



ENERGY-AWARE MULTI-OBJECTIVE OPTIMIZATION OF SUS304 DEEP DRAWING BASED ON FINITE ELEMENT SIMULATIONS

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Abstract: Deep drawing of SUS304 stainless steel is widely used in industrial manufacturing but remains challenged by excessive thinning, high forming loads, and significant energy consumption. This study presents an energy-aware multi-objective investigation of the deep drawing process by analysing the combined effects of relative thickness ratio (s/D), friction coefficient (μ), and blank holder force (BHF) on thinning ratio, total forming energy, and maximum forming force. Finite element simulations were performed using Dynaform 5.9.4, and the process parameters were systematically arranged according to a Taguchi L9 orthogonal array. To achieve a balanced improvement in forming quality and energy efficiency, a multi-objective optimisation was carried out using the integrated Taguchi–Grey relational analysis (GRA) approach. The optimal parameter combination was identified as $s/D = 0.006$, $\mu = 0.125$, and $BHF = 45$ kN, resulting in a thinning ratio of 5.083%, a total forming energy of 5.65 kJ, and a maximum forming force of 170 kN. Compared with the mean performance, the optimised condition reduced energy consumption and peak forming load by 11.9% and 12.8%, respectively. The results demonstrate that combining finite element simulation with physical interpretation and energy-based optimisation provides practical guidelines for designing energy-efficient and stable deep drawing processes of stainless-steel sheets.

Key words: deep drawing; SUS304 stainless steel; Taguchi method; grey relational analysis; energy consumption; optimization; finite element simulation.

1. INTRODUCTION

Sheet metal forming is widely employed in the automotive, electronics, household appliance, and medical industries due to its capability to produce lightweight components with high dimensional accuracy and excellent surface finish, [1, 2]. Among commonly used sheet metals, SUS304 stainless steel is particularly attractive because of its superior corrosion resistance, mechanical stability, and formability under complex loading conditions. Nevertheless, deep drawing of SUS304 sheets remains challenging owing to common defects such as tearing, wrinkling, excessive thinning, and elevated energy consumption, [3,4]. These limitations highlight the need to investigate the influence of process parameters to enhance formability and promote energy-efficient manufacturing.

Extensive research has addressed the effects of key forming parameters on deep drawing performance. Guo et al. [5] and Jiang et al. [6] emphasized that blank holder force (BHF) is essential for controlling material flow and preventing wrinkling; however, excessively large BHF can induce high tensile stresses, increasing both thinning and forming force. In terms of tribological behavior, Zein & Irfan [7] and Palmieri et al. [8] demonstrated that friction significantly affects strain distribution and forming stability: lower friction facilitates smoother draw-in and reduces forming load, whereas higher friction leads to localized stress concentration and increased risk of fracture. Geometric characteristics, particularly the relative thickness ratio (s/D), also play a crucial role in governing deformation behavior. Sheets with a smaller thickness or tighter die clearance experience higher stress gradients, making them more susceptible to instability and thickness reduction. In addition to geometric accuracy and defect prevention, energy consumption has emerged as a critical evaluation index in recent manufacturing research. Gao et al. [9, 10] pointed out that forming energy is directly related to the plastic deformation energy accumulated during material flow, and improving energy efficiency is important for both economic and environmental sustainability. Similarly, Edis et al. [11] showed that force–energy measurements can serve as real-time indicators for monitoring process stability and tool–material interaction. Therefore, integrating traditional quality metrics (e.g., thinning) with energy-based objectives is essential for a more comprehensive evaluation of forming performance.

Various optimization strategies have been applied to enhance deep drawing quality. Palmieri et al. [8] developed an in-line BHF control method to improve draw-in behavior, while Taşkın & Dengiz [12] applied the Taguchi

method to optimize deep drawing parameters for medical containers. Multi-objective optimization approaches—including variable BHF control [5,6] and hybrid statistical–numerical strategies—have also been adopted to improve strain uniformity and minimize defects. Furthermore, several studies have demonstrated that combining the Taguchi method with Grey Relational Analysis (GRA) is effective for solving multi-objective optimization problems in sheet forming processes, [13–17]. However, despite these advances, existing studies mainly focus on optimizing individual responses such as thinning or forming force, whereas very few works simultaneously consider thinning ratio, total forming energy, and peak forming force for SUS304 stainless steel. Additionally, integrated finite-element and multi-objective statistical frameworks that target both forming quality and sustainability remain limited.

