

THE EFFECT OF BLANK THICKNESS, CURVATURE RADIUS, AND FRICTION COEFFICIENTS ON THE QUALITY OF PRODUCTS IN THE METAL FORMING PROCESS USING ABAQUS

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Received: October 24, 2024; Revised: January 04, 2025; Accepted: January 29, 2025

Abstract

In recent years, mechanical techniques have been exponentially developing, among which metal forming is indispensable. The mechanical parts by this method often exhibit uneven thickness, directly affecting the durability of the product. This study investigates and analyzes the effect of material thickness, friction coefficient, and the fillet radius between the punch and die mechanism on the quality of the product using the metal forming method. The simulation process is conducted using Abaqus software, with the Taguchi method subsequently applied to evaluate the effect of the technological parameters. The results show that the material thickness and curvature radius have the greatest impact on the performance of the product.

Keywords: Abaqus; Blank thickness; Friction coefficient; Metal forming

Introduction

The metal forming process is a primary mechanical method for producing complex-shaped products from metal sheets. Its advantages include low cost, significant mechanical properties, high level of automation, and wide application in the manufacture of medical equipment, aerospace, and household appliances (Jeswiet *et al.*, 2005, Jackson *et al.*, 2008). The excessive thinning or thickening ratio of the deformation zone during the metal sheet forming process significantly affects the forming limit (Echrif and Hrairi, 2011). In their study of the thinning-thickening ratio of forming parts in single molds, Mingshun Yang and colleagues proposed

a progressive forming process, indicating that the excessive thinning ratio of the deformation zone during the progressive increase at a specific point in the metal sheet forming process significantly affects the forming limit (Yang *et al.*, 2018). Moreover, the thinning ratio directly correlates with the formability of the forming parts. Hence, investigating the thickness law of forming parts is of great significance (Li *et al.*, 2012). There are numerous studies worldwide on the thickness law of forming details. Bouffioux and colleagues (Bouffioux *et al.*, 2011) simulated the forming process and provided better predictions of thickness.

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DOI: <https://doi.org/10.55766/sujst7188>

Suranaree J. Sci. Technol. 32(1):010348(1-6)

Kim and Park (Kim and Park, 2002) analyzed the influence of processing parameters on thickness. Young and Jeswiet (Young and Jeswiet, 2004) found that the thickness of the deformation zone depends only on the forming angle through theoretical analysis and the use of the cosine law to predict the thickness value of the sheet. Hirt and colleagues (Hirt *et al.*, 2003) demonstrated the cosine law through experiments and finite element simulations.

During the forming process, CAM software is used to create molds based on the shape of the part, enabling the sheet to deform step by step and between the die and the part to achieve the required dimensions (Do *et al.*, 2016). This study focuses on analyzing the influence of blank thickness on the final material thickness, as well as the relationship between the friction coefficient and material deformation during the forming process.

Numerical analysis methods have been developed to simulate the forming process and predict outcomes based on these factors. A deep understanding of the blank thickness, curvature radius, and friction coefficient effects on the product's quality can help optimize the forming process, minimize waste, and enhance product quality.

In this study, a simulation model is constructed, with the results obtained using the finite element method through Abacus software. Utilizing simulation helps minimize experimental costs and ensures highly accurate results. The collected data are evaluated by the Taguchi method (Roy, 2010) to identify the effect of each factor on product quality through the following four steps: (1) define the objective and the factors; (2) utilize an orthogonal array based on the number of factors and levels for each factor; (3) conduct simulation to obtain results; (4) conduct an analysis of variance (ANOVA) with Signal-to-Noise Ratio (S/N) to explore the effect of each factor on product quality.

Methodology

Sheet metal forming method

Sheet metal forming is a popular manufacturing method used to create complex metal parts from flat metal sheets. This process is often employed in industries such as automotive manufacturing, aerospace, and various other industries that require precise and high-strength metal components.

Uneven thickness can significantly influence the durability of the part by causing stress

concentrations, dimensional instability, and poor surface quality. These issues depend on various factors, including the type of material, the forming technique, and the applied forming pressure. To minimize unevenness, it is important to use suitable materials, employ precise forming techniques, and apply proper forming pressure. Simulation could save time and manufacturing costs by achieving highly accurate results. In this study, experiments were conducted using three types of workpieces of various thicknesses: 1 mm, 2 mm, and 3 mm, with varying friction coefficients (0.1, 0.2, 0.3). The material used was HSLA420 steel with a radius of $R = 30$ mm.

