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Influence of Drilling Parameters on the Chip Formation of Machining Aluminum 6061 Using HSS Twist Drill

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ABSTRACT – The influence of drilling parameters on chip formation during the machining of aluminium workpieces using High-Speed Steel (HSS) tools plays a critical role in optimizing the process for enhanced efficiency, surface quality, and sustainability. Drilling parameters like cutting speed, feed rate and drill bit point angle can significantly influence the machining performance. This research investigates the relationship between key drilling parameters such as spindle speed, feed rate, and drill bit point angle to the chip formation and hole surface roughness. Design of experiment (DoE) using Response Surface Methodology (RSM) was employed to optimize the experimental work. The machining operation employed a CNC machine to drill a hole on aluminum 6061 using 10mm HSS twist drill. The input parameters studied are spindle speed, feed rate and tool drill point angle while the chip formation and surface roughness are considered as an output parameter. The result reveals that continuous, segmental and discontinuous chip are produced at drill bit angle of 90°, 118° and 135° respectively. In addition, the ANOVA analysis identifies that the point angle is the most significant factor contributes to surface roughness of drilled hole of p-value of 0.0001 which then followed by spindle speed of p-value of 0.0103. Both spindle speed and point angle critically determine surface roughness, with lower spindle speeds and larger point angles resulting in rougher surfaces due to discontinuous chip formation. These findings provide valuable insights into optimizing drilling parameters to achieve desired machining outcomes, thereby supporting the development of more efficient and sustainable manufacturing processes.

KEYWORDS: Chip formation, drilling, machining, ANOVA, Response Surface Methodology

1.0 INTRODUCTION

Chip formation refers to the creation of metal chips during the machining operation, which directly impacts the efficiency, quality, and tool life. The effectiveness of the drilling process was influenced by various parameters, and their optimization was crucial for achieving desired outcomes. Several drilling parameters significantly affected chip formation, including cutting speed, spindle speed, feed rate, depth of cut, drill bit diameter, and drill bit point angle [1].

Chip formation created by drilling operations can be categorized into continuous chips, discontinuous chips and segmented chips. Continuous chips were long, ribbon-like chips that formed during drilling, as shown in Figure 1. This type of chip was typically associated with high cutting speeds and low feed rates. Continuous chips adhered to the tool and caused a BUE (Built-Up Edge) [2]. The advantages of continuous chips were that smooth and long chip formation could result in a better surface finish on the workpiece and reduced tool wear due to lower friction between the tool and the chip. Continuous chip formation allowed for more consistent removal of material along the cutting path, resulting in a more uniform surface finish. However, continuous chips were difficult to manage and evacuate from the drilling area, leading to chip clogging and reduced tool life, particularly at high cutting speeds and low feed rates. If chips were not effectively removed from the cutting area, they could re-cut the workpiece, leading to surface defects and a poor finish. Long continuous chips could pose safety hazards and could cause injury to operators [3][4][5].

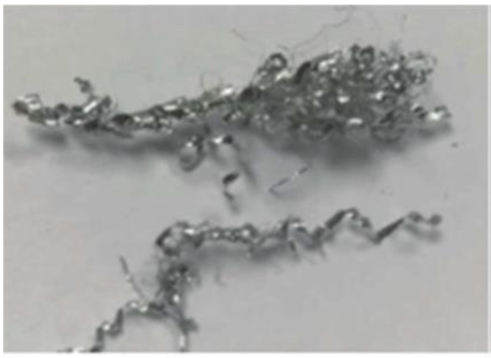

Figure 1. Example of continuous chips [1]

Discontinuous chips were short, fragmented chips that broke into small pieces during the drilling process, as shown in Figure 2. This type of chip was often associated with low cutting speeds and high feed rates. Aamir, M. et al. highlighted that higher feed rates increased the cross-sectional area of the chips, thus increasing their stiffness and making them easier to break [1]. Discontinuous chips were often easier to evacuate from the machining zone compared to long continuous chips. This helped in reducing the risk of chip clogging, especially in applications where chip removal was critical for maintaining machining efficiency and part quality. However, a disadvantage of discontinuous chips was that the surface finish might not have been as smooth as with continuous chips. The irregular nature of discontinuous chips could lead to variations in surface roughness, which might have required additional finishing operations to achieve the desired surface quality [4][5][6].

The advantages of discontinuous chips were that they were easier to manage and reduced the risk of tool jamming. They also contributed to improved surface finish. The formation of discontinuous chips might have been associated with increased cutting forces and energy consumption, which was one of the disadvantages of discontinuous chips. Serrated chips had a sawtooth-like pattern and were characterized by periodic variations in chip thickness [1][3][7].

Figure 2. Example of discontinuous and smaller chips [1]

A combination of both continuous and discontinuous chips was referred to as a segmental chip. These chips were pieces that separated from the main chip during the drilling process, as shown in Figure 3. Aamir, M. et al. gave examples such as lamellar chips, which were semi-continuous chips produced at high cutting speed and feed rate, whereas segmented chips, a form of discontinuous chips, were formed at low cutting speeds. Segmental chips offered a balance of some advantages associated with both continuous and discontinuous chip formations [6][8]. Compared to continuous chips, segmental chips provided improved chip evacuation, making them easier to remove from the cutting area and reducing the risk of clogging.

