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Using the Taguchi Method and Finite Element Method to Analyze a Robust New Design for Titanium Alloy Prick Hole Extrusion

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Abstract

In the process of prick hole extrusion, many factors must be controlled to obtain the required plastic strain and desired tolerance values. The major factors include lubricant, extrusion speed, billet temperature, and die angle. In this paper, we employed rigid-plastic finite element (FE) DEFORM^{TM} software, to investigate the plastic deformation behavior of a titanium alloy (Ti-6Al-4V) billet as it was extruded through a conical prick hole die. We systematically examined the influence of the semi-cone angle on the prick hole die, the diameter of prick hole die, the factor of friction, the velocity of the ram and the temperature of the billet, under various extrusion conditions. We analyzed the strain, stress and damage factor distribution in the extrusion process. We used the Taguchi method to determine optimum design parameters, and our results confirmed the suitability of the proposed design, which enabled a prick hole die to achieve perfect extrusion during finite element testing.

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Keywords: Prick hole extrusion, Finite element, Optimum design;

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1. Introduction

Extrusion has long been used in metallurgical industries to make bars, tubes, wires, and strips with significant efforts being made to describe the processes in fundamental terms. Titanium alloys have been widely used in aerospace applications thanks to their high strength-to-weight ratio, excellent toughness, fatigue resistance at elevated temperatures, and good resistance to corrosive environments. Li *et al.* [1] simulated the forward extrusion process of Ti-6Al-4V bar using finite element software to study the influence of process variables on the product; and compared these results with some experimental measurements. Balasundar and Raghu [2] used finite element analysis to determine the effect of important extrusion parameters such as extrusion ratio, extrusion die angle, deformation zone height, friction, and

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how the constitution of materials affects deformation. Giuliano [3] proposed using commercial finite element software for multi-stage process design, which could prevent defects in the flow in the combined forward-backward cold extrusion of billets.

Domanti *et al*. [4] used a commercial finite element package (ABAQUS) to simulate the extrusion of a paste using an elastic-plastic material model based on the stress and strain within the deforming material required for evaluation of the fracture criteria. Fang *et al*. [5] studied metal flow through a series of pocket dies using DEFORM 3D and to verify their experiments on the distribution of velocity, extrusion pressure and extrusion temperature. This experimental approach and finite element analysis were employed to study the effects of the process parameters on the multi-hole extrusion of aluminum-alloy A7075 tubes using the indirect extrusion process by Chen *et al.* [6]. Finally, we [7] used DEFORM^{TM} 3D software to investigate the plastic deformation of Ti-6Al-4V titanium alloy during its indirect extrusion through a four-hole die.

In this study, we used rigid-plastic finite element (FE) DEFORM^{TM} software to investigate the plastic deformation behavior of titanium alloy (Ti-6Al-4V) billet as it was extruded through a conical prick hole die. We used the Taguchi method to determine the optimum design parameters. Our results confirmed the suitability of the proposed design process, which allowed a prick hole die to achieve a perfect extrusion during finite element method.

2. Simulation process analysis and Taguchi method

The DEFORM^{TM} 2D FE simulations performed in this study were based on a flow formulation approach using an updated Lagrangian procedure. The nonlinear equations in the FE software were solved using a combined direct iteration method/Newton-Raphson scheme. In the solution, direct iteration method was used to generate a suitable initial estimate, and the Newton-Raphson method was applied to obtain a rapid convergence to the final solution. The iterative solution was continued until the following termination criteria had been achieved a velocity error norm of $\|\Delta\mathbf{v}\|/\|\mathbf{v}\| \le 0.001$ and a force error norm of $\|\Delta F\|/\|F\| \le 0.01$, where $\|\mathbf{v}\|$ is $(\mathbf{v}^T\mathbf{v})^{1/2}$

The Taguchi method uses a generic signal-to-noise (S/N) ratio to quantify variations. Depending on the characteristics involved, it is possible to use various S/N ratios: “lower is better” (LB), “nominal is best” (NB), or “higher is better” (HB). William & Creveling [8] and Belavendram [9] described the S/N ratio for the LB characteristics of the current prick hole extrusion as:

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

where n is the number of simulation repetitions under the same design parameters, y_i indicates the measured results, and i indicates the number of design parameters in the Taguchi orthogonal array (OA).