To address these research gaps, this study investigates the combined effect of relative thickness (s/D), friction coefficient, and blank holder force on the deep drawing performance of SUS304 cylindrical cups. Finite element simulations were carried out using Dynaform 5.9.4, and the Taguchi L9 orthogonal array was employed to evaluate parameter significance. A multi-objective optimization procedure was implemented by integrating Taguchi analysis with Grey Relational Analysis (GRA) to simultaneously minimize thinning, forming energy, and maximum forming load. The present study aims to numerically investigate the combined effects of relative thickness ratio, friction coefficient, and blank holder force on the deep drawing behaviour of SUS304 stainless steel sheets. Finite element simulation together with statistical and Grey relational analyses are employed to evaluate thinning behaviour, forming force, and energy consumption within the investigated parameter range.

2. MATERIALS AND METHODOLOGY

2.1. Model geometry and material properties

The simulated part is a cylindrical cup, as shown in Figure 1. The blank material is SUS304 stainless steel, according to the Japanese Industrial Standard (JIS), approximately equivalent to X5CrNi18-10 stainless steel specified in EN10088, commonly used for high-strength, corrosion-resistant sheet components. The mechanical properties were obtained from the material database of Dynaform 5.9.4. The sheet was modeled as an isotropic, elastoplastic material under plane stress conditions, allowing large deformation. All tools were modeled as rigid bodies, and Coulomb friction was applied between the sheet and the tools.

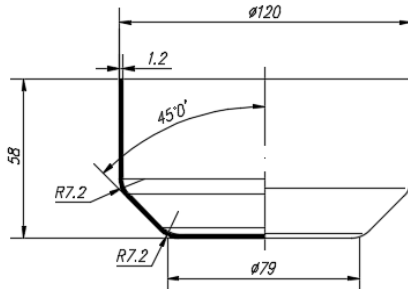


Fig.1. Simulation part model

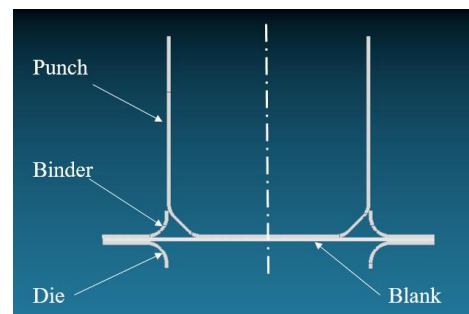


Fig.2. Simulation problem model

2.2. Finite element model

The forming setup consists of four main components: punch, die, blank holder, and blank (Figures 2–3). The blank was meshed using quadrilateral shell elements with an average element size of 1 mm, ensuring higher accuracy around curved regions. The die and punch were meshed coarser to reduce computation time. The boundary conditions constrained the punch and die motions according to the press stroke, and frictional contact was modeled using the Coulomb law.

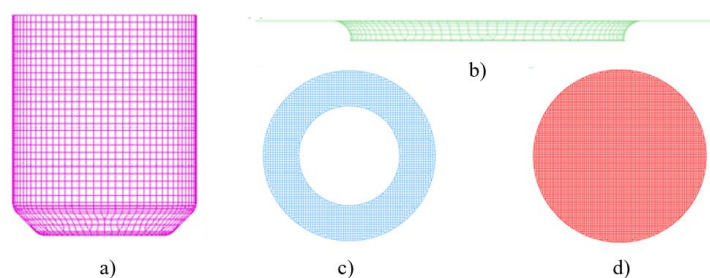


Fig.3. Mesh model of the working components: Punch (a), die (b), blank holder (c). Blank (d)

2.3. Process parameters and experimental design

The blank diameter was determined by the principle of area conservation, giving $D_0 = 200$ mm.

Three process parameters were selected:

Relative thickness (s/D) - geometric ratio between sheet thickness and blank diameter;

Friction coefficient (μ) - representing lubrication conditions;

Blank holder force (BHF) - controlling sheet flow and wrinkling resistance.

The sheet thicknesses considered were 1.2 mm, 1.3 mm, and 1.4 mm, corresponding to relative thickness ratios (s/D) of 0.005, 0.0065, and 0.007, respectively.

