FEM-Based Deformation Regression Analysis of ECAE Strains

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The present article is focused on the regression-based generalization of FEM simulation results, derived through the introduction of QForm 2D FEM software to copper workpieces simulated flow through 2θ angular dies with external R and internal r die radii in channel intersection zone, and the width of the inlet and outlet die channels is $a = 35.4$ mm. Regression power dependences for ECAE strain, strain unevenness, and workpiece waste fore part area have been derived for the 125 cases of FEM simulations for the angular dies with different values of channel intersection angles $65^\circ \le 2\theta \le 135^\circ$, external and internal die dimensionless radii $0.028 \le R/a$; $r/a \le 1.977$ and dimensionless workpiece length $5.226 \le L/a \le 16.836$. Good agreement of derived computational results with known published experimental and computational data for strain and strain unevenness has been found. The derived results of regression analyses provide improvement in the understanding of the influence of generalized ECAE die geometry and workpiece length on copper workpiece pressure working conditions.

Keywords: *ECAE, die, FEM, copper, regression, QForm 2D, strain, waste.*

1. INTRODUCTION

For the past 20 years the Equal Channel Angular Extrusion (ECAE) method has found wide research applications in material science related fields [1-24]. However, the ECAE technique still is not widely used in manufacturing engineering because of the large gap between theoretical and experimental research, and difficulties with the ECAE process [1-2, 4, 6-19, 21-23]. There are geometric constraints on the length of the inlet die channel which limit the length of the processed workpiece [1-2, 9, 12-13]. Moreover, ECAE process dynamics cause mechanical loads on the die tooling that reduce die tooling lifetime [1-2, 4, 6-19, 21-23].

The major experimental studies have been focused on the structural changes within the workpiece material volume during ECAE. Most analytical computational estimations for accumulated plastic shear do not take into account the strain hardening of the workpiece material. At the same time numerical finite simulation data are visualized by FEM software in the form of colorful diagrams [2-3, 9, 12-13, 16, 20, 22-24]. Generalization of such FEM derived distributions requires additional interpretation and computations for the estimation of averaged numerical values for 2D or 3D distributed parameters due to complexity with visual generalization of computational 2D or 3D colorful diagrams [2-3, 9, 12-13, 16, 20, 22-24].

Taking into account all above-stated reasons Medeiros et al. (2010, 2012) [6-7, 22] have applied the methods of experimental design for generalization of the upper bound solutions, derived by Pérez (2004) [10] and Pérez & Luri (2008) [11]. However, there are no formula expressions in the works [6-7, 22] for predicted results derived with experimental planning techniques. This fact essentially reduces the general nature of the regression formulae by Medeiros et al. (2010, 2012) [6-7, 22]. Perig et al. (2013) [12] have derived regression formulae for frictionless flow of a copper workpiece of the length L through an angular die with channel intersection angle $2\theta = 90^\circ$ with external R and internal r radii. However, the work [12] deals only with an angular die where $2\theta = 90^\circ$ and needs further generalizations for $2\theta > 0^\circ$.

Suo et al. (2008) have studied the influence of workpiece diameter on strain unevenness during ECAE [23]. The computational study of work [23] is based on an Abaqus 3D FEM simulation of metal workpiece flow through an angular die with channel intersection angle $2\theta = 120^\circ$ and external rounding R. However, the article [23] contains only 4 FEM computations for different workpiece diameters that reduce the general character of the derived numerical results.

Nonferrous metals are the most commonly used materials for physical and numerical simulation of metal forming and SPD processes [1-2, 4, 6-23] in comparison with ferrous metals [1-2, 3, 5, 8, 21, 24]. E.g., Medeiros et al. (2010, 2012) [6-7, 22] have used aluminum materials for ECAE processes modeling. Laptev et al. (2014) [4] and Perig et al. (2013-2015) [12-17] have addressed the simulation of copper workpieces flow during ECAE. This tendency of nonferrous metals usage for SPD working is assumed by high sensitivity of these materials to SPD forming [1-2, 4, 6-23]. Moreover, the widespread usage of nonferrous metals in SPD [1-2, 4, 6-23] is often preferable for die tooling life enhancement.

The object of the present research is the process of angular extrusion of a metal workpiece through a 2θ

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angular die. The subject of this research is focused on the main trends of ECAE frictionless flow of copper workpieces through *2θ* angular dies with external and internal radii in the channel intersection zone.

The aim of the present work is the derivation of power regression expressions for strain intensities, strain unevenness and waste fore part of workpiece in the case of frictionless plastic flow of copper workpiece with the length *L* through angular *2θ*-die with channel intersection angle $2\theta > 0^\circ$ with external *R* and internal *r* radii (Figure 1).

