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Review Article

Recent advances in abrasive water jet machining for structural materials: A comprehensive review

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Abstract

Abrasive Water Jet Machining (AWJM) has emerged as a versatile non-conventional machining process for a wide range of engineering materials, including metals, composites, and ceramics. It's cold cutting action prevents thermal damage and residual stresses, making it particularly suitable for temperature-sensitive and difficult-to-machine materials commonly used in structural and functional applications. This review consolidates recent research progress in AWJM, with emphasis on process parameter optimization, abrasive selection, nozzle design, and system integration. Material-oriented studies that address surface integrity, dimensional accuracy, and machinability are highlighted. Developments in hybrid approaches, where AWJM is coupled with other manufacturing techniques to improve efficiency and versatility, are also examined. Current limitations, such as the lack of robust real-time monitoring systems, limited predictive modelling capability, and insufficient attention to sustainability, are critically discussed. Future perspectives include the adoption of data-driven modelling and machine learning for intelligent process control, exploration of environmentally benign abrasives, and the advancement of AWJM at micro- and nano-scales. The review aims to provide researchers and practitioners with a comprehensive understanding of AWJM, offering insights into its role in advancing modern manufacturing of engineering structures and materials.

1. Introduction

Abrasive Water Jet Machining (AWJM) has established itself as one of the most versatile and promising non-traditional machining processes in contemporary manufacturing industries. Recognized for its unique cold cutting mechanism, AWJM eliminates the thermal effects typically associated with conventional machining methods, thereby preventing heat-affected zones (HAZ) and residual stresses. The process involves the injection of abrasive particles into a high-velocity water jet, allowing it to cut through a wide array of materials with high precision. Since its first commercial implementation in 1983 for cutting brittle materials like glass, AWJM has undergone significant development and is now widely employed for machining hard-to-cut materials, such as titanium alloys, advanced ceramics, nickel-based superalloys, and fibre-reinforced polymer composites. These materials, although essential in sectors such as aerospace, automotive, defense, and biomedical engineering, pose substantial challenges when processed with conventional techniques. The limitations of traditional machining, including excessive tool wear, poor surface integrity, thermal distortion, and reduced dimensional accuracy, have created a strong need for alternative machining approaches [1-3]. AWJM provides a highly adaptable solution, owing to its low cutting forces, minimal mechanical stresses, and capability to produce intricate geometries with excellent surface finish.

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The principle of AWJM operation centers on a mixture of pressurized water and abrasives expelled at extremely high velocities through a specialized nozzle. This high-energy jet impinges on the target material, causing erosion and facilitating material removal. The effectiveness of this process is governed by several parameters, such as abrasive flow rate, traverse speed, standoff distance, water jet pressure, nozzle diameter, and abrasive particle size. Each of these parameters influences critical performance indicators like material removal rate (MRR), surface roughness (SR), kerf width, and depth of cut (DOC). The complex interplay between these variables necessitates thorough investigation and optimization to ensure that machining objectives are met, especially in applications requiring high-dimensional accuracy and surface quality. Over the past few decades, researchers have systematically explored the effects of AWJM process parameters. For example, increased abrasive flow rate can enhance MRR but may also lead to higher kerf width and degraded surface finish. Similarly, an increase in traverse speed often accelerates machining but could compromise cut quality. Achieving the optimal balance between productivity and quality remains a key research focus. Numerous experimental and statistical techniques, such as Design of Experiments (DoE), regression modelling, Taguchi methods, Grey Relational Analysis, and artificial intelligence-based optimization, have been employed to determine the ideal operating conditions. AWJM stands out when compared to other advanced machining techniques like laser cutting, electrical discharge machining (EDM), and ultrasonic machining [4-6]. While these methods also offer precision and adaptability, they often induce thermal or electrical damage, have limited material applicability, or require frequent tool maintenance. In contrast, AWJM offers the dual advantage of being a non-thermal and non-contact process, reducing the possibility of microstructural changes or tool wear. These attributes make it particularly advantageous for applications involving heat-sensitive or layered composite materials. Recent studies have also shed light on the morphological and geometric characteristics of AWJM cuts. The nature of kerf formation, which includes taper angle and surface striations, is a critical aspect, especially in applications involving layered or laminated composites. These geometric features are influenced by a combination of jet energy, material ductility, and abrasive behavior. For instance, in oscillation cutting, where the nozzle follows a sinusoidal path, the depth of cut and material erosion mechanisms differ significantly from conventional linear cutting, offering new avenues for performance enhancement. Investigations into thermally assisted AWJM techniques have demonstrated potential in further improving material removal and surface characteristics. By introducing localized heating to the workpiece, researchers have observed enhanced ductility and reduced material resistance, leading to better cutting performance in hard-to-machine metals like tool steels and Inconel alloys [7-10]. However, careful control is required to prevent reintroducing the thermal damage that AWJM was originally designed to avoid.

