SELÜLOZ ESASLI LİF TAKVİYELİ KOMPOZİTLERİN MİKRO DELİNMESİNDE DELİK KALİTESİNİ ETKİLEYEN PROSES PARAMETRELERİNİN ANALİZİ

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Özet

Bu çalışmada, selüloz esaslı lif takviyeli kompozitlerin mikro delme işlemini analiz etmek için Taguchi ve ANOVA deneysel tasarım teknikleri kullanılmıştır. Selüloz esaslı lif takviyeli kompozitler mikro delinmiş ve bu kompozitlerin aşırı kesim, delik hasar faktörü ve konikliğinin analizine odaklanılmıştır. Mikro delikler, 4 mm kalınlığındaki plakalara Taguchi ortogonal dizi (L27) tasarımı kullanılarak delinmiştir. ANOVA ve Taguchi analizleri, takım çapının kompozitlerdeki aşırı kesim ve konikliği önemli ölçüde etkilediğini ortaya koymuştur. Delik hasar faktörünün öncelikli olarak kesme hızından etkilendiği bulunmuştur. ANOVA sonuçlarına göre takım çapı aşırı kesim ve konikliği sırasıyla %60 ve %47 oranında etkilemektedir. Kesme hızının delik hasar faktörünün üzerindeki etkisi yaklaşık %65 olarak bulunmuştur. Kesme hızı, aşırı kesim ve konikliği etkileyen ikinci en etkili parametre iken, ilerleme oranı en az etkili olandır. Delik hasar faktörü için, ilerleme oranı ikinci en etkili parametre iken, takım çapı en az etkili olandır. Delme işleminde aşırı kesme, delik hasar faktörü ve konikleşme oranını en aza indirmek için A1–B2–C1 (0,4 mm – 7500 dev/dak – 0,3 mm/dak) kontrol faktörlerinin optimum kombinasyonu belirlenmiştir. Bu sonuçlar, sektöre, üretim maliyetlerini düşürürken yüksek kaliteli mikro delinmiş selüloz esaslı lif takviyeli kompozitler üretmek için kullanılabilecek değerli veriler sunmaktadır.

Anahtar Kelimeler: Doğal lif bazlı kompozit, mikro delme, optimizasyon, karakterizasyon

ANALYSIS OF PROCESS PARAMETERS AFFECTING HOLE QUALITY IN MICRO-DRILLING OF CELLULOSIC-BASED FIBER REINFORCED COMPOSITES

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Abstract

In this study, Taguchi and ANOVA optimization was employed to analyze the micro-drilling of cellulosic-based fiber reinforced composites. These composites were micro drilled and the analysis of composites focused on overcut, hole damage factor (HDF), and taper ratio. Micro-holes were drilled on plates with thicknesses of 4 mm using a Taguchi orthogonal array (L27) design. ANOVA and Taguchi analysis revealed that tool diameter significantly impacts overcut and taper ratio in composites. The hole damage factor (HDF) was found to be primarily influenced by spindle speed. Tool diameter also influences the overcut and taper ratio by 60%, and 47%, respectively. The effect of spindle speed on HDF was determined to be approximately 65%. Spindle speed is the second most influential parameter for overcut and taper ratio, while feed rate is the least influential. For HDF, feed rate is the second most influential parameter, while tool diameter is the least influential. The optimum combination of control factors A1–B2–C1 (0.4 mm – 7500 rpm – 0.3 mm/min) was determined to minimize overcut, HDF, and taper ratio in the drilling process. These results provide the industry with valuable data that can potentially be utilized to manufacture high-quality micro-drilled cellulosic-based fiber reinforced composites while potentially reducing production costs.

