

A Comprehensive DoE Framework for the Optimization of Punching Process

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Abstract: The Design of Experiments (DoE) is a powerful statistical approach that enables the optimization of process parameters through a limited number of well-structured tests. In this study, the Taguchi method is applied to the punching test to investigate the influence of key parameters on the maximum punching force (Fmax). Four control factors are considered: punch speed (V), clearance between punch and die (J), punch diameter (D), and sheet thickness (e). Two mathematical models are developed to predict Fmax: a first-order model that neglects factor interactions, and a second-order model that accounts for them. The comparison between both models demonstrates that the second-order formulation provides a significantly better fit to experimental data. These findings underline the importance of considering factor interactions in the analysis and optimization of the punching process to achieve improved cutting accuracy and predict Fmax.

Key words: Taguchi design of experiments, Optimization, Punching test, Analytical model.

1. Introduction

Optimization methods, like Design of Experiments (DoE) and response surface methodology (RSM) are powerful statistical tools dedicated to studying the effects of various factors on process performance and output parameters. Their main objective is to efficiently identify the most influential parameters while minimizing the number of required experiments. These approaches have also demonstrated great potential in the energy sector, where they are employed to optimize system efficiency, improve material performance, and enhance renewable energy conversion processes [1-2]. It has been extensively applied in both advanced technologies [3-5] and conventional manufacturing processes [6-8].

On one hand, integrating the DoE methodology with numerical simulations allows a significant reduction in the number of iterations needed during computational

analyses, thereby contributing to the optimization of manufacturing processes [9-10]. On the other hand, coupling the Taguchi design with experimental studies enables the minimization of experimental tests while maintaining result accuracy. Previous research has mainly focused on the influence of manufacturing parameters on the geometric characteristics of formed parts and on the critical load leading to the initiation of cracks. In the present work, attention is focused on the punching test, considered as a metal sheet cold cutting process governed after plastic deformation.

Design of Experiments (DoE) methods have been effectively applied to optimize various machining and forming operations by identifying the most influential parameters and their interactions. Felhó et al. [11] employed a Taguchi L₁₈ experimental design to investigate the effects of cutting parameters on surface integrity during the turning of X5CrNi18-10 stainless

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steel, demonstrating the efficiency of DoE in reducing the number of tests while maintaining high predictive accuracy. Similarly, Yıldız et al. [12] applied the Box-Behnken design method to optimize turning parameters for AISI 52100 bearing steel, leading to improved surface finish and tool life. Hasçelik [13] used a Taguchi L_{18} approach to minimize wall deformation in micro-milling operations, highlighting the adaptability of DoE in micro-manufacturing processes. Extending these methodologies to forming operations, Claver et al. [14] applied a DoE-based optimization to analyze and enhance the punching process of steel sheets, achieving improved dimensional accuracy and reduced defect rates. Likewise, Wen et al. [15] employed response surface methodology to optimize wear parameters in motor rotor blanking, confirming the effectiveness of statistical modeling in predicting tool performance and extending tool life in punching operations. These studies collectively demonstrate the versatility of DoE techniques for optimizing both cutting and forming processes.

In addition, it was found in previous experimental studies in blanking process that the maximum blanking force (F_{max}) are affected mainly by sheet thickness (e), clearance (J_{md}) and punch diameter (d) [16-18]. Furthermore, the systematic approach of DOE helps in understanding not only the individual effects but also the synergistic interactions among variables, which is essential for tailoring materials with superior punching endurance performance for practical applications. These studies collectively highlight the utility of DOE as a powerful tool in the optimization of punching endurance tests, enabling quality control and formulation improvements based on statistically designed experiments.

The present study investigates the influence of key punching parameters on the maximum punching force (F_{max}) using the Design of Experiments (DoE) based on the Taguchi method. Four control factors are analyzed: punch speed (V), clearance between punch

and die (J), punch diameter (D), and sheet thickness (e). To predict F_{max} , two mathematical models are developed. The first-order model assumes independent effects of the factors, neglecting their interactions, whereas the second-order model accounts for these interaction effects, providing a more comprehensive representation of the punching process behavior.

2. Material and punching method

The examined material is a commonly used structural steel according to ASTM A36, whose chemical composition is presented in Table 1. It is a low-carbon manganese steel, known for its good impact resistance and general structural performance.

Table 1. Chemical composition of ASTM A36 structural steel (%wt)

%C	%Mn	%P	%S	%Si
0.22 max	1.6 max	0.05 max	0.05 max	0.05 max

The punching process involves the plastic deformation and the damage of sheet metal. In this study, the experimental tests were carried out using a universal tensile testing machine (Figure 1), which provides precise control of the applied force and bending motion.

In the punching test, a flat sheet is subjected to concentrated compressive and shearing loads delivered by a punch-die assembly, producing a progressive penetration and eventual separation of the material. Experimental punching trials were performed on a universal testing machine (Figure 1) equipped with a high-precision load cell to record the load–displacement response and to determine the maximum generated force (F_{max}).