In specific applications, such as glass sheet machining, nozzle design, and standoff distance have been identified as crucial variables affecting surface integrity and kerf geometry. In such brittle materials, even small deviations in process parameters can result in micro-cracks or excessive chipping. Consequently, advanced nozzle systems and precision control methods are being developed to ensure optimal outcomes. Surface quality has remained a primary area of concern, particularly when machining high-hardness or brittle materials like borosilicate glass and granitic rocks. Surface roughness, which directly impacts part performance and post-processing requirements, is influenced by parameters like abrasive size and jet velocity. Recent research indicates that multi-objective optimization techniques can significantly enhance surface finish while maintaining acceptable MRR. AWJM has also proven effective in turning operations and pocket milling, especially in high-performance alloys such as Inconel 718 and AISI 316 stainless steel [11-12]. Studies focusing on turning applications highlight the process's adaptability and its ability to deliver consistent results in terms of dimensional accuracy and minimal thermal influence. Moreover, when grinding and polishing operations are required, adaptations of AWJM such as abrasive jet polishing have been employed to achieve superior surface finishes, especially on tool and mold steels. Taguchi-based designs and fuzzy logic models have been instrumental in fine-tuning these processes [13]. Notably, research into water jet technologies has expanded to include soft material applications, such as coal and soft polymers. While AWJM is typically associated with hard-to-machine materials, its adaptation for soft material cutting, especially through multi-response optimization techniques, demonstrates its growing versatility. Studies applying Taguchi-Fuzzy models to coal cutting, for instance, have achieved effective parameter optimization to improve both performance and energy efficiency.

In parallel, advances in modeling and simulation have contributed significantly to understanding AWJM behavior. Computational fluid dynamics (CFD), finite element modeling (FEM), and artificial intelligence tools are increasingly being used to simulate jet dynamics, predict material response, and forecast process outcomes. These tools allow researchers to explore hypothetical scenarios, reduce experimental costs, and accelerate the development of new AWJM configurations. Despite its clear advantages, AWJM is not without challenges. Key limitations include relatively low MRR compared to mechanical cutting and occasional inconsistencies in depth of cut, especially in heterogeneous or multilayered materials [14-15]. These drawbacks underscore the importance of continued research to refine process parameters and develop hybrid technologies that integrate AWJM with other machining or heating methods. The current article addresses these complexities and aims to consolidate the vast body of research related to AWJM. By reviewing more than 80 publications over the last two decades, the article offers a comprehensive overview of the technological advancements, material-specific studies, process optimizations, and emerging trends in the field. The novelty lies in its systematic classification of AWJM processes based on both input parameters and output metrics, thereby offering deeper insight into their interrelationships. A novel framework is also proposed for tailoring AWJM parameters to suit specific materials and applications, enhancing both efficiency and quality. As manufacturing trends evolve toward higher precision, material diversity, and environmental consciousness, AWJM continues to stand out as a sustainable and capable machining solution. Its non-thermal, tool-free, and flexible nature makes it a strong candidate for the future of advanced manufacturing [16]. This review not only maps the current status of AWJM research but also identifies the gaps and opportunities for future exploration, thereby serving as a valuable reference for researchers, engineers, and practitioners in the field.

