Iranian Journal of Materials Forming 7 (2) (2020) 26-31

IJMF

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

Research article

Analysis of Strain Inhomogeneity in Vortex Extrusion using Finite Element Method and Response Surface Methodology

G. Ranjbari[1], A. Doniavi[1] and M. Shahbaz[2*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Urmia University, Urmia, Iran
[2] Department of Materials Science and Engineering, Faculty of Engineering, Urmia University, Urmia, Iran

ARTICLE INFO

Article history:

Received 15 July 2020
Revised 7 August 2020
Accepted 17 August 2020

Keywords:

Vortex extrusion
Response surface methodology
Finite element analysis
Strain inhomogeneity

ABSTRACT

The effect of geometrical parameters involved in vortex extrusion (VE) die design, on AA1050 aluminium alloy processed by VE were investigated using finite element analysis (FEA) and response surface methodology (RSM). For this, VE die length (L), reduction in area (RA), twist angle (φ), and position of control points in Beziers' formulation (C_1) were considered as input parameters and strain inhomogeneity was considered as a response. Both standard deviation (S.D) and inhomogeneity index (C_i) were used to quantify the strain inhomogeneity from FEA results. Analysis of variance (ANOVA) was used to determine the significant parameters and to mathematically model the strain inhomogeneity. It was concluded that standard deviation (S.D) is not a good choice for examining the strain inhomogeneity distribution in VE technique. ANOVA results showed that φ, RA, and interaction between φ and RA are the most significant parameters affecting the strain inhomogeneity.

1. Introduction

Over the last decades, ultrafine grained materials (UFG), with grain size less than 1 μm, have been used extensively due to their unique combination of high strength and ductility which is obtained by imposing a high amount of plastic strain on the bulk material through using severe plastic deformation (SPD) techniques [1-3]. Among SPD techniques some are torsion based, including: high pressure torsion (HPT) [4], twist extrusion (TE) [5, 6], off-axis twist extrusion [7], vortex extrusion (VE) [8], and rectangular vortex extrusion (RVE) [9]. Vortex extrusion is a promising SPD technique that benefits from a specially designed die (Fig. 1) which is composed of three different zones namely; zone I (first transition zone), zone II (twist zone), and zone III (second transition zone). As shown in Fig. 1, material is twisted through passing the converging die, that simultaneous twist and reduction in area in a single die introduces the additional deformation mechanism in VE process compared to conventional extrusion (CE) process [10]. However, the amount and distribution of effective strain resulted from this additional deformation mode are caused due to designed indents inside of the VE die and are affected by the geometrical parameters of VE dies. A streamline approach based on Beziers' formulation was used to mathematically model the materials flow in the VE die [11]. The proposed model was used to VE die design, finite element analysis (FEA) and developing the power losses terms in upper-bound analysis to investigate the effective strain distribution and load of VE process [11, 12]. Effects of geometrical parameters including; length of the twist zone (L), twist angle (φ), position of control points in Beziers' formulation (C_1 and C_2 that; $0 \leq C_1 \ll 1$ and $C_1+C_2=1$), and reduction in area (RA) were investigated in different frictional conditions (constant friction factor m=0 and m=0.1) using response surface methodology (RSM) and FEA. Results were used to

*Corresponding author
E-mail address: m.shahbaz@urmia.ac.ir (M. Shahbaz)

mathematically model the efficient twist of the material and the process load and it was shown that, there is a good agreement between the results from FEA with those predicted from developed mathematical models [13]. Strain inhomogeneity and process load of severely deformed AL-Mg-Si alloy by VE process were investigated using RSM and FEA. Twist angle (φ), reduction in area (RA), and interaction of twist angle and reduction in area ($\varphi \times RA$) were determined as the most effective parameters affecting strain inhomogeneity, while the processing parameters of φ, RA, and the interactions of $\varphi \times RA$, $\varphi \times \varphi$ and $RA \times RA$ are the most effective parameters on the load of VE process [14].

