(a)), from the dependence the influence of the reduction in the third channel on the deformation behaviour is evident.

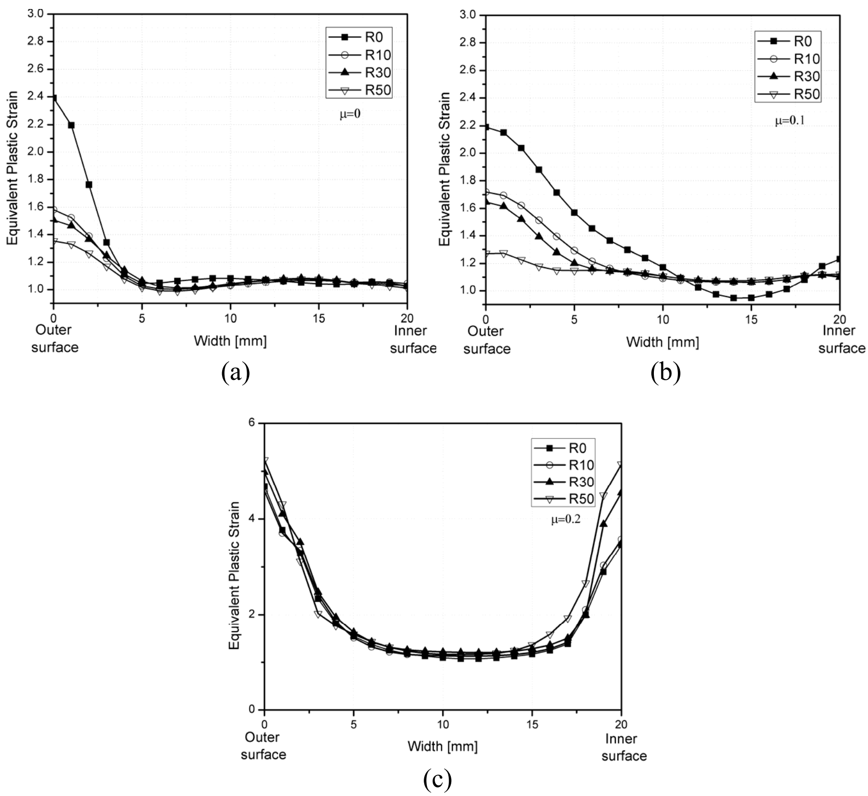

Figure 8: Equivalent plastic strain through second channel at different reduction ratios for (a) μ = 0, (b) μ = 0.1 and (c) μ = 0.2.

The PEEQ at the outer zone decrease with the reduction percentage increase. It is give evident that back pressure induced by reduction in the third channel affected on the bottom side further than the upper one. It can't be judged on the homogeneity in this case because of first, the difference between the highest and lowest value of strain was about 0.5 for all reduction cases , second, the absent of friction doesn't simulate the real process. It can be mentioned that the sever deformation in the bottom area of second stage provided pressure to the upper side of the first stage to restrict the bottom. It gives clear evidence to the effect of friction side by side to the back pressure. In Fig. 8(b), the effect of friction appears distinctly especially in the bottom of the workpiece. The PEEQ decreases gradually with reduction increase. This effect is matching the behaviour in Fig. 7(a). The altitude in the strain appeared for 50% reduction case was ideal (minimum difference in plastic strain between surfaces). This manner is based on satisfaction of back pressure effect and undesirable friction value. The upper side behaviour was almost the same for all cases, with respect to the increase in PEEQ in comparison to frictionless case. This gives clear vision for need for a balance between the back pressure imposed by reduction and friction coefficient value. The impact of highest friction with several reduction ratios shown in Fig. 8(c). The PEEQ pushed up with high rate. This increasing was limited to the upper and lower surface, with reasonable homogenate in the interior zone. All models appear with symmetrical trend and maximum. This phenomenon was critical to be explained. The significant raising in the strain may attached to sever plastic deformation in the second intersection (this lack compensated in the third channel), or the raising of temperature due to high friction and reduction value tempered the effect of friction in this case. So, the distribution of PEEQ in the third channel studied and shown in Fig. 9.

Focusing on the effect of reduction percentage in the third channel was observed in Fig. 9. The horizontal axis is the normalize of the distance from the outer of the vertical channel (third channel) of the height of this channel. The distribution of PEEQ in all cases was non-uniform especially in the bottom area. The behaviour was the same to the rest of channel width. The effect of reduction reflects only in the strains values, it became higher with suddenly increasing rate for μ=0.2 in the bottom of workpiece. The performance of strain was most uniform in case of μ= 0.1 for all reduction cases and limited to 80% of the workpiece length (Fig. 9(b)). The effect of either extrusion ratio and friction success in raising the stain overall the workpiece. With friction increasing, the strain in the outer layer increase by 30% to reach to 7 for μ=0.2. The homogeneity is acceptable (the middle 80% of the width gained from 2.5 to 3 plastic strain), especially in the interior. It is very important to separate between the effect of friction and reduction ratio. It gives opportunity to optimize the design of the die and resultant homogeneity [12].