2. Fundamental Working Principles of AWJM

AWJM works by accelerating a stream of water to ultra-high pressures (typically 200–400 MPa) and mixing it with abrasive particles like garnet or alumina. The resulting high-velocity jet impinges on the work surface, eroding the material through a combination of mechanical abrasion and hydraulic impact. Key components of an AWJM system include the high-pressure pump, abrasive feeding system, mixing chamber, and nozzle assembly. The key areas of investigation in AWJM research include material-specific machinability, process parameter optimization, surface quality and kerf geometry, advanced optimization techniques, hybrid and multi-pass machining, and sustainability [17]. These areas represent continuing efforts to improve AWJM's efficiency, accuracy, and cost-effectiveness across a wide range of industrial applications. Future research is anticipated to concentrate on further optimizing process parameters, investigating novel materials, and incorporating modern technologies like as AI and IoT for real-time monitoring and control. Based on the given literature review, the area-specific investigations are summarized in Table 1 and discussed in depth.

Table 1. Areas of investigation in AJWM

Area of Investigation	References	Main Findings (with Quantitative Trends)	Research Gaps
Material-Specific Machinability	Alberdi et al. [1]	Kerf width in aluminum increased by 8–15% with a 20% rise in traverse speed; predictive model accurately estimated kerf profile deviation within ±0.05 mm.	Limited studies on varying feed rates for different alloys and composite materials.
	Adnan et al. [3]	AWJM produced smooth surfaces on Al alloys with Ra 2.1–3.5 µm, maintaining original microstructure.	Lack of cross-comparative studies with EDM, LBM, or hybrid processes for similar alloys.
	Mogul et al. [13]	Increasing traverse speed from 50 to 150 mm/min reduced depth of cut by 30–40%;	Need for hybrid machining studies on titanium alloys

		higher water pressure (250–400 MPa) decreased surface roughness by 25–30%.	integrating ultrasonic or laser assistance.
	Aich et al. [11]	Optimal GFRP cutting achieved at jet pressure of 300 MPa and abrasive flow 300 g/min, improving dimensional accuracy by 20%.	Limited work on minimizing delamination and fiber pull-out in composite cutting.
	Khan et al. [4]	SiC abrasives enhanced MRR by 18% compared to Al_2O_3 and by 25% compared to garnet during glass machining.	Lack of research on biodegradable or recyclable abrasives for glass and ceramic materials.
Process Parameter Optimization	Shaikh et al. [2]	In metal-polymer laminates, increasing traverse rate from 100 to 300 mm/min reduced cutting depth by 35%; water pressure above 350 MPa improved kerf straightness by 15%.	Insufficient multi-objective optimization integrating both depth and surface quality.
	Lui et al. [7]	For AISI 4340 steel, surface roughness improved by 28% when reducing feed rate from 200 to 80 mm/min.	Need for adaptive, sensor-based control systems for real-time parameter correction.
	Karakurt et al. [10]	Kerf angle in granite reduced by 40% when increasing pressure from 250 to 400 MPa; traverse speed beyond 200 mm/min led to a 10% rise in taper.	Lack of studies on particle size distribution impact on cut uniformity.
	Aydin et al. [36]	Smaller abrasive particles (80 mesh) reduced cut depth by 20–25% compared to coarser abrasives in granitic rocks.	Need for research on rock heterogeneity effects in AWJM.
Surface Quality and Kerf Geometry	Selvn et al. [14]	Surface roughness reduced from Ra 4.5 µm to 2.8 µm with lower traverse speed (150 → 60 mm/min).	Studies lacking on how ambient temperature or humidity influence surface integrity.
	Shanmugam & Masood [17]	Kerf taper angle decreased by 35% when pressure increased from 200 to 400 MPa and traverse speed lowered by 25%.	Limited insights into kerf formation in multi-layered and sandwich composites.
	Doreswamy et al. [16]	In composites, kerf width rose 12–18% with pressure increases from 250 to 400 MPa, while higher feed reduced width by 10–15%.	Need for kerf geometry studies on curved or contoured surfaces.
Advanced Optimization Techniques	Patel et al. [18]	PSO-based optimization improved MRR by 17% and reduced surface roughness by 12% compared to GA for titanium.	Lack of integration of AI-driven adaptive control for live process optimization.
	Panchal et al. [51]	ANN prediction accuracy for specific energy consumption reached $R^2 = 0.98$, with energy savings of 10–15% after optimization.	Limited ANN modeling for multi-material machining or hybrid processes.
	Satyanarayana & Srikar[85]	Grey relational analysis improved MRR by 22% and reduced kerf width by 18% in Inconel 718.	Few studies link ML optimization with predictive maintenance or tool wear tracking.
Hybrid and Multi-Pass Machining	Yuvaraj N et al. [6]	AWJM achieved smoother finishes (Ra < 3 µm) compared to plasma and laser cutting (Ra > 6 µm) for aluminum alloys.	Limited hybrid AWJM–laser investigations for titanium or ceramic materials.
	Panchal et al. [51]	ANN-based optimization reduced energy consumption by 12% and improved cutting efficiency by 10%.	Limited studies on low-energy AWJM system design.
	Demiral et al. [39]	SPH modeling predicted CFRP thermal damage zones of <200 µm thickness.	Need for physical validation of SPH-based simulation results.

