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Optimization of Drilling Parameters and Tool Geometry for Enhanced Performance and Hole Quality in AISI 1050 Steel

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ABSTRACT

This study presents a comprehensive statistical analysis of the effects of drilling parameters on cutting forces and hole quality in AISI 1050 steel, utilizing Analysis of Variance (ANOVA) to evaluate the significance of various factors. The research employs a full factorial experimental design to systematically investigate the influence of drill geometry, cutting speed, and feed rate on thrust force, torque, and several metrics of hole quality. The ANOVA results indicate that drill geometry is the predominant factor, accounting for a significant portion of the variance in thrust force and torque, with statistically significant F-values, thereby confirming its critical role in drilling performance optimization. Moreover, cutting speed and feed rate also demonstrate substantial contributions to the variance in cutting forces and hole quality metrics. These findings highlight the importance of these parameters in enhancing drilling efficiency and minimizing defects such as burr formation and surface roughness. The interaction between these parameters is essential for achieving optimal drilling conditions, as evidenced by the statistical modeling approaches employed in the study. In addition to ANOVA, the study incorporates Taguchi method's signal-to-noise ratio analysis to further validate the findings. This method underscores the superior performance of specific drill geometries in minimizing variability in drilling outcomes, thereby reinforcing the significance of drill design in achieving high-quality holes. The insights derived from this research provide a robust foundation for optimizing drilling processes in industrial applications, particularly for medium-carbon steels like AISI 1050, and offer valuable guidance for future research endeavors aimed at enhancing machining efficiency and quality. The implications of this study extend to practical applications in manufacturing, where understanding the interplay of drilling parameters can lead to improved operational efficiencies and product quality. The findings contribute to the existing body of knowledge by elucidating the critical factors influencing drilling performance, thus serving as a reference point for further investigations in the field of machining and materials processing.

Keywords: *AISI 1050 Steel, Drilling Parameters, ANOVA, Taguchi Method*

AISI 1050 Çeliğinde Kesme Verimliliği ve Delik Kalitesini Artırmak için Delme Parametrelerinin Optimizasyonu

ÖZET

Bu çalışma, AISI 1050 çeliğinde delme parametrelerinin kesme kuvvetleri ve delik kalitesi üzerindeki etkilerini kapsamlı bir istatistiksel analizle sunmaktadır. Çalışmada, çeşitli faktörlerin önemini değerlendirmek için Varyans Analizi (ANOVA) kullanılmıştır. Araştırma, matkap geometrisi, kesme hızı ve ilerleme hızının itme kuvveti, tork ve delik kalitesinin çeşitli metrikleri üzerindeki etkisini sistematik olarak incelemek amacıyla tam faktöriyel deney tasarımı kullanmaktadır. ANOVA sonuçları, matkap geometrisinin itme kuvveti ve torktaki varyansın önemli bir kısmını açıklayan baskın faktör olduğunu ve istatistiksel olarak anlamlı F-değerleri ile delme performansının optimizasyonundaki kritik rolünü doğruladığını göstermektedir. Ayrıca, kesme hızı ve ilerleme hızı da kesme kuvvetleri ve delik kalitesi metriklerindeki varyansa önemli katkılar sağlamaktadır. Bu bulgular, bu parametrelerin delme verimliliğini artırmada ve çapak oluşumu ile yüzey pürüzlülüğü gibi kusurları en aza indirmede önemini vurgulamaktadır. Bu parametreler arasındaki etkileşim, çalışmada kullanılan istatistiksel modelleme yaklaşımlarıyla kanıtlandığı üzere, optimal delme koşullarının elde edilmesi için esastır. ANOVA'ya ek olarak, çalışma bulguları daha da doğrulamak için Taguchi'nin sinyal-gürültü oranı analizini içermektedir. Bu yöntem, belirli matkap geometrilerinin delme sonuçlarındaki değişkenliği en aza indirmedeki üstün performansını vurgulamakta ve yüksek kaliteli delikler elde etmede matkap tasarımının önemini pekiştirmektedir. Bu araştırmadan elde edilen içgörüler, özellikle AISI 1050 gibi orta karbonlu çelikler için endüstriyel uygulamalarda delme süreçlerinin optimize edilmesi için sağlam bir temel sağlamakta ve işleme verimliliği ve kalitesini artırmayı amaçlayan gelecekteki araştırma çabalarına değerli rehberlik sunmaktadır. Çalışmanın etkileri, delme parametrelerinin etkileşimini anlamanın operasyonel verimlilikleri ve ürün kalitesini artırabileceği üretim alanındaki pratik uygulamalara kadar uzanmaktadır. Bulgular, delme performansını

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etkileyen kritik faktörleri açıklayarak, işleme ve malzeme işleme alanındaki daha ileri araştırmalar için bir referans noktası olarak mevcut bilgi birikimine katkıda bulunmaktadır.

***Anahtar Kelimeler**: AISI 1050 Çeliği, Delme Parametreleri, ANOVA, Taguchi Yöntemi*

1. INTRODUCTION

Drilling is a fundamental material removal process, integral to numerous manufacturing sectors, constituting a substantial portion of machining operations [1]. This process is essential for creating precise holes in a variety of materials, such as metals, polymers, and composites. The efficiency and quality of drilling operations are influenced by numerous factors, including the type of cutting tool, its geometry, hole diameter, machine rigidity, cutting fluids, and cutting parameters. A comprehensive understanding of these dynamics is critical for optimizing process efficiency and ensuring product quality, especially in high-precision applications where tolerances are critical [2, 3]. Despite its critical importance, drilling poses several challenges that can adversely affect the quality of the drilled holes. Variability in cutting forces and material removal rates often lead to complications such as tool jamming and excessive wear [4, 5]. Additionally, the use of suboptimal spindle and drill chuck configurations can introduce geometric errors, resulting in circular deviations and axial misalignments-collectively referred to as cylindrical deviation-between entry and exit holes. Such deviations risk compromising the integrity of the final product by exceeding acceptable tolerance limits [6].

The demand for high-precision machining has intensified with technological advancements, necessitating stringent control over key parameters that affect hole quality, including dimensional accuracy, circularity, cylindrical deviation, and surface finish. Achieving these quality indicators often necessitates secondary operations, such as reaming, which enhance precision but also increase machining time and production costs [7]. Literature indicates that surface roughness is significantly impacted by drilling parameters like cutting speed and feed rate, which can cause thermal softening and subsequent surface damage [8, 9]. Extensive research has explored a variety of factors impacting drilling performance. Studies highlight the significant influence of cutting tool type on surface roughness and tool wear [10, 11]. Investigations reveal that coated tools often outperform uncoated ones in surface finish and longevity [12, 13]. Furthermore, the geometry of the drill bit, including its diameter and point angle, is crucial for determining drilling efficiency and hole quality [14]. Additionally, the application of cutting fluids can enhance drilling performance by mitigating friction and heat, thereby improving surface finish and extending tool life [15]. Minimum Quantity Lubrication (MQL) techniques are particularly noteworthy for offering effective cooling solutions with minimal environmental impact [16]. The effectiveness of these strategies, however, varies with the material and specific operational conditions [17].

