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Analysis of Machining Parameters Influencing Thrust Force in Drilling of Carbon Dot Nanoparticle-Reinforced Epoxy Matrix Composites

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Abstract: Epoxy matrix composites reinforced with carbon dot nanoparticles are increasingly utilized in industries due to their enhanced mechanical, thermal, and electrical properties. Drilling, a critical machining process for assembling these composites, often induces defects, such as delamination and stress concentrations, that impact structural integrity. Unlike prior studies that primarily focused on surface quality or delamination in conventional composites, this work systematically investigates the thrust force response in nanomodified epoxy composites reinforced with carbon dot nanoparticles. A full factorial design of experiments was employed, with thrust forces measured using a high-precision load cell. Statistical analysis revealed that drill bit diameter is the dominant factor, contributing 66.18% to thrust force variation, followed by spindle speed (19.90%) and feed rate (7.16%). The regression model, with an R-squared value of 98.90%, captured significant linear and nonlinear parameter interactions. Increasing feed rate and tool diameter elevated drilling forces, while higher spindle speeds slightly reduced them. The incorporation of carbon dots up to 1 wt.% reduced thrust force by enhancing interfacial bonding, although excessive concentrations led to embrittlement. Optimization results identified ideal drilling conditions—spindle speed of 2500 rpm, feed rate of 10 mm/min, drill bit diameter of 0.3 mm, and 1 wt.% carbon dots—achieving a minimum thrust force of 0.0639 N.

Keywords: Carbon-Dot Nanoparticle, Drilling, Statistical Analysis, Optimization, Thrust Force

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Research paper

1 INTRODUCTION

Nanotechnology refers to the manipulation and utilization of materials at the nanometer scale (1–100 nm), where their physical and chemical properties may significantly differ from those observed at larger scales [1]. This field has found extensive applications across various disciplines, including medicine, electronics, energy, environmental science, and advanced materials. Epoxy is a thermosetting polymer widely employed in industries such as coatings, adhesives, composites, and electronics due to its superior mechanical, chemical, and thermal properties [2]. These properties can be further enhanced by incorporating nanofillers, such as carbon dots (CDs). CDs are carbon-based nanomaterials with unique optical and electronic characteristics, making them suitable for applications in sensors, solar cells, optoelectronics, and biomedicine. CDs can be synthesized through various methods, including combustion, laser ablation, chemical synthesis, and biological routes [3]. Epoxy/carbon dot nanocomposites are fabricated by dispersing CD nanoparticles within an epoxy matrix. These nanocomposites exhibit enhanced electromagnetic, optical, mechanical, and thermal properties compared to pure epoxy. For instance, the incorporation of CDs can improve electrical conductivity, light absorption, tensile strength, and Young's modulus [4]. However, machining these nanocomposites, particularly drilling, poses challenges including delamination, fiber pull-out, and stress concentration, which can compromise structural integrity. Previous studies have identified delamination as a critical failure mode in carbon fiber-reinforced composites during drilling operations [5-7].

Composite materials are widely recognized for their near-net-shape manufacturing capabilities through molding processes, which allow them to closely match the final part geometry. However, machining operations such as drilling remain essential for assembling composite components, making the analysis of machining parameters critically important in engineering design. Drilling composites is inherently more challenging than machining metals or alloys due to the material's anisotropic nature and susceptibility to machining-induced damage. Over 60% of industrial composite machining involves drilling, driving extensive research into optimizing cutting parameters to reduce thrust forces and improve hole quality [8]. Gao et al. [9] investigated the surface characteristics of machined carbon composites, with Analysis of variance (ANOVA) results highlighting the significant influence of cutting speed. Similarly, Pólachon et al. [10] analyzed the surface topography of drilled carbon fiber composites, noting that increasing feed rates markedly alters surface quality. Tsao et al. [11] conducted drilling experiments on carbon composites using high-speed steel (HSS) drills under varying cutting speeds and feed rates, concluding that both parameters profoundly affect surface roughness. Wang et al. [12] developed a thrust force prediction model for CFRP drilling by focusing on the chisel edge, which significantly contributes to exit delamination. They introduced the novel concept of an azimuth angle to characterize better the contact between the chisel edge and carbon fibers. Modeling a single fiber as a beam on an elastic foundation, they used bending fracture theory to account for material properties, tool geometry, drilling parameters, and ultrasonic vibration effects. Magyar et al. [13] investigated the drilling of basalt fiber-reinforced polymer (BFRP) composites, focusing on the effect of feed rate and cutting speed on thrust force. Using response surface methodology (RSM) and advanced statistical modelling, they developed predictive models based on experimental data. Thrust force was measured during mechanical drilling and processed via FFT-based low-pass filtering. Their models demonstrated high prediction accuracy (96.74% for RSM and 95.01% for advanced models), with the latter also capturing force characteristics with a determination coefficient of 0.68. Results were also compared with those for CFRP composites to highlight performance differences.