In this study the effect of the geometrical parameters of VE die (Table 1), as input parameters, on the strain inhomogeneity of severely deformed Al1050 aluminium alloy, as a response, was investigated using FEA and RSM. For this, VE dies were designed for RSM proposed runs (Table 2) and then were considered for FEA. The strain inhomogeneity of individual runs was calculated from FEA results using; inhomogeneity index (C_i) and standard deviation (S.D), Eqs. 1 and 2, respectively, as follows:

$$C_i = \frac{\varepsilon_{max} - \varepsilon_{min}}{\varepsilon_{avg}} \quad (1)$$

$$\text{S.D}=\sqrt{\frac{\sum_{i=1}^{n}(\varepsilon_i-\varepsilon_{avg})^2}{n}} \quad (2)$$

where; ε_i, ε_{max}, ε_{min} and ε_{avg} are the through radius of product, maximum, minimum and average effective strain, respectively, and n is the number of measured effective strain through radius of product.

Finally, analysis of variance (ANOVA) was used for RSM results for the purpose of mathematically modelling the effective strain inhomogeneity.

2. Response Surface Methodology (RSM)

In this study, RSM central composite design (CCD) was used to plan the experiments based on four input parameters in five levels (Table 1) using design expert V.11 software [15]. A total of 30 experimental conditions (24 separate experiments with 6 repetitions of the central point) were planned for frictional condition of m=0.1 (μ=0.047 [16]) as shown in Table 2. The multiple regression model was used to develop mathematical equation for responses. Analysis of variance (ANOVA) was used to evaluate the accuracy of mathematical model and detecting the significant terms by evaluating with p-value lower than 0.05. The lack-of-fit higher than 0.1 was considered for insignificant parameters. It should be noted that A, B, C and D in Tables 1-3 were used for simplicity and ease of indicating interactions of input factors by design expert software.

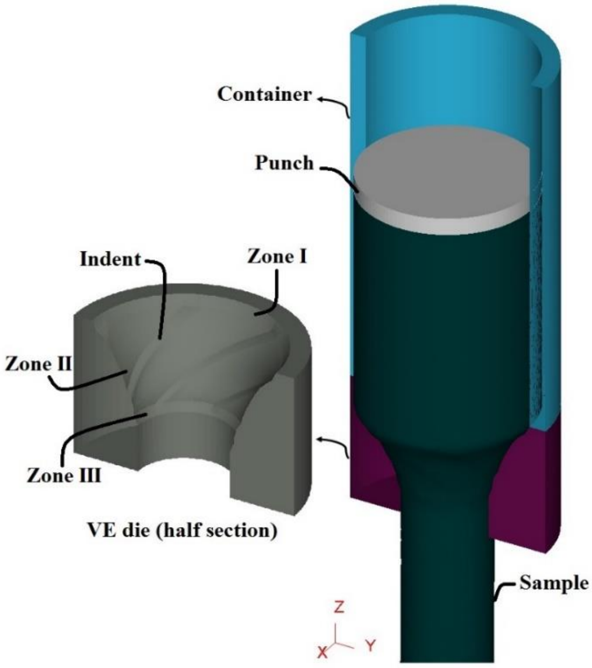

Fig. 1. Schematic dies assembly for FEA (right) and half section of VE die (left).

Table 1. Processing parameters and their levels

A: Twist angle (φ)	0.00	22.5	45.0	67.5	90.0
B: Reduction in area (RA)	0.1	0.3	0.5	0.7	0.9
C: Length of twist zone(L)	5.0	7.5	10	12.5	15
D: Control points position in Beziers' curve(C_1)	0.1	0.2	0.3	0.4	0.5

3. Finite Element Simulation

Simulations were carried out using commercial Deform-3D V.11 [17] software for all RSM planned experiments. The mathematical model based on Beziers' formulation for material flow in VE method (Eq. (3)) [11] was used to design VE die for each of the 30 planned experiments. VE die, punch and container were assumed to be rigid bodies and the stress-strain relation $\sigma = \sigma_0 + \sigma_1 \left[1 - \exp(\frac{-\varepsilon^n}{\varepsilon_c})\right]$ of an aluminium alloy with numerical constants reported in [18] was used for the deformable AA1050 sample. The work-piece was assumed to be plastic having cylindrical shape with 20 *mm* diameter and 40 *mm* height and was meshed with tetrahedral element with a total number of 55000 based on the mesh convergence criterion. Automatic remeshing was considered to accommodate large deformation in the analyses. The punch, was considered as a rigid cylinder with a 20 *mm* diameter and 2 *mm* height that extruded the work-piece with a ram speed of 0.2 *mm/s*. The value of 0.1 was selected as a constant friction factor for all simulations. All analyses were performed at room temperature.

