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A Review of Abrasive Water Jet Cutting Technology for Composite Materials

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Abstract: *With the growing demand for high-precision and high-reliability machining of composite materials in aerospace, automotive, and electronics industries, abrasive waterjet (AWJ) technology has emerged as a promising method for cutting non-metallic composites due to its cold cutting nature and multi-material adaptability. Compared with pre-2020 studies that mainly focused on parameter trials, recent research has shifted towards modeling of cutting-induced damage, microstructure-level precision control, intelligent optimization, and real-time monitoring, indicating a dual advancement in mechanism understanding and system-level integration. This review summarizes typical damage modes and modeling methods in AWJ cutting of composite materials, compares the applicability of various predictive models and quality indicators, and evaluates representative optimization strategies across different composite systems. Furthermore, it highlights trends in AWJ system intelligence, including acoustic emission monitoring, AI-based modeling, and the integration of digital twin technologies. Future challenges are identified, such as multi-scale modeling of damage-performance coupling, closed-loop process control, and standardized quality assessment frameworks. This review aims to provide structured insights and forward-looking references for advancing AWJ in composite precision manufacturing.*

Keyword: *Abrasive Waterjet (AWJ); Composite Cutting; Damage Modeling; Parameter Optimization; Smart Manufacturing.*

Introduction

Abrasive Water Jet (AWJ) technology, as a key technique in the field of modern precision machining, has demonstrated significant potential in the cutting of hard-to-machine materials, particularly fiber-reinforced composites. Since its initial application in cleaning and mining in the early 20th century, the technology has undergone continuous development. In the 1970s, Professor Norman Franz introduced the concept of adding abrasive particles to the waterjet, which significantly improved its cutting performance and eventually established AWJ as a prominent method for machining metals, non-metals, and composites [1]. With rapid advancements in ultra-high-pressure pumps, jet control systems, and abrasive materials, the operating pressure of AWJ has markedly increased, and the types of abrasives have diversified (e.g., garnet, alumina, silicon carbide). These innovations have substantially improved its machining efficiency and cutting quality. In non-metallic composite processing, such as carbon fiber reinforced polymers (CFRP) and aramid fiber reinforced polymers (AFRP), AWJ offers non-contact and thermally neutral machining advantages, thereby effectively avoiding common problems such as thermal damage, tool wear, and edge degradation frequently observed in traditional machining [2].

Compared to the trial-and-error paradigm dominated by parameter-based experimentation prior to 2020, studies since 2020 have increasingly shifted toward modeling the evolution of microscale damage, implementing multi-objective optimization in complex structures, and enhancing real-time sensing and system integration capabilities. This reflects a dual trend toward theoretical refinement and system-level intelligence. Despite the clear advantages of AWJ in cutting performance, typical defects such as delamination, fiber pullout, matrix tearing, and abrasive embedment remain prevalent in practice [3]. In addition, cutting depth is significantly affected by jet morphology, abrasive particle size distribution, and nozzle parameters [4]. Furthermore, AWJ still faces challenges in maintaining

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high-precision control when machining complex geometries and microscale features, which is critical for ensuring edge quality in high-end manufacturing [5]. Recent studies have therefore focused on integrating jet modeling, intelligent parameter optimization, sensing-based monitoring, and quality prediction systems [6].

This review aims to systematically summarize the advances of AWJ technology in the cutting of non-metallic composites since 2020, with emphasis on the influence of process parameters on cutting quality, the mechanisms and prediction models of typical damage forms, as well as representative optimization methods and advanced system integration strategies. Although AWJ has also demonstrated wide applicability in the cutting of metals, this review specifically focuses on its mechanism modeling, defect suppression, and quality enhancement strategies in non-metallic composite machining.

Current Applications and Challenges of AWJ in Composite Cutting

Abrasive Water Jet (AWJ) technology, owing to its high precision, minimal thermal impact, and compatibility with diverse materials, has found widespread application in modern manufacturing. It has demonstrated particular advantages in high-end sectors such as aerospace, automotive engineering, and shipbuilding [7]. In these industries, fiber-reinforced composites are extensively used due to their low weight, high strength, and excellent corrosion resistance. The non-contact, cold-state cutting nature of AWJ technology effectively avoids thermal-affected zones and tool wear, making it a preferred method for achieving high-precision machining of composites [2].

The cutting response of different composite types significantly influences the adaptability of AWJ technology. For instance, carbon fiber reinforced polymers (CFRP), aramid fiber reinforced polymers (AFRP), and glass fiber reinforced polymers (GFRP) exhibit distinct behaviors during AWJ machining. CFRP, characterized by its high strength and anisotropic structure, is prone to fiber pullout and interlayer delamination during cutting. However, these defects can be mitigated by optimizing parameters such as jet pressure, abrasive grit size, and traverse speed, thereby improving kerf quality [8]. In contrast, AFRP, due to the high toughness and low density of aramid fibers, tends to exhibit abrasive embedment and burr formation. Nevertheless, under suitable pressure and abrasive flow conditions, high-quality cuts can still be achieved [9]. For GFRP, the brittle nature of glass fibers makes the cutting process more sensitive to jet energy and abrasive type. Optimizing jet parameters can reduce crack propagation and enhance surface integrity [10].

Table 1 provides a comparative summary of the AWJ cutting characteristics across three representative fiber-reinforced composites, highlighting their advantages, challenges, and recommended optimization strategies.

Moreover, AWJ technology is not limited to composites; it has also been widely applied in the high-precision machining of metals, ceramics, glass, and homogeneous polymers. Representative applications include components for aerospace engines, intelligent vehicle structures, and advanced medical devices [11]. The inherent flexibility of AWJ cutting allows it to meet the evolving demands of modern manufacturing for complex geometries, high-quality surface finishes, and efficient material removal.

The distinct cutting responses and defect modes summarized in Table 1 are fundamentally governed by the intrinsic physical and mechanical properties of the constituent materials. A deeper understanding of these properties is crucial for selecting appropriate AWJ parameters and interpreting the underlying damage mechanisms.

CFRP, characterized by its high-strength, brittle fibers and pronounced anisotropy, is highly prone to delamination due to interlaminar stress from the water hammer effect and impact stress waves. Surface quality is primarily determined by the transition between brittle fiber fracture (under optimal parameters, yielding a smoother surface) and fiber pull-out (under insufficient energy, increasing roughness).