While segmental chips offered improved chip evacuation compared to continuous chips, they still had challenges compared to fully discontinuous chips. Complete discontinuity in chips generally allowed for easier and more efficient removal. The surface finish resulting from segmental chips could lead to surface irregularities on the interior surface of the drilled hole, which combines the smoother finish associated with continuous chips and the potentially rougher finish from fully discontinuous chips. As the drill bit entered the workpiece material, the irregular breaking of chips created uneven surfaces along the hole walls, resulting in roughness or scalloping [5][8].

Figure 3. Example of segmental chips [1]

1.1 Effect of Drilling Parameter on the Chip Formation

Different cutting speeds influenced chip formation as depicted in Figure 4 and Figure 5. Higher cutting speeds often resulted in continuous and well-formed chips. However, excessively high speeds could cause issues such as overheating, which could lead to poor chip formation. The continuous, entangled curly chips were predominantly observed across various spindle speeds. It was noted that higher spindle speeds increased the kinetic energy imparted to the chips, potentially causing chip breakage [9].

Higher feed rates could result in thicker chips, while lower feed rates might produce thinner chips. Optimal feed rates were crucial for achieving desired chip characteristics. An increased feed rate tended to produce smaller chips. The drilling of CFRP/aluminium stacks required sufficiently high feed rates to produce fragmented chips and achieve better hole quality in aluminum panels [8][10]. Discontinuous and segmented chips formed at higher feed rates. As the feed rate increased, the chips began to break into pieces because the higher feed rate increased the cross-sectional area and stiffness of the chips, making them easier to break [6][8]. The influence of feed rate and tool diameter on chip thickness ratio was noted, with increased cross-sectional area and chip stiffness observed at higher feeds and diameters [11]. Furthermore, continuous chips transformed into fractured and broken structures, attributed to reduced edge sharpness resulting from tool wear at higher feed rates [9].

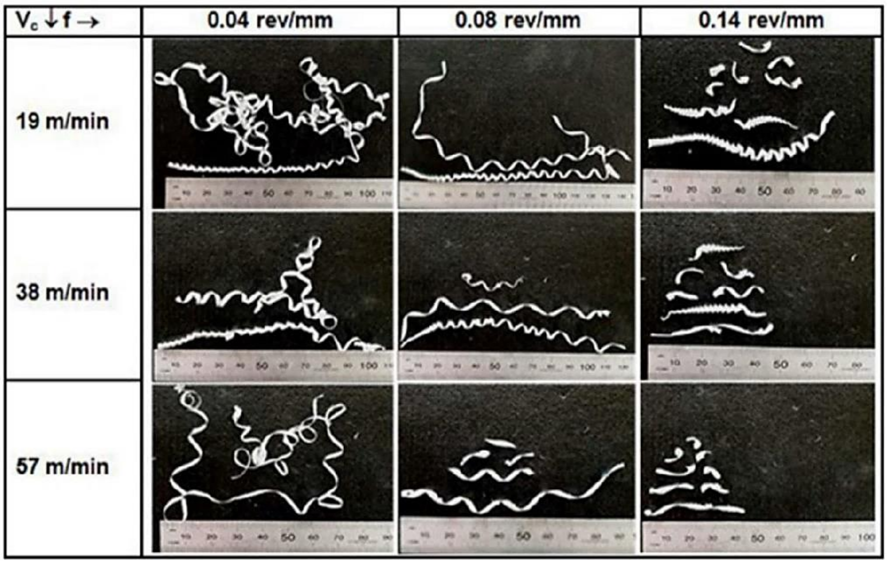

Figure 4. Example of chip formation from one-shot drilling under different cutting speeds and feed rates [8]

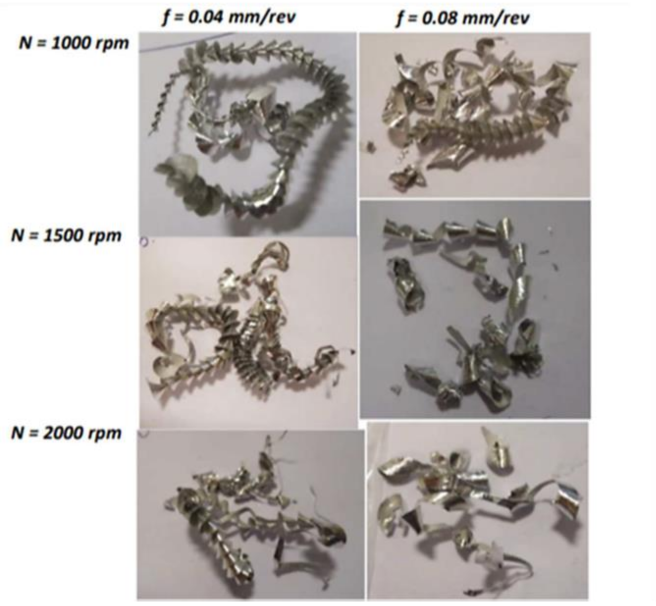

Figure 5. Example of chip formation under different spindle speeds and feed rates [8]

