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Investigation of the Forming Force in Torsion Extrusion Process of Aluminum Alloy 1050

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ABSTRACT

In this paper, torsion extrusion (TE) process on 1050 aluminum alloy (AA) was investigated by simulation as a severe plastic deformation (SPD) method and the effects of friction coefficient, angular velocity of the rotating die and punch speed on maximum punch force were studied. A finite element (FE) model was developed to simulate the TE process via DEFORM software. The FE results were validated compared with experimental results and then the FE model was used for implementing the set of simulations designed by Taguchi's L9 orthogonal array. Maximum punch force was determined and put into signal to noise (S/N) ratio and the analysis of variance (ANOVA) techniques to specify the importance and contribution of parameters. The results indicated that the friction coefficient has the most effect on maximum punch force and effects of the angular velocity and punch speed are not sensible. Results analysis represented that maximum punch force enhances by increasing the friction coefficient. Moreover, friction coefficient of 0.18, angular velocity of 0.11 rad/s and punch speed of 0.2 mm/s lead to the minimum punch force.

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1. INTRODUCTION

Severe plastic deformation (SPD) method is one of the newest approaches to producing ultrafine grained products in which large strains are applied to the material and cause a significant increase in mechanical properties [1-3]. Torsion extrusion (TE) process is one of the SPD methods to reach such high strength metal material that is very close to forward extrusion (FE) process. The main difference of TE compared to FE is the presence of a rotating die with a certain angular velocity. This certain angular velocity causes severe strains on final parts [4]. Figure 1 schematically shows the TE process [5]. As it can be seen, in addition to punch a rotating die is used. Furui and Aida [6] investigated the TE process on AZ91D magnesium alloy. They found that the grain size gradually decreases by increasing the torsion speed. Also, hardness enhances with increasing of the torsion speed. Mizunuma [7] performed the TE process on AA 1070 and AZ31 alloys. The results showed that in optimum conditions of the die and temperature, the fracture does not occur on the surface of samples. TE process successfully applied on the pure lead by Ma et al. [8]. They reported that forming force decreases with the rotation of die. Chino et al. [9] experimentally investigated the TE process on the AZ31 alloy. Their results demonstrated that material ductility increases at room temperature. Khosravifard et al. [10] successfully implemented TE process on AA1050 alloy samples at room temperature. They used ABAQUS/Explicit code to simulate the process. They stated that forming force reduces in TE in comparison to FE. Also, the distribution of strain in TEed samples is more smooth than FEed ones. Shamsborhan et al. [11] carried out planar twist channel angular extrusion (PTCAE) as a novel severe plastic deformation method using response surface methodology (RSM). They investigated the effects of α angle, ϕ angle, radius and friction coefficient on minimum and maximum effective strain and maximum load. They concluded that optimum condition can be reached in α= 400, ϕ= 450, r=2 mm and μ=0.1.

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In spite of the valuable works in connection with TE process, a study based on the design of experiments has not been found in the literature. In this research, effects of the TE process parameters including friction coefficient, angular velocity of the rotating die and punch speed on maximum punch force was investigated using finite element and Taguchi methods.

2. FINITE ELEMENT SIMULATION

The explicit FE code DEFORM/V6.1 was used for simulating the TE process. A 3D model was used for die set (punch, rotating die, and container) and billet. The length and diameter of the billet are 40 mm and 20 mm, respectively. The container diameter was considered as 20 mm and the first and second stages of the extrusion were considered to be 16 mm and 13 mm, respectively [5]. The die set was modeled as a rigid body and the billet was assumed to be plastic. The flow stress (σ) and true strain (ε) were obtained from compression test and introduced to software in form of $\sigma=124.3\varepsilon^{0.318}$ as stress-strain data [5]. Shear friction interfaces were used to define contact between the billet and the die set. According to reference [5], a constant friction factor of m=0.18 was used in the simulation. The billet was meshed using tetrahedral mesh by 40,000 elements. The meshing of the initial billet is shown in Figure 2. The die set did not mesh because they considered as a rigid body.

The rotating die was constrained fully. The punch moves down with a speed of 0.2 mm/s and the rotating die rotates with an angular velocity of 0.21 rad/s. The process was performed at room temperature [5]. In order to solve the equations, direct iteration method was used. When the elements became too distorted, the system was automatically remeshed [12].