	Monoralu et al. [13]	AWJ-machined CFRP showed Ra 3–5 µm and up to 25% fiber pull-out.	Limited post-machining surface restoration or coating studies.
Abrasive Selection and Performance	Khan et al. [4]	SiC abrasives improved cutting speed by 18% and reduced surface roughness by 20% compared to Al_2O_3.	Lack of abrasive recyclability and cost-efficiency evaluations.
	Azmir et al. [55]	Using smaller abrasive grit (80 mesh) lowered kerf angle by 15% and improved surface finish by 25%.	Insufficient data on the role of abrasive hardness and shape.
	Trivedi et al. [76]	Reducing traverse speed from 200 to 100 mm/min improved surface roughness by 22% in AISI 316L.	Need for IoT-based online monitoring systems.
	Adnan et al. [3]	AWJM preserved aluminum microstructure and hardness variations within ±2%.	Limited research on AWJM's influence on fatigue strength.
	Uhlmann et al. [23]	AWJ turning on Ti alloys showed minimal mechanically affected zone (<50 µm) and Ra ≈ 1.2 µm.	Need for tensile and fatigue property evaluations post-AWJ.
	Nanduri et al. [74]	Garnet abrasives caused nozzle wear of 0.05–0.08 mm/hr under 350 MPa pressure.	Lack of long-term testing of novel nozzle alloys.
	Chakravarthy & Babu [75]	Increasing pump pressure from 200 to 400 MPa reduced Ra by 30% in brass.	Limited optimization studies on nozzle exit geometry.
	Shanmugam & Masood [17]	High-pressure (400 MPa) and low feed rate (50 mm/min) reduced kerf taper by 35%.	Need for kerf taper control models in multi-layer structures.
Environmental and Economic Impact	Hoogstrate et al. [45])	Higher pressure operation improved productivity by 12–18% and reduced abrasive cost by 10%.	Lack of techno-economic analysis for sustainable operation.
	Panchal et al. [51]	Energy optimization via ANN led to 15% reduction in total power use per cut.	Absence of life cycle assessment (LCA) for AWJM energy chains.

3. Influence of Process Parameters

The abrasive water jet machining (AWJM) method has various aspects that affect its efficiency, cost-effectiveness, and output quality. Using experimental methods to determine the best mix of these traits is both time-consuming and expensive. Thus, developing a mathematical model that links cutting factors to end performance is critical, particularly for automated and computer-controlled operations. Such modelling focusses on predicting crucial output features based on defined input conditions.

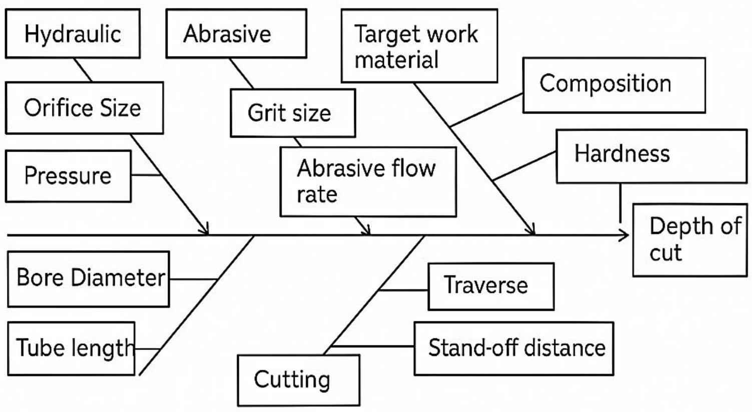


Fig. 1. Cause and effect diagram for AWJM

One significant outcome is the depth of cut, which measures the thickness of the material being machined [18-19]. This depth is largely determined by numerous operational elements, including pump pressure, cutting speed (traverse rate), abrasive mass flow rate, abrasive particle type and size, and water jet and orifice sizes. These factors are represented in Figure 1.

