



OPEN Robust prediction and optimization of surface roughness and kerf taper in AWJM of titanium mesh basalt carbon hybrid composites

E. S. Essakiraj^{1✉}, Sikiru O. Ismail², N. Rajini^{3✉}, Faruq Mohammad⁴, Kumar Krishnan⁵ & M. P. Indira Devi⁶

This study investigates abrasive water jet machining (AWJM) of a hybrid titanium mesh/basalt fiber/carbon fiber stacked composite, focusing on machining behavior at dissimilar metal–fiber interfaces. Unlike homogeneous composites, the laminate shows non-uniform erosion due to combined ductile metallic and brittle polymeric phases, limiting conventional machining models. A design of experiments approach integrated with response surface methodology (RSM) was used to evaluate the effects of abrasive jet pressure, traverse speed, abrasive flow rate, and stand-off distance on surface roughness and kerf angle. Abrasive jet pressure is identified as the dominant factor due to its influence on jet energy distribution and interlayer erosion stability. The study highlights how material heterogeneity and interfacial interactions govern erosion mechanisms in hybrid stacked composites, an area underexplored in existing AWJM literature focused mainly on uniform materials. The developed RSM models show high predictive accuracy ($R^2 > 0.99$) within the investigated experimental design space, although their applicability beyond the studied parameter range requires further validation. Results confirm that AWJM can machine complex hybrid laminates without thermal damage, minimizing machining defects and post-processing needs. Overall, the work extends AWJM understanding from conventional composites to multi-material systems, improving insight into erosion behavior and predictive modeling of hybrid laminates.

Keywords Titanium mesh, Basalt/carbon fiber, Abrasive, Surface roughness, Kerf angle, Desirability, Process innovation

In fiber-reinforced polymer (FRP) composites technology, the stacking sequence of laminates with varying fiber orientations plays a critical role in determining mechanical, dynamic, and thermal performance. Proper lay-up design governs stress distribution, stiffness, damage tolerance, and energy dissipation. Numerous studies have examined the structural behavior of fiber-based stacking configurations in FRP composites. More recent investigations have shown that combining fibers with different mechanical properties within stacked composites (SCs) enhances load-bearing capacity, impact resistance, damping performance, and durability. Furthermore, hybridization with metallic layers has been increasingly adopted to improve tensile and flexural strength, impact resistance, and structural adaptability. As a result, optimized stacking configurations are widely applied in aerospace, automotive, marine, sports, and civil engineering sectors due to their lightweight and multifunctional characteristics^{1–3}.

Carbon fiber-reinforced composites exhibit high specific strength and stiffness, making them ideal for weight-sensitive applications^{4,5}. Kumar et al.⁶ analyzed the effect of stacking sequence on glass/carbon hybrid laminates fabricated using the hand lay-up technique. Their results showed that the carbon/glass/carbon configuration

¹Department of Mechanical Engineering, Dambi Dollo University, DambiDollo, Ethiopia. ²Centre for Engineering Research, School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield, Hertfordshire AL10 9AB, UK. ³Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil 626126, India. ⁴Department of Chemistry, College of Science, King Saud University, P.O. Box 2455, 11451 Riyadh, Kingdom of Saudi Arabia. ⁵INTI International University, Persiaran Perdana BBN, 71800 Nilai, Negeri Sembilan, Malaysia. ⁶Department of Physics, Ramco Institute of Technology, Rajapalayam 626117, India. ✉email: essakiraj@dadu.edu.et; rajiniklu@gmail.com

achieved superior tensile and flexural strength, with fractographic analysis confirming its suitability for structural applications.^{7,8}

The integration of synthetic and natural fibers has gained attention for enhancing performance while reducing environmental impact. Basalt fiber, an inorganic reinforcement, offers higher strength and stiffness compared to plant-based natural fibers. Previous studies have explored basalt fiber in combination with synthetic fibers such as carbon, glass, and Kevlar.^{9,10,11} In parallel, metal–fiber laminates (MFLs), consisting of alternating FRP layers and thin metallic sheets, have emerged as advanced hybrid materials with improved strength-to-weight ratio, corrosion resistance, and fatigue performance.^{12–14} Rajamurugan et al.¹⁵ demonstrated that incorporating stainless-steel wire mesh into hybrid composites enhances interlaminar bonding and mechanical properties.

Stacked titanium mesh/basalt/carbon fiber hybrid composites are increasingly utilized in high-performance applications due to their superior strength-to-weight ratio and corrosion resistance. However, machining these multi-material systems is particularly challenging due to the contrasting behavior of ductile metallic layers and anisotropic fiber-reinforced polymer layers. Conventional machining methods often result in excessive tool wear, delamination, and poor surface finish.^{16–19} Abrasive water jet machining (AWJM) has emerged as a promising alternative, offering low cutting forces, minimal thermal damage, and improved surface integrity.^{20,21} Previous studies have demonstrated its effectiveness in machining various composite materials.^{21,22,24} Although AWJM has been investigated for fiber-reinforced polymers and conventional fiber–metal laminates, comparatively fewer studies have examined highly heterogeneous laminates incorporating titanium mesh together with multiple fiber reinforcements. Consequently, the influence of material heterogeneity and dissimilar metal–fiber interfaces on machining behaviour remains less well understood.²³

Optimization of AWJM parameters has been widely performed using response surface methodology (RSM) and central composite design (CCD), enabling efficient evaluation of process variables and their interactions.^{24–26} Among these, water pressure significantly influences machining performance, including material removal rate (MRR), surface quality, and kerf characteristics.^{27–29} Multi-response optimization techniques such as the desirability approach have also been successfully applied.^{30,31} Recent studies have further focused on improving AWJM performance using statistical optimization techniques such as RSM, Taguchi methods, and grey relational analysis.^{24–34} While these methods effectively identify optimal parameter settings, they are generally limited to simplified regression models and may not accurately capture the complex relationships present in highly heterogeneous material systems. In contrast, advanced approaches incorporating machine learning (ML) techniques, such as artificial neural networks (ANN) and Random Forest (RF), have demonstrated improved capability in modeling nonlinear interactions between process parameters and machining responses.^{31,32} Additionally, metaheuristic algorithms such as genetic algorithms (GA) and particle swarm optimization (PSO) have been applied for multi-objective optimization. However, their application to AWJM of hybrid metal–fiber stacked composites remains limited, and these approaches often lack integration with material-specific machining mechanisms.

The TiBCBCBCTi stacking configuration was selected to achieve a balanced combination of mechanical reinforcement, interfacial stability, and machining performance. In this configuration, titanium mesh layers were positioned at the outer surfaces to improve structural integrity, constrain delamination, and enhance load transfer across the laminate. The metallic outer layers also provide improved resistance to impact and localized deformation during abrasive water jet machining. In contrast, the internal basalt and carbon fiber layers contribute lightweight stiffness and high specific strength. Basalt fibers improve toughness and damage resistance, while carbon fibers provide enhanced rigidity and dimensional stability. From a machining perspective, the titanium mesh outer layers help stabilize jet entry and exit behavior, reduce excessive lateral erosion, and improve kerf uniformity by constraining abrupt jet dispersion at the laminate boundaries. Therefore, the selected stacking sequence provides both structural and machining-related advantages for hybrid multi-material laminate systems.

Although AWJM has been widely studied for homogeneous composites and conventional fiber–metal laminates, comparatively fewer investigations have focused on hybrid laminates containing titanium mesh together with multiple fiber reinforcements^{20,21,33}, and³⁴. Existing studies have largely emphasized the effects of machining parameters on overall cutting performance, whereas the influence of material heterogeneity and dissimilar metal–fiber interfaces on erosion behaviour, surface integrity, and kerf formation remains less well understood. Consequently, further investigation is needed to establish predictive relationships between machining parameters and machining quality for these complex hybrid laminate architectures. Most existing AWJM predictive models have been developed for homogeneous metallic materials, monolithic composites, or conventional fiber-reinforced polymer laminates. These models generally assume relatively uniform material properties and erosion behavior throughout the workpiece. However, such assumptions become less valid for heterogeneous hybrid laminates consisting of dissimilar constituents, such as titanium mesh, basalt fibers, and carbon fibers. In these materials, significant variations in hardness, ductility, fracture behavior, and interfacial bonding result in non-uniform energy absorption and material removal mechanisms during machining.

Furthermore, conventional regression-based and empirical AWJM models often focus primarily on process parameters while treating the workpiece as a homogeneous medium. As a result, they may not adequately capture the localized erosion, jet deflection, interfacial damage evolution, fiber pull-out, matrix cracking, and differential wear mechanisms that occur when the abrasive jet transitions between metallic and composite layers. These complexities can lead to deviations between predicted and actual machining responses, particularly under conditions involving strong material heterogeneity.

Another limitation of existing models is their restricted applicability to the specific material systems and parameter ranges used during model development. Consequently, models developed for homogeneous composites or traditional fiber–metal laminates may not be directly transferable to advanced hybrid architectures. This highlights the need for enhanced predictive approaches that integrate material-specific erosion mechanisms,

interfacial effects, and advanced data-driven techniques to improve prediction accuracy and generalization capability for complex hybrid laminate machining.

