TOOLING DESIGN IMPROVEMENT OF MULTISTAGE COLD FORGING OF SPECIALTY SHAPED NUTS USING CAE AND 3D PRINTING

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ABSTRACT
Given its critical role in the fastener industry, cold forging is widely performed in automotive production, manufacturing, aviation, and 3C products. Personnel experience and trying error approaches provide a subjective and unreliable background despite their extensive use in fastener forming and die design owing to the difficulty in controlling the development schedule. This study used DEFORM-3D analysis software to investigate the die service life from producing specialty shaped nuts in a multistage cold forging process. Effective stress, effective strain, velocity field, and other quantitative metrics of dies and work-pieces can be obtained from numerical simulations. Herein, 3D printing technology is also implemented to create cold forging dies and deformed work-pieces for assessing the dimension of tooling assembly. This process allows engineers to gain a better understanding of the tooling design at development phase and derives the parts, which were previously just simulation results from DEFORM-3D forming software. Results can help a multistage processing factory establish a cold forming capacity for the development of new products. Consequently, the ability of self-design and self-manufacture of specialty shaped fasteners in Taiwan could be increased widely to enhance the international competitiveness of domestic industries.

Keywords: die service life; special shaped nut; 3D printing technology; multistage process.
NOMENCLATURE

\[ A_0 \] initial cross-sectional area
\[ h \] height
\[ h_0 \] initial height
\[ P \] load
\[ r \] reduction ratio

Greek symbols

\[ \sigma_0 \] engineering stress
\[ \epsilon_0 \] engineering strain
\[ \sigma_t \] true stress
\[ \epsilon_t \] true strain

1. INTRODUCTION

The forging process, which refers to changing the shape of metal materials with pressure to form them into particular sizes and shapes possessing certain mechanical properties, is an important technology in the fastener industry. That is, part of an entire piece of metal material is changed in height and width by compression or extrusion processes to form the required shape. A forging die affects the quality, cost, and efficiency of its product; therefore, it is important to tooling design and verifies its reliability rapidly to enhance its industrial value.

O’Connell et al. [1] developed the Slab method and Finite Element Method DEFORM-2D in 1996 to calculate the forming loading of hexagon bolt flashless close die forging to help choose a suitable forming machine and avoid wasting energy and reducing production speed. Park et al. [2] considered friction, slippage, punch speed, and geometric shape of a billet in the cold forging rotational upsetting process for discussing cold forging pressure and forming force, which was further verified by experiments. In comparison to the traditional cold forging upsetting process, deformation distribution of the rotational upsetting process, total deformed height, forming force, and axial load were reduced. Wu et al. [3] analyzed axisymmetric extrusion forging with Finite Element DEFORM software to determine the effects of die parameters on formability. Their analysis presented few effects of the tilt angle of the die hole and the fillet size on forming force, instead focusing on the effects of extrusion height and width of forges. Under a larger tilt angle and smaller fillet, a larger extrusion height will enlarge the extrusion width. A 3D contour chart relating die tilt angle, fillet radius, and forming plasticity strain was made to observe distribution trends. The present research also verified relevant extrusion forging experiments. Landre et al. [4] simulate the 1040 carbon steel cylindrical compression process with Finite Element software to investigate the effects of three different preform billet shapes on forming limit, predict strain location where billets fail, and compare process-applicable criteria to the failure ratio. Min et al. [5] proposed a new method to produce high-precision mobile steering yokes, where the application of a rigid-plastic Finite Element Method to the high-precision cold forging process can effectively reduce development time and production cost. In their research, DEFORM was utilized to simulate and analyze the mobile steering yoke cold forging process. This was further verified with experiments and the result successfully applied to mass production. Hsia et al. [6–9] analyzed fastener cold forging with DEFORM-3D Finite Element software to integrate fastener theory and practice and thus improve the fastener forming process. Their results defined stress, strain, and die loading during the forming process for use in process improvements or new process research and development.

