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Establishment of a Predictive Model for Cold Forging Force in Fastener Manufacturing Using Numerical Analysis †

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Abstract: Precise metal parts are manufactured using cold forged screw forming, but this method has drawbacks such as material damage and the possibility of imprecise parts. To ensure the accuracy and quality of parts, it is crucial to analyze and predict the forging force in this process. There are various methods to predict the forging force including laboratory testing, numerical simulation techniques, and simulation techniques. To provide forging information that cannot be measured by forging-forming machines, we simulated the nut-forming process based on actual manufacturing conditions using SolidWorks (v2020) with DEFORM-3D (v6.1). The results showed that the performance of the prediction of forging force specifications by the currently available nut-forming machines was improved by 8−20%. As the product becomes larger, the difference in forging force also increases proportionally. This research result, combined with appropriate experimental analysis, can be used as parameter controls for manufacturers in the future implementation of smart manufacturing.

Keywords: predictive model; cold forging force; fasteners; DEFORM-3D software

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1. Introduction

In nut production, the industry uses nut-forming machines. Due to the different design dimensions of nut-forming machines, machines with different forging forces are required. The size of nuts produced by this machine depends on the design of its forging force. In the past, the industry relied on accumulated practical experience and repeated testing results to design the forging force of the machines. The forging forces listed by different manufacturers for the same specification of forming machines are, accordingly, not consistent. For nut manufacturers, costs are an important factor. Thus, accurate specifications of nut forging forces provided by the machine manufacturer are important for nut manufacturers. Therefore, if the result of simulation and analysis using the software can be combined with the practical experience of designers for cross-data comparison and mutual verification, reasonable and effective design criteria can be obtained to reduce costs and enhance the overall competitiveness of the enterprise.

Matthew O'Connell et al. [1] developed the slab method with a finite element method DEFORM-2D to estimate the forming load of hexagonal head bolts without flash closed-die forging. The method was used to select suitable forming equipment to reduce energy consumption and increase the production rate. Kim et al. [2] used the FORMEX and DEFORM finite element software to design a process and establish a database for the process. They reduced the time for forming process sequencing and mold design during product production. Vazquez et al. [3] compared the use of tungsten carbide insert and segmented insert in cold forging dies and explored the influence of material changes on die life using the DEFORM finite element software. The results could be used to reduce the cost of forging dies by calculating the cold forging die life. Falk et al. [4] proposed a

method related to the volume of forged parts using the DEFORM finite element software and provided and validated a simple and accurate estimation of the life of cold forging dies. Lee et al. [5] analyzed the axial extrusion process and designed parameters such as axial diameter, die corner radius, and friction coefficient with the finite element method. They investigated the individual effects. The research results showed that all design parameters including the axial diameter influenced the forming load, while increasing the die corner radius reduced the maximum forming load. The simulation results were consistent with the experimental results. MacCormack et al. [6] proposed multi-stage cold forging analysis using the finite element analysis software DFFORM for aerospace engineering key locks. The strain distribution, three stages of failure, and flow patterns were observed after product forming, allowing for the understanding of failure values and equivalent strain values, as well as identifying the locations of maximum failure values and maximum equivalent strain values.

Behrens et al. [7] performed a failure analysis of various production processes using the MSC.SuperForm2002 finite element analysis software. They investigated material fractures in cold forging and warm forging and showed that the generation of surface cracks and material damages was reduced by slightly modifying the geometric shape of critical components. Landre et al. [8] investigated the influence of three different preform shapes on the forming limits of the billet and predicted the strain locations of billet failure using finite element software to simulate the cylindrical compression process of 1040 carbon steel. The suitability of various criteria was compared using the fracture ratio. Kim et al. [9] conducted a multi-stage forming analysis of automotive steering joints using the DEFORM-3D finite element analysis software. A new process was proposed to improve product performance, increase production efficiency, shorten development time, and reduce costs for large-scale production. Hsia et al. [10] studied the extrusion processing of thin-layer aluminum products. In the simulation of the product, difficulties were found in welding when the material entered the welding chamber, which affected the subsequent forming analysis. By using the DEFORM-3D forming software, the development speed of the product was increased, development risks were reduced, and product quality was improved. Optimizing the extrusion forming of aluminum materials was important in extending the life of the mold. Hsia et al. [11] noted the scarcity of production techniques related to hobbing forming in previous studies. An example of a pointed tail tooth plate mold for iron sheets was investigated with the drawing software SolidWorks (v2012) and the DEFORM-3D (v6.1) finite element analysis software. They simulated plate hobbing to determine the conditions in hobbing forming. The consistency between the numerical analysis results and the actual finished products was determined to provide better quality and increase customer satisfaction.