Critical comparison with previous studies: Previous AWJM investigations on glass-fiber, carbon-fiber, and conventional fiber–metal laminates generally reported that increasing abrasive jet pressure improves surface finish and reduces kerf taper due to enhanced particle kinetic energy and penetration capability^{20,21,24,25,33,34}. However, most of these studies focused on relatively homogeneous material systems and attributed machining performance primarily to process parameters. In contrast, the present TiBCBCBCTi hybrid laminate exhibited a stronger sensitivity to abrasive jet pressure and stand-off distance, indicating that material architecture plays a more dominant role in governing erosion behavior. The observed reductions in surface roughness and kerf angle are greater than those typically reported for conventional FRP laminates, which may be attributed to the titanium mesh layers that stabilize jet propagation and suppress excessive fiber pull-out. Furthermore, unlike homogeneous composites where erosion mechanisms are relatively uniform, the present laminate involves transitions between ductile titanium mesh and brittle basalt/carbon fiber layers, resulting in heterogeneous energy dissipation and interfacial damage evolution. The present work provides additional experimental evidence for titanium mesh/basalt/carbon hybrid laminates, a material system that has received comparatively limited attention.

The present study investigates the AWJM performance of a titanium mesh/basalt fiber/carbon fiber stacked laminate (TiBCBCBCTi) using a Response Surface Methodology (RSM)-based experimental framework. Rather than introducing a new machining technique, this work extends existing AWJM studies by examining a complex hybrid laminate architecture in which dissimilar metallic and composite layers influence erosion behaviour and machining quality^{20,21,24,25,33,34}. Predictive models for surface roughness and kerf angle are developed, and a desirability-based multi-response optimization is employed to identify suitable machining conditions. The findings contribute additional experimental evidence and process understanding for hybrid laminate systems that have received comparatively limited attention in the AWJM literature.

Materials and methods

Raw materials, fabrication of SC and AWJM process

The TiBCBCBCTi fiber metal laminate (FML) is a stacked composite material made up of layers of titanium mesh, basalt, and carbon fiber. The titanium mesh/basalt fiber/carbon FML composite was developed through a semi-manufactured technique, followed by an advanced consolidation and bonding process to ensure consistent patterns of manufacturing and interfacing. The first step in developing the composite fabrication process of the composite was to cut the required size of titanium mesh sheets and surface preparation of the sheets using either mechanical or chemical (acetone) treatment to enhance bonding with the polymer matrix. Next, basalt and carbon fiber fabrics were cut based on a predetermined fabrication sequence. The epoxy resin and curing agent were mixed in a specified ratio to ensure optimum curing behavior. A suitable release agent was applied to the mold surface prior to lay-up.

The lay-up process began by placing the titanium mesh layer in the mold, followed by uniform resin application. Subsequently, basalt and/or carbon fiber layers were added, and each layer was carefully impregnated using hand rollers to eliminate air entrapment. This stacking sequence was repeated until the required thickness and configuration were achieved. The laminate was then covered with a release film and consolidated using a hydraulic press under controlled temperature and pressure to ensure uniform thickness, minimal void content, and strong interfacial bonding. Figure 1 shows the step-by-step fabrication process of the TiBCBCBCTi laminate, including stacking, resin impregnation, and compression curing.

AWJM experimental setup and measurement procedure

The AWJM experiments were conducted to evaluate the effect of reinforcement stacking on machining quality. The cutting process was performed using an AQUAJET CNC machine with a working bed size of 320 × 1700 cm and a table height of 91 cm. The machine operates on three axes (A, B, and C) with travel ranges of 300 cm, 150 cm, and 20 cm, respectively. A 37 kW high-pressure pump capable of delivering up to 400 MPa was used. The waterjet was maintained at a constant impingement angle of 90°, with an injection-type nozzle having an orifice diameter of 0.032 cm and a focusing tube diameter of 0.11 cm.

The surface roughness (SR) of the top and bottom surfaces was measured at the mid-depth point along the cut path using a contact stylus-type surface profilometer (Surfcorder: SE3500). The measurements were performed with a probe speed of 0.1 mm/s, an assessment length of 4 mm, and a cut-off length of 0.8 mm.

To ensure measurement accuracy, the profilometer was calibrated prior to each measurement session according to manufacturer specifications. To ensure statistical reliability, five SR readings were taken at the mid-region of each cut surface, and the final value was reported as the arithmetic mean. This approach minimizes variability caused by jet entry and exit effects. To ensure experimental repeatability, each test condition was conducted three times under identical settings, and the average response values were used for analysis. Standard deviation was calculated to quantify experimental uncertainty.

To ensure the reliability of experimental measurements, all measuring instruments were calibrated according to manufacturer specifications prior to data collection. Surface roughness measurements (Fig. 2) were repeated five times at different locations within the central cutting region, and the reported value represents the arithmetic mean. The standard deviation was calculated to quantify measurement variability and assess repeatability.

Similarly, kerf width measurements were obtained at multiple locations along the machined edge, and average values were used for kerf angle calculations. Measurement uncertainty was estimated using repeated observations and instrument resolution. The combined uncertainty was determined by considering both systematic uncertainties associated with instrument precision and random uncertainties associated with measurement variability.

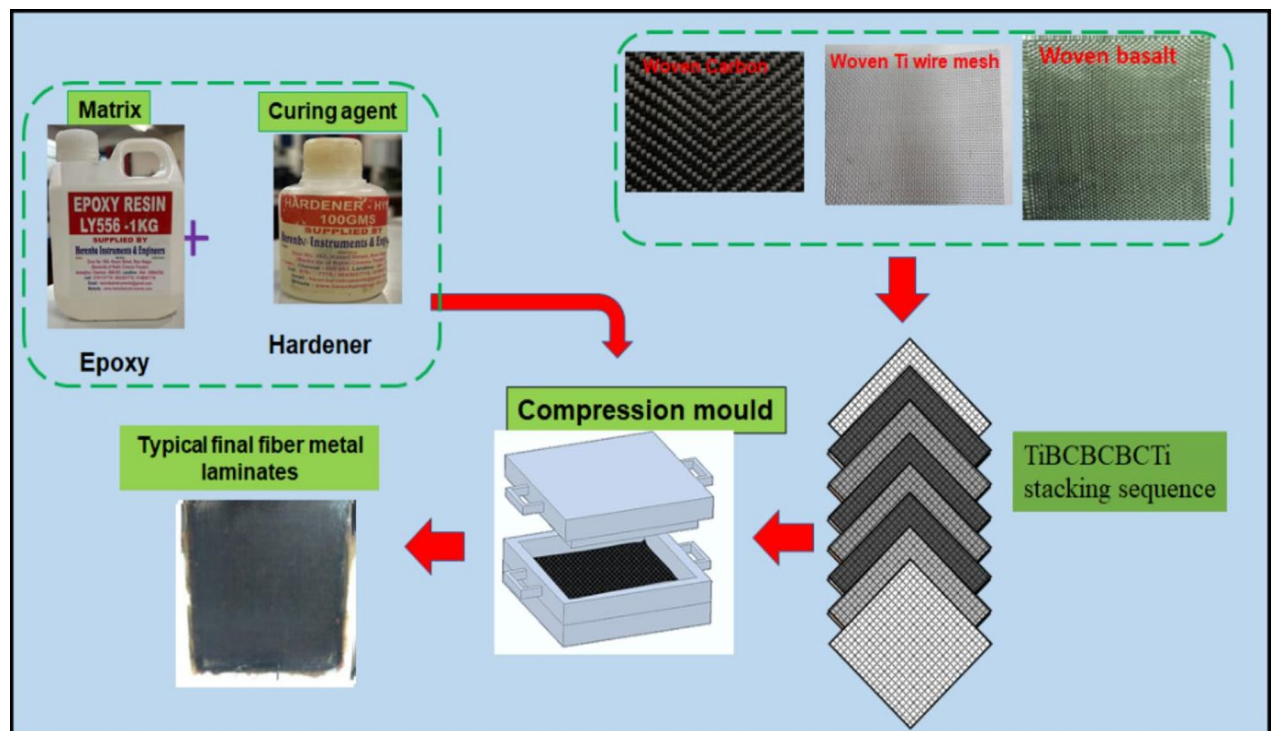


Fig. 1. Fabrication process of TiBCBCBCTi stacked composite.