The cold forging process is a multi-function and high-strength forming technique, presenting great benefits to corporate competitiveness and reducing the costs of high-precision and high-value added products [10, 11]. It also plays an important role in green production for saving material and energy and reducing other environmental loadings. With the introduction of computer integrated applications (CIA) and CAD/CAE/RP
processes, the rapidly developing 3D printing technology is being applied by engineers as a method for rapid cold forging die design. By this research, wastes caused by the uncertainty can be reduced. And the expense of developing a mold, which is compared to try-error or personal experience, is also decreased to promote the competitiveness of the fastener industry.

2. METHODOLOGY

2.1. Research Methodology and Procedure

In this study, a workflow chart of the steps taken is shown in Fig. 1. The multistage process for special nuts, which includes 3D geometric model files of die and billet, was planned and established using SolidWorks commercial software and converted to STL format for constructing the 3D printing file. DEFORM-3D was used in the analysis of forming and the rationality of its result afterwards. The analytical results are presented with 3D modeling technology. AISI 1010, a carbon steel containing C 0.08 ∼ 0.13%, Si 0.10%, Mn 0.30 ∼ 0.60%, P below 0.04%, and S below 0.05%, was chosen as the product for analysis. Material core diameter was 7.8 mm, core material processed with 2 ball 2 pumping, and hardness below HRB 60. The cold forging process was divided into five main stages (Fig. 2) and a mold was divided into upper punch, lower punch, and die (Fig. 3). The punch was placed in the die insert and extruded by a slab to form the material into the required shape, and the product was then ejected. The positioning of the punch and the die insert do not need to be considered. The upper module was used for guiding the counterpoint of the punch and the die insert. In addition to the ejection effect, the ejector also presents a forming function. The first and second passes preformed the material, the upper and lower design through-holes in the third pass having a guiding function, and the inner hole is created during the fourth pass. Some inner-hole forming was done during the fourth pass, and a deep hole in the design continued to form in the fifth pass and was slightly shaped, to complete the design’s shape and size.
2.2. Compression Experiment
Simulations should precede compression tests in order to acquire the load and strain (displacement) values of the material and estimate its stress-strain curve and forgeability flow curve (Fig. 4). An axisymmetric cylinder was placed under an axial (z-direction) load, the strain measured along the axis being axial strain. In practice, a universal testing machine would be used for the compression test. Load and strain values were recorded for estimating engineering and the true stress/strain values. In general, after test specimen height reductions reached 60%, failure values could not be continuously acquired by strain measurement because of excessive deformation. However, the failure values of more ductile materials cannot be acquired by this test.

To obtain more accurate simulation results, a simple compression test was utilized for acquiring the true stress-true strain curve of the material for simulating fine fastener cold forging with Finite Element software DEFORM-3D. The equations for the compression test are shown below.
Fig. 4. True-stress and true-strain curve of AISI 1010 and compressed specimens.

\[ \sigma_0 = \frac{P}{A_0}, \]  
(1)
\[ 52 \varepsilon_0 = \frac{h_0 - h}{h_0}, \]  
(2)

where \( \sigma_0 \) is the engineering stress, \( \varepsilon_0 \): engineering strain, \( P \): load, \( A_0 \): original cross-sectional area, \( h_0 \): original height, and \( h \): height. The equations for true stress and true strain are shown below.

\[ \sigma_t = \sigma_0 (1 - r), \]  
(3)
\[ \varepsilon_t = \ln(1 - r)^{-1}, \]  
(4)

where \( \sigma_t \) is the true stress, \( \varepsilon_t \): true strain, \( r \): reduction, and \( r = h_0 - h/h_0 \). The test specimen was compressed through a universal testing machine to acquire the loading schedule, which was further used for calculating true stress and strain and constructing the flow stress curve using Grapher software program.