The complexities associated with drilling operations necessitate ongoing investigation to develop robust models and strategies for optimization. This is especially true for materials like AISI 1050 steel, which present unique challenges due to their specific metallurgical properties [18]. Research suggests that optimizing parameters such as feed rate and cutting speed can significantly improve surface finish and dimensional accuracy [19]. Moreover, integrating advanced technologies like fuzzy logic and artificial intelligence enhances the predictive capabilities of drilling models, enabling real-time process adjustments [20]. In summary, while drilling is a cornerstone of modern manufacturing, it poses challenges that can compromise quality. A thorough understanding of drilling dynamics is essential to optimizing process efficiency and achieving high-quality outcomes. Continued research in this domain is critical to addressing the complexities of drilling operations and developing innovative solutions to enhance precision and reliability.

This study aims to systematically investigate the individual and interactive effects of cutting speed, feed rate, and drill geometry on thrust force and torque during the drilling of AISI 1050 steel. By employing a full factorial experimental design and rigorous statistical analysis, the research seeks to elucidate the impact of these parameters on critical hole quality metrics. The findings will contribute to the development of empirical models and optimization strategies, ultimately enhancing the efficiency and quality of drilling operations in industrial applications.

2. MATERIAL AND METHOD

2.1. Experimental Setup

The drilling experiments were conducted on a CNC vertical machining center (Johnford VMC-850 model). Drilling was performed directly on the chamfered surface without prior spot-facing, simulating real-world manufacturing conditions where preparatory operations are often impractical. This study aimed to assess the performance of cutting tools and process parameters under these challenging conditions. A full factorial experimental design was utilized to systematically analyze the effects of drilling parameters—cutting speed, feed rate, and drill geometry—on cutting forces and torque during the machining of AISI 1050 steel. This material, widely used in gear manufacturing, was selected for its mechanical strength and moderate machinability. The test samples, crafted from AISI 1050 steel, were prepared to replicate the industrially relevant thickness and curvature of a 16-B sprocket. The chemical composition of the workpiece material is detailed in Table 1.

Table 1. Chemical composition of AISI 1050 manufacturing steel

% C	% Si (Max)	% Mn	% P (Max)	% S (Max)
0.45-0.55	0.40	0.6-0.9	0.035	0.035

The cutting speed (Vc, m/min) was varied across three distinct levels: Low (20 m/min), Medium (40 m/min), and High (60 m/min). This range was chosen to encompass typical operational conditions, allowing for a thorough assessment of its influence on cutting forces and surface integrity. The feed rates (f, mm/rev) selected for the study were set at 0.11, 0.13, and 0.15 mm/rev. These levels were specifically chosen based on preliminary tests to cover a broad spectrum of material removal rates, from conservative to aggressive, thus enabling the identification of optimal feed conditions that maximize efficiency without compromising quality. Three different drill geometries were investigated: the U-Drill, a standard drill with a 180° point angle, and a 140° point angle drill. These geometrical variations were selected to discern their respective impacts on the drilling dynamics and resultant hole quality, as tool geometry is a critical determinant of cutting performance. The experimental design's full factorial nature ensures comprehensive coverage of parameter combinations, thus allowing for robust statistical analysis of main effects and interactions. This approach not only facilitates the identification of optimal drilling conditions but also enhances the understanding of the underlying mechanical processes influencing hole quality in AISI 1050 steel. The specific cutting parameters and tool specifications are presented in Table 2. In Figure 1, the technical drawing of the 16B chain sprocket and the experimental specimen are shown.

Table 2. Control factors and their levels

Control Factors	Level 1	Level 2	Level 3
Cutting Speed (Vc, m/min)	Low(20 m/min)	Medium(40 m/min)	High(60 m/min)
Feed Rate (f, mm/rev)	0.11	0.13	0.15
Drill Geometry	U-Drill	180°	140°

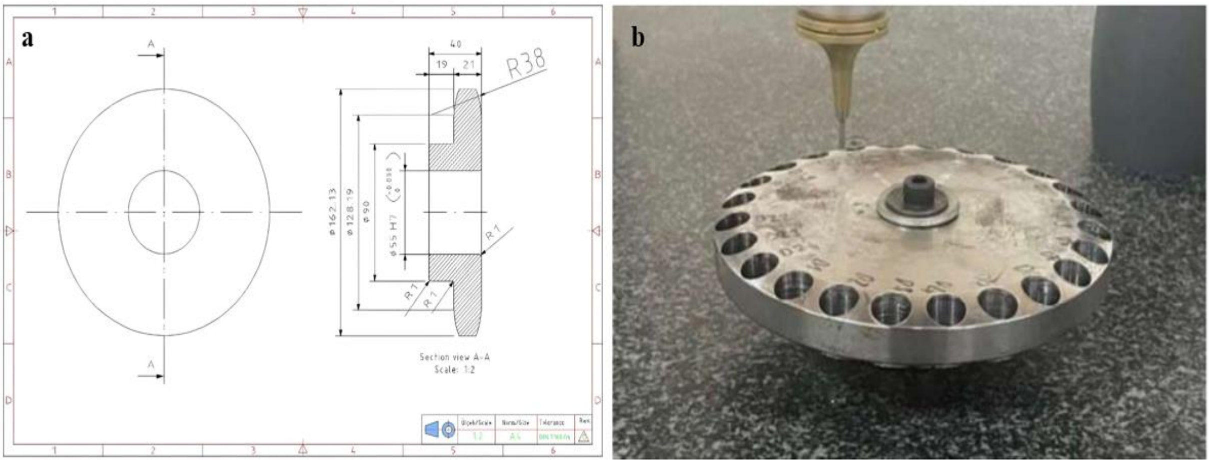

Figure 1. 16B chain sprocket techinal drawaing (a) and Test spicemen (b)

Cutting forces and torque were meticulously recorded using a Kistler 9272-A 4-component dynamometer paired with a Kistler 5070-A multi-channel amplifier, ensuring precision in data acquisition. Post-drilling evaluations involved measuring hole diameters, circular deviations, and cylindrical deviations using a coordinate measuring machine (CMM) for high precision.

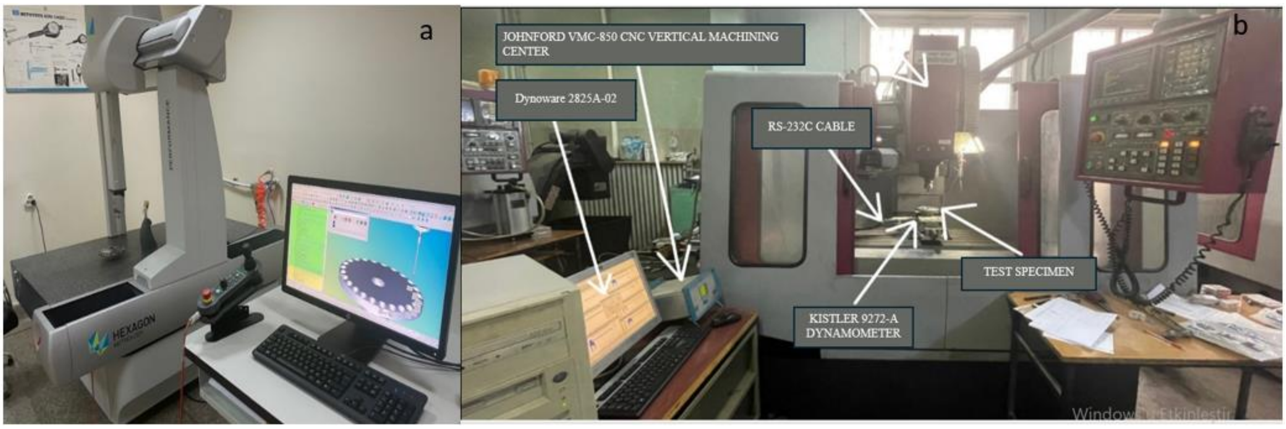

Fig.2 Experimental setup of the CMM (a) and JOHNFORD VMC-850 CNC vertical machining center with integrated Kistler 9272-A dynamometer, (b) Kistler 5070-A signal amplifier, and Dynoware 2825A-02 data acquisition system for machining force measurement.