Based on the previous results, we analyzed the forging force in the cold forming of screws. Cold forming of screws is a common metal processing method to manufacture various shaped parts. However, due to the complexity of cold forming of screws, there are unknown mechanical behaviors. Therefore, it is necessary to analyze the mechanical behavior of cold-forming screws to better understand their mechanical behavior. Firstly, we introduced the basic principles and mechanical behavior of cold-forming screws. Next, using the basic principles of simulation software, their functions and applications were reviewed. As there is limited research on thread rolling, we adopted examples of a plate with pointed teeth. We used SolidWorks to import the finite element analysis software DEFORM-3D and simulated plate thread rolling. The result was used to allow for the rapid and accurate determination of the conditions and directions of thread rolling. The DEFORM-3D simulation software was used to analyze the mechanical behavior of cold-forming screws to understand their mechanical behavior. The results of this study contribute to a better understanding of cold-forming screws and provides a reference for future research and applications.

2. Materials and Methods

2.1. Research Methods

In the design of the method in this study, the cold forging of external and external hexagon flange screws was considered. Finite element software was used to simulate and analyze the forming process to understand the corresponding stress and strain variations generated during the cold forging process. The simulation was conducted to verify the forging force generated during the production of screws and provide a reference for the improvement of the design. The mold design drawings provided by "Chung Hsing Ta Mold Co., Ltd. (Tainan, Taiwan)." were created using SolidWorks for three nut specifications: M18, M20, and M22. Since we focused on the magnitude of the forging force, the female die and the back punch were merged in the drawings. The workpiece material was made of low-carbon steel material C1010 in order to model it using the DEFORM-3D preprocessor. The material parameters were set using the built-in parameters of DEFORM-3D. The simulation was conducted in the 5 stages of forging. After analysis, post-processing was conducted to output the peak forging force and compare the result with those of various manufacturers.

2.2. Material Mechanical Properties

The material used in this study was low-carbon steel C1010. The mold used in the formation of hexagonal nuts is shown in Figure 1. It consisted of a front punch, back punch, die insert, and die casing. In practice, the front punch must be made of high-speed steel SKH55, the back punch must be made of SKH9, the die insert must be made of WC, and the die casing must be made of SKD61. However, since we focused on the design of the nut-forming machine, the mold materials were assumed to be rigid bodies in the simulation to prevent deformation caused by unnecessary idle energy and excessive forging force, which increased production costs.

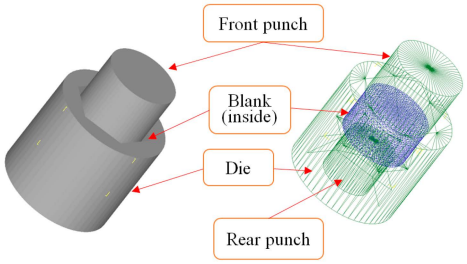


Figure 1. Configuration diagram showing the positions of the die, punch, and forging blank.

2.3. DEFORM Simulation Parameter Planning

The DEFORM-3D simulation software was used with the following conditions. During the forming process, except for the workpiece, all other mold components were regarded as rigid bodies, and the cold forging temperature was set to room temperature at 20 °C. The material selected was C1010, and the speed of the punch was set to 7.36 mm/s downward, with a step size of 0.1 mm per movement. The friction interface coefficient was set to 0.12 in the constant shear friction mode. Relevant simulation parameters are presented in Table 1. Figure 1 illustrates the configuration of the die, punch, and forging blank positions.

