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Investigating and Optimizing Factors Affecting Thinning in Sheet Deep Drawing through Simulation and Taguchi Experimental Planning

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Abstract:This research endeavors to explore the intricate dynamics of factors influencing the thinning process in flat sheet deep-drawing process. It delves into the optimization of crucial parameters that shape the outcome of the deep-drawing process, including punch radius (Rp), die radius (Rd), and workpiece clamp force (F). Employing advanced CAE (Computer-Aided Engineering) software, this study harnesses finite element analysis to simulate the deformation experienced during the stamping process. By doing so, it not only provides a comprehensive understanding of the thinning process but also predicts the material's formability. Furthermore, it aims to determine the optimal parameters for this stamping process. In addition to simulation, this research employs the Taguchi orthogonal array experimental planning method and utilizes analysis of variance (ANOVA) to evaluate the influence of these parameters, quantifying their impact in terms of percentages. The findings revealed that die radius exerts the most significant influence among the three factors, accounting for 90.02% of the variability, followed by punch radius at 9.56%. In contrast, the workpiece blocking force falls within an insignificant range, making up only 0.42% of the overall impact.

Keywords: *Finite Element Analysis (FEM), Computer-Aided Engineering (CAE), Plate Stamping, Taguchi Experimental Planning, Analysis of Variance (ANOVA).*

1. Introduction:

Stamping is a ubiquitous manufacturing technique employed in various industries, including automotive, aerospace, marine, electrical equipment, and consumer appliances. Understanding the factors that influence the stamping process is paramount for achieving precision and consistency in product manufacturing. Traditionally, this understanding has been obtained through experimentation. While experiments offer a direct and tangible insight into the process, conducting a large number of them can be prohibitively costly and time-consuming.

With the advent of computational technology, simulation methods using Computer-Aided Engineering (CAE) software have gained popularity as they mitigate the limitations of experimental approaches. CAE software, based on the finite element method (FEM), discretizes the problem domain into numerous subdomains or elements [1]. Prominent CAE software packages such as Abaqus, ANSYS, and Hyperworks are widely used to facilitate these simulations [2]. In this study, Abaqus software is employed to conduct finite element simulations of the stamping process.

The Taguchi method has emerged as an increasingly adopted approach in experimental planning [3]. This method offers significant advantages in enhancing productivity during the research and development phase while delivering high-quality products at reduced costs. The Taguchi method seeks to streamline experimental parameters by optimally configuring controllable factors while still examining the influence of each parameter on the output results.

Simulating to determine optimal parameters helps avoid defects such as wrinkles, tears [4], and excessive thinning during actual production. In this study, we investigate three key factors: punch radius, die radius, workpiece blocking force, and thinning of the material post-forming. Previous research has explored product thickness using CAE [5,6] to investigate factors such as the friction coefficient and its impact on thinness. Additionally, others have employed experiments and Taguchi experimental planning [7] to investigate die and punch radii, clamping force, and identify optimal parameters for product thickness.

Notably, Mark Colgan and John Monaghan [8] integrated experiments and simulations to assess the influence of various factors in the plate stamping process on thickness and punch force. Their model, implemented using Abaqus software in conjunction with Taguchi optimization, facilitates a comparative analysis of simulation results against actual outcomes, enabling the determination of influential factors and the provision of design solutions for real-world products. This research builds upon and extends the work conducted by Colgan and Monaghan [8], enhancing our understanding of the stamping process and advancing the field by providing novel insights and solutions.

2.Material Model:

The material chosen for this study is EN10130 FeP01 steel, and its properties are detailed as below:

The EN10130 FeP01 steel exhibits a density of 7850 kg/m³, a modulus of elasticity of 204,000 MPa, a Poisson coefficient of 0.33, and a yield stress of 210 MPa. These material properties are critical in understanding how the material responds to the stamping process.

Banabic and his colleagues [10] conducted a series of tests on this material to extract the stress-strain behavior, as depicted in Figure 1. The stress-strain relationship is aptly described by Equation (1), where the material's response is characterized by n = 0.208 and K = 615.

$\sigma = K\,\varepsilon^{n}$(1)

Here, σ represents stress, ε is strain, n is the strain hardening exponent, and K is the strength coefficient.