AISI 1010 test specimens were first cut into billets similar to the special nut; with external diameter and length ratio being about 1:1.5 (actual external diameter was 6 mm and height 9 mm). They were then compression-tested with a universal testing machine under a pressure of 100 tons. Test specimens were covered with lubricant (manganese dioxide) before compression so that the material was close to actual production line conditions. After compression (Fig. 4), test specimens were presented with strain test reductions of 30, 60, 75, and 90%. The loading, schedule, and times of the experiments were recorded and Excel used for calculating true stress and true strain. These values were then applied to Grapher for acquiring a power-law flow stress curve (Fig. 4) and flow stress equation \( \sigma_t = 633.63 \varepsilon^{0.13} \), where the strength coefficient 633.63 is the strength coefficient and 0.13 the work hardening exponent.

2.3. DEFORM Simulation
DEFORM-3D Finite Element software was applied to simulate the cold forging of specialty nuts. DEFORM-3D was used for simulating and analyzing various passes, and the data for billet, punch, and die as well as AISI material settings which were inputted, and the material’s property considered rigid-plastic. Young’s modulus and Poisson’s ratio were 210 GPa and 0.3, respectively, the flow stress equation acquired from the compression test showed \( \sigma_t = 633.63 \varepsilon^{0.13} \), and constant shear friction factor \( m = 0.12 \).

In terms of billet mesh setting, the minimum feature size of the billet was regarded as the basis and one-third of the feature size was the minimum side for convergence analysis. Forging loading was analyzed when the workpiece filled the die. When the loading difference in comparison to the previous number of meshes was within 0.01%, it was considered convergence. The punch speed in the process was assumed
to be 420 mm/sec. The analytical results can be used for discussing the differences between the simulated pass process and the field process and for evaluating the effective stress-strain, material flow, and reactions of the simulated predicted material to the punch during forming. They are used as the evaluation standard for punch and die strength in die design.

2.4. Printing Technology
3D printing, or additive manufacturing (AM), is a quick forming technology for the direct manufacturing of 3D entities of any shape based on digital model files. Adhesive metal or plastic powder is applied in 3D printing to construct an object through “additive manufacturing”. Different from traditional mechanical processing, which often uses cutting or drilling (material reduction) for die production and industrial design, 3D printing is often used for producing molds and is gradually applied to the direct manufacturing of products. In particular, some high-value products (e.g. hip joint, teeth, and airplane parts) have been printed, revealing the popularity of 3D printing.

A digital material printer is generally used for 3D printing. Computer aided design (CAD) or computer animation software is first used for establishing a mold, which is then “separated” into layered cross sections, and then the printer is guided for the printing. STL files are the coordination format between the design software and the printer. An STL file simulates the surface of an object with triangular facets such that smaller triangular facets generate surfaces with higher resolution. After reading the cross-section STL files, the printer prints the layers with liquid, powder, or chips of material, which are further adhered to become a solid physical object. Traditionally, it normally requires several hours to several days to produce a mold, depending on its size and complexity, whereas 3D printing can reduce the time to several hours, depending on the size and complexity of the mold as well as printer efficiency. Traditional manufacturing, such as injection molding, largely produces polymer products at lower costs, while 3D printing can more quickly, flexibly, and economically produce small quantities of products. A merely table-sized 3D printer can satisfy the demands of a designer or a development team for producing molds.

