

Article

Experimental Investigation of Hot Drilling and Their Effect on the Damage Mechanisms in CFRP Nanocomposites

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Abstract

Carbon fiber-reinforced polymer (CFRP) composites modified with alumina (Al_2O_3) and silicon carbide (SiC) nanoparticles were developed to produce hybrid nanocomposites with improved mechanical and thermal characteristics. This study investigates the hot drilling behavior of unidirectional CFRP and hybrid nanocomposites by examining the effects of spindle speed, feed rate, drill diameter, and drill geometry (step, core, and twist). Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) were used to identify the most influential parameters governing drilling-induced damage. ANOVA results revealed that drill geometry was the most dominant factor, contributing more than 89% to delamination, burr formation, and surface roughness, followed by drill diameter with over 7% contribution. For temperature rise, drill geometry accounted for more than 50% of the total variation, while drill diameter contributed over 17%. Among the tools evaluated, the step drill produced the minimum drilling-induced damage, followed by the twist drill. In terms of material performance, the Al_2O_3 -reinforced hybrid nanocomposite exhibited superior drilling behavior compared to the SiC-reinforced and neat CFRP laminates. Overall, the results demonstrate that drilling-induced damage under hot drilling conditions can be effectively minimized through appropriate selection of tool geometry and process parameters, confirming the suitability of hot drilling for machining aerospace-grade CFRP hybrid nanocomposites.

Keywords: carbon fiber-reinforced polymer; nanocomposites; hot drilling; delamination factor; burr area; sustainable development goal 9 (industry, innovation and infrastructure)



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1. Introduction

Carbon fiber-reinforced polymer (CFRP) composites have become increasingly essential in aerospace, automotive, and marine industries due to their superior strength-to-weight ratio, corrosion resistance, and fatigue durability [1]. Recent studies have further highlighted their excellent specific stiffness, tailorability, and damage tolerance, making them suitable for primary load-bearing structures in aircraft, wind turbine blades, and high-performance automotive components [2,3]. These composites enable the production of lightweight yet high-performance structures crucial for advancing modern engineering applications [4,5]. Although CFRP components are typically fabricated to near net shape,

precise secondary machining operations, such as drilling, are invariably required to form holes for mechanical fastening using rivets and bolts.

Drilling CFRP composites presents significant manufacturing challenges due to their heterogeneous, anisotropic microstructure and abrasive carbon fibers. Several investigations report that interlaminar delamination, fiber pull-out, matrix cracking, and rapid tool wear remain the most critical issues limiting hole quality and structural reliability during drilling of CFRP laminates [6,7]. These factors lead to rapid tool wear and machining defects, that include delamination, fiber pull-out, poor surface finish and burr formation [8,9]. These issues adversely affect the mechanical integrity and longevity of the final assembly [6,10]. Therefore, it is crucial to understand and optimize drilling parameters to minimize damage and ensure the production of reliable, high-quality CFRP components.

The quality of drilling is significantly influenced by tool design, machining conditions, and environmental factors. The studies have shown that drill geometry, such as step drills and twist drills, plays a crucial role in determining the thrust forces and damage mechanisms. Advanced drill designs have been reported to reduce thrust force by modifying chisel edge length and improving chip evacuation, thereby suppressing exit delamination and surface damage in CFRP laminates [11,12]. For example, step drills can reduce delamination by minimizing the contact area and distributing stress more evenly at the hole exit [12]. Additionally, the thermal effects generated during drilling affect the behavior of the polymer matrix. Higher temperatures tend to soften the resin, making it more susceptible to cracking. To counteract these thermal effects, cooling techniques such as cryogenic machining have been explored. However, these methods add to the complexity and overall manufacturing cost [13,14].

Since the advancements in machining technology, the reinforcement of CFRP composites with nanoparticles such as alumina (Al_2O_3) and silicon carbide (SiC) has emerged as a promising method to enhance their mechanical and thermal properties. This potentially improves the machinability and drilling performance. However, most current literature primarily focuses on CFRP composites without nanoparticle additions or evaluates machining under wet conditions. There is a significant gap in comprehensive studies evaluating the hot drilling performance of these hybrid nanocomposites, which are highly important due to the environmental and economic advantages of hot drilling [15]. At higher temperatures, the epoxy matrix in CFRP becomes softer, which weakens the fiber–matrix bonding and increases the chances of delamination during drilling. Hot drilling introduces controlled external heat during the cutting process, and while this can lower cutting resistance, it may also promote heat-related damage if not properly managed.

This study addresses the above-mentioned gaps by systematically investigating the hot drilling behavior of unidirectional CFRP composites reinforced with Al_2O_3 and SiC nanoparticles. This work employs Design of Experiments (DOEs) using Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) to evaluate the effects of spindle speed, feed, drill geometry and drill diameter on critical quality metrics, including delamination factor, surface roughness and burr area. The results provide clear insights into optimizing hot drilling parameters and drill geometries for hybrid nanocomposites, which have significant implications for aerospace manufacturing, where precision and minimal damage are crucial.

2. Materials and Methods

2.1. Fabrication of Composites

The fabrication of CFRP nanocomposites was performed using the wet layup method, followed by compression molding. The nanoparticles Al_2O_3 and SiC were added in the resin solution by the combination of ultrasonication and magnetic stirring method to

achieve homogeneous dispersion. The detailed fabrication procedure is described in the authors' previous works, where the dispersion of nanoparticles at different weight percentages was systematically examined using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) [16]. For the fabrication of composite laminates, a unidirectional carbon fabric with a 200 GSM weight was used, along with epoxy resin and an amine-based hardener, for the layup process. Both carbon fiber and resin were procured from Bhor Chemicals and Plastics Pvt. Ltd., Maharashtra, India, whereas alumina (Al_2O_3) and silicon carbide (SiC) nanoparticles were obtained from Sisco Research Laboratories Pvt. Ltd. (Mumbai, India), for preparing hybrid nanocomposites. For the drilling experiments, three types of drill bits were used (twist, step and core drill) made of silicon carbide with physical vapor deposition (PVD) coating; a detailed description of the drill material is provided in the authors' previous work [17].

2.2. Experimental Designs for Drilling Using DOE

Statistical Tools

In the present work, the drilling experiments were formulated by using Response Surface Methodology (RSM) based on a Central Composite Design (CCD) in Minitab V15 software. The following process parameters such as spindle speed, feed rate, drill diameter, and drill type as listed in Table 1 were selected for the experiment—whereas the CCD experimental matrix used during the experiment is presented in Table 2.

Table 1. Process parameters for drilling.

Sl. No.	Parameters			
	Spindle Speed (rpm)	Feed (mm/rev)	Drill Diameter (mm)	Drill Type
1	1500	0.01	4	Twist
2	3500	0.02	6	Step
3	5500	0.03	8	Core

Table 2. RSM for process parameters and drill type.

Trial	Spindle Speed (rpm)	Feed (mm/rev)	Drill Diameter (mm)	Drill Type
1	5500	0.01	8	Step
2	5500	0.01	8	Core
3	5500	0.02	6	Core
4	1500	0.01	4	Twist
5	3500	0.02	6	Step
6	1500	0.01	4	Core
7	3500	0.01	6	Step
8	1500	0.01	4	Step
9	3500	0.02	6	Twist
10	5500	0.02	6	Twist
11	5500	0.03	8	Twist
12	5500	0.03	4	Core
13	1500	0.01	8	Core
14	3500	0.01	6	Core
15	3500	0.03	6	Step
16	1500	0.03	4	Core
17	5500	0.03	4	Twist
18	3500	0.02	6	Core

Table 2. *Cont.*

Trial	Spindle Speed (rpm)	Feed (mm/rev)	Drill Diameter (mm)	Drill Type
19	5500	0.01	4	Core
20	3500	0.02	6	Core
21	3500	0.02	8	Step
22	5500	0.03	8	Core
23	3500	0.03	6	Twist
24	1500	0.03	8	Twist
25	3500	0.02	6	Core
26	3500	0.02	6	Twist
27	1500	0.03	8	Step
28	1500	0.01	8	Step
29	5500	0.01	8	Twist
30	1500	0.02	6	Core
31	3500	0.02	6	Step
32	1500	0.03	4	Step
33	3500	0.02	6	Core
34	1500	0.03	4	Twist
35	1500	0.03	8	Core
36	3500	0.02	8	Core
37	3500	0.02	6	Core
38	3500	0.02	6	Step
39	3500	0.02	8	Twist
40	3500	0.03	6	Core
41	5500	0.03	8	Step
42	3500	0.02	6	Twist
43	3500	0.02	4	Core
44	5500	0.01	4	Step
45	3500	0.02	6	Step
46	1500	0.02	6	Step
47	3500	0.01	6	Twist
48	3500	0.02	6	Core
49	5500	0.02	6	Step
50	3500	0.02	6	Twist
51	3500	0.02	6	Twist
52	5500	0.03	4	Step
53	5500	0.01	4	Twist
54	3500	0.02	4	Twist
55	1500	0.01	8	Twist
56	3500	0.02	6	Step
57	3500	0.02	6	Step
58	3500	0.02	6	Twist
59	1500	0.02	6	Twist
60	3500	0.02	4	Step

A second-order regression model of the CCD form as represented in Equation (1) was employed to establish a relationship between the process parameters and the output responses including delamination factor, burr area, surface roughness, and hole temperature. In the equation below, A, B, C, and D represent the coded values of the process parameters, namely, spindle speed (A), feed rate (B), drill diameter (C), and drill type (D), respectively. The response variable y denotes the output responses, including delamination factor, burr area, surface roughness, and hole temperature.

$$y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 A^2 + \beta_6 B^2 + \beta_7 C^2 + \beta_8 D^2 + \beta_9 AB + \beta_{10} AC + \beta_{11} AD + \beta_{12} BC + \beta_{13} BD + \beta_{14} CD + \varepsilon \quad (1)$$

where $\beta_0, \beta_1, \beta_2, \dots, \beta_{13}, \beta_{14}$ represent the regression coefficient and the random error is represented as ε .

Analysis of Variance (ANOVA) was conducted to identify statistically significant parameters and interactions at a 95% confidence level. Main effects and contour plots are also generated to assess the influence of individual and combined factors on the measured responses that are discussed in the results and discussion section.

In addition to ANOVA, a multi-response optimization was carried out using the desirability function approach. Individual and overall desirability indices were computed as per Equation (2) and Equation (3), respectively. The desirability function converts the output variable that includes delamination factor, burr area, surface roughness, and hole temperature into a dimensionless metric known as desirability index d_i . The d_i assumes values in the closed interval range of (0, 1). A higher value of the d_i indicates a higher contribution towards the product performance by the certain output variable. The d_i is expressed as a function of the output variable (y_i). Through the individual desirability function, each output variable is mapped to a number between 0 and 1, where 0 represents undesirable outcome and 1 represents a desirable outcome [18].

$$d_i = \left(\frac{y - y_{\min}}{y_{\text{target}} - y_{\min}} \right)^q \quad y_{\min} < y < y_{\text{target}} \quad (2)$$

The calculation of the product performance is achieved by using the geometric mean of all the desirability indices to obtain an aggregate (global or composite) desirability index D , as shown in Equation (3) [19].

$$D = (d_1 \times d_2 \times d_3 \dots d_m)^{1/m} \quad (3)$$

where m is the desired output variable.