Key words: Natural fibres-based composites, micro drilling, optimization, characterization

1. INTRODUCTION

At present, interest in sustainable material technologies is growing. This, in turn, is encouraging the use of composite materials with natural reinforcement elements [1-2]. Cellulose-based fibers, characterized by their renewable, biodegradable, and environmentally friendly properties, offer a significant alternative to the environmental impacts associated with the production processes of traditional glass and carbon fibers. Their low density, adequate mechanical properties, ease of processing, and affordability make them preferred in many areas such as automotive, biomedical, and electronics [3-5]. Composite structures produced from these materials with polymer matrices offer significant potential in terms of both mechanical performance and sustainability.

Hole drilling is a crucial component of the assembly and joining processes in the industrial production of composite materials [6-8]. Creating holes, particularly those requiring high precision at the micrometer scale (microdrilling), has become a critical phase of modern industrial production [9]. Microdrilling is a fundamental manufacturing step in a wide variety of applications, including electronic circuit boards, biomedical implants, microfluidic systems, sensor technologies, aerospace components, and precision mechanical parts [10]. The accuracy, surface finish, and geometric precision of microdrilling directly impact product performance, functionality, and reliability. Therefore, optimizing microdrilling is of strategic importance for advanced manufacturing technologies [8,11-13].

The behavior of cellulose-based fiber-reinforced composites in machining is quite complex due to the material's heterogeneous structure [14]. Fiber orientation, matrix-fiber interface properties, fiber-matrix bond quality, and the material's thermal properties significantly influence the cutting forces, heat accumulation, and chip formation mechanisms generated during drilling. Undesirable defects such as matrix fracture, fiber pullout, delamination, tearing at the hole entry and exit zones, and surface roughness can occur during microdrilling; these defects can negatively impact the material's mechanical strength and structural integrity. The inherent structural variability and hygroscopic nature of cellulose-based fibers make the need for precision in microdrilling even more crucial.

Hole quality, the output of microdrilling, is evaluated using metrics such as hole diameter deviation, surface roughness, delamination factor, and exit zone damage [9-10,12]. Process parameters such as feed rate, cutting speed, tool geometry, tool coating, cutting environment (dry/lubricated/cooled), and drilling strategy play a decisive role in these outputs. While research on the machinability of natural fiber-reinforced composites is increasing, scientific data on hole quality of cellulose-based composites [14-18], particularly in microdrilling, remains limited [19-20]. This difference is critical for both academic research and industrial applications.

This study aims to systematically investigate the key process parameters that determine hole quality during microdrilling in cellulose-based fiber-reinforced composites. The study utilizes experimental design and analysis methods to comprehensively evaluate the effects of parameters such as tool geometry, cutting speed, and feed rate on hole quality. Based on the findings, we aim to determine optimal microdrilling conditions and provide a scientific framework for the more efficient use of sustainable composite materials in precision machining processes. In this context, the study will contribute to both the development of sustainable composite technologies and the optimization of precision manufacturing processes.

2. MATERIALS AND METHOD

In this study, composite parts were fabricated by reinforcing raw jute fabric within a low-density polyethylene (LDPE) matrix. Prior to fabrication, surface treatments were applied to both the LDPE matrix and the jute fabric to enhance interfacial compatibility between the fiber and the matrix. The fiber content in composite parts is 25% by volume. The properties of jute fabric and a low-density polyethylene used in the production of composite parts are detailed in Table 1. Figure 1 shows jute fabric reinforced composite parts.

Table 1. Structural properties of raw jute fabric and low-density polyethylene.

Raw jute fabric	**Fabric Weight (g/m^2)**	**Weft Density (thread/cm)**	**Warp Density (thread/cm)**
	200	5	5
Low-density polyethylene	**Density (g/cm^3)**	**Ultimate Strength (MPa)**	**Impact Strength (Kg/j)**
	0.935	17.8	59.7-79.6