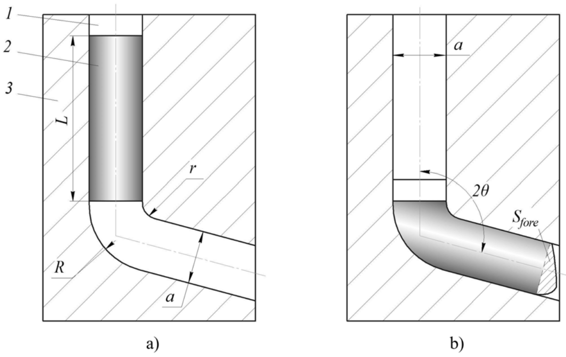

Figure 1. Initial (a) and final (b) positions of workpiece in 2θ ECAE die, where 1 is inlet channel; 2 is workpiece, and 3 is ECAE die

The primary novelty of this research is the derivation of numerical values for regression coefficients of power regression models for strain intensities, strain unevenness and waste fore part of workpieces in the case of 125 FEM QForm 2D computations for the angular ECAE dies for the range of channel intersection angles $60^\circ \leq 2\theta \leq 135^\circ$, external and internal die dimensionless radii $0.028 \leq R/a;\ r/a \leq 1.977$; and dimensionless workpiece lengths $5.226 \leq L/a \leq 16.836$.

2. GEOMETRIC ANALYSIS TECHNIQUE FOR PROCESSING OF FEM DERIVED COMPUTATIONAL EXPERIMENTS

The general trends of ECAE flow through 2θ angular dies (Figure 1) have been numerically studied (Figure 2) for copper workpiece extrusion with QForm 2D version 4.3.3 commercial code (license DSEA N U1221). However, the QForm software generated only strain distribution diagrams in Figure 2 without the computation of averaged values for strain intensities.

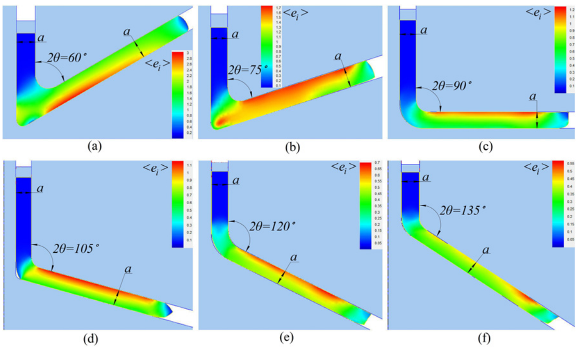

Figure 2. QForm derived strain intensities diagrams for copper workpieces in ECAE dies with channel intersection angles 2θ = 60˚ (a), 2θ = 75˚ (b), 2θ = 90˚ (c), 2θ = 105˚ (d), 2θ = 120˚ (e), 2θ = 135˚ (f)

So for averaging of computational results the following geometrical analysis technique has been applied (Figure 3):

$$\langle e_i \rangle = \frac{1}{S} \sum_{k=1}^{n} \left(\left(\langle e_i \rangle_k \right) \cdot S_k \right), \qquad (1)$$

where *k* is summation variable; *n* is the number of partition regions for workpiece area; S_k is the area of current partition region; $<e_i>_k$ is the average strain intensity within the current partition region; *S* is the workpiece area (Figure 3).

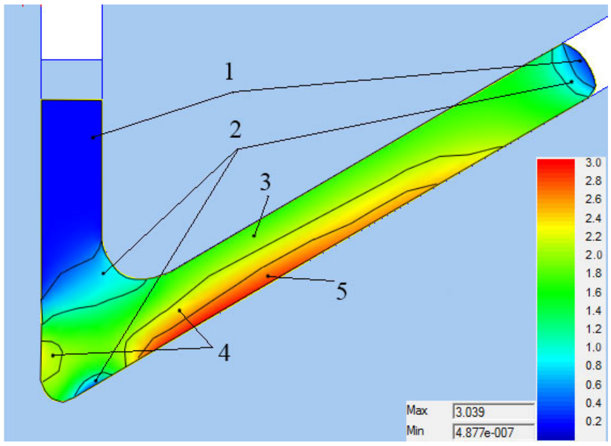

Figure 3. Partitioning scheme for workpiece FEM model in 2θ ECAE die, where isochromatic regions 1…5 are conditional partition equal strain zones