2.3. Drilling Experimental Setup

A vertical machining center (Model: TRIAC VMC) obtained from DENFORD, UK with a computer numerical control (CNC) was used to perform the drilling experiment. The 6 ± 0.2 mm thick neat and hybrid nanocomposites were cut into strips of dimension $250 \text{ mm} \times 25 \text{ mm}$ using a water jet cutting machine. The hot air drilling was performed using a heat gun that supplies hot air at a flow rate range from 2 m/s to 4 m/s. The initial hot air temperature measured was 60°C . The flow rate was measured using a digital anemometer at a distance of 20 mm from the nozzle, as shown in Figure 1. To maintain a constant flow rate of hot air, the distance between the nozzle and the surface of the composite strip was also maintained at 20 mm. Hot air was continuously supplied for an in-depth heat penetration throughout the thickness of the composite during drilling. A vacuum suction was placed near the drilling surface to remove the dust during the drilling operation. The infra-red thermal gun with digital indicator was used to measure the output temperature of the drilled hole at the end of the drilling operation. The experimental setup for hot air drilling using a heat gun and a thermal infrared gun is shown in Figure 2. A total of 180 holes were drilled during the experiment.



Figure 1. Flow rate measurement of hot air using Digital Anemometer.

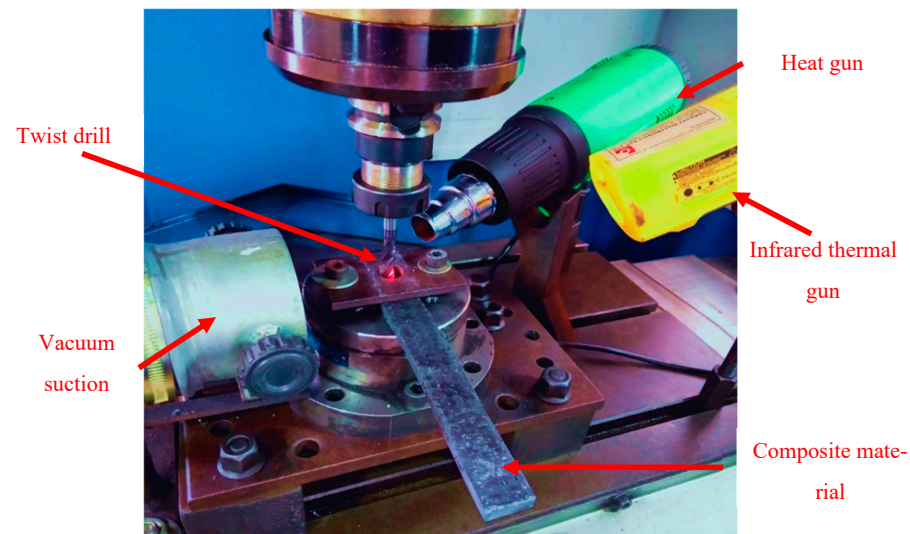


Figure 2. Experimental setup of hot air drilling.

2.4. Measurements of Drilling-Induced Damages

2.4.1. Delamination Factor and Burr Area Measurement

Maximum delamination and burr formation are observed at the exit side (push-down delamination) after the drilling operation; therefore, in the present work, surface area damages are analyzed at the exit hole as shown in Figure 3. Using the Nikon Stereo Zoom Microscope (SMZ745T series from Nishioi, Shinagawa-ku, Tokyo, Japan) (Figure 4), the drilled image was added to Image-J software, version 1.54r and by the proper selection of threshold, the outputs' delamination and burr area were measured. The delamination factor (F_d) was calculated using Equation (4), whereas the exit burr area (A_b) was calculated using Equation (5) [19,20].

$$\text{Delamination factor} = \frac{D_{\max}}{D_{\text{nom}}} \quad (4)$$

$$\text{Burr area} = A_{\text{nom}} - A_{\text{free}} \quad (5)$$

where $D_{\max}$ —maximum diameter of hole (mm)

D_{nom} —nominal hole diameter (mm)

A_{nom} —nominal hole area (mm²)

A_{free} —burr free area (mm²)

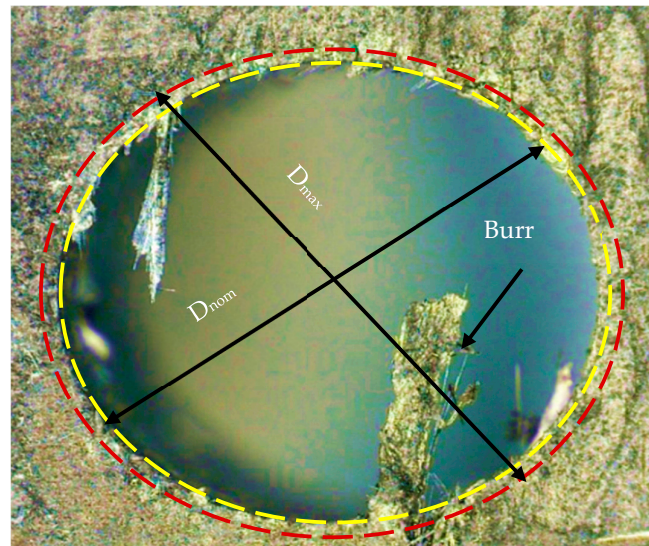


Figure 3. Optical microscope image of delamination and burr.



Figure 4. Stereo zoom microscope for delamination and burr measurement.

2.4.2. Measurement of Surface Roughness

The surface roughness (R_a) was measured using a Taylor–Hobson Surtronic 3+ instrument, as represented in Figure 5 below. The measurement was performed at six different locations in the transverse direction at 0.5 mm/s as the probe speed setting, for a length range of 4 mm.

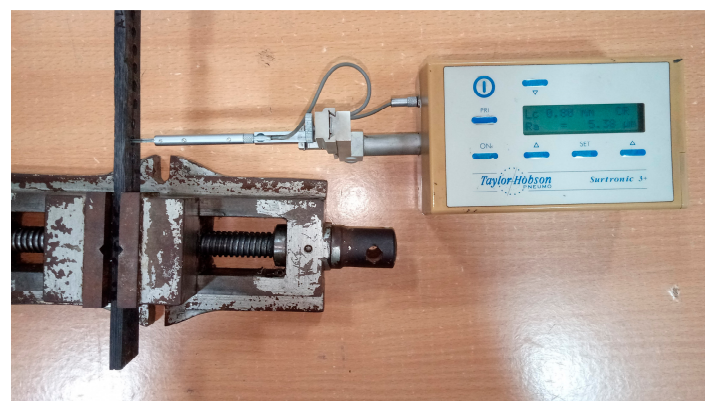


Figure 5. Taylor–Hobson Surtronic instrument for measuring surface roughness.

2.4.3. Output Hole Temperature

The output hole temperature was measured for hot drilling conditions using the infrared thermal gun. The measurement was performed at the inner side of the hole immediately after the tool's exit to capture the immediate temperature.

3. Results and Discussion

3.1. Thermogravimetric Analysis

TGA is a thermal analysis technique that investigates the change in weight of a substance when subjected to a constant heat flow rate, as a function of time or temperature. Absorption, adsorption, decomposition, oxidation, and reduction can be studied using this technique. In addition to the above thermal events, TGA is used for studying the kinetics of chemical reactions under various conditions [21]. Before conducting the drilling operation, thermogravimetric analysis (TGA) was performed to study the thermal stability of the composite, where above the glass transition temperature of the polymer matrix, fiber-reinforced composite materials tend to display extreme reduction in mechanical properties, consequently leading to the matrix reducing the distribution of forces to the fiber [22,23].

Figure 6 represents the thermal characteristics evaluated as per the conventional standards, for neat composite and hybrid nanocomposites with varying weight percent of Al_2O_3 and SiC nanoparticles [24].

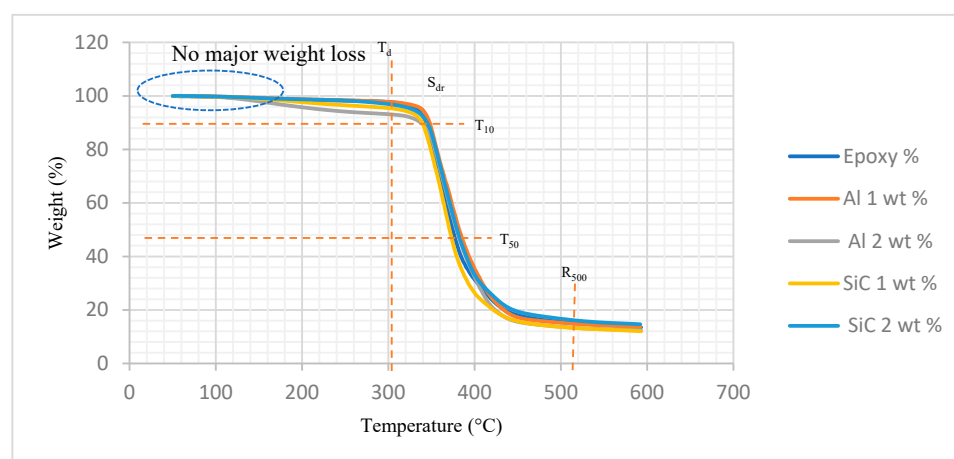


Figure 6. Thermal behavior of neat and hybrid nanocomposites.

In Table 3, as shown below, T_d signifies the decomposition initiating temperature at the mass loss of 2%; T_{10} is the temperature at 10% mass loss; similarly, T_{50} is the temperature corresponding to 50% of mass loss; S_{dr} is the threshold value of rapid decomposition taking place; R_{500} denotes residue mass remaining at a temperature of 500 °C.

Table 3. Thermal characteristics of samples studied at the temperature range of 50–600 °C.

Composite	T_d (°C)	T_{10} (°C)	T_{50} (°C)	S_{dr} (°C)	R_{500} (%)
Neat	150	333	356	346	15.521
Al_2O_3 1 wt%	283	343	374	345	13.732
Al_2O_3 2 wt%	285	347	382	349	15.223
SiC 1 wt%	188	338	371	340	13.622
SiC 2 wt%	265	344	332	350	16.702

From the above results, it can be clearly stated that the hybrid nanocomposites exhibit thermal stability, which is attributed to the formation of high cross-linked networks. From

the thermogram shown above, the epoxy nanocomposite is thermally stable in the temperature range from 50 °C to 260 °C. It can be observed that the significant weight loss is initiated at 340 °C temperature for neat epoxy, which is similar to the decomposition temperature reported by Grich et al. [25,26]. From the above results, it can be concluded that the nanoparticles have been dispersed uniformly, as there is a very slight deviation in terms of the rapid degradation of the polymer matrix with and without nanoparticles. This behavior can be attributed to the low nanoparticle loading levels (1–2 wt%), which are insufficient to significantly modify the intrinsic thermal degradation mechanism of the epoxy matrix. At these concentrations, Al₂O₃ and SiC nanoparticles primarily act as inert fillers, not substantially altering the cross-linked network degradation processes that govern epoxy decomposition. Similar observations have been reported in previous studies on ceramic nanoparticle-reinforced epoxy composites, where low filler contents resulted in negligible changes in thermal stability and decomposition temperatures [27,28]. With the addition of nanoparticles of Al₂O₃ and SiC, there is no major phase change up to 260 °C, proposing that the composites fabricated can be subjected to a temperature range from 0 °C to 100 °C, which is required for the drilling operation of neat and hybrid nanocomposites. The thermal stability observed from TGA is relevant to this study because hot drilling involves elevated temperatures that can affect matrix softening and fiber–matrix bonding.

