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(Research Article)

Performance investigation of punching operation to optimize the over cut of circular hole using Design of Experiment Technique "Taguchi Method"

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Abstract

Current research investigates the optimization of over-cut in circular hole punching operations using a CNC turret punching machine. The study employs the Design of Experiment (DOE) technique, specifically the Taguchi method, to systematically analyze the influence of three critical factors: cutting load, hit rate, and material type. The factors were varied across three levels: cutting load (10, 12, and 14 kN), hit rate (100, 150, and 200 punches per minute), and materials (EN-8, EN-24, and EN-31). An L9 orthogonal array was used to design the experimental runs, resulting in nine unique combinations to explore the effects on over-cut (OC). Over-Cut (OC) was the key response parameter, measured using a microscopic testing machine to capture high-resolution images of the punched holes. ImageJ software was employed for image processing to accurately assess the deviations. The data were analyzed using Minitab software, focusing on signal-to-noise (S/N) ratio analysis with the criterion "smaller is better." The S/N ratio results indicated that the cutting load had the most significant impact on minimizing dimensional deviation, followed by material type and hit rate.

The study revealed that the lowest dimensional deviation was achieved at a cutting load of 10 kN, hit rate of 200 punches per minute, and using EN-8 material. The mean effect and S/N ratio plots further confirmed that increasing the cutting load generally led to higher over-cut values, while higher hit rates improved precision. Interaction plots indicated that EN-31 material performed robustly across varying conditions, making it a suitable choice for diverse operational settings. ANOVA analysis supported these findings, with cutting load contributing the most to the variability in OC, followed by material type and hit rate. Current study provides valuable insights into the optimization of punching parameters to achieve minimal over-cut and enhance machining accuracy. The findings underscore the importance of selecting appropriate levels of cutting load, hit rate, and material type to optimize the performance of CNC punching operations.

Keywords: Turret punching; Over cut; Hit rate; Cutting load; EN Series; Taguchi method

1. Introduction

Sheet metal cutting is a fundamental process in the manufacturing industry, enabling the production of various parts and components from metal sheets. The precision and efficiency of this process are crucial for ensuring the quality and functionality of the final products. Various methods are employed in sheet metal cutting, including shearing, laser cutting, plasma cutting, water jet cutting, and punching. Each method has its own set of advantages and limitations, determined by factors such as material type, thickness, desired precision, and production volume. Among these methods, punching, especially with Computer Numerical Control (CNC) machines, has gained prominence due to its versatility, speed, and precision. The CNC punching process uses a computer-controlled punch and die system to create holes, slots, and shapes in sheet metal. The integration of CNC technology allows for automation, high repeatability, and complex patterning, making it an essential tool in the production of components for various industries. This research

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focuses on the application of the Taguchi method for optimizing cutting parameters in CNC punching, specifically for creating circular holes in three different steel configurations. The Taguchi method, known for its robust design and optimization capabilities, helps in systematically studying the effects of multiple parameters on the quality and efficiency of the cutting process.

Surface quality and dimensional accuracy are critical parameters in sheet metal cutting processes, significantly impacting the performance, aesthetics, and functionality of the final products. High surface quality ensures a smooth finish, reducing the need for additional post-processing operations such as grinding or polishing. This not only saves time and costs but also enhances the overall appearance and corrosion resistance of the parts. Dimensional accuracy refers to the degree to which the dimensions of the cut parts conform to the specified tolerances. Achieving high dimensional accuracy is essential for ensuring proper fit and assembly of components in complex structures. Deviations from the desired dimensions can lead to assembly issues, increased wear and tear, and compromised structural integrity.

In CNC punching, surface quality is influenced by factors such as the sharpness of the punch and die, cutting speed, and lubrication. A sharp punch and die produce cleaner cuts with minimal burr formation, while appropriate cutting speed and lubrication help in reducing friction and heat generation, further enhancing the surface finish. Dimensional accuracy in CNC punching is affected by parameters like punch and die alignment, machine rigidity, and tool wear. Proper alignment of the punch and die ensures consistent and precise cuts, while machine rigidity minimizes vibrations and deflections during the cutting process. Regular maintenance and timely replacement of worn tools are crucial for maintaining high dimensional accuracy. The significance of surface quality and dimensional accuracy extends beyond the manufacturing process to the performance and longevity of the final products. For instance, in the automotive industry, precisely cut and finished sheet metal components contribute to the aerodynamic performance, structural integrity, and aesthetic appeal of vehicles. In the electronics industry, accurate and smooth cuts are vital for ensuring proper fit and function of components in compact and intricate assemblies. This study aims to investigate the optimal cutting parameters for CNC punching to achieve the best possible surface quality and dimensional accuracy for three different steel configurations using the Taguchi method.