Table 1. Parameters for the forming simulation.

Mesh type	Tetrahedron
Material of blank	C1010
Blank/die property	Plastic/rigid

Table 1. *Cont.*

Temperature	20 °C
Speed of punch	7.36 mm/s
Quantity of mesh	90,000
Step distance	0.1 mm
Friction model	Constant shear friction
Coefficient of friction	0.12

2.4. Convergence Analysis

After establishing the workpiece and mold model and importing them into DEFORM-3D, element construction was performed. Finite element software was used for a numerical analysis method to divide the mesh for the structural analysis. As the number of meshes increases, the accuracy of the numerical analysis results increases, but the computational load also increases. With more data, the simulation calculation time also increases. Therefore, it is necessary to balance between achieving the accuracy of the simulation results and reducing the simulation calculation time by performing convergence analysis on the mesh. The convergence analysis method was used to compare the forging force in the Z-axis when the workpiece filled the mold with the difference in meshes. The difference in simulated load between the current and previous mesh numbers within 0.5% convergence was considered. Using the M18 workpiece material, the first forging consisted of 24 steps. The simulation was conducted with a mesh range of 10,000 to 100,000 in intervals of 10,000. The simulation results showed that convergence was reached when the mesh number reached 50,000. Based on actual factory interviews and considering current computer performance, a mesh number of 90,000 was used for the cold forging analysis to ensure the accuracy of the simulation results.

2.5. Calculation of Punch Speed

When simulating the 5-step forming of an M22 nut using DEFORM-3D, the speed of the front punch was initially set to 1 mm/s. After completing the entire process, 25 s were spent. The estimated production speed of the nut was 12 pcs/min, which was significantly different from the commonly set 100–140 pcs/min in manufacturer catalogs. In the second simulation, a speed of 350 mm/s was used, and 0.06 s were spent. The estimated production speed of the nut was 5000 pcs/min. In the third simulation, a speed of 8 mm/s was estimated, taking approximately 2.6 s. The estimated production speed of the nut was 118 pcs/min. If the simulated production rate was 100 pcs/min, and the average of the results from 3 simulations was used to calculate the velocity of the punch, then the velocity was 7.36 mm/s.

3. Results and Discussion

We estimated the forging force and related forming information for different workpiece dimensions using simulation methods. The data generated from the DEFORM-3D simulation were analyzed using linear regression to identify the forming trends. These results were then compared with the forging force data collected from manufacturer catalogs. The findings were expected to be used as a reference for forming machine manufacturers and nut manufacturers in terms of procurement costs and production management.

First, mold drawings provided by "Lian-Shyang industries Co., Ltd. (Tainan, Taiwan)" were created using SOLIDWORKS (v2020) and converted into STL files for simulation using DEFORM-3D (v6.1), as shown in Figures 2–4. However, there were differences between the simulated shape and the actual product (Figure 5).

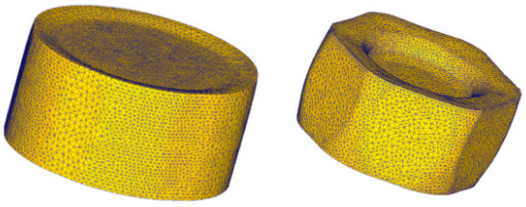


Figure 2. Completed blanks for the first pass (**left**) and the second pass (**right**).

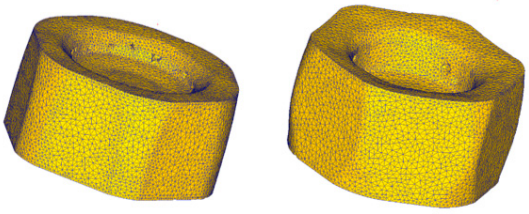


Figure 3. Completed blanks for the third pass (**left**) and the fourth pass (**right**).