The drilling process often leads to matrix cracking, fiber breakage, and delamination—the latter being a critical concern in composite assembly, as it compromises structural integrity and service life. Ramuluet al. [14] attributed delamination to inadequate support of upper plies during drilling and milling. Delamination extent and damage zones are governed by drilling forces and tool geometry, often resulting in irregular hole profiles. Beyond mechanical forces, heat generation during drilling further degrades composite strength. Elevated temperatures induce matrix deterioration and thermal damage, making temperature control a pivotal parameter in the process.

Ying et al. [15] compared three drill types (tungsten carbide, chemical vapor deposition diamond-coated, and multi-edge tools), monitoring thrust force, temperature, and delamination. Results underscored feed rate as the dominant factor influencing thrust forces, while multi-edge tools minimized delamination. Pathak et al. [16] reported that adding 0.3 wt.% graphene oxide to carbon fiber composites increased flexural strength by 60%, modulus by 70%, and interlaminar shear strength by 25%. Moreover, Baraheni et al. [17] conducted a comprehensive study on the drilling of CFRP laminates, evaluating the effects of nano-graphene addition, ultrasonic vibration, tool type, and feed rate on thrust force. Using statistical and machine learning methods along with image processing, they developed predictive models with high accuracy. Their findings showed that feed rate had the most significant effect on thrust force and burr formation. While nano-graphene increased thrust force due to enhanced rupture resistance, it reduced burr formation. Additionally, ultrasonic vibration and high-cobalt tools significantly improved hole quality by minimizing both thrust force and burr damage. The shift from metals to composites—driven by their high strength-to-weight ratio, near-net-shape production, and minimal machining needs—has revolutionized industries like aerospace and automotive. For instance, passenger aircraft components demand durable, dimensionally stable joints, necessitating optimized machining processes. Recent decades have seen remarkable progress in carbon fiber composite research. Early 21st century, studies focused on cutting parameters and tool geometry, whereas contemporary work explores alternative strategies.

In this study, the thrust force generated during drilling of carbon dot–reinforced epoxy composites was thoroughly analyzed. A detailed statistical analysis was conducted to examine the influence of key machining parameters, including spindle speed, feed rate, and drill bit diameter on drilling performance. These parameters were systematically varied to understand their individual effects on thrust force. The findings aim to provide a comprehensive understanding of the drilling behavior of nanomodified composite materials. This work not only addresses the growing need for precision in composite manufacturing but also opens new avenues for future research on carbon dot enhanced polymer composites.

2 MATERIALS AND METHODS

Epoxy matrix composites reinforced with carbon dot nanoparticles were fabricated for this study. The epoxy resin (ML 506 from Mokarrar company) and hardener were mixed in the manufacturer-recommended ratio under continuous stirring to ensure homogeneity. Carbon dot nanoparticles were synthesized and dispersed into the epoxy resin at a concentration of 1 wt.%, using ultrasonic agitation for 30 minutes to promote uniform dispersion. The mixture was then poured into a pre-designed mold and cured at room temperature for 24 hours, followed by post-curing at 80°C for 2 hours to achieve optimal mechanical properties. After curing, the composite sheets were cut into rectangular samples of dimensions 100 mm × 100 mm × 5 mm using a diamond saw.