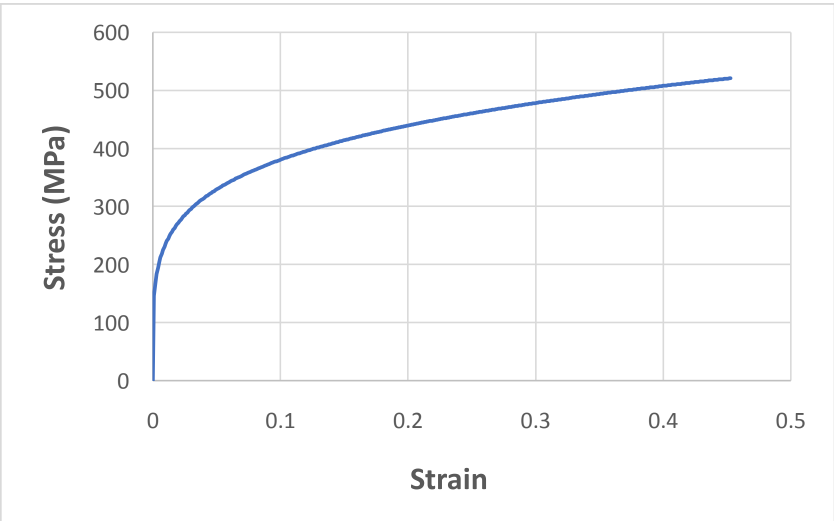

Figure 1:the stress-strain curve of EN10130 FeP01 [10]

3.Simulation by Taguchi Orthogonal Array:

To conduct a systematic investigation into the deep-drawing process, we employed Abaqus software for simulation, simulating the flat sheet deep-drawing process. A 3D CAD simulation of the deep-drawing process is illustrated in Figure 2, where the die remains fixed, and the punch is capable of vertical movement.

Table 1 summarizes the geometric parameters used in the experiment. It is worth noting that, in line with prior research [8], we assumed that friction forces between the plate and the punch, die, and stop plate are negligible, with a coefficient of friction set at 0.1.

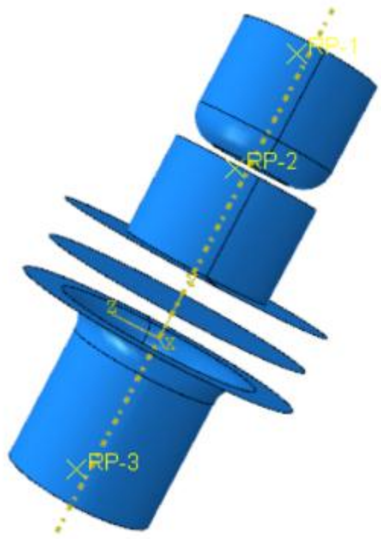

Figure 2: 3D CAD simulation of the plate stamping process

Table 1: Parameters used in the deep drawing process

Parameter	**Value**
Original plate diameter	76 mm
Sheet thickness	1 mm
Diameter of punch	39.4 mm
Die inner diameter	41.7 mm
Curve radius of die and punch	2-8 mm
Holding force	11-18 kN

This study primarily focused on investigating the influence of three critical parameters: punch radius (Rp), die radius (Rd), and blocking force (F). These parameters and their respective levels are detailed in Table 2.

Table 2: Coefficients and levels in the simulation

Coefficients	Level		
	1	2	3
Punch radius,R_p(mm)	2	5	8
Die radius,R_d(mm)	2	5	8
Blocking force, F(KN)	11	14,5	18

In accordance with the Taguchi method, an orthogonal array was created based on these parameters and their respective levels, resulting in the L9 orthogonal array shown in Table 3.

Table 3: L9 orthogonal array

Experiment	Coefficients		
	R_p(mm)	R_d(mm)	F(kN)
1	1(2)	1(2)	1(11)
2	1(2)	2(5)	2(14,5)
3	1(2)	3(8)	3(18)
4	2(5)	1(2)	2(14,5)
5	2(5)	2(5)	3(18)
6	2(5)	3(8)	1(11)
7	3(8)	1(2)	3(18)
8	3(8)	2(5)	1(11)
9	3(8)	3(8)	2(14,5)

4.Results and Discussion

To validate the simulation results against actual experiments, the thickness of the product after stamping was measured at eight distinct points, as depicted in Figure 3 [8].

For a case involving punch and die radii of 2 mm and a clamping force of 18 kN, a comparison of results in Figure 4 and Table 4 demonstrates that the largest deviation between simulated and experimental values is approximately 5%, with the average thickness deviation across all measurements amounting to only 1.23%. It is noteworthy that the thinnest point among the eight measuring locations is found at point 5.Để kiểmchứngkếtquảmôphỏngvớithựcnghiệmđộdàycủasảnphẩmsaukhidậpsẽđượcđotại 8 điểmđượcthểhiệntrênhình3[8].