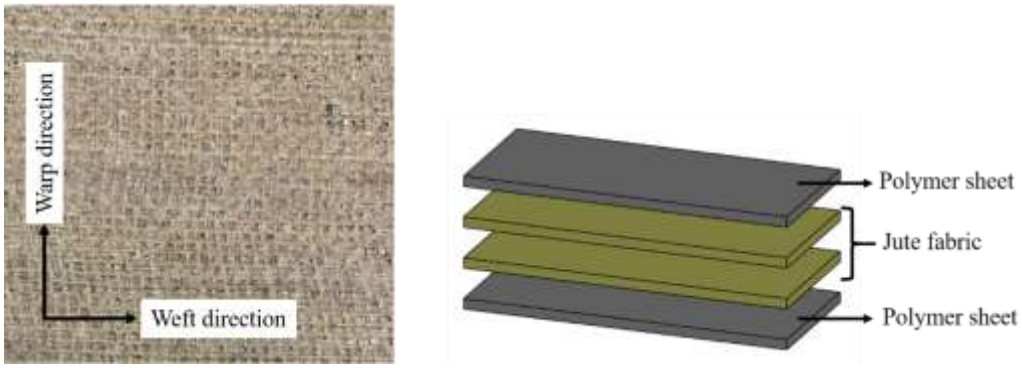

Figure 1. Jute fabric reinforced composite parts.

The tests were conducted using a three-axis Johnford VMC-550 CNC milling machine, which is equipped with a maximum spindle speed of 3000 rpm and a motor power of 7.45 kW. During the dry condition experiments, standard two-channel micro drill bits, made of tungsten carbide and produced by Seco Tools GmbH, were employed. The drilling process was performed with a fixed cutting depth of 5 mm. A new drill bit was used for each trial, and the tests were replicated three times to ensure consistency. Following the setup of the experimental configuration, drilling operations were carried out, and the resulting data was analyzed with respect to the quality of the drilled holes. Design of Experiments (DOE), a statistical method widely applied in process optimization [21–24], was employed in the study, and the experimental parameters are detailed in Table 2. The experimental design adhered to the Taguchi L27 orthogonal array (as shown in Table 3).

Table 2. Input factors and levels.

Input factors	**Symbol**	**Level**			**Unit**
		Level 1	Level 2	Level 3	
Tool diameter	A	0.4	0.6	0.8	mm
Spindle speed	B	5000	7500	10000	rpm
Feed rate	C	0.3	0.5	0.7	mm/min

Table 3. L27 orthogonal matrix of input and output factors.

Exp.no	Input factors/ Symbol			Output factors		
	A	B	C	Overcut (mm)	Hole damage factor (mm)	Taper ratio
1	0.4	5000	0.3	0.0033	1.0083	0.00087
2	0.4	5000	0.5	0.0038	1.0095	0.00098
3	0.4	5000	0.7	0.0050	1.0125	0.00113
4	0.4	7500	0.3	0.0019	1.0048	0.00070
5	0.4	7500	0.5	0.0039	1.0098	0.00093
6	0.4	7500	0.7	0.0055	1.0138	0.00110
7	0.4	10000	0.3	0.0069	1.0173	0.00110
8	0.4	10000	0.5	0.0078	1.0195	0.00120
9	0.4	10000	0.7	0.0091	1.0228	0.00134
10	0.6	5000	0.3	0.0067	1.0112	0.00115
11	0.6	5000	0.5	0.0079	1.0132	0.00128
12	0.6	5000	0.7	0.0098	1.0163	0.00146
13	0.6	7500	0.3	0.0060	1.0100	0.00118
14	0.6	7500	0.5	0.0069	1.0115	0.00126
15	0.6	7500	0.7	0.0099	1.0165	0.00161
16	0.6	10000	0.3	0.0108	1.0180	0.00154
17	0.6	10000	0.5	0.0121	1.0202	0.00170
18	0.6	10000	0.7	0.0145	1.0242	0.00192
19	0.8	5000	0.3	0.0097	1.0121	0.00123
20	0.8	5000	0.5	0.0106	1.0133	0.00134
21	0.8	5000	0.7	0.0129	1.0161	0.00154
22	0.8	7500	0.3	0.0105	1.0131	0.00125
23	0.8	7500	0.5	0.0117	1.0146	0.00141
24	0.8	7500	0.7	0.0141	1.0176	0.00169
25	0.8	10000	0.3	0.0163	1.0204	0.00179
26	0.8	10000	0.5	0.0179	1.0224	0.00195
27	0.8	10000	0.7	0.0208	1.0260	0.00221