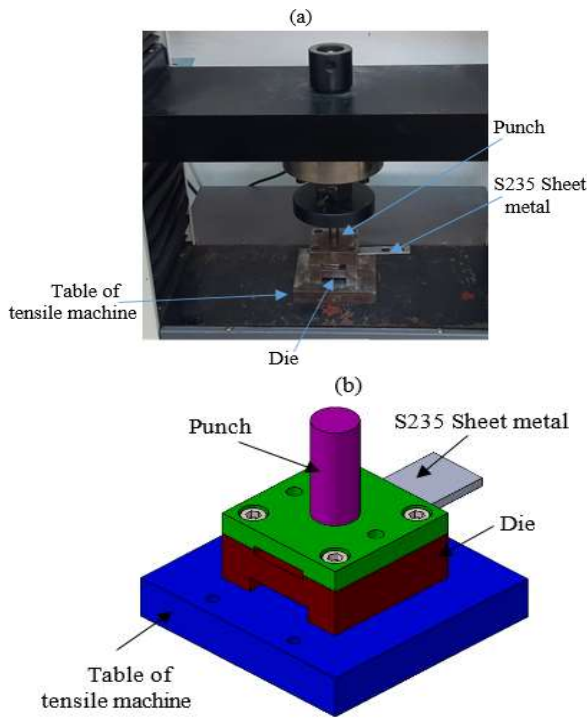


Figure 1. Experimental punching tool: (a) Tools and strip during punching test; (b) 3D design of punching tool

The variation in F_{max} can be reliably attributed to process parameters. This configuration enables a systematic investigation of how key factors, which are punch speed, die clearance, and sheet thickness, influence the punching response and the peak force required for material failure. Four process factors were therefore selected and varied at discrete levels (i) as reported in Table 2: punch speed (V -i), clearance between punch and die (J -i), and sheet thickness (e -i).

Table 2. Input factors in punching tests

Factors	e -1 (mm)	e -2 (mm)	J -1 (mm)	J -2 (mm)
Value	1	2	10	20
Level	1	2	1	2
Factors	D -1 (mm)	D -2 (mm)	V -1 (mm/min)	V -2 (mm/min)
Value	14	18	20	40
Level	1	2	1	2

3. First-order model of maximum punching force

A classical polynomial relationship was used to model the punching process by expressing the maximum generated force (F_{max}) as a function of the selected process parameters. The developed mathematical model accounts for the main effects of the four control factors, which are punch speed (V), clearance between punch and die (J), punch diameter (D), and sheet thickness (e), without take into account their possible interactions. The related coefficients are identified from experimental data using a least-squares regression approach. This allows quantification of the relative influence of each parameter on F_{max} . The resulting analytical formulation establishes a predictive model of the punching response. The first-order polynomial model was constructed by varying the four selected process parameters at different levels according to the Taguchi design of experiments. This first-order model neglects factor interactions and provides an initial approximation of F_{max} behavior, as expressed in Equation (1).

$$F_{max} = -3.33471 \cdot 10^4 + 37.58 V - 23.68 J + 1.84716 \cdot 10^3 D + 1.97111 \cdot 10^4 e \quad (1)$$

As shown in Figure 2, analytical results of maximum punching force, calculated by the mathematical model (equation 2), are compared with those that were experimentally determined. It is observed that the theoretical result is not well validated by the experimental tests.

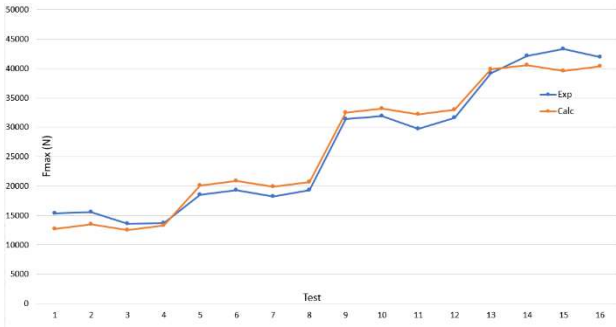


Figure 2. Experimental and analytic results

4. Second-order model of maximum punching force

The second-order polynomial relation allows the modeling of the process. We denote the coefficients of factor effects as b_i and their interactions as b_{ij} .

This statistical study allows the development of the maximum punching force mathematical model that is given by equation 2.

$$\begin{aligned}
 F_{\max} = & 2.1568 \cdot 10^4 + 22.8 V - 1.058 \cdot 10^3 J \\
 & - 1.413 \cdot 10^3 D - 8.1 \cdot 10^3 e \\
 & - 3.54 V \cdot J + 22.6 V \cdot e \\
 & + 2.13 V \cdot D + 57.4 J \cdot D \\
 & + 1.557 \cdot 10^3 D \cdot e
 \end{aligned} \tag{2}$$

As shown in Figure 3, analytical results of the maximum punching force that calculated by the empirical model (equation 2) are compared with those that were experimentally determined.

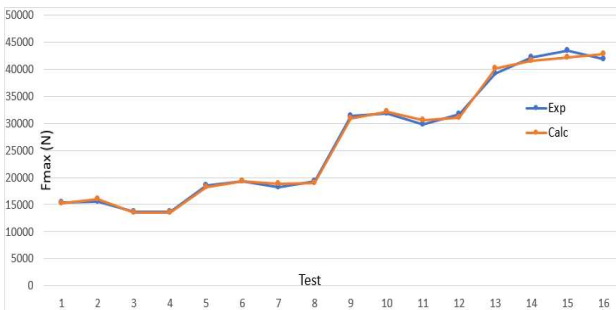


Figure 3. Validation of mathematical model of F_{\max}

The agreement between the two values, measured and predicted by this model, proves that the developed model provides a precise and exact estimation of maximum punching force.

5. Conclusion

This study investigated the influence of key punching parameters on maximum punching force in metal sheet cutting using the Taguchi Design of Experiments. Four factors, which are punch speed (V), clearance between punch and die (J), punch diameter (D), and sheet thickness (e), were systematically analyzed. Two mathematical models were developed: a first-order model neglecting factor interactions, and a second-order model incorporating these interactions. The comparison revealed that the second-order model provides significantly better predictions, highlighting the crucial role of factor interactions. The findings demonstrate that combining Taguchi DoE with second-order modeling enables efficient optimization of punching process parameters while minimizing the number of required experiments. Future work may extend this methodology to other cutting and forming processes and materials, as well as explore the integration of numerical simulations with experimental DoE for further process optimization.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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