$$\vec{\gamma} = \overrightarrow{\gamma(t)} = (1-t)^3\overrightarrow{r_0} + 3t(1-t)^2\overrightarrow{r_1} + 3t^2(1-t)\overrightarrow{r_2} + t^3\overrightarrow{r_3} \quad (3)$$

where; $\vec{\gamma}$ is the vector equation of the streamline with $\overrightarrow{r_0}$, $\overrightarrow{r_1}$, $\overrightarrow{r_2}$, and $\overrightarrow{r_3}$ as the position vectors of four control points [11].

Table 2. Experimental design matrix and response values of processed AA1050 for *m*=0.1

Run	Input parameters				Responses	
	A: Twist angle(φ)	B: Reduction in Area (*RA*)	C: Length (L)	D: Control points position in Beziers' curve(C_1)	Standard Deviation (S.D.)	strain Inhomogeneity(C_i)
1	67.5	0.3	12.5	0.2	0.53	3.13
2	45.0	0.5	10.0	0.5	0.39	0.95
3	67.5	0.3	12.5	0.4	0.45	2.03
4	22.5	0.7	7.5	0.2	0.45	0.80
5	67.5	0.7	7.5	0.2	0.60	0.98
6	67.5	0.3	7.5	0.4	0.60	2.50
7	67.5	0.7	12.5	0.2	0.28	0.67
8	90.0	0.5	10.0	0.3	0.67	1.90
9	45.0	0.5	5.0	0.3	0.69	1.57
10	45.0	0.5	10.0	0.3	0.46	1.24
11	0.0	0.5	10.0	0.3	0.19	0.76
12	67.5	0.3	7.5	0.2	0.56	2.51
13	22.5	0.7	12.5	0.4	0.36	0.69
14	45.0	0.5	10.0	0.3	0.46	1.24
15	45.0	0.5	15.0	0.3	0.32	0.87
16	22.5	0.3	12.5	0.4	0.28	1.08
17	45.0	0.5	10.0	0.3	0.46	1.24
18	45.0	0.9	10.0	0.3	0.21	0.16
19	22.5	0.3	7.5	0.2	0.31	1.30
20	22.5	0.7	7.5	0.4	0.47	0.66
21	45.0	0.5	10.0	0.1	0.39	1.02
22	22.5	0.7	12.5	0.2	0.31	0.55
23	45.0	0.5	10.0	0.3	0.46	1.24
24	45.0	0.1	10.0	0.3	0.36	3.47
25	22.5	0.3	12.5	0.2	0.28	1.10
26	45.0	0.5	10.0	0.3	0.46	1.24
27	67.5	0.7	7.5	0.4	0.56	0.86
28	22.5	0.3	7.5	0.4	0.34	1.25
29	45.0	0.5	10.0	0.3	0.46	1.24
30	67.5	0.7	12.5	0.4	0.40	0.67