Drilling experiments were conducted using a vertical universal milling machine. The manual milling machine used in this experiment is an FP4M model, manufactured by Tabriz Machine Manufacturing Company. All drilling experiments were performed using high-speed steel (HSS) twist drills of varying diameters (“Fig. 1”). A total of 54 drilling tests were carried out based on a full factorial design of experiments (DOE), with three levels for each factor (“Table 1”). The sample of the drilled holes is shown in “Fig. 2”.

Fig. 1 The used carbide tools.

Table 1 Process factors

Factor	Symbol	Level		
		1	2	3
Spindle speed (rpm)	N	1000	2000	2500
Feed rate (mm/min)	F	10	30	50
Tool diameter (mm)	D	0.3	0.6	0.9
Carbon dot (%)	C	0	1	-

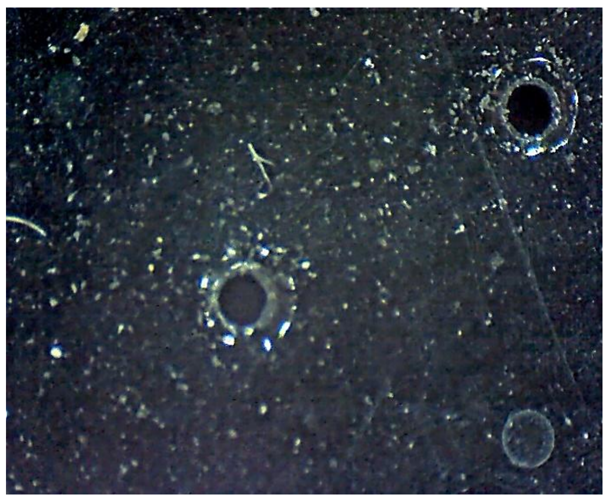

Fig. 2 The sample of the drilled holes.

Drilling experiments were conducted using a vertical universal milling machine (FP4M model, manufactured by Tabriz Machine Manufacturing Company). High-speed steel (HSS) twist drills were used throughout the experiments (“Fig. 1”). A total of 54 drilling tests were carried out based on a full factorial DOE, with three levels for each factor (“Table 1”). The drilling process was performed under dry conditions without the use of coolant to avoid altering the mechanical properties of the epoxy matrix or introducing additional variables related to coolant interaction with the composite. The specimens were rigidly clamped using a custom fixture with a clamping force of approximately 500 N to ensure stability and minimize vibration during drilling, which could affect thrust force measurements or induce machining defects such as delamination. The clamping force was monitored using a torque wrench to maintain consistency across all experiments.

The thrust force during drilling was measured using a loadcell (manufactured by SEWHA). The used load cell is capable of measuring forces ranging from 1 to 200 kgs, an accuracy of ±0.1% of full scale (equivalent to ±0.2 kg), and a sampling rate of 1000 Hz, enabling precise capture of dynamic force variations during drilling. It has an IP67 protection rating, indicating resistance to water and dust ingress. The device is primarily used for both tensile and compressive force applications. The recommended operating voltage for this load cell is 10 volts. The loadcell is connected to a data acquisition system. Force signals were recorded in real-time, and the peak thrust force for each trial was extracted for analysis. The setup ensured rigid clamping of the specimen to minimize vibration and displacement during drilling ("Fig. 3").