3.2. Analysis of Delamination

3.2.1. Effect of Drilling Parameters and Drill Type on Delamination Factor

The delamination factor was evaluated by studying the effects of drill diameter, drill type, spindle speed, and feed on hot drilling conditions. It can be observed from the main effects plot (Figure 7) that the delamination factor rises with increasing spindle speed and drill diameter. The contribution of feed on delamination is almost constant/low for both hybrid and neat composites. This is because, as there is already a temperature increase due to the high contact surface area of the core with the composite, the additional heat applied from the heat gun further softens the matrix. As a result, the fibers cannot support the drilling force applied by the drill. Hence, for the core drill, the delamination factor is less compared to other drill types in hot conditions [29]. Similar results were obtained by Krishnaraj et al. [30] and Kumaran [31]. The main effect plots also show that by varying the spindle speed, the delamination factor can be reduced and feed can be set to an optimum range, i.e., 0.02 mm/rev. The lowest delamination factor was noted for the core drill at 4 mm drill diameter, lower spindle speed of 1500 rpm and moderate feed of 0.02 mm/rev, followed by step and twist drills.

ANOVA analysis for the delamination factor was determined as shown in Table 4. The complete regression equations corresponding to the developed models are provided in the Supplementary Materials (S1). From the analysis, it is noted that the drill diameter and drill type, followed by spindle speed, showed a prominent influence on delamination. The contribution of drill type showed 94.68%, 94.04%, and 94.03% for the delamination factor in hybrid (Al₂O₃, SiC) and neat composites, respectively. Additionally, the drill diameter contribution was 4.46, 5.07, and 5.02% for hybrid (Al₂O₃, SiC) and neat composites, respectively, whereas the contribution of spindle speed was 0.26, 0.32, and 0.38%. However, the feed affecting the delamination is less than 0.1%, respectively. This indicates that the feed has less influence on delamination and can be kept constant in the case of hot drilling conditions. Additionally, it can be observed from Table 4 that the adjusted R-squared value is very close to the R-squared value, and both are high (exceeding 99%). This signifies that the model is fitting the data extremely well. The dominance of drill type can be attributed to its strong influence on chip evacuation and thrust force generation during the drilling process. Compared with the conventional twist drill, step and core drills generate lower

thrust forces due to their reduced effective chisel edge length, which facilitates progressive material removal. In addition, drill diameter is the next significant factor influencing the output response (delamination), as larger diameters increase the tool–workpiece contact area, thereby enhancing friction. The increased contact area leads to higher thrust force and heat generation, which in turn aggravates surface damage.

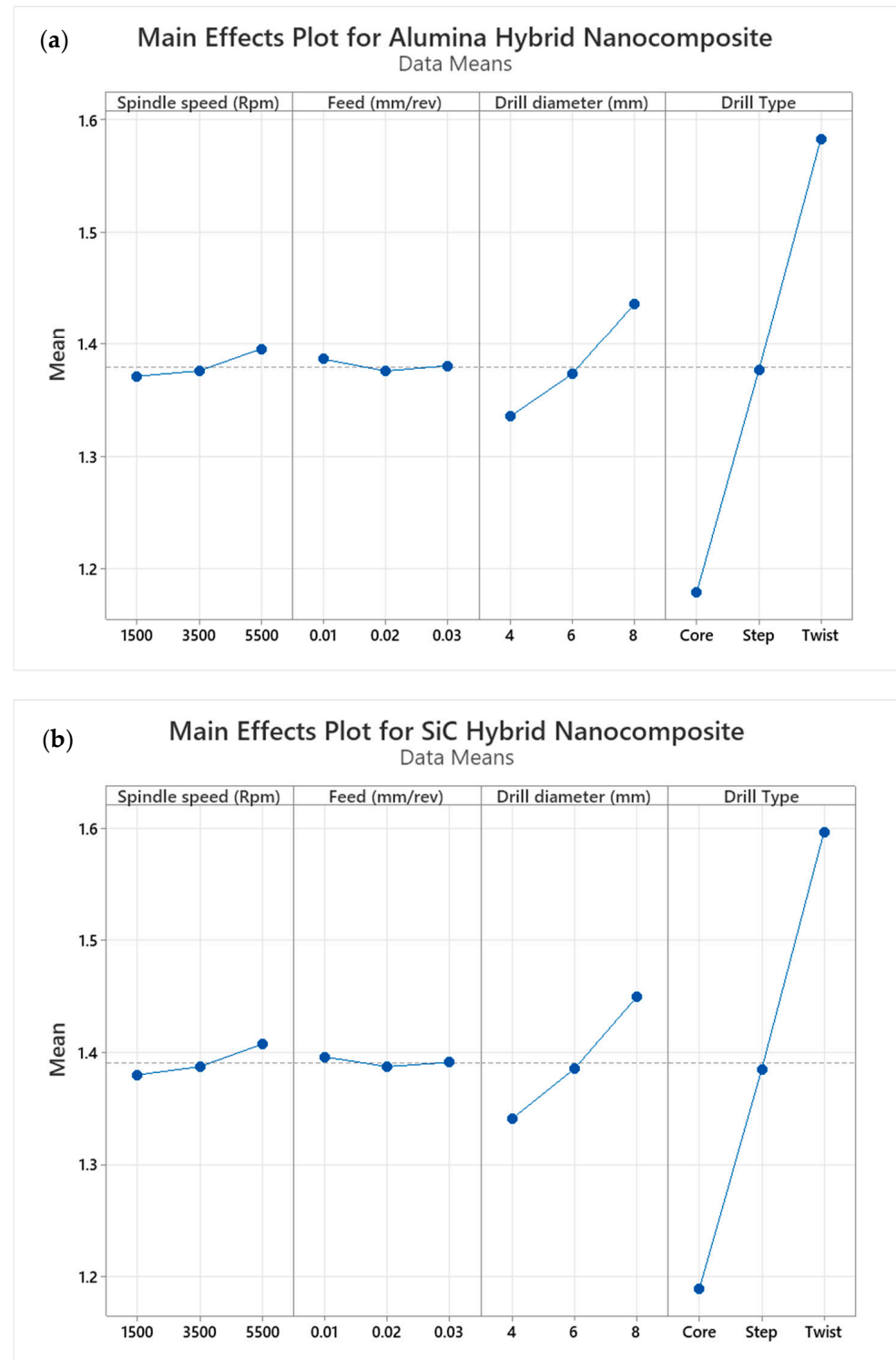


Figure 7. Cont.

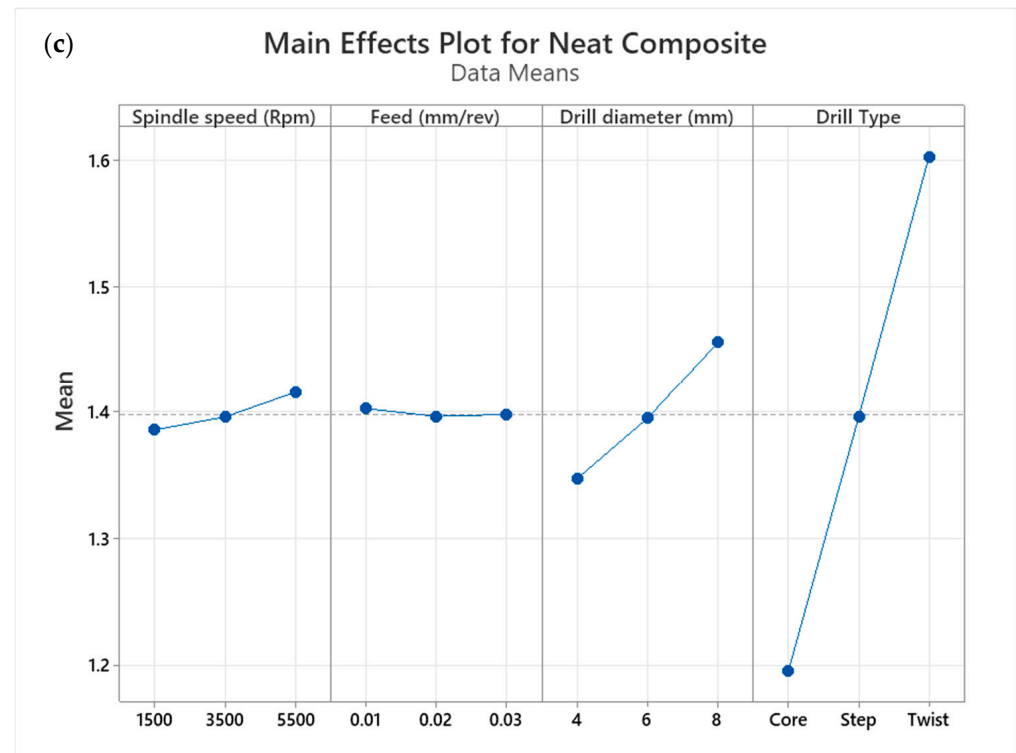


Figure 7. Main effect trends of delamination factor at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

Table 4. Analysis of Variance (ANOVA) results for the delamination factor.

Source	Al ₂ O ₃ Hybrid			SiC Hybrid			Neat		
	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution
Spindle Speed (rpm)	36.28	0.000	0.26%	35.85	0.000	0.32%	40.89	0.000	0.38%
Feed (mm/rev)	2.15	0.150	0.02%	1.17	0.286	0.01%	1.00	0.322	0.01%
Drill Dia (mm)	622.41	0.000	4.46%	571.56	0.000	5.07%	542.34	0.000	5.02%
Drill type	6613.41	0.000	94.68%	5304.90	0.000	94.04%	5083.65	0.000	94.03%
Square	6.45	0.001	0.14%	3.07	0.038	0.08%	1.34	0.276	0.04%
Spindle Speed (rpm) × Spindle Speed (rpm)	0.01	0.935	0.05%	0.02	0.879	0.03%	0.11	0.737	0.02%
Feed (mm/rev) × Feed (mm/rev)	0.00	0.963	0.01%	0.01	0.939	0.01%	0.02	0.881	0.00%
Drill Dia (mm) × Drill Dia (mm)	10.78	0.002	0.08%	4.44	0.041	0.04%	1.82	0.184	0.02%
Two-Way Interaction	2.28	0.035	0.15%	1.38	0.227	0.11%	1.67	0.126	0.14%
Spindle Speed (rpm) × Feed (mm/rev)	0.00	0.971	0.00%	0.00	0.987	0.00%	0.04	0.836	0.00%
Spindle Speed (rpm) × Drill Dia (mm)	0.16	0.688	0.00%	0.19	0.662	0.00%	0.25	0.623	0.00%
Spindle Speed (rpm) × Drill type	0.74	0.483	0.01%	0.10	0.902	0.00%	0.01	0.994	0.00%
Feed (mm/rev) × Drill Dia (mm)	0.66	0.423	0.00%	0.22	0.638	0.00%	0.57	0.456	0.01%
Feed (mm/rev) × Drill Type	0.11	0.893	0.00%	0.03	0.971	0.00%	0.24	0.788	0.00%
Drill Dia (mm) × Drill Type	9.01	0.001	0.13%	5.88	0.006	0.10%	6.85	0.003	0.13%
R-square	99.70			99.63			99.61		
Adjusted R-square	99.58			99.48			99.45		

F-value—Variance ratio; p-value—Smallest level of significance.