The friction coefficient values were adopted from the material database of Dynaform 5.9.4, with levels of 0.125, 0.148, and 0.17.

The blank-holder force values were theoretically estimated and set to 45 kN, 50 kN, and 55 kN for the numerical simulations.

The simulation study was designed based on the Taguchi experimental method. The process parameters and their corresponding levels of variation are presented in Table 1. The simulation matrix followed a Taguchi L9 orthogonal array, as shown in Table 2, allowing efficient evaluation of parameter effects with only nine runs.

Table 1. Process parameters and their levels.

Process parameters	Symbol	Level		
		1	2	3
s/D	A	0.006	0.0065	0.007
μ	B	0.125	0.148	0.17
BHF, N	C	45000	50000	55000

Table 2. Orthogonal array (L9) of Taguchi Method

Exp. No	Process parameters					
	A	B	C	s/D	μ	BHF, N
1	1	1	1	0.006	0.125	45000
2	1	2	2	0.006	0.148	50000
3	1	3	3	0.006	0.17	55000
4	2	1	2	0.0065	0.125	50000
5	2	2	3	0.0065	0.148	55000
6	2	3	1	0.0065	0.17	45000
7	3	1	3	0.007	0.125	55000
8	3	2	1	0.007	0.148	45000
9	3	3	2	0.007	0.17	50000

2.4. Evaluation criteria

Three response variables were used: thinning ratio (Δs , %), total forming energy (U_{total} , kJ), and maximum forming force (F_{max} , kN).

The thinning ratio was calculated according to equation (1):

$$\Delta s = 100 \frac{s_0 - s_{min,i}}{s_0} \quad (1)$$

where s_0 is the initial sheet thickness (mm), and $s_{min,i}$ the minimum thickness measured at the location of maximum thinning in the i -th experiment (mm).

The total forming energy corresponds to the area under the force–stroke curve and was determined using equation (2):

$$U_{total} = \int_0^h F(x) dx \quad (2)$$

where F is the forming force (N) and h is the punch stroke (mm).

All three responses - thinning ratio, total forming energy, and maximum forming force were evaluated according to the “smaller – is - better” criterion. Accordingly, the signal-to-noise (S/N) ratio for this criterion was calculated using equation (3):

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

where n is the number of experiments and y_i represents the measured value in the i -th trial.

2.5. Multi-objective optimization using Taguchi - GRA

For multi-objective optimization, the Grey relational analysis (GRA) method was integrated with Taguchi design. The experimental results were normalized to eliminate differences in units and ranges, and Grey relational coefficients (GRC) were calculated to quantify the closeness of each experiment to the ideal performance. The overall Grey relational grade (GRG) was then obtained as the average of the GRC for the three objectives. A higher GRG indicates better overall performance. Finally, the mean GRG at each factor level was analyzed to predict the optimal parameter set.

After normalization (smaller – is - better), the Grey relational coefficient (GRC) for each response was computed as:

$$\xi_i = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_i + \zeta \Delta_{\max}} \quad (4)$$

where $\zeta = 0.5$ is the distinguishing coefficient.

The Grey relational grade (GRG), representing the overall performance, is the mean of all GRCs:

$$\gamma_i = \frac{1}{m} \sum_{j=1}^m \xi_{ij} \quad (5)$$

The experiment with the highest GRG indicates the optimal combination (see flowchart in Figure 4).

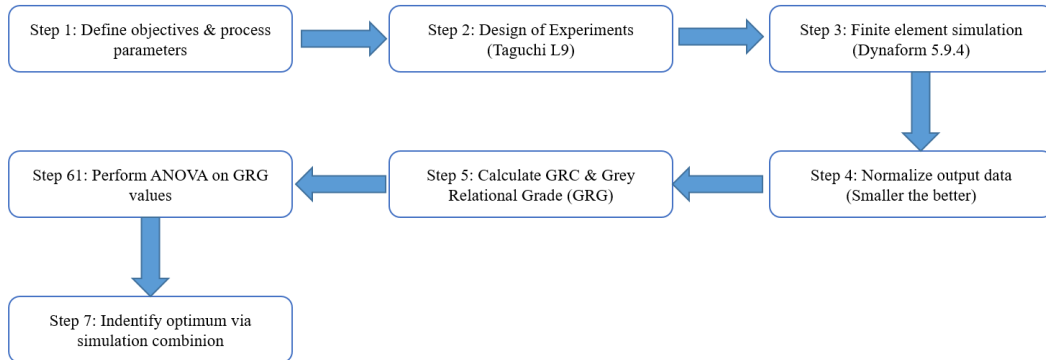


Fig.4. Flowchart of the Taguchi–Grey Relational Analysis (GRA) optimization procedure