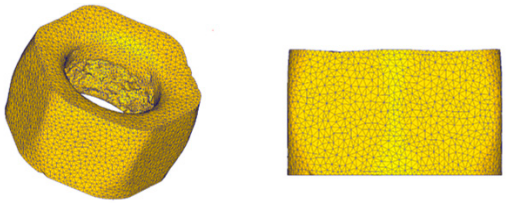


Figure 4. Completed blank for the fifth pass (**left**) and front view (**right**).



Figure 5. Actual stamped blank shape on-site.

The DEFORM-3D post-processing operation was used to extract the forging force data (Figure 6), and the sum of the peak forging forces for the punch was calculated as 183.3 tons using EXCEL. After identifying this error, the simulation was re-conducted, and the corrected workpiece profiles were obtained.

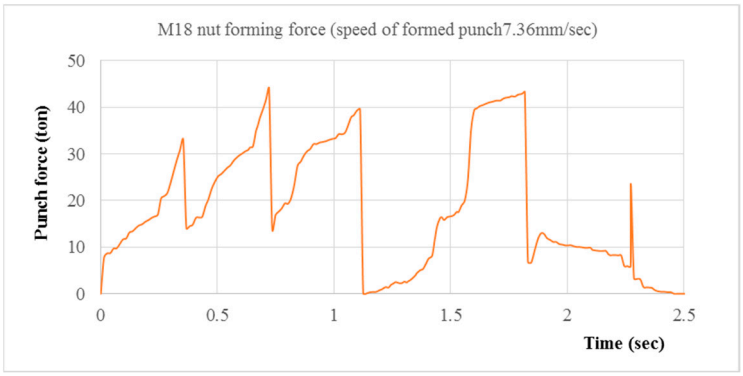


Figure 6. Distribution of the forging forces for the M18 nut.

Interviews were conducted with on-site engineers from "Lian-Shyang industries Co., Ltd. (Tainan, Taiwan)" and "NES LIMITED (Kaohsiung, Taiwan)" Both engineers confirmed that the mold shapes were correct and stated that in practical applications, it was crucial to

avoid overflow during the simulation like in DEFORM-3D (Figure 7). The punch stroke must not be adjusted to the extent that the punch and the workpiece come into direct contact, as this might rupture and damage the punch and the mold. Therefore, the stopping position after each step was chosen to be about 0.1 mm before overflow, and attention must be paid to the geometric symmetry of the workpiece (Figure 8), as it affected the symmetry of the final product.

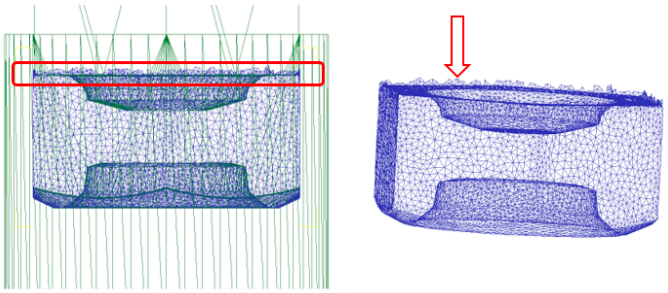


Figure 7. Excess material condition during the forming software simulation.

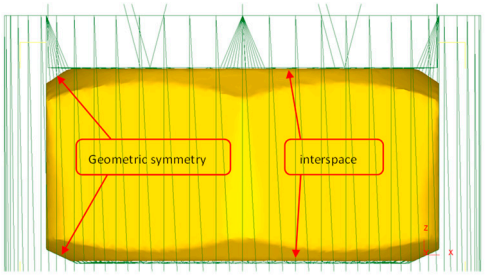


Figure 8. The gap between the mold and material, as well as the symmetry of geometric shapes during the analysis.

The corrected sketches were converted back into STL files and imported into DEFORM-3D for simulation. Since the mesh used was 90,000, a complete five-step simulation took approximately 18 h. After the simulation, the DEFORM-3D post-processor was used to obtain the relationship between the forging force and time for the punch. The data extracted from DEFORM-3D was then used to plot the relationship graphs for each step using EXCEL (Figure 9) and calculate the total forging force.