3.2.2. Analysis of the Delamination Factor Using Contour Plots

The contour plot for the delamination factor under hot drilling conditions is shown in Figure 8. The plot illustrates the interaction effects of spindle speed, feed rate, drill diameter

and drill type on delamination for the neat, Al_2O_3 , and SiC hybrid nanocomposites. From the contour map, it can be observed that higher spindle speeds, combined with larger drill diameters, lead to higher delamination values due to the increased thrust force acting on the heat-softened matrix. Regions corresponding to lower delamination are obtained at lower spindle speeds, moderate feed rates, and smaller drill diameters. This behavior is attributed to reduced thermal softening of the resin and lower thrust loading in these parameter zones. The core drill consistently exhibits lower delamination regions in the contour plot compared to step and twist drills under hot drilling. The pilot section of the core drill stabilizes the cutting zone and minimizes fiber push-out, which becomes increasingly important when the matrix softens under elevated temperature. The contour plot clearly highlights the parameter combinations that minimize delamination during hot drilling for hybrid and neat composites.

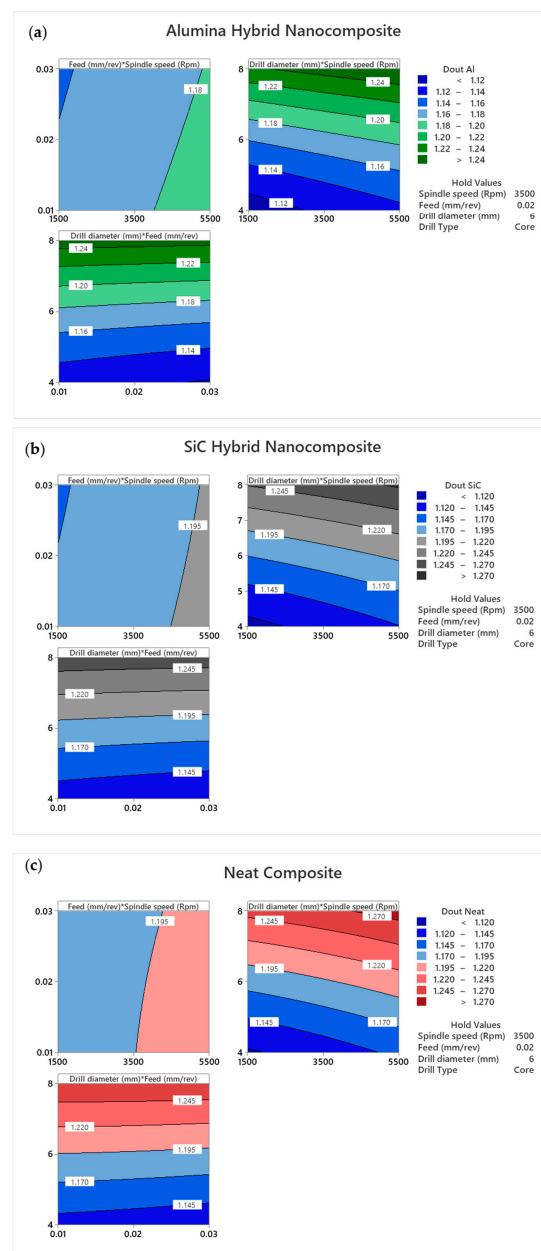


Figure 8. Contour plots of delamination factor at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

3.3. Analysis of Burr Area

3.3.1. Effect of Drilling Parameters and Drill Type on Burr Area

The main effects plot of different drilling parameters and drill type on burr formation are shown in Figure 9. It is noted that from Figure 9a–c, the burr area increases for both Al_2O_3 and SiC hybrid nanocomposites and neat composites, and the maximum burr occurs at higher spindle speed (3000 rpm), higher feed (0.03 mm/rev), and lower drill diameter (4 mm). This is due to the thermal softening of the matrix caused by the externally applied heat, which weakens the fiber–matrix interface and results in increased fiber breakout at the hole exit. The core drill exhibits lower burr compared to the twist and step drills under hot drilling because the pilot portion stabilizes the cutting zone and reduces fiber displacement during tool exit. The nanoparticles are found to reduce burr formation even under hot drilling conditions, as Al_2O_3 and SiC help in distributing heat at the tool–work interface and limit excessive thermal damage. The significance of each drilling parameter on burr formation under hot drilling is shown in Table 5. Among the composites, the Al_2O_3 hybrid nanocomposite recorded the lowest burr area, followed by the SiC hybrid, while the neat composite recorded the maximum burr area.

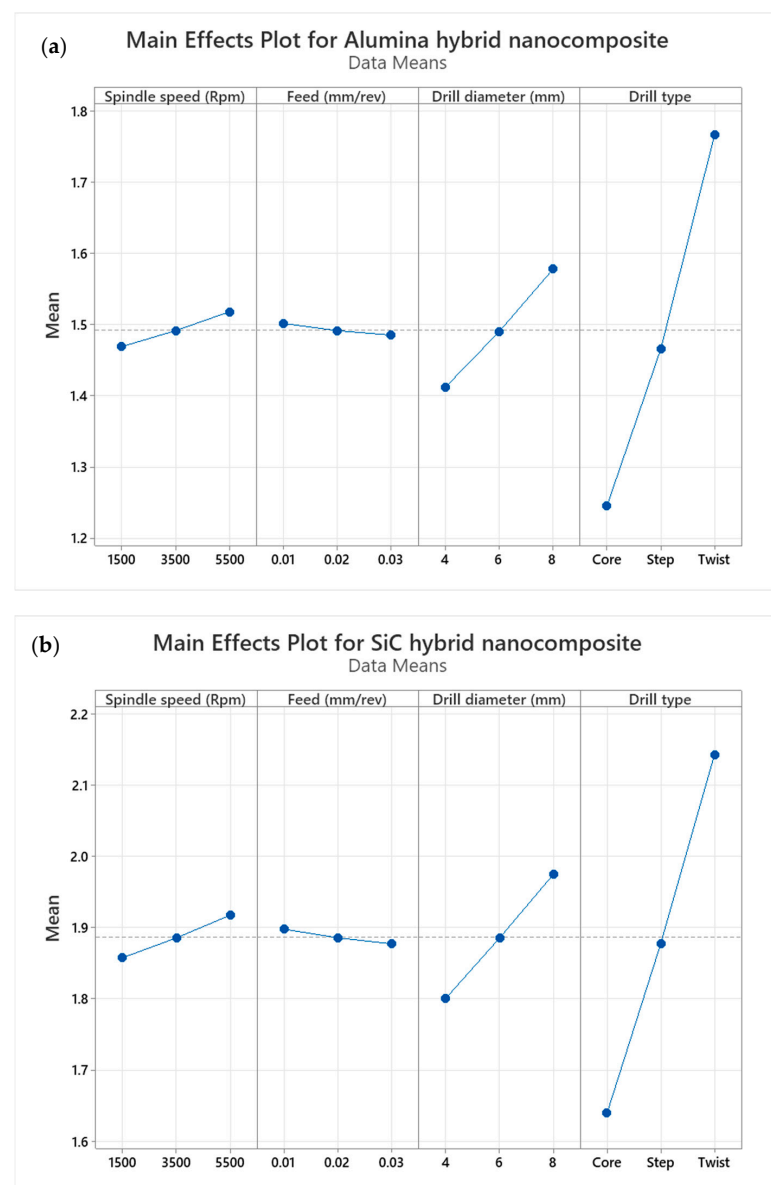


Figure 9. Cont.

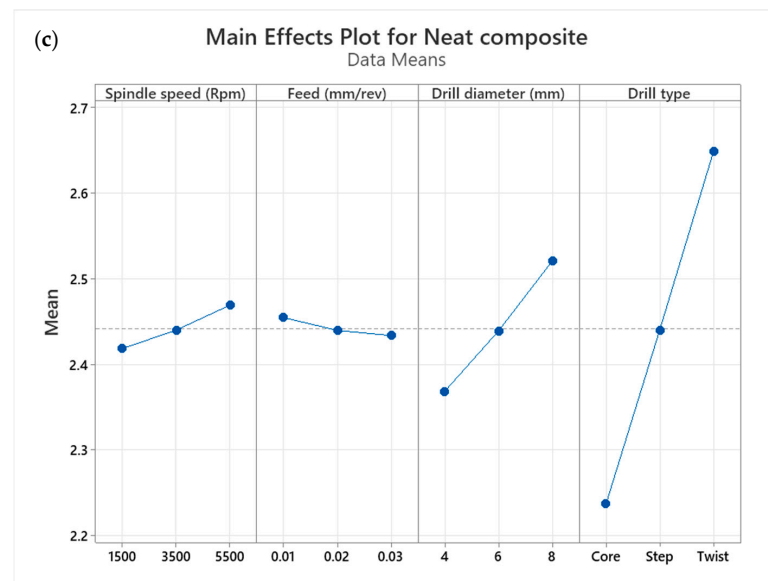


Figure 9. Main effect trends of burr area at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

Table 5. Analysis of Variance (ANOVA) results for the burr area.