3.1 Water Pressure

Determines jet velocity and has a direct effect on material removal rate (MRR). The effect of process variables on AWJM in cast iron. When the mass flow rate, traverse speed, and standoff distance are maintained constant, the results reveal that increasing water pressure improves the depth of cut within the operating range selected [20]. When water pressure is increased, the jet's kinetic energy increases, resulting in a deeper cut. This was revealed to be due to the rise in water pressure, which raises the velocity of the water-jet, and the abrasive particle's kinetic energy is boosted after being accelerated, thereby boosting the material's abrasion and erosion effect.

3.2 Traverse Speed

The traverse speed plays a crucial role in determining the jet’s exposure time on the workpiece surface. It was observed that increasing the traverse speed has an adverse effect on the top kerf width. This occurs because a higher traverse speed allows fewer abrasive particles to strike the material, resulting in a narrower cut. Hence, the nozzle’s traverse speed emerged as a critical parameter in the machining process.

Experimental results revealed that a smooth surface finish on carbon fiber-reinforced plastic (CFRP) and unidirectional CERP composites was obtained when machining at lower traverse speeds. However, lower cutting speeds also led to reduced material removal rates, thereby increasing production time and cost. Therefore, an optimal traverse speed must be carefully selected to achieve the desired balance between surface quality and economic efficiency. It was further noted that while higher traverse speeds shorten machining time, the limited interaction between the jet and material results in increased surface roughness. For instance, at a traverse speed of 40 mm/min, the jet exhibited lateral dispersion from the central axis, leading to a wavy surface texture on the machined composite. In the case of Ti-6Al-4V alloy, machining trials conducted with traverse speeds between 60 and 200 mm/min showed a distinct influence on surface morphology. Microscopic analysis indicated that as traverse speed increased, the number of abrasive particles striking a particular area decreased, slightly reducing the width of the initial damage region (IDR) [21–23]. Moreover, the smooth cutting zone became narrower due to a reduction in penetration depth. Consequently, it was inferred that higher traverse speeds result in greater jet deflection and a corresponding decline in surface smoothness.

3.3 Stand-off Distance and Nozzle Design

Participate in jet coherence and energy distribution. The standoff distance is the distance between the nozzle and the workpiece. The research on AWJ review and parameter selection using the analytic hierarchy process (AHP) compared all of the parameters. According to his AHP studies, the most essential metric for cutting material is standoff distance, which ranks first, while weight age accounts for 19% of other factors. The investigated process parameters in AWJ cutting of stainless steel [24]. He observed that raising the nozzle standoff distance reduced the depth of cut while the other parameters tested in this study remained constant. However, it was shown that the standoff distance on depth of cut had negligible effect when compared to the traversal rate. The influence of process factors on depth of cut in AWJM cast iron. While the other parameters stay constant, the cut depth decreases as the standoff distance increases. It was revealed that the standoff distance had less impact on the depth of cut when compared to the other components investigated in this study.

4. Material-Specific Investigations

Non-traditional techniques are gaining favor because they can deliver extremely high performance. Because of the aforementioned qualities, precision machining of various metal alloys and polymeric matrix composite materials has become one of the most difficult tasks in recent times. These hybrid materials were developed using a variety of technologies, including traditional drilling and milling processes, water-jet cutting procedures, and laser technology. Figure 2 [25] illustrates a typical AWJM. AWJM's core working structure consists of a high-pressure pump system, a cutting head, a table, and a computer-based controller [26].