3. RESULTS AND DISCUSSION

3.1. Finite element simulation results

Finite element simulations of the deep drawing process were carried out according to the Taguchi L9 orthogonal array, in which three process parameters - relative thickness (s/D), friction coefficient (μ), and blank holder force (BHF) - were varied at three levels. Figure 5 illustrates the final deformation configuration of the SUS304 cup, while Figure 6 presents the thickness distribution and the corresponding force - stroke curve obtained from the simulations.

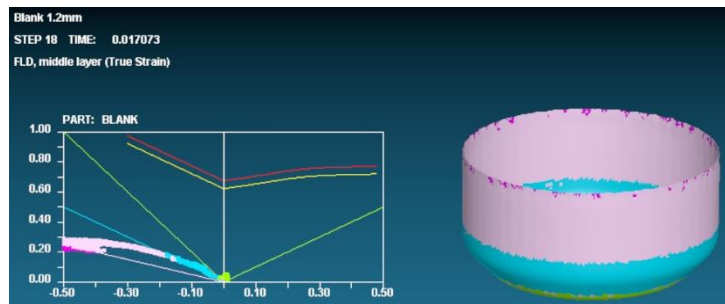


Fig.5. Simulation results of the SUS304 deep drawing process

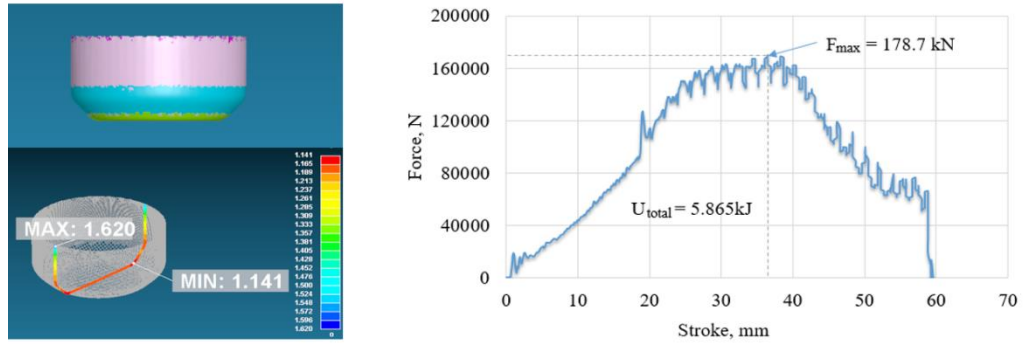


Fig.6. Thickness distribution (mm) and Force–stroke curve obtained from the simulation

As shown in Figure 6, the maximum thinning occurs in the punch corner region, where the sheet undergoes combined bending, unbending, and tensile stretching. This area is subjected to the highest tensile stress and strain concentration, making it the most critical zone for formability evaluation. In contrast, the flange region experiences limited thickness reduction, indicating that material flow is mainly governed by tensile stretching rather than compressive wrinkling under the investigated conditions. The values “Max: 1.620” and “Min: 1.141” shown in the contour plot represent the maximum and minimum local sheet thickness values (mm), respectively. The force - stroke curve in Figure 6 exhibits a typical deep drawing behavior. The initial stage corresponds to tool sheet contact and elastic plastic transition, followed by a relatively steady deformation stage characterized by stable material draw in. The peak force occurs near the end of the stroke, reflecting the maximum resistance to deformation when the material is fully engaged in the die cavity. The smooth evolution of the force curve without abrupt fluctuations confirms stable forming conditions without severe wrinkling or tearing. Across all simulations, the maximum forming force ranged from approximately 170 kN to 220 kN, depending on the selected parameter combination.

The thinning ratio (Δs), thickness s , total forming energy (U_{total}), and maximum forming force (F_{max}) extracted from the simulations are summarized in Table 3 and serve as the basis for subsequent statistical and optimization analyses.