CNC punching machines have revolutionized the sheet metal cutting industry by offering enhanced precision, efficiency, and versatility. These machines leverage advanced computer control systems to automate the punching process, enabling the production of complex and high-quality parts with minimal human intervention. One of the key advantages of CNC punching machines is their ability to handle intricate and repetitive tasks with high accuracy. The integration of CNC technology allows for precise control over the movement and positioning of the punch and die, ensuring consistent and repeatable cuts. This level of precision is particularly beneficial in industries such as aerospace, automotive, and electronics, where tight tolerances and high-quality standards are paramount.

CNC punching machines also offer significant time and cost savings by streamlining the production process. The automation of punching operations reduces the need for manual labor, minimizing the risk of human errors and improving overall efficiency. Additionally, CNC machines can perform multiple operations, such as punching, notching, and forming, in a single setup, further reducing production time and costs. The versatility of CNC punching machines extends to their ability to handle a wide range of materials and thicknesses. With programmable parameters, these machines can adapt to different material properties, ensuring optimal cutting conditions for each job. This flexibility makes CNC punching machines suitable for various applications, from producing small electronic components to manufacturing large structural parts. Cutting parameters are the various factors and conditions that influence the efficiency, quality, and accuracy of the sheet metal cutting process. These parameters are critical in determining the performance outcomes such as surface finish, dimensional accuracy, and tool life. By adjusting cutting parameters, manufacturers can optimize the cutting process to meet specific requirements and improve overall productivity. The main types of cutting parameters include cutting speed, feed rate, punch and die material, and lubrication. Each of these parameters plays a unique role in the cutting process and must be carefully controlled to achieve the desired results. A CNC (Computer Numerical Control) punching machine is a sophisticated tool used in sheet metal fabrication to create holes and intricate shapes in metal sheets with high precision. It integrates computer technology to control the movement and operation of the punch and die, which are the primary components responsible for the cutting process. The working principle of a CNC punching machine involves the use of pre-programmed software instructions to guide the machine's actions. This process begins with the creation of a detailed design using CAD (Computer-Aided Design) software, which is then converted into a CNC program. This program contains precise instructions regarding the positioning and movement of the sheet metal, as well as the operation of the punch and die. Once the program is loaded into the CNC punching machine, the sheet metal is placed on the machine's worktable, which moves along the X and Y axes according to the program's specifications. The punch, which is mounted on a vertical axis (Z-axis), descends into the die to create holes or shapes in the metal sheet.

The aim of this study is to evaluate the dimensional accuracy of circular holes in three different steel configurations created using a CNC punching machine. The study employs the Taguchi method to generate various experimental conditions and uses Design of Experiments (DOE) techniques along with analysis tools like Minitab software to analyze and optimize the cutting parameters, ultimately enhancing the precision and quality of the punched holes.

2. Literature Review

The research questions and PRISMA methodology are central to systematically exploring the relationship between cutting parameters and the critical performance metrics of surface quality and dimensional accuracy in sheet metal components. The primary research question seeks to identify key cutting parameters significantly influencing these metrics, while secondary questions delve into the effects of individual parameters such as cutting speed, feed rate, punch and die material, and lubrication on surface finish and dimensional tolerances. A thorough review of existing literature reveals the multifaceted nature of sheet metal cutting processes and the complex interplay of factors affecting product quality. By addressing these questions through empirical experimentation and quantitative analysis, this study aims to contribute valuable empirical evidence to the body of knowledge in manufacturing engineering. The findings are expected to provide practical insights for optimizing cutting processes, enhancing product performance, and informing decision-making in industrial settings. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology is a structured approach used primarily in systematic reviews and meta-analyses within healthcare and biomedical sciences. Its principles of systematic searching, screening, and synthesizing literature can be effectively adapted to engineering and manufacturing studies. In this research, the PRISMA methodology serves as a comprehensive framework for conducting a thorough literature review on sheet metal cutting processes.