3. REGRESSION ANALYSIS OF STRAIN INTENSITY

The statistical generalization of 125 FEM QForm 2D computations for the angular ECAE dies for the range of channel intersection angles $60^\circ \leq 2\theta \leq 135^\circ$, external and internal die dimensionless radii $0.028 \leq R/a;\ r/a \leq 1.977$; and dimensionless workpiece lengths $5.226 \leq L/a \leq 16.836$ in Figures 1 – 3 yields the following non-linear regression for strain intensities (Figure 4):

$$\langle e_i \rangle = a_0 \cdot (2\theta)^{a1} \cdot \left(\frac{R}{a}\right)^{a2} \cdot \left(\frac{r}{a}\right)^{a3} \cdot \left(\frac{L}{a}\right)^{a4}, \qquad (2)$$

where $a_0 = 0.44736$; $a_1 = -1.62269$; $a_2 = -0.19621$; $a_3 = -0.07654$; and $a_4 = 0.41587$.

4. REGRESSION ANALYSIS OF STRAIN UNEVENNESS

The statistical generalization of 125 FEM QForm 2D computations for the angular ECAE dies for the range of channel intersection angles $60^\circ \leq 2\theta \leq 135^\circ$, external and internal die dimensionless radii $0.028 \leq R/a;\ r/a \leq 1.977$; and dimensionless workpiece lengths $5.226 \leq L/a \leq 16.836$ in Figures 1 – 3 yields the following non-linear regression for strain unevenness (Figure 5):

$$\langle e_{SU} \rangle = a_0 \cdot (2\theta)^{a1} \cdot \left(\frac{R}{a}\right)^{a2} \cdot \left(\frac{r}{a}\right)^{a3} \cdot \left(\frac{L}{a}\right)^{a4} \qquad (3)$$

where $a_0 = 1.9278$; $a_1 = -0.6378$; $a_2 = -0.0455$; $a_3 = 0.1343$; and $a_4 = -0.3197$ (Figure 5).

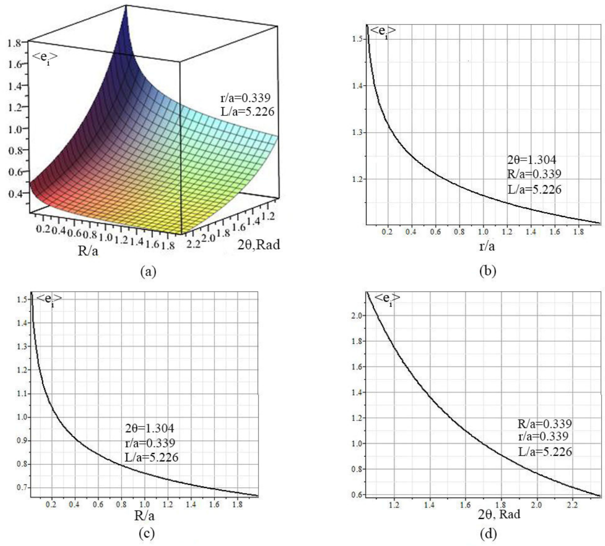

Figure 4. Computational dependences of strain intensity on die geometry parameters: $\langle e_i\rangle$ = f(2θ, *R/a*) (a); $\langle e_i\rangle$ = f(*r/a*) (b); $\langle e_i\rangle$ = f(*R/a*) (c); $\langle e_i\rangle$ = f(2θ) (d), where the dimensionless workpiece length is *L/a* = 5.226 (——)

Graphical plots in Figure 5 show the reduction of strain unevenness with increase of channel intersection angle Figure 5(a, d), increase of workpiece length Figure 5(a-d), and increase of external die radius *R/a* Figure 5(c). Graphical plot in Figure 5(b) shows the increase of strain unevenness with reduction of internal die radius *r/a*.