Table 3. Orthogonal array (L9) of Taguchi Method and Results

Exp. No	Process parameters			Results			
	A	B	C	s , mm	Δs , %	U_{total} , kJ	F_{max} , kN
1	1	1	1	1.139	5.083	5.650	170
2	1	2	2	1.141	4.917	5.865	178.7
3	1	3	3	1.140	5	6.072	187.2
4	2	1	2	1.233	5.154	6.191	184.7
5	2	2	3	1.231	5.308	6.632	195.5
6	2	3	1	1.231	5.308	6.41	205.2
7	3	1	3	1.325	5.357	6.713	200.2
8	3	2	1	1.324	5.429	6.959	211.2
9	3	3	2	1.324	5.429	7.198	222

3.2 Effect of process parameters: ANOVA results

Single objective optimization was first conducted using signal-to-noise (S/N) ratio analysis and analysis of variance (ANOVA) for the three responses: thinning ratio, total forming energy, and maximum forming force. The ANOVA results (Figures 7 - 9) indicate that the relative thickness ratio (s/D) is the most influential parameter for all three performance indicators.

Quantitatively, s/D contributes 72.45% to the variation in thinning ratio, 67.55% to total forming energy, and 59.02% to maximum forming force. The friction coefficient exhibits a moderate influence, while the contribution of blank holder force is comparatively lower within the investigated range (45 - 55 kN). These findings suggest that geometric parameters dominate the deformation behavior, whereas contact conditions and boundary constraints act as secondary control factors.

Increasing s/D (i.e., using thicker sheets or reducing the drawing severity) enhances resistance to plastic deformation, leading to slightly reduced thinning but increased forming force and energy consumption. Higher friction coefficients significantly elevate both forming force and total energy due to restricted material flow and increased interfacial shear resistance. In contrast, BHF mainly influences flange stability and wrinkle suppression, with a limited effect on the overall stress–strain state in the main deformation zone. The Taguchi L9 orthogonal array employed in the present study does not include experimental replication. Therefore, the ANOVA results are interpreted primarily in terms of relative contribution and sensitivity trends rather than strict statistical hypothesis testing. The dominant influence of s/D was consistently supported by the highest contribution ratios, S/N response trends, and the regression-based sensitivity analysis presented in Section 3.4

Factors levels	Average S/N for thinning ratio		
	A	B	C
1	-13.98	-14.31	-14.44
2	-14.41	-14.34	-14.26
3	-14.66	-14.39	-14.35
Mean	-14.35	-14.35	-14.35
Max	-13.98	-14.31	-14.26
Delta	0.68	0.08	0.18
Contribution, %	72.45	8.10	19.45

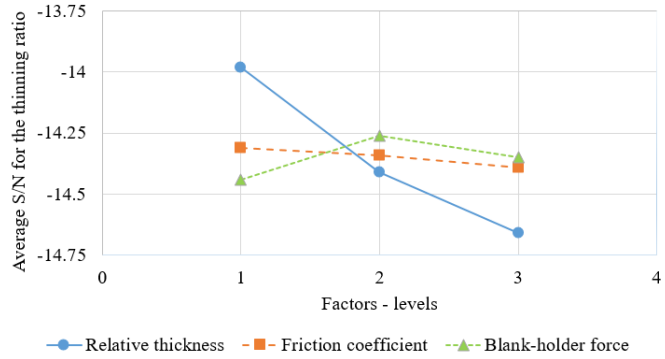


Fig.7. Results ANOVA analysis (a) and S/N ratio response diagram of thinning ratio (b)

Factors levels	Average S/N for total forming energy		
	A	B	C
1	-15.36	-15.80	-16.01
2	-16.14	-16.22	-16.11
3	-16.84	-16.32	-16.21
Mean	-16.11	-16.11	-16.11
Max	-15.36	-15.80	-16.01
Delta	1.49	0.51	0.20
Contribution, %	67.55	23.23	9.22