Larger diameter bits could produce thicker chips, and the chip formation process needed to be considered about the chosen drill bit size. The depth of cut affected the size and shape of chips produced during drilling. Proper control of the depth ensured adequate chip formation and evacuation. Improper chip control could result in chip packing, reduced tool performance, and lower hole quality. The selection of drill diameter and material composition influenced chip size and the formation of built-up edges [12]. The continuous chips were formed due to high cutting speeds, low feed rates, materials with high ductility, and tools with sharp edges [8].

The point angle and helix angle of the drill bit influenced the chip formation process. The point angle affected chip thickness, while the helix angle influenced chip evacuation. Well-designed drill bits with suitable point and helix angles contributed to efficient chip formation and evacuation. According to Demir, Z., changes in the point angle affected chip geometry and size, thus influencing the chip-breaking process [13]. An optimal point angle facilitates better chip control in the past, preventing chip accumulation and enhancing overall drilling performance.

Chip formation during drilling was influenced by various parameters including spindle speed, feed rate, and drill bit point angle. The characteristics of chips, such as size, shape, and consistency, directly impacted the surface finish of the drilled hole. Moreover, improper chip evacuation could lead to surface defects, tool wear, and reduced machining efficiency. The morphology and behavior of chips provided valuable insights into the effectiveness of drilling parameters and tool configurations. By controlling chip formation, manufacturers could improve surface finish, minimize burrs, and ensure dimensional accuracy in drilled components [14]. This research aimed to investigate the complex relationship between chip formation and surface quality, focusing on identifying which drilling parameters could be optimized to improve machining efficiency based on the analysis of chip formation. Furthermore, achieving optimal chip formation was not only essential for improving the efficiency of the machining process but also for minimizing tool wear, reducing energy consumption, and enhancing the surface finish of the machined parts [15] [16]. As industries continued to seek more sustainable and cost-effective manufacturing processes, understanding the intricate interplay between drilling parameters and chip formation became imperative.

2.0 METHODOLOGY

2.1 Experimental Work

The experiment was conducted using a 3-axis CNC drilling machine to drill a 10mm hole depth on an aluminum 6061 block of 100mm x 80mm x 20mm, with several manipulative variables of drilling parameters chosen for use. These parameters included spindle speed, feed rate, and drill bit point angle which each played a distinct role in shaping the resulting chip formation during the drilling process. A design of experiment (DOE) approach was implemented to optimize the experimental setup for the drilling process using response surface methodology (RSM) which was utilized by Design Expert software. A face-centered central composite design (CCD) was employed with the three input factors listed in Table 1. This design resulted in a total of 20 experimental runs, each corresponding to a unique combination of drilling parameters as outlined in Table 2. Meanwhile, Figure 6 shows the HSS twist drill with 3 different point angles which was used to drill an Aluminium 6061 workpiece as in Figure 7.

Table 1: The range of drilling parameters

Range	Spindle speed, n (RPM)	Feed rate, V (mm/min)	Drill bit point angle,(°)
Minimum	1000	20	90
Middle	1500	30	118
Maximum	2000	40	135

Table 2. List of experiments with various settings of drilling parameters

Run	Spindle speed, (RPM)	Feed rate, mm/min	Drill bit point angle, °
1	1000	20	135
2	1500	40	118
3	1500	30	118
4	1500	20	118
5	1000	40	135
6	1000	40	90
7	1000	30	118
8	1500	30	90
9	2000	40	135
10	2000	40	90
11	1500	30	118
12	1500	30	118
13	1500	30	118
14	2000	30	118
15	2000	20	135
16	1000	20	90
17	1500	30	135
18	1500	30	118
19	1500	30	118
20	2000	20	90

Figure 6. HSS twist drill bit with 3 different point angles of 90°, 118° and 135°

Figure 7. Aluminium 6061 block

2.2 *Chip Length*

Chip length refers to the distance from where the chip begins to form as it separates from the workpiece surface to where it ends. The length of the chip formation was measured by using a ruler aligned parallel to the chip's direction as shown in Figure 8.

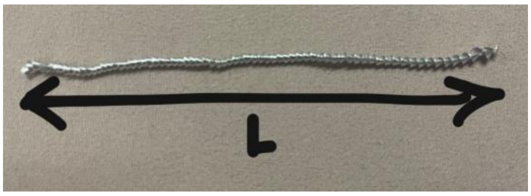

Figure 8. Length of the chip formation

2.3 *Surface Rughness (Ra)*

The average surface roughness, Ra of each hole are measured using the Mitutoyo SJ-410 Roughness Measuring Machine. The drilled workpiece was carefully cut into half using an ED wire-cut machine to expose the internal surface for surface measurement.