AFRP, characterized by its tough, compliant fibers and relatively weak fiber-matrix interface, exhibits a distinct damage profile.

Table 1. Comparison of AWJ Cutting Characteristics of CFRP, AFRP, and GFRP Composites

Material Type	Main Advantages	Major Cutting Challenges	Recommended AWJ Optimization Strategies
CFRP	High strength, lightweight	Prone to delamination, fiber pull-out	Increase jet pressure, reduce stand-off distance, improve abrasive purity
AFRP	High toughness, Impact resistance	Abrasive embedment, burr formation	Use finer abrasive particles, optimize feed rate, adjust abrasive flow
GFRP	High rigidity, chemical corrosion resistance	Cracking, high surface roughness	Control jet energy, optimize abrasive type, reduce traverse speed

GFRP, with its brittle glass fibers and typically good interfacial bonding, exhibits mechanisms similar to CFRP. The key challenges are micro-cracking that propagates to the surface (increasing roughness) and along ply interfaces (promoting delamination), as well as noticeable matrix erosion from the abrasive stream.

Although abrasive waterjet (AWJ) technology offers several advantages in composite machining, it still faces a range of technical challenges. The primary issues include the optimization of cutting depth and precision, achieving uniform cutting in multilayer composites, and addressing key factors that affect cutting efficiency. These problems not only constrain the application of AWJ in high-precision manufacturing but also compromise its reliability in processing complex composite structures [12].

The purpose of this study is to systematize developments in the field of ensuring the quality of processing composite materials with an AWJ.

Material and results

Optimization of cutting depth and precision. The cutting depth in AWJ machining is primarily influenced by jet energy, abrasive flow rate, and material properties. Studies have shown that increasing the waterjet pressure can improve material removal rates; however, excessive pressure may result in increased kerf taper, thus compromising dimensional accuracy [13]. Additionally, factors such as jet morphology, abrasive particle size distribution, and the stand-off distance between the nozzle and the workpiece significantly affect cutting accuracy. For example, an excessively large stand-off distance may cause jet dispersion, leading to degraded edge quality, whereas a smaller stand-off distance can improve cutting precision but may reduce the cutting depth [14]. In recent years, researchers have adopted fluid dynamic modeling and AI-based optimization techniques-such as artificial neural networks (ANN) and response surface methodology (RSM) – to enhance cutting precision and optimize key process parameters, thereby improving overall cutting quality [6].

Uniformity in multilayer composite cutting. Composite materials are typically composed of various reinforcement fibers and matrix layers. Due to their anisotropic nature, AWJ cutting often results in uneven material removal between layers, delamination, and crack propagation [15]. In CFRP/metal hybrid laminates, the differences in cutting behavior between the metallic and fiber-reinforced layers-attributable to the metal layer's energy absorption and reflection-can lead to severe interfacial damage and intensified delamination [16]. Additionally, the interfacial bonding strength between internal layers greatly influences AWJ cutting quality. Interfaces between dissimilar matrices may act as crack initiation sites, compromising the overall structural integrity [17]. To improve the cutting quality of multilayer composites, researchers have recently proposed strategies such as adjusting the jet incident angle, modifying abrasive flow rate, and adopting stepwise cutting approaches. These methods help reduce interlaminar stress concentration during cutting, thereby enhancing uniformity and mitigating delamination defects[9].

Limiting factors of AWJ cutting efficiency. In addition to material properties and process parameters, AWJ cutting efficiency is also constrained by abrasive quality, jet stability, and nozzle wear. Abrasive quality directly influences the cutting performance of AWJ. High-purity abrasives with uniform particle size (e.g., garnet) help reduce nozzle clogging, enhance cutting efficiency, and minimize surface damage [18]. However, the high cost of premium abrasives may limit their widespread application in industrial settings. Moreover, nozzle wear is a critical factor affecting the stability of AWJ cutting. Deformation of the nozzle shape due to wear can lead to jet divergence, reducing both cutting depth and precision. Studies have shown that using wear-resistant materials (e.g., tungsten carbide or polycrystalline diamond) for nozzle fabrication can extend nozzle life and help maintain stable cutting quality [19].

So, comparative Analysis with Alternative Machining Techniques will be next.

Although AWJ technology demonstrates considerable potential in composite material machining, its performance merits and development bottlenecks should be evaluated within a broader spectrum of advanced cutting technologies. To this end, it is essential to conduct a horizontal comparison between AWJ and other mainstream composite machining methods – such as high-power fiber laser (HPFL), conventional drilling (CD), and ultraviolet laser (UVL) – to clarify its positioning in practical applications and inform directions for further improvement [20].

Taking carbon fiber reinforced polymer (CFRP) laminates as an example, Li et al. conducted a systematic comparison of these four methods in terms of hole quality, retention of mechanical performance, and geometric accuracy. The findings indicate that AWJ, due to its inherent cold-cutting nature, excels at minimizing thermal damage, making it particularly advantageous for thermally sensitive composites. However, it shows relative disadvantages in maintaining circularity and cut-edge consistency, which require compensation through parameter control and optimized path planning [21].

A comparative analysis of typical cutting technologies is presented in Table 2, with emphasis on their process advantages, inherent constraints, and application compatibility across composite materials.

Advances in Cutting Mechanisms and Multiscale Material Response Modeling

The fundamental process of abrasive waterjet (AWJ) cutting relies on high-pressure water streams carrying high-velocity abrasive particles that impact and erode the material surface, thereby achieving effective material removal. The underlying mechanism of this non-traditional

Table 2. Comparison of Various Cutting Technologies

Cutting Method	Main Advantages	Main Limitations
AWJ	No thermal effect, suitable for various materials	Large roundness deviation, requires parameter optimization
Laser Cutting (HPFL)	High precision, applicable to complex shapes	Large heat-affected zone, potential thermal damage
High-Speed Milling (HSM)	High surface quality, suitable for metals	Severe tool wear, high processing cost
Ultraviolet Laser (UVL)	Best circularity, ideal for micro-machining	Low efficiency, high cost

machining method consists of two key components: the transient stress waves generated by the waterjet and the high-energy impact and shear-induced erosion by abrasive particles [22]. During the cutting process, particle impacts induce multiscale damage responses in the material matrix, such as micro-delamination, crack propagation, and fiber breakage. These dynamic interactions ultimately determine the quality and stability of the resulting kerf [23]. Previous studies have shown that abrasive particles undergo diameter reduction, secondary edge sharpening, and changes in energy distribution during high-speed jetting. These evolutions directly affect the specific energy consumption and cutting depth control [24]. Therefore, to gain deeper insight into the damage evolution and kerf morphology in AWJ cutting, it is necessary to reexamine the material removal mechanism from a microscale perspective.