3. Results and discussion

Figure 1 presents a schematic illustration of a titanium alloy (Ti-6Al-4V) prick hole extrusion. The design of the structure was symmetric and in the simulations, the objects were all modeled as rigid. Figure 2 shows stress-strain relationship for Ti-6Al-4V titanium alloy. Three billet temperatures has three kinds including were employed: 700°C, 750°C, and 800°C.

Table 1 specifies the five design factors, each with three levels, for the prick hole extrusion. We arranged the experimental trials in an $L_{18}(3^5)$ orthogonal array matrix. We adopted a prick hole extrusion process (**Table 1**) using the following design factors: Factor A, semi-cone angle; Factor B, diameter of prick hole die; Factor C, friction factor; Factor D, velocity of ram; and Factor E, temperature of billet. Table 2 presents eighteen different designs for prick hole extrusion.

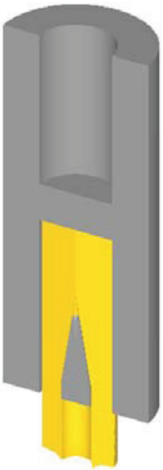

Fig. 1. Schematic illustration of titanium alloy (Ti-6Al-4V) prick hole extrusion

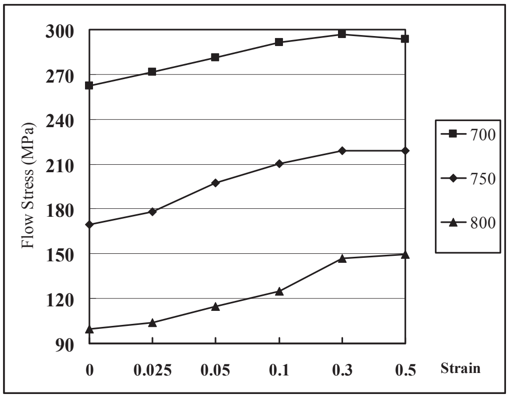

Fig. 2. Stress-strain relationship for Ti-6Al-4V titanium alloy

Table 1. Design parameters and levels for titanium alloy prick hole extrusion

Factors	Description	Level 1	Level 2	Level 3
A	semi-cone angle	9°	10°	11°
B	diameter of prick hole die	6 mm	8 mm	10 mm
C	friction factor	0.05	0.1	0.2
D	velocity of ram	2 mm/sec	3 mm/sec	4 mm/sec
E	temperature of billet	700°C	750°C	800°C

Table 3 presents the effective stress, strain, and damage in titanium alloy during prick hole extrusion, using eighteen different designs, in the first and second experiment. We used multi-quality characteristics:

the stress weight was 35%; the strain weight was 35%; and the damage was 30%. All the factors supported the rationale of “lower is better” (LB).

Table 4 presents the corresponding factor response data; these are graphically plotted in Figure 3. Following the principles of the Taguchi method, we assumed that a higher S/N ratio indicated higher product quality. Therefore, Figure 3 shows the following optimal parameter settings for prick hole extrusion: *A2*, semi-cone angle (10^{o}), *B2*, diameter of prick hole die (8mm); *C2*, friction factor (0.1); *D1*, velocity of ram (2mm/sec); and *E1*, temperature of billet (700^{o}C).

Figure 4 depicts the stress distribution during prick hole extrusion using a perfect design (A2B2C2D1E1). These results indicated the ideal specifications of the design of the new mold and die, with an effective stress of 297MPa, strain of 15.7, and damage of 1.64, for the extruded billet.