3.0 RESULT AND DISCUSSION

3.1 Type of Chip Formation

The sample of chip formation during the drilling operation using different tool drill point angles was collected and observed as shown in Figure 9. The 90° drill point angle tended to produce a continuous chip while the segmental chip was created by 118°point angle of the tool. Besides, the discontinuous chip can be produced using a 135° tool drill point angle.

(a) (b) (c)

Figure 9. Chip formation produced during drilling at 20mm/min feed rate and 1000 rpm spindle speed using (a) 90°(continuous chip) (b) 118°(segmental chip) and (c) 135°(discontinuous chip) tool drill point angle

3.2 Effect of Drilling Parameter on the Chip Size and Surface Roughness

The effect of drilling parameters was observed in the series of machining runs conducted as shown in Table 3. Various combinations of spindle speed, feed rate, drill bit point angle to the resulting chip length and surface roughness were obtained.

Table 3. Result of chip length and width for various settings of drilling parameter

Run	Spindle speed, (RPM)	Feed rate, mm/min	Drill bit point angle, °	Chip length, mm	Surface roughness, µm
1	1000	20	135	3	0.381
2	1500	40	118	114	0.266
3	1500	30	118	96	0.259
4	1500	20	118	105	0.282
5	1000	40	135	142	0.473
6	1000	40	90	236	0.391
7	1000	30	118	169	0.281
8	1500	30	90	458	0.385
9	2000	40	135	12	0.297
10	2000	40	90	203	0.244
11	1500	30	118	131	0.248
12	1500	30	118	135	0.255
13	1500	30	118	100	0.258
14	2000	30	118	102	0.244
15	2000	20	135	66	0.455
16	1000	20	90	213	0.255
17	1500	30	135	4	0.486
18	1500	30	118	50	0.260
19	1500	30	118	287	0.253
20	2000	20	90	210	0.270

According to Table 3, the highest chip length observed was during run 8, where a spindle speed of 1500 RPM, a feed rate of 30 mm/min, and a drill bit point angle of 90° resulted in a chip length of 458 mm. Conversely, the shortest chip length measured only 3 mm was noted in run 1, with a spindle speed of 1000 RPM, a feed rate of 20 mm/min, and a drill bit point angle of 135°.

3.3 ANOVA Analysis of Chip Length

Based on Table 4, the ANOVA analysis indicated that the model was significant (p = 0.0029), which indicates that at least one of the parameters had a significant effect on chip dimensions specifically for chip length. P-values less than 0.0500 indicate model terms are significant. Spindle Speed (A) and Feed Rate (B) had p-values which were 0.4937 and 0.6565 respectively greater than 0.05, suggesting that their effects on chip length were not statistically significant. However, point angle (C) had a very low p-value which was 0.0003, indicating that it significantly affected the chip length.

The effect of the drilling parameter on the chip length is shown in Figure 10 (a), (b) and (c) indicating that the tool drill point angle has the highest slope than spindle speed and feed rate. The graphically represented relationships between chip length and these variables were consistent with the ANOVA results, highlighting how point angle had a more significant impact on chip dimensions compared to spindle speed and feed rate. The lack of significance suggested that changes in spindle speed and feed rate had minimal influence on chip length variations, leading to shallower slopes in their respective graphs.

Table 4: ANOVA analysis for chip length

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1.269E+05	3	42296.34	7.18	0.0029
A-spindle speed	2890.00	1	2890.00	0.4906	0.4937
B-feed rate	1210.00	1	1210.00	0.2054	0.6565
C-point angle	1.228E+05	1	1.228E+05	20.84	0.0003
Residual	94250.19	16	5890.64	-	-
Lack of Fit	61179.36	11	5561.76	0.8409	-
Pure Error	33070.83	5	6614.17	-	-
Cor Total	2.211E+05	19	-	-	-