4. Results and Discussion

Table 3 shows the analysis of variance (ANOVA) results. In table 3, F value indicates whether the variance between the means of two populations is significantly different or not, that, the larger the F value, the greater the relative variance among the group means. The p value, the probability that a result happened by chance, is compared to a predetermined significance level, which is 0.05 (by default). If the p value of individual factor is less than 0.05, the factor is considered to be significant [19]. The results of table 3 show that the model is significant. Also, it is shown that the process parameters of the twist angle (φ denoted by A), reduction in area (*RA* denoted by B) and interaction of twist angle and reduction in area ($\varphi \times RA$ denoted by AB) are significant parameters affecting the inhomogeneity index (C_i) as well as the length of the twist zone (*L* denoted by C) which is not considered as an effective parameter in this case. On the other hand, the ANOVA results for S.D show that the process parameters of φ, L, interaction between φ and RA, interaction between RA and L ($RA \times L$ denoted by BC) and interaction of RA with RA ($RA \times RA$ denoted by B^2), are the most significant parameters. Figure 2 represents the effect of reduction in area (*RA*), twist zone length and twist angle on the maximum, average, and minimum effective strains. It can be seen that, increasing the reduction in area from 0.3 to 0.7 leads to an increase in effective strain values (maximum, average and minimum), however these values are almost similar in different twist zone lengths. Results are in good agreement with those published in Ref. [13]. So, it can be claimed that the influence of reduction in area (*RA*) is greater than the length of the twist zone (L) on strain distribution. Also, ccomparison of the maximum and minimum effective strain difference ratio for different *RA* ($\frac{(\varepsilon_{max}-\varepsilon_{min})|_{RA=0.7}}{(\varepsilon_{max}-\varepsilon_{min})|_{RA=0.3}}$) in conventional extrusion (CE) and VE shows that, its value for VE is lower than that for CE (Fig. 2), which is due to the torsional deformation mode and velocity differences between material elements at the surface and the centre of VE processed sample and its effect on minimum effective strain at the centre of ample [10]. For these reasons, inhomogeneity index (C_i) can model strain inhomogeneity better than standard deviation (S.D). The mathematical relationship between input factors and inhomogeneity index (C_i) is presented in the form of multiple regression equations for frictional condition of *m*=0.1 according to Eq. 4 as depicted below:

$$\textbf{Strain inhomogeneity } (C_i) = +0.655874 + 0.056622 \times \varphi - 0.562077 \times RA + 0.029297 \times L + 0.789718 \times C_1 - 0.068634 \times \varphi \times RA + 0.000256 \times \varphi \times L - 0.032312 \times \varphi \times C_1 - 0.062212 \times RA \times L + 3.37780 \times RA \times C_1 - 0.161706 \times L \times C_1 \quad (4)$$

Table 3. ANOVA results for the processed AA1050 by VE to identify significant factors in strain inhomogeneity

Source	m=0.1			
	Strain inhomogeneity(C_i)		Standard Deviation (S.D.)	
	F-value	**p-value**	**F-value**	**p-value**
Model	17.26	< 0.0001	11.23	< 0.0001
A: (φ)	44.12	< 0.0001	70.06	< 0.0001
B: (RA)	117.09	< 0.0001	0.76	0.3978
C: (L)	2.01	0.1727	47.13	< 0.0001
D: (C_1)	1.46	0.2417	0.40	0.5389
AB: (φ × RA)	17.52	0.0005	9.85	0.0068
AC:(φ × L)	0.04	0.8476	2.23	0.1561
AD: (φ × C_1)	0.97	0.3368	0.07	0.7970
BC: (RA× L)	0.18	0.6781	4.91	0.0426
BD: (RA×C_1)	0.84	0.3713	0.53	0.4789
CD: (L× C_1)	0.30	0.5901	0.08	0.7818
A^2: (φ × φ)	-------	--------	0.12	0.7393
B^2: (RA×RA)	-------	--------	15.87	0.0012
C^2: (L×L)	-------	--------	2.02	0.1753
D^2: (C_1× C_1)	-------	--------	2.14	0.1637

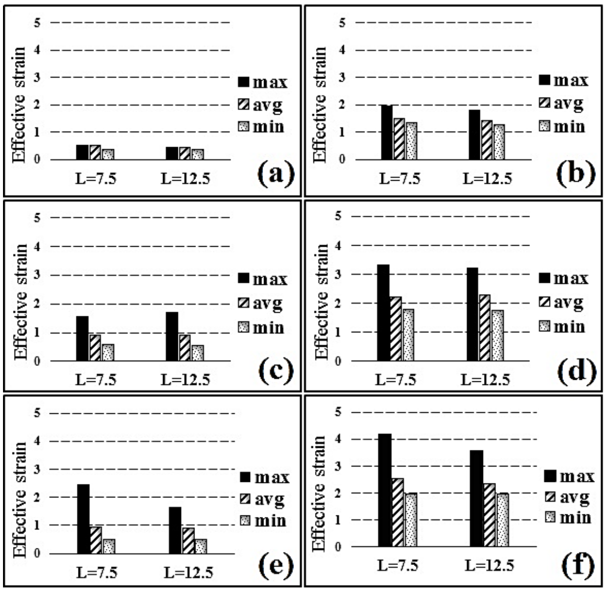

Fig. 2. Effect of twist angle, twist zone length and reduction in area on the maximum, average, and minimum effective strain in VE process with C_1=0.4 and (a) $\varphi = 0$, *RA*=0.3, (b) $\varphi = 0$, RA=0.7, (c) φ =22.5°, *RA*=0.3, (d) φ =22.5°, *RA*=0.7, (e) φ =67.5°, RA=0.3, and (f) φ =67.5°, *RA*=0.7.

Figure 3 shows the effect of twist angle (φ), reduction in area (*RA*), length of twist zone (L) and position of control points in Beziers' formulation (C_1) as input factors and their interactions on strain inhomogeneity index (C_i). Comparison the curvature of surface plots of Fig. 3 shows that there is an interaction between twist angle and reduction in area which is in good agreement with ANOVA results. As shown in Fig. 3(a) increasing the twist angle increases the effective strain inhomogeneity. However, the effect of increasing *RA* on C_i depends on the twist angle. That is because of vortex like flow of material in VE, which arises from synergetic effect of simultaneous reduction in area and twist angle [10, 20]. Vortex like flow and the suggested mathematical model for materials flow in VE by Beziers' formulation makes; (i) the surface elements twisted more than the central elements, and (ii) the materials element at the surface pass the longer distance than those at the center of sample. All these, cause velocity differences between the material elements at the surface and the center of processed sample by VE in comparison to what is seen in the CE technique [10]. So, increasing the twist angle at higher reduction in area will increase the $\bar{\varepsilon}_{min}$ (compare Figs. 2(b), 2(d) and 2(f)), which will decrease the effective strain inhomogeneity (C_i) (Fig. 3(a)). Figure 3(b) shows that the effect of twist angle on the C_i is similar in all twist zone length that shows no interaction between L and φ and confirms the ANOVA results. Considering Figs. 3(c)-3(f) show no interaction between C_1 and φ, L and *RA*, C_1 and *RA*, and C_1 and L, respectively which are in good agreement with results obtained from ANOVA.

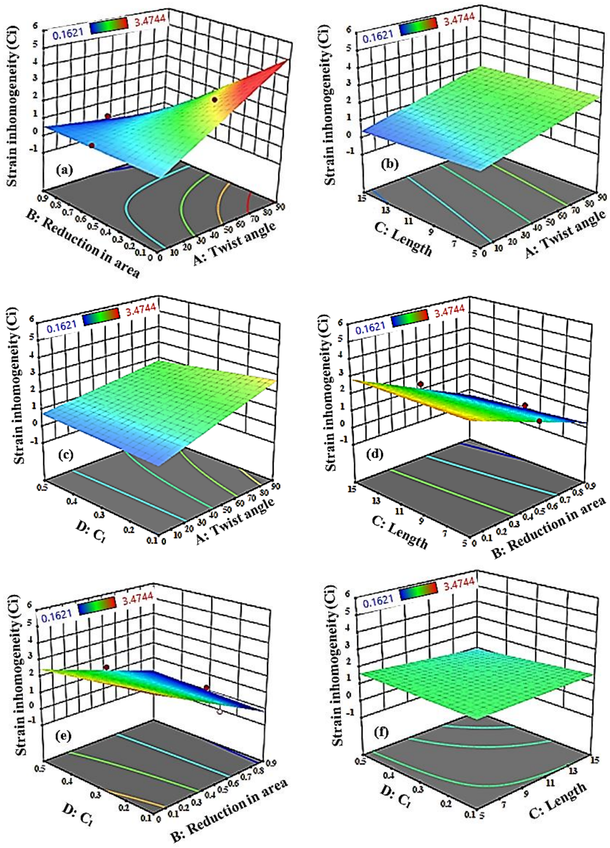

Fig. 3. Surface plots of effect of input parameters on the strain inhomogeneity (C_i) in VE for *m*=0.1.

5. Conclusions

In this study 30 runs for VE dies with different twist angle (φ), reduction in area (RA), length of twist zone (L) and position of control points in Beziers' formulation (C_1), were designed and analyzed by response surface methodology (RSM). Finite element analysis was done for individual runs and strain inhomogeneity, finally calculated results were considered for analysis of variance (ANOVA). The influences of geometrical factors involved in VE die design on strain inhomogeneity were analyzed via two parameters namely, inhomogeneity index (C_i) and standard deviation (S.D). The following conclusions can be drawn:

- Results of ANOVA showed that the mathematical model proposed by RSM is significant and the process parameters of twist angle (φ), reduction in area (RA) and interaction of twist angle and reduction in area ($\varphi \times RA$) have deeper impacts on inhomogeneity index (C_i) while others are less significant in this regard.
- Considering that the decreasing of reduction in area (RA) causes higher strain heterogeneity, standard deviation (S.D) is not a suitable candidate to quantify the strain inhomogeneity. On the other hand, standard deviation (S.D) shows that the length of the twist zone (L) is a significant factor on strain inhomogeneity. However, Comparison of the simulation results showed that the variation of twist length has almost no effect on maximum, average and minimum effective strain values.
- For VE process of AA1050 in frictional condition of m=0.1, the magnitude of C_i increases by increasing the twist angle (φ) and decreasing the reduction in area (RA).

6. References

[1] E. Bagherpour, N. Pardis, M. Reihanian, R. Ebrahimi, An overview on severe plastic deformation: research status, techniques classification, microstructure evolution, and applications, *The International Journal of Advanced Manufacturing Technology* 100 (2019) 1647-1694.

[2] E. Bagherpour, M. Reihanian, N. Pardis, R. Ebrahimi, T.G. Langdon, Ten years of severe plastic deformation (SPD) in Iran, part I: equal channel angular pressing (ECAP), *Iranian Journal of Materials Forming* 5 (2018) 71-113.

[3] M. Reihanian, E. Bagherpour, N. Pardis, R. Ebrahimi, Nobuhiro Tsuji, Ten years of severe plastic deformation (SPD) in Iran, part II: accumulative roll bonding (ARB), *Iranian Journal of Materials Forming* 5 (2018) 1-25.

[4] A. P. Zhilyaev, T. G. Langdon, Using high-pressure torsion for metal processing: fundamentals and applications, *Progress in Materials Science* 53 (2008) 893-979.

[5] Y. Beygelzimer, V. Varyukhin, S. Synkov, D. Orlov, Useful properties of twist extrusion, *Materials Science and Engineering A* 503 (2009) 14-17.

[6] M. I. Latypov, I. V. Alexandrov, Y. E. Beygelzimer, S. Lee, H. S. Kim, Finite element analysis of plastic deformation in twist extrusion, *Computational Materials Science*: 60 (2012) 194-200.

[7] Y. Beygelzimer, R. Kulagin, M. I. Latypov, V. Varyukhin, H. S. Kim, Off-axis twist extrusion for uniform processing of round bars, *Metals and Materials International* 21 (2015) 734-740.

[8] M. Shahbaz, N. Pardis, R. Ebrahimi, B. Talebanpour, A novel single pass severe plastic deformation technique: Vortex extrusion, *Materials Science and Engineering A* 530 (2011)469-472.

[9] H. Ataei, M. Shahbaz, H. S. Kim, N. Pardis, Finite element analysis of severe plastic deformation by rectangular vortex extrusion (RVE), *Metals and Materials International* (2020).

[10] M. Shahbaz, N. Pardis, J. G. Kim, R. Ebrahimi, H. S. Kim, Experimental and finite element analyses of plastic deformation behavior in vortex extrusion, *Materials Science and Engineering A* 674 (2016) 472-479.

[11] M. Shahbaz, R. Ebrahimi, H. S. Kim, Streamline approach to die design and investigation of material flow during vortex extrusion process, *Applied Mathematical Modelling* 40 (2015) 3550-3560.

[12] M. Shahbaz, J. G. Kim, R. Ebrahimi, H. S. Kim, Prediction of extrusion pressure in vortex extrusion using a streamline approach, *Iranian Journal of Materials Forming* 4 (2017) 52-56.

[13] G. Ranjbari, A. Doniavi, M. Shahbaz, Numerical modelling and simulation of vortex extrusion as a severe plastic deformation technique using response surface methodology and finite element analysis, *Metals and Materials International*, in print, 7 (2020).

[14] G. Ranjbari, A. Doniavi, M. Shahbaz, R. Ebrahimi, Effect of processing parameters on the strain inhomogeneity and processing load in vortex extrusion of Al-Mg-Si alloy, *Metals and Materials International*, (2020).

[15] Design Expert 11, Stat-Ease, Inc.

[16] SH. Molaei, M. Shahbaz, R. Ebrahimi, The relationship between constant friction factor and coefficient of friction in metal forming using finite element analysis, *Iranian Journal of Materials Forming* 1 (2014) 14-22.

[17] DEFORM-3D V10, Scientific Forming Technologies Corporation (SFTC).

[18] N. Q. Chinh, G. Horváth, Z. Horita, T. G. Langdon, A new constitutive relationship for the homogeneous deformation of metals over a wide range of strain, *Acta Materialia* 52 (2004) 3555-3563.

[19] U. M. Iqbal, V. S. Kumar, S. Gopalakannan, Application of response surface methodology in optimizing the process parameters of twist extrusion process for AA6061-T6 aluminium alloy, *Measurement*, 94 (2016) 126-138.

[20] M. Shahbaz, N. Pardis, J. Moon, R. Ebrahimi, H. S. Kim, Microstructural and mechanical properties of the material processed by streamline proposed vortex extrusion, *Metals and Materials International*, (2020) Accepted.

آنالیز ناهمگنی کرنش در اکستروژن گردابی با استفاده از روش المان محدود و رویکرد سطح پاسخ

گوهر رنجبری[۱]، علی دنیوی[۱] و مهرداد شهباز[۲]

۱- گروه مهندسی مکانیک، دانشکده فنی و مهندسی، دانشگاه ارومیه، ارومیه، ایران.

۲- گروه مهندسی مواد، دانشکده فنی و مهندسی، دانشگاه ارومیه، ارومیه، ایران.

چکیـــده

در تحقیق حاضر با استفاده از آنالیز المان محدود و روش سطح پاسخ، تأثیر پارامترهای هندسی مطرح در طراحی قالب اکستروژن گردابی بر آلیاژ آلومینیوم ۱۰۵۰ تغییر شکل شدید یافته به روش اکستروژن گردابی مورد مطالعه قرار گرفت. برای این منظور، طول قالب (L)، کاهش سطح مقطع (*RA*)، زاویه پیچش (φ) و موقعیت نقاط کنترلی در معادله بزیر (C_1)، به عنوان پارامترهای ورودی و ناهمگنی کرنش به عنوان پاسخ در نظر گرفته شدند. برای محاسبه ناهمگنی کرنش از نتایج آنالیز المان محدود، از اندیس ناهمگنی (C_i) و انحراف معیار (SD) استفاده شد. از آنالیز واریانس برای تعیین پارامترهای مهم و مدلسازی ریاضی ناهمگنی کرنش استفاده شد. نتایج نشان داد که انحراف معیار برای تعیین ناهمگنی کرنش در روش اکستروژن گردابی گزینه مناسب نمی باشد. با استفاده از نتایج آنالیز واریانس؛ زاویه پیچش، کاهش سطح مقطع، و تداخل بین زاویه پیچش و کاهش سطح مقطع به عنوان پارامترهای بسیار مهم تأثیرگذار بر ناهمگنی کرنش تعیین گردیدند.

واژه‌های کلیدی: اکستروژن گردابی، روش سطح پاسخ، آنالیز المان محدود، ناهمگنی کرنش