Prandtl-Reuss model

This model applies the Reuss and Voigt coefficients (Thomas, 1955; Temam, 1986; Meaud and Hulbert, 2013; Dou and Xia, 2015) to estimate the thickness of the product in the metal forming method, as described by Equation (1).

$$h = h_0 \left(1 - \frac{\sigma}{E}\right) \quad (1)$$

Where:

- h is the thickness of the material after forming (mm)
- h_0 is the initial thickness of the workpiece (mm)
- σ is the forming stress (N/mm²)
- E is the modulus of elasticity (N/mm²)

The technological parameters are investigated and depend on the specific conditions of the forming process and the material's properties.

Determining the forming force using the Von Mises equation

The Von Mises stress is defined by Equation (2).

$$\sigma_{vM} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\tau_{xy}^2} \quad (2)$$

Where σ_{vM} is the Von Mises stress, σ_x and σ_y are the stresses in the x and y directions, respectively, τ_{xy} is the shear stress.

The forming force can be calculated by Equation (3).

$$F = A \cdot \sigma_{vM} \quad (3)$$

Where F is the forming force (N), A is the cross-sectional area to be stamped (mm²).

Simulation model in Abaqus

To save time and costs, this Abaqus simulation software is used in this study to simulate the metal forming process. The process using Abaqus software to simulate nine experimental cases is presented below.

The diameter and thickness of the workpiece are measured. The punch and die are discretized with rigid meshes, meaning that they would not be affected by the forces during analysis. The type and number of elements in the mesh remain constant throughout the simulation.

Design of punch and die

Figure 1 presents a simulation model in Abaqus while the punch and die are set as Discrete Rigid (completely rigid material). To shorten the simulation time, the punch is located close to the blank. Simultaneously, it is above the die, as shown in Figure 2.

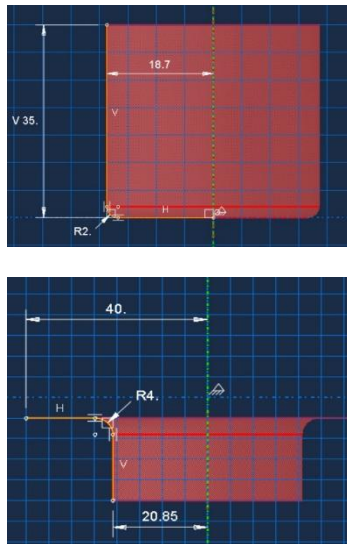


Figure 1. 3D design of the punch and die in Abaqus

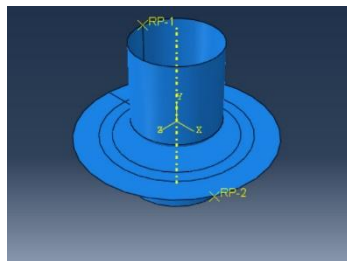


Figure 2. Metal forming in simulation

After creating the simulation steps, the components are fixed. First, two points are created on the punch and die using the Reference Point command in the Tools toolbar, and these are then

rigidly attached to the two blocks using the Constraint/Create command, selecting the Rigid Body mode. After attaching them, the points are then fixed using the Special command, and the values are added to the corresponding cells.

In real experiments, there is always friction between the component surfaces, so it is also necessary to create friction for the simulated surfaces in the Interaction module. In the Interaction Property Manager/Create card, friction coefficients for the surfaces are created by selecting the Contact type as tangential friction in the Tangential Behavior card and selecting Penalty to enter the coefficient. In the Surface to Surface/Contact mode, two surfaces are selected to create friction and define the friction coefficient.

In the Load module, the Boundary Condition Manager/Create card applies force to the two points on the punch and die, creating a single rigid block. This simulation fixes the die while the punch moves in the y-direction.

Material properties

After creating the three objects, namely the punch, die, and blank, the property module is manipulated to create material properties for the steel sheet blank to ensure accurate simulation. The chemical composition is detailed in Table 1, while properties such as the material density, elastic modulus, and Poisson's ratio of the HSLA420 material in the annealed condition are obtained from the literature on steel sheet metal and summarized in Table 2.

Table 1. Chemical composition of HSLA420 (Bringas, 2004).

Alloy composition	Percentage (%)
Carbon (C)	0.15-0.4
Iron (Fe)	82.3-87.9
Manganese (Mn)	<= 1.0
Silicon (Si)	<= 1.0
Nickel (Ni)	<= 0.75
Molybdenum (Mo)	<= 0.5
Phosphorus (P)	<= 0.04
Sulfur (S)	<= 0.03

Table 2. Physical properties of HSLA420 (Bringas, 2004)

Mechanical properties	HSLA420
Young modulus (GPa)	190
Poisson coefficient	0.3
Yield strength (MPa)	350
Tensile strength (MPa)	488
Density (g/cm ³)	7.8

The stress of the material was defined by the Swift law as described in Equation (4).

$$\sigma = K. (\varepsilon + \varepsilon_0)^n \quad (4)$$

Where K , ϵ_0 , and n are defined by the experiment as follows: $K = 832,7$; $\epsilon_0 = 0,013$; $n = 0,146$. A set of 20 values of σ was generated by changing ϵ in a range from 0 to 0.2 with a step of 0.001.

