International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:6, No:7, 2012

Study of Forging Process in 7075 Aluminum Alloy Professional Bicycle Pedal using Taguchi Method

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***Abstract*—**The current of professional bicycle pedal's manufacturing model mostly used casting, forging, die-casting processing methods, so the paper used 7075 aluminum alloy which is to produce the bicycle parts most commonly, and employs the rigid-plastic finite element (FE) DEFORM^{TM} 3D software to simulate and to analyze the professional bicycle pedal design. First we use Solid works 2010 3D graphics software to design the professional bicycle pedal of the mold and appearance, then import finite element (FE) DEFORM^{TM} 3D software for analysis. The paper used rigid-plastic model analytical methods, and assuming mode to be rigid body. A series of simulation analyses in which the variables depend on different temperature of forging billet, friction factors, forging speed, mold temperature are reveal to effective stress, effective strain, damage and die radial load distribution for forging bicycle pedal. The analysis results hope to provide professional bicycle pedal forming mold references to identified whether suit with the finite element results for high-strength design suitability of aluminum alloy.

***Keywords*—**Bicycle pedal, finite element analysis, 7075 aluminum alloy, Taguchi method

I. Introduction

In recent years, because of greenhouse effect, the green energy became more popular, and rises up the high-priced of bicycles market. Under the up-rising environmental consciousness, bicycles gradually emphasizes what they are lightweight, precision, high-quality and high mobility. Therefore, the material selections were very importance. In the market, bicycles' materials commonly used aluminum and carbon fiber, because aluminum has low density and strong intensity properties. The superior properties of aluminum attracted attentions from the light-trend industry recently and widely used in household appliances, automobile, aerospace industry, daily necessities and so on. Bontcheva and Petzov [1] presented an approach for numerical simulation of die forging on the basis of the FEM.

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The realization of such a simulation re-quires simultaneously taking into account of velocity, thermal and strain resistance fields as well as their influence on microstructure change. Castro et al. [2] used an evolutionary genetic algorithm topropose calculate the optimal work-piece shape geometry and work-piece temperature. Ganapathysubramanian and Zabaras [3] applied the method to the optimization of grain size and process parameters by appropriately defining the die geometry and ram velocity during the steady extrusion of plain carbon steel. Hartley and Pillinger [4] provided a short overview of recent research in the numerical simulation of forging, including Process Modelling, Tool and Die Design, Interface Phenomena, Material Phenomena and Computational Aspects. Prasad and Rao [5] presented investigation model the isothermal forging of a rib–web shape component in electrolytic copper by integrating the materials models with the finite element simulation and to validate the results in laboratory forging trials.

We used rigid-plastic finite element (FE) DEFORM^{TM} software to investigate the plastic deformation behavior of an aluminum alloy (A7075) workpiece as it was forged for professional bicycle pedal. Firstly, we used Solid Works 2010 CAD software to build a simulative model to import DEFORM^{TM} 3D finite element analysis software. Moreover, we used the Taguchi method to determine the optimal design parameters to achieve perfect forging for professional bicycle pedal.

II. Finite Element Method

The rigid-plastic finite element (FE) DEFORM^{TM} 3D software is based on the design and forming processes for analytical models of two dimensional and three dimensional rigid-plastic deformations. Variations in forming processes appear in the control model, constant critical damage value, temperature after plastic deformation, effective stress, effective strain, plastic flow rate, and die radius load distribution of the work piece. Using this software simulating model not only saves time and money in tooling and mold testing but also provides highly critical information. Rigid-plastic finite element (FE) DEFORM^{TM} 3D software is widely used in forging, extrusion, pulling, rolling, stamping, upsetting, and other forming processes of precision metals. This software is composed of multiple modules. The main structure can be divided into pre-treatment modules, simulation engine, post-processor modules, and multifunction modules. DEFORM^{TM} 3D also simulates plastic deformation express plastic flow stress (flow stress). The flow stress equation is (1):

$$\overline{\sigma} = \overline{\sigma}(\overline{\varepsilon}, \dot{\overline{\varepsilon}}.T) \quad (1)$$

where T is temperature, $\bar{\varepsilon}$ is the strain, and $\dot{\bar{\varepsilon}}$ is the strain rate. The location of greatest damage and destruction of the value of the occurrence is due to the accumulated energy. The maximal tensile stress reaches a certain value formed by the critical damage value, such as the criterion of Equation (2). Normalized C&L criterion [6] employed rigid-plastic finite element DEFORM™ 3D software with the critical damage value as (2).