In AWJ cutting, the instantaneous collisions between abrasive particles and the workpiece surface form the fundamental microscale units of the material removal mechanism. Early studies were primarily based on the shear and deformation failure theories proposed by Finnie and Bitter, focusing on the influence of impact angle and velocity on erosion efficiency. However, with improvements in observational resolution and advances in modeling approaches, recent studies have incorporated parameters such as particle size, density, sharpness, and material strength to reconstruct erosion models from an energy-based perspective [25].

Hashish (2024) systematically integrated classical shear and impact erosion models and proposed a compound erosion prediction formula. This expression takes into account multiple physical variables including particle diameter, density, sphericity coefficient, shear strength of the target material, and abrasive hardness, and is analytically derived as follows:

$$\delta v \propto d_p^3 \rho_p^{1.25} V_a^{2.5} \sigma_f^{-1.25} R_f^{-0.75} . \quad (1)$$

The formula reveals the nonlinear relationship between particle attributes and material removal volume, and also explains the transition zone between impact-dominant and ploughing-dominant mechanisms as a function of the impact angle [7]. In recent years, studies on the kinetic energy matching of abrasive particles and the selection of critical particle sizes have emerged as important foundations for parameter optimization and green process modeling [26].

In contrast to the conventional assumption of homogeneous cutting, the AWJ process exhibits significant energy attenuation of abrasive particles along the depth direction, and the material response demonstrates clear spatial heterogeneity. Based on the morphological features of AWJ-cut surfaces, Popan et al. divided the typical kerf interface into three functional zones: Initial Damage Zone (IDZ), Smooth Cutting Zone (SCZ), and Rough Cutting Zone (RCZ), corresponding respectively to the initial unstable erosion upon jet entry, the stable energy transfer period, and the secondary damage zone formed after downstream energy dissipation [27]. The IDZ is primarily governed by high-speed, unstable particle impacts during the initial jet contact, leading to surface erosion and interfacial damage. In the SCZ, particle energy is well-matched with the shear strength of the material, resulting in stable material removal. In contrast, the RCZ is characterized by severe energy attenuation and a noticeable decline in kerf quality. The spatial structure of these functional zones is schematically illustrated in Fig. 1, providing a visual understanding of the progressive energy and damage transitions along the cutting depth.

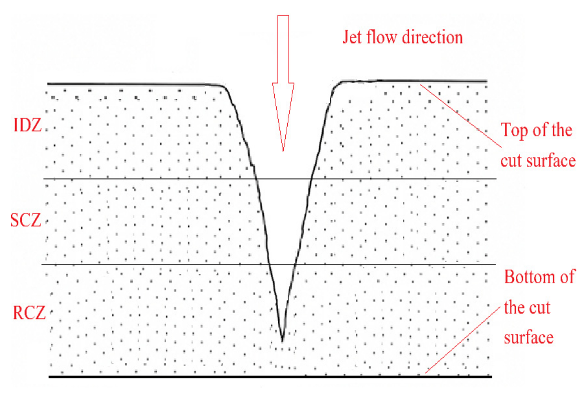

Fig. 1. Schematic representation of the three-zone kerf response model in AWJ cutting [27]

In practical cutting scenarios, the incident angle between abrasive particles and the material surface is not fixed at a perpendicular direction but varies within a certain angular range, which alters the prevailing erosion mechanism. Based on theoretical modeling, Hashish (2024) proposed a dual-mechanism coupling model that decomposes the total cutting depth into a ploughing-dominated component (h_c) and an impact-dominated component (h_d), with the following expression:

$$h = h_c + h_d . \quad (2)$$

Here, h_c is primarily influenced by feed rate and abrasive flow rate, representing shear-dominated material removal under shallow impact angles, while h_d is governed by water pressure and particle energy density, indicating brittle fracturing under steep impact conditions [7]. This model not only better reflects the actual kerf morphology observed in AWJ cutting but also provides a physical basis for variable decoupling and feature extraction in subsequent intelligent modeling.

Damage Mechanisms, Evaluation, and Predictive Modeling

In abrasive waterjet (AWJ) cutting of non-metallic composite materials, the anisotropic structure and weak interfacial bonding often result in various damage types, which directly affect the mechanical integrity and surface quality of the workpiece. The most frequently observed damage modes include delamination, fiber pullout, matrix washout, and abrasive embedment. This section analyzes their respective formation mechanisms, parameter sensitivities, and visual evidence.

Delamination arises primarily from the abrupt impact pressure generated during jet entry, leading to the propagation of interlaminar cracks along the weak bonding planes. Water hammer effect and high shear stress are recognized as the main drivers of this failure mode [28].

Fig. 2 displays stepped crack morphology along the laminate thickness, which is characteristic of AWJ-induced interlayer separation.

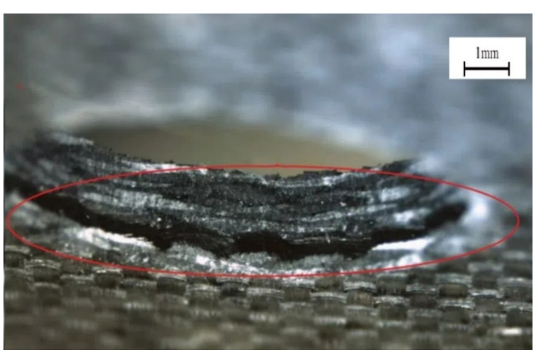

Fig. 2. Optical image showing delamination in CFRP after AWJ cutting, highlighting interlaminar crack propagation (scale = 1 mm) [29]

Fiber pullout occurs when fibers are not completely severed but are instead extracted from the matrix due to insufficient energy transfer or improper cutting parameters. This often happens under high feed rates or low-pressure conditions, where the jet's shearing action fails to overcome fiber-matrix adhesion [29]. As shown in Fig. 3, fiber strands remain partially intact and aligned with the kerf wall, confirming interfacial failure under shear loading.

