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Optimizing Formability in the Production of 304 Stainless Steel Parts: A Comprehensive Study Using SIMULIA ABAQUS and Taguchi Method

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Abstract: This research endeavors to enhance the formability of 304 stainless steel parts manufactured from SUS304 material. The application of SIMULIA ABAQUS software facilitates a numerical simulation of the sheet metal forming deformation process, enabling the prediction of formability, identification of optimal solutions, and mitigation of potential errors in the machining process. The study employs a combination of simulated deformation machining and experimental calculations based on the Taguchi orthogonal array, considering factors such as punch/die corner radius, friction coefficient, material thickness, and blank holder force in the simulation. Additionally, an analysis of variance (ANOVA) is conducted to assess the influence of these factors. The study identifies friction as the most significant factor affecting metal sheet forming deformation and determines the optimal set of technological parameters to achieve the highest product quality.

Keywords: Stainless steel 304; SUS 304; SIMULIA ABAQUS; Taguchi;

1. Introduction

The intricate process of manufacturing sheet metal products demands a nuanced understanding of the complex interplay between various processing and geometric parameters, each contributing significantly to the final quality of the product. In the realm of this study, we delve into the critical aspects surrounding the production of 304 stainless steel brass, where the anticipation and prevention of damage during the manufacturing process are central concerns. Employing finite element simulation, this study establishes itself as a robust and viable method for comprehensively addressing the challenges associated with the intricate world of sheet metal production.

To gauge the multifaceted impact of technological, machining, and geometrical parameters on the quality of the end product post-forming, our investigation extends beyond the existing body of knowledge. Drawing from the foundations laid by prior research [1-2], we integrate advanced methodologies, particularly utilizing the Finite Element Method (FEM) in tandem with the Taguchi orthogonal algorithm [3]. This strategic amalgamation allows for the systematic selection of an optimized set of machining parameters tailored to the specifics of the products under consideration.

At the heart of our approach is the utilization of the plastic deformation model, anchored by the Forming Limit Curve (FLC), recognized as the most suitable framework for analyzing sheet materials. Leveraging experimental data from the FLC curve of SUS304 material garnered from previous studies [4-5], our simulation endeavors to faithfully replicate the intricate forming shape of brass. The systematic exploration of key influencing parameters, namely blank holder force, die corner radius, friction coefficient, and sheet thickness, constitutes a comprehensive evaluation of their individual and collective impacts on brass formability.

The results stemming from our extensive Taguchi orthogonal table simulations are subjected to meticulous scrutiny and in-depth analysis. Through the application of ANOVA analysis of variance [4], we navigate through the intricate web of data to discern the correct parameter sets. This judicious selection ensures the identification of defect-free parameters, laying the groundwork for simulating the production of a high-quality end product. As we embark on this academic journey, our aim is not only to contribute to the existing knowledge base but also to pave the way for a nuanced understanding of the dynamics influencing the production of sheet metal products, thereby fostering advancements in the field.

2. Material and Product Properties

Product Technical Requirements:

The successful stamping of 304 stainless steel products demands strict adherence to technical specifications to ensure high-quality outcomes. The detailed requirements include:

Defect-Free Details (Shown in Fig. 1 and 2):

- The stamped details must be free from defects such as wrinkles, tears, and warping.

Smooth Surface Finish:

- The surface of the stamped details should exhibit a flawless, smooth finish, devoid of scratches, ensuring an aesthetically pleasing appearance.

Nominal Thickness:

- The nominal thickness of the stamped details is set at a minimum of 1 mm.