Table 2. Eighteen designs for prick hole extrusion

No.	semi-cone angle	diameter of prick hole die	friction factor	velocity of ram	temperature of billet ^{o}C
1	9	6	0.05	2	700
2	9	8	0.1	3	750
3	9	10	0.2	4	800
4	10	6	0.05	3	750
5	10	8	0.1	4	800
6	10	10	0.2	2	700
7	11	6	0.1	2	800
8	11	8	0.2	3	700
9	11	10	0.05	4	750
10	9	6	0.2	4	750
11	9	8	0.1	2	800
12	9	10	0.05	3	700
13	10	6	0.1	4	700
14	10	8	0.2	2	750
15	10	10	0.05	3	800
16	11	6	0.2	3	800
17	11	8	0.05	4	700
18	11	10	0.1	2	750

4. Conclusions

This study utilizes finite element software to simulate the plastic deformation behavior of titanium alloy (Ti-6Al-4V) during the prick hole extrusion. Results show that (1) the optimal parameter settings for the prick hole extrusion: *A2*, semi-cone angle ($10^{o)}$; *B2*, diameter of prick hole die (8mm); *C2*, friction factor (0.1); *D1*, velocity of ram (2mm/sec); and *E1*, temperature of billet (700^{o}C.); and (2) the design of the new mold and die, with an effective stress of 297MPa, effective strain of 15.7, and damage of 1.64 of the extruded billet.

Table 3. Effective stress, effective strain, and damage in titanium alloy during prick hole extrusion using eighteen different designs

No.	Experiment 1			Experiment 2		
	Effective stress (MPa)	Effective strain	Damage	Effective stress (MPa)	Effective strain	Damage
1	297	21.7	3.51	295	21.6	3.41
2	219	29.9	2.50	221	29.7	2.56
3	177	29.2	3.08	178	29.4	3.10
4	219	17.8	3.20	220	17.9	3.21
5	175	21.9	2.72	178	21.7	2.74
6	297	27.4	1.75	295	27.5	1.77
7	174	16.7	2.35	175	16.8	2.37
8	297	22.7	2.97	298	22.8	2.99
9	1190	21.6	2.48	1191	21.7	2.49
10	219	23.1	3.26	220	23.2	3.27
11	176	26.8	2.49	177	26.9	2.50
12	297	31.9	2.18	298	31.5	2.19
13	297	23.5	3.7	298	23.7	3.9
14	219	23.8	3.38	219	23.9	3.34
15	175	23.1	3.31	175	23.5	3.36
16	1180	22.3	3.08	1180	22.5	3.10
17	297	20.3	2.29	297	20.4	2.30
18	219	23.5	1.9	219	23.6	1.91

Table 4. Factor response table for prick hole extrusion

Control factor	A	B	C	D	E
Level1	35.131	35.067	35.314	35.77	35.364
Level2	35.403	35.536	35.643	34.909	35.147
Level3	35.201	35.131	34.777	35.055	35.223
Effects	0.272	0.469	0.866	0.861	0.217

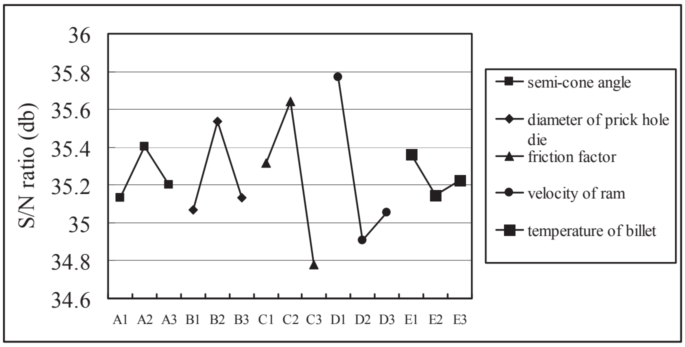

Fig.3. S/N response graph of the prick hole extrusion

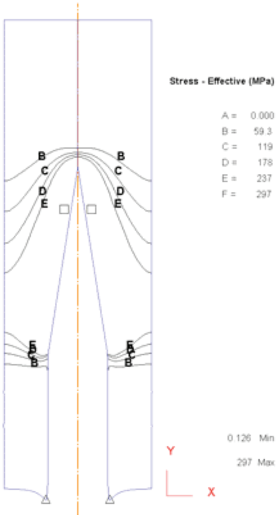

Fig. 4. Effective stress distribution in prick hole extrusion using the perfect design (A2B2C2D1E1)

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