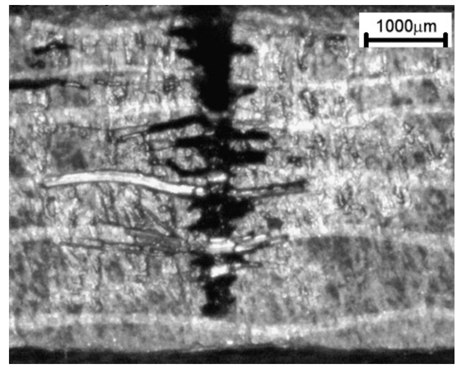

Fig. 3. Cross-sectional micrograph showing fiber pullout zones and uncut fiber remnants within the kerf wall (scale = 1000 μm) [30]

Matrix washout is defined as the premature removal of the polymer matrix preceding fiber fracture, resulting in unsupported fibers and reduced load-bearing capacity. This damage mode is particularly prominent under coarse abrasives or reduced traverse speeds, which extend local jet-material interaction time [30]. Fig. 4 illustrates exposed fibers and distinct resin erosion, providing microstructural evidence of matrix washout.

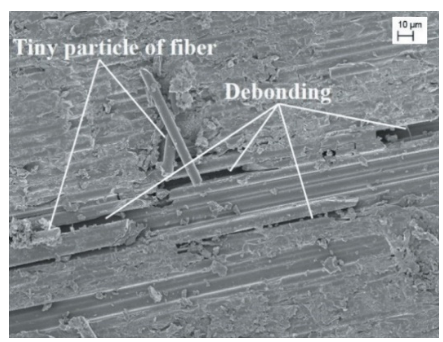

Fig. 4. FESEM image showing matrix removal and fiber debonding under AWJ impact, indicating weak fiber support (scale = 10 μm) [51]

Abrasive embedment refers to the mechanical entrapment of abrasive grains within the machined surface, often due to insufficient jet energy for complete particle ejection. Conditions such as low pressure, short stand-off distance, and excessive abrasive flow promote this phenomenon [31]. Fig. 5 schematically presents abrasive penetration paths, highlighting typical embedment zones.

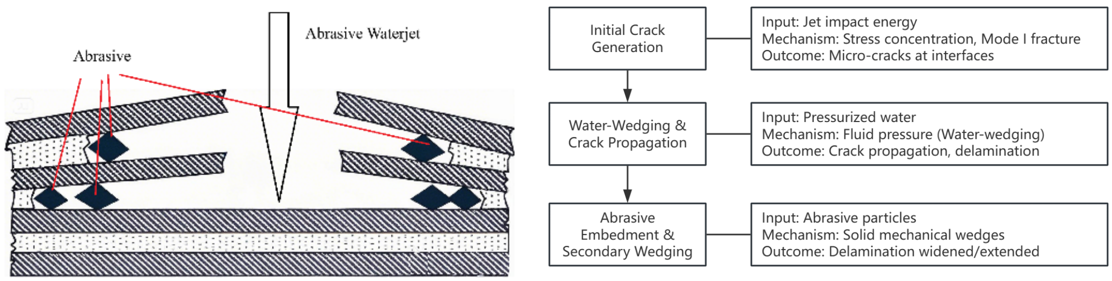

Fig. 5. Mechanism of delamination and abrasive embedment in AWJ cutting of composites; (Left) schematic diagram of the process; (Right) [31]

The sequential damage process, as detailed in Fig. 5, initiates upon jet impact and propagates via coupled fluid-mechanical interactions. This chain reaction is most severe at the jet entry point, where the confined geometry leads to the highest stress concentration, resulting in the largest number and length of cracks. As the jet traverses the workpiece, the availability of escape paths for the energy dissipates these secondary stresses, leading to a observable reduction in crack density and propagation length along the kerf wall.

In the study of AWJ cutting of non-metallic composite materials, several predictive models have been proposed to evaluate damage behavior, optimize process parameters, and improve machining quality. Among them, four models are particularly representative in this field: (1) a fluid-structure interaction (FSI)-based numerical simulation model [32], (2) an erosion model based on quantum mechanics and dimensional analysis [26], (3) an empirical model for surface roughness prediction [33], and (4) a geometric modeling approach for predicting kerf morphology in ultra-thick CFRP laminates [34].

These models have been validated against experimental data and provide effective theoretical support for damage evolution analysis, jet penetration modeling, surface roughness optimization, and kerf geometry prediction.

The following sections provide a detailed explanation of the theoretical foundations, predictive accuracy, and experimental validation of each model.

Numerical Modeling Based on Fluid–Structure Interaction (FSI)

This model is based on a fluid-structure interaction (FSI) approach that integrates computational fluid dynamics (CFD) with finite element analysis (FEA) to predict damage modes in CFRP under AWJ processing. It employs the Volume of Fluid (VOF) method to capture the free surface dynamics of the waterjet and incorporates the Cohesive Zone Model (CZM) to simulate interfacial delamination behavior. This allows for effective prediction of delamination depth and crack propagation paths[32].

Governing Equations. The jet flow field is described by the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0\,, \tag{3}$$

where ρ is the fluid density and is the velocity vector.

The delamination damage is evaluated based on the energy release criterion:

$$G_n + G_t = 1\,, \tag{4}$$

where G_n and G_t represent the normalized normal and tangential energy release rates, respectively.

Experimental Validation: Under operating conditions of P = 350 MPa and a stand-off distance (SOD) of 2 mm, the simulated crack lengths were 2.12±1.01 mm in the *XZ* plane and 2.44±1.26 mm in the *YZ* plane, with deviations from experimental results within 5 %.

Erosion Modeling Based on Quantum Mechanics and Dimensional Analysis

This model applies quantum mechanics and dimensional analysis to calculate the erosion depth of CFRP under AWJ and to quantify the material removal mechanism during abrasive impact [26].