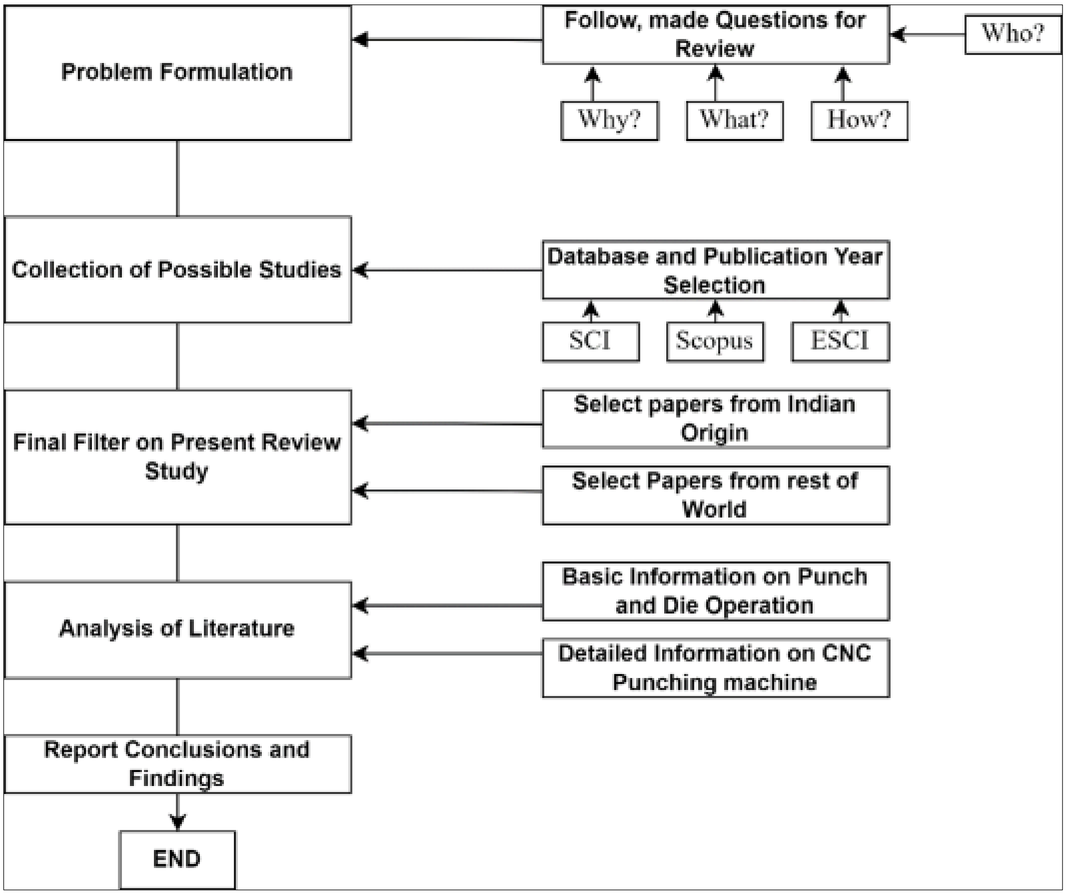

Figure 1 Methodology adopted for Literature Review

Key stages of the PRISMA methodology include the formulation of a research protocol, systematic literature search, screening and selection of studies, data extraction and synthesis, critical appraisal and quality assessment, and reporting and documentation. The research protocol outlines the objectives, search strategy, inclusion and exclusion criteria, and methods for data extraction and synthesis. The systematic literature search involves exhaustive searching across multiple databases, academic journals, conference proceedings, and grey literature sources using relevant keywords and search terms. Identified studies are then screened based on predefined inclusion and exclusion criteria, reviewing titles, abstracts, and full texts to determine eligibility. Data from selected studies are systematically extracted, including key findings, methodologies, and conclusions. This data is organized and summarized to identify trends, patterns, and gaps in the literature. The quality and reliability of included studies are critically appraised to assess their methodological rigor and potential biases, ensuring only high-quality evidence contributes to the synthesis of findings.

The recent literature highlights various advancements in punching processes and their applications in manufacturing. Hawryluk et al. (2023) investigate the impact of hot work tool steels' grades and microstructural features on the durability of punches used in precision forging of nickel-chrome steel valve forgings, emphasizing the critical role of tool material selection in high-stress applications. Sun et al. (2023) examine the surgical outcomes of locking plate fixation techniques in treating complex ankle fractures, focusing on the die-punch fragment size. Matsuno et al. (2024) explore the degradation of delayed fracture stress thresholds in ultra-high-strength steel sheets due to the shear punching process, combining experimental tests and simulations. Bouchaâla et al. (2021) study the effects of punch and die radii on flange earing formation in aluminum alloys during deep drawing processes, providing insights for optimizing process parameters. Han et al. (2024) propose a single-step self-punching lockbolt process for aluminum sheets, eliminating the need for pre-hole drilling. Sampaio et al. (2023) investigate double-flush riveting using punching and compression techniques, contributing to hybrid joining technologies. Siimut and Nielsen et al. (2023) introduce an adjustable ironing punch concept to enhance metal forming precision. Redžić et al. (2024) focus on optimizing the cutting performance of carbide punching tools for ultra-high-strength steel strips. Wang et al. (2023) present a novel exhaust punch for improving the formability of hot embossing in microstructure fabrication. Latorre et al. (2023) propose a mechanical interlocking punching process for joining metal sheets and fiber-reinforced polymer composites, advancing hybrid material joining techniques. These studies collectively advance the understanding and application of punching processes in various manufacturing contexts.