A full factorial experimental design was implemented, allowing thorough investigation of the effects of three primary parameters-drill diameter, feed rate, and cutting speed-across three levels, and drill type across two levels. This approach enabled analysis of individual and interaction effects of control parameters, resulting in a total of 27 experimental trials (Table 3).

Table 3. Taguchi design

Experiment No	Drill Geometry	Cutting Speed (Vc, m/min)	Feed Rate (f, mm/rev)
1	U-Drill	Low(20 m/min)	0.11
2	U-Drill	Low(20 m/min)	0.13
3	U-Drill	Low(20 m/min)	0.15
4	U-Drill	Medium(40 m/min)	0.11
5	U-Drill	Medium(40 m/min)	0.13
6	U-Drill	Medium(40 m/min)	0.15
7	U-Drill	High(60 m/min)	0.11
8	U-Drill	High(60 m/min)	0.13
9	U-Drill	High(60 m/min)	0.15
10	180°	Low(20 m/min)	0.11
11	180°	Low(20 m/min)	0.13
12	180°	Low(20 m/min)	0.15
13	180°	Medium(40 m/min)	0.11
14	180°	Medium(40 m/min)	0.13
15	180°	Medium(40 m/min)	0.15
16	180°	High(60 m/min)	0.11
17	180°	High(60 m/min)	0.13
18	180°	High(60 m/min)	0.15
19	140°	Low(20 m/min)	0.11
20	140°	Low(20 m/min)	0.13
21	140°	Low(20 m/min)	0.15
22	140°	Medium(40 m/min)	0.11
23	140°	Medium(40 m/min)	0.13
24	140°	Medium(40 m/min)	0.15
25	140°	High(60 m/min)	0.11
26	140°	High(60 m/min)	0.13
27	140°	High(60 m/min)	0.15

3. EXPERIMENT AND OPTIMIZATION RESULTS

The experimentation conducted using the L27 orthogonal design represents a robust and well-established methodology for analyzing the effects of various drilling parameters on critical machining outcomes. The L27 orthogonal array facilitates a systematic exploration of multiple factors and their interactions, which is essential for optimizing drilling processes. This methodological approach has been effectively employed in numerous studies to evaluate the influence of parameters such as spindle speed, feed rate, and drill point angle on drilling performance [21, 22].

In this context, the analysis of variance (ANOVA) table serves as a fundamental analytical tool, enabling the determination of the significance of each parameter's contribution to the variability in response variables. For instance, empirical studies have demonstrated that factors like cutting speed and feed rate significantly influence the quality of drilled holes and surface finish [23, 24]. The integration of ANOVA with the L27 orthogonal design enhances the reliability of the findings and supports the derivation of robust conclusions regarding optimal drilling conditions.

Moreover, response curves play a pivotal role in visualizing the relationship between drilling parameters and their corresponding responses. The larger-the-better and smaller-the-better approaches are frequently employed in the analysis of signal-to-noise (S/N) ratios, which are crucial for optimizing the drilling process [21, 24]. This methodological framework not only facilitates an understanding of the effects of individual parameters but also aids in making informed decisions regarding the selection of optimal machining conditions. In summary, the integration of the L27 orthogonal design, ANOVA provides a comprehensive and effective framework for analyzing the effects of drilling parameters.

3.1. Taguchi Analysis

3.2. Fz (N) and M (N.cm) versus Drill Geometry; Cutting Speed (Vc, m/min); Feed Rate (f, mm/rev)

The Taguchi method is a powerful statistical tool widely utilized for optimizing drilling parameters, particularly in the context of composite materials and various drilling geometries. The method employs orthogonal arrays to systematically analyze the influence of multiple factors, such as cutting speed (Vc), feed rate (f), and drill geometry, on performance metrics like thrust force (Fz) and surface roughness. For instance, studies have shown that the selection of optimal drilling parameters can significantly reduce surface roughness and thrust force, thereby enhancing the overall quality of drilled holes [25-27]. The outcome of procedure parameters on Fz(N) and M(N.cm) was found as given below Table 4.

Table 4. Fz (N) and M (N.cm) results

Experiment no	Fz(N)	M(N.cm)	S/N Ratio (Fz)	S/N Ratio (M(N.cm)
1.	1340	7432	-62.5421	-77.4221
2.	1611	8125	-64.1419	-78.1965
3.	1340	8105	-62.5421	-78.1751
4.	1229	8984	-61.7910	-79.0694
5.	1405	8968	-62.9535	-79.0539
6.	1304	7696	-62.3056	-77.7253
7.	1204	7656	-61.6125	-77.6800
8.	1492	8567	-63.4754	-78.6566
9.	1404	7895	-62.9473	-77.9470
10.	967	8551	-59.7085	-78.6403
11.	1047	8767	-60.3989	-78.8570
12.	1133	9055	-61.0846	-79.1378
13.	112	113	-40.9844	-41.0616
14.	112	113	-40.9844	-41.0616
15.	112	113	-40.9844	-41.0616
16.	107	5578	-40.5877	-74.9296
17.	1107	5564	-60.8830	-74.9077
18.	1107	5564	-60.8830	-74.9077
19.	807	5733	-58.1375	-75.1676
20.	1142	5568	-61.1533	-74.9140
21.	1142	5568	-61.1533	-74.9140
22.	532	5565	-54.5182	-74.9093
23.	1148	5615	-61.1988	-74.9870

24.	1148	5615	-61.1988	-74.9870
25.	532	5565	-54.5182	-74.9093
26.	1148	5615	-61.1988	-74.9870
27.	1148	5615	-61.1988	-74.9870

When Figure 3 is examined, the analysis reveals that the 180° drill geometry exhibits the highest S/N ratio, indicating its superior performance in minimizing variability in thrust force. Additionally, a medium cutting speed is identified as optimal, yielding the best S/N ratio and suggesting its effectiveness in reducing variability. Furthermore, a feed rate of 0.11 mm/rev achieves the highest S/N ratio, demonstrating its efficacy in minimizing thrust force variability.