3. RESULTS AND DISCUSSION

The experimental results were analyzed with respect to hole geometry. The primary parameters influencing hole quality include overcut, hole damage factor (HDF), and taper ratio. In micro-drilling applications, direct visual inspection of hole geometry presents significant challenges due to the minute scale of the features involved. To overcome this, a Keyence digital optical microscope was employed to measure the entrance and exit profiles of the drilled holes. The diameters of both the entrance and exit profiles were determined by fitting a circle within the boundaries of each drilled hole (Fig. 2). The difference between the tool diameter and the resulting hole diameter was defined as the overcut (Equation 1). The hole damage factor (HDF) was calculated by dividing the measured hole diameter by the corresponding tool diameter, with the HDF of the entrance hole specifically evaluated in this study (Equation 2). Furthermore, the taper ratio was determined based on the measured hole diameters and the workpiece thickness (Equation 3). The calculated hole quality parameters results are given in Table 3.

Overcut = $D_0 - D_t$ (1), Hole damage factor = D_0 / D_t (2), Taper ratio = $(D_o - D_1) / 2t$ (3) where, D_0 = Entry hole diameter; D_1 = Exit hole diameter; D_t = Tool diameter; t = Part thickness.

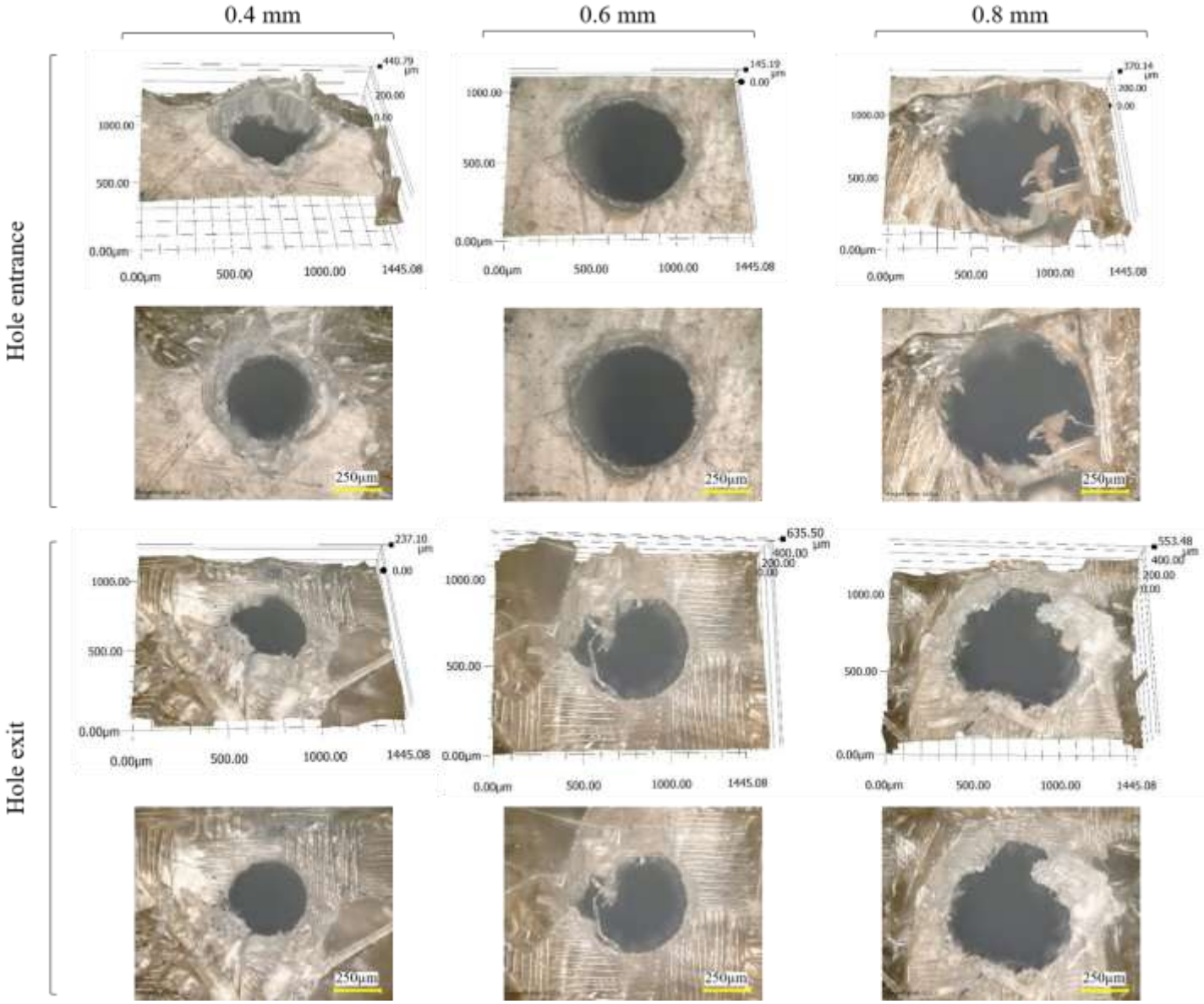

Figure 2. Images of the holes at the entrance and exit.

The influence of the experimental factors and their levels on the results was analyzed using the signal-to-noise ratio (SNR). In manufacturing processes, minimizing parameters such as overcut, hole damage factor, and taper ratio is essential for achieving high-quality outcomes. Therefore, the "smaller-the-better" criterion was adopted for calculating the signal-to-noise (S/N) ratio in the experimental design. The S/N ratios corresponding to the hole quality parameters are presented in Table 4. Table 4 indicates that the most influential parameters affecting overcut are the tool diameter (A), spindle speed (B), and feed rate (C), respectively. It