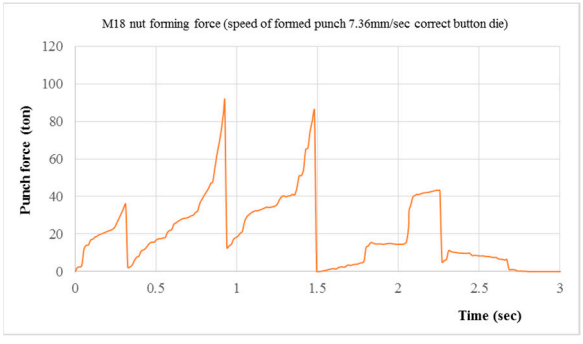


Figure 9. Distribution of the forging forces for five passes plotted in EXCEL using data extracted from the forming software.

From the extracted data, it was found that the sum of the peak forging forces for the M18 nut during the forming process was approximately 268 tons. On further inspection, an error was found in the original workpiece dimensions (height should be 14.43 mm but was incorrectly recorded as 14.13 mm). After making the necessary adjustments, the simulation

was re-conducted, and the data were processed using EXCEL, resulting in a total forging force of about 265 tons (Figure 10), with minimal difference.

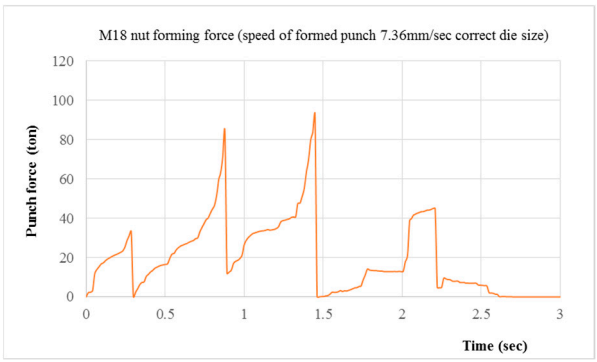


Figure 10. Calculation of the M18 nut simulation results extracted to EXCEL after correcting the original blank dimensions.

Similarly, the forging force data for the punch were extracted from the DEFORM-3D post-processor, and the sum of the forging forces was approximately 321 tons (Figure 11) and 329 tons (Figure 12) before and after correction, respectively. The same analysis process was repeated for M18 and M20, and errors in the original workpiece dimensions were identified. After correction, the data were extracted and used to plot the forging force relationship graphs for each step. The sum of the forging force peak values was approximately 343 tons (Figure 13) and 391 tons (Figure 14). The red box of the second pass in Figure 13 represented the corrected forging force, while the red box in Figure 14 represented the forging force before correction. Therefore, during simulation analysis, it is necessary to refer to practical experience in the field.

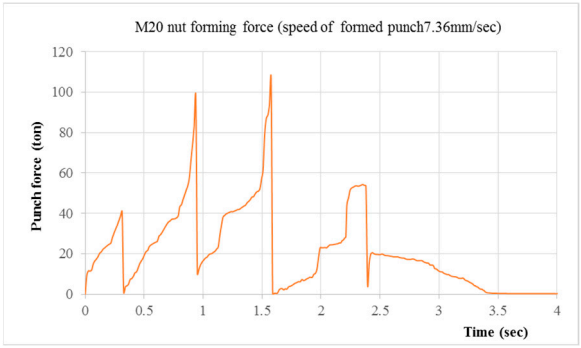


Figure 11. Distribution of the forging forces for the M20 nut at each pass.

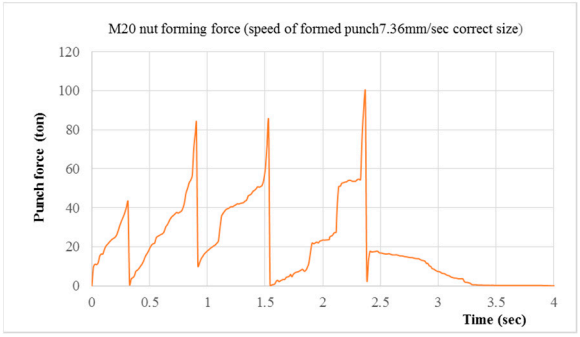


Figure 12. Distribution of the forging forces for the M20 nut at each pass after correcting the original blank dimensions.