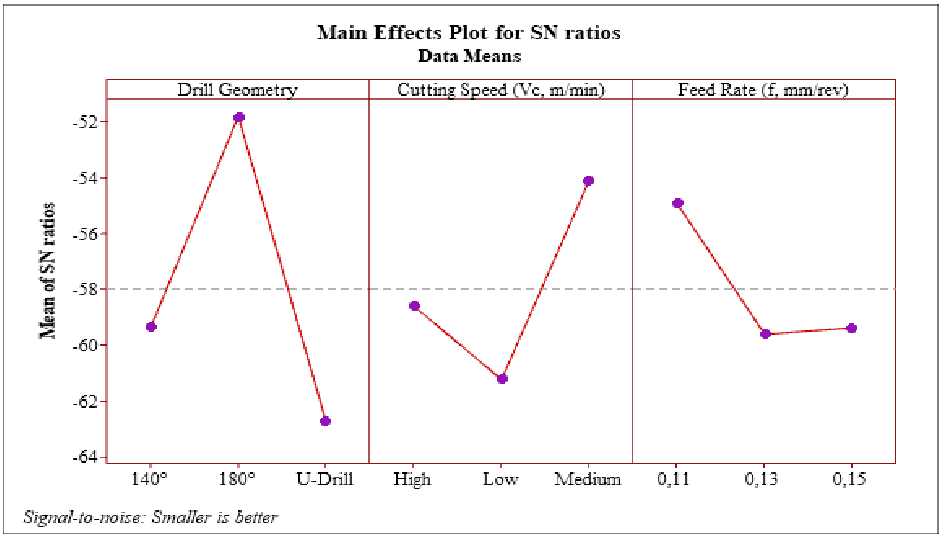

Figure 3. Effect of essential parameters Fz (N) S/N Ratio.

The analysis indicates that the 180° drill geometry achieves the highest S/N ratio, highlighting its superior performance in minimizing variability in torque (M). A medium cutting speed is optimal, yielding the best S/N ratio and effectively reducing variability. Additionally, a feed rate of 0.11 mm/rev results in the highest S/N ratio, demonstrating its efficacy in minimizing torque variability (Figure 4).

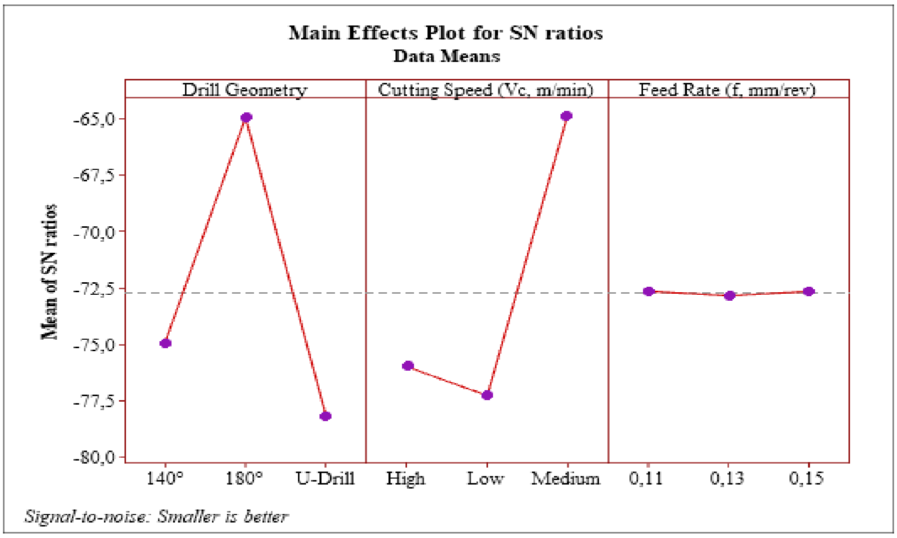

Figure 4. Effect of essential parameters M (N.cm) S/N Ratio.

3.3. Taguchi Analysis of Hole Diameter Deviation (mm), Center Distance Difference (mm), Ovality Deviation (mm) and Parallelism Deviation (%)

The Taguchi analysis was conducted to evaluate the impact of various factors on four critical dimensional parameters in the manufacturing process: hole diameter deviation (mm), center distance difference (mm), ovality deviation (mm), and parallelism deviation (%). This robust design methodology aims to optimize process parameters while minimizing variability in the output. Table 5 presents the signal-to-noise (S/N) ratios for these parameters, which are crucial indicators of process stability and product quality. The S/N ratios, calculated using Taguchi's "smaller-is-better" characteristic, provide valuable insights into the relative influence of each factor on the respective deviations. By analyzing these S/N values, it becomes possible to identify the optimal combination of process parameters that simultaneously minimizes all four types of deviations, thereby enhancing the overall quality and precision of the manufactured components.

Table 5. Hole Diameter Deviation (HDD) (mm), Center Distance Difference (CDD) (mm), Ovality Deviation (OD) (mm) and Parallelism Deviation (PD) (%) results

Experiment no.	HDD (mm)	CDD (mm)	OD (mm)	PD (%)	SNRA3	SNRA4	SNRA5	SNRA6
1.	0.110	31	21	5	19.1721	-29.827	-26.444	-13.979
2.	0.099	36	26	6	20.0873	-31.126	-28.299	-15.563
3.	0.145	197	36	8	16.7726	-45.889	-31.126	-18.061
4.	0.175	36	26	6	15.1392	-31.126	-28.299	-15.563
5.	0.135	136	26	6	17.3933	-42.670	-28.299	-15.563
6.	0.109	36	26	6	19.2515	-31.126	-28.299	-15.563
7.	0.105	36	26	6	19.5762	-31.126	-28.299	-15.563
8.	0.107	36	26	6	19.4123	-31.126	-28.299	-15.563
9.	0.109	36	26	6	19.2515	-31.126	-28.299	-15.563
10.	0.105	36	26	6	19.5762	-31.126	-28.299	-15.563
11.	0.107	36	26	6	19.4123	-31.126	-28.299	-15.563
12.	0.109	36	26	6	19.2515	-31.126	-28.299	-15.563
13.	0.112	36	26	6	19.0156	-31.126	-28.299	-15.563
14.	0.112	36	26	6	19.0156	-31.126	-28.299	-15.563
15.	0.112	36	26	6	19.0156	-31.126	-28.299	-15.563
16.	0.107	36	26	6	19.4123	-31.126	-28.299	-15.563
17.	0.107	36	26	6	19.4123	-31.126	-28.299	-15.563
18.	0.107	36	26	6	19.4123	-31.126	-28.299	-15.563
19.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
20.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
21.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
22.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
23.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
24.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
25.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
26.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563
27.	0.092	36	26	6	20.7242	-31.126	-28.299	-15.563

The analysis shows (in Figure 5) that the 140° drill geometry achieves the highest S/N ratio, indicating its superior performance in minimizing hole diameter deviation. A high cutting speed is optimal, yielding the best S/N ratio and effectively reducing variability. Additionally, a feed rate of 0.13 mm/rev results in the highest S/N ratio, demonstrating its efficacy in minimizing hole diameter deviation.

The analysis in Figure 6 indicates that the 140° drill geometry achieves the highest S/N ratio, highlighting its superior performance in minimizing center distance difference. A high cutting speed is optimal, yielding the best S/N ratio and effectively reducing variability. Additionally, a feed rate of 0.11 mm/rev results in the highest S/N ratio, demonstrating its efficacy in minimizing center distance difference.

The analysis shows (in Figure 7) that the 140° drill geometry achieves the highest S/N ratio, indicating its superior performance in minimizing ovality deviation. A medium cutting speed is optimal, yielding the best S/N ratio and effectively reducing variability. Additionally, a feed rate of 0.11 mm/rev results in the highest S/N ratio, demonstrating its efficacy in minimizing ovality deviation.