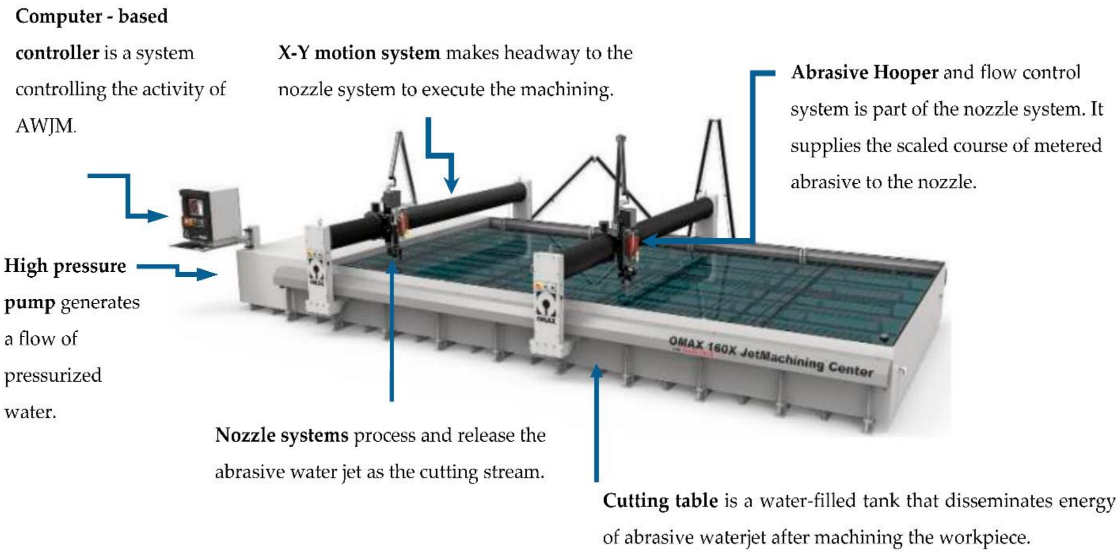


Fig. 2. Mechanism and components of AWJM [83]

The AWJM method produces zones with varying surface quality based on the thickness of the material. It also produces kerf width fluctuations at the material's entrance and departure, known as conicity or taper angle, which are mostly induced by the dispersion of the water jet's kinetic energy. These defects are due to micro and macro-geometric differences in the final output. These variations are key criteria for evaluating the geometry within the design and assembly specifications. Water-jet machining accelerates a mix of fluid and solid particles, producing deformation or removal of the target material that is impacted. The jet can be made of any liquid, but for economic and environmental reasons, it is usually a combination of water and air. The higher density of the water produces a greater impact pressure during milling. [27-28]

The cutting process is extremely important in the industrial sector. AWJM is extremely capable of cutting hard to soft materials with low machining force, hence reducing damage to the target workpiece's qualities [29]. Abrasive waterjet machining (AWJM) is a non-traditional cold processing method for material processing that offers substantial benefits [30], contributing to its growing acceptance, particularly in metallic materials [31]. Cooling water lowers the temperature, leading in AWJM [32]. Experimental testing on a range of workpieces [33–41] demonstrate the superiority of AWJM over other non-traditional machines, as shown in Table 2. It supports AWJM in contrast to other technologies by displaying adaptability in cutting various materials with a wide range of thickness, lack of tool wear, and flexibility in cutting complicated patterns.

Table 2. Comparative analysis of modern with non-traditional machining processes [33-41]

Sl. No.	Activity	AWJM (Abrasive Water Jet Machining)	EDM (Electrical Discharge Machining)	ECDM (Electrochemical Discharge Machining)	LBM (Laser Beam Machining)
1	Material Removal Rate (MRR)	Moderate MRR, typically 1–25 mm^3/min, increasing up to 30% with higher abrasive flow and pressure.	Medium MRR, ranging 5–50 mm^3/min, depending on discharge energy (50–300 μJ) and pulse duration.	Generally moderate, about 2–15 mm^3/min, governed by electrochemical and discharge effects.	High MRR for thin materials, often 20–200 mm^3/min, with rates up to 40% higher than EDM for non-metals.