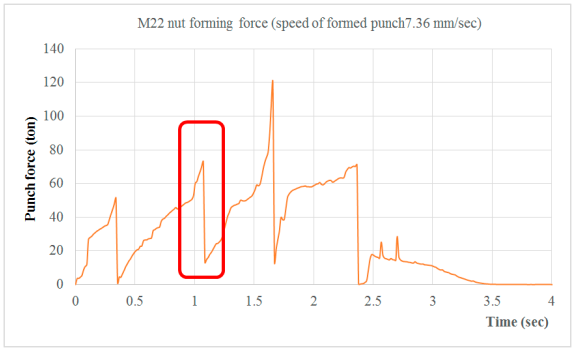


Figure 13. Distribution of the forging forces for the M22 nut at each pass; the area marked with the red box indicated the corrected forging force.

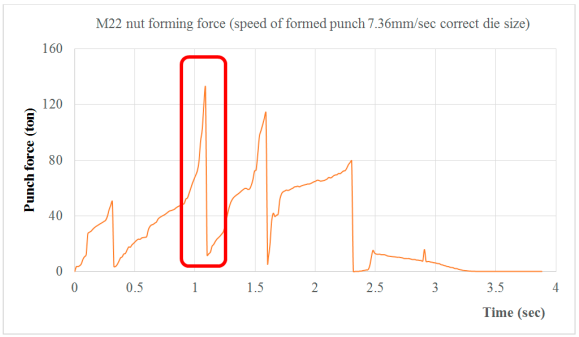


Figure 14. Distribution of the forging forces for the M22 nut at each pass after correcting the original blank dimensions; the area marked with the red box indicated the forging force before correction.

The results were obtained from the DEFORM-3D simulations of the M18, M20, and M22 nut-forming processes. Regression analysis was performed with the forging force set as the dependent variable (y) and the volume (or weight) of the original workpiece as the independent variable (x). From the data analysis, we obtained an equation $y = 0.0057x + 253.10$ (Figure 15). A comparison with the blank at 20 °C (●), using the manufacturer's catalog specifications (●), and the blank at 30 °C (●) revealed that the manufacturer's specifications were higher than the others. When the blank was set to a higher operating temperature, the forging force decreased significantly and uniformly.

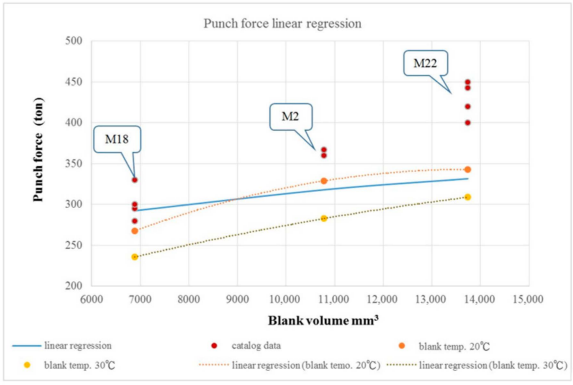


Figure 15. Comparison between the linear regression of forging forces from the simulation experiment and the manufacturer's catalog.

4. Conclusions

After a series of simulations and comparisons with the actual production process, the following conclusions were drawn from the results of this study. For the M18, M20, and

M22 nuts, the forging force specified for commercially available nut-forming machines was 8−20% higher than that from the initial simulation results. However, when considering the ambient temperature, the difference increased to 19−27%. Additionally, it was observed that the larger the size of the nut, the greater the disparity. The analysis result of abnormal simulation data showed that precise adjustment of the punch stroke was crucial as it directly affected the total forging force during the forming process. An experienced on-site engineer can maximize the efficiency of the machine and extend the lifespan of the mold based on the result of this study.

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