was observed that the overcut value increases with the rise in tool diameter, spindle speed, and feed rate. To achieve the minimum overcut values in the drilling process, the optimal levels of the control factors were identified as A1–B2–C1 (0.4 mm – 7500 rpm – 0.3 mm/min). The dynamic stability of both the tool and the machine plays a significant role in controlling overcut. Lower overcut values were obtained due to the enhanced tool stability at lower feed rate

levels. As the tool diameter increases, a greater volume of material is removed, resulting in more extensive contact between the micro-drill and the workpiece surface. Consequently, higher tool diameters led to increased overcut values. The taper ratio and overcut were found to exhibit a similar trend. As shown in Table 4, the most influential parameters affecting the taper ratio are the tool diameter (A), spindle speed (B), and feed rate (C), respectively. The optimal control parameters for achieving the lowest taper ratio during the drilling were determined as A1–B2–C1 (0.4 mm – 7500 rpm – 0.3 mm/min). Lower feed rate and spindle speed values enhanced the stability and positional accuracy of the tool, resulting in minimal variation between the entrance and exit hole diameters, and consequently, a reduced taper ratio. Unlike overcut and taper ratio, the hole damage factor (HDF) was primarily influenced by spindle speed (B), feed rate (C), and tool diameter (A), respectively, as shown in Table 4. It was observed that the HDF value increased with rising tool diameter, spindle speed, and feed rate. The optimal control parameters for achieving the minimum HDF value in the drilling process were identified as A1–B2–C1 (0.4 mm – 7500 rpm – 0.3 mm/min). The positional accuracy of the drill bit has a significant impact on the HDF value. Lower HDF values were obtained due to the enhanced positional accuracy of the tool at low feed rate and spindle speed levels. This outcome can be attributed to the increased tool stability achieved under low feed rate conditions.

Table 4. S/N ratios of output factors.