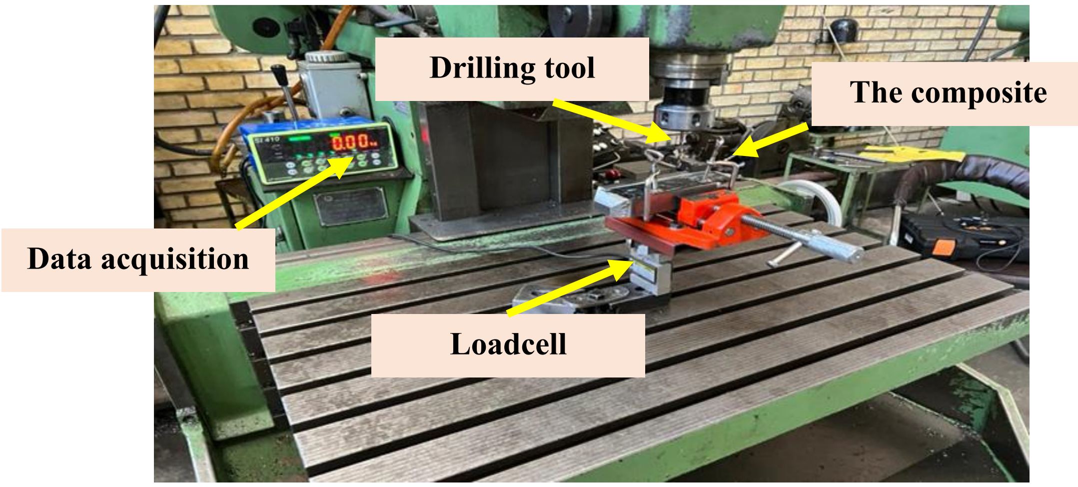

Fig. 3 Experimental setup.

3 RESULTS AND DISCUSSION

This section presents the experimental results and statistical analyses performed on the drilling process of carbon dot–reinforced epoxy composites. It focuses on quantifying how the machining parameters—spindle speed, feed rate, drill bit diameter, and their interactions—affect the maximum thrust force during drilling. The following details the model performance, main effects, and analysis of variance.

3.1. Model Performance and Regression Analysis

The developed regression model ("Eq. (1)") demonstrated excellent predictive capability, with an R-squared value of 98.90% and an adjusted R-squared of 98.55%. The low standard error (S = 0.0077351) and the high predicted R-squared value (97.84%) further confirm the robustness of the model. The regression equation obtained is as "Eq. (1)":

$$\text{Thrust force} = 0.0654 - 0.000054\,N + 0.002106\,F + 0.1857\,D + 0.01020\,M - 0.000015\,F{*}F + 0.0926\,D{*}D - 0.000048\,N{*}D + 0.000004\,N{*}M + 0.001042\,F{*}D + 0.000139\,F{*}M - 0.05926\,D{*}M \quad (1)$$

This comprehensive model illustrates both the linear and nonlinear effects of the drilling parameters, indicating that each factor, as well as their combined interactions, plays a significant role in determining the maximum thrust force.

3.2. Main Effects and Interaction Contributions

ANOVA results, presented in "Table 2", provide a detailed statistical evaluation of the factors influencing the thrust force during the drilling of carbon dot-reinforced epoxy composites. The table summarizes the contribution of each machining parameter—spindle speed, feed rate, drill bit diameter, and material (carbon dot reinforcement level)—along with their quadratic and interaction effects on the maximum thrust force. The ANOVA was conducted using Minitab software, based on a full factorial DOE with 54 trials, ensuring a robust assessment of the model's significance and the individual effects of the parameters. The overall regression model is highly significant, as indicated by an F-value of 277.46 and a p-value less than 0.001, confirming that the model effectively explains the variability in thrust force. The model accounts for 98.90% of the total variation (Contribution), with an R-squared value of 98.90% and an adjusted R-squared of 98.55%, underscoring its predictive accuracy. The low standard error (S = 0.0077351) further validates the model's precision.