Governing Equations. The kinetic energy of abrasive particles is calculated as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 E_p = \frac{1}{2} m_a v_a^2\,, \tag{5}$$

where m_a is the mass of an abrasive particle and v_a is its velocity.

The predicted erosion depth is expressed as:

$$d_p = C\left(\frac{P}{v_t}\right)^{\alpha}, \tag{6}$$

where C is an empirical constant, P is the jet pressure, and v_t is the feed rate.

Experimental Validation: At a jet pressure of 250 MPa and feed rate of 50 mm/min, the predicted penetration depth deviated by less than 7 % from the experimental results, indicating high applicability of the model.

Empirical Model for Surface Roughness Prediction.

This model uses regression analysis based on experimental data to establish relationships between surface roughness parameters (maximum roughness depth *Rz1max* and total roughness height *Rt*) and process variables [33].

Regression Equation: The surface roughness R_t is predicted using the following empirical formula:

$$R_t = a_0 + a_1 P + a_2 v_t + a_3 d + a_4 q_a, \quad (7)$$

where P is the jet pressure, v_t is the feed rate, d is the stand-off distance, and q_a is the abrasive mass flow rate.

The regression model achieved a coefficient of determination (R^2) greater than 0.95, indicating high predictive accuracy. Under high pressure (> 300 MPa) and low feed rate (< 40 mm/min), a reduced surface roughness of Rt < 3.5 μm was achieved.

Kerf Prediction Model for Ultra-Thick CFRP Based on Geometric Morphology Analysis.

This model adopts an energy balance theory to predict kerf geometry in ultra-thick CFRP laminates, including inlet width, outlet width, and cutting front morphology [34].

Geometric Prediction Equations:

$$W_{in} = C_1 P^{\beta_1} v_t^{-\beta_2}, \quad (8)$$

$$W_{out} = C_2 P^{\gamma_1} v_t^{-\gamma_2}, \quad (9)$$

where W_{in} and W_{out} are the inlet and outlet kerf widths, respectively, and P and v_t represent jet pressure and feed rate.

The model achieved a high predictive accuracy with R^2 > 0.97, demonstrating strong applicability across different cutting parameters. At a jet pressure of 400 MPa, the kerf taper was reduced by 20 %, resulting in improved machining precision.

The four predictive models introduced above collectively address distinct but interrelated aspects of AWJ machining of composite materials. From damage propagation and erosion depth to surface integrity and kerf geometry, each model contributes specific insights and tools for process understanding and optimization.

Table 3 provides a structured comparison of these models in terms of predicted variables, methodological frameworks, accuracy metrics, and application domains. The FSI-based simulation excels in capturing damage evolution through coupled field modeling, while the erosion model offers a physics-driven estimation of material removal rates under varying jet energies. The empirical roughness model stands out for its predictive efficiency and adaptability to parameter tuning, and the geometric model for kerf analysis serves as a robust tool for evaluating morphology in thick-section laminates.

Together, these models form a complementary toolbox for intelligent prediction and quality control in AWJ cutting of advanced non-metallic composites.

Process Parameter Optimization and Multi-Physics Coupling

Building on the understanding of damage mechanisms and predictive modeling, precise parameter control and optimization modeling are key to further improving AWJ cutting quality. Composite materials are prone to defects such as delamination, fiber pullout, and interfacial separation during machining, which significantly affect dimensional precision and functional integrity. While AWJ offers a cold and flexible machining solution for composites, its final quality remains highly sensitive to the rationality and precision of parameter settings.

Extensive studies have confirmed that key process variables – including jet pressure, feed rate, abrasive mass flow rate, nozzle height, and orifice diameter – directly influence performance metrics such as material removal rate *(MRR),* surface roughness (*Ra*), kerf taper (*Kt*), and delamination factor (*DF*) [35]. Therefore, systematically identifying these influencing factors, establishing response relationships with quality metrics, and applying multi-objective optimization strategies are critical to enhancing AWJ machining quality, process stability, and material adaptability.

This chapter reviews the representative optimization pathways and modeling techniques reported in the literature, categorizes them based on material types and algorithmic strategies, and analyzes their logical basis and mutual compatibility. A summary chart of optimization trends and outcomes is presented at the end of the chapter to enhance the systematization and clarity of the discussion.

Within the Taguchi, Grey relational analysis, and RSM framework, numerous studies have adopted classical statistical design of experiments (e.g., Taguchi, RSM) to

Table 3. Comparative analysis of typical AWJ modeling approaches for composite machining

Model Type	Applicable Range	Key Predicted Variables	Prediction Accuracy (R^2)	Main Contribution
FSI Numerical Model	CFRP Cutting	Delamination Depth, Crack Propagation	0.95	Combines CFD and FEA to simulate dynamic damage
Erosion Model	Various Composites	Jet Penetration Depth	0.93	Uses quantum mechanics and dimensional analysis to improve generality
Surface Roughness Model	Kevlar Composites	*Rt*, *Rz1max*	0.95	Uses experimental data regression to optimize surface quality
Kerf Prediction Model	Ultra-thick CFRP	Kerf Width, Taper	0.97	Applies energy balance to improve geometric prediction accuracy

explore the functional relationships between process parameters and output responses. These are often supplemented by grey decision-making or principal component analysis tools for multi-objective trade-off optimization.

Karatas et al. (2020) applied the Taguchi method to optimize AWJ drilling of CFRP, achieving reduced kerf taper and improved hole quality [36]; Kodandappa *et al*. (2024) combined the Taguchi and RSM methods with ANOVA to identify v_t (feed rate) as a dominant factor affecting *Ra* and *MRR* [37]; Pandian and Jailani (2021) imp-lemented a Taguchi-TOPSIS framework to simultaneously optimize multiple responses including *MRR*, *Ra*, and *Kt* [38].

While these studies share consistency in algorithm selection and target responses, they differ in modeling complexity, trade-off strategies, and constraint handling. The Taguchi-based methods are easy to implement and highly adaptable for engineering practice but tend to exhibit limitations in handling multivariable interactions, reflecting their inherently local optimization nature.