Table 1 Summary of Published Literature on Punch and Die operation

Reference	Study Focus	Key Findings
Hawryluk et al. (2023)	Influence of hot work tool steels on punch durability in precision forging	Examined impact of tool steel grade and microstructure on punch longevity in forging processes
Sun et al. (2022)	Locking plate fixation for Bartoníček Type IV posterior malleolar fractures	Investigated outcomes of plate fixation focusing on die-punch fragment size
Matsuno et al. (2024)	Shear punching effects on ultra-high-strength steel sheets	Analyzed degradation of fracture stress thresholds due to shear punching, using experimental and numerical methods
Bouchaâla et al. (2021)	Effect of punch and die geometry on flange earing in aluminum alloy deep drawing	Numerical investigation of corner and shoulder radii influence on flange ear formation
Han et al. (2024)	Self-punching lockbolt process for aluminum sheets	Developed a single-step assembly method without pre-hole drilling for aluminum components
Sampaio et al. (2023)	Double-flush riveting by punching and compression	Studied mechanical properties and joint performance of riveted assemblies
Nielsen et al. (2023)	Novel ironing punch concept with adjustable tool diameter	Introduces a flexible tool design for improving precision in metal forming processes
Redžić et al. (2024)	Cutting edge preparation effects on punching ultra-high-strength steel strips	Investigated the influence of tool edge preparation on cutting performance
Wang et al. (2023)	Formability improvement in hot embossing with exhaust punch	Enhanced manufacturing capabilities for micro-array structures using innovative punching techniques
Latorre et al. (2023)	Punching process for joining metal sheets and fiber-reinforced composites	Explored mechanical interlocking as a method for integrating metal and composite materials

Velraja and Srinivasan conducted several studies investigating the performance of sputtered silicon nitride cutting inserts in CNC machining, highlighting their effectiveness in enhancing tool life and machining efficiency. Published in Materials Today: Proceedings, their research underscored the advantages of silicon nitride coatings in reducing wear and improving cutting performance, advancing the field of cutting tool materials for precision machining (Velraja & Srinivasan, 2023a). In another study, they explored the performance of DC magnetron sputtered coated inserts, focusing on the impact of various coating materials on tool wear and machining accuracy. This work, published in Measurement: Sensors, emphasized the importance of coating technologies in extending tool life and improving machining quality (Velraja & Srinivasan, 2023b). Additionally, they analyzed the performance of sputtered carbide inserts, providing insights into optimizing tool selection and process parameters for enhanced productivity and cost-effectiveness in CNC machining (Velraja & Srinivasan, 2023c). These studies collectively contribute to a deeper understanding of the role of advanced coating technologies in CNC machining, offering valuable knowledge for improving industrial manufacturing processes.

3. Research Methodology

In the present study, an AE2510 NT turret CNC punching machine was employed to investigate the dimensional accuracy and surface quality of circular holes punched in different steel configurations. The circular hole was selected as the geometric feature for this analysis due to its common application in various industrial components. The research methodology comprised the following steps:

- **Material Selection and Preparation**: Three different steel configurations (EN-8, EN-14 and EN-31) were selected for the experiments. Each steel sheet was cut into standardized sizes to ensure consistency across all tests.
- **Experimental Design**: The Taguchi method was used to design the experiments, focusing on three key process parameters: cutting speed, feed rate, and punch-die clearance. A total of 16 experiments were generated based on an orthogonal array to systematically explore the influence of these parameters on the outcome.
- **Machining Process**: Using the AE2510 NT turret CNC punching machine, circular holes were punched into the prepared steel sheets according to the Taguchi-designed experiments. Each experiment was performed under controlled conditions to minimize variability.
- **Measurement and Analysis**: Dimensional accuracy of the punched holes was measured using precision metrology tools. Surface quality was evaluated through surface roughness measurements. The collected data was analysed using Design of Experiments (DOE) methods and statistical analysis tools, such as Minitab software, to identify significant factors and their interactions. This structured approach ensured a comprehensive analysis of the punching process, providing valuable insights for improving CNC punching operations.

Figure 2 Machine and final object made by this machine

3.1. Factor and levels

In this study, the CNC turret punching machine was utilized to create circular holes, with three factors investigated: cutting load, hit rate, and material type. The cutting load, measured in kilonewtons (kN), was tested at three levels: 10 kN, 12 kN, and 14 kN. The hit rate, expressed as punches per minute, was varied at 100, 150, and 200 punches per minute. Additionally, three different material types were examined: EN-8, EN-24, and EN-31. By varying these factors and levels, the study aimed to assess their impact on the quality and efficiency of the punching process.