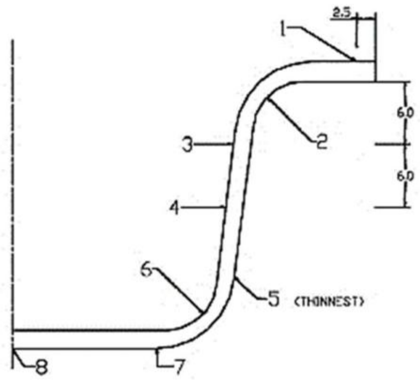

Figure 3: Thickness measurement points

This comparison underscores the proximity of the simulation results to real-world outcomes, highlighting the potential of simulations to predict actual results and significantly reduce time and costs in the manufacturing process.

Table 4: Comparison of thickness distribution between experiment and simulation

Measurement Point	1	2	3	4	5	6	7	8	Avg.
Simulation	1.131	1.079	0.895	0.812	0.782	0.842	0.936	0.951	0.9285
Experiment	1.132	1.032	0.888	0.83	0.823	0.871	0.966	0.979	0.940125

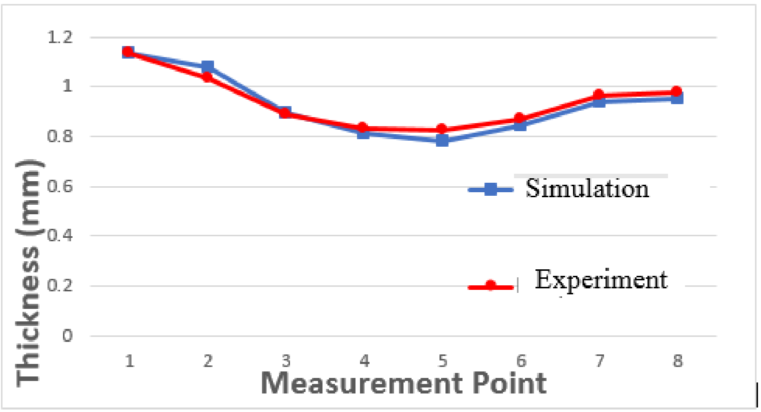

Figure 4: Thickness measurement between simulation and experiment

By simulating each case from Table 4 with the specified input conditions, the results presented in Table 5 illustrate the thickness values at the position with the minimum thickness. To evaluate the impact of these variations, the Signal-to-Noise (S/N) ratio was calculated according to the "Larger is better" criterion within the Taguchi method using Equation (2), where Smin represents the minimum thickness of the product.

η_i= - 10*log(1/S_{min}^2)(2)

Table 5: Simulation results using Taguchi orthogonal array

Experiment	coefficients			Thingning	η_i
	R_p(mm)	R_d(mm)	F(KN)		
1	1(2)	1(2)	1(11)	0,7718	-2.2499
2	1(2)	2(5)	2(14,5)	0,8831	-1.0798
3	1(2)	3(8)	3(18)	0.8844	-1.0670
4	2(5)	1(2)	2(14,5)	0.7962	-1.9796
5	2(5)	2(5)	3(18)	0.9287	-0.6425
6	2(5)	3(8)	1(11)	0.9325	-0.6070
7	3(8)	1(2)	3(18)	0.7984	-1.9555
8	3(8)	2(5)	1(11)	0.9401	-0.5116
9	3(8)	3(8)	2(14,5)	0.9392	-0.5448

Following the Taguchi method, an analysis of variance (ANOVA) was conducted to delineate the relationships between parameters and observed thinness values. The results, as summarized in Table 7, are calculated using the sum of squares formula (Equation 3).

$3(m_{j1} - m)^2 + 3(m_{j2} - m)^2 + 3(m_{j3} - m)^2$(3)

Where m=(1/9)$\sum_{i=1}^{9} \eta_i$=-1.18198 và $m_{ij} = (1/3) \sum_{i=1}^{3} (\eta_j)_i$

The findings reveal that the die radius plays the most significant role in influencing product thinness, accounting for 90.02% of the variance, followed by the punch radius at 9.56%. In contrast, the clamping force exhibits minimal impact in the range of 11 kN to 18 kN. Changing the die radius proves to be the most beneficial in enhancing product thickness within the given problem conditions, aligning with previous research [8]. This highlights the novel contribution of our study in confirming and expanding upon existing knowledge regarding the impact of various parameters on product thinness.