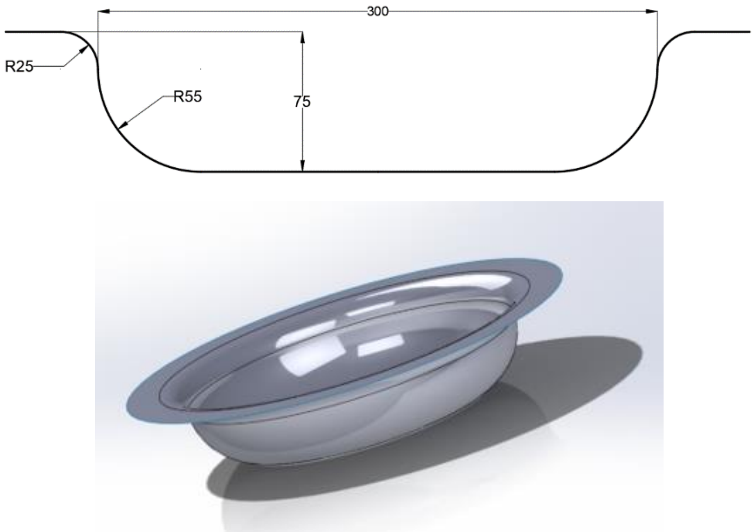

Figure 1. Dimensions and 3D Model of the Product - 304 Stainless Steel Products

Figure 2: Actual Product

Figure 3 intricately illustrates the stress curve specific to the SUS304 material, which serves as the primary constituent in the production of brass. This depiction is rooted in Swift's continuity equation, a mathematical framework chosen for its compatibility with small strain values. The utilization of small strain values is strategic, as it facilitates a meticulous examination and determination of the various parameters embedded within the equation.

Swift's continuity equation (1), when applied to the stress curve, emerges as a pivotal tool in discerning critical aspects of the material's behavior during the forming process. This equation is tailored to capture the nuanced interplay between stress (σ), deformation (ε), deformation deviation (ε0), and key material-specific parameters. The effectiveness of Swift's continuity equation is particularly accentuated when dealing with materials like SUS304, known for their intricate response to mechanical forces and forming conditions.

The stress curve encapsulates the material's response to the applied forces, offering insights into its elastic and plastic behaviors. By navigating the intricacies of this curve, researchers gain a profound understanding of how the SUS304 material behaves under various conditions, shedding light on its formability, resilience, and susceptibility to plastic deformation. Such insights are crucial for optimizing the manufacturing process, ensuring the desired product quality, and mitigating potential issues such as wrinkling, tearing, or warping. Material Characteristics in Table 1.

Table 1. Properties of SUS304 Material:

SUS304	Material
Density	7.8e-06
Elastic Modulus (E, kN/mm²):	193
Possion's Coefficient:	0.30
Strength (Mpa)	500
ε0	: 0.000177
K	864.2
n	0.195

$$\sigma(\varepsilon) = K(\varepsilon_0 + \varepsilon)^n \quad (1)$$

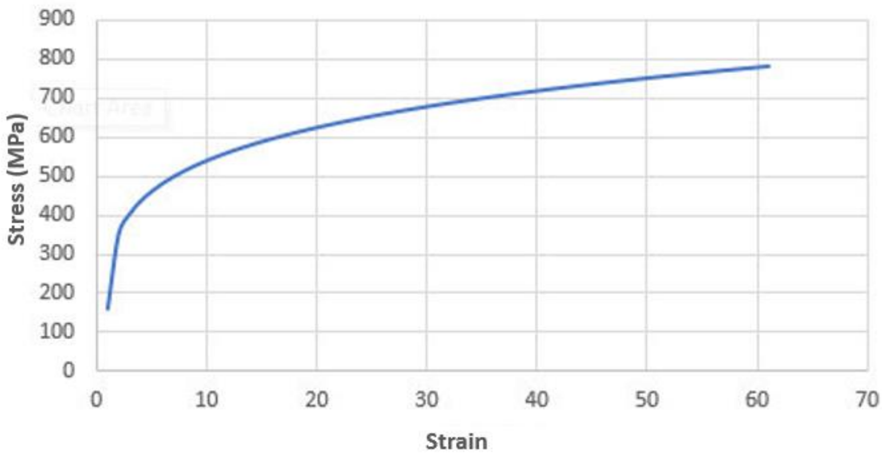

Figure 3: Stress-Strain Curve of SUS304 Material

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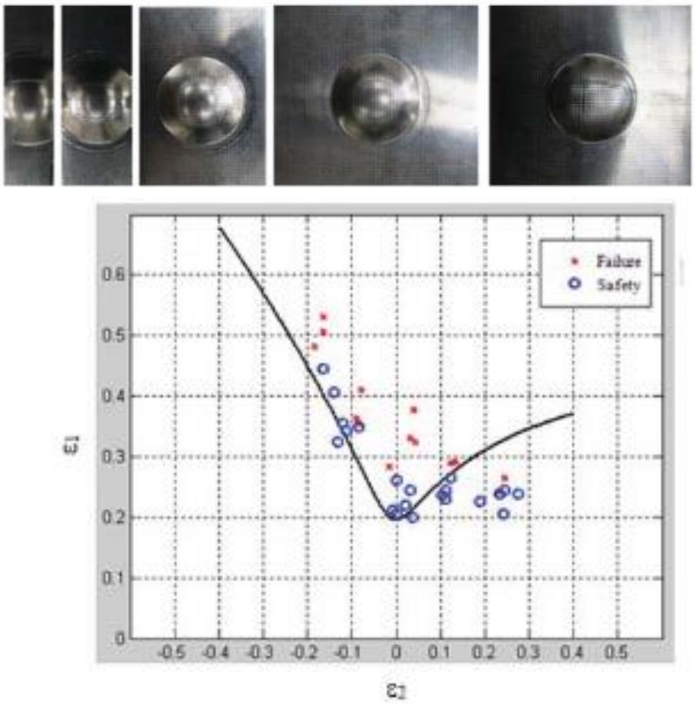
Evaluation of Deformation Possibilities:

To assess the likelihood of deformation, wrinkles, tears, etc., various software tools typically utilize the Forming Limit Diagram (FLD) graph. FLD represents the limit of deformation a metal sheet can endure without tearing. The product's deformation characteristics are compared with FLD deformation curves to evaluate the material's formability.

a)



b)

Figure 4. FLC test specimens (a) and FLC curve (b)

Determining FLD Curvature:

The FLD curvature of a material is determined through plastic deformation tests using a spherical punch (standard 50.8mm). Specimens with equal lengths and varying widths, marked by circular indicators, are subjected to deformation until cracking. Measurements at cracked, fractured, and unfractured regions are taken, and the data is plotted on a two-axis diagram. The boundary between the crack and the safe point represents the FLD of the test material.

3. Finite element simulation (FEM)

In the realm of sheet metal manufacturing, a pivotal aspect of this study involves the utilization of ABAQUS software for Finite Element Simulation (FEM) to delve into the intricacies of the deep drawing process for stainless steel brass, specifically employing SUS304 material. Figure 4 encapsulates the detailed product model under consideration. The die is securely fixed, allowing for the vertical movement of both the punch and blank holder. Within this simulation framework, a nominal friction coefficient of 0.1 is assumed between the sample and the punch, die, and stop plate.

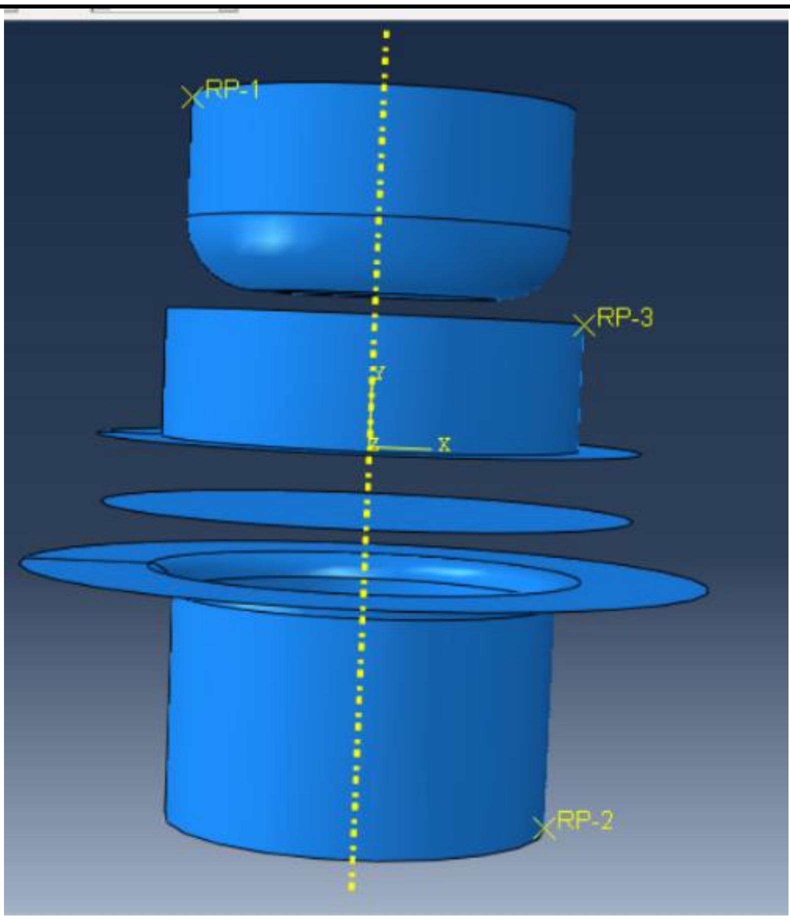


Figure 4: Detailed Simulation of 304 Stainless Steel

Figure 5 poignantly showcases the impact of various input parameters on the potential destruction of the material. It serves as a visual representation of the intricate relationship between the chosen parameters and the resulting material behavior, offering a dynamic perspective on the consequences of different simulation conditions.