Source	Al ₂ O ₃ Hybrid			SiC Hybrid			Neat		
	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution
Spindle Speed (rpm)	108.85	0.000	0.60%	325.46	0.000	0.96%	145.38	0.000	1.01%
Feed (mm/rev)	12.36	0.001	0.07%	39.30	0.000	0.12%	24.97	0.000	0.17%
Drill Dia (mm)	1261.19	0.000	6.96%	2759.27	0.000	8.10%	1312.98	0.000	9.15%
Drill type	8303.75	0.000	91.64%	15,437.72	0.000	90.66%	6405.66	0.000	89.24%
Square	0.75	0.531	0.01%	0.37	0.773	0.00%	1.24	0.307	0.03%
Spindle Speed (rpm) × Spindle Speed (rpm)	0.05	0.821	0.00%	0.06	0.808	0.00%	0.00	0.982	0.01%
Feed (mm/rev) × Feed (mm/rev)	0.05	0.821	0.00%	0.02	0.890	0.00%	0.19	0.666	0.01%
Drill Dia (mm) × Drill Dia (mm)	1.80	0.187	0.01%	0.26	0.613	0.00%	1.30	0.260	0.01%
Two-Way Interaction	9.85	0.000	0.49%	1.52	0.172	0.04%	1.69	0.123	0.11%
Spindle Speed (rpm) × Feed (mm/rev)	0.23	0.636	0.00%	0.06	0.805	0.00%	0.07	0.791	0.00%
Spindle Speed (rpm) × Drill Dia (mm)	1.54	0.221	0.01%	1.03	0.316	0.00%	1.17	0.285	0.01%
Spindle Speed (rpm) × Drill type	1.90	0.162	0.02%	3.03	0.059	0.02%	0.83	0.441	0.01%
Feed (mm/rev) × Drill Dia (mm)	0.41	0.528	0.00%	0.06	0.805	0.00%	0.30	0.585	0.00%
Feed (mm/rev) × Drill Type	2.34	0.109	0.03%	0.31	0.739	0.00%	0.44	0.644	0.01%
Drill Dia (mm) × Drill Type	39.02	0.000	0.43%	2.93	0.064	0.02%	5.54	0.007	0.08%
R-square		99.77			99.88			99.71	
Adjusted R-square		99.67			99.82			99.59	

F-value—Variance ratio; p-value—Smallest level of significance.

3.3.2. Analysis of the Burr Area Using Contour Plots

The contour plots for hot drilling conditions are illustrated, showing the combined effects of feed rate, spindle speed, drill diameter, and drill type on burr. From Figure 10a–c, it is seen that the burr area rises with increasing feed and spindle speed due to enhanced thermal softening of the matrix. Higher temperatures weaken the fiber–matrix interface, resulting in fiber breakout and larger burr formation. Regions corresponding to lower burr area appear at lower spindle speeds, moderate feed rates, and smaller drill diameters. The core drill consistently shows lower burr formation compared to twist and step drills under

hot drilling conditions due to better stabilization of the cutting zone. These contour plots clearly identify the parameter ranges that minimize burr formation during hot drilling for neat and hybrid nanocomposites.

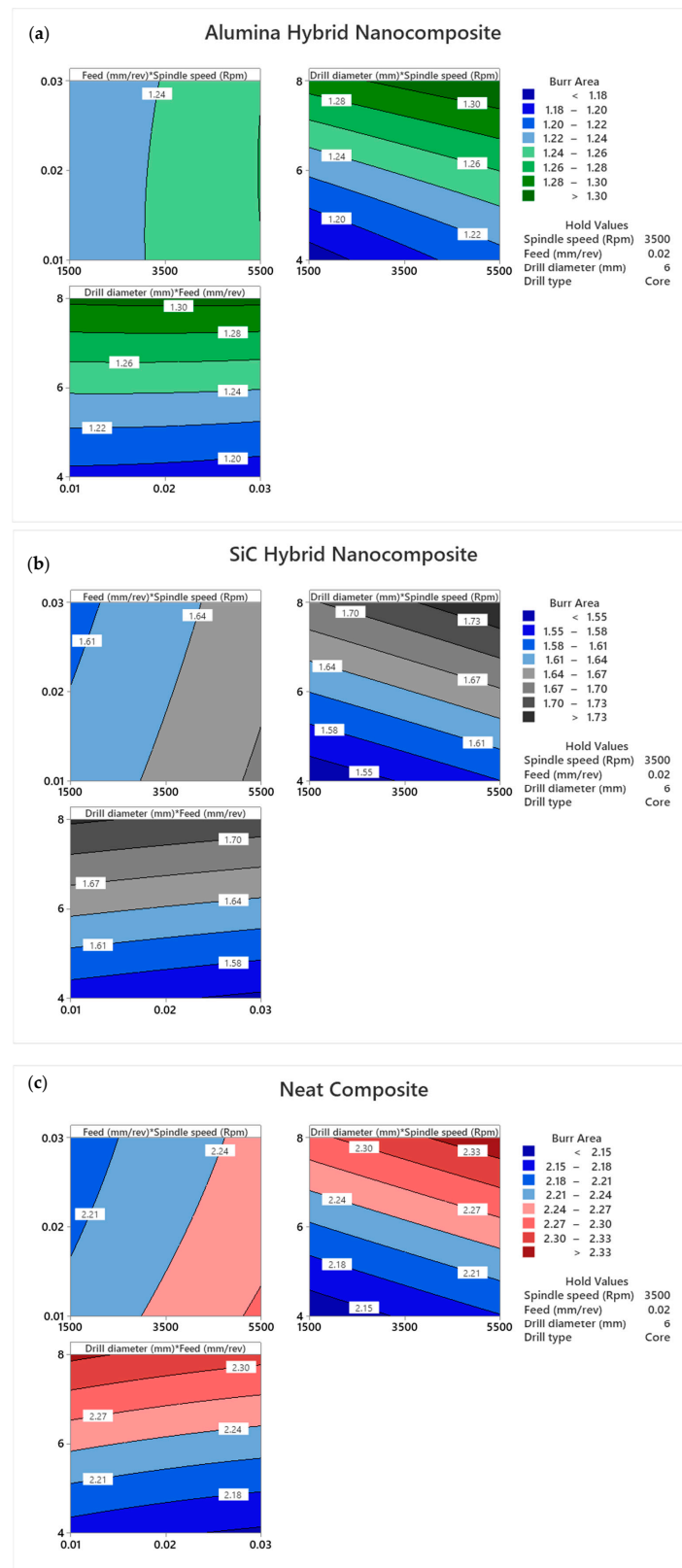


Figure 10. Contour plots of burr area at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

3.4. Analysis of Surface Roughness

3.4.1. Effect of Drilling Parameters and Drill Type on Surface Roughness

Surface roughness is one of the key parameters that determines the quality of drilled holes in composite laminates. It is primarily influenced by drilling parameters, tool geometry, and the cutting forces produced during drilling.

The effect of drilling parameters is represented below by a main effects plot for hybrid nanocomposites and neat composites, as shown in Figure 11. It can be seen that (Figure 11a–c), the surface roughness increases with increasing spindle speed and feed. Surface roughness decreases with increasing drill diameter due to reduced thrust loading and improved chip evacuation. The lowest surface roughness is found for the core drill as compared to the step and twist drill. The statistical significance of the drilling parameters on surface roughness under hot drilling is shown in Table 6. From Table 6, the contribution of drill type on surface roughness is 89.60, 90.79, 91.51% for hybrid Al_2O_3 , SiC and neat CFRP composites.

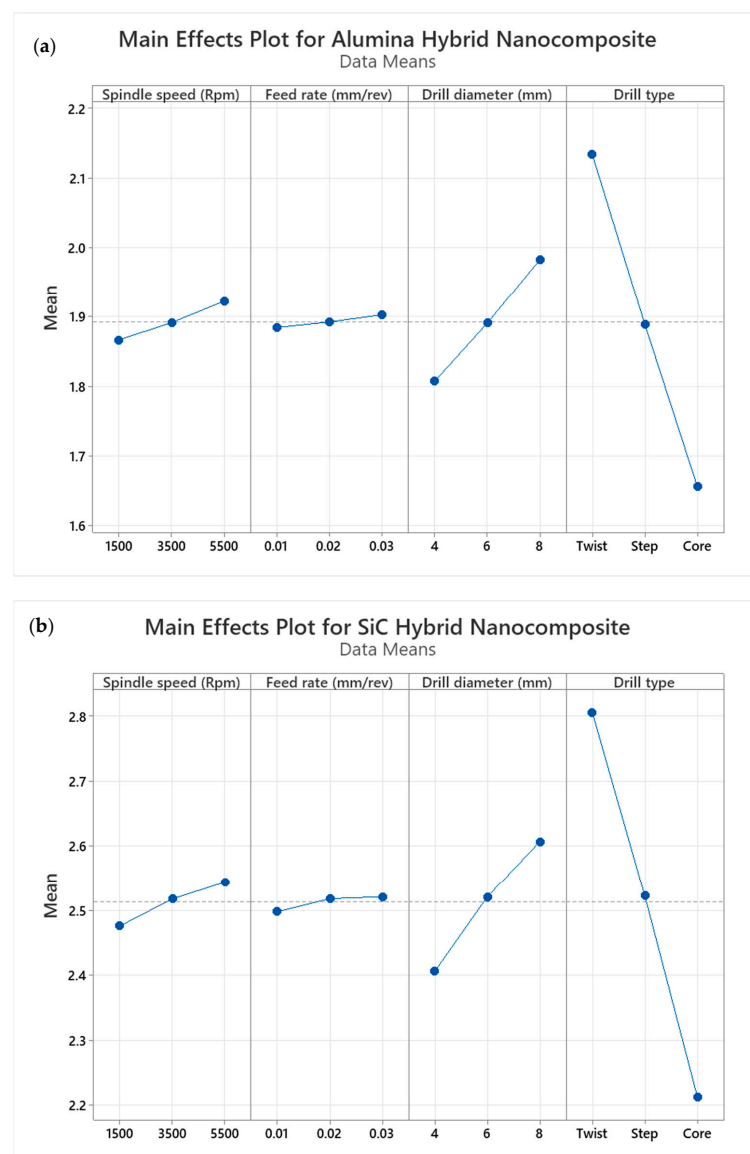


Figure 11. Cont.

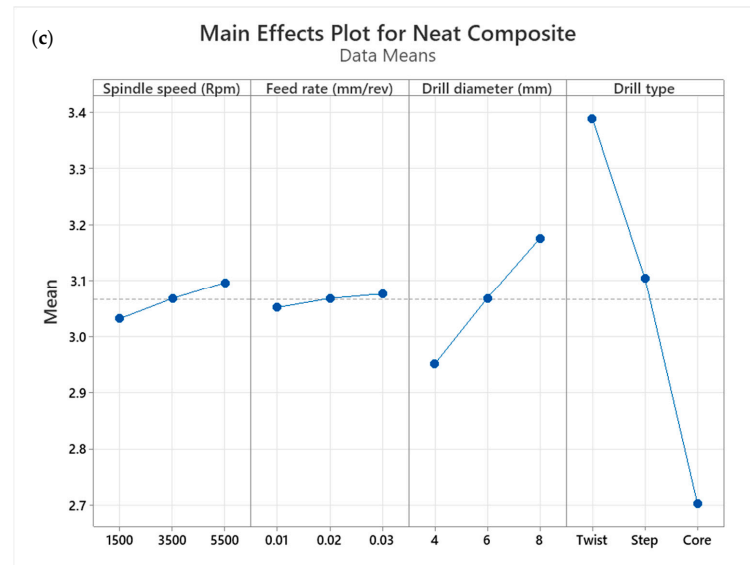


Figure 11. Main effect trends of surface roughness at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

Table 6. Analysis of Variance (ANOVA) results for the surface roughness.