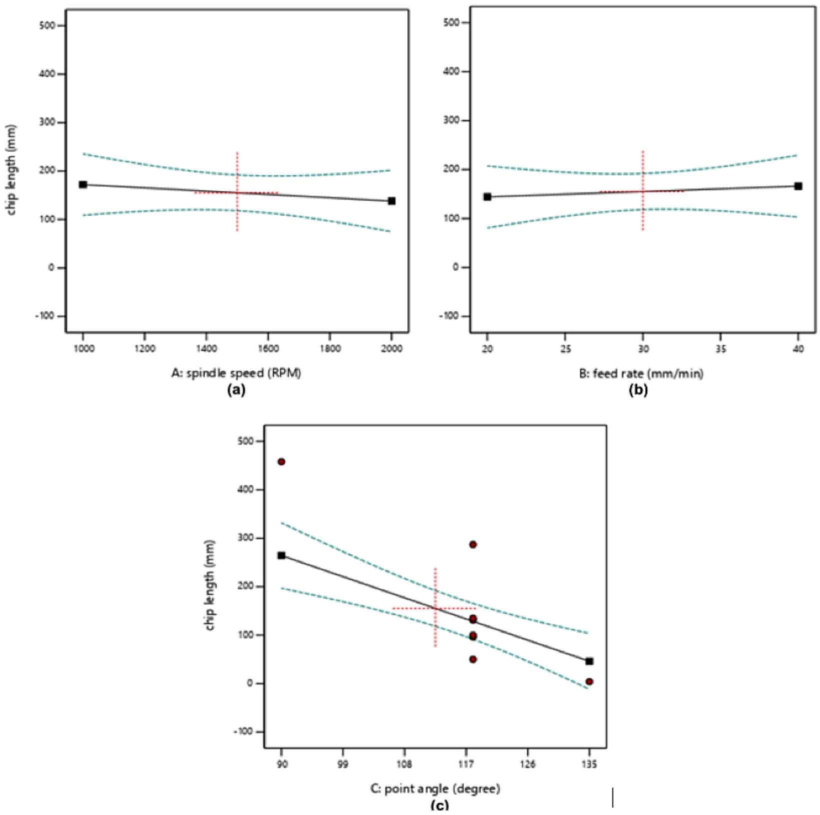

Figure 10. The main parameter effect of drilling parameters (a) spindle speed, (b) feed rate and (c) drill point angle to the chip length.

Based on the 3D surface plot Figure 11, it was observed that a spindle speed of 1000 RPM with a feed rate of 40 mm/min yielded the highest chip lengths. Meanwhile, a spindle speed of 2000 RPM with a feed rate of 20 mm/min resulted in the lowest chip lengths. However, statistical analysis indicated that the p-values for Spindle Speed (A) and Feed Rate (B) were 0.4937 and 0.6565 respectively, both greater than 0.05. This suggests that their effects on chip length were not statistically significant.

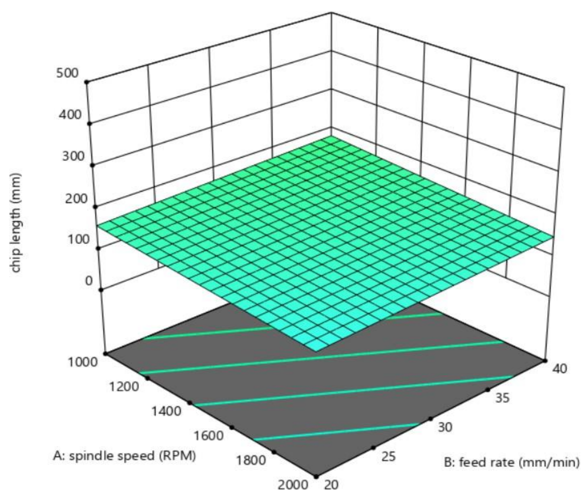

Figure 11. 3D surface graph of the relation between spindle speed and feed rate with chip

Higher spindle speeds typically result in faster cutting speeds, which can lead to smaller chips if other factors remain constant. In the case where a spindle speed of 2000 RPM was used with a drill bit point angle of 135°, the resulting chip length of 12 mm suggests that this combination provided an optimal balance between cutting efficiency and chip formation.

The point angle of the drill bit affects how it engages with the material being machined. A smaller drill bit point angle such as 90° tends to create a more aggressive cutting action, potentially leading to larger chips being produced during machining. This aligns with the observation of a chip length of 213 mm when using a lower spindle speed of 1000 RPM combined with a drill bit point angle of 90°. Figure 12, the 3D surface graph, further supports these findings by illustrating that at the lowest spindle speed and lower drill bit point angle, chip length reaches its maximum value.

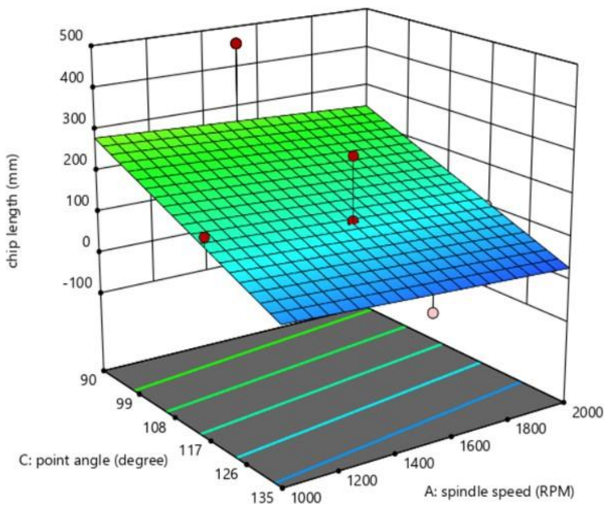

Figure 12. 3D surface graph of the relation between spindle speed and point angle with chip length

However, the value of R2 is 0.5738 which indicates that spindle speed, feed rate, and point angle collectively explain about 57.38% of the variability in chip dimensions observed in the data as shown in Table 5. The lower value of R2 is due to the variations of the drill bit conditions such as sharpness, wear, or defects, which can affect the consistency and quality of the drilling process. To increase the reliability of the data, it is suggested to use individual tool drills for each hole to minimize the variation of tool drill conditions.