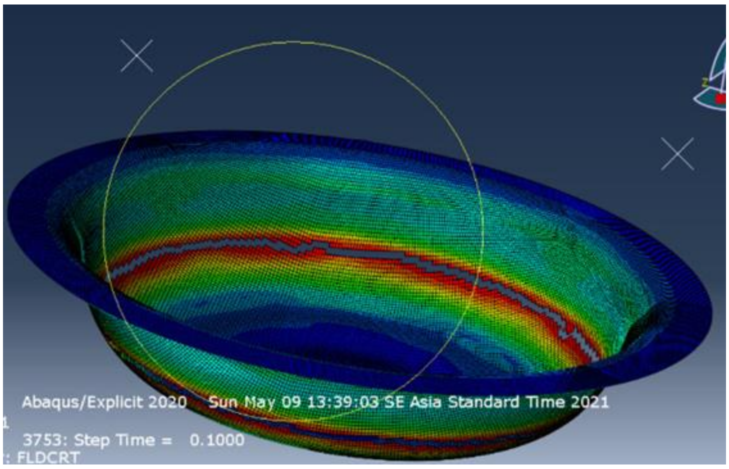


Figure 5: Effect of Input Parameters on Material Destruction

To gauge the formability of the product, the study employs the Forming Limit Diagram (FLD) curve, drawing on experimental data detailed in Part 2. These experimental insights are input into the software, enabling the simulation of the manufacturing process and predicting potential issues. The significance of this predictive approach lies in its capacity to anticipate failure conditions, denoted by FLDCRT values exceeding 1, indicating the occurrence of fractures.

In instances where forming conditions and geometrical parameters are inadequately selected, as exemplified in Photo 1, tearing phenomena are likely to manifest. To enhance the manufacturing process's quality, Finite Element Method (FEM) simulation is judiciously integrated with the Taguchi orthogonal method. Notably, when extracting brass from a thin plate, failures tend to manifest near the die and punch radii due to elevated stress and strain in these regions.

The Taguchi method, a venerable experimental statistical approach, is seamlessly incorporated into this study. This method, revered in the engineering domain, facilitates the systematic identification of optimal solutions post data-collection experiments. Its global applicability and efficacy in experiments and statistics render it a widely embraced methodology.

By leveraging the Taguchi method, engineers can discern optimal data considering factors influencing the testing process, product quality, and cost. According to Taguchi's tenets, a smaller Forming Limit Diagram (FLD) value correlates with enhanced product formability. The Signal-to-Noise (S/N) ratio (Eq. 2), a key metric in Taguchi's methodology, is calculated through a defined formula, offering a quantitative measure of the product's formability and aiding in the pursuit of manufacturing excellence.

$$\eta_i = -10\log_{10}[\mathrm{FLDCRT}^2] \quad (2)$$

4. Simulation Using Taguchi Orthogonal Array:

The investigation into the formability of the product involves a comprehensive analysis of blank holder force (F), die radius (Rc), friction coefficient (μ), and sheet ethickness (s). To systemically study their impact, Table 1 elucidates the chosen levels for each parameter:

Table 2: Coefficients and their levels in the simulation

COEFFICIENT	NAME	1	2	3
F (KN)	blank holder force	100	150	200
Rc(mm)	die radius	20	25	30
μ	friction coefficient	0.01	0.1	0.2
S(mm)	sheet ethickness	1	1.2	1.5

Throughout the simulation process, three levels for each coefficient are considered, resulting in the application of an L9 orthogonal array to devise the experimental plan. With this approach, a mere 9 experiments are required to evaluate the effects of parameter variations during simulation, significantly reducing the number of experiments from 81 to 9, as facilitated by the Taguchi orthogonal algorithm. Table 3 encapsulates the results obtained from these simulated Taguchi experiments.