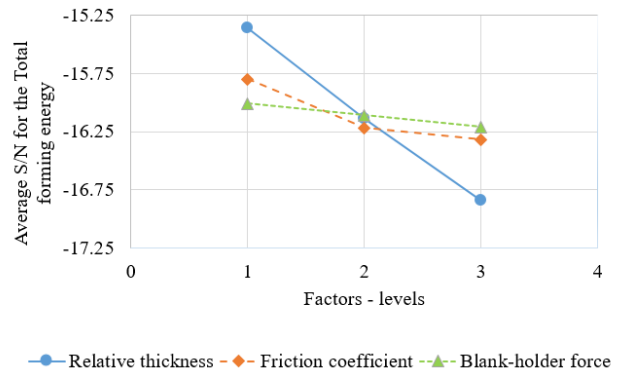


Fig.8. Results ANOVA analysis (a) and S/N ratio response diagram of total forming energy (b)

Factors levels	Average S/N for maximum forming force		
	A	B	C
1	-45.03	-45.32	-45.64
2	-45.80	-45.93	-45.77
3	-46.48	-46.07	-45.91
Mean	-45.77	-45.77	-45.77
Max	-45.03	-45.32	-45.64
Delta	1.45	0.74	0.26
Contribution, %	59.02	30.22	10.76

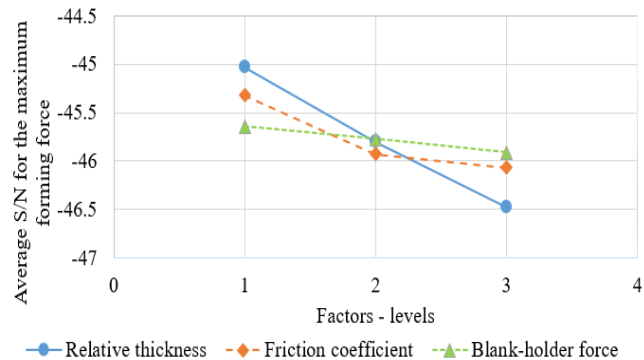


Fig.9. Results ANOVA analysis (a) and S/N ratio response diagram of maximum forming force (b)

3.3. Physical interpretation of the dominant role of relative thickness (s/D)

The pronounced dominance of relative thickness observed in the ANOVA results can be explained from a mechanical perspective by considering strain localization and the bending–stretching interaction during deep drawing.

During the forming process, the sheet material in the punch corner and die radius regions undergoes complex deformation involving simultaneous bending, unbending, and membrane stretching. For a fixed cup geometry, reducing the sheet thickness (i.e., lowering s/D) significantly decreases the bending stiffness of the blank and

weakens the through-thickness constraint on plastic flow. Consequently, the ratio of tool curvature to sheet thickness increases, intensifying bending-induced strain gradients through the thickness.

This condition promotes strain localization, as the material accommodates deformation through localized thinning rather than uniform membrane stretching. Once localized necking initiates, small changes in s/D can lead to pronounced variations in minimum thickness, explaining the high sensitivity of thinning ratio to relative thickness. At the same time, a smaller s/D effectively increases the drawing severity, raising both axial and circumferential tensile stresses required to pull the material into the die cavity.

From an energy standpoint, relative thickness directly governs the amount of plastic work accumulated during deformation. Thicker sheets require higher stresses to sustain bending and stretching, resulting in increased forming force and total forming energy. Conversely, thinner sheets reduce global deformation resistance but become more susceptible to localized thinning and instability. Compared with friction and blank holder force - which mainly influence interfacial conditions and flange draw-in the relative thickness intrinsically alters the stiffness, stress distribution, and strain localization behavior of the entire blank. This explains why s/D emerges as the primary controlling parameter for both formability and energy efficiency in SUS304 deep drawing.

3.4. Sensitivity analysis and regression-based interpretation

To further substantiate the statistical findings obtained from ANOVA and to quantitatively evaluate the sensitivity of the forming responses to the investigated parameters, a linear regression-based sensitivity analysis was conducted. Given that the Taguchi L9 orthogonal array represents a main-effects design, a first-order regression model was considered appropriate and statistically valid. Accordingly, the response variables were expressed as linear functions of the coded process parameters as follows:

$$Y = b_0 + b_1A + b_2B + b_3C \quad (6)$$

where Y denotes the response variable (thinning ratio Δs , total forming energy U_{total} , or maximum forming force F_{max}), and A , B , and C are the coded values of relative thickness ratio (s/D), friction coefficient (μ), and blank holder force (BHF), respectively. The coded levels -1 , 0 , and $+1$ correspond to the low, medium, and high levels of each factor.

Based on the simulation results summarized in Table 3, the fitted regression models for the three responses are given as:

$$\Delta s = 5.2206 + 0.2025A + 0.0238B - 0.0258C \quad (7)$$

$$U_{total} = 6.41 + 0.5472A + 0.1877B + 0.0663C \quad (8)$$

$$F_{max} = 194.967 + 16.25A + 9.917B - 0.583C \quad (9)$$

The coefficients of determination (R^2) obtained for thinning ratio, total forming energy, and maximum forming force were approximately 0.889, 0.968, and 0.998, respectively, indicating a good agreement between the regression models and the numerical simulation data within the investigated design space.

From the magnitude of the standardized regression coefficients, it is evident that the relative thickness ratio (s/D) exhibits the highest sensitivity for all three responses. Specifically, the absolute value of b_1 is significantly larger than those of b_2 and b_3 , confirming that variations in s/D induce more pronounced changes in thinning, energy consumption, and forming force than equivalent variations in friction coefficient or blank holder force. The friction coefficient shows a moderate influence, particularly on forming energy and force, while the effect of blank holder force remains relatively weak within the studied range.

These regression - based sensitivity results are fully consistent with the ANOVA contribution ratios and the Grey relational analysis outcomes, thereby reinforcing the robustness of the conclusions. It should be emphasized that the regression models are employed here to support sensitivity interpretation and engineering insight rather than to serve as predictive surrogate models beyond the investigated parameter ranges. From a practical standpoint, the results indicate that controlling the relative thickness ratio during the early design stage is critical for achieving stable forming behavior and improved energy efficiency, while friction conditions and blank holder force can be used as secondary tuning parameters.

3.5. Multi-objective optimization with Taguchi - Grey relational analysis (GRA)

To simultaneously optimize all three responses (Δs , U_{total} , and F_{max}), the Taguchi - Grey relational analysis approach was adopted. All output data were normalized using the “smaller-is-better” criterion to eliminate unit and range differences. The normalized values and deviation sequences are presented in Table 4, and the corresponding GRC and GRG are shown in Table 5.

Table 4. Normalized and Deviation Data

Exp. No	Normalized Data			Deviation Data (Δ)		
	Δs , %	U_{total} , kJ	F_{max} , kN	Δs , %	U_{total} , kJ	F_{max} , kN
1	0.674	1	1	0.326	0	0
2	1	0.861	0.833	0.000	0.139	0.167
3	0.837	0.727	0.669	0.163	0.273	0.331
4	0.537	0.651	0.717	0.463	0.349	0.283
5	0.236	0.366	0.323	0.764	0.634	0.677
6	0.236	0.509	0.510	0.764	0.491	0.490
7	0.140	0.313	0.419	0.860	0.687	0.581
8	0	0.154	0.208	1	0.846	0.792
9	0	0	0	1	1	1

Table 5. Calculation of Grey relation analysis

Exp. No	Grey relation coefficient (GRC)			Grey Relation Grade (GRG)	Rank
	Δs , %	U_{total} , kJ	F_{max} , kN		
1	0.606	1	1	0.869	1
2	1	0.783	0.749	0.844	2
3	0.754	0.647	0.602	0.668	3
4	0.519	0.589	0.639	0.582	4
5	0.396	0.441	0.425	0.420	6
6	0.396	0.505	0.505	0.468	5
7	0.368	0.421	0.316	0.368	7
8	0.333	0.372	0.279	0.328	8
9	0.333	0.333	0.250	0.306	9

Among the nine experiments, experiment No.1 (A1 – B1 – C1) exhibited the highest GRG value (0.8596), corresponding to the optimal combination: $s/D = 0.006$, $\mu = 0.125$, and $BHF = 45$ kN. This set provides the best balance between forming quality and energy efficiency.

At this optimum condition:

The thinning ratio (Δs) reached 5.083%, representing a 3.1% reduction compared to the average and a 0.39% increase relative to the single-objective optimum.

The total forming energy (U_{total}) decreased to 5.65 kJ, about 11.9% lower than the mean.

The maximum forming force (F_{max}) dropped to 170 kN, an 12.8% reduction from the average.