Table 5. *R-sq* (R^2) value of chip length analysis

Std. Dev.	Mean	C.V. %	R^2	Adjusted R^2	Predicted R^2	Adeq Precision
76.75	141.80	54.13	0.5738	0.4939	0.3485	7.9939

3.4 ANOVA Analysis of Surface Roughness

The ANOVA results as shown in Table 6 reveal that the model was significant ($p < 0.0001$). Specifically, spindle speed (A) was found to have significant effects on the response variable which was surface roughness with a 0.0103 p-value. It indicates that changes in spindle speed have affected the surface roughness of the drilled hole. However, factors such as feed rate (B) did not demonstrate significant influence where the p-value is 0.7513 which was higher than 0.05. These variations in feed rate parameters did not significantly impact the surface roughness under tested conditions. In contrast, point angle (C) exhibited a highly significant impact which has the lowest p-value ($p < 0.0001$) among all the parameters which indicates a strong relationship between this parameter and surface roughness.

Table 6. ANOVA analysis for surface roughness

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.1233	9	0.0137	18.55	<0.0001
A-spindle speed	0.0073	1	0.0073	9.94	0.0103
B-feed rate	0.0001	1	0.0001	0.1061	0.7513
C-point angle	0.0299	1	0.0299	40.51	<0.0001
AB	0.0212	1	0.0212	28.73	0.0003
AC	0.0001	1	0.0001	0.1523	0.7045
BC	0.0039	1	0.0039	5.24	0.0450
A^2	0.0034	1	0.0034	4.54	0.0590
B^2	0.0015	1	0.0015	2.04	0.1837
C^2	0.0524	1	0.0524	71.00	<0.0001
Residual	0.0074	10	0.0007	-	-
Lack of Fit	0.0073	5	0.0015	71.77	0.0001
Pure Error	0.0001	5	0.0000	-	-
Cor Total	0.1307	9	-	-	-

Based on Figure 13, the surface roughness versus point angle model graphs had a higher steeper slope compared to the graph of surface roughness versus spindle speed and feed rate. This observed that small changes in the point angle resulted in larger changes in the surface roughness compared to equivalent changes in feed rate or spindle speed. This steep slope indicates that optimizing the point angle could potentially have a more pronounced effect on the outcome such as surface roughness. This is related to a low p-value in ANOVA as shown in Table 12 where the point angle has the lowest p-value which was $p < 0.0001$ compared to spindle speed and feed rate with 0.0103 and 0.7513 respectively.