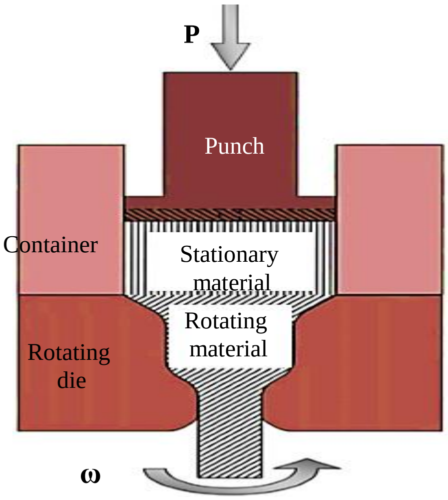

Figure 1. Schematic of TE process [5]

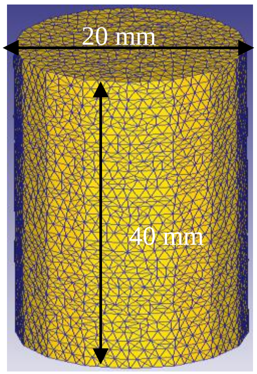

Figure 2. Meshing of initial billet

TABLE 1. Experimental condition of reference [5]

Parameter	Value
Billet material	AA 1050
Billet diameter (mm)	20
Billet length (mm)	40
Container diameter (mm)	20
First stage diameter (mm)	16
Second stage diameter (mm)	13
Angular velocity (rad/s)	0.21
Ram speed (mm/s)	0.2

The experimental condition of reference [5] is given in Table 1 for more understanding. The simulation results are reliable and can be used when they were been verified by experimental results. For this goal, force/displacement curve of the simulation was compared with the result of the experiment TEed sample of reference [5]. This comparison is depicted in Figure 3 and as it can be seen, there is a good agreement between the simulation result and experiment result.

Figure 4 shows the final workpiece at the end of the process. Also, the von mises plastic strain versus distance in cross section of the final workpiece is illustrated in Figure 5.

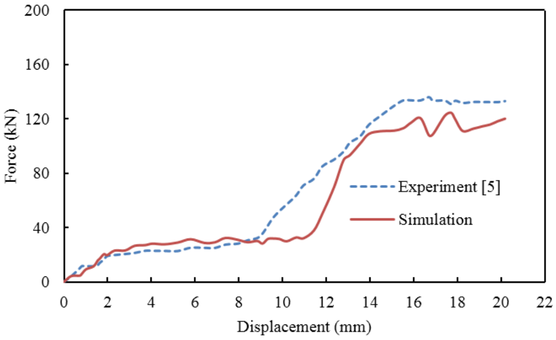

Figure 3. Force/displacement curve of TE process

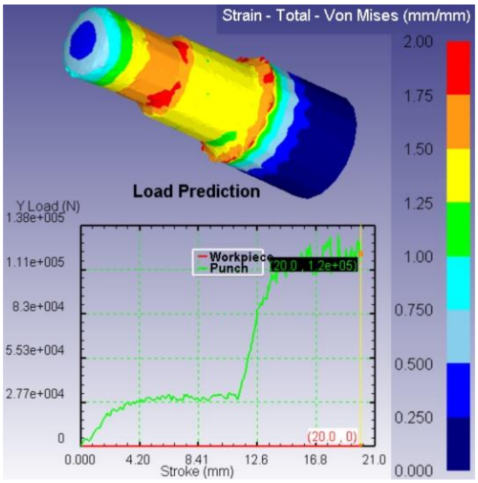

Figure 4. FE model of the final workpiece

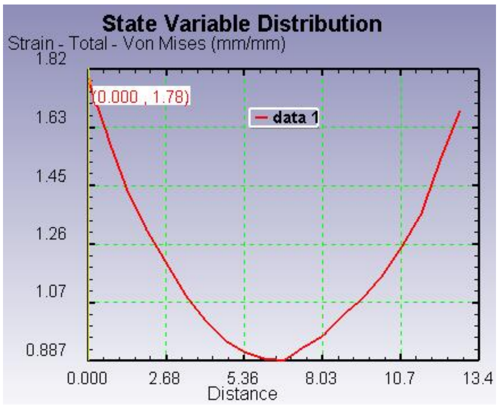

Figure 5. Distribution of the von mises plastic strain at the normal cross section of the final workpiece

As it is depicted, the plastic strain from the surface to the center decreases with a sharp slope. This subject occurs because of the torsion effect due to die rotation that affects the material near the surface [5]. The path of measuring the plastic strain is shown in Figure 6.