The ANOVA of GRG values (Figure 10) shows that the relative thickness (A) is the most dominant factor, contributing 67.87% to the overall performance, followed by friction coefficient (B) (18.58%) and blank holder force (C) (13.54%). This confirms that geometric parameters, especially s/D , play a decisive role in both formability and energy performance.

Level	Mean Grey relation grade		
	A	B	C
1	0.79	0.61	0.55
2	0.49	0.53	0.58
3	0.33	0.48	0.49
Mean	0.54	0.54	0.54
Delta	0.46	0.13	0.09
Contribution, %	67.87	18.58	13.54

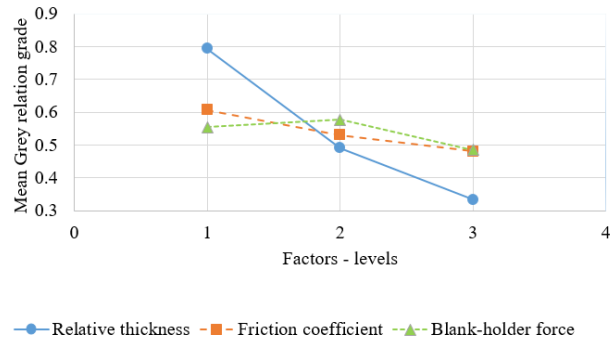


Fig.10. Results ANOVA analysis (a) and diagram of mean Grey relation grade (b)

These findings are consistent with previous multi-objective studies by Arjunan & Pasupathy [13] and Ramanjaneyulu et al. [14], which also highlighted the strong influence of geometric parameters on forming quality. Compared with single-objective optimization, the Taguchi - GRA method provides a more balanced solution, simultaneously improving product quality and reducing energy consumption.

4. CONCLUSIONS

This study presented a comprehensive numerical and statistical investigation into the deep drawing of SUS304 stainless steel sheets, focusing on the simultaneous improvement of thinning ratio, total forming energy, and maximum forming force. A finite element model was developed using Dynaform 5.9.4 to numerically investigate deformation behavior, thickness evolution, force–stroke characteristics, and forming energy consumption during the deep drawing of SUS304 stainless steel sheets. The simulation results provided useful insight into the deformation characteristics and parameter-dependent forming responses within the investigated numerical framework.

ANOVA results revealed that the relative thickness ratio (s/D) is the most dominant parameter affecting all three performance indicators, contributing 72.45% to thinning, 67.55% to energy consumption, and 59.02% to maximum forming force. The friction coefficient and blank holder force (BHF) showed secondary but non-negligible influences, highlighting the importance of simultaneously adjusting both geometric and process conditions to achieve stable forming.

Single-objective analysis indicated that thinner sheets, lower friction, and reduced BHF tend to minimize forming energy and peak load, although these settings may compromise deformation stability. To obtain a more balanced parameter configuration, a multi-objective optimization was performed using the integrated Taguchi–Grey Relational Analysis (GRA) approach. The optimal combination $s/D = 0.006$, $\mu = 0.125$, and $BHF = 45$ kN was identified, yielding a thinning ratio of 5.083%, total forming energy of 5.65 kJ, and maximum forming force of 170 kN. Compared with the mean values of the experimental set, this parameter configuration resulted in reductions of 11.9% in total energy and 12.8% in maximum forming load, while maintaining acceptable thinning. Overall, the findings confirm that the Taguchi–GRA framework is a powerful and efficient tool for multi-objective optimization of sheet metal forming processes. The integration of FE simulation, ANOVA, and GRA provides a systematic methodology that not only improves forming quality but also supports energy-efficient and sustainable manufacturing of stainless-steel components.

The outcomes of this study offer practical guidelines for selecting forming parameters in industrial deep drawing operations, particularly for SUS304 stainless steel. Future research should include experimental validation of the optimized conditions, the exploration of variable blank holder force trajectories, and the extension of the optimization framework to more complex geometries and advanced materials.

Nevertheless, the present conclusions are limited to the investigated numerical framework and should be further validated experimentally before direct industrial implementation. Future work will therefore focus on experimental verification and the development of coupled numerical–experimental optimization strategies for SUS304 deep drawing processes.

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Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors; therefore, ethical approval was not required.

Data Availability: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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