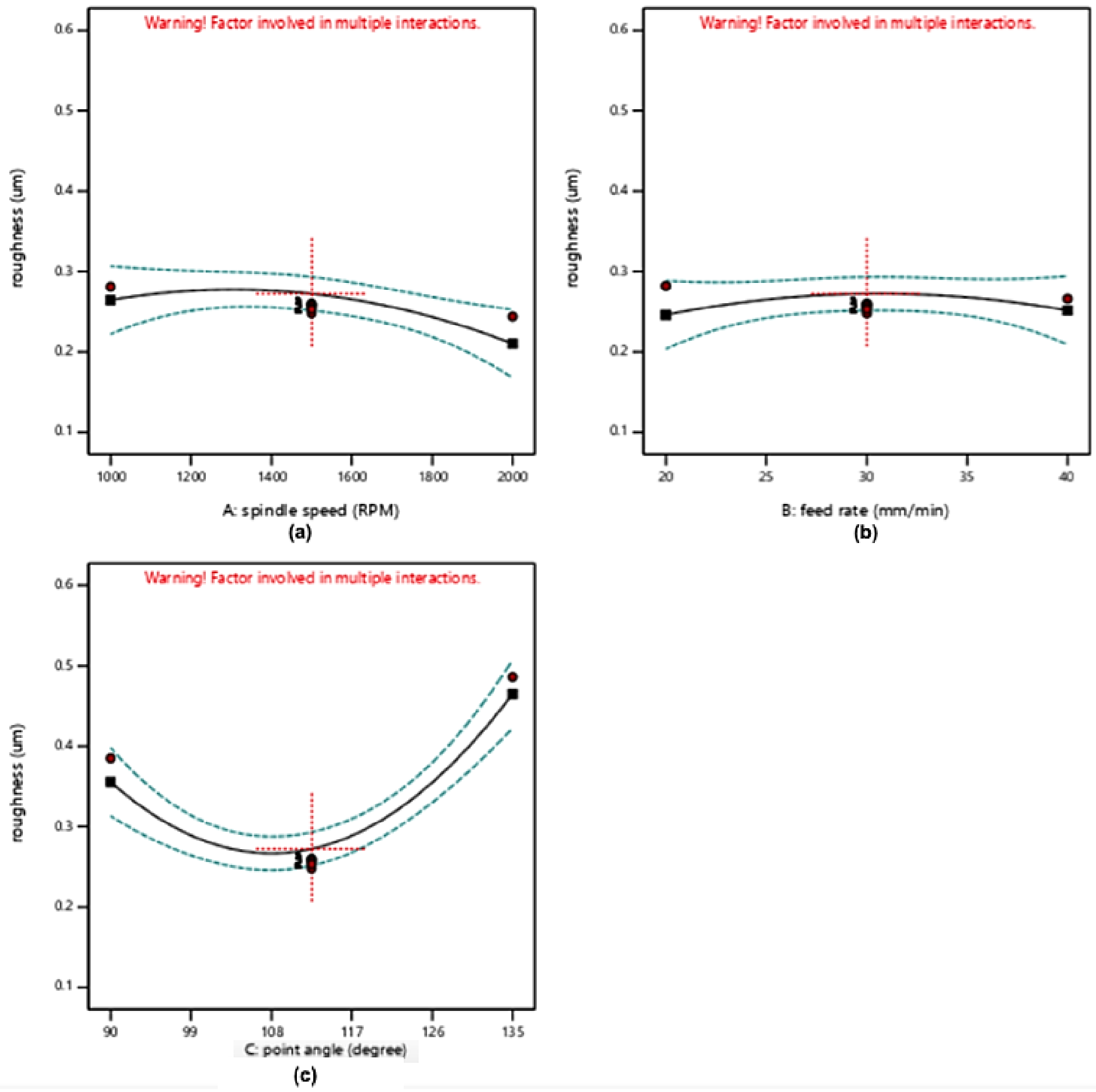

Figure 13. The main parameter effects of drilling parameters (a) spindle speed, (b) feed rate and (c) drill point angle to the surface roughness of the wall hole.

In Figure 14, it was observed that a spindle speed of 1000 RPM combined with a feed rate of 40 mm/min resulted in the highest Ra value. Conversely, a spindle speed of 2000 RPM at the same feed rate produced the lowest Ra value, shown in a darker blue shade. This suggests that higher spindle speeds generally lead to smoother surfaces, characterized by lower Ra values. The 3D surface graph, illustrates that at the highest tested spindle speed and feed rate, Ra values were minimized, indicating the smoothest surface finish achieved in the experiments.

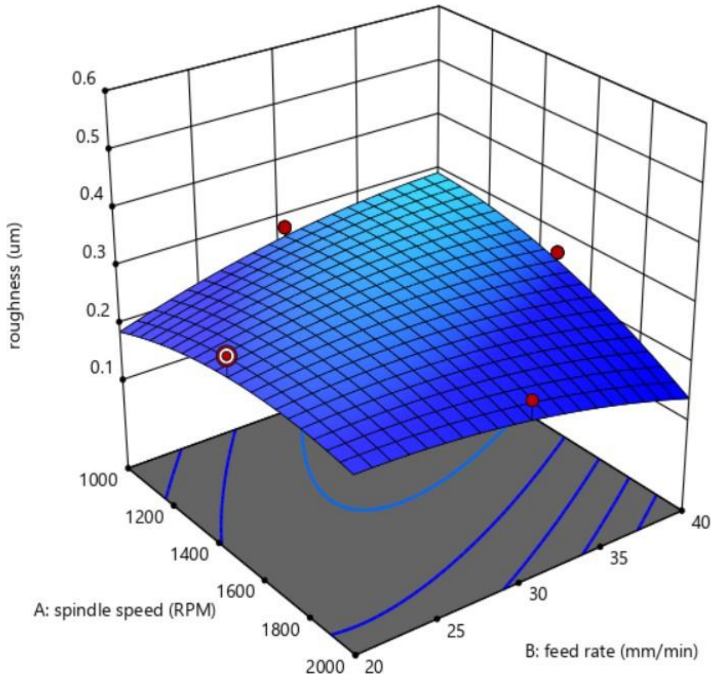

Figure 14. 3D surface graph of the relation between feed rate and spindle speed with surface roughness

Meanwhile, according to Figure 15, the highest Ra value was observed at a spindle speed of 1500 RPM and a point angle of 135°. However, the lowest Ra values, indicated by the darker blue color, were found at a spindle speed of 2000 RPM with a point angle close to 108°, approximated by using a 90°-point angle in the experimental setup.