Meshing setup

To implement the simulation in this research, the meshing procedure of the model is as follows:

- Select the Seed Part to determine the mesh density of the components.
- Go to Mesh Controls and choose Hex mesh type to divide the mesh into squares, and finally, in Element Type, select Explicit.
- It is advisable to divide the metal sheet into at least three layers using the Seed command on the toolbar, selecting Edges. If the meshing density is finer, the simulation accuracy will be higher. However, for the first simulation run, it is recommended that a realistic mesh density be used to check for any errors during the process.

The workpiece is meshed into 880 elements, as shown in Figure 3.

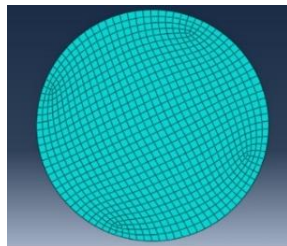


Figure 3. Meshing process

Results and discussion

Simulation results using Abacus

Figure 4 presents the results obtained from the simulation process using Abaqus software. As can be observed, the thinnest part of the product after stamping is at the bottom, measuring 0.93 mm, while the thickest part is at the top and equals 1.33 mm. The product from the metal forming process is shown in Figure 5. As can be observed, the shape of the product is similar to the simulation result, and its thickness is regular at the bottom and wall. For the metal forming method, the steel grains become elongated along the direction of deformation. The dislocation density increases significantly due to plastic deformation. This leads to strain hardening, which enhances the strength and hardness of the material. Residual stresses appear due to non-uniform deformation, and the residual stress is concentrated at a significant deformation

position, such as Position 1 or 2. Therefore, the simulation model is confirmed to be acceptable for the next stage of this research.

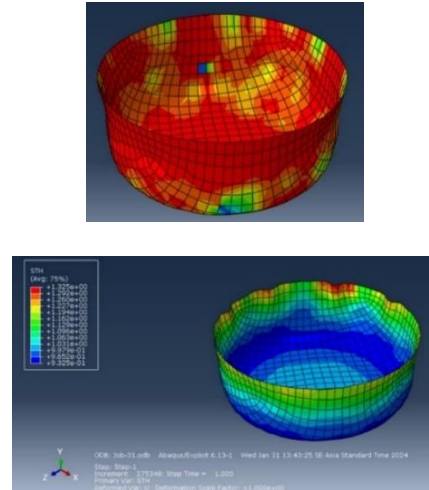


Figure 4. Simulation results



Figure 5. Product created from the metal forming process

Taguchi method and analysis of variance

The Taguchi method is a statistical approach developed by Genichi Taguchi aimed at improving the quality of manufactured goods and has also recently been applied to the fields of engineering and biotechnology (Miranda *et al.*, 2019, Duc *et al.*, 2018). Professional designers have embraced and continue to improve the Taguchi method in various studies. Although every production process is known to be affected by external influences, the Taguchi method has identified these impacts as significantly affecting product quality. Therefore, manufacturers worldwide have widely adopted this method because it generates superior production processes at low cost.

ANOVA partitions deformations in experiments into identifiable sources of variation and related levels. Additionally, ANOVA helps to analyze the percentage contribution of each influencing factor to the quality of the part after processing (Roy, 2010).

After performing the simulation process using Abaqus software, the thickness difference in the product is obtained for each corresponding case of a

certain blank thickness (A), curvature radius (B), and friction coefficient (C).

In the next stage, the Taguchi method and ANOVA are applied to evaluate the effect of the factors on the difference in the product thickness. The thickness difference in the product is defined by the difference between the maximum and minimum thickness. The product quality achieves the best performance when the thickness difference is minimal. Thus, this study uses the signal-to-noise (S/N) ratio with the target of “smaller is better” to measure the sensitivity of the quality characteristic. The S/N ratio is determined in Equation 5, where MSD denotes a mean of squared deviation. In the experiment, the Taguchi method is applied to the orthogonal array to reduce the number of experiments. Since each factor is investigated according to three levels, as described in Table 3, the orthogonal matrix of L9 is used, as shown in Table 4.