Table 2 Factor and Levels

Factor/Level	Unit	I	II	III
Cutting Load	kN	10	12	14
Hit Rate	Per min	100	150	200
Material	-	EN-8	EN-24	EN-31

The Taguchi method was employed to structure the experimental design using an L9 orthogonal array for this study. The array consisted of nine experimental runs, systematically combining different levels of three factors: cutting load, hit rate, and material type. Each run involved varying the cutting load across three levels (10, 12, and 14 kN), the hit rate at three levels (100, 150, and 200 punches per minute), and the material type among three variants (EN-8, EN-24, and EN-31). The resulting combinations are detailed in Table 3, with each run designed to explore the effects of these factors on the CNC turret punching process.

Table 3 L9 Orthogonal Array for present study

Run	Cutting Load	Hit Rate	Material
1	10	100	EN8
2	10	150	EN24
3	10	200	EN31
4	12	100	EN24
5	12	150	EN31
6	12	200	EN8
7	14	100	EN31
8	14	150	EN8
9	14	200	EN24

3.2. Response Parameters

In this study, the dimensional deviation parameter, commonly referred to as the over-cut parameter, was selected to assess the precision of the circular holes cut by the CNC turret punching machine. This parameter is crucial for evaluating the accuracy of the punching process. To measure the over-cut, a microscopic testing machine was employed, which provided high-resolution imaging to determine the actual dimensions of the cut holes. The use of this advanced measurement technique ensured precise quantification of any deviations from the desired dimensions, allowing for a detailed analysis of how variations in cutting load, hit rate, and material type influence the quality of the punched holes. By focusing on the dimensional deviation, the study aimed to identify optimal process conditions that minimize discrepancies and improve overall machining accuracy. This approach enhances the reliability and performance of the CNC punching process in achieving the required specifications. The microstructural image of the microstructural image was processed by using imageJ software.

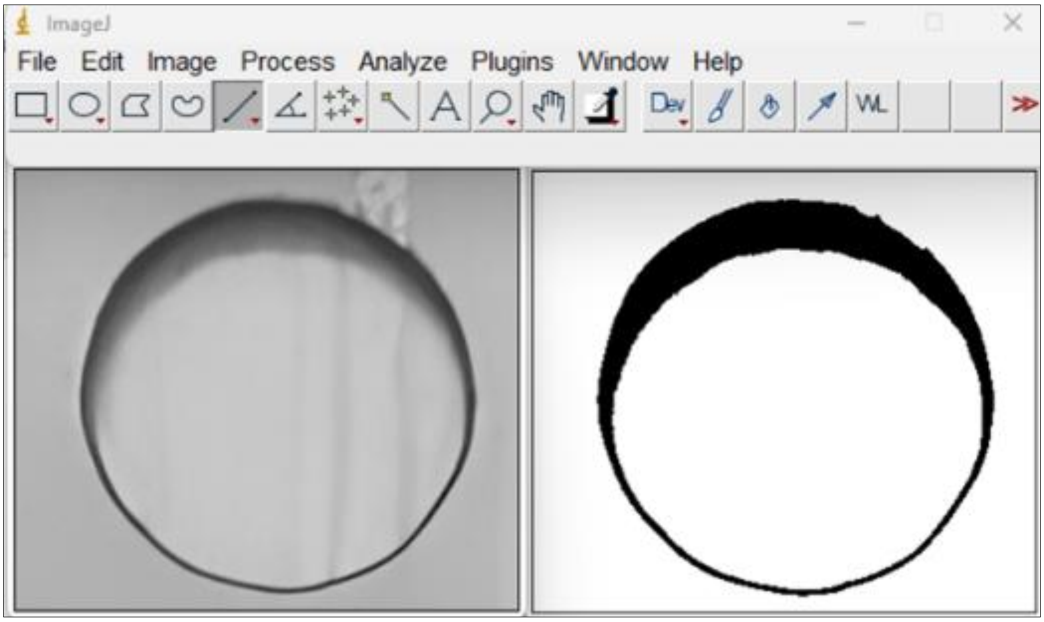

Figure 3 Image processing of the microstructural image of the circular hole

The final dimensional deviation of the circular hole made by using CNC punching machine was present in table 4 and the signal to noise ratio analysis was also present in the same table for option "smaller is better".

Table 4 Signal to noise ratio analysis of Dimensional Deviation (DD)/over cut

Run	Cutting Load	Hit Rate	Material	DD/OC (mm)	S/N ratio
1	10	100	EN8	0.306	10.286
2	10	150	EN24	0.316	10.006
3	10	200	EN31	0.306	10.286
4	12	100	EN24	0.316	10.006
5	12	150	EN31	0.326	9.736
6	12	200	EN8	0.296	10.574
7	14	100	EN31	0.356	8.971
8	14	150	EN8	0.316	10.006
9	14	200	EN24	0.336	9.473

4. Result and Discussion

4.1. Signal to Noise ratio analysis of DD/OC

In this study, the signal-to-noise ratio (SNR) analysis was performed to evaluate the dimensional deviation (DD) or over-cut using Minitab software, focusing on the quality of the punched holes. The SNR is a crucial metric in determining the impact of different factors on process precision, where a higher ratio indicates better performance. The results, summarized in the table, reveal the following signal-to-noise ratios for each factor level:

Table 5 S/N ratio analysis for DD/OC

Level	Cutting Load	Hit Rate	Material
1	10.192	9.754	10.289
2	10.105	9.916	9.829
3	9.483	10.111	9.664
Delta	0.709	0.357	0.625
Rank	1	3	2

- **Cutting Load:** Level 1 (10 kN) yielded the highest SNR of 10.192, indicating superior precision in dimensional deviation compared to higher loads. Level 2 (12 kN) and Level 3 (14 kN) showed lower SNRs of 10.105 and 9.483, respectively. This suggests that increasing the cutting load tends to increase the over-cut, leading to less precise dimensional control.
- **Hit Rate:** Level 1 (100 punches per minute) had an SNR of 9.754, while Level 2 (150 punches per minute) and Level 3 (200 punches per minute) showed SNRs of 9.916 and 10.111, respectively. The trend indicates that a higher hit rate improves the precision of the cut, with the highest SNR observed at the maximum rate.
- **Material:** The material EN-8 at Level 1 achieved an SNR of 10.289, while EN-24 and EN-31 yielded lower SNRs of 9.829 and 9.664. This result suggests that EN-8 material offers better dimensional accuracy compared to the other materials tested.

The mean effect plot and signal-to-noise (S/N) ratio plot for dimensional deviation (DD) or over-cut (OC) provide valuable insights into the impact of various factors on machining precision. The mean effect plot illustrates how each factor—cutting load, hit rate, and material type—affects the average dimensional deviation. It helps identify which levels of each factor yield the smallest average deviations. The S/N ratio plot, on the other hand, highlights the variability in the measured over-cut relative to the noise, with higher S/N ratios indicating better precision. Analysing these plots allows for optimization of process parameters to achieve minimal dimensional deviations and enhanced accuracy.

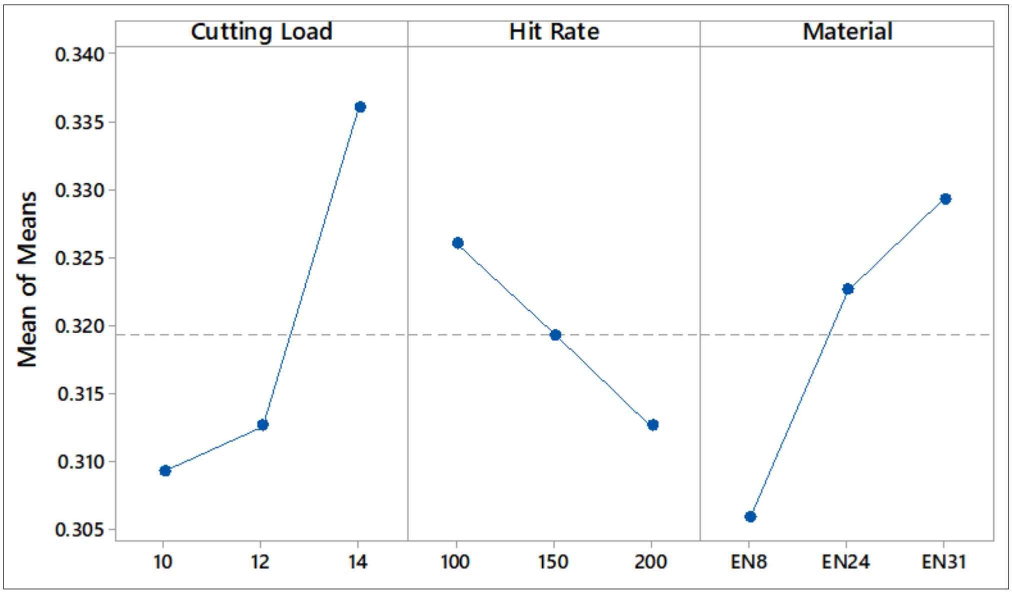

Figure 4 Mean effect plot analysis of DD/OC

The Delta values, which represent the range between the maximum and minimum SNR for each factor, reveal that cutting load has the most significant impact on the dimensional deviation (Delta = 0.709), followed by material type (Delta = 0.625), and hit rate (Delta = 0.357).

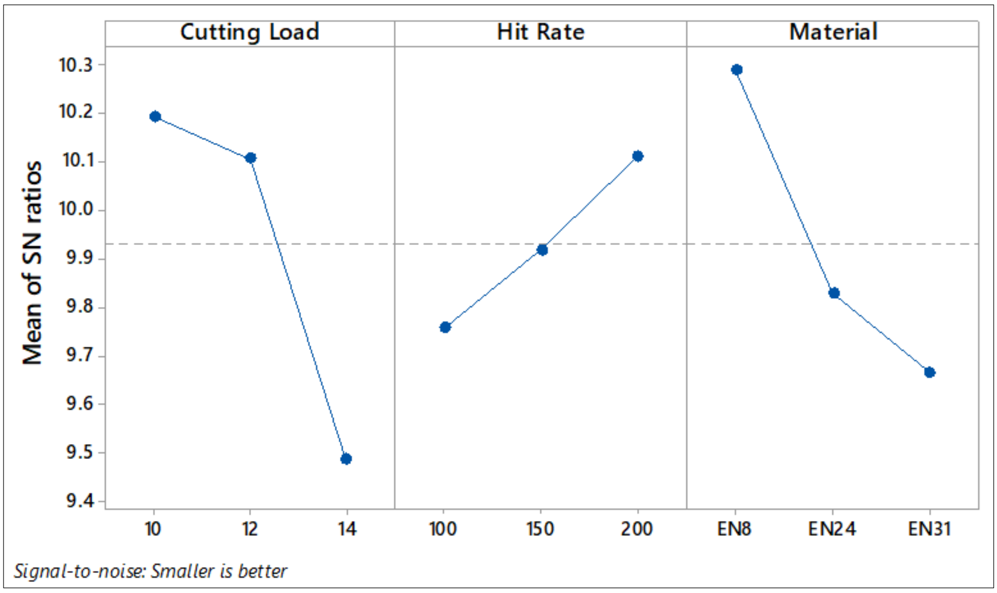

Figure 5 S/N ratio plot analysis of DD/OC

The ranking indicates that minimizing cutting load is crucial for improving dimensional precision, while material type also plays a significant role. Overall, the analysis suggests that optimizing these parameters can significantly enhance the accuracy of the CNC punching process.

4.2. Interaction Plot analysis of DD/OC

The interaction plot in figure 6, the relationships between three factors: Cutting Load, Hit Rate, and Material, each represented on the axes and legends. The y-axis represents a response variable, likely a measure of performance or efficiency, although it is not labelled explicitly.

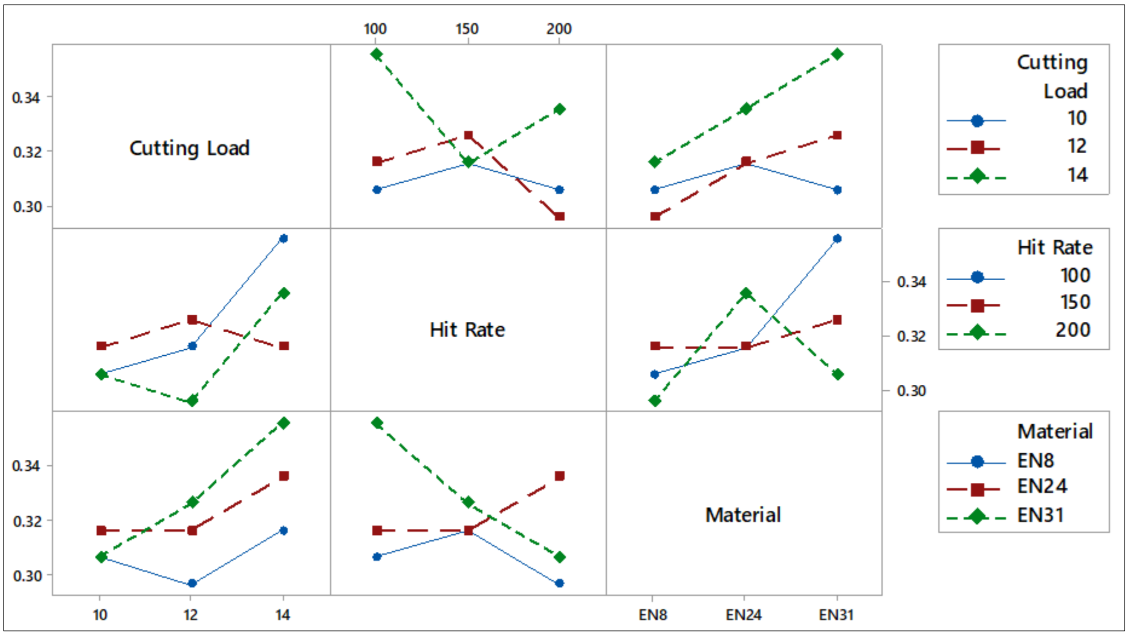

Figure 6 Interaction plot analysis for DD/OC

- **Cutting Load**: The interaction between Cutting Load and Material shows that EN8 material's performance increases with increasing load, peaking at the highest load. EN24 shows a slight decrease, while EN31 shows a notable increase, especially from 12 to 14 load units.