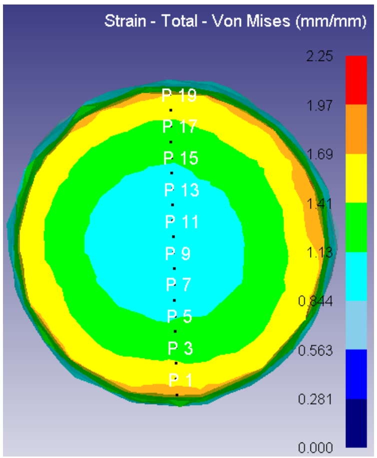

Figure 6. Path of measuring the von mises strain

3. DESIGN OF EXPERIMENTS

Taguchi method (TM) is widely used in engineering analysis for optimizing the performance of the characteristics of the combination of design parameters. The TM considers three stages in a process development including system design, parameter design, and tolerance design. Among these stages, parameter design is the key step in the Taguchi method to achieve high quality without increasing the costs. The focus of the system design is on determining the suitable working levels of design factors [13, 14]. Three levels of the input parameters that were used in FE simulations are given in Table 2. Table 3 shows the 9 terial conditions based on Taguchi L9 orthogonal array.

The Minitab 16 software [15] was used to analyze the data. In TM, with respect to the type of the response (smaller, nominal or larger), Equations (1) to (3) can be used to determine S/N ratio, respectively [16]. In this study, the smaller maximum punch force, the better result. Hence, the Equation (1) was used.

$$\frac{S}{N} = -10\,log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

$$\frac{S}{N} = -10\,log\left(\frac{1}{n}\sum_{i=1}^{n} (y_i - S)^2\right) \tag{2}$$

$$\frac{S}{N} = -10\,log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \tag{3}$$

TABLE 2. Input parameters and levels

Parameter	**Designation**	**Level**		
		Low (1)	**Medium (2)**	**High (3)**
Friction coefficient	μ	0.18	0.3	0.42
Angular velocity (rad/s)	ω	0.11	0.21	0.31
Punch speed (mm/s)	V	0.1	0.2	0.3

TABLE 3. Taguchi L9 orthogonal array

Trial No.	**Friction coefficient**	**Angular velocity (rad/s)**	**Punch speed (mm/s)**
1	0.18	0.11	0.1
2	0.18	0.21	0.2
3	0.18	0.31	0.3
4	0.3	0.11	0.2
5	0.3	0.21	0.3
6	0.3	0.31	0.1
7	0.42	0.11	0.3
8	0.42	0.21	0.1
9	0.42	0.31	0.2

4. RESULTS AND DISCUSSION

Table 4 shows the maximum punch force for 9 experiments based on Taguchi L9 orthogonal array performed by the FE simulation. Also, S/N ratio results for maximum punch force from experiments are presented in Table 5. Figure 7 shows the main effects plot for means. As it can be seen from S/N ratio results, the friction coefficient is the most effective parameter for maximum punch force. Level 1 of friction coefficient (0.18) is the optimum level. Results indicate that angular velocity and punch speed have no considerable influence on maximum punch force. Increasing the friction coefficient leads to an increase in maximum punch force. To justify this subject, it can be mentioned that by enhancing the friction coefficient, larger shear stresses are imposed the material and therefore the required force for material flow increases. Also, in cold metal forming processes, the forming force is independent of the forming speed or strain rate.

Figure 8 demonstrates the interaction effects of parameters for maximum punch force. As it can be seen, angular velocity and punch speed have interaction with each other. The maximum punch force increases by an increase in the punch speed, when angular velocity is 0.11 rad/s. It should be remembered that because of the gap between the container and rotating die due to the relative motion of them, flash creation is inevitable. Also, a severe shear strain causes the torsion effect on the surface of the sample [5]. These two phenomena are illustrated in Figure 9.