$$\int_0^{\bar{\varepsilon}_f} \frac{\sigma_{\max}}{\bar{\sigma}} d\bar{\varepsilon} = C \qquad (2)$$

Where $\sigma_{\max}$ is the maximum tensile stress, $\bar{\sigma}$ is the effective strain, $\bar{\varepsilon}_f$ is the effective strain at failure, C is the damage value.

III. TAGUTHI METHOD

Taguchi method uses a generic signal-to-noise (S/N) ratio to quantify variations. Depending on the characteristics involved, it is possible to use different S/N ratio criteria: "lower is better" (LB), "nominal is best" (NB), or "higher is better" (HB). William & Creveling [7] and Belavendram [8] have adopted the S/N ratio to describe the LB characteristics of the forging process of professional bicycle pedal. The equation is as follows:

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

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).

IV. NUMERICAL SIMULATION

A. Structure Design

The present analysis adopts the following assumptions: (1) the mold and die are all rigid bodies; (2) the aluminum alloy (A7075) billet is a rigid-plastic material. Since researchers typically adopt the coulomb friction equation for cold working, and the shear friction equation for hot working, this study uses the shear friction equation for finite element analysis.

Figure 1 presents the finite element model of a professional bicycle pedal forging mold.

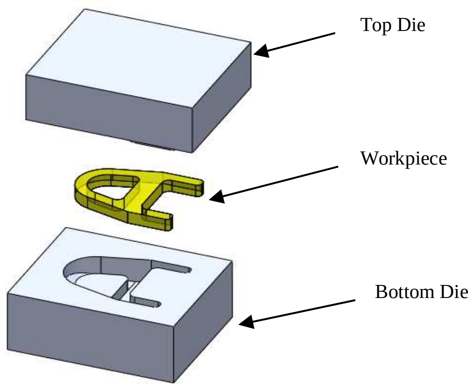
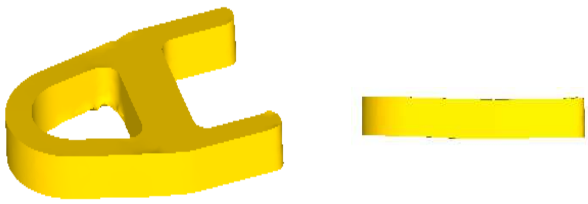
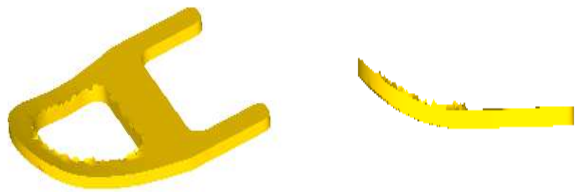


Fig. 1 Finite element model of professional bicycle pedal forging process

Figure 2 presents mesh models of the 7075 aluminum alloy billet and die before and after the forging process.



(a) Before forming process



(b) After forming process

Fig. 2 Mesh models of the aluminum alloy billet and die before and after the forming process

B. Factor Selection

The Taguchi experimental trials in this study adopted designed mold/die for professional bicycle pedal. Table 1 shows that four design factors, each with three levels, were specified for the professional bicycle pedal. Accordingly, the experimental trials were arranged in an $L_9(3^4)$ orthogonal array matrix. The design factors in the professional bicycle pedal (Table 1) include the following: factor A, workpiece temperature,20°C,150 °C,300 °C; factor B, mold temperature,20 °C,150 °C,300 °C; factor C, forging speed,50mm/sec,60 mm/sec,70 mm/sec; and factor D, friction factor,0.25,0.4,0.6.

TABLE I
DESIGN PARAMETERS AND LEVELS FOR THE A7075 FORGING PROCESS

Symbol	Parameters	Level1	Level2	Level3
A	Workpiece Temperature (°C)	20	150	300
B	Mold Temperature (°C)	20	150	300
C	Forging speed (mm/sec)	50	60	70
D	Friction factor	0.25	0.4	0.6

C. Discussion of Simulation Results

Table II shows multi-quality characteristics: the effective stress weight is 40%; the effective strain weight is 30%; the die load weight is 30%.The factors include effective stress, and mold load, supporting the rationale of " lower is better" (LB). The effective strain supports the rationale of "higher is better" (HB).