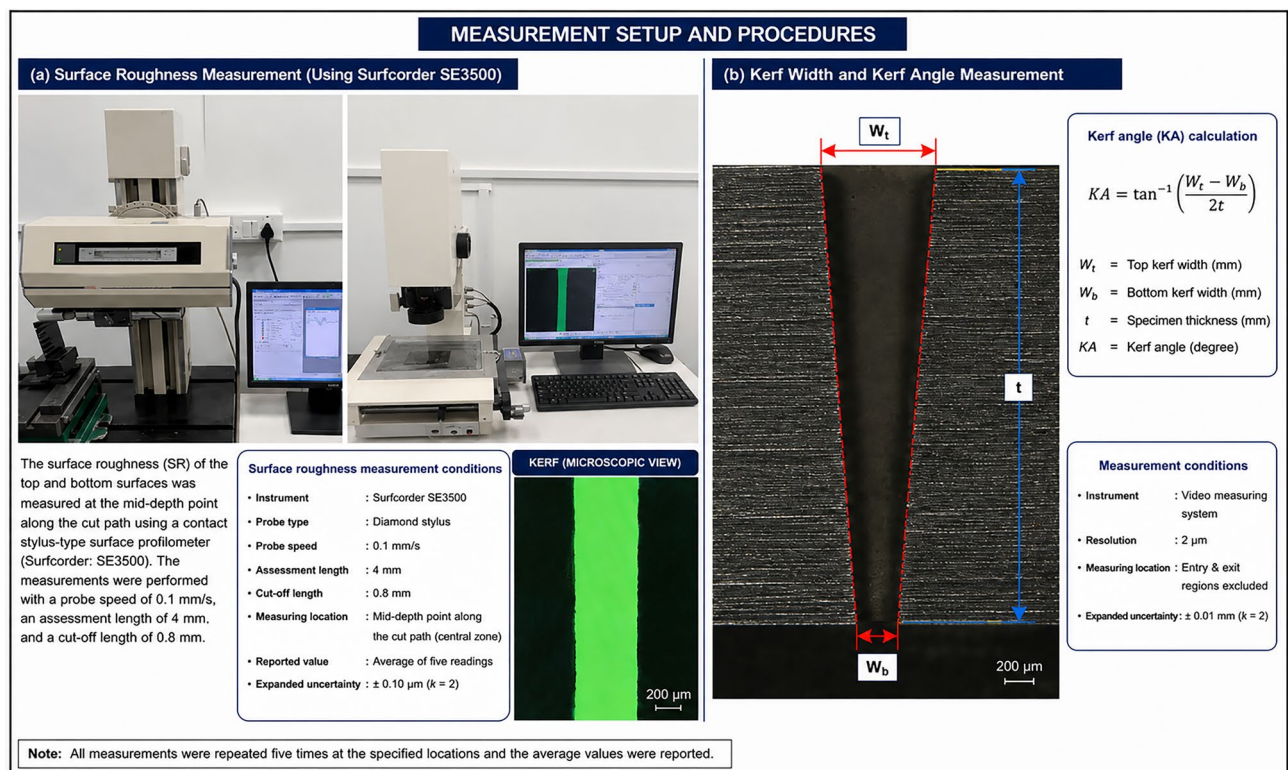


Fig. 2. Measurement setup and procedures.

The standard uncertainty was evaluated using:

$$u = \frac{s}{\sqrt{n}}$$

where s is the standard deviation of repeated measurements and n is the number of observations. The expanded uncertainty was estimated at a 95% confidence level using an appropriate coverage factor ($k \approx 2$). This approach provides a quantitative assessment of experimental reliability and supports the validity of the reported machining responses.

The average standard deviation for surface roughness measurements was below $\pm 0.05 \mu\text{m}$, while the expanded uncertainty was estimated to be $\pm 0.10 \mu\text{m}$ at a 95% confidence level. The corresponding expanded uncertainty for kerf width measurements was $\pm 0.01 \text{ mm}$.

The kerf formation mechanism is governed by high-velocity erosion caused by abrasive particles entrained in the water jet, resulting in micro-cutting and impact-based material removal.

Kerf widths were measured at multiple locations (top, middle, and bottom regions) along the cut length, and the average value was used to minimize local variation effects. The kerf angle (KA) was calculated based on the difference between the top kerf width (W_t) and bottom kerf width (W_b) relative to the specimen thickness (t). Undulations were measured at intervals of 5 mm along the kerf profile to evaluate surface variation and taper characteristics. The AWJM setup used in this study is shown in Fig. 3.

Kerf angle (KA) was determined using the following relation:

$$K_A = \tan^{-1} \left(\frac{W_t - W_b}{2t} \right)$$

where W_t is the top kerf width, W_b is the bottom kerf width, and t is the material thickness.

Response surface methodology (RSM) and experimental

A systematic evaluation of AWJM process variables was carried out using Response Surface Methodology (RSM). RSM was employed to develop second-order polynomial regression models describing the relationship between input parameters and output responses (Eqs. (1) and (2)).

The selection of RSM combined with Central Composite Design (CCD) was based on its ability to efficiently model nonlinear process–response relationships with a limited number of experiments. Unlike machine learning approaches such as ANN and Random Forest, which require large datasets and act as black-box models, RSM provides explicit mathematical equations that enable both prediction and physical interpretation of machining behavior. This is particularly important for heterogeneous titanium mesh/basalt/carbon fiber systems, where parameter interaction effects must be physically interpretable.

The machining parameters considered were average feed rate (AFR), abrasive jet pressure (AJP), traverse speed (TS), and stand-off distance (SoD). Experimental modeling and statistical analysis were performed using Design-Expert Version 13 software. The selected parameter ranges were determined based on (i) manufacturer operating limits of the AQUAJET system, (ii) literature reports on AWJM of composite materials^{24–31}, and

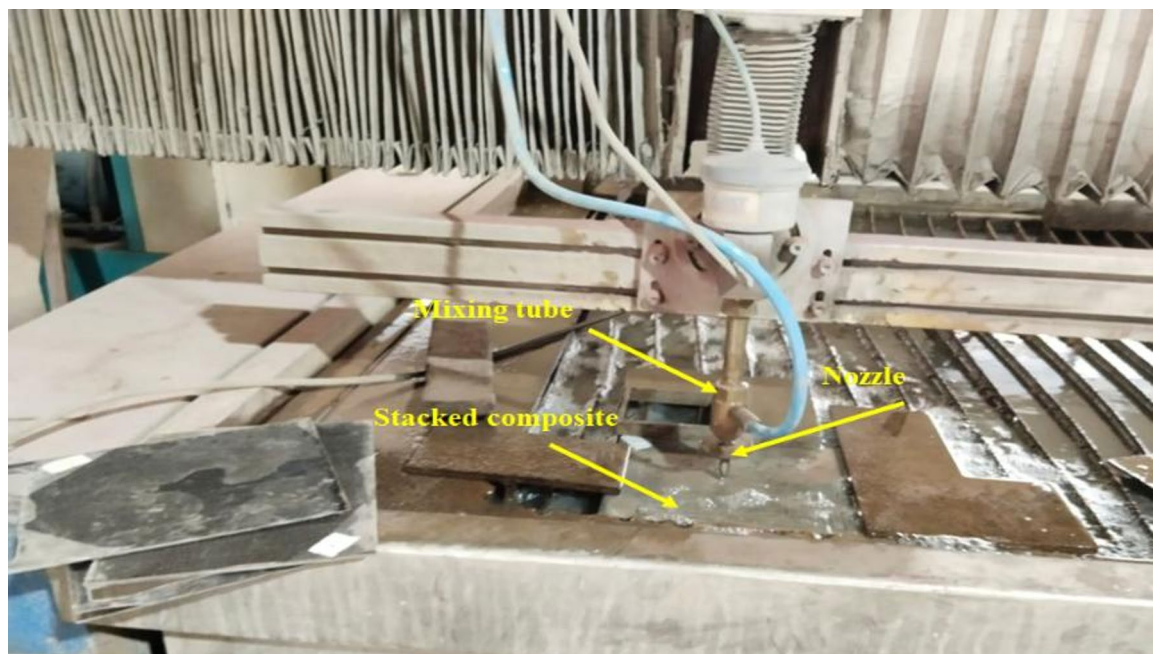


Fig. 3. AWJM center used.

Level		−2	−1	0	1	2
Parameters	Units					
AFR	kg/min	0.25	0.3	0.35	0.4	0.45
AJP	MPa	120	180	240	300	360
SoD	mm	1.5	2	2.5	3	3.5
TS	mm/min	80	105	130	155	180

Table 1. Levels of process parameters by CCD.

Run order	SoD (mm)	AJP (MPa)	AFR (kg/min)	TS (mm/min)	SR (μm)	KA (°)
1	3.5	120	0.45	180	4.61	1.73
2	1.5	120	0.25	80	4.62	1.75
3	3.5	120	0.25	80	4.86	1.83
4	3.5	360	0.25	80	3.59	1.45
5	1.5	120	0.25	180	4.88	1.83
6	1.5	360	0.25	180	3.58	1.46
7	3.5	120	0.25	180	5.14	1.91
8	3.5	360	0.25	180	3.85	1.53
9	2.5	240	0.30	130	4.17	1.62
10	2.5	240	0.35	105	3.94	1.54
11	2.0	240	0.35	130	3.93	1.55
12	1.5	360	0.25	80	3.31	1.38
13	2.5	180	0.35	130	4.31	1.66
14	2.5	240	0.35	130	4.01	1.56
15	2.5	240	0.35	130	4.01	1.56
16	2.5	240	0.35	130	4.01	1.56
17	2.5	240	0.35	130	4.01	1.56
18	2.5	240	0.35	130	4.01	1.56
19	2.5	300	0.35	130	3.69	1.48
20	3.0	240	0.35	130	4.11	1.59
21	2.5	240	0.35	155	4.15	1.59
22	2.5	240	0.40	130	3.86	1.52
23	1.5	120	0.45	80	3.97	1.56
24	1.5	360	0.45	80	2.79	1.21
25	3.5	120	0.45	80	4.31	1.65
26	3.5	360	0.45	80	3.09	1.28
27	1.5	120	0.45	180	4.28	1.64
28	1.5	360	0.45	180	3.06	1.27
29	3.5	360	0.45	180	3.35	1.37

Table 2. Experimental observations of SR and KA.