Kumar et al. (2020) integrated Grey relational analysis and fuzzy logic to rank parameter influence, leading to substantial reductions in *Ra* and *Kt* [39]; Murthy *et al*. (2023) employed fuzzy weighting to evaluate the trade-offs between delamination factor and surface quality, achieving a balanced outcome when combined with the Taguchi method [40]. Vijayananth *et al*. were the first to integrate the CRITIC-COPRAS method in the machining of filler-reinforced composites. By extracting weights of quality indicators through information entropy and mutual information analysis, they eliminated subjective bias and achieved overall improvements in *Ra*, *Kt*, and *MRR* [31], making this strategy a recent hotspot in parameter optimization.

The integration of intelligent algorithms with response surface modeling has demonstrated excellent performance in complex multi-objective optimization tasks. Tamilarasan and Renugambal (2023) introduced an improved Seagull Optimization Algorithm (ISOA) into NFRP material processing, constructing a multi-response model via BBD design to achieve coordinated optimization across multiple objectives [35]; Siva Kumar *et al*. (2022) used BP neural networks to regressively predict machining responses of FIL composites, with TOPSIS aiding the decision process and overcoming limitations of traditional models in handling nonlinear coupling and high-dimensional disturbance [41].

Compared to statistical models, these approaches demonstrate superior global optimization capabilities and adaptability to nonlinear mappings, making them particularly suited for novel composites, complex structures, and systems with strong nonlinear responses.

In traditional parameter sensitivity analyses, Altin Karataş *et al.* (2022) investigated the effects of varying water pressure and nozzle stand-off distance on delamination and *Ra* in CFRP; Youssef *et al*. (2021) used parameter variation and repeated trials to quantify the trends of AWJM effects on *Ra* and *Kt* [22]; Yang *et al*. (2020) proposed a secondary CNC milling strategy to compensate for AWJ-induced initial kerf morphology, reducing *Ra* from 5.6 µm to 1.2 µm and showcasing a novel hybrid process optimization concept [42].

These studies addressed the impact of parameter variations from multiple perspectives, including composite type, filler configuration, physical modeling, and equipment sensitivity. Ishfaq *et al*. (2020) proposed a layered modeling approach to micro-edge damage in multilayer

Table 4. Representative AWJ optimization techniques and performance outcomes

Optimization Method	Characteristics	Material Type	Optimization Results	Example
Taguchi	Single-objective, variable independence	CFRP, Sandwich	Reduced *Kt*, *Ra*, good for rapid screening	[36]
Taguchi + RSM	Enhanced parameter interaction analysis	CFRP	*MRR*↑21.5 %, *Ra*↓15.4 %	[37]
Taguchi + TOPSIS	Multi-response extension	Natural Fiber Sandwich	*Ra* down to 4.6 µm, overall improvement	[38]
Grey-Fuzzy	Suitable for incomplete data and fuzzy goals	GFRP, CFRP	*Ra*↓26.8 %, *Kt*↓13.2 %	[39]
CRITIC–COPRAS	Objective weight assignment and decision ranking	Hybrid Filler Composite	*Ra* to 3.86 µm, *Kt* < 0.3°	[31]
BBD + ISOA	Response modeling with global intelligent search	NFRP	*Ra*↓32.5 %, *MRR*↑28 %	[35]
ANN + TOPSIS	Nonlinear mapping with decision support	FIL	*Ra* ≈ 2.65 µm, significantly reduced *DF*	[41]

coatings under AWJ, providing a refined prediction framework [43]; Popan *et al*. conducted a series of three studies, introducing methods for piercing preprocessing, cut-in/cut-out shape correction, and acoustic emission-based fault detection to improve cut-in quality and taper calibration [44]; Chen et al. proposed a path-smoothing strategy for small-radius corners, enhancing the adaptability of AWJ in complex geometric profiles [5].Table 4 summarizes the adaptability and performance outcomes of various optimization strategies across composite types, including representative applications of Taguchi, RSM, grey-fuzzy, CRITIC-COPRAS, ISOA, and neural network methods.

Summary

This chapter reviewed the pivotal role of AWJ parameter optimization in enhancing machining quality, covering six representative strategies including Taguchi, RSM, grey-fuzzy, CRITIC-COPRAS, neural networks, and ISOA. It clarified the applicability logic of different methods across target types, material systems, model complexity, and data sufficiency, as summarized in Table 4.

Findings suggest that Taguchi and RSM are best suited for systems with clearly defined causality and limited variables. In contrast, grey-fuzzy and TOPSIS perform better in scenarios with vague priority rankings, while intelligent algorithms offer clear advantages in highly nonlinear, multi-objective environments.

Looking ahead, future research should focus on the integration of hybrid models, adaptive optimization techniques, and real-time control mechanisms. Moreover, developing transferable strategies across material platforms will be essential for ensuring quality consistency under multi-structure and disturbance-prone AWJ conditions.

Future Directions Driven by Intelligence and Precision

Extensive research has systematically explored the influence of AWJ process parameters on the cutting responses of composite materials, leading to the development of various optimization strategies. To address the modeling challenges arising from nonlinear, multivariable interactions, artificial intelligence (AI) methods have been increasingly introduced to enhance prediction accuracy and parameter optimization efficiency, marking a significant trend in AWJ research [45]. A commonly used approach involves employing artificial neural networks (ANN) to map the relationships between input parameters and output responses. While much of the literature compares ANN with response surface methodology (RSM), other studies have introduced swarm intelligence techniques, such as genetic algorithms and particle swarm optimization, to balance trade-offs between cutting rate, surface roughness, and energy consumption [41]. Notably, some studies have begun integrating deep learning with process monitoring signals such as acoustic emission and visual data to construct intelligent perception systems that unify prediction, recognition, and control [46].

With the increasing functional integration of composites in advanced manufacturing, a growing number of structural components now exhibit microscale features, such as fine channels, micro-slots, and intricate edge chamfers. These features are commonly found in thin-walled aerospace components, electronic packaging molds, and miniature composite structures, posing stringent requirements on cutting accuracy, heat-affected zone minimization, and kerf width control.