The analysis shows in Figure 8 that the 140° drill geometry achieves the highest S/N ratio, indicating its superior performance in minimizing parallelism deviation. A medium cutting speed is optimal, yielding the best S/N ratio and effectively reducing variability. Additionally, a feed rate of 0.11 mm/rev results in the highest S/N ratio, demonstrating its efficacy in minimizing parallelism deviation.

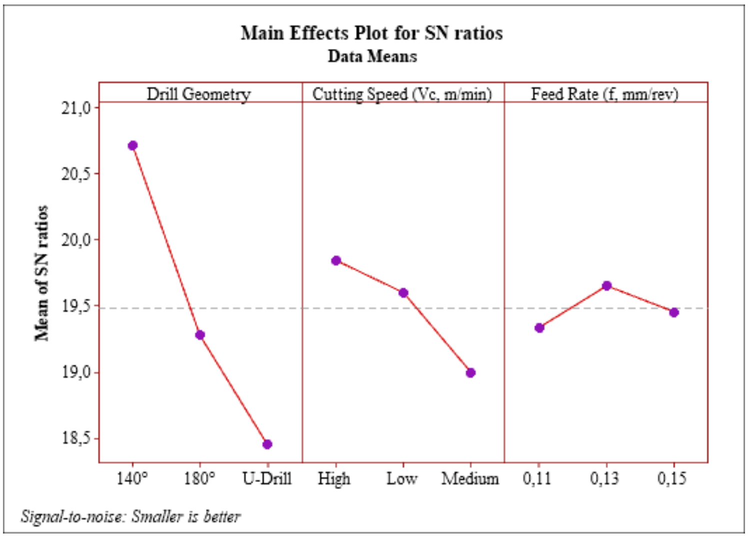

Figure 5. Effect of essential parameters of hole diameter deviation S/N ratio.

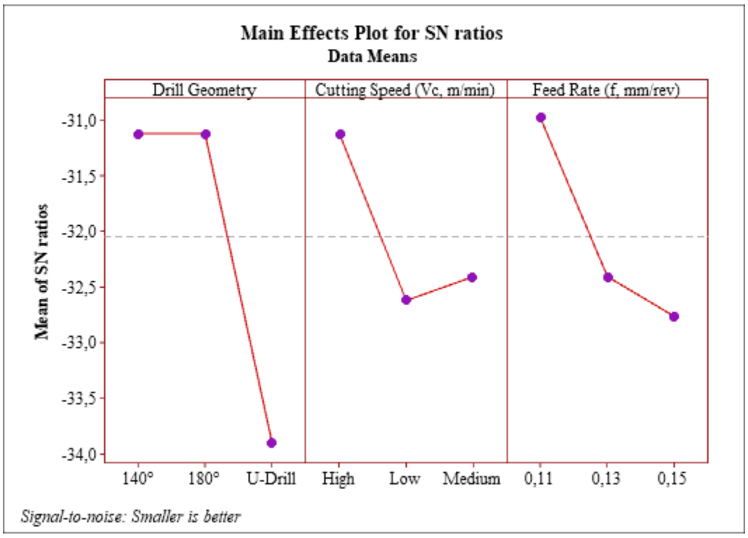

Figure 6. Effect of essential parameters center distance difference S/N ratio.

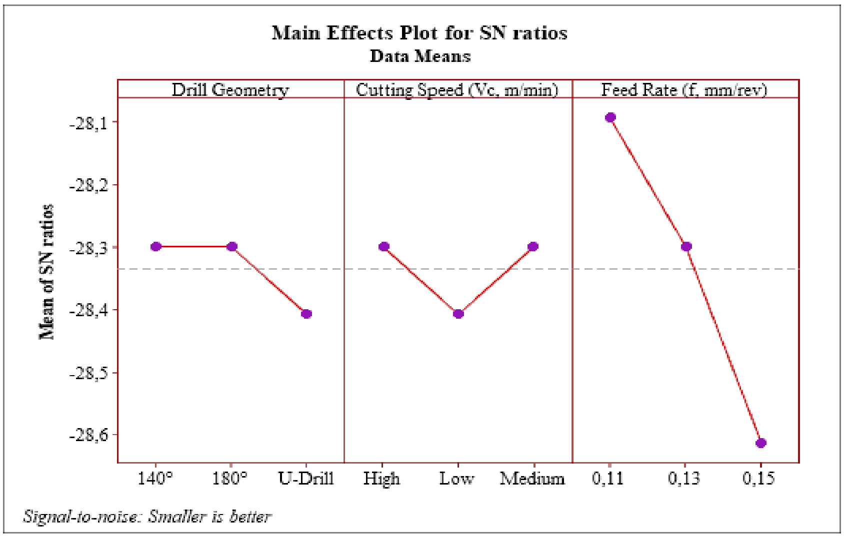

Figure 7. Effect of essential parameters ovality deviation S/N ratio.

3.4. Analysis of variance

The ANOVA results in Table 6 indicate that drill geometry is the most significant factor affecting the variance, contributing 45.90% to the total variance with a highly significant F-value of 17.36 (p = 0.000). Cutting speed also plays a notable role, contributing 12.89% with an F-value of 4.88 (p = 0.019). The feed rate contributes 14.78% to the variance, with an F-value of 5.59 (p = 0.012). The error accounts for 26.44% of the total variance. These findings highlight the critical influence of drill geometry on the process, followed by feed rate and cutting speed, in determining the overall.

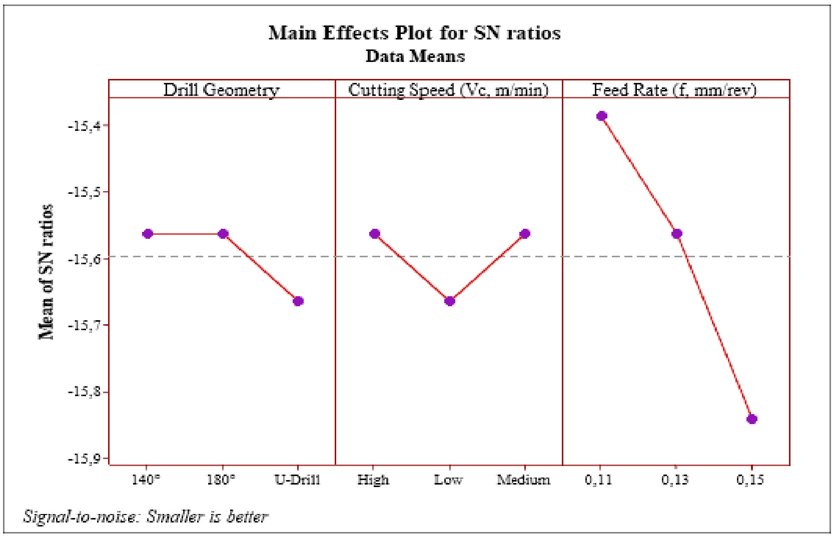

Figure 8. Effect of essential parameters parallelism deviation (%) S/N ratio.

Table 6. Fz variance analysis results.