In Table 6, the culmination of our research efforts is presented. This table encapsulates the key findings derived from the extensive Taguchi orthogonal array-based simulations. Our investigation sought to understand the varying impact of punch radius (Rp), die radius (Rd), and blocking force (F) on the thinness of the stamped product. Each parameter was studied at three different levels, and the analysis encompassed the average values, the sum of squares, and the resulting percentage contributions.

Table 6: Comprehensive Results and Analysis

Coefficients	Average Value on Each Level			Sum of Squares	Percentage (%)
	1	2	3		
Punch radiusR_p(mm)	-1.4655	-1.0763	-1.0040*	0.3697	9.56
Die radius R_d(mm)	-2.0618	-0.7446	-0.7396*	3.4825	90.02
Blocking force F(KN)	-1.1228*	-1.2014	-1.2217	0.0163	0.42
* Optimal Level					

This tabulated data provides valuable insights into the percentage contributions of each parameter, with the asterisk indicating the optimal level for each factor. Notably, the die radius (Rd) emerged as the most influential factor, accounting for a substantial 90.02% of the observed variation, underscoring the critical importance of this parameter in shaping product thinness. In comparison, punch radius (Rp) had a significant but less pronounced effect, contributing 9.56% to the variability. The blocking force (F) exhibited minimal influence, constituting just 0.42% of the observed variance.

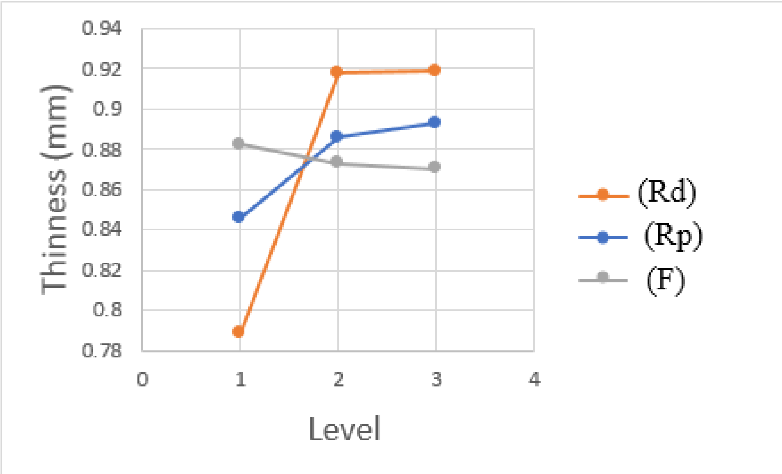

Figure 5: Thinness Variation Relative to Parameter Changes

Figure 5 provides a visual representation of the influence of parameter changes on the thinness of the stamped product. It is evident that the die radius (Rd) has a substantial impact on product thickness. However, this effect is predominantly noticeable within the range of 2mm to 5mm, with minimal changes observed beyond 5mm. This figure also highlights the optimal parameter values: die radius (Rd) at level 3, punch radius (Rp) at level 3, and blocking force (F) at level 1, which yield the most favorable results.

By combining the outcomes of our simulations with Taguchi orthogonal array calculations, we have conducted an in-depth analysis of the factors affecting product thinness. This analytical approach has allowed us to pinpoint the optimal combination of parameters, namely punch radius (Rp) = 8mm, die radius (Rd) = 8mm, and workpiece blocking force (F) = 11 kN.

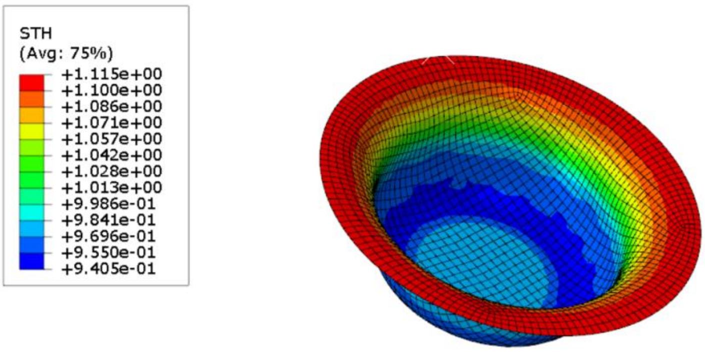

Figure 6: Simulated Optimal Thickness

The simulation with these optimal parameters yields a simulated thickness at the thinnest position of 0.9405 mm (Figure 6). This result is in close agreement with the maximum value obtained from the nine experiments conducted using the Taguchi orthogonal array, which is 0.9401 mm. The negligible deviation reinforces the robustness of our findings.