Although AWJ offers inherent advantages such as cold-state processing and high geometric adaptability, its extension into microscale machining faces several significant bottlenecks. As cutting dimensions approach the nozzle diameter scale, boundary diffusion disturbances become more pronounced, compromising kerf accuracy and contour precision. In addition, frequent turning paths and high trajectory density in micro-patterns exacerbate trailing effects and angular errors due to jet inertia lag. Furthermore, the size ratio between abrasive particles and kerf width becomes non-negligible, leading to nonlinear evolution in mechanisms such as particle collision frequency and effective erosion cross-section [47].

To overcome these challenges, research has focused on improvements in nozzle design, path planning, and process modeling. For instance, long and narrow orifice nozzles (0.2–0.4 mm) combined with high-pressure systems have demonstrated the potential to achieve sub-millimeter cutting precision without compromising jet energy. In path design, trajectory smoothing with overlap control and corner compensation functions has effectively reduced profile deviations in micro-feature fabrication [47]. On the modeling side, Hashish et al. proposed an improved multi-zone response model that divides the kerf profile into entry, stable cutting, and trailing zones. The model couples particle kinetic energy dissipation with local material removal functions to better reflect microscale behavior [48].

Moreover, the amplified impact of material-scale heterogeneity is gaining attention. Microscale delamination, interface redistribution, and edge tearing are more easily triggered in thin channels and miniaturized components. Literature suggests using high-mesh (120–180 mesh) fine abrasives and low-speed precision feed strategies to mitigate surface disturbance caused by stochastic particle impacts [47].

Compared to established macroscale techniques, microscale AWJ still lacks comprehensive modeling methods and standardized process windows. Its advancement hinges on multiscale mechanism integration and precise coordination across the processing chain.

Although AWJ is known for its cold-processing and soft-cutting advantages, instability during system operation remains a critical risk to consistent machining quality. Unlike conventional machining, AWJ systems rely on the coordinated operation of high-pressure pumps, water transport, and abrasive delivery subsystems. A failure in any of these can lead to cutting interruptions, kerf defects, or even part rejection. Typical issues include nozzle clogging, abrasive feed disruption, pressure fluctuations, and focusing tube wear – many of which are abrupt, process-dependent, and difficult to detect early through manual observation [46].

A promising approach to address these issues is the use of acoustic emission (AE) signals for process condition monitoring. Since AWJ involves high-energy impact erosion, energy fluctuations generate measurable acoustic signals. Studies have shown that the root mean square amplitude (AERMS) of AE signals is highly sensitive to jet energy stability, making it a potential early-warning indicator of process instability.

Experimental setups with AE sensors placed at the nozzle and workpiece have successfully identified fault modes. For instance, with a 48 % reduction in abrasive flow rate, the AERMS dropped by ~33 % at the nozzle but increased by ~87 % at the workpiece, indicating an energy imbalance across the system [46]. Such signal trends can distinguish between fault types and hold promise for integration into predictive maintenance frameworks.

Beyond fault identification, AE feature-based models are being developed to estimate fault locations and severity. This transition from post-event diagnosis to real-time pre-failure alerting marks a shift from passive sensing to proactive control. A more advanced vision involves linking AE systems with CNC controllers to dynamically adjust cutting paths, reduce feed rates, or trigger emergency stops in response to anomaly signals – thereby realizing an 'audible' AWJ system.

AWJ process stability is not only vital for individual machining quality but also essential for continuous manufacturing, autonomous production, and future smart factory deployment. Traditional operator-dependent monitoring is no longer sufficient, while integrated intelligent sensing systems offer a viable path forward.

Driven by the ongoing evolution of Industry 4.0 and 5.0 paradigms, manufacturing systems are being redefined through digitalization, connectivity, and intelligent integration. For AWJ systems – known for their high energy density and operational complexity – this shift presents both challenges and opportunities for technological upgrades.

Future AWJ units will no longer operate as isolated toolheads, but rather as intelligent nodes capable of data sensing, smart actuation, and remote orchestration within the digital manufacturing ecosystem (Abrasive Waterjet Machining). Technologies such as the Internet of Things (IoT) and artificial intelligence (AI) are being embedded into core components like pumps, focusing tubes, and cutting heads to enable real-time condition monitoring. By capturing pressure, temperature, and vibration data via sensors and applying AI-driven pattern recognition, the system can predict component wear and enable preventive maintenance, thus reducing downtime and maintenance costs.

In addition to hardware diagnostics, intelligent algorithms are being applied to adjust process parameters such as feed rate, pressure, and nozzle distance in real time based on historical cutting data, enhancing consistency and surface quality (Abrasive Waterjet Machining). The concept of a digital twin, a cornerstone of Industry 4.0, is also emerging as a critical pathway to close the loop between monitoring, control, and feedback. Some studies have integrated acoustic emission monitoring with machine models, proposing digital twins to enable remote coordination, predictive analytics, and real-time status reproduction of AWJ cutting [46]. Others advocate integrating AWJ digital twins with AI, edge computing, and MES/ERP systems to realize synchronized equipment-, system-, and enterprise-level control [7].

On the integration front, AWJ systems are increasingly connected with enterprise management platforms like MES and ERP. Edge computing and cloud infrastructure are being leveraged for cross-regional, cross-process scheduling and coordinated control. These developments enable virtual-physical linkage and support real-time parameter optimization and fault forecasting.

Looking ahead, more visionary efforts focus on enhancing human-machine integration. For example, Hashish (2024) introduced the AWJ 5.0 concept, emphasizing the importance of enhanced human-machine interfaces, assisted decision-making systems, and operator-system interaction quality as emerging factors shaping machining efficiency [7]. This suggests a transition toward cognitive machining platforms capable of adaptive learning, error prediction, and autonomous operation under high-precision, high-sensitivity scenarios.

The functional boundaries of AWJ systems are expanding, transitioning from material removal tools to intelligent manufacturing nodes capable of data generation, feedback, and process optimization. This transformation not only redefines AWJ's role in high-end equipment systems but also enables broader deployment in aerospace, precision molding, and flexible production environments.

Despite the clear advantage of cold-state processing in AWJ machining of composites, significant uncertainties remain in the evaluation of cutting quality. For decades, *Ra* has been the most widely used surface metric in various manufacturing methods. However, for heterogeneous, multiscale composite structures, *Ra* alone often fails to fully capture the internal kerf morphology and edge integrity, especially in applications involving fatigue resistance or adhesive bonding performance [49].