Output factors	Overcut			Hole damage factor			Taper ratio		
Input factors	A	B	C	A	B	C	A	B	C
Level 1	46.45	43.03	43.35	-0.1130	-0.1078	-0.1102	59.80	58.40	58.70
Level 2	40.88	43.42	41.71	-0.1349	-0.1070	-0.1281	56.86	58.42	57.67
Level 3	37.46	38.33	39.72	-0.1488	-0.1820	-0.1584	56.08	55.92	56.36
Delta	8.99	5.09	3.62	0.0358	0.0750	0.0482	3.72	2.50	2.34
Rank	1	2	3	3	1	2	1	2	3

The effects of the control parameters and process levels on overcut, HDF, and taper ratio are illustrated in the one-dimensional (1D) graphs presented in Figure 3. It can be observed that the average S/N ratio trends depicted in the graphs are consistent with the findings summarized in Table 4.

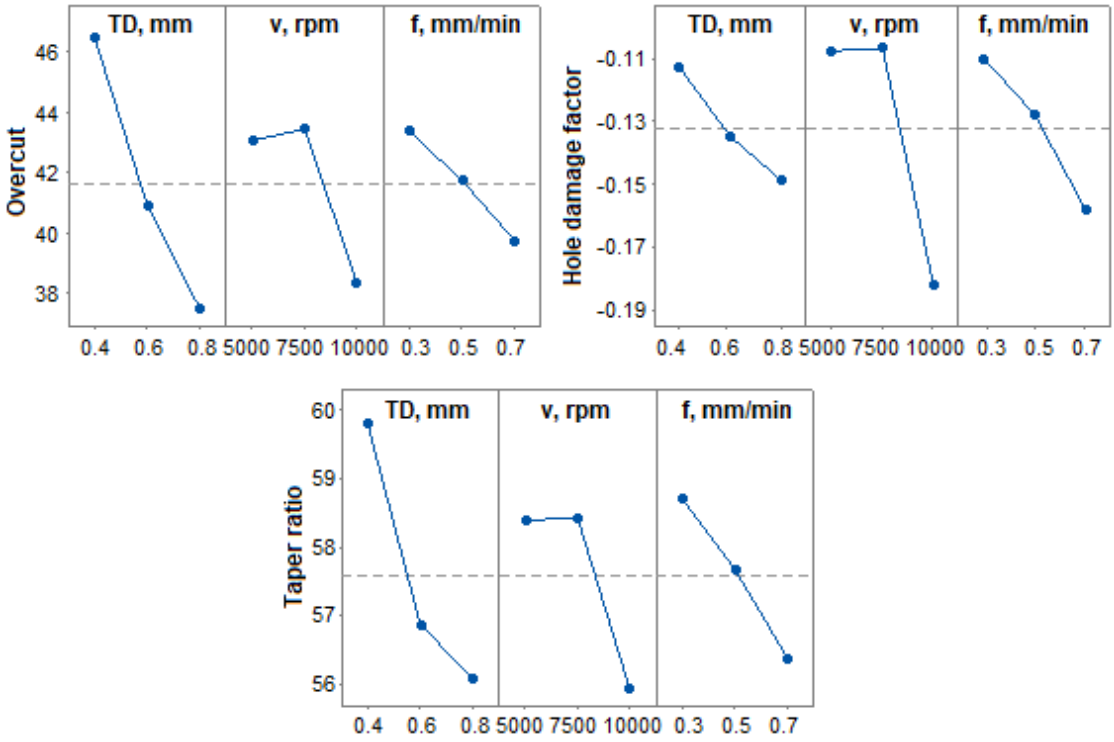

Figure 3. Average S/N ratios for hole quality parameters.

The ANOVA results for overcut, HDF, and taper ratio are presented in Table 5. A comparative analysis of the ANOVA and Taguchi results reveals a strong consistency between the two methods, indicating the reliability of the experimental findings.

According to the ANOVA results, the most influential parameter on overcut and taper ratio was the tool diameter, whereas the feed rate was identified as the least effective factor. For the hole damage factor (HDF), spindle speed was the most significant parameter, accounting for approximately 65% of the observed variation.