TABLE 4. The results of maximum punch force (punch stroke: 16 mm)

Trial No.	Maximum punch force (kN)
1	108
2	116
3	111
4	122
5	130
6	136
7	162
8	173
9	159

TABLE 5. S/N ratio results of maximum punch force

Level	Friction coefficient	Angular velocity (rad/s)	Punch speed (mm/s)
1	-40.95	-42.20	-42.70
2	-42.23	-42.78	-42.35
3	-44.33	-42.54	-42.46
Delta	3.37	0.58	0.35
Rank	1	2	3

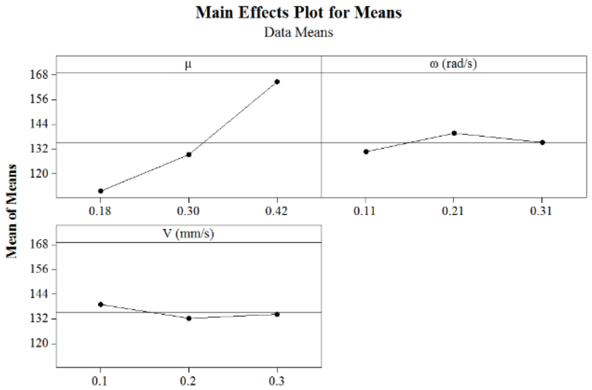

Figure 7. Main effects plot for maximum punch force

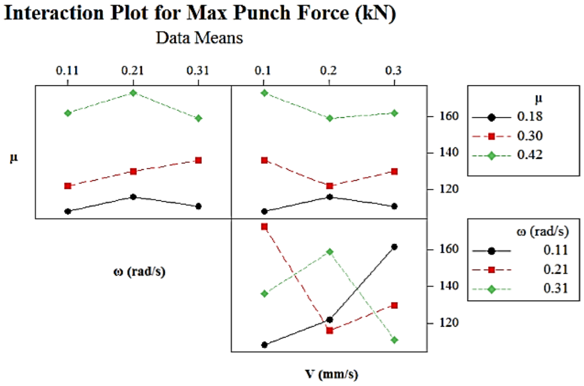

Figure 8. Interaction effect of parameters on maximum punch force

Figure 10 shows the probability plot for the maximum punch force according to Anderson-Darling test. As it is depicted, because of the P-Value greater than 0.05 (0.328), the distribution of data is normal [17]. ANOVA results of maximum punch force are given in Table 6. ANOVA results state that friction coefficient with the contribution of 94.80% is the most effective parameter.

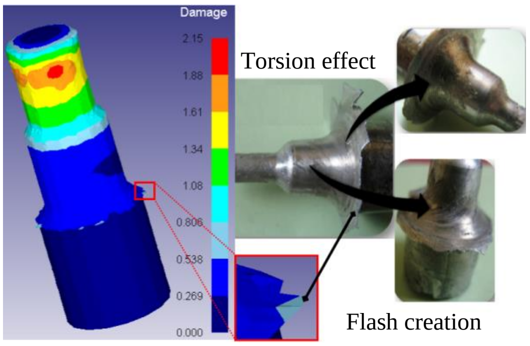

Figure 9. Flash creation and torsion effect in simulation and experiment sample [5]

On the other hand, angular velocity and punch speed with the contribution of 2.64 and 1.52%, respectively are almost ineffective parameters. In addition, the goodness of the ANOVA model (R-square) was obtained 98.95% which is so desirable.

Regression analysis of maximum punch force versus friction coefficient (μ), angular velocity (ω) and punch speed (V) was performed in Minitab software. The regression model based on input parameters was obtained as Equation (4):

$$Max\ Punch\ Force = 68.7 + 221\mu + 23.3\omega - 23.3V \qquad (4)$$

Figure 11 represents the predicted response from regression versus actual response from 9 experiments of the Taguchi L9 orthogonal array.