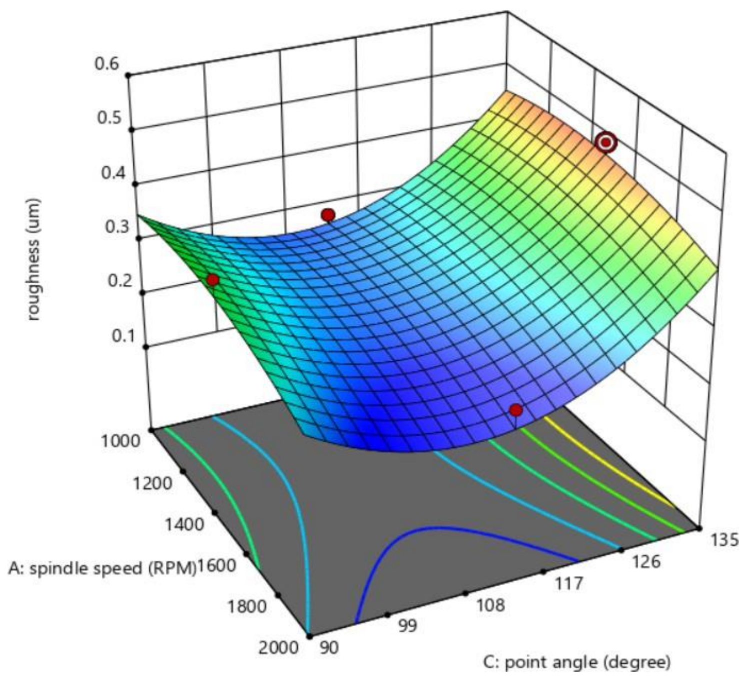

Figure 15. 3D surface graph of the relation between point angle and spindle speed with surface roughness

Moreover, the analysis of the 3D surface and contour graphs suggested that an optimal combination of parameters, specifically a spindle speed of approximately 1700 RPM and a point angle of 100°, resulted in the lowest Ra values. Deviations from these optimal parameters, whether increasing or decreasing the spindle speed or point angle, led to a rougher surface.

Based on Figure 47, at a feed rate of 30 mm/min combined with a point angle of 135 °, the highest value of Ra was observed, as indicated by the red coloration. Meanwhile, the lowest Ra values were recorded at a feed rate of 20 mm/min with a point angle close to 108 °, illustrated by the darker blue color. It can be concluded that the lowest Ra values were achieved at the lowest feed rate and lower point angle. In contrast, the combination of a middle feed rate and the highest point angle resulted in the maximum Ra value. These results highlighted the significant influence of point angle on surface roughness, as confirmed by the ANOVA analysis, where the point angle exhibited the lowest p-value ($p < 0.0001$), indicating a highly significant effect. Meanwhile, the feed rate did not show a significant impact.

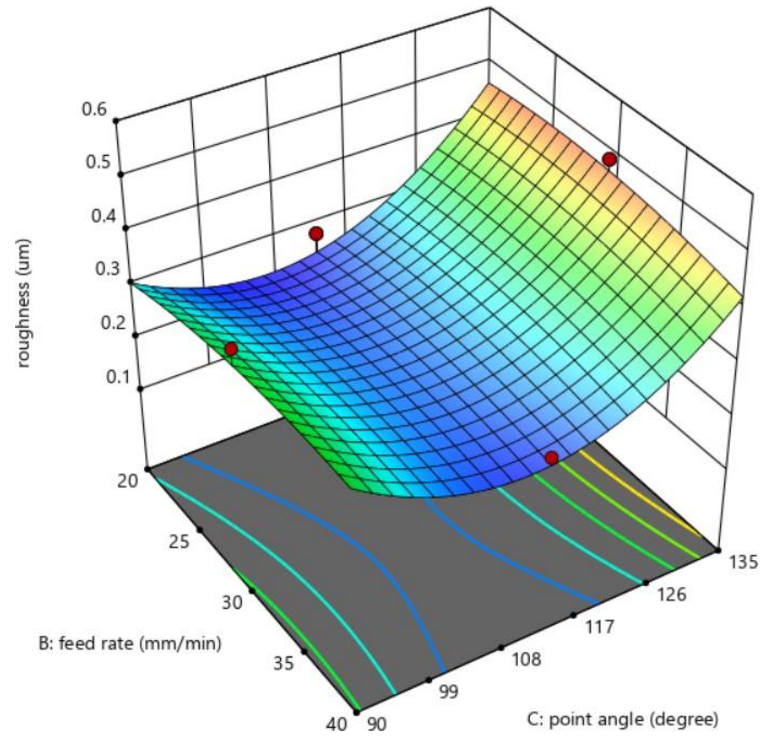

Figure 16. 3D surface graph of the relation between point angle and feed rate with surface roughness

4.0 CONCLUSION

In conclusion, this study investigated the impact of spindle speed, feed rate, and drill bit point angle on chip formation characteristics and surface roughness during drilling operations. The findings revealed that drill bit point angle significantly influenced chip length, with smaller angles producing longer, continuous chips that contributed to smoother surface finishes. Conversely, larger angles resulted in shorter, discontinuous chips, leading to rougher surfaces. Spindle speed played a crucial role in chip width, where higher speeds generated narrower chips, enhancing surface smoothness.

Feed rate, while influential, had a less pronounced effect compared to spindle speed and drill bit angle. Statistical analyses using ANOVA confirmed the significance of drill bit point angle and spindle speed in determining chip characteristics and surface roughness. Feed rate, while a factor, exhibited less significant effects compared to the other parameters studied. The study identified lower spindle speeds of 1000 rpm combined with smaller drill bit point angles of 118° as optimal for producing continuous chip and smooth surface finishes. Adjustments in feed rate were found to play a secondary role in balancing material removal rates without substantially altering surface quality. Future research could further explore additional factors such as tool wear and lubrication effects to refine machining strategies and broaden the understanding of these complex interactions in drilling operations.

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