(iii) preliminary trial experiments ensuring stable jet formation, nozzle safety, and consistent material erosion behavior.

A central composite design (CCD) with five center points and a total of 29 experimental runs was used to estimate linear, quadratic, and interaction effects efficiently while minimizing experimental effort.

Despite its effectiveness, Response Surface Methodology (RSM) has inherent limitations. The method assumes that the relationship between input parameters and responses can be approximated using a second-order polynomial, which may not fully capture highly nonlinear or complex interactions in heterogeneous hybrid composites. Additionally, RSM models are valid only within the studied parameter range and may not accurately extrapolate beyond it. Therefore, while RSM provides strong interpretability and efficient optimization, it should be complemented in future studies with advanced techniques such as artificial neural networks or hybrid optimization algorithms for improved predictive capability (Table 1).

Results and discussion

Surface roughness

Both machining-induced damage responses, known as average SR and KA, were obtained under various machining variables (Table 2), and comprehensively analyzed.

Figure 4a–C depict three-dimensional (3D) response surface plots, which represent the interaction effects of various AWJM parameters upon SR during MFSC cutting. The plots show the joint effect of AJP, SoD, TS and AFR on the SR quality of the machined MFSC under different operating conditions. Figure 4a shows that the relationship between AJP and SoD produced similar effects on the SR when responding to different levels of AJP and SoD. For example, increasing AJP resulted in lower SR, with SR attaining its lowest value at 360 MPa, as depicted by the increasing negative slope of the SR curve (Fig. 4a).

The observed reduction in surface roughness (SR) with increasing abrasive jet pressure (AJP) is attributed to the enhanced kinetic energy of abrasive particles, which improves micro-cutting efficiency and reduces surface irregularities. However, this relationship is not strictly linear; the rate of improvement diminishes at higher pressure levels, indicating a saturation effect where further increases in AJP yield only marginal benefits. This suggests that beyond a threshold, material removal transitions from controlled erosion to more aggressive particle impact, which does not proportionally enhance surface quality.

This trend is consistent with recent studies (2023–2025) on AWJM of fiber-reinforced composites. However, the magnitude of SR reduction observed in this study (~27.23%) is comparatively higher, which can be attributed to the presence of titanium mesh layers that stabilize jet penetration and reduce fiber pull-out. In contrast, polymer-based composites often exhibit irregular erosion due to fiber–matrix debonding, leading to less uniform surface finishes.

Furthermore, the interaction between AJP and AFR reveals a synergistic effect, where increased abrasive availability promotes more uniform material removal across dissimilar material layers. This is particularly significant in hybrid laminates, where differences in hardness and ductility between titanium and fiber-reinforced layers can otherwise lead to uneven erosion. In contrast, increasing SoD resulted in increasing SR until it reached an approximate maximum of 4.756 μm , which occurs at higher SoD combined with lower AJP levels. Therefore, reducing the stand-off distance from 3.5 to 1.5 mm produced a minimum SR of around 3.209 μm , assuming the higher AJP was maintained. This observation reinforces that higher AJP enhances jet kinetic energy, improving abrasive penetration and material removal efficiency, thereby enhancing the overall cutting performance of the abrasive jet. Figure 4b illustrates the interaction effects of TS and AJP on SR. An increase in the TS from 80 to 180 mm/min resulted in an approximately 7.31% increase in SR at lower AJP levels.

Further analysis indicates that when TS is at the lower end of its range and AJP is at higher levels, SR is reduced, resulting in improved surface finish. Similarly, an increase in the AJP reduced the influence of the TS, while maximizing good SR characteristics across the entire pressure operating range. As shown in Fig. 4c, the interaction of AFR with AJP caused a noticeable decrease in SR when increasing the AFR from 0.25 to 0.45 kg/min. The overall drop in SR, because of an increase in AFR by 0.15 kg/min, was approximately 12.47%. The lowest SR recorded at an AFR of 0.45 kg/min at AJP of 300 MPa was approximately 3.22 μm . The higher AFR

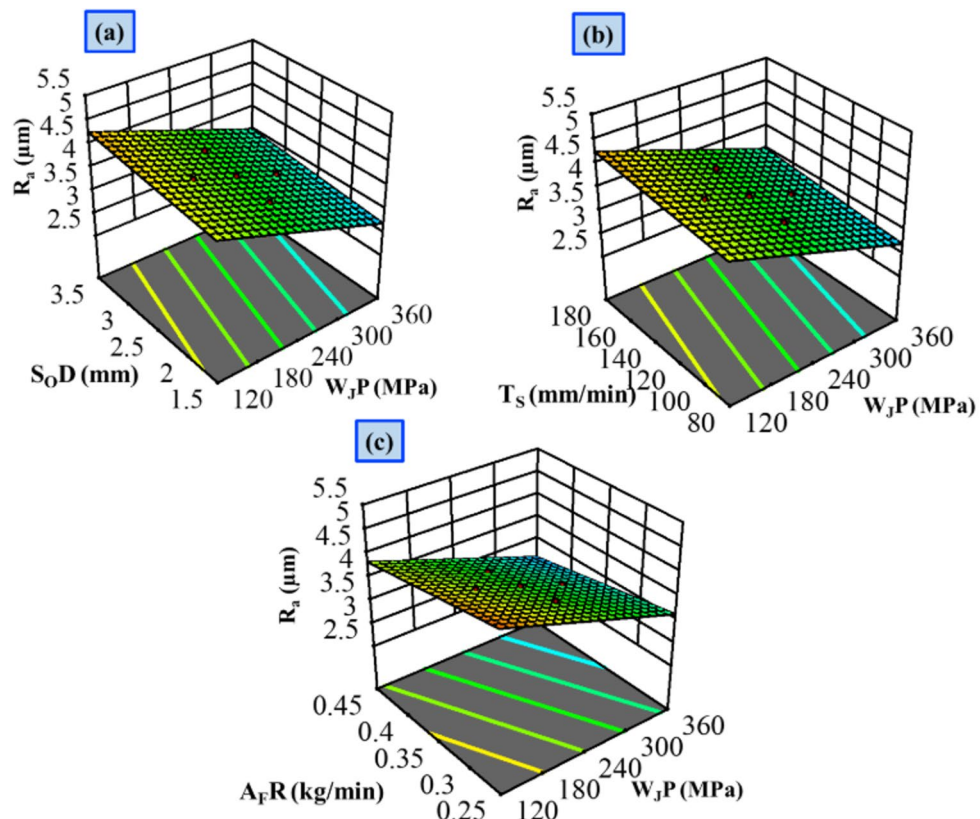


Fig. 4. (a)–(c) 3D plot and interaction of SR.

Source	Sum of squares	df	Mean square	F-value	p-value
Model	8.419664	4	2.104916	1177.145	3.74E-27
SoD	0.349091	1	0.349091	195.2243	5.04E-13
AFR	1.240947	1	1.240947	693.9825	3.19E-19
TS	0.324802	1	0.324802	181.6408	1.09E-12
AJP	6.504824	1	6.504824	3637.733	1.02E-27
Residual	0.042916	24	0.001788	–	–
Cor total	8.462579	28	–	–	–
$R^2 = 0.9949$		Adjusted $R^2 = 0.9941$		Predicted $R^2 = 0.9923$	

Table 3. ANOVA table for SR.