Table 5. Analysis of variance for output factors.

Output factors	Source	Degree of freedom	Sum of squares	Squares average	F value	P value	Percentage of contribution (%)
Overcut	A	2	0.000332	0.000166	237.79	0.000	59.99%
	B	2	0.000158	0.000079	112.99	0.000	28.51%
	C	2	0.000050	0.000025	35.58	0.000	8.98%
	Error (e)	20	0.000014	0.000001			2.52%
	Total	26	0.000554	-	-	-	100.00%
Hole damage factor	A	2	0.000080	0.000040	37.26	0.000	11.35%
	B	2	0.000457	0.000229	213.07	0.000	64.88%
	C	2	0.000146	0.000073	68.06	0.000	20.72%
	Error (e)	20	0.000021	0.000001			3.05%
	Total	26	0.000705	-	-	-	100.00%
Taper ratio	A	2	0.000002	0.000001	99.41	0.000	46.67%
	B	2	0.000001	0.000001	66.05	0.000	31.01%

	C	2	0.000001	0.000000	37.54	0.000	17.63%
	Error (e)	20	0.000000	0.000000			4.69%
	Total	26	0.000003	-	-	-	100.00%

First-degree (linear) equations were developed to predict overcut, HDF, and taper ratio through regression analysis (Equation 4), where A, B, and C represent the control factors. The coefficients of the prediction equations derived from the linear regression analysis are presented in Table 6. Using the developed regression equations, the predicted values for overcut, HDF, and taper ratio were calculated and are presented in Table 7.

First-degree (linear) equations for overcut, HDF, and taper ratio = a x A + b x B + c x C + d (4)

Table 6. Coefficients of regression analysis for overcut, HDF, and taper ratio.

Output factors	Overcut				HDF				Taper ratio			
Coefficients	a	b	c	d	a	b	c	d	a	b	c	d
	0.021472	0.000001	0.008194	- 0.015238	0.010451	0.000002	0.014086	0.989015	0.001403	0.0000001	0.000888	- 0.000548

Table 7. Experimental and regression results obtained for overcut, HDF, and taper ratio.

Output factors	Overcut (mm)	HDF (mm)	Taper ratio
Experimental resuts	0.00198	1.00484	0.000709
Regression results	0.00209	1.00758	0.000746
Confirmatory test results	0.00201	1.00627	0.000715

4. CONCLUSION

The findings derived from the study are presented below.

- The results show that the most influential parameters affecting overcut are the tool diameter (A), spindle speed (B), and feed rate (C), respectively. The overcut increases as the tool diameter, spindle speed, and feed rate increase. Accordingly, the optimum combination of control factors A1–B2–C1 (0.4 mm – 7500 rpm – 0.3 mm/min) was determined to minimize overcut in the drilling process.
- It was observed that the taper ratio and overcut follow a similar pattern. The parameters with the greatest impact on the taper ratio are tool diameter (A), spindle speed (B), and feed rate (C), respectively. The optimum control parameter sets for achieving the minimum taper ratio in the drilling process were determined as A1–B2–C1 (0.4 mm – 7500 rpm – 0.3 mm/min).
- In contrast to overcut and taper ratio, the hole damage factor (HDF) was predominantly governed by spindle speed (B), followed by feed rate (C) and tool diameter (A), respectively. The HDF value was found to increase with higher levels of tool diameter, spindle speed, and feed rate. The optimal combination of control parameters for minimizing HDF during the drilling process was determined to be A1–B2–C1 (0.4 mm – 7500 rpm – 0.3 mm/min).
- A comparison of the ANOVA and Taguchi outcomes demonstrates a high degree of agreement between the two methods, thereby reinforcing the reliability and validity of the experimental results. While the influence of tool diameter on overcut and taper ratio was determined to be approximately 60% and 47%, respectively, the effect of spindle speed on HDF was found to be around 65%.

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