Source	DF	Adj SS	Adj MS	F	P	Contribution (%)
Drill Geometry	2	2372874	1186437	17.36	0.000	45.8972223
Cutting Speed (Vc, m/min)	2	666383	333191	4.88	0.019	12.889487
Feed Rate (f, mm/rev)	2	763921	381960	5.59	0.012	14.776112
Error	20	1366795	68340			26.4371787
Total	26	5169973				100

ANOVA results in Table 7 demonstrate that drill geometry significantly influences the variance, contributing 31.65% with an F-value of 6.43 (p = 0.007). Cutting speed also has a notable impact, contributing 19.03% with an F-value of 3.97 (p = 0.038). The feed rate shows minimal influence, contributing only 0.12% with an F-value of 0.03 (p = 0.975). The error accounts for 49.20% of the total variance. These results underscore the importance of optimizing drill geometry and cutting speed to enhance performance.

Table 7. M variance analysis results

Source	DF	Adj SS	Adj MS	F	P	Contribution (%)
Drill Geometry	2	54731509	27365754	6.43	0.007	31.6533841
Cutting Speed (Vc, m/min)	2	32896988	16448494	3.87	0.038	19.0256219
Feed Rate (f, mm/rev)	2	214333	107167	0.03	0.975	0.1239572
Error	20	85066040	4253302			49.1970363
Total	26	172908871				100

The ANOVA results in Table 8 reveal that drill geometry is the most significant factor affecting hole diameter deviation, contributing 43.71% to the total variance with a highly significant F-value of 9.38 (p = 0.001). Cutting speed contributes 8.30% with an F-value of 1.78 (p = 0.194), while the feed rate has a minimal impact, contributing only 1.36% with an F-value of 0.29 (p = 0.750). The error accounts for 46.62% of the total variance. These findings emphasize the critical role of drill geometry in controlling hole diameter deviation.

Table 8 Hole diameter deviation variance analysis results

Source	DF	Adj SS	Adj MS	F	P	Contribution (%)
Drill Geometry	2	0.003952	0.001976	9.38	0.001	43.7119788
Cutting Speed (Vc, m/min)	2	0.000750	0.000375	1.78	0.194	8.29554253
Feed Rate (f, mm/rev)	2	0.000123	0.000061	0.29	0.750	1.36046897
Error	20	0.004215	0.000211			46.620949
Total	26	0.009041				100

The ANOVA results in Table 9 indicate that drill geometry contributes 14.48% to the variance in center distance difference, with an F-value of 1.89 (p = 0.177). Cutting speed contributes 4.14% with an F-value of 0.54 (p = 0.591), and feed rate contributes 4.67% with an F-value of 0.61 (p = 0.553). The error accounts for 76.70% of the total variance. These results suggest that while drill geometry has some influence, the majority of the variance is attributed to error, indicating potential variability in the process.

Table 9. Center distance difference variance analysis results

Source	DF	Adj SS	Adj MS	F	P	Contribution (%)
Drill Geometry	2	4855	2427.3	1.89	0.177	14.4843223
Cutting Speed (Vc, m/min)	2	1388	693.9	0.54	0.591	4.14093499
Feed Rate (f, mm/rev)	2	1567	783.4	0.61	0.553	4.67496047
Error	20	25710	1285.5			76.7027656
Total	26	33519				100

The ANOVA results in Table 10 show that feed rate is the most influential factor on ovality deviation, contributing 7.49% to the variance with an F-value of 1.21 (p = 0.320). Drill geometry and cutting speed each contribute 1.08% with an F-value of 0.17 (p = 0.843). The error accounts for 90.43% of the total variance. These findings suggest that feed rate has a minor impact, while most of the variance is due to error.

Table 10. Ovality deviation variance analysis results

Source	DF	Adj SS	Adj MS	F	P
Drill Geometry	2	1.852	0.9259	0.17	0.843
Cutting Speed (Vc, m/min)	2	1.852	0.9259	0.17	0.843
Feed Rate (f, mm/rev)	2	12.963	6.4815	1.21	0.320
Error	20	107.407	5.3704		
Total	26	172908871			

The ANOVA results in Table 11 indicate that feed rate is the most significant factor affecting parallelism deviation, contributing 10.44% to the variance with an F-value of 1.21 (p = 0.320). Drill geometry and cutting speed each contribute 1.49% with an F-value of 0.17 (p = 0.843). The error accounts for 86.58% of the total variance. These results highlight that feed rate has a slight influence, with the majority of the variance attributed to error.

A more in-depth analysis of the ANOVA results reveals the nuanced impact of each factor on the drilling process outcomes. For thrust force (Fz), drill geometry emerged as the most influential factor, with a remarkably high F-value of 17.36 (p = 0.000), accounting for 45.90% of the total variance. This substantial effect size, as indicated by the partial eta squared (η^2p) of 0.459, underscores the critical role of drill geometry in optimizing thrust force. Cutting speed and feed rate also demonstrated significant effects, with F-values of 4.88 (p = 0.019) and 5.59 (p = 0.012), respectively. Their contributions to the variance were

12.89% ($\eta^2p = 0.129$) for cutting speed and 14.78% ($\eta^2p = 0.148$) for feed rate, indicating moderate but meaningful influences on thrust force variability.

Table 11. Parallelism deviation (%) variance analysis results

Source	DF	Adj SS	Adj MS	F	P
Drill Geometry	2	0.07407	0.03704	0.17	0.843
Cutting Speed (Vc, m/min)	2	0.07407	0.03704	0.17	0.843
Feed Rate (f, mm/rev)	2	0.51852	0.25926	1.21	0.320
Error	20	4.29630	0.21481		
Total	26	4.96296			

In the case of torque (M), drill geometry again exhibited the strongest effect, with an F-value of 6.43 ($p = 0.007$), explaining 31.65% of the variance ($\eta^2p = 0.317$). Cutting speed showed a notable impact with an F-value of 3.87 ($p = 0.038$), contributing 19.03% to the variance ($\eta^2p = 0.190$). Interestingly, the feed rate's influence on torque was minimal, with a negligible F-value of 0.03 ($p = 0.975$) and a contribution of merely 0.12% to the variance ($\eta^2p = 0.001$).

For hole diameter deviation, drill geometry once more demonstrated its paramount importance, with an F-value of 9.38 ($p = 0.001$), accounting for 43.71% of the total variance ($\eta^2p = 0.437$). The effects of cutting speed and feed rate were less pronounced in this case, with F-values of 1.78 ($p = 0.194$) and 0.29 ($p = 0.750$), respectively, contributing 8.30% ($\eta^2p = 0.083$) and 1.36% ($\eta^2p = 0.014$) to the variance.

These detailed ANOVA results elucidate the hierarchical influence of drilling parameters, with drill geometry consistently emerging as the most critical factor across multiple outcome measures. The varying effect sizes and significance levels for cutting speed and feed rate across different outcomes highlight the complex interplay of these factors in the drilling process, emphasizing the need for careful optimization strategies tailored to specific performance metrics.