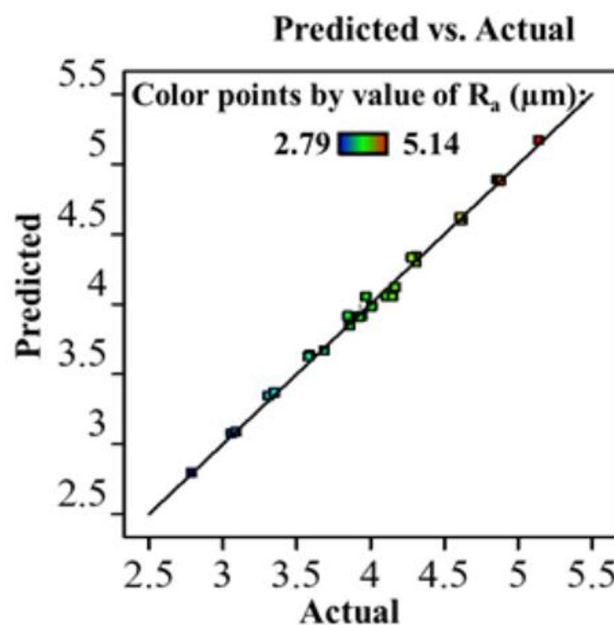


Fig. 5. Comparison between predicted and experimental values of the SR.

increased the availability of abrasive particles, promoting more uniform material removal, thereby allowing the finished material to have less SR. Therefore, the 3D response surfaces supported the conclusion that higher AJP and AFR, along with lower SoD and TS, result in reduced SR and improved machining quality. SR regression model is given by Eq. (1).

$$SR = 5.46 + 0.1454 (SoD) - 2.742 (AFR) + 0.0028 (TS) - 0.005232 (AJP) \quad (1)$$

The analysis of variance (ANOVA) data for SR are presented in Table 3, where both statistical significance and contribution of the individual machining parameters are included. The value of the F statistic of model of 1177.145 and the associated low p-value indicated that the regression model developed for this analysis is of high statistical significance and can be construed as accurately predicting SR (Table 3). The Coefficient of Determination (R^2) for this model was high (0.9949); therefore, it implied that 99.49% of the variation of SR was explained, using the regression model as previously established. The Adjusted R^2 (0.9941) and Predicted R^2 (0.9923) also demonstrated good agreement between each other and therefore confirm strong reliability and predictors based upon the model. With respect to the individual factors, AJP recorded the largest F statistic (3637.733), which implied the greatest influence on SR, and the p-value of AJP was much lower than 0.05 (1.02×10^{-27}). Hence, this indicated that it has a dominant effect. Other individual factors affecting SR were AFR, SoD and TS, and all of them have p-values less than 0.05; therefore, they had significant impact on SR. The Residual Mean Square for this Model was very low (0.001788), which implied that there was a very little experimental error present in the analysis. This established the adequacy of the model. To conclude on the ANOVA results, the parameters selected significantly affected the SR and were statistically suitable for use in optimization and prediction purposes. Figure 5 shows the comparison between predicted and experimental values of the SR values obtained.

The machining behavior of the TiBCBCBCTi laminate is strongly governed by the heterogeneous erosion response of its constituent layers. The titanium mesh exhibits predominantly ductile erosion behavior, where material removal occurs through localized plastic deformation and micro-cutting induced by high-velocity abrasive particles. In contrast, basalt fiber layers display relatively brittle fracture characteristics due to their high stiffness and mineral-based composition, leading to micro-fracture and fragmented material removal under abrasive impact. Carbon fiber layers exhibit anisotropic erosion behavior, where material removal depends on fiber orientation and matrix bonding strength, often resulting in localized fiber pull-out and matrix debonding.

During AWJM, the transition of the abrasive jet across these dissimilar layers produces non-uniform energy dissipation and varying erosion rates along the cutting path. The titanium mesh layers help stabilize jet propagation by constraining excessive lateral erosion, while the fiber-reinforced regions are more susceptible to irregular fracture and interfacial damage. This interaction between ductile metallic layers and brittle composite layers governs the overall surface integrity and contributes to variations in surface roughness and kerf geometry observed during machining.

The observed reduction in surface roughness with increasing abrasive jet pressure is consistent with previous AWJM studies on glass-fiber, carbon-fiber, and hybrid composites, where higher jet energy improved cutting efficiency and surface finish. However, the magnitude of improvement observed in the present study is comparatively greater. This difference may be attributed to the presence of titanium mesh layers, which provide additional structural support and stabilize abrasive jet penetration. Unlike conventional polymer composites that often exhibit extensive fiber pull-out and matrix cracking, the hybrid laminate promotes more controlled erosion, resulting in improved surface integrity. These findings indicate that material architecture plays a significant role in governing machining quality and should be considered alongside process parameters during optimization.

Kerf angle

Figure 6 illustrates the relationship between AJP and SoD on KA. The maximum KA (1.783°) was observed under low AJP and high SoD conditions. Increasing AJP from 120 to 360 MPa reduced KA by 20.12%, while SoD showed a positive correlation with kerf angle due to enhanced jet dispersion and energy dissipation prior to material impact. The KA regression model is expressed in Eq. (2).

$$KA = 2.03 + 0.040606SoD - 0.8969AFR + 0.000794 TS - 0.001535AJP \quad (2)$$

The reduction in KA with increasing AJP is attributed to improved jet coherence and increased particle momentum, which enhances penetration stability and suppresses lateral jet deflection. In the present hybrid laminate, this effect is further intensified by titanium mesh layers, which mechanically constrain jet spreading

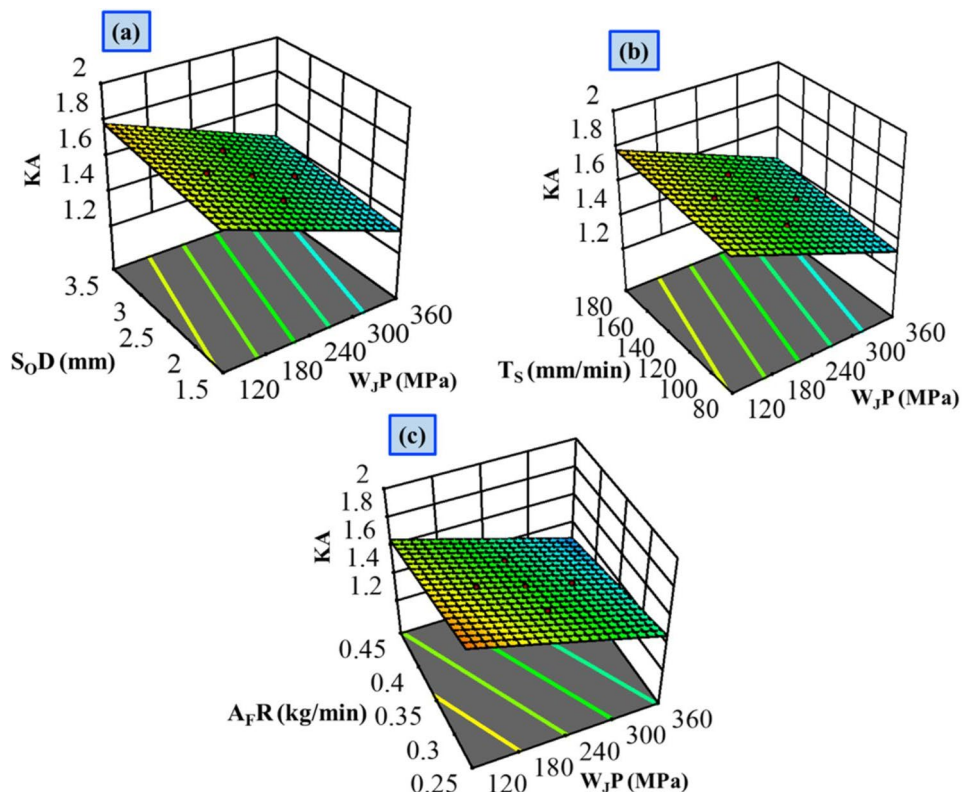


Fig. 6. 3D plot, showing the effect of relationship between AJP and SoD on KA.

and promote through-thickness kerf uniformity. This confirms that kerf formation is governed not only by process parameters but also by material architecture.

Compared with conventional AWJM studies, which primarily relate kerf taper to pressure and traverse speed, the present results highlight the dominant influence of interfacial heterogeneity. The metallic layers modify erosion progression by redistributing impact stresses and stabilizing jet–material interaction, an effect not captured in homogeneous composite models.

SoD further intensifies kerf formation due to increased jet divergence and kinetic energy loss prior to impact. Unlike previously reported linear trends, the present results show higher sensitivity, indicating that hybrid interfaces are more susceptible to jet energy attenuation. This necessitates stricter control of SoD during machining of multi-material systems.

The influence of AWJM parameters is further evident in the 3D response surfaces. Increasing traverse speed (TS) from 80 to 180 mm/min increases KA due to reduced jet–workpiece interaction time, resulting in incomplete material removal and increased taper formation.

KA increases with SoD, with an approximate 6.25% rise per 1 mm increase (1.5–3.5 mm), attributed to jet expansion and loss of kinetic energy prior to impact, which weakens penetration efficiency and increases top–bottom kerf mismatch. Higher AJP produces a more uniform kerf profile by enhancing jet momentum and improving penetration stability, thereby reducing taper. Similarly, increasing AFR (0.25 to 0.45 kg/min) reduces KA by ~10.92–11.52% due to improved abrasive availability and enhanced cutting efficiency, which limits jet deflection.

ANOVA confirms the robustness of the developed model ($F = 1177.145$, $p \ll 0.05$), with AJP identified as the most influential parameter ($F = 6435.532$). The high R^2 value (0.9972) confirms excellent predictive accuracy. Figure 7 compares experimental and predicted KA values, showing strong agreement.

The kerf formation mechanism can be further interpreted through combined micro-cutting, plastic deformation, and brittle fracture induced by high-velocity abrasive impact. At higher AJP, increased particle momentum stabilizes erosion and reduces lateral jet deviation. In hybrid laminates, titanium mesh redistributes impact energy across interfaces, reducing localized damage concentration and suppressing taper formation.