Table 3: Simulation Results using Taguchi Orthogonal Array

No.		**F(KN)**	**Rc(mm)**	**μ**	**s**	**FLDCRT coefficients**	**ŋ (dB)**
1		100	20	0.01	1.5	0.957	0.381
2		100	25	0.1	1.2	0.973	0.238
3		100	30	0.2	1	1.081	-0.677
4		150	20	0.1	1	1.019	-0.163

No.		F(KN)	Rc(mm)	µ	s	FLDCRT coefficients	ŋ (dB)
5		150	25	0.2	1.2	1.0751	-0.628
6		150	30	0.01	1.5	0.906	0.857
7		200	20	0.2	1.2	1.1	-0.828
8		200	25	0.01	1	0.922	0.705
9		200	30	0.1	1.5	0.961	0.346

According to the Taguchi methodology, Analysis of Variance (ANOVA) is employed (Table 3) to articulate the relationships between parameters and observed FLDCRT values. This is calculated using the sum formulas (3, 4), leading to the results in Table 4.

$$SS = 3(m_{j1} - m)^2 + 3(m_{j2} - m)^2 + 3(m_{j3} - m)^2 \quad (3)$$

$$m_{ji} = \frac{1}{3}\sum_{n=1}^{3}(\eta_j)_i ; \; m = \frac{1}{9}\sum_{n=1}^{9}\eta_i \quad (4)$$

Table 4: Results Obtained After Calculation

Coefficient	Average Value ŋ Each Level			Sum of Squares	Percentage
	1	2	3		
F (N)	-0.02	0.022	0.074	0. 00636	0.043%
Rc(mm)	-0.203	0.105	0.175	0.082859	5.589%
µ	0.65	0.14	-0.711	0.947621	63.921%
s(mm)	-0.045	-0.406	0.528	0.445645	30.447%
All				1.482485	100%

5. Results and Conclusions:

In line with the Taguchi orthogonal table (Table 3), simulations for each case are conducted to predict the forming limit. Notably, Table 3 reveals the simulation outcomes, emphasizing the destructive values (FLD) at vulnerable locations, where FLD values exceeding 1 indicate potential workpiece tearing.

The synthesis of results from Table 3 (FLD values) and Table 4 (ANOVA) underscores the paramount influence of friction on material destruction and shaping quality. The quest for optimal results leads to the following values:

- Blank Holder Force (F): 200 kN
- Die radius (Rc): 30 mm
- Sheet thickness (s): 1.5 mm
- Friction coefficient (µ): 0.01

These identified values engender the highest quality pots, characterized by minimal FLD, ensuring the fulfillment of the requirement for a product devoid of wrinkles or tears (shown in Figure 6)

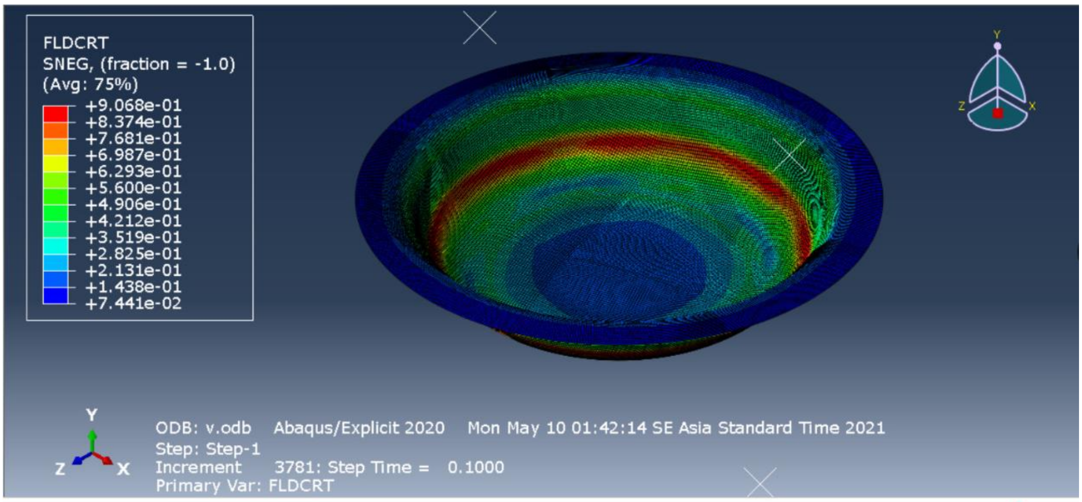


Figure 6: Deformed shape without wrinkles or tears

In conclusion, our study exemplifies the transformative power of interdisciplinary methodologies in reshaping conventional manufacturing paradigms. Through the seamless integration of simulation and sophisticated statistical analyses, we have introduced an innovative framework for elevating product quality, simultaneously achieving substantial reductions in costs and resource utilization. Our research not only contributes to the theoretical advancements in stamping processes but also furnishes practical insights with direct relevance to industrial applications. This underscores the significance of adopting a holistic approach in engineering research, where the synergistic combination of diverse methodologies propels the boundaries of knowledge and facilitates tangible improvements in real-world manufacturing scenarios.

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