Table 2 ANOVA results of thrust force

Source	DF*	Seq SS*	Contribution	Adj SS*	Adj MS*	F-Value	P-Value
Regression	13	0.215807	98.90%	0.215807	0.016601	277.46	0.000
Spindle	1	0.043430	19.90%	0.000636	0.000636	10.63	0.002
Feed	1	0.015625	7.16%	0.001464	0.001464	24.46	0.000
Diameter	1	0.144400	66.18%	0.001801	0.001801	30.10	0.000
Material	1	0.002400	1.10%	0.000074	0.000074	1.23	0.273
Spindle*Spindle	1	0.000604	0.28%	0.000604	0.000604	10.09	0.003
Feed*Feed	1	0.000408	0.19%	0.000408	0.000408	6.82	0.013
Diameter*Diameter	1	0.000833	0.38%	0.000833	0.000833	13.93	0.001
Spindle*Feed	1	0.001302	0.60%	0.001302	0.001302	21.76	0.000
Spindle*Diameter	1	0.002857	1.31%	0.002857	0.002857	47.75	0.000
Spindle*Material	1	0.000096	0.04%	0.000096	0.000096	1.61	0.212
Feed*Diameter	1	0.000937	0.43%	0.000937	0.000937	15.67	0.000
Feed*Material	1	0.000069	0.03%	0.000069	0.000069	1.16	0.288
Diameter*Material	1	0.002844	1.30%	0.002844	0.002844	47.54	0.000
Error	40	0.002393	1.10%	0.002393	0.000060		
Total	53	0.218200	100.00%				

DF: Degrees of Freedom, Seq SS: Sequential Sum of Squares, Adj SS: Adjusted Sum of Squares, Adj MS: Adjusted Mean of Squares.

Among the main effects, drill bit diameter is the dominant factor, contributing 66.18% to the thrust force variation, followed by spindle speed (19.90%) and feed rate (7.16%). The material factor, representing carbon dot reinforcement, has a minimal direct effect (1.10%, $p = 0.273$), but its interactions with other parameters are significant. Quadratic effects, such as those for spindle speed (0.28%, $p = 0.003$), feed rate (0.19%, $p = 0.013$), and diameter (0.38%, $p = 0.001$), indicate nonlinear relationships that influence thrust force. Key interaction effects include spindle speed × diameter (1.31%, $F = 47.75$, $p < 0.001$) and diameter × material (1.30%, $F = 47.54$, $p < 0.001$), highlighting that the impact of one parameter often depends on the level of another. The error term, contributing only 1.10% to the total variation, suggests that unaccounted factors have a negligible impact, reinforcing the model's robustness.

The ANOVA results provide critical insights into the relative importance of each parameter and their interactions, guiding the optimization of drilling processes for carbon dot-reinforced epoxy composites. The significant contributions of drill bit diameter and its interactions underscore the need for careful tool selection, while the nonlinear and interaction effects emphasize the importance of balanced parameter settings to minimize thrust forces and machining-induced damage.

3.3. Main effects plot

The main effects plot ("Fig. 4") provides a comprehensive visual representation of the relationships between the drilling parameters—spindle speed, feed rate, drill bit diameter, and carbon dot reinforcement level—and the resultant thrust force during the drilling of carbon dot-reinforced epoxy composites.

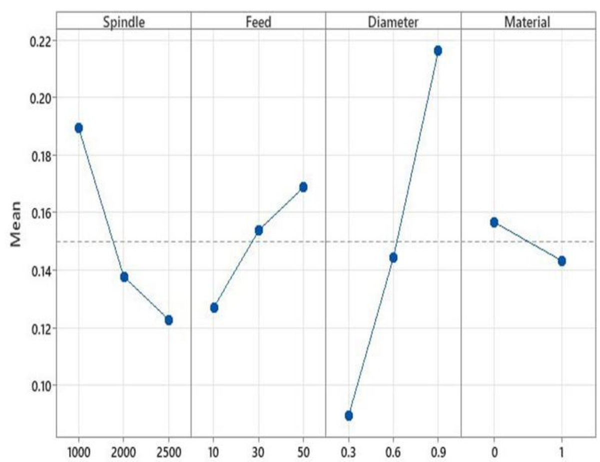

Fig. 4 Main effects plot of thrust force.

These relationships, derived from a full factorial DOE and analyzed using Minitab software, offer critical insights into the mechanical behavior of the composite under varying machining conditions. The following discussion elaborates on the observed trends, their underlying mechanisms, and their implications for optimizing the drilling process.