These findings may provide useful insight for other hybrid configurations such as metal–FRP laminates, sandwich composites, and functionally graded materials. However, additional experimental validation is required before broader generalization can be established.

From an industrial standpoint, the results provide direct guidance for precision AWJM of advanced hybrid structures used in aerospace, automotive, and energy applications. The study demonstrates that accurate kerf control requires simultaneous optimization of AJP and SoD, and that classical AWJM models developed for homogeneous materials are insufficient for multi-material systems.

Residual analysis was performed to validate model adequacy. The residual plots indicate that residuals are randomly distributed around zero, confirming the absence of systematic bias. Normal probability plots show approximate linearity, indicating that the normality assumption is satisfied. Furthermore, constant variance of residuals across predicted values confirms homoscedasticity. No significant outliers or influential data points

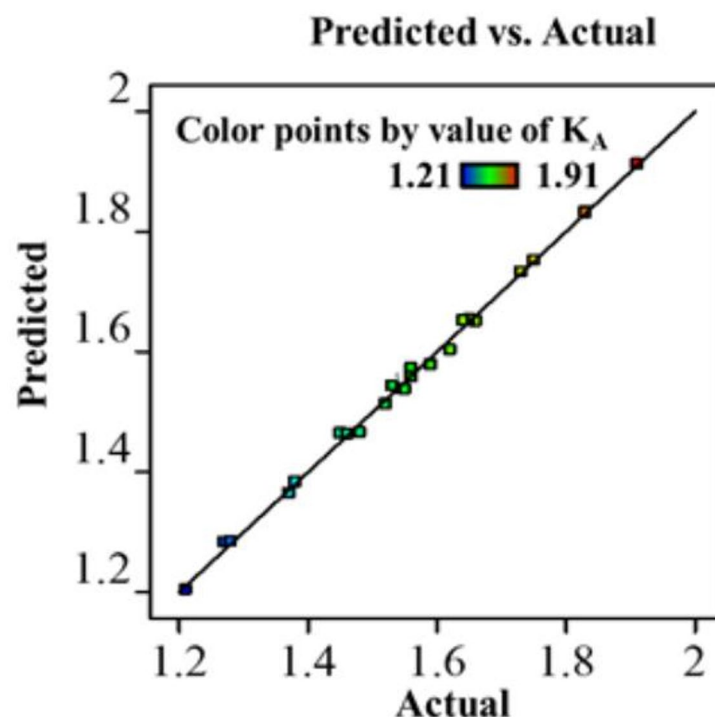


Fig. 7. Comparison between predicted and experimental values of KA.

were detected, demonstrating the stability and reliability of the regression models. These diagnostics confirm the suitability of the RSM models for predicting machining responses (Table 4).

The extremely low p-values (10^{-27} to 10^{-30}) confirm strong statistical significance of all process parameters. However, statistical significance does not necessarily imply equal practical importance. Based on F-values, abrasive jet pressure (AJP) is identified as the most dominant parameter, followed by abrasive flow rate (AFR), stand-off distance (SoD), and traverse speed (TS). From an engineering perspective, optimization should primarily focus on AJP and AFR, as they provide the highest improvement in machining performance. The high statistical significance may also be influenced by the controlled experimental conditions, which reduce variability and enhance model sensitivity. While this improves internal consistency, it may slightly limit broader generalisation.

The distinct erosion responses of the constituent materials also significantly influence kerf formation behavior. Titanium mesh layers resist excessive jet divergence due to their higher ductility and structural continuity, thereby reducing lateral kerf expansion. Conversely, basalt and carbon fiber regions experience localized brittle fracture, fiber breakage, and matrix erosion, which promote uneven material removal and taper development. At higher abrasive jet pressures, improved particle momentum enhances penetration consistency across all layers, minimizing interfacial discontinuities and reducing kerf angle. These observations confirm that kerf formation in hybrid laminates is governed not only by machining parameters but also by the combined erosion mechanics of metallic and fiber-reinforced phases.

The reduction in kerf angle with increasing abrasive jet pressure agrees with findings reported by Dahiya et al.²⁴ and Bekal et al.²⁵, who observed improved kerf uniformity due to enhanced particle momentum and penetration capability. Nevertheless, the present hybrid laminate exhibited greater sensitivity to stand-off distance than many conventional composite systems. This behavior is attributed to the heterogeneous metal–fiber interfaces, where differences in hardness, ductility, and erosion resistance influence jet energy dissipation and kerf development. Therefore, while the general trends are consistent with existing literature, the quantitative responses differ because of the complex multi-material architecture investigated in this study.

Desirability approach for optimization and validation

Desirability analysis

The desirability-based multi-response optimisation approach employed in this study is a well-established and widely adopted method in machining research. While it does not represent a novel optimisation algorithm, its strength lies in its simplicity, transparency, and ease of implementation for engineering applications. Unlike more complex optimisation techniques, the desirability function provides an interpretable framework that enables simultaneous optimisation of multiple responses without requiring extensive computational resources or large datasets. This makes it particularly suitable for experimental studies with limited runs, such as the present CCD-based design.

Recent studies have increasingly explored advanced multi-objective optimisation techniques, including metaheuristic algorithms such as genetic algorithms (GA) and particle swarm optimisation (PSO), as well as hybrid approaches integrating artificial neural networks (ANN). These methods offer advantages in exploring global optima and handling highly nonlinear relationships between process parameters and responses. However, they typically require larger datasets, increased computational effort, and may lack direct physical interpretability.

In contrast, the desirability-based RSM approach used in this study enables clear identification of parameter–response relationships while maintaining statistical rigor. Although it may not capture highly complex nonlinearities to the same extent as machine learning-based models, it provides a balanced trade-off between accuracy, interpretability, and experimental feasibility. Therefore, the present approach is particularly suitable for initial process optimisation and understanding of machining behavior in complex hybrid laminates.

Optimizing the input parameters, including abrasive jet pressure (AJP), stand-off distance (SoD), traverse speed (TS), and abrasive flow rate (AFR), was aimed at minimizing the AWJM responses, namely surface roughness (SR) and kerf angle (KA). As expressed in Eq. (3), the individual desirability function, (d_i), transforms each response into a normalized desirability value:

$$d_i = \left(\frac{Max_i - R_i}{Max_i - Min_i} \right)^{w_i}$$
 (3)

Source	Sum of squares	df	Mean square	F-value	p-value
Model	0.7461	4	0.1865	2143.05	3.24E-27
SoD	0.027206	1	0.027206	312.5985	2.88E-15
AFR	0.132752	1	0.132752	1525.3190	3.10E-23
TS	0.026002	1	0.026002	298.7582	4.77E-15
AJP	0.560097	1	0.560097	6435.5320	1.12E-30
Residual	0.002089	24	8.70E-05		
Cor total	0.748145	28			
R ² = 0.9972		Adjusted R ² = 0.9967		Predicted R ² = 0.9957	

Table 4. ANOVA results for KA.

Overall desirability equation:

$$D = (d_1 \times d_2 \times \dots \times d_n)^{1/n}$$

where (Max_i) and (Min_i) denote the upper and lower limits of the i^{th} response, respectively, (R_i) denotes the predicted response value, and (W_i) represents the weight assigned to the (i^{th}) response. The desirability value ranges from 0 to 1, where 0 indicates a completely undesirable response and 1 indicates a fully desirable response.

The overall desirability was used to identify the optimal parameter combination that yielded minimum SR and KA under the specified constraints. Higher desirability values correspond to improved machining performance. Figure 8a depicts the perturbation plots for the composite responses, illustrating the relative influence of each input parameter on the optimization outcome.

The RSM was employed to create a response region, which is displayed through the perturbation plots. These plots are useful for displaying how individual input parameters interacted with each other and their effect on global desirability by assuming that all the other variables remained constant. By analyzing the trends associated with the process variables; the SR and KA, it was evident from the results obtained from this study that while the desirability increased with an increase in AJP and AFR, there was a much smaller response associated with SoD and TS. Based upon the magnitude of the desirability ranking, AJP was the most influential parameter, followed by AFR, SoD and finally TS, regarding the responses produced by the AWJC process. The bar graph presented in Fig. 8b depicts the inclusion of the parameters TS, AJP, SoD and AFR, and indicated that they all achieved desirability values of 1.0, which indicated their compliance with all of the optimization objectives of this research. The Ramp Function presented in Fig. 8c depicts the predicted optimal process conditions for MFSC machining at AJP of 360 MPa, SoD of 1.50 mm, TS of 80 mm/min and AFR of 0.45 kg/min. Finally, the Cube Plot shown in Fig. 8d depicts the high desirability condition of both AJP and AFR when at their respective highest levels and SoD and TS when at their respective lowest levels. Under these conditions, uniform material erosion occurred, resulting in narrower kerf widths and smoother surfaces. In summary, Fig. 8a–d depict the effective evaluation of the relationships among all the four main input parameters for the AWJM process.

From a practical manufacturing perspective, the optimized parameter combination (AJP = 360 MPa, SoD = 1.5 mm, TS = 80 mm/min, AFR = 0.45 kg/min) provides clear guidelines for achieving improved surface quality and dimensional accuracy in AWJM of hybrid laminates. The reduction in surface roughness and kerf taper directly translates to reduced need for secondary finishing operations, improved assembly fit, and enhanced structural integrity of machined components.

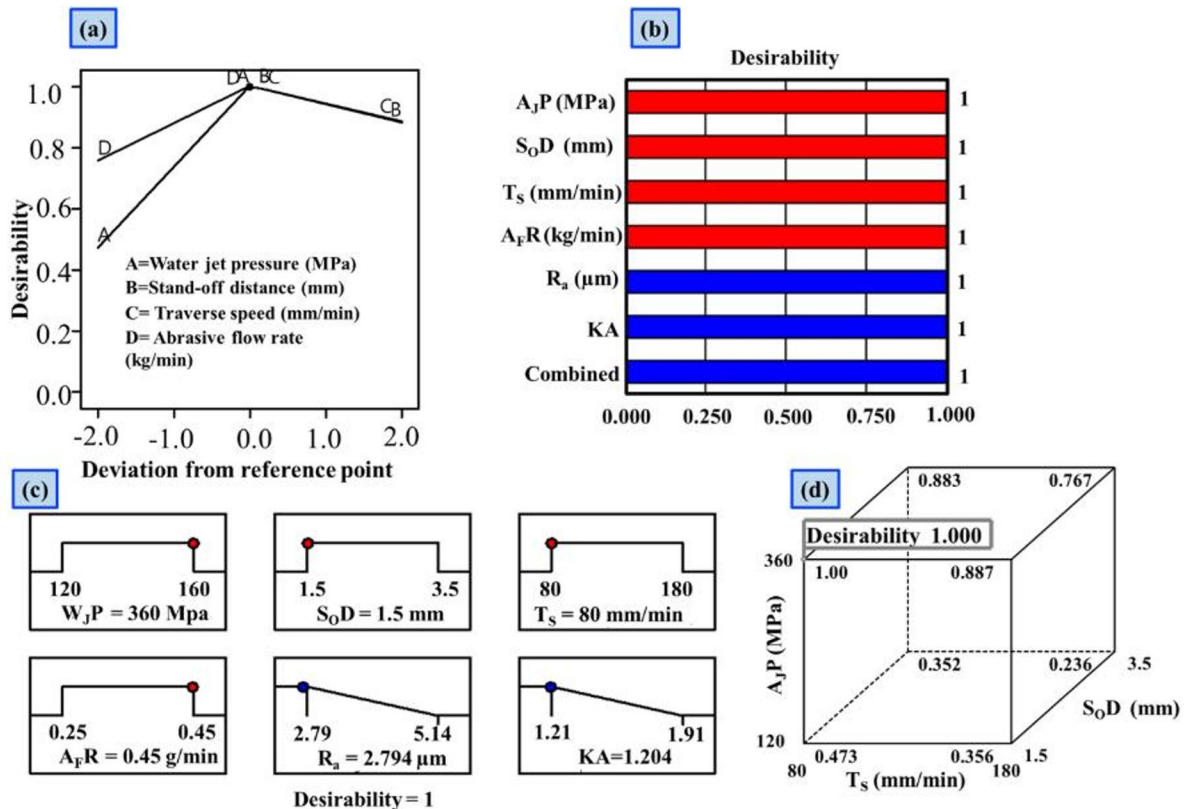


Fig. 8. (a)–(d) Perturbation, bar graph, ramp and cube plots.

SoD (mm)	AFR (kg/min)	TS (mm/min)	AJP (MPa)	Desirability	Predicted		Actual		Error %	
					SR	KA	SR	KA	SR	KA
1.5	0.45	80	360	1.00	2.794	1.204	2.798	1.218	0.140	1.160
1.7	0.45	80	359	0.97	2.826	1.213	2.843	1.229	0.610	1.310
1.5	0.43	82	349	0.93	2.846	1.220	2.861	1.245	0.520	2.040

Table 5. Validation of RSM model with confirmatory experimental results.

In industrial environments, where consistency and repeatability are critical, the ability to identify a stable operating window is more valuable than achieving a theoretical global optimum. The desirability-based approach facilitates this by providing a robust and easily implementable solution that can be readily adopted in CNC-based AWJM systems.

Furthermore, the findings are particularly relevant for industries such as aerospace and automotive manufacturing, where hybrid composite materials are increasingly used. The optimized parameters have the potential to reduce machining defects, improve dimensional accuracy, and decrease the need for secondary finishing operations. However, additional industrial-scale validation would be beneficial before broader implementation.

Experimental validation

The predictive capability of the developed RSM models was evaluated using confirmatory experiments at selected optimal and near-optimal conditions. The observed prediction error for both surface roughness (SR) and kerf angle (KA) was below 5%, indicating good agreement between model predictions and experimental results within the studied design space.

However, this validation primarily reflects internal consistency within the experimental domain due to the limited number of confirmatory runs. Therefore, the developed models should be interpreted as reliable only within the investigated parameter ranges, and caution is required when extrapolating beyond these conditions.

No independent external validation dataset was employed in the present study due to the experimental nature and limited dataset size typical of CCD-based investigations. While such datasets are common in data-driven and machine learning approaches, their generation in abrasive water jet machining experiments is often resource-intensive.

Overall, the low prediction error (<5%) confirms the adequacy of the developed models within the experimental domain and supports their suitability for process analysis and optimization of hybrid composite machining.

The developed RSM models produced exceptionally high coefficients of determination ($R^2 = 0.9949$ for surface roughness and $R^2 = 0.9972$ for kerf angle). Although these values indicate excellent agreement between experimental and predicted responses, they should not be interpreted as definitive evidence of universal predictive capability. The high R^2 values are likely influenced by the structured Central Composite Design (CCD), controlled machining conditions, and relatively low experimental noise observed during testing. Therefore, the models demonstrate strong predictive performance within the investigated design space rather than across all possible AWJM operating conditions.

To mitigate concerns regarding overfitting, additional statistical indicators were evaluated. The close agreement between R^2 , adjusted R^2 , and predicted R^2 suggests that the models retain predictive consistency and do not exhibit substantial loss of predictive power. Residual analyses further confirmed random error distribution and the absence of systematic bias. Nevertheless, because the models were developed from 29 experimental runs within a specific parameter range, their applicability outside the investigated domain should be considered with caution.

The high model accuracy is primarily attributed to the controlled CCD-based experimental design and the relatively low variability observed during machining trials. Sensitivity analysis based on ANOVA results confirmed that abrasive jet pressure (AJP) is the dominant governing parameter, followed by abrasive flow rate (AFR), stand-off distance (SoD), and traverse speed (TS), indicating stable parameter–response relationships within the selected operating range.

However, because the models were developed using a limited experimental dataset, extrapolation beyond the studied parameter space may introduce increased prediction uncertainty, particularly under extreme machining conditions or different laminate configurations. In industrial applications, process variations such as nozzle wear, abrasive quality fluctuations, and material inconsistencies may also influence machining behavior. Therefore, the present models should be considered reliable primarily within the investigated parameter window and for similar hybrid laminate systems. Future studies may incorporate larger datasets, cross-validation strategies, and hybrid data-driven approaches to further improve model robustness and generalisation capability under broader manufacturing conditions (Table 5).

Conclusion

This study investigated the abrasive water jet machining (AWJM) of TiBCBCBCTi hybrid laminates and developed predictive models for surface roughness (SR) and kerf angle (KA) using Response Surface Methodology (RSM). Among the investigated parameters, abrasive jet pressure (AJP) exhibited the greatest influence on machining performance, followed by abrasive flow rate (AFR), stand-off distance (SoD), and traverse speed (TS).

The desirability-based optimization identified the optimal machining conditions as $AJP = 360$ MPa, $AFR = 0.45$ kg/min, $SoD = 1.5$ mm, and $TS = 80$ mm/min. Under these conditions, significant reductions in SR and KA were achieved, demonstrating improved machining quality and dimensional accuracy. The developed RSM models showed strong predictive capability, with prediction errors below 5% and coefficients of determination exceeding 0.99 within the investigated parameter range.

The results further revealed that machining behavior is strongly influenced by the heterogeneous architecture of the laminate. The interaction between ductile titanium mesh layers and brittle basalt/carbon fiber composite layers governs erosion behavior, surface integrity, and kerf formation, highlighting limitations of conventional AWJM models developed for homogeneous materials.

Overall, the results demonstrate that AWJM is a promising low-thermal machining technique for TiBCBCBCTi hybrid laminates, capable of producing improved surface quality and kerf characteristics within the investigated operating conditions. Future studies should focus on larger datasets, advanced data-driven modeling approaches, and broader validation across different hybrid composite configurations.

Data availability

The dataset generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 17 February 2026; Accepted: 16 July 2026

Published online: 21 July 2026

References

- Mahmud, S. H. et al. Fabrication and mechanical performance investigation of jute/glass fiber hybridized polymer composites: effect of stacking sequences. *Next Mater.* **5**, 100236 (2024).
- Chowdhury, I. R. & Summerscales, J. Woven fabrics for composite reinforcement: a review. *J. Compos. Sci.* **8**, 280 (2024).
- Wang, H., Guo, J. & Liu, Z. Tensile properties and failure of hybrid fiber reinforced polymer composite laminate with different fiber types, hybrid ratios, and stacking sequences. *Polym. Compos.* **46**, 9348–9364 (2025).
- Al-Furjan, M. S. H. et al. A review on fabrication techniques and tensile properties of glass, carbon, and Kevlar fiber reinforced polymer composites. *J. Mater. Res. Technol.* **19**, 2930–2959 (2022).
- Husain, A., Khan, S. H. & Mourad, A. H. I. Stacking sequence effects on flexural stiffness, failure progression, and energy absorption in asymmetric CFRP laminates. *Results Eng.* **105863** (2025).
- Kumar, K. et al. Exploration of stacking effects of carbon/glass fabric in polymer hybrid composites: analysis of mechanical properties. *Discover Appl. Sci.* **6**, 636 (2024).
- Venkatasudhahar, M., Ravichandran, A. T. & Dilipraja, N. Effect of stacking sequence on mechanical and moisture absorption properties of abaca-kenaf-carbon fiber reinforced hybrid composites. *J. Nat. Fibers.* **19**, 7229–7240 (2022).
- Margabandu, S. & Subramaniam, S. K. Influence of fiber stacking sequences and matrix materials on mechanical and vibration behavior of jute/carbon hybrid composites. *World J. Eng.* **19**, 639–651 (2022).
- Saleh Mousavi-Bafrouyi, S. M., Eslami-Farsani, R. & Geranmayeh, A. Effect of stacking sequence on the mechanical properties of pseudo-ductile thin-ply unidirectional carbon-basalt fibers/epoxy composites. *J. Ind. Text.* **51**, 2835S–2852S (2022).
- Ramraji, K., Rajkumar, K., Rajesh, M. & Gnanavelbabu, A. A comparative study on abrasive water jet machining characteristics of entry and exit layers of glass and basalt woven polymer composites. In *ICMechD 2019 Proceedings*, 27–37 (2020).
- Fadil, D., Erklig, A. & Bulut, M. The influence of fiber stacking sequence on the mechanical and impact performance of sustainable epoxy/basalt/aramid-balsa sandwich composites. *Polym. Adv. Technol.* **36**, e70465 (2025).
- Kirubakaran, R., Kaliyamoorthy, R., Munusamy, R. & Annamalai, B. Mechanical and vibration behavior of surface-modified titanium sheet interleaved with woven basalt/flax fiber metal laminates. *Polym. Compos.* **44**, 8442–8453 (2023).
- Karuppasamy, A., Kirubakaran, R., Gopalan, V., Munusamy, R. & Krishnasamy, K. Influences of basalt fiber position and addition on the mechanical and viscoelastic behaviors of steel mesh/flax/basalt fiber metal laminates. *Iran. Polym. J.* **34**, 1167–1179 (2025).
- Singh, C. Q. J., Krishnasamy, G. R., Suttrave, P., Jain & S. & A. A review on wire mesh reinforced polymer composite. *Polymer-Plastics Technol. Mater.* **62**, 1067–1076 (2023).
- Rajamurugan, G. Mechanical properties of hybrid composites with alternately woven carbon/glass fibers on stainless steel wire mesh. *Results Eng.* **106066** (2025).
- Bilal, M., Jamil, T., Wasif, M. & Ul Ahad, I. Impact of fiber orientation and stacking sequence on drilling-induced delamination in CFRP laminates. *Int. J. Interact. Des. Manuf.* **1**–9 (2025).
- Du, J., Geng, M., Ming, W., He, W. & Ma, J. Simulation machining of fiber-reinforced composites: a review. *Int. J. Adv. Manuf. Technol.* **117**, 1–15 (2021).
- Nguyen-Dinh, N., Hejjaji, A., Zitoun, R., Bouvet, C. & Crouzeix, L. Machining of FRP composites: surface quality, damage and material integrity. In *Futuristic Composites: Behavior, Characterization, and Manufacturing*, 1–35 (2018).
- Slamani, M. & Chatelain, J. F. A review on machining of polymer composites reinforced with carbon, glass, and natural fibers. *Discover Mech. Eng.* **2**, 4 (2023).
- Doğan, M. A., Gemi, L., Yazman, Ş., Ceritbinmez, F. & Yapici, A. Effect of hybridization and stacking sequence on damage development in AWJ machining of Al/FRP/Al FML composites. *J. Manuf. Process.* **131**, 141–159 (2024).
- Chenrayan, V. et al. Experimental and empirical assessment of machining damage of hybrid glass–carbon FRP composite during AWJM. *J. Mater. Res. Technol.* **19**, 1148–1161 (2022).
- Madhu, S. & Balasubramanian, M. Challenges in abrasive jet machining of fiber-reinforced polymeric composites: a review. *World J. Eng.* **18**, 251–268 (2021).
- Esakkiraj, E. S. et al. Enhanced mechanical and thermomechanical performance of basalt–carbon hybrid composites reinforced with titanium wire mesh. *J. Mater. Res. Technol.* **39**, 4963–4972 (2025).
- Dahiya, A. K., Bhuyan, B. K. & Kumar, S. Abrasive water jet machining of GFRP composites: experimental investigation, modelling and optimization. *Int. J. Interact. Des. Manuf.* **17**, 1933–1947 (2023).
- Bekal, S. M., Hiremath, A., BRN, M., MC, G. S. & K, S., BM, G. & Optimization of process parameters for minimum kerf taper angle and surface roughness in abrasive water jet machining of a hybrid composite. *J. Compos. Sci.* **9**, 604 (2025).
- BRN, M., Beedu, R., PK, J. & Potti, S. R. Study on machining quality in abrasive water jet machining of jute-polymer composite using grey relational analysis. *J. Compos. Sci.* **8**, 20 (2024).
- Altın Karataş, M., Gökaya, H., Akıncioğlu, S. & Biberici, M. A. Assessment of abrasive water jet drilling parameters on glass fiber-reinforced polymer composites. *J. Elastomers Plastics* (2025).
- Jagadish, Bhowmik, S. & Ray, A. Prediction and optimization of process parameters of green composites in AWJM process using response surface methodology. *Int. J. Adv. Manuf. Technol.* **87**, 1359–1370 (2016).

29. Gnanasekaran, K., Rajesh, M. & Hariram, V. Optimization of abrasive water jet parameters for metal-stacked hybrid fiber laminate. *J. Mater. Eng. Perform.* **34**, 14708–14721 (2025).
30. Thakur, R. K. & Singh, K. K. Abrasive waterjet machining of fiber-reinforced composites: a state-of-the-art review. *J. Brazilian Soc. Mech. Sci. Eng.* **42**, 381. <https://doi.org/10.1007/s40430-020-02463-7> (2020).
31. Subramani, K., Vasudevan, A., Karthik, K. & Kolappan, S. Insights of abrasive water jet polishing process characteristics and its advancements. *Mater. Today: Proc.* **52**, 1113–1120 (2022).
32. Kartal, F. Abrasive water jet machining of carbon fiber-reinforced PLA composites. *Polymers* **17**, 445. <https://doi.org/10.3390/poly17040445> (2025).
33. Hashish, M. Abrasive waterjet machining. *Materials* **17**, 3273. <https://doi.org/10.3390/ma17133273> (2024).
34. Vasudevan, B., Nagarajan, L. A. K., Siva Kumar, M., Panchal, H. & Siddiqui, M. I. H. Experimental study, modeling, and parametric optimization on abrasive waterjet drilling of YSZ-coated Inconel 718 superalloy. *J. Mater. Res. Technol.* **29**, 4662–4675. <https://doi.org/10.1016/j.jmrt.2024.02.134> (2024).

Acknowledgements

The authors acknowledge the funding from the Ongoing Research Funding Program (ORF-2026-355), King Saud University, Riyadh, Saudi Arabia.

Author contributions

E. S. Esakkiraja: Conceptualization, experimental design, fabrication of hybrid stacked composites, abrasive water jet machining experiments, data acquisition, and original draft preparation. Sikiru O. Ismail: Design of experiments (DoE), statistical analysis, response surface methodology (RSM) modeling, multi-response optimization, data interpretation, and manuscript review. N. Rajini*: Supervision, conceptual guidance, methodology validation, results interpretation, critical revision of the manuscript, and overall project administration. Faruq Mohammad: Materials characterization, surface roughness and kerf angle measurements, experimental validation, and data curation. Kumar Krishnan: Manufacturing support, compression molding of laminated composites, machining setup optimization, and technical assistance during experimentation. M. P. Indira Devi: Literature survey, sustainability assessment of materials and processes, graphical preparation, and manuscript editing.

Funding

The authors acknowledge the funding from the Ongoing Research Funding Program (ORF-2026-355), King Saud University, Riyadh, Saudi Arabia.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to E.S.E. or N.R.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026