Source	Al_2O_3 Hybrid			SiC Hybrid			Neat		
	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution
Spindle Speed (rpm)	227.17	0.000	0.91%	283.39	0.000	0.89%	171.89	0.000	0.61%
Feed (mm/rev)	25.00	0.000	0.10%	32.86	0.000	0.10%	24.27	0.000	0.09%
Drill Dia (mm)	2250.25	0.000	9.06%	2477.63	0.000	7.82%	2058.99	0.000	7.30%
Drill type	11,129.27	0.000	89.60%	14,390.78	0.000	90.79%	12,907.12	0.000	91.51%
Square	1.07	0.373	0.01%	8.72	0.000	0.08%	0.70	0.559	0.01%
Spindle Speed (rpm) × Spindle Speed (rpm)	0.22	0.642	0.01%	0.09	0.763	0.03%	0.02	0.898	0.00%
Feed (mm/rev) × Feed (mm/rev)	0.58	0.451	0.00%	0.00	0.966	0.01%	0.07	0.789	0.00%
Drill Dia (mm) × Drill Dia (mm)	1.87	0.179	0.01%	15.54	0.000	0.05%	0.64	0.429	0.00%
Two-Way Interaction	4.15	0.001	0.15%	6.28	0.000	0.18%	10.50	0.000	0.34%
Spindle Speed (rpm) × Feed (mm/rev)	0.15	0.703	0.00%	0.10	0.755	0.00%	0.29	0.591	0.00%
Spindle Speed (rpm) × Drill Dia (mm)	1.72	0.197	0.01%	5.33	0.026	0.02%	0.01	0.905	0.00%
Spindle Speed (rpm) × Drill type	1.61	0.211	0.01%	3.13	0.054	0.02%	1.41	0.255	0.01%
Feed (mm/rev) × Drill Dia (mm)	0.05	0.825	0.00%	1.03	0.316	0.00%	0.48	0.493	0.00%
Feed (mm/rev) × Drill Type	0.07	0.928	0.00%	1.41	0.257	0.01%	0.33	0.722	0.00%
Drill Dia (mm) × Drill Type	16.01	0.000	0.13%	20.49	0.000	0.13%	45.14	0.000	0.32%
R-square		99.83			99.87			99.82	
Adjusted R-square		99.76			99.78			99.74	

F-value—Variance ratio; p-value—Smallest level of significance.

3.4.2. Analysis of the Surface Roughness Using Contour Plots

Similar to the above contour plots, the contour plots were created for surface roughness under various thermal conditions for hybrid nanocomposites and the neat composite (Figure 12). Under hot drilling conditions (Figure 12a), Al_2O_3 hybrid nanocomposites exhibit superior surface finish at feed below 0.02 mm/rev, spindle speeds under 3500 rpm, and a 4 mm drill diameter. In SiC hybrid nanocomposites (Figure 12b), an improved surface finish is observed with drill diameter of 4 mm, 3000 rpm spindle speed, and a feed below 0.015 mm/rev, whereas for neat composite (Figure 12c), minimizing surface

roughness requires a drill diameter (4 mm), spindle speeds of 2000 rpm, and a feed less than 0.03 mm/rev.

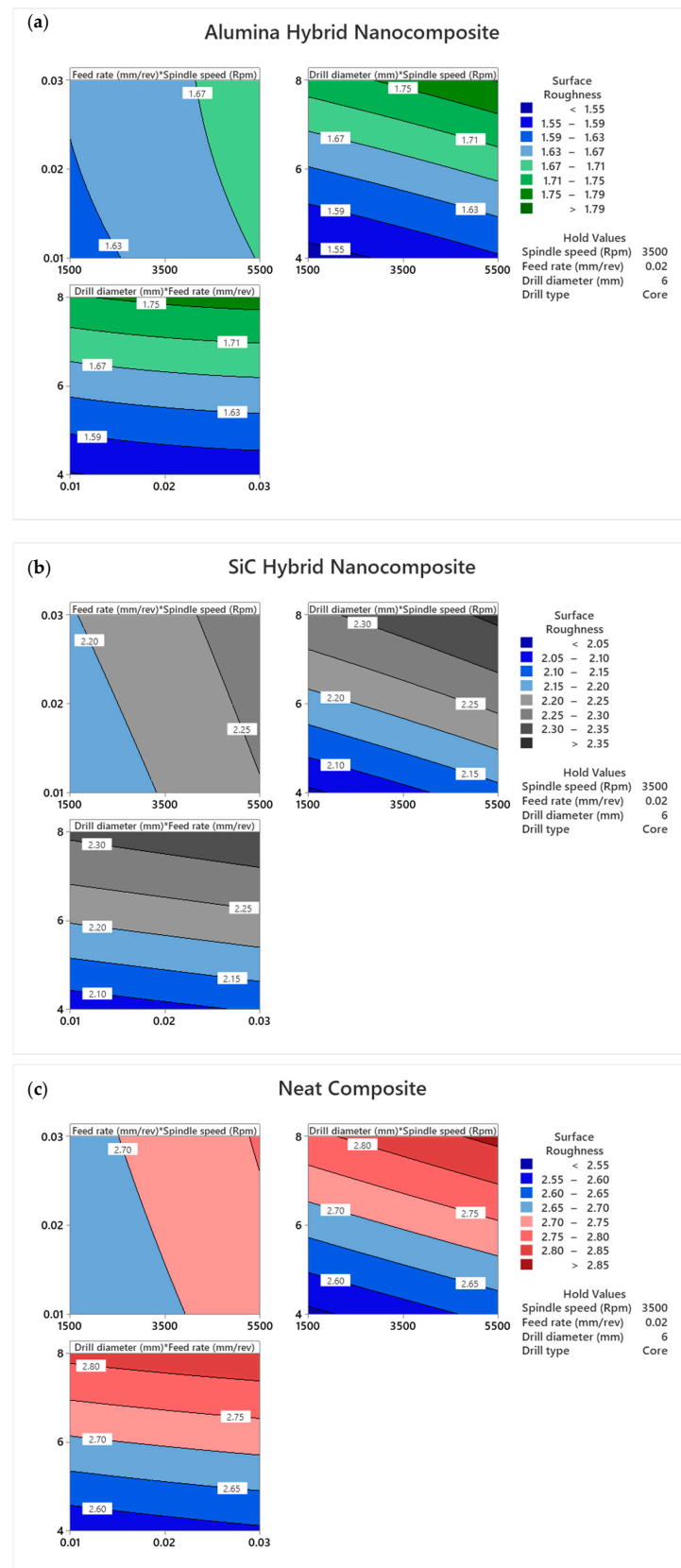


Figure 12. Contour plots of surface roughness at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

3.5. Analysis of Hole Temperature

3.5.1. Effect of Drilling Parameters and Drill Type on Hole Temperature

Similar to the above output factors, the main effects plot (Figure 13a–c) was plotted to determine the effect of drilling parameters and drill type on output hole temperature. The main effects plot shows that hole temperature maximizes with spindle speed, feed rate, and drill diameter. Also, the externally applied heat combined with mechanical friction results in a higher temperature rise as these parameters increase. Among the drill geometries, the core drill produces the lowest hole temperature, followed by the step drill and twist drill, due to its improved chip evacuation and stabilized cutting action.

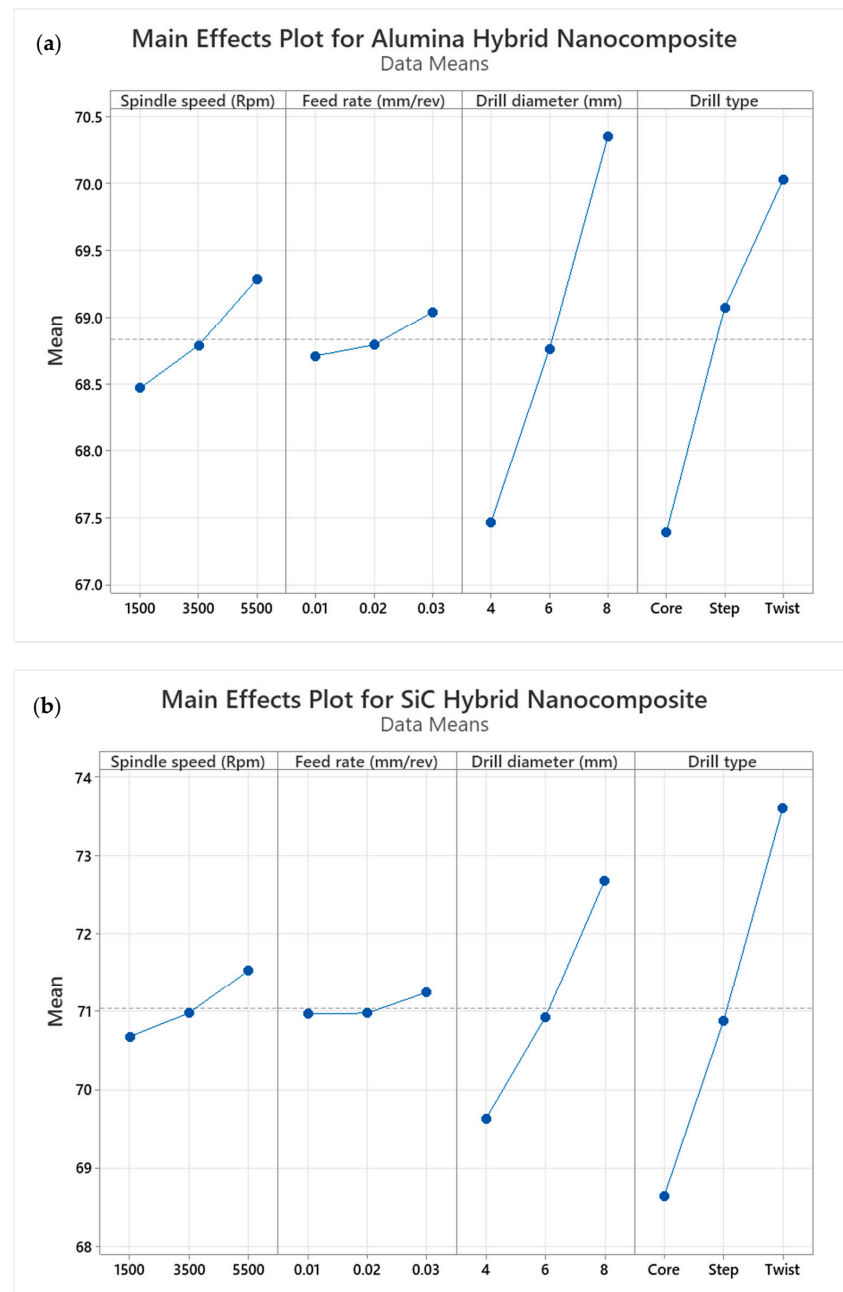


Figure 13. Cont.