For spindle speed, the regression model reveals a negative coefficient, indicating that an increase in spindle speed (from 1000 to 2500 rpm) results in a slight reduction in thrust force. This trend can be attributed to the enhanced cutting efficiency at higher rotational speeds, which reduces the contact time between the drill bit and the workpiece. Higher spindle speeds facilitate smoother chip evacuation and lower frictional resistance at the tool-workpiece interface, thereby decreasing the axial force required for material removal [18]. However, the relatively modest contribution of spindle speed (19.90% to thrust force variation, as per ANOVA results) suggests that its effect is less pronounced compared to other parameters, likely due to the anisotropic nature of the composite, which limits the extent of speed-induced force reduction. The main effects plot illustrates this subtle downward trend, with a shallow negative slope, underscoring the need for balanced spindle speed settings to avoid excessive heat generation, which could induce thermal damage in the epoxy matrix [19].

In contrast, feed rate exhibits a strong positive correlation with thrust force, as evidenced by the steep upward slope in the main effects plot. As the feed rate increases from 10 to 50 mm/min, the thrust force rises proportionally, contributing 7.16% to the total variation. This near-linear relationship reflects the dominance of mechanical forces in the drilling process, where higher feed rates increase the rate of material removal, leading to greater resistance from the composite [20]. The increased feed rate amplifies the shear and compressive stresses at the cutting zone, necessitating higher axial forces to advance the drill [21]. This behavior is consistent with the composite's heterogeneous structure, where the epoxy matrix and carbon dot reinforcements create varying resistance to tool penetration [22]. The linear progression observed in the plot suggests that feed rate increments produce predictable, proportional increases in thrust force, making it a critical parameter for controlling machining-induced stresses and minimizing defects such as delamination.

The drill bit diameter emerges as the dominant factor influencing thrust force, contributing 66.18% to the variation, as confirmed by the ANOVA results. The main effects plot demonstrates a strong positive relationship, with thrust force increasing significantly as the diameter rises from 0.3 to 0.9 mm. This trend is driven by the larger tool-workpiece contact area associated with wider drill bits, which increases the volume of material removed per revolution and amplifies the cutting forces required. The larger diameter also enhances the shear and compressive stresses at the cutting interface, leading to higher axial loads [23]. Additionally, the increased chip load with larger diameters contributes to greater resistance, further elevating the thrust force [24]. The pronounced slope in the plot underscores the critical role of tool geometry in drilling performance, highlighting the need for careful diameter selection to balance material removal efficiency with the risk of machining-induced damage, such as matrix cracking or fiber pull-out.

The incorporation of carbon dot nanoparticles up to 1 wt.% results in a notable reduction in thrust force, as observed in the main effects plot. This reduction is attributed to the enhanced interfacial bonding and load distribution within the composite, facilitated by the uniform dispersion of carbon dots within the epoxy matrix. Carbon dots, with their high surface area and unique mechanical properties, strengthen the matrix-reinforcement interface, improving the composite's resistance to shear and compressive forces during drilling [25-26]. This leads to a more efficient stress transfer, reducing the axial force required for material removal. However, the plot also indicates that increasing carbon dot concentrations beyond 1 wt.% induces material embrittlement, characterized by a transition from ductile to brittle fracture behavior. This shift is likely due to the agglomeration of nanoparticles at higher concentrations, which creates stress concentration points and weakens the matrix integrity. As a result, the composite becomes more susceptible to brittle fracture, reducing the thrust force but potentially compromising structural integrity at critical concentrations. This dual effect of carbon dot reinforcement underscores the importance of optimizing nanoparticle content to achieve a balance between enhanced mechanical properties and machining performance.

The interplay of these parameters, as visualized in the main effects plot, provides a robust framework for understanding the drilling behavior of carbon dot-reinforced epoxy composites. The significant influence of drill bit diameter, coupled with the linear effect of feed rate and the subtle mitigating effect of spindle speed, highlights the need for a holistic approach to parameter optimization.