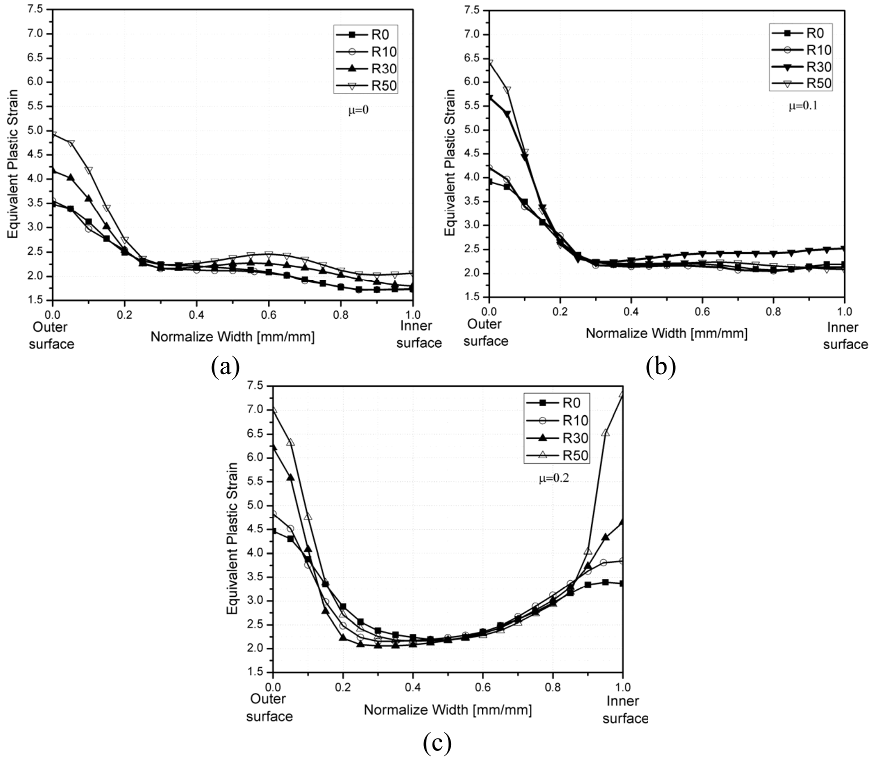

Figure 9: Equivalent plastic strain through third channel at different friction value for (a) $\mu = 0$, (b) $\mu = 0.1$ and (c) $\mu = 0.2$.

4 Conclusions

The current study investigated the effects of friction on material behaviour during the non-equal channel multi angular extrusion (NECMAE) process. It was found that, for effective processing, NECMAE should be optimized for many characteristics. The optimal balance corresponds to accepted friction contact and proper reduction ratio. In this study, friction up to 0.1 was sufficient with aid of reduction to get much homogeneous plastic strain over 80% of workpiece length with incomparable plastic strain in the second stage. Highest frictions have mainly effect in the outer region and eliminate the benefits of reduction ratio in either plastic strain values or homogeneity. Finally, in order to take advantage of this optimized process, it is necessary to associate the modelling analysis of the deformation behaviour of workpiece with experimental tests. Hence, a new NECMAE die will be manufactured in order to achieve experimental data on the microstructural and mechanical aspects.

Acknowledgements

The authors gratefully acknowledge the Missions Sector-Higher Education Ministry, Egypt for financially supporting the current project, and the Japan International Cooperation Agency (JICA) for their continuous scientific and technical support to the Department of Materials Science and Engineering at Egypt-Japan University of Science and Technology (E-JUST).

References

[1] Segal, V.M.: Severe plastic deformation: Simple shear versus pure shear. Mater. Sci. Eng. A. 338, 331–344 (2002).

[2] Kim, W.J., Sa, Y.K., Kim, H.K., Yoon, U.S.: Plastic forming of the equal-channel angular pressing processed 6061 aluminum alloy. Mater. Sci. Eng. A. 487, 360–368 (2008).

[3] Yapici, G.G., Karaman, I.: Common trends in texture evolution of ultra-fine-grained hcp materials during equal channel angular extrusion. Mater. Sci. Eng. A. 503, 78–81 (2009).

[4] Ferry, M., Burhan, N.: Structural and kinetic aspects of continuous grain coarsening in a fine-grained Al–0.3Sc alloy. Acta Mater. 55, 3479–3491 (2007).

[5] Iwahashi, Y., Wang, J., Horita, Z., Nemoto, M., Langdon, T.G.: Principle of equal-channel angular pressing for the processing of ultra-fine grained materials. Scr. Mater. 35, 143–146 (1996).

[6] Dobatkin, S.: Investigations and Applications of Severe Plastic Deformation, TC Lowe, RZ Valiev (ed.), nATo Science Series. (2000).

[7] Eivani, A.R., Karimi Taheri, A.: An upper bound solution of ECAE process with outer curved corner. J. Mater. Process. Technol. 182, 555–563 (2007).

[8] Hasani, A., Tóth, L.S., Beausir, B.: Principles of Nonequal Channel Angular Pressing. J. Eng. Mater. Technol. 132, 031001 (2010).

[9] Mohamed S. El-Asfoury, Mohamed N. A. Nasr, A.A.-M.: Non-equal Channel Multi Angular Extrusion (NECMAE) – A New Severe Plastic Deformation Process. Mater. Sci. Eng. A. under revision, 20 (2014).

[10] Balasundar, I., Sudhakara Rao, M., Raghu, T.: Equal channel angular pressing die to extrude a variety of materials. Mater. Des. 30, 1050–1059 (2009).

[11] Kim, H.S., Seo, M.H., Hong, S.I.: On the die corner gap formation in equal channel angular pressing. Mater. Sci. Eng. A. 291, 86–90 (2000).

[12] Balasundar, I., Raghu, T.: Effect of friction model in numerical analysis of equal channel angular pressing process. Mater. Des. 31, 449–457 (2010).