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TABLE II
OVERALL EVALUATION CRITERIA (OEC)

Criteria Description	Worst Value	Best Value	QC	Rel wt
Effective stress	1000	200	<<S	40%
Effective stain	2	13	B>>	30%
Mold load	3000000	70000	<<S	30%

Table III and Table IV present the corresponding factor response data. Following the principles of the Taguchi method, we assumed that a higher S/N ratio indicates higher product quality. Therefore, Table 5 shows the following optimal parameter settings for forging professional bicycle pedal: A1, workpiece temperature 20°C; B2, mold temperature 150°C; C2, forging speed of 60 mm/sec; and D1, friction factor,0.25.

TABLE III
S/N RATIO FOR PROFESSIONAL BICYCLE PEDAL

Exp.	A	B	C	D	Averages	S/N (dB)
1	1	1	1	1	54.77	-34.857
2	1	2	2	2	30.78	-29.78
3	1	3	3	3	52.93	-34.566
4	2	1	2	3	56.629	-34.955
5	2	2	3	1	49.14	-34.07
6	2	3	1	2	70.9	-37.477
7	3	1	3	2	75.76	-38.978
8	3	2	1	3	76.6	-38.969
9	3	3	2	1	63.73	-36.486
The total average					59.026	-35.571

TABLE IV
FACTOR RESPONSE TABLE FOR S/N RATIO

	A	B	C	D
Level1	-33.992	-35.678	-36.49	-34.896
Level2	-35.172	-34.748	-34.497	-35.777
Level3	-37.121	-35.858	-35.298	-35.611
Effects (ΔP)	3.129	1.11	1.993	0.881
Rank	1	3	2	4

Table VI presents the variance of forging professional bicycle pedal. We analyzed the results of the experimental trials using the ANOVA statistical method. The confidence and significance are highly critical for control factors. The factors with the highest contribution percentage is workpiece temperature at 99.99 %, forging speed at 99.99 %.The workpiece temperature and forging speed F value are higher than the others and is the most influential factor; whereas the factor with the lowest contribution percentage is punch speed at 91.2 %,and friction factor at 91.66 %.

TABLE V
FACTOR RESPONSE TABLE FOR MULTI-QUALITY CHARACTERISTICS

	A	B	C	D
Level1	49.851	61.556	67.423	55.88
Level2	58.059	55.865	53.241	62.838
Level3	72.029	62.52	59.276	61.223
Effects	22.178	6.655	14.182	6.958
Rank	1	4	2	3

TABLE VI
ANALYSIS OF VARIANCE (ANOVA) RESULTS FOR THE PROFESSIONAL BICYCLE PEDAL A7075 FORGING PROCESS

	SS	**DOF**	**Var.**	**F-Ratio**	**Probability**	**Confidence**	**Signi-ficant**
A	**1508.828**	**2**	**754.414**	**27.351**	**4.8608E-06**	**99.99%**	**Yes**
B	**155.228**	**2**	**77.614**	**2.813**	**0.08797042**	**91.2%**	**No**
C	**607.817**	**2**	**303.908**	**11.018**	**0.000853641**	**99.99%**	**Yes**
D	**159.157**	**2**	**79.578**	**2.885**	**0.083400846**	**91.66%**	**No**
Error	**248.236**	**9**	**27.581**				
Total	**2679.266**	**17**		***NOTE : At least 95% confidence**			

Figures 3, 4 and 5 depict the effective strain, effective stress, and die load distribution in professional bicycle pedal using a perfect design (A1B2C2D1). These results indicate the ideal specifications of the new design's mold and die, with an effective strain of 4.58 mm/mm, effective stress of 834 MPa, and mold and die load of 5860 kN. It can be seen that Figure 6 shows the greater effective stress on the periphery of the professional bicycle pedal. Figure 6 shows the strain-Max principal can be able to 2380 MPa. Figure 7 shows the damage value of professional bicycle pedal can be able to 3.19