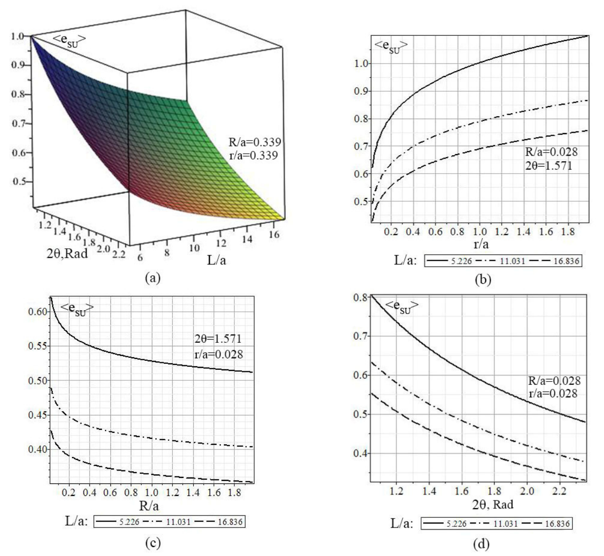

Figure 5. Computational dependences of strain unevenness on die geometry parameters: $\langle e_{SU}\rangle$ = f(2θ, *L/a*) (a); $\langle e_{SU}\rangle$ = f(*r/a*) (b); $\langle e_{SU}\rangle$ = f(*R/a*) (c); $\langle e_{SU}\rangle$ = f(2θ) (d), where the dimensionless workpiece lengths are as follows: *L/a* = 5.226 (——); *L/a* = 11.031 (– · –); *L/a* = 16.836 (— —)

5. MATERIAL WASTE ESTIMATION FOR 2θ DIE

The statistical generalization of 125 FEM QForm 2D computations for the angular ECAE dies for the range of channel intersection angles $60^\circ \le 2\theta \le 135^\circ$, external and internal die dimensionless radii $0.028 \le R/a$; $r/a \le 1.977$; and dimensionless workpiece lengths $5.226 \le L/a \le 16.836$ in Figures 1 – 3 yields the following non-linear regression for relative area of workpiece waste fore part (Figure 6):

$$\frac{S_f}{S} = a_0 \cdot (2\theta)^{a_1} \cdot \left(\frac{R}{a}\right)^{a_2} \cdot \left(\frac{r}{a}\right)^{a_3} \cdot \left(\frac{L}{a}\right)^{a_4}, \quad (4)$$

where $a_0 = 0.2201$; $a_1 = 0.6639$; $a_2 = 0.0667$; $a_3 = -0.0593$; and $a_4 = -0.8656$ (Figure 6).

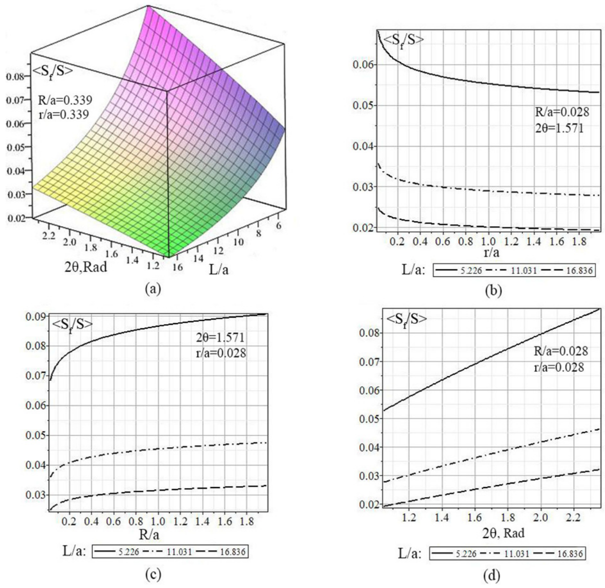

Figure 6. Computational dependences of relative area of workpiece waste fore part on die geometry parameters: $\langle S_f/S\rangle$ = f(2θ, *L/a*) (a); $\langle S_f/S\rangle$ = f(*r/a*) (b); $\langle S_f/S\rangle$ = f(*R/a*) (c); $\langle S_f/S\rangle$ = f(2θ) (d), where the dimensionless workpiece lengths are as follows: *L/a* = 5.226 (——); *L/a* = 11.031 (– · –); *L/a* = 16.836 (— —)

Graphical plots in Figure 6 show the reduction of relative area of workpiece waste fore part $\langle S_f/S\rangle$ with increase of workpiece length *L/a* and increase of internal die radius *r/a* in Figure 6(b).

6. DISCUSSION OF DERIVED RESULTS

Let's compare derived results with known publications in SPD field using formula (5):

$$\delta = \frac{1}{2}\left(\frac{\left|\langle e_i\rangle - (e_i)_{pub}\right|}{\langle e_i\rangle} + \frac{\left|\langle e_i\rangle - (e_i)_{pub}\right|}{(e_i)_{pub}}\right) \cdot 100\%. \quad (5)$$

Laptev et al. (2014) have studied plastic flow of a metal workpiece model without taking into account the workpiece length [4]. We have $m = 0$ for frictionless flow in formula (4) of the work [4]. The formula (4) in [4] for $m = 0$ yields a dead zone height $x = 0$. So the total shear during frictionless ECAE is $\gamma_s = 2$ (according to formula (8) of [4] and Figure 4b of [4]), and the total equivalent plastic strain is $\gamma_s/(3^{0.5}) = 2/(3^{0.5}) = 1.155$. For this case the derived regression formula for strain intensity gives 1.131 for die radii $R = r = 1$ mm. So the relative discrepancy of computational results is $\delta = 2.1$ % as it follows from equation (5).