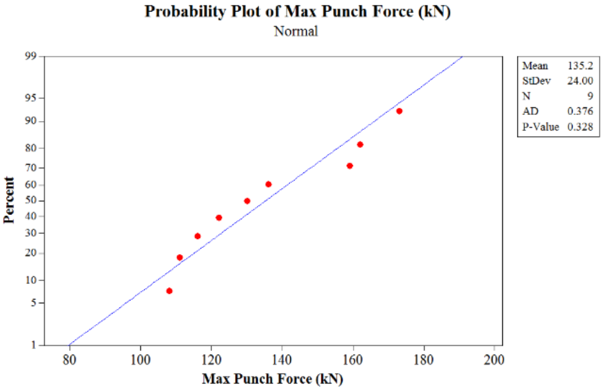

Figure 10. Probability plot of maximum punch force

TABLE 6. ANOVA result for maximum punch force

Source	DF	Mean Square	P-Value	Contribution (%)
μ	2	2184.78	0.011	94.80
ω	2	60.78	0.284	2.64
V	2	35.11	0.407	1.52
Error	2	24.11	-	1.04
Total	8	-	-	100

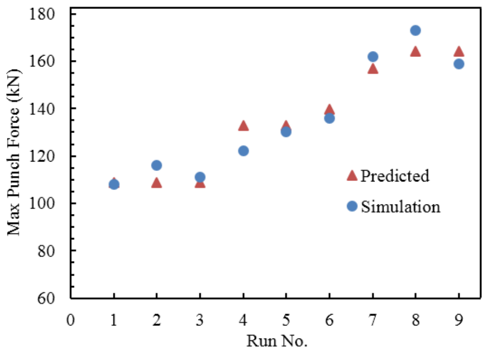

Figure 11. Predicted results of regression versus simulation results for maximum punch force

TABLE 7. ANOVA result for regression

Source	DF	SS	MS	F	P
Regression	3	4278.8	1426.3	21.56	0.003
Residual Error	5	330.7	66.1	-	-
Total	8	4609.6	-	-	-

It can be clearly seen that regression model can properly predict the maximum punch force with respect to input parameters. The goodness of the regression model was obtained 92.80% that is desirable. Also, ANOVA results for regression are given in Table 7.

According to S/N ratio and ANOVA, it was found that the combination of parameters as μ1ω1V2 leads to minimum punch force. This value was obtained 106.383 kN and 104.222 kN from regression and Taguchi analysis, respectively that both of them are lower than the minimum value of the maximum punch force from L9 experiments (run number 1: 108 kN).

5. CONCLUDING REMARKS

In this paper, the effects of friction coefficient, angular velocity of the rotating die and punch speed on maximum punch force in torsion extrusion (TE) process was investigated using finite element analysis and Taguchi method. By examining the signal to noise and analysis of variance techniques, some useful results are summarized as follows:

1. It was found that the friction coefficient is the most important parameter in comparison to angular velocity and punch speed.
2. By enhancing the friction coefficient, the maximum punch force increases.
3. Minimum punch force can be obtained by a set of parameters as friction coefficient of 0.18, angular velocity of 0.11 rad/s and punch speed of 0.2 mm/s.

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چکیده

در این مقاله، فرآیند روزنرانی چرخشی بعنوان یک روش تغییر شکل پلاستیک شدید روی آلیاژ آلومینیوم ۱۰۵۰ با شبیه‌سازی بررسی و تاثیر ضریب اصطکاک، سرعت زاویه‌ای قالب مدور و سرعت سنبه روی بیشینه نیروی سنبه مطالعه شد. یک مدل اجزای محدود با استفاده از نرم‌افزار DEFORM برای شبیه‌سازی فرآیند استفاده شد. صحت نتایج شبیه‌سازی در مقایسه با نتایج تجربی تایید شد و سپس از مدل اجزای محدود برای اجرای آزمایشات طراحی شده با آرایه متعامد L9 تاگوچی استفاده شد. بیشینه نیروی سنبه استخراج شده و با استفاده از تکنیک‌های نسبت سیگنال به نویز و آنالیز واریانس، میزان اهمیت و درصد مشارکت پارامترها مشخص شد. نتایج نشان داد که ضریب اصطکاک بیشترین تاثیر را بر بیشینه نیروی سنبه دارد و تاثیر سرعت زاویه‌ای و سرعت سنبه نامحسوس است. با تحلیل نتایج مشخص شد که بیشینه نیروی سنبه با افزایش ضریب اصطکاک افزایش می‌یابد. بعلاوه ضریب اصطکاک ۰/۱۸، سرعت زاویه‌ای ۰/۱۱ رادیان بر ثانیه و سرعت سنبه ۰/۲ میلیمتر بر ثانیه منجر به کمترین میزان نیروی سنبه می‌شود.

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