3.4. Optimization

In this section, desirability method is conducted to determine the optimized condition to obtain least possible thrust force. In this order, desirability amount (d) will be acquired from the "Eq. (2)" and "Eq. (3)" relationships:

$$d_i = \begin{cases} 1 & Y_i < Low_i \\ \left(\dfrac{Y_i - Low_i}{High_i - Low_i}\right)^w & Low_i < Y_i < High_i \\ 0 & Y_i > High_i \end{cases} \tag{2}$$

$$D = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{1/\sum r_i} \tag{3}$$

That Y is the thrust force factor, Low and High are the minimal and maximal thrust force values, respectively, r is the number of experimental tests and w is the weigh coefficients. Figure 5, an optimization plot, illustrates the impact of spindle speed, feed rate, drill bit diameter, and carbon dot concentration on thrust force during drilling of carbon dot-reinforced epoxy composites. Each panel shows the parameter's range on the x-axis and predicted thrust force on the y-axis, with red lines marking current (Cur) and high/low settings, and a blue dashed line indicating the target minimum thrust force ($y = 0.0639$, desirability $d = 0.98552$). The settings—spindle speed of 2500 rpm, feed rate of 10 mm/min, tool diameter of 0.3 mm, and 1 wt.% carbon-dot—minimize thrust force effectively, ensuring better hole quality and structural integrity.

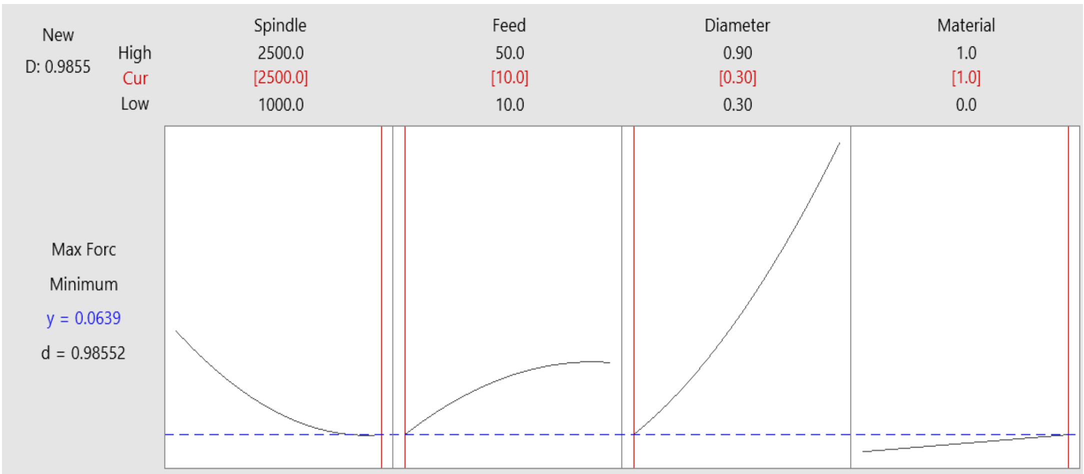

Fig. 5 Optimization results.

4 CONCLUSIONS

This study examined the effects of drilling parameters—spindle speed, feed rate, and drill bit diameter—on thrust force during the machining of epoxy composites reinforced with carbon dot nanoparticles. Drill bit diameter was identified as the most influential factor (66.18%), followed by spindle speed (19.90%) and feed rate (7.16%). A regression model ($R^2 = 98.90\%$) confirmed significant parameter interactions. Increased feed rate and tool diameter raised thrust force, while higher spindle speeds reduced it slightly. Carbon dot additions up to 1 wt.% lowered thrust forces through improved bonding, though higher contents led to embrittlement and brittle fracture. The optimal drilling conditions (2500 rpm, 10 mm/min feed rate, 0.3 mm diameter, and 1 wt.% carbon dots) minimized thrust force (0.0639 N) with high desirability (0.98552), offering valuable insights for precision machining of nanocomposites in advanced applications.

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