3.5. Regression Analysis

In machining processes, regression analysis is employed to examine and establish the relationship between process parameters and their outcomes [28]. The thrust force (Fz) during drilling operations was modeled using multiple linear regression analysis. The regression equation, incorporating the effects of drill geometry (DG), cutting speed (CS), and feed rate (FR). The regression model derived from this study is presented below (Eq.1):

$$Fz = \beta_0 + \beta_1(DG) + \beta_2(CS) + \beta_3(FR) + \varepsilon \tag{1}$$

Where:

- Fz is the thrust force in Newtons (N)
- β_0 is the intercept (baseline thrust force)
- β_1, β_2, β_3 are the regression coefficients for drill geometry, cutting speed, and feed rate, respectively
- ε is the error term

The fitted regression model is (Eq.2):

$$Fz = 767 + \beta_1(DG) + \beta_2(CS) + \beta_3(FR) + \varepsilon \tag{2}$$

The coefficients for each factor level are as follows (Table 12):

Table 12. Coefficeints level of drilling parameters for Fz.

Drill Geometry (DG)	**Cutting Speed (CS)**	**Feed Rate (FR)**
140°: $\beta_1 = 0$ (reference level)	High: $\beta_2 = 0$ (reference level)	0.11 mm/rev: $\beta_3 = 0$ (reference level)
180°: $\beta_1 = -327$	Medium: $\beta_2 = -239$	0.13 mm/rev: $\beta_3 = +376$
U-Drill: $\beta_1 = +398$	Low: $\beta_2 = +142$	0.15 mm/rev: $\beta_3 = +334$

This regression model allows for the prediction of thrust force based on the selected drilling parameters. The coefficients indicate the change in thrust force relative to the reference level for each factor. For instance, using a 180° drill geometry is expected to decrease the thrust force by 327 N compared to the 140° geometry, while the U-Drill is expected to increase it by 398 N. The model's intercept ($\beta_0 = 767$ N) represents the baseline thrust force when all factors are at their reference levels (140° drill geometry, high cutting speed, and 0.11 mm/rev feed rate). The inclusion of the error term (ε) acknowledges that the model may not account for all sources of variation in thrust force. Similarly, the torque (M) during drilling operations was modeled using multiple linear regression analysis. The regression equation for torque, incorporating the effects of drill geometry (DG), cutting speed (CS), and feed rate (FR), is expressed as follows (Eq.3):

$$M = \beta_0 + \beta_1(DG) + \beta_2(CS) + \beta_3(FR) + \varepsilon \tag{3}$$

Where:

- M is the torque in Newton-centimeters (N.cm)
- β_0 is the intercept (baseline torque)
- β_1, β_2, β_3 are the regression coefficients for drill geometry, cutting speed, and feed rate, respectively
- ε is the error term

The fitted regression model for torque is(Eq.4):

$$M = 5746 + \beta_1(DG) + \beta_2(CS) + \beta_3(FR) + \varepsilon \tag{4}$$

The coefficients for each factor level are as follows (Table 13):

Table 13. Coefficeints level of drilling parameters for M.

Drill Geometry (DG)	**Cutting Speed (CS)**	**Feed Rate (FR)**
140°: $\beta_1 = 0$ (reference level)	High: $\beta_2 = 0$ (reference level)	0.11 mm/rev: $\beta_3 = 0$ (reference level)
180°: $\beta_1 = -782$	Medium: $\beta_2 = -1649$	0.13 mm/rev: $\beta_3 = +192$
U-Drill: $\beta_1 = +2552$	Low: $\beta_2 = +1032$	0.15 mm/rev: $\beta_3 = +5$

This regression model allows for the prediction of torque based on the selected drilling parameters. The coefficients indicate the change in torque relative to the reference level for each factor. For example, using a 180° drill geometry is expected to decrease the torque by 782 N.cm compared to the 140° geometry, while the U-Drill is expected to increase it by 2552 N.cm. The model's intercept ($\beta_0 = 5746$ N.cm) represents the baseline torque when all factors are at their reference levels (140° drill geometry, high cutting speed, and 0.11 mm/rev feed rate). As with the thrust force model, the inclusion of the error term (ε) acknowledges that the model may not account for all sources of variation in torque. Comparing the two models, we can observe that the factors affect thrust force and torque differently. For instance, while the U-Drill geometry increases both thrust force and torque, its effect on torque (2552 N.cm increase) is proportionally larger than its effect on thrust force (398 N increase). This highlights the importance of considering multiple performance metrics when optimizing drilling parameters.

3.6. Enhanced Statistical Analysis

The Taguchi method and ANOVA employed in this study have facilitated a profound examination of the effects of various parameters in the drilling process of AISI 1050 steel. In this section, we delve further into the statistical significance of the obtained results and the impact of each parameter on variance.

The ANOVA results demonstrate that the influence of drill geometry on thrust force (Fz) is highly significant ($F = 17.36$, $p = 0.000$). This parameter accounts for 45.90% of the total variance, indicating that optimizing drill geometry may considerably enhance drilling performance. Cutting speed ($F = 4.88$, $p = 0.019$) and feed rate ($F = 5.59$, $p = 0.012$) also exhibit statistically significant effects, explaining 12.89% and 14.78% of the variance, respectively. These results emphasize the critical importance of jointly optimizing these three parameters for effective thrust force control. For torque (M), ANOVA analysis again identifies drill geometry as the most influential factor ($F = 6.43$, $p = 0.007$), accounting for 31.65% of the total variance. The influence of cutting speed is also significant ($F = 3.87$, $p = 0.038$), explaining 19.03% of the variance. These findings underscore the importance of optimizing drill geometry and cutting speed in torque control. The relative impact of various drilling parameters on thrust force (Fz) and torque (M) is visually represented in Figure 10.

In the analysis of hole diameter deviation, the effect of drill geometry is once more prominent (F = 9.38, p = 0.001), explaining 43.71% of the total variance. This result highlights the critical importance of selecting appropriate drill geometry in precision drilling operations. Signal-to-noise (S/N) ratio analyses obtained via the Taguchi method corroborate these ANOVA results. For example, the 180° drill geometry exhibited the highest S/N ratios for both thrust force and torque, indicating its effectiveness in minimizing variability for these parameters. Similarly, the 140° drill geometry achieved the highest S/N ratios for hole quality parameters, demonstrating its superiority in optimizing hole quality.

This enhanced statistical analysis underscores the significance of a multifactorial approach in the optimization of drilling parameters. Understanding the interactive effects of drill geometry, cutting speed, and feed rate is crucial for optimizing both cutting forces and hole quality in the drilling of AISI 1050 steel. These findings provide valuable guidance for improving the efficiency and quality of drilling operations in industrial applications.