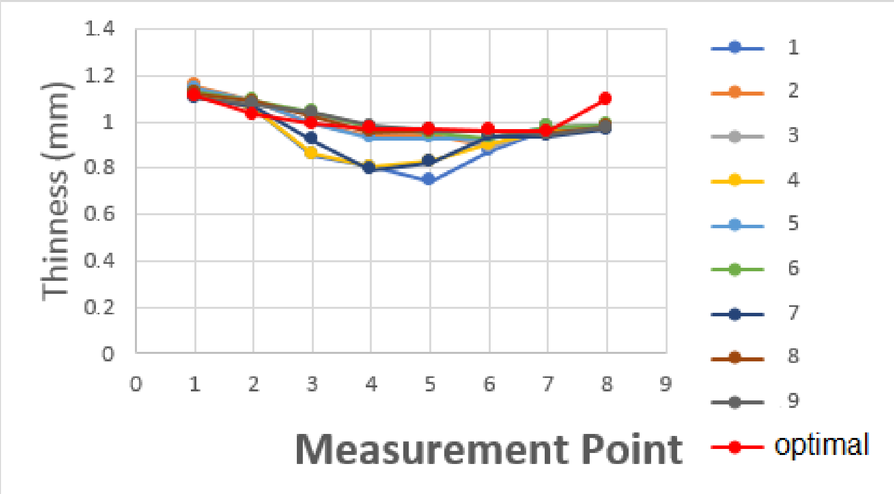

Figure 7: Thinning Measurement at Various Points

Figure 7 provides a comprehensive depiction of the thickness measurements across different points in nine cases outlined by the Taguchi orthogonal table. It is evident that optimizing the parameters not only enhances the thinnest section of the product but also contributes to an improved uniformity in product thickness. Notably, in the case of parameters 1, 4, and 7, where the mortar radius is set at level 1 (2mm), the product exhibits the most significant thinning, with a noticeable non-uniformity in thickness distribution. In contrast, the optimal parameter values lead to less significant improvements as the die radius transitions from level 2 to level 3, primarily affecting the product's center thickness.

In summation, this comprehensive analysis underpins the novel contributions of our research, emphasizing the pivotal role of die radius in determining product thinness and uniformity, which has practical implications for the optimization of flat sheet deep drawing processes.

5. Conclusion

In this study, our comprehensive investigation into the flat sheet deep drawing process has yielded valuable insights and innovative contributions that advance our understanding of this manufacturing technique. The convergence of simulation, experimentation, and advanced analytical methods has shed light on the factors influencing product thickness and has paved the way for the development of an optimal set of parameters for the stamping process. Our research has shown that simulation results closely align with experimental outcomes in terms of product thickness. The maximum disparity observed between the experimentally measured and simulation-derived values is approximately 5%. This level of consistency reaffirms the efficacy of our simulation approach and underscores its potential to serve as a predictive tool, thereby significantly reducing time and costs in the manufacturing process. Moreover, by employing the Taguchi experimental planning method in conjunction with ANOVA analysis, we have conducted a systematic evaluation of the influence of key parameters on product thinness. The results have highlighted the paramount role played by the mortar radius, which accounts for an impressive 90.02% of the observed variation. In comparison, the punch radius contributes significantly but to a lesser extent, at 9.56%, and the blocking force exerts a marginal impact, amounting to a mere 0.42%. This deep understanding of parameter influence has introduced a new perspective on the hierarchy of factors that affect the stamping process, redefining the industry's approach to optimizing product quality. The most significant revelation of our study is the identification of the optimal parameters for the flat sheet stamping process, which includes a punch radius (Rp) of 8mm, a die radius (Rd) of 8mm, and a blocking force (F) of 11 kN. Selecting these parameters leads to a dual enhancement in product quality – not only does it improve the thinnest sections of the product but it also augments the uniformity of thickness across the entire stamped material. This innovative optimization is a significant contribution to the field, offering a practical and cost-effective solution to achieve superior product quality in flat sheet stamping.

In summary, our research showcases the potential for interdisciplinary methodologies to redefine manufacturing processes. By integrating simulation, experimentation, and advanced statistical analysis, we have unveiled a novel approach to improving product quality, all while reducing costs and resource consumption. Our findings not only advance the theoretical underpinnings of stamping but also provide actionable insights for industrial applications, emphasizing the value of a holistic approach to engineering research.

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