Medeiros et al. (2010) in Figure 7 at p. 2839 of [7], and at p. 2841 of [7] outline that for an angular die with channel intersection angle $2\theta = 60^\circ$ and $R = r$ the effective plastic strain is 2.0. For this case, the derived regression formula for strain intensity yields 2.185 for die radii $R = r = 1$ mm.

Suo et al. (2008) have shown that strain unevenness increases with an increase of workpiece diameter [23]. The authors of [23] performed their computations for workpiece length $L = 5d$ [23]. So the increase in workpiece diameter d in [23] causes an increase in workpiece length L as well. It allows us to make the conclusion that strain unevenness also increases with increased workpiece length L that corresponds with our computational results (3) and Figure 5.

The derived result about the reduction of relative area of workpiece waste fore part $\langle S_f/S \rangle$ with increase of workpiece length L/a (formula (4) and Figure 6) numerically confirms the well-known experimental trend about ECAE processing of longer workpieces for technological waste reduction.

7. CONCLUSIONS

The non-linear four-parametric power regressions for strain intensities, strain unevenness and waste fore part of copper workpieces have been derived in the case of 125 FEM QForm 2D computations for angular ECAE dies with a range of channel intersection angles $60^{\circ} \leq 2\theta \leq 135^{\circ}$, external and internal die dimensionless radii $0.028 \leq R/a$; $r/a \leq 1.977$; and dimensionless workpiece lengths $5.226 \leq L/a \leq 16.836$.

The derived regression results provide the numerical illustration of known experimental facts and in this way supply a better understanding of ECAE SPD forming schemes for copper workpieces processing through 2θ angular dies. This research will have further generalizations which will take into account the contact friction between the workpiece and the die walls.

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LIST OF ACRONYMS

ECAE	Equal Channel Angular Extrusion
SPD	Severe Plastic Deformation
FEM	Finite Element Method

NOMENCLATURE

2θ	Channel intersection angle of ECAE die
a	Dimensional channel width
L	Dimensional workpiece length
R	Dimensional external radius of ECAE die
r	Dimensional internal radius of ECAE die
S	Dimensional area of workpiece model
S_f	Dimensional area of waste fore part of workpiece model
L/a	Dimensionless workpiece length
R/a	Dimensionless external radius of ECAE die
r/a	Dimensionless internal radius of ECAE die
$a_0 \ldots a_4$	Coefficients of nonlinear regression
$<e_i>$	Dimensionless average strain intensity
$<e_{SU}>$	Dimensionless average strain unevenness
$<S_f/S>$	Dimensionless average area of waste fore part of workpiece model
γ_s	Dimensionless total accumulated plastic shear, acquired after one pass of ECAE
δ	Dimensionless disagreement of results

РЕГРЕСИОНА АНАЛИЗА ДЕФОРМАЦИЈЕ ЗАСНОВАНА НА ФЕМ МЕТОДИ КОД ПРИМЕНЕ ЈЕДНОЛИЧНОГ УГАОНОГ ПРЕСОВАЊА (ЕЦАЕ)

А.В. Периг, И.А. Матвејев

Рад има за циљ да изврши генерализацију базирану на регресионој анализи резултата ФЕМ симулације, добијених применом QForm 2D FEM софтвера при симулацији протока бакарних обрадака кроз 20 угаоних калупа са спољашњим и унутрашњим полупречником у зони пресека канала и ширином улазних и излазних канала калупа a = 35,4 мм. Регресионе зависности снаге код ЕЦАЕ напрезања, неравномерног напрезања и шкарта са предње површине обратка изведене су за 125 случајева симулације код угаоног канала при различитим вредностима пресецања углова $65^0 \leq 20^0 \leq 135^0$, унутрашњег и спољашњег пречника калупа без димензија 0,028 ≤ R/a; r/a ≤ 1,977 и дужине обратка без димензија 5,226 ≤ L/a ≤ 16,836. Утврђено је добро слагање између резултата добијених прорачуном и објављених резултата добијених експериментом и прорачуном за напрезање и равномерност напрезања. Резултати добијени регресионом анализом доприносе бољем разумевању утицаја генерализоване геометрије ЕЦАЕ и дужине обратка у условима притиска на радном предмету од бакра.