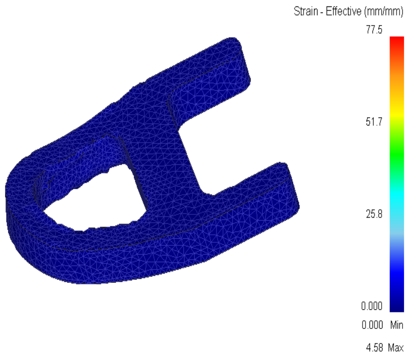

Fig. 3 Distribution of effective strain of professional bicycle pedal

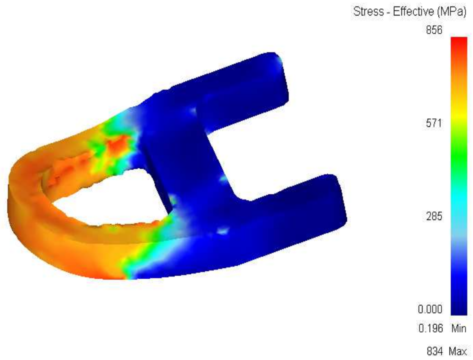

Fig. 4 Distribution of effective stress of professional bicycle pedal

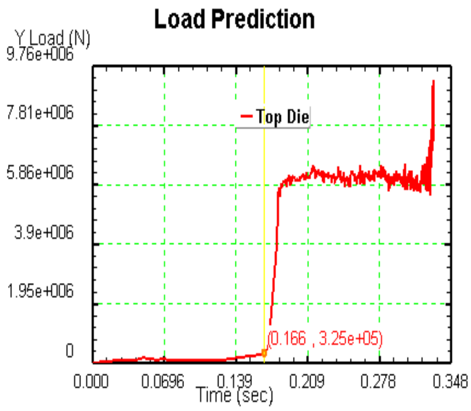

Fig. 5 Y load of forging process mold

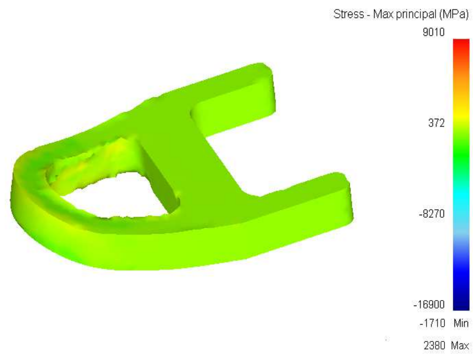

Fig. 6 Distribution of strain-max principal of professional bicycle pedal

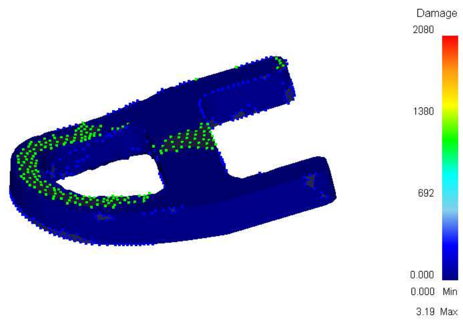

Fig. 7 Distribution of damage of professional bicycle pedal

V. CONCLUSIONS

This study utilized finite element software to simulate the plastic deformation behavior of an 7075 aluminum alloy during the forging process. Results show that the optimal parameter settings for the forging process are: (1)A1, workpiece temperature (20^{o}C); B2, mold temperature (150^{o}C); C2, forging speed of 60 mm/sec; and D1, friction factor,0.25; (2) the factor with the highest contribution percentage is workpiece temperature and forging speed, at 99.99%, while the factor with the lowest contribution percentage is the mold temperature and friction factor, at 91.2%,and 91.66%; and (3) the greater effective stress on the periphery of the professional bicycle pedal. We forecast three combinations for the optimal combination of parameters, as well as the effective strain, effective stress, and die load distribution in professional bicycle pedal using a perfect design (A1B2C2D1). These results indicate the ideal specifications of the new design's mold and die: the mean of effective strain is 4.58 mm/mm; the mean of effective stress is 834 MPa; and the mean of die load is 5860 kN.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support of the National Science Council of the Republic of China under Grant No. NSC 100-2221-E-018-012.

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