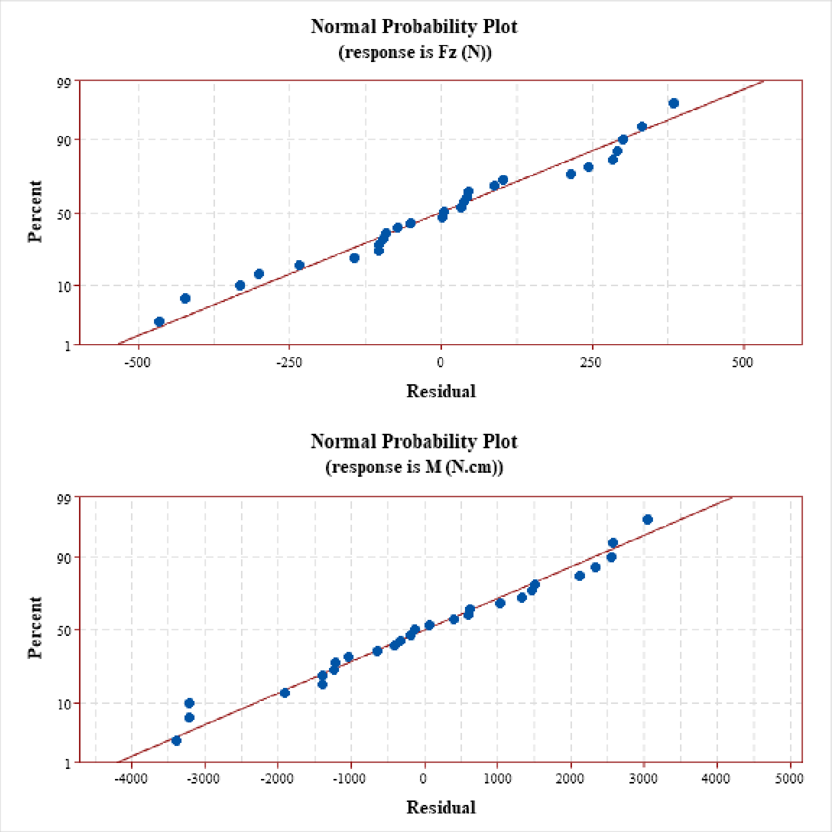

Figure 9. Normal probability plots of residuals for (a) Fz and (b) M.

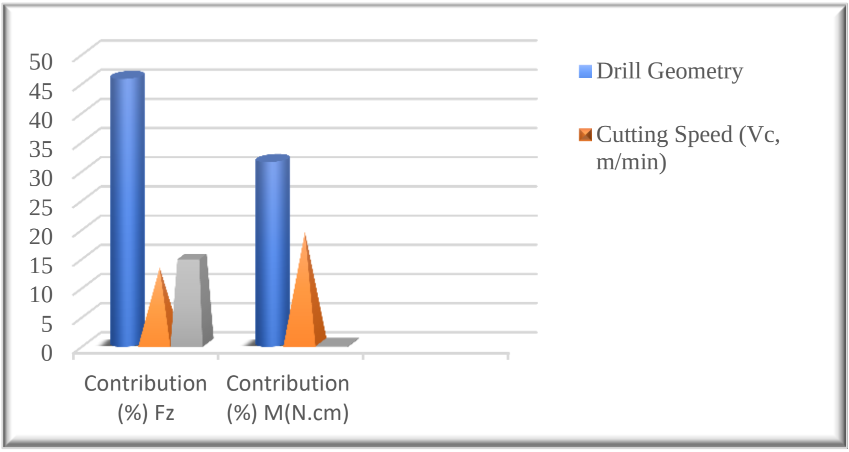

Figure 10. Contribution of drilling parameters on Fz and M

3.7. Discussion

The experimental investigation into the drilling parameters of AISI 1050 steel has yielded critical insights into the interplay between drill geometry, cutting speed, and feed rate, particularly concerning thrust force, torque, and hole quality. The findings align with existing literature, underscoring the importance of these parameters in enhancing drilling performance.

The study identifies drill geometry as the most significant factor influencing thrust force, torque, and hole diameter deviation. Specifically, the 180° drill geometry exhibited superior performance in minimizing thrust force and torque variability. This observation is consistent with the work that highlighted the pivotal role of cutting tool geometry in drilling operations [29, 30]. Conversely, the 140° drill geometry proved optimal for minimizing hole diameter deviation, corroborating the findings of Rajendra Singh et al. and Fernández-Pérez et al., who emphasized the influence of tool geometry on dimensional accuracy [31, 32].

In terms of cutting speed, the study found that medium cutting speeds were generally optimal for reducing variability in thrust force and torque. This conclusion is supported by Ellenberger et al. (2022) and Scarano et al., 2020, who reported significant impacts of cutting speed on drilling performance and surface quality. The results suggest that medium cutting speeds strike a balance between efficient material removal and minimal thermal damage, thereby enhancing overall drilling performance [33, 34].

The investigation also revealed that a feed rate of 0.11 mm/rev was most effective in minimizing thrust force and torque variability. This finding aligns with the research conducted by Maleki et al., who identified feed rate as a crucial parameter in optimizing drilling processes [35]. Lower feed rates contribute to maintaining stability during drilling, which reduces the likelihood of tool deflection and improves hole quality.

Drill geometry was found to significantly influence hole diameter deviation, accounting for a substantial portion of the total variance. This finding is consistent with the observations of Fernández-Pérez et al., who reported the importance of process parameters in achieving dimensional accuracy and surface quality in drilled holes [31]. The results emphasize the necessity of selecting appropriate drill geometries to ensure high-quality outcome.

The analysis of variance (ANOVA) conducted in this study revealed that drill geometry, cutting speed, and feed rate exert varying degrees of influence on different aspects of the drilling process. This multi-factorial influence is corroborated by the findings of Hale & Ng, who employed statistical analyses to explore the complex interplay of drilling parameters [36]. The ANOVA results underscore the importance of a comprehensive approach to parameter optimization, considering the interactions between different factors to achieve optimal drilling performance.

4. CONCLUSIONS

In this study, the experimental investigation into the drilling parameters of AISI 1050 steel has illuminated the critical impact various factors have on cutting forces and hole quality. A systematic analysis was conducted to understand how drill geometry, cutting speed, and feed rate affect drilling efficacy and efficiency. The impact of drill geometry on thrust force and torque was unmistakable. Specifically, a drill with a 180° geometry was found to maximize the signal-to-noise ratio for thrust force, validating its use as a key influence on cutting efficiency. Mid-range cutting speeds emerged as optimal, reflecting a balance between performance and stability, while a feed rate of 0.11 mm/rev proved effective in achieving minimal variability in thrust force. Regarding the quality of drilled holes, parameters such as hole diameter deviation, centering accuracy, ovality, and parallelism were assessed. The 140° drill geometry excelled, significantly minimizing diameter deviations. This finding highlights the need for precise control of both geometry and cutting conditions—high cutting speeds and a feed rate of 0.13 mm/rev were found to yield the best results, ensuring high-quality hole production. The statistical analysis underscored the predominance of drill geometry in affecting thrust force variability, contributing nearly half of the observed variation and reaffirming its statistical significance. Contributions from cutting speed and feed rate, though less pronounced, were still substantial, indicating their role in refining the drilling process. For torque considerations, drill geometry maintained its critical role, emphasizing the necessity of selecting optimal geometries alongside suitable cutting speeds for effective drilling. Similarly, deviations in hole diameter due to drill geometry were significant, underscoring the pressing need for exacting tool geometry to maintain dimensional precision. Finally, feed rate was identified as a strong influencer in managing parallelism deviations, highlighting the importance of accurately controlling operational parameters to ensure quality. Thus, the outcomes of this study contribute significantly to our understanding of the dynamics involved in drilling operations.

In summary, this research offers a thorough understanding of the interdependencies between various drilling parameters and their combined effects on cutting forces and hole quality in AISI 1050 steel. The insights provided herein are invaluable for optimizing drilling practices, enhancing both performance and quality in industrial applications.

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