2	Material Thickness Range (mm)	Efficiently cuts materials 1–300 mm thick without thermal distortion.	Works effectively for conductive materials 1–300 mm thick.	Best for micro-cutting and small parts within 1–50 mm thickness.	Limited to <20 mm due to restricted beam penetration and reflection losses.
3	Type of Shapes Produced	Capable of intricate 2D/3D profiles with ±0.1 mm accuracy and Ra 2–3 μm surface finish.	Produces cavities and holes with ±0.02 mm accuracy; typical surface finish Ra 0.8–2 μm.	Generates micro-slots and holes (diameter <1 mm) with Ra 1–2 μm finish.	Ideal for precise micro-patterns and contours with dimensional accuracy ±0.01 mm and Ra 0.5–1 μm.
4	Tool Wear	No measurable tool wear since there is no direct contact; nozzle wear rate <0.01 mm/hr.	High tool wear, electrode erosion rate up to 0.3–0.5 mm^3/min, affecting dimensional accuracy.	Moderate wear (≈0.05 mm/hr) due to combined electrochemical and thermal effects.	No tool wear; only optical lens degradation over long usage.
5	Workpiece Distortion	Nil distortion (temperature rise <50°C), ensuring near-zero residual stresses.	Very low distortion; heat-affected zone (HAZ) limited to 10–50 μm.	Minor distortion possible due to localized heating; HAZ about 30–100 μm.	Negligible distortion, but reflective metals may show 2–3% warping under high power density.
6	Burr Formation	Burr height typically <10 μm, yielding clean edges.	High burr formation (20–80 μm) due to re-solidified molten material.	Minimal burrs (<5 μm) as material removal is mainly electrochemical.	High burr tendency (30–100 μm) in melted and re-solidified zones.
7	Vapour / By-products	No harmful vapours; only spent abrasives and water residue.	Produces CO, carbon soot, and dielectric fumes; particle concentration may reach 50–200 mg/m^3.	Generates NaOH vapour and hydrogen bubbles; reaction by-products ≈0.2–0.5 g/min.	Produces metallic fumes; fume rate around 0.1–0.3 g/min, requiring exhaust ventilation.
8	Type of Material Processed	Cuts almost all materials (metals, ceramics, composites); productivity gain 25–40% over conventional cutting.	Restricted to conductive materials (Cu, Al, steel); non-conductive materials not machinable.	Best for conductive brittle materials (glass, ceramics with coating); improved surface integrity by 15–20%.	Works well with polymers, ceramics, and non-reflective metals; productivity improvement 30–50% for thin sections.

Abrasive Water Jet Machining (AWJM) has evolved as a very adaptable and efficient non-traditional machining technology that can handle a broad range of materials, including metals, composites, ceramics, and glass. Its remarkable ability to cut complicated profiles without causing severe heat damage makes it ideal for machining difficult-to-cut and brittle materials. Over the years, different researchers have conducted material-specific researches to understand and optimize the AWJM parameters for producing high-quality machining outputs across diverse material categories.

4.1 Metals and Alloys

AWJM has shown significant promise in machining high-strength metals and advanced alloys such as titanium, Inconel, and hardened steels. These materials are commonly used in aerospace, automotive, and biomedical sectors due to their excellent mechanical and thermal properties. However, their inherent hardness and low thermal conductivity pose challenges for conventional machining processes. AWJM, being a cold cutting process, overcomes these limitations and ensures minimal heat-affected zones and negligible distortion. Studies have reported enhanced surface integrity and minimal microstructural alterations when machining titanium and Inconel alloys using optimized jet parameters, such as pressure, abrasive flow rate, and traverse speed. For hardened steels, the erosion-based mechanism of AWJM allows for precise material removal without compromising tool life or dimensional accuracy [42-43]. Researchers have also focused on optimizing standoff distance and abrasive particle size to further improve kerf quality and surface finish in metallic materials.

4.2 Composites

Composite materials such as Carbon Fiber Reinforced Polymers (CFRP) and Glass Fiber Reinforced Polymers (GFRP) exhibit outstanding tensile strength values ranging from 600 to 1500 MPa and specific stiffness between 25 GPa and 40 GPa, making them ideal for aerospace, automotive, and defence applications. However, due to their anisotropic and layered structure, machining these materials often leads to strength degradation up to 10–20% when processed through conventional cutting techniques. Issues such as delamination, fiber pull-out, and matrix cracking are commonly observed, which significantly reduce the interlaminar shear strength (ILSS) and fatigue resistance of the machined component. Abrasive Water Jet Machining (AWJM) provides an effective non-contact alternative that helps preserