Iranian Journal of Materials Forming 8 (3) (2021) 46-52

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

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

Research Article

Numerical Analysis of Plastic Strain Inhomogeneity in Rectangular Vortex Extrusion (RVE) Process

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ARTICLE INFO

Article history:

Received 18 May 2021
Reviewed 22 May 2021
Revised 19 June 2021
Accepted 7 July 2021

Keywords:

Severe plastic deformation
Rectangular vortex extrusion
Strain inhomogeneity
Finite element analysis
Response surface methodology

ABSTRACT

In this study, the effect of geometrical parameters of rectangular vortex extrusion die, including twist angle (φ), reduction in area (RA), and twist zone length (L), on deformation inhomogeneity is investigated using the finite element analysis and response surface methodology. Analysis of variance (ANOVA) was used to determine the primary parameters and accuracy of the mathematical model obtained from response surface methodology results. The results showed that the suggested mathematical model predicts the strain inhomogeneity with high accuracy. Additionally, it revealed that the input parameters of φ, RA, L, the interaction between φ and RA ($\varphi \times RA$), and interaction between RA and L ($RA \times L$) are the main significant factors affecting the inhomogeneity. Perturbation plots and 3D surface diagrams were used to check the results of ANOVA, the sign, and the magnitude of the coefficient of the suggested mathematical model.

1. Introduction

Rectangular vortex extrusion (RVE) is a new severe plastic deformation (SPD) process based on the simultaneous extrusion and twisting of workpiece material inside a die [1]. Considering the advantages of the vortex extrusion (VE) process for processing samples with circular cross-sectional areas [2-4], the RVE was developed for non-circular cross-sections.

Fig. 1 shows a schematic of the RVE die and geometrical parameters involved in its design. In this technique, reduction in area (RA) naturally provides the required back pressure (BP) to completely perform the process which is a significant concern in twist extrusion (TE) [5, 6]. This feature of the RVE process makes it unnecessary to use any additional facilities necessary for the TE process to generate the required BP. Indeed, BP has a significant effect on the plastic strain distribution in TE, and uniform distribution of plastic deformation can be obtained using a high amount of BP in frictionless conditions [7, 8]. Simultaneous use of RA and twist angle (φ) imposes a high amount of plastic strain in a single pass to the workpiece, which has a prominent effect on microstructural evolution and the processing cost [9, 10].

Inhomogeneity in plastic strain distribution from the center towards the surface of the sample processed

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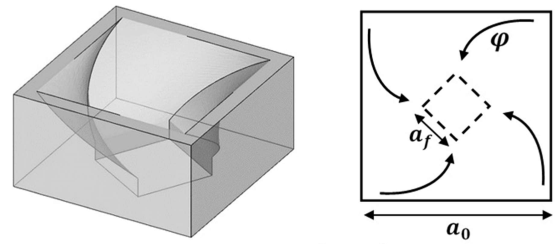
https://doi.org/10.22099/ijmf.2021.40696.1183

by SPD techniques has been investigated in some research works [11-15]. The effect of different routes of the TE process on the inhomogeneous deformation and mechanical properties of SPD commercial pure copper was investigated by Eivani et al. [16]. It was shown that the resulted microstructure in route A of TE is more homogeneous than that in route D. In addition, the mechanical properties, including hardness, yield strength, and ultimate tensile strength, increase from the center to the surface of the sample [16].

In this study, the results of a numerical simulation conducted on the experiments designed by response surface methodology (RSM) were used to investigate the plastic strain inhomogeneity in the RVE processed commercial pure titanium grade 2. For this purpose, geometrical parameters involved in RVE die design were used as inputs, and a standard deviation formulation was used to calculate the strain inhomogeneity. Analysis of variance (ANOVA) was used to determine the primary parameters and to check the accuracy of the developed mathematical model. Considering the capabilities of the RVE process for industrialization, the results of the current study could be important.

2. Response Surface Methodology (RSM)

In this study, the central composite approach was used in the Design Expert V.11 software [17] to design runs for finite element analysis (FEA). Fig. 1 shows the



$$RA = \frac{a_0^2 - a_f^2}{a_0^2}$$

Fig. 1. Schematics and the geometrical parameters of RVE die.

schematics of RVE die and its related geometrical parameters. Twist angle (φ), reduction in area (RA), and twist zone length (L) were considered as input parameters, involved in the rectangular vortex extrusion (RVE) die design, to study the effective strain inhomogeneity using standard deviation (S.D.) formulation as a response (Table 1). In this equation, N, ε_i, and ε_{avg} are the number of selected points on the cross-section of the product along A-B line in Fig. 2 to determine the effective strain, the effective strain at the i_{th} point, and the average effective strain of points, respectively. RVE dies were designed for all 15 proposed runs (Table 2) using CATIA V.5R21 software [18], separately. A multiple regression model was considered to obtain the mathematical model for effective strain inhomogeneity. The accuracy of the developed mathematical model was checked using ANOVA. Additionally, the ANOVA results were used to determine the primary parameters.

Table 1. Input parameters, their levels, and the response

	Parameter	**Index**	**Levels**
Input parameters	Twist angle, φ (degree)	A	30, 60, 90
	Reduction in area, *RA* (%)	B	25, 50, 75
	Twist zone length, *L* (*mm*)	C	5, 10, 15
Response	**Parameter**	**Equation**	
	Standard deviation (S.D.)	$SD = \sqrt{\frac{\sum_{i=1}^{N}(\varepsilon_i - \varepsilon_{avg})^2}{N-1}}$ $\varepsilon_{avg} = \frac{\sum_{i=1}^{N}(\varepsilon_i)}{N}$	

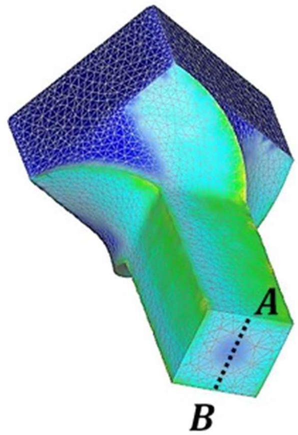


Fig. 2. Selected points on the cross-section of the product along A-B line to calculate S.D.

3. Finite Element Analysis (FEA)

Commercial software DEFORM-3D V.11 [19] was used for the finite element analysis of runs of Table 2 and the results are presented in Table 3. Commercial pure titanium grade 2 with the rectangular cubic geometry $(20 \times 20 \times 40\ mm^3)$ was considered as a deformable plastic workpiece and was meshed using a total number of 75146 tetrahedral elements. The stress-strain data for the pure titanium grade 2 was used from the software database. The mesh convergence criterion was used to determine the appropriate mesh numbers. The boundary curvature and the distribution of effective strain were selected as the weighting factors. The

Table 2. Runs and their level of parameters

Run	Twist angle, φ (degree)	Reduction in area, *RA* (%)	Twist zone length, *L* (*mm*)
1	60	50	**10**
2	60	50	**15**
3	90	25	**15**
4	90	25	**5**
5	30	75	**5**
6	90	75	**5**
7	60	75	**10**
8	30	25	**5**
9	30	25	**15**
10	30	75	**15**
11	90	75	**15**
12	60	50	**5**
13	90	50	**10**
14	30	50	**10**
15	60	25	**10**

Table 3. FEA results of standard deviation

Run	Twist angle, φ (degree)	Reduction in area, *RA* (%)	Twist zone length, *L* (*mm*)	Standard deviation (S.D.)
1	60	50	10	**1.35**
2	60	50	15	**1.06**
3	90	25	15	**1.00**
4	90	25	5	**2.64**
5	30	75	5	**2.70**
6	90	75	5	**5.99**
7	60	75	10	**2.39**
8	30	25	5	**0.82**
9	30	25	15	**0.53**
10	30	75	15	**1.61**
11	90	75	15	**2.56**
12	60	50	5	**2.42**
13	90	50	10	**1.94**
14	30	50	10	**1.01**
15	60	25	10	**0.86**

Table 4. ANOVA results

	Standard deviation (S.D.)	
	$F-Value$	$P-Value$
Model	203.64	< 0.0001
A: Twist angle ($\boldsymbol{\varphi}$)	301.26	< 0.0001
B: Reduction in area ($\boldsymbol{RA}$)	583.84	< 0.0001
C: Twist zone length ($\boldsymbol{L}$)	232.86	< 0.0001
AB: ($\boldsymbol{\varphi} \times \boldsymbol{RA}$)	76.41	< 0.0001
AC: ($\boldsymbol{\varphi} \times \boldsymbol{L}$)	0.02	0.9042
BC: ($\boldsymbol{RA} \times \boldsymbol{L}$)	27.48	0.0008
A^2: ($\boldsymbol{\varphi} \times \boldsymbol{\varphi}$)	–	–
B^2: ($\boldsymbol{RA} \times \boldsymbol{RA}$)	–	–
C^2: ($\boldsymbol{L} \times \boldsymbol{L}$)	–	–

automatic remeshing, done in order to consider any possible problem related to excessive mesh distortion, was used. All other bodies, including punch, container, and the RVE die, were considered rigid bodies. Simulations were done at room temperature, and the heat generation due to plastic deformation was neglected. Frictional conditions in the interface of master-slave bodies were considered using a constant friction factor of m = 0.1, and the simulation was carried out by the punch speed of 0.2 mm/sec.

4. Results and Discussion

The resulting P-Value and F-Value from ANOVA (Table 4), which was done using Design Expert V.11 software, showed that the model is accurate, and the 2FI model was suggested for mathematical modeling of effective strain inhomogeneity (Eq. (1)). Also, the results show that the parameters of twist angle ($\boldsymbol{\varphi}$), reduction in area (RA), twist zone length (L), the interaction between twist angle and reduction in area ($\boldsymbol{\varphi} \times RA$), and the interaction between reduction in area and twist zone length ($RA \times L$) are significant parameters.

Table 5. Results of R^2, adj-R^2, and pre-R^2 values form ANOVA

Model	Standard deviation (S.D.)
	2FI
R^2	0.9935
$adj\text{-}R^2$	0.9886
$pre\text{-}R^2$	0.9840

$$SD^{-0.87} = +1.69521 - 0.016827 \times \varphi - 1.73715 \times RA + 0.072514 \times L + 0.017692 \times \varphi \times RA + 0.000013 \times \varphi \times L - 0.063662 \times RA \times L \quad (1)$$

Table 5 shows the R^2, $adj\text{-}R^2$, and $pre\text{-}R^2$ values used to check the agreement of the results obtained from FEA, RSM, and Eq. (1). The result of R^2 is almost equal to 1, which shows that the determined 2FI model has high accuracy. In addition, the difference between the values of $adj\text{-}R^2$ and $pre\text{-}R^2$ is lower than 0.2, which offers a good agreement between the results obtained from FEA with those from Eq. (1) [20, 21].

Fig. 3 shows that the FEA results (colorful points) are along the y=x line, which implies a good agreement between the FEA and RSM results. To analyze the effect of input parameters on the response, the perturbation plot was used (Fig. 4). This plot is based on the deviation about a reference point, and the slope of lines shows how (intensity and constructive/destructive nature of parameter) the parameter affects the response. It can be

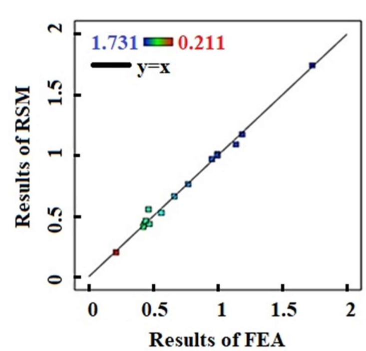


Fig. 3. Comparison of the FEA and RSM results.

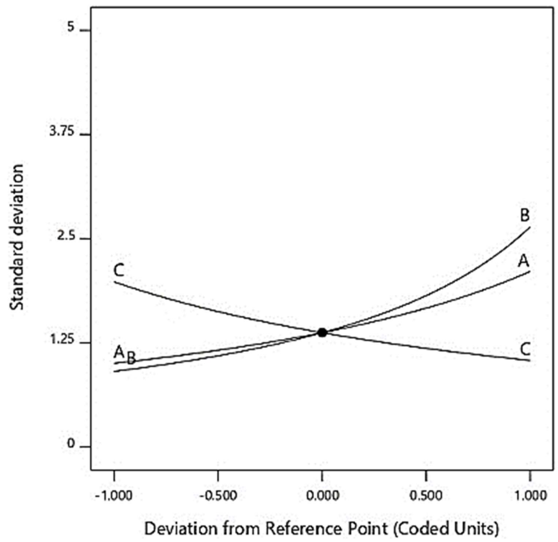


Fig. 4. Perturbation plot of standard deviation (S.D.).

seen that the effect of twist angle and reduction in area, denoted by symbols A and B, respectively, are depicted with a positive slope, meaning that these two parameters have a constructive effect on the standard deviation. It means that, by increasing the twist angle and reduction in area, the standard deviation increases. However, the twist zone length, denoted by symbol C, has a destructive effect on the standard deviation. This means that the standard deviation is decreased when the twist zone length increases. The results of Fig. 4 are in good agreement with the sign of coefficients of Eq. (1). Additionally, the twist angle has a higher slope than that of a reduction in area, which is in good agreement with the coefficients of parameters in Eq. (1).

Fig. 4 shows the interactions between the parameters and their effect on the standard deviation. The different effects of the first parameter on the response in various levels of the second parameter are considered as an interaction between two parameters. This is depicted by the curvature on the projected lines of the 3D surface shown in Fig. 5. As can be seen, there are interactions between twist and reduction in area, and between reduction area and twist zone length, which is in good agreement with the ANOVA results. Also, the results of Fig. 5 are in good agreement with those of Fig. 4 and Eq. (1).

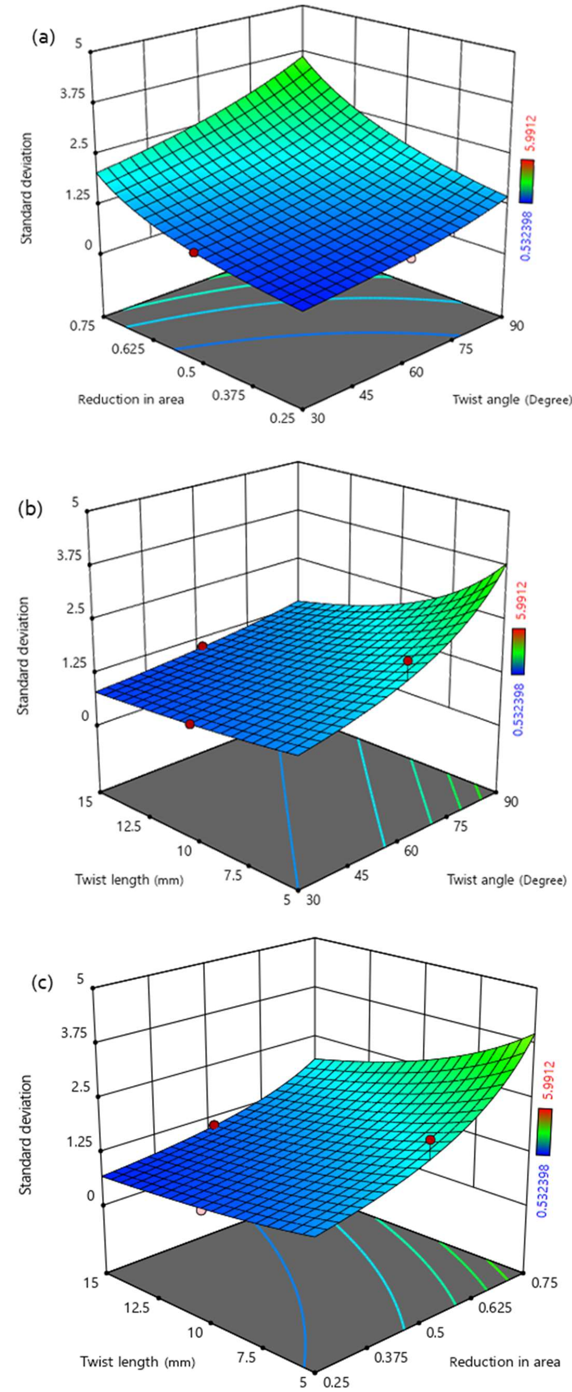


Fig. 5. 3D surface diagrams to investigate the interaction between parameters and their effect on the response, a) $\varphi \times RA$, b) $\varphi \times L$, and c) $RA \times L$.

5. Conclusion

In the current study, the finite element analysis (FEA) and response surface methodology were used to investigate the effects of geometrical parameters of RVE die on the effective strain inhomogeneity using standard deviation formulation. Analysis of variance (ANOVA) was used to determine significant parameters, to develop a mathematical model for effective strain inhomogeneity, and to check the accuracy of the model. The results of ANOVA, the sign, and the magnitude of the coefficient of the suggested mathematical model were checked by perturbation plot and 3D surface diagrams. In the end, the following conclusions can be drawn:

- The model is accurate, and there is a good agreement between the FEA results and those predicted by the suggested mathematical model.
- Twist angle (φ), reduction in area (RA), twist zone length (L), the interaction between twist angle and reduction in area ($\varphi \times RA$), and interaction between reduction in area and twist zone length ($RA \times L$) were determined as significant parameters.
- The results showed a good agreement between the ANOVA and 3D surface diagram results.

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