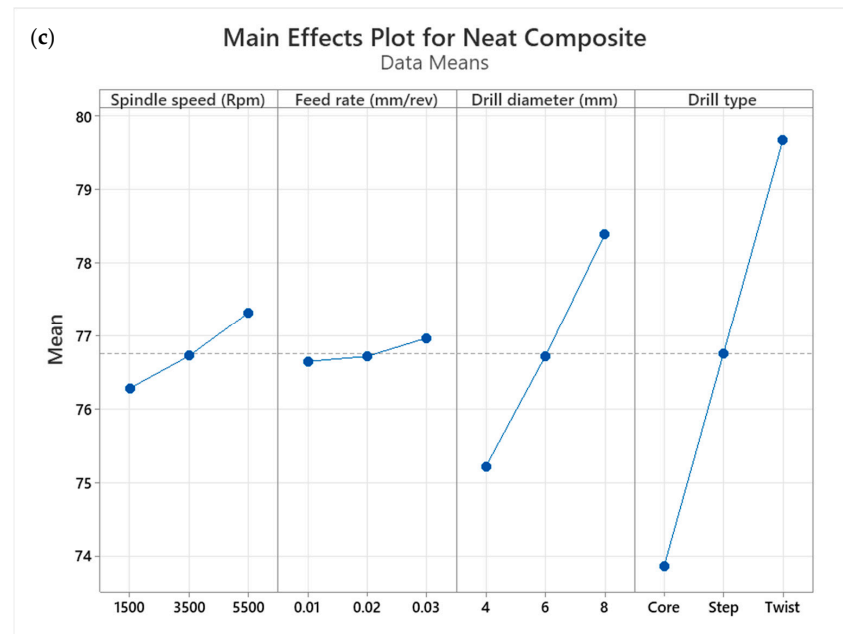


Figure 13. Main effect trends of hole temperature at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

The ANOVA results presented in Table 7 indicate that drill type contributes the most to hole temperature, with contributions of 50.45%, 75.19%, and 78.94% for Al_2O_3 , SiC, and neat composites, respectively. Drill diameter is the next major contributing factor, with 43.91%, 21.25%, and 17.59% contributions. The contribution of spindle speed is comparatively small (3.56%, 1.66%, and 1.90%), and feed rate contributes less than 1% for all materials. These results confirm that drill type and drill diameter are the dominant parameters influencing temperature rise under hot drilling conditions. The spindle speed contribution is 3.56, 1.66 and 1.90%, respectively for hybrid and neat composites. The feed contribution towards the hole temperature is noted to be less than 1%, respectively.

Table 7. Analysis of Variance (ANOVA) results for the hole temperature.

Source	Al_2O_3 Hybrid			SiC Hybrid			Neat		
	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution
Spindle Speed (rpm)	171.90	0.000	3.56%	187.53	0.000	1.66%	284.90	0.000	1.90%
Feed (mm/rev)	28.41	0.000	0.59%	19.24	0.000	0.17%	26.97	0.000	0.18%
Drill Dia (mm)	2120.52	0.000	43.91%	2400.99	0.000	21.25%	2641.38	0.000	17.59%
Drill type	1218.16	0.000	50.45%	4247.01	0.000	75.19%	5927.74	0.000	78.94%
Square	3.85	0.016	0.24%	9.14	0.000	0.24%	1.70	0.181	0.03%
Spindle Speed (rpm) × Spindle Speed (rpm)	0.01	0.940	0.09%	0.13	0.723	0.07%	0.13	0.720	0.02%
Feed (mm/rev) × Feed (mm/rev)	0.04	0.840	0.01%	0.01	0.939	0.02%	0.86	0.358	0.01%
Drill Dia (mm) × Drill Dia (mm)	6.72	0.013	0.14%	17.07	0.000	0.15%	0.42	0.523	0.00%
Two-Way Interaction	2.05	0.057	0.38%	14.02	0.000	1.12%	17.99	0.000	1.08%
Spindle Speed (rpm) × Feed (mm/rev)	0.51	0.479	0.01%	0.52	0.477	0.00%	0.37	0.549	0.00%
Spindle Speed (rpm) × Drill Dia (mm)	9.60	0.003	0.20%	0.00	1.000	0.00%	20.03	0.000	0.13%
Spindle Speed (rpm) × Drill type	1.94	0.156	0.08%	3.10	0.055	0.05%	6.74	0.003	0.09%

Table 7. Cont.

Source	Al ₂ O ₃ Hybrid			SiC Hybrid			Neat		
	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution	F-Value	p-Value	Contribution
Feed (mm/rev) × Drill Dia (mm)	0.51	0.479	0.01%	0.06	0.812	0.00%	1.77	0.190	0.01%
Feed (mm/rev) × Drill Type	0.73	0.489	0.03%	0.18	0.833	0.00%	0.11	0.900	0.00%
Drill Dia (mm) × Drill Type	1.26	0.294	0.05%	59.52	0.000	1.05%	63.02	0.000	0.84%
R-square		99.13			99.63			99.72	
Adjusted R-square		98.78			99.48			99.61	

F-value—Variance ratio; p-value—Smallest level of significance.

3.5.2. Analysis of the Hole Temperature Using Contour Plots

Contour plots were generated to assess the influence of spindle speed, feed rate, and drill diameter on hole temperature for hybrid nanocomposites and the neat composite (Figure 14a–c). For Al₂O₃ hybrid nanocomposites (Figure 14a), minimum hole temperatures were achieved at spindle speed (less than 5000 rpm), feed rates below 0.03 mm/rev, and drill diameter of 4 mm, whereas SiC hybrid nanocomposites (Figure 14b) exhibited reduced temperature at spindle speed (less than 3500 rpm), feed rates at lower than 0.02 mm/rev, and at drill diameter (4 mm). For the neat composite (Figure 14c), minimal hole temperatures were detected at spindle speed (lower than 1500 rpm), a feed rate less than 0.03 mm/rev, and a drill diameter of 4 mm. These contour plots clearly indicate that the use of moderate feed rate, lower spindle speed, and larger drill diameter helps reduce the hole temperature under hot drilling conditions.

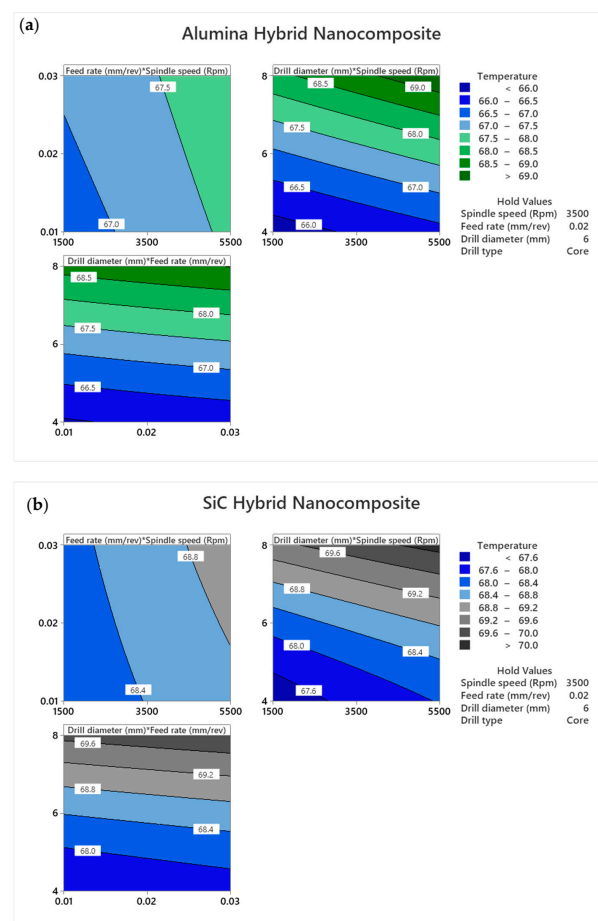


Figure 14. Cont.

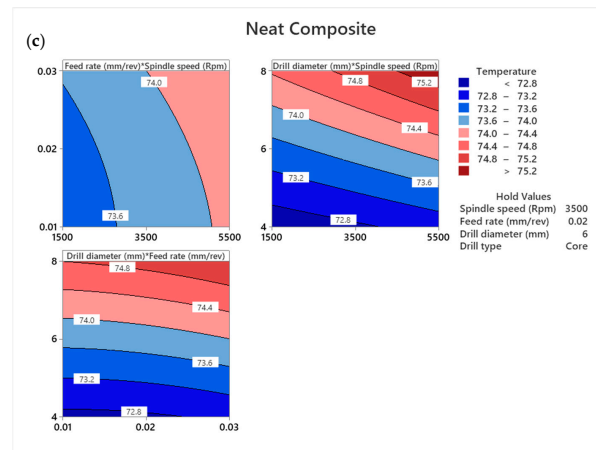


Figure 14. Contour plots of hole temperature at hot drilling condition for (a) Al_2O_3 hybrid, (b) SiC hybrid, (c) neat composite.

3.6. Optimization of Process Parameters

The primary objective of optimization is to determine a combination of process parameters that results in the most desirable output response values. This is achieved using the desirability function in RSM, which converts multiple responses into a single composite desirability value. In the case of the delamination factor, the optimum parameter settings for the hot drilling condition are obtained from Figure 15. The optimized combination of feed, drill diameter, spindle speed, and drill type gives the desirability value corresponding to minimum delamination. For the burr area, the optimum parameter settings for hot drilling conditions are shown in Figure 16. These parameters minimize the burr formation for the hybrid and neat composite. Similarly, for surface roughness, the optimization plot (Figure 17) gives the optimum feed, drill diameter, spindle speed, and drill type that minimize the value of surface roughness for all three composites. For hole temperature, the optimization plot under hot drilling condition (Figure 18) shows the optimum parameters that result in minimum hole temperature values. The optimization results confirm that for hot drilling, the selected parameter combinations effectively minimize surface roughness, and hole temperature, delamination and burr area for neat and hybrid nanocomposites.

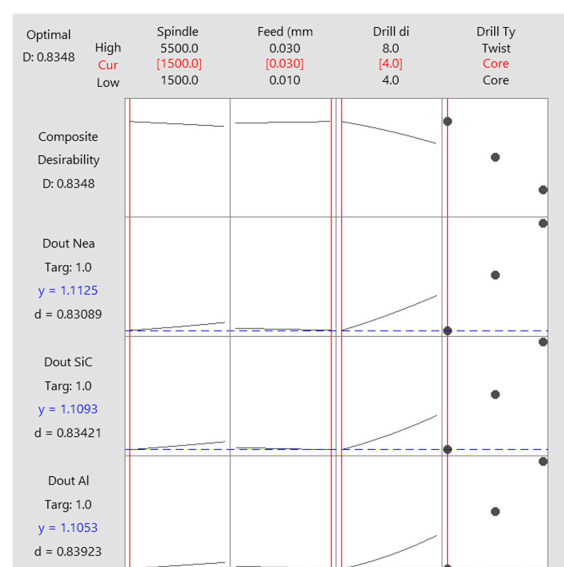


Figure 15. Optimization plot of delamination factor.

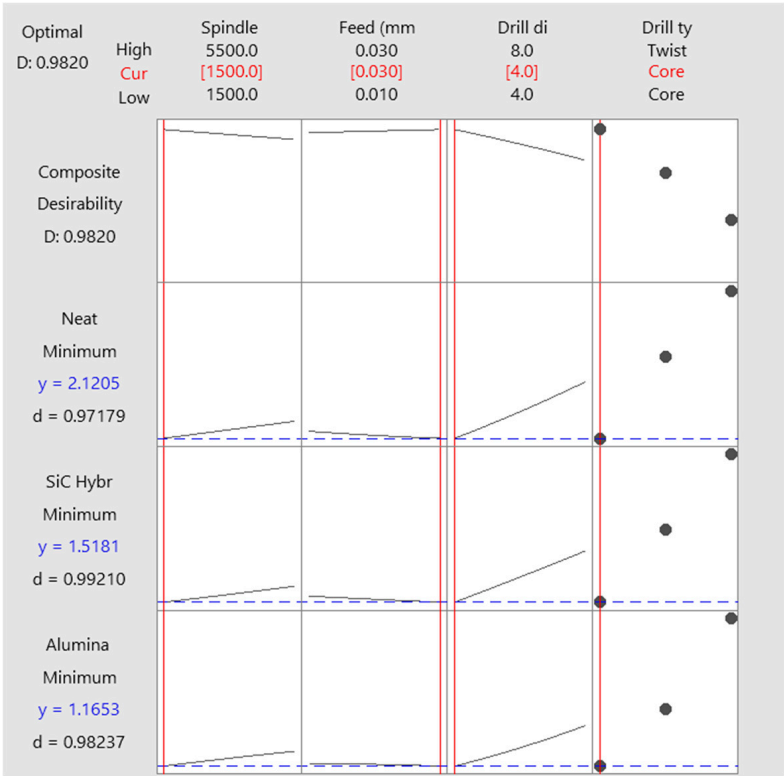


Figure 16. Optimization plot of burr area.

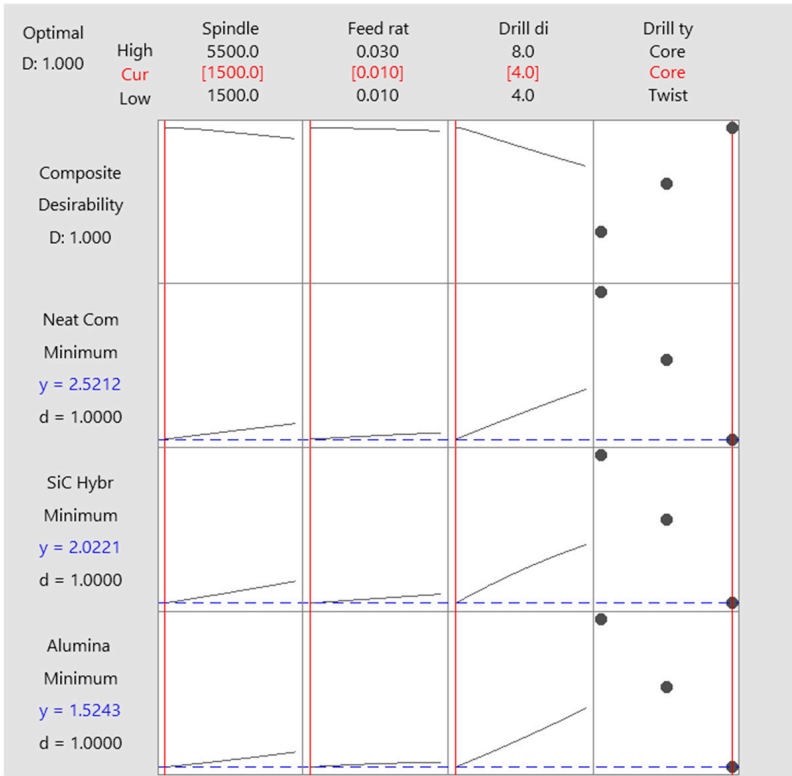


Figure 17. Optimization plot of surface roughness.

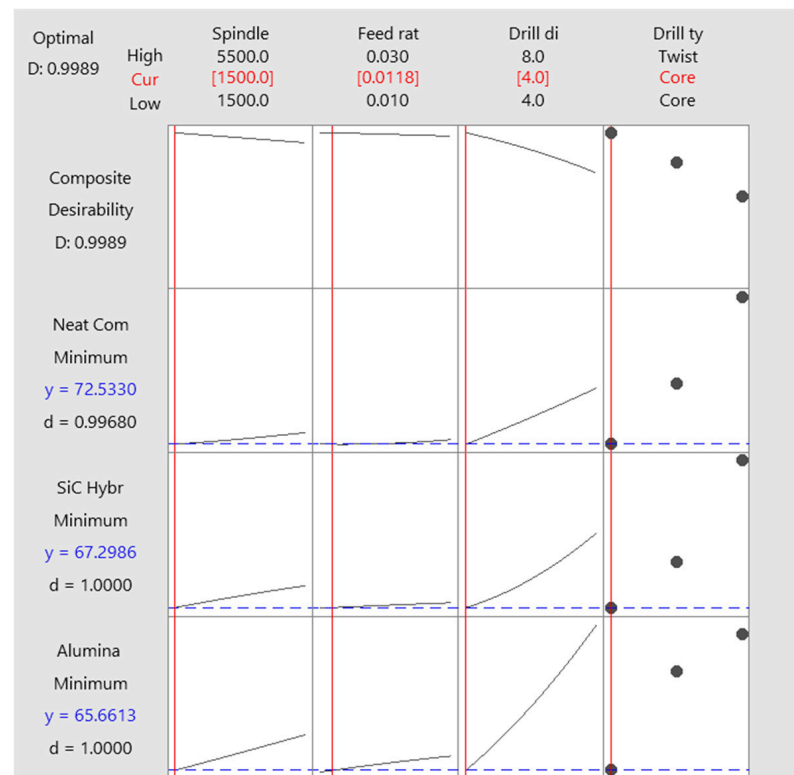


Figure 18. Optimization plot of hole temperature.

3.7. Test Validation

The test validation was performed to determine the appropriateness of the developed regressions models from RSM. The different sets of input process parameters as shown in Table 8 were selected, which were not used in performing the experiment before, but they fall within the defined range of experiments. The test validation was conducted to evaluate the accuracy and predictive capability of the RSM model under hot drilling conditions. The experimental results were compared with the model-predicted values for burr area, surface roughness, delamination factor, and hole temperature for Al_2O_3 hybrid nanocomposite, SiC hybrid nanocomposite, and neat composite.

Table 8. Process parameters adopted for validation trial.

Experiment No.	Spindle Speed (rpm)	Feed (mm/rev)	Drill Diameter (mm)	Drill Type
1	1500	0.02	4	Twist
2	5500	0.03	6	Step
3	1500	0.01	8	Core

The validation results are presented in Tables 9–11. The percentage error between the experimental and predicted values was found to be minimal for all responses, demonstrating that the developed regression models are reliable and capable of accurately predicting performance under hot drilling conditions. The test validation confirms that the optimized parameters obtained from the desirability analysis are effective in minimizing burr formation, delamination, surface roughness, and hole temperature during hot drilling of neat and hybrid nanocomposites.

Table 9. Test validation results for Al₂O₃ hybrid nanocomposite.

Optimum Input Process Parameters				Composite Type	Experimental Value	RSM Predicted Value	Error (%)
SS (rpm)	F (mm/rev)	DD (mm)	D				
1500	0.02	4	Twist	Delamination factor	1.527	1.432	6.22
				Burr area (mm ²)	1.629	1.585	2.70
				Surface roughness (μm)	2.022	2.121	4.90
				Hole temperature (°C)	68.2	65.3	4.25
5500	0.03	6	Step	Delamination factor	1.389	1.348	2.95
				Burr area (mm ²)	1.481	1.391	6.08
				Surface roughness (μm)	1.917	1.715	10.54
				Hole temperature (°C)	69.4	67.3	3.03
1500	0.01	8	Core	Delamination factor	1.242	1.163	6.36
				Burr area (mm ²)	1.288	1.223	5.05
				Surface roughness (μm)	1.721	1.632	5.17
				Hole temperature (°C)	68.6	67.3	1.90

SS—Spindle speed; F—Feed; DD—Drill diameter; D—Drill type.

Table 10. Test validation results for SiC hybrid nanocomposite.

Optimum Input Process Parameters				Composite Type	Experimental Value	RSM Predicted Value	Error (%)
SS (rpm)	F (mm/rev)	DD (mm)	D				
1500	0.02	4	Twist	Delamination factor	1.537	1.489	3.12
				Burr area (mm ²)	2.014	2.105	4.52
				Surface roughness (μm)	2.670	2.513	5.88
				Hole temperature (°C)	71.6	70.5	1.54
5500	0.03	6	Step	Delamination factor	1.397	1.346	3.65
				Burr area (mm ²)	1.868	1.745	6.58
				Surface roughness (μm)	2.572	2.416	6.07
				Hole temperature (°C)	71.5	70.3	1.68
1500	0.01	8	Core	Delamination factor	1.252	1.236	1.28
				Burr area (mm ²)	1.700	1.725	1.47
				Surface roughness (μm)	2.277	2.263	0.61
				Hole temperature (°C)	69.4	65.2	6.05

SS—Spindle speed; F—Feed; DD—Drill diameter; D—Drill type.

Table 11. Test validation results performed for neat composite.

Optimum Input Process Parameters				Composite Type	Experimental Value	RSM Predicted Value	Error (%)
SS (rpm)	F (mm/rev)	DD (mm)	D				
1500	0.02	4	Twist	Delamination factor	1.541	1.446	6.16
				Burr area (mm ²)	2.552	2.342	8.23
				Surface roughness (μm)	3.281	2.298	8.20
				Hole temperature (°C)	77.3	76.4	1.16
5500	0.03	6	Step	Delamination factor	1.402	1.416	1.00
				Burr area (mm ²)	2.466	2.345	4.91
				Surface roughness (μm)	3.158	3.002	4.94
				Hole temperature (°C)	74.5	73.6	1.21
1500	0.01	8	Core	Delamination factor	1.254	1.345	7.26
				Burr area (mm ²)	2.311	2.123	8.14
				Surface roughness (μm)	2.776	2.712	2.31
				Hole temperature (°C)	74.6	74.3	0.40

SS—Spindle speed; F—Feed; DD—Drill diameter; D—Drill type.

4. Conclusions

In the present work, the hot drilling behavior of UD-CFRP laminates reinforced with Al₂O₃ and SiC nanoparticles was investigated by analyzing burr formation, delamination, surface roughness, and temperature rise at the drilled hole. The results demonstrate that nanoparticle-reinforced composites exhibit improved thermal stability compared to neat CFRP, leading to reduced matrix softening and lower drilling-induced damage

under hot drilling conditions. Among the machining parameters studied, drill geometry and drill diameter were identified as the most influential factors affecting hole quality, whereas spindle speed and feed rate showed comparatively lower contributions. Core drills generally produced lower damage levels due to their favorable geometry, which reduced fiber pull-out and ensured more stable cutting at elevated temperatures. ANOVA confirmed the statistical significance of these parameters for all material systems. Furthermore, RSM-based optimization successfully identified optimal drilling conditions, and validation experiments showed good agreement between predicted and experimental results. Overall, the findings confirm that hot drilling, combined with appropriate drill geometry and optimized parameters, can significantly improve hole quality in nanoparticle-reinforced CFRP laminates, highlighting its potential for applications requiring controlled thermal input and reduced drilling-induced damage.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/sci8020038/s1>.

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Conflicts of Interest: The authors declare no conflicts of interest.

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