- **Hit Rate**: The graph suggests that for EN8 and EN24 materials, performance slightly decreases with increasing hit rates. In contrast, EN31 shows an increase, particularly significant at the highest hit rate of 200.
- **Material Comparison**: Across different levels of Cutting Load and Hit Rate, EN31 generally exhibits higher performance, particularly under higher load and hit rate conditions. EN24's performance is less responsive to changes in Hit Rate and Cutting Load, while EN8 shows variable responses.

These interactions indicate that EN31 is the most robust material under varying conditions, while EN8 and EN24 show more specific optimal ranges. This information is crucial for selecting appropriate materials and operating conditions in industrial applications.

4.3. Regression Modeling analysis of DD/OC

The ANOVA table presented summarizes the analysis of variance for a model examining the effects of three factors: Cutting Load, Hit Rate, and Material, on a response variable. The model accounts for 84.62% of the total variation (Seq SS = 0.0022) with a significant F-value of 5.5 (P = 0.06), indicating that the factors considered are relevant.

Table 6 ANOVA analysis of response DD/OC

Source	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Model	4	0.0022	84.62%	0.00055	5.5	0.06
Linear	4	0.0022	84.62%	0.00055	5.5	0.06
Cutting Load	1	0.001067	41.03%	0.001067	10.67	0.03
Hit Rate	1	0.000267	10.26%	0.000267	2.67	0.17
Material	2	0.000867	33.33%	0.000433	4.33	0.10
Error	4	0.0004	15.38%	0.0001		
Total	8	0.0026	100.00%			

Regression Equation in Uncoded Units

EN8 OC = 0.2460 + 0.00667 Cutting Load - 0.000133 Hit Rate

EN24 OC = 0.2627 + 0.00667 Cutting Load - 0.000133 Hit Rate

EN31 OC = 0.2693 + 0.00667 Cutting Load - 0.000133 Hit Rate

Cutting Load contributes the most to the model, with a 41.03% contribution (Seq SS = 0.001067), and a significant F-value of 10.67 (P = 0.031), suggesting it has a substantial effect on the response variable. Material follows with a 33.33% contribution (Seq SS = 0.000867) and an F-value of 4.33 (P = 0.1), indicating a notable but less significant impact. Hit Rate has the least impact, with a 10.26% contribution (Seq SS = 0.000267) and a non-significant F-value of 2.67 (P = 0.178). The residual error contributes 15.38% of the total variation (Seq SS = 0.0004).

5. Conclusion

Current study thoroughly examined the factors influencing the over-cut (OC) in the CNC punching process, focusing on the signal-to-noise ratio (SNR), interaction plots, and regression modeling. The SNR analysis, a critical metric for assessing process precision, revealed that Cutting Load had the most significant impact on dimensional deviation, followed by Material and Hit Rate. Specifically, the lowest Cutting Load (10 kN) resulted in the highest SNR (10.192), indicating superior precision. This suggests that minimizing the cutting load is crucial for reducing dimensional deviations and improving accuracy. Material selection also played a pivotal role, with EN-8 demonstrating the highest SNR (10.289), outperforming EN-24 and EN-31. This finding indicates that EN-8 is the most suitable material for applications requiring high precision. The Hit Rate, although having the least impact, still showed a positive trend with higher rates correlating with better precision.

The interaction plot analysis further highlighted the complex relationships between these factors. It was observed that EN31 exhibited superior performance across various cutting loads and hit rates, making it a robust choice under different operational conditions. In contrast, EN8 and EN24 showed more specific optimal ranges, which necessitates careful parameter selection to achieve the best results. The ANOVA results supported these findings, showing that the model explained 84.62% of the total variation in OC. Cutting Load was the most influential factor, with a 41.03% contribution, and a significant F-value of 10.67 (P = 0.031). Material type followed, contributing 33.33% with an F-value of 4.33 (P = 0.1), while Hit Rate had the least impact, contributing 10.26%. The current study underscores the importance of optimizing cutting load and material selection in enhancing the precision of CNC punching processes. The findings provide valuable insights for industrial applications, suggesting that careful tuning of these parameters can significantly improve manufacturing quality and efficiency.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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