Studies have shown that even kerfs with similar *Ra* values can exhibit more than 10 % variance in strength retention depending on directionality and interlaminar structure – particularly in textured and 3D woven composites. This phenomenon highlights the inadequacy of *Ra* as a single scalar to capture the complex structural evolution of the cut interface after AWJ processing. As a response, more physically meaningful indicators such as "Crater Volume" (Cv), defined as the total erosion volume per unit area, have been proposed to better correlate micro-damage with mechanical performance [50].

Experimental findings indicate that increasing Cv from 1 mm^3/cm^2 to 2 mm^3/cm^2 leads to over 10 % reduction in fatigue strength, whereas *Ra* remains largely unchanged. Moreover, Cv demonstrates a more consistent response across varying conditions such as jet energy density, pulse frequency, and abrasive flow stability, making it a promising metric for unified quality assessment across materials and processes.

Beyond the parameter dimension, the scope of evaluation is also expanding from "surface morphology" to "functional integrity." Recent studies have proposed multi-parameter evaluation models that integrate *Ra*, Cv, crack density, and kerf taper angles, using fuzzy comprehensive evaluation and grey relational analysis to enable holistic quantification of cutting quality [51].

However, challenges remain in standardizing quality metrics due to inconsistencies in experimental setups, the diversity of composite architectures, and complexity in parameter acquisition. Parameters such as Cv currently lack efficient online measurement solutions, limiting their industrial applicability.

Nevertheless, quality assessment has become a widely acknowledged direction in AWJ research. Future work should systematically explore standardized data formats, acquisition protocols, and sensitivity analysis of evaluation indicators to establish a universal, cross-scale, and cross-material quality assessment framework. This advancement will be crucial for enabling AWJ to meet the demands of precision manufacturing and high-reliability applications.

An interesting direction for improving the quality of composites processing is the work of individual researchers in applying a functional approach to processing technologies [53]. This approach has a comprehensive impact on the workpiece, considering its structure and physical and mechanical properties. Thanks to this approach, it is possible to reduce defects formed during abrasive water jet cutting of composites.

Conclusions and Outlook

This review systematically summarizes the recent advancements in abrasive water jet (AWJ) machining of non-metallic composite materials, with a focus on damage mechanisms, predictive modelling, process optimization, and system integration. From the perspective of damage, AWJ cutting frequently induces typical defects such as delamination, fiber pull-out, matrix washout, and abrasive embedment, all of which are strongly influenced by the anisotropic nature of the materials and interfacial force fields. To address these behaviors, a range of predictive models have been developed, including fluid–structure interaction simulations, energy dissipation frameworks, surface roughness regression, and geometrical kerf morphology derivations. These approaches have established a theoretical basis for improving the predictability of AWJ behavior and guiding process design.

In terms of parameter optimization, techniques such as the Taguchi method, response surface methodology (RSM), grey-fuzzy modeling, CRITIC–COPRAS multi-criteria decision-making, and AI-based strategies have each demonstrated unique advantages. These methods have been extensively employed to systematically regulate multi-objective performance indicators such as surface roughness (*Ra*), kerf taper (*Kt*), material removal rate (*MRR*), and delamination factor (*DF*) [52].

Furthermore, this review identifies emerging trends over the past five years that indicate a clear technological evolution: AWJ systems are transitioning from isolated processing units to intelligent systems capable of sensing, prediction, and closed-loop control. In this context, technologies such as acoustic emission monitoring, AI-driven modeling, microscale machining strategies, and digital twin architectures are gradually being integrated, driving AWJ toward cognitive, self-optimizing, and feedback-enabling systems. At the same time, key limitations remain in microscale modeling, system stability control, coupled modeling between damage and mechanical performance, and the standardization of quality metrics – factors that currently hinder widespread deployment in precision manufacturing and flexible production environments.

Looking forward, the future of AWJ research and application will likely follow three major directions: (1) **Deepening of cross-scale physical modeling**, to quantify the correlation between damage evolution and structural performance; (2) **Intelligent coupling of data-driven mechanisms**, enabling unified frameworks for real-time monitoring and adaptive process control; (3) **Establishment of standardized quality metrics**, to support universal evaluation systems across composite material platforms.

Through technological breakthroughs and interdisciplinary integration, AWJ holds significant promise for precision shaping of non-metallic composites, supporting the advancement of quality and intelligence in next-generation high-end manufacturing.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other nature that could affect the research and its results presented in this article.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Технології гідроабразивного різання композиційних матеріалів: огляд методу

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Анотація: *Зі зростанням попиту на високоточну та високонадійну обробку композитних матеріалів в аерокосмічній, автомобільній та електронній промисловості, технологія абразивного гідроструминного різання (AWJ) стала перспективним методом різання неметалевих композитів завдяки своїй природі холодного різання та адаптивності до різних матеріалів. Порівняно з дослідженнями до 2020 року, які в основному зосереджувалися на параметричних випробуваннях, останні дослідження змістилися в бік моделювання пошкоджень, викликаних різанням, контролю точності на рівні мікроструктури, інтелектуальної оптимізації та моніторингу в режимі реального часу, що свідчить про подвійний прогрес у розумінні механізму та інтеграції на системному рівні.*

У цьому огляді узагальнено типові режими пошкоджень та методи моделювання при різанні AWJ композитних матеріалів, порівняно застосовність різних прогнозних моделей та показників якості, а також оцінено репрезентативні стратегії оптимізації для різних композитних систем. Крім того, він висвітлює тенденції в інтелекті систем AWJ, включаючи моніторинг акустичної емісії, моделювання на основі штучного інтелекту та інтеграцію технологій цифрових двійників. Визначено майбутні виклики, такі як багатомасштабне моделювання зв'язку пошкодження та продуктивності, замкнутий цикл управління процесами та стандартизовані рамки оцінки якості. Цей огляд має на меті надати структуровані висновки та перспективні рекомендації для розвитку AWJ у точному виробництві композитів.

Ключові слова: *абразивне гідроструминне різання (AWJ); різання композитних матеріалів; моделювання пошкоджень; оптимізація параметрів; розумне виробництво.*