3. RESULTS AND DISCUSSION
This study used software simulation in an attempt to acquire distinct information after various passes of formation and present analytical results with 3D printing. The result of this study can be used for engineering the design of a cold forging die to reduce time and development costs. Figures 5–9 show the analyses of special fasteners from first through fifth passes. Since stress affects the life of materials and the forming process and its results, higher stress presents higher hardening exponents that the material might not easily
process. Besides, stress is generally focused on corners in the processing that the fillet is designed for so that the material can flow smoothly in a die. Strain information can help in understanding the deformation and the velocity field presents knowledge of material flow in the cavity during the compression process. Figure 5 shows first pass preforming, the maximum effective stress being 672 MPa and the maximum effective strain 2.31 mm/mm. Deformation appeared on the turning corner in the die and the fastest velocity field of 961 mm/sec appeared at the head. Figure 6 displays the second pass, where a guiding hole was required to avoid buckling; the maximum effective stress of 672 MPa and maximum effective strain of 2.78 mm/mm appeared on the upper and lower periphery and turning corner, respectively; and the maximum velocity was 1,050 mm/sec. Figure 7 presents side forming in the third pass, when the maximum effective stress of 675 MPa was concentrated on the material and the lower periphery, the maximum effective strain was 7.31 mm/mm, and the highest velocity field 533 mm/sec. Figure 8 demonstrates that in the fourth pass, during which a deeper hole was made within the guiding hole during the second pass, that the bottom was made into an aperture shape with a punch and served as the guiding hole of the next pass. The fourth pass produced a maximum effective stress of 676 MPa, maximum effective strain of 5.74 mm/mm, and maximum velocity field of 1000 mm/sec at the top of the periphery. Figure 9 depicts the fifth pass, when the guiding hole from the previous pass continued to form the deeper design size. The maximum effective stress on the fifth pass was 675 MPa and maximum effective strain 4.90 mm/mm, appearing at the inner aperture and the periphery, and the maximum velocity field was 463 mm/sec. In the five-pass processing of special fasteners, flash appeared on the second pass and the cavity at the third pass was oversized so that compressed material could not reach design size. The material forming height was set at 11.97 mm in this pass while the
maximum compressed height was merely 11.78 mm, a 0.19 mm difference. More compression would have resulted in flash and smaller height. Deformation was so obvious after the third pass that folds appeared on the bottom of the specialty fastener after compression.

This section analyzes the die formation for special shaped fasteners and simulates the forging load from the first stage to the fifth stage, as shown in Fig. 10. The forging load at various stages is shown below. In the workpiece reshaping at the first stage, the die approaches closed forging in which the forging load, 159.37 kN (about 8.17%), is second small when comparing to other load. In the reshaping forming at the second stage, the engineering resembles the first stage, and the forging load reveals 271.43 kN (i.e. about 13.91%). In the guiding function third stage, the forging load, 573.25 kN (i.e. about 29.38%), appears to linearly increase as the material flow space is restricted. In the inner-hole forming with closed upsetting at the fourth stage, the forging load, i.e. 869.82 kN (about 44.58%), is the largest among all stages. With the same engineering as the third stage, the extending stroke at the fifth stage is 19.85 mm, and the forging load, 77.15 kN (i.e. about 3.95%). It is obviously less than the other stages. Overall, the total forging load for special nuts from the first stage to the fifth stage shows 1951.02 kN.

Figure 11 displays the workpieces after DEFORM simulation at different stages, in which they are the result of 3D printing with DEFORM 3D Finite Element Analysis. Figure 12 presents 3D printing of the upper punch, workpiece, die, and lower punch for the fourth stage. Obviously, good configuration agreement is illustrated between the simulation and 3D printing results. By the color representation in 3D printing results, the dimension clearance between designed tooling and formed workpiece is easily found. This process allows engineers to gain a better understanding of the tooling design and development phase and touches on parts that were previously just simulation results from DEFORM-3D forming software. The
Fig. 10. Forging force versus stroke in each stage.

Fig. 11. 3D printing using products of the workpiece from first to fifth stages.

| Upper punch |  
| Die |  
| Workpiece |  
| Lower punch |  

Fig. 12. 3D printing using products of the upper punch, lower punch, workpiece, die, and mold system at the fourth stage.
results can help a multistage processing factory establish a cold forming capacity for the development of new products.

4. CONCLUSIONS

The development and design of a new automobile product begins with the production of high-cost parts, which are manufactured in mass production mechanically to reduce costs and enhance profits. Previous designs relied upon experience with similar products and often involve several iterations of failure. Lost time and costs can be made up with continuous production and improvement. Based on our preliminary numerical analysis and 3D printing technique as applied to specialty shaped fasteners and relevant analyses are summarized below:

1. The application of DEFORM 3D enables the dynamic simulation of fastener forming during pre-design simulations in the development of new products.

2. Cold forming close upsetting generates a forging load of 869.82 kN (44.58%) at the fourth stage, which is the maximum for all stages of forming.

3. 3D printing technology with numerical simulation can be used in the design of process modeling to reduce human resource and production costs.

REFERENCES