$$S/N = -10 \cdot \log(MSD) \quad (5)$$

Table 3. Factors with three levels

Factor	Process parameter	Level 1	Level 2	Level 3
A	Blank thickness (mm)	1	2	3
B	Curvature radius (mm)	2	3	4
C	Friction coefficient	0.1	0.15	0.2

Table 4. Orthogonal array of L9

No.	A	B	C	Surface quality	
				X	S/N
1	1	2	0.1	0.430	16.87
2	1	3	0.15	0.416	17.16
3	1	4	0.2	0.453	16.42
4	2	2	0.15	0.795	11.53
5	2	3	0.2	0.750	12.04
6	2	4	0.1	0.758	11.04
7	3	2	0.2	1.412	6.540
8	3	3	0.1	1.388	6.690
9	3	4	0.15	1.535	5.820
				$Y_{average} = 11.68$	

The aim of any experiment is always to determine the highest possible S/N ratio. A high value of S/N implies that the signal is much higher than the random effects of the noise factors (Roy, 2010). This paper utilizes the target of “smaller

is better” for better quality characteristics, thus, MSD is calculated by Equation (6).

$$MSD = \frac{(Y_1^2 + Y_2^2 + \dots + Y_n^2)}{N} \quad (6)$$

where Y_i is the thickness difference of the product, and N is the number of trials.

The effect of the factor is determined as the difference between the highest and lowest average S/N ratio across its levels. The percentage contribution of the three considered parameters, such as blank thickness (A), curvature radius (B), and friction coefficient (C), on the metal forming process are described in Table 5 and Figures 6-8. Factors with larger differences in average S/N ratio have a more significant effect on the response.

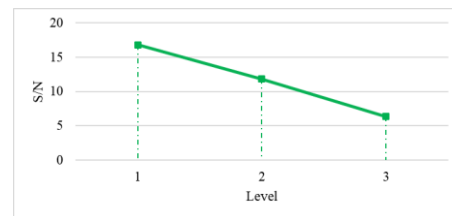


Figure 6. Effect of the blank thickness

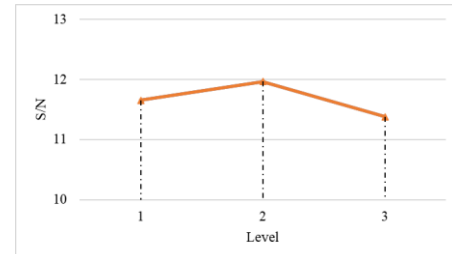


Figure 7. Effect of the curvature radius

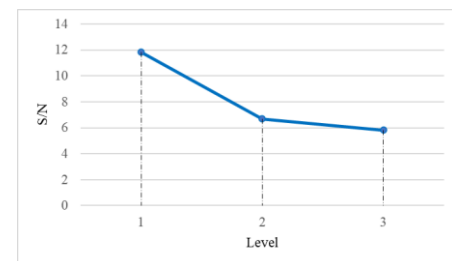


Figure 8. Effect of the friction coefficient

Table 5. Analysis of variance

Parameter	Average S/N ratio			Sum of squares	Percentage (%)
	1	2	3		
A	16.80	11.84	6.35	163.80	48.04
B	11.65	11.97	11.38	0.52	0.15
C	11.84	6.69	5.82	176.67	51.81

As can be observed, the effect of the friction coefficient (C) on product quality is 51.81%, followed by a blank thickness (A) of 48.04%. The curvature radius (B) has the smallest effect at only 0.15%. This means that the product quality is sensitive to changes in curvature radius and blank thickness.

Figure 6 illustrates the effect of blank thickness on the thickness difference in the product after the metal forming process, represented by a nearly linear graph with a relatively large gradient. This confirms that the blank thickness has a significant effect on product quality. Likewise, Figure 8 evidences an important impact of the friction coefficient where the line chart initially declines rapidly and decreases more slowly. The effect of the curvature radius is shown in Figure 7. Such a small change indicates that the curvature radius has a minor impact on the product's quality. It can, therefore, be concluded that the blank thickness and friction coefficient are sensitive to the thickness difference in the product, and the engineers involved should change them to improve product quality during the metal forming process.

Conclusion

This study examines the effect of blank thickness, curvature radius, and friction coefficient between the punch and die in the metal forming process using Abaqus software. The simulation results show that the friction coefficient has the most effect on the thickness difference at 51.81%, followed by the effect of the blank thickness at around 48.04%, indicating that these parameters are the most sensitive to the thickness difference in the product after stamping. The curvature radius evidences the smallest effect with a makeup of only 0.15%. It is, therefore, recommended that manufacturers adjust sensitive parameters such as the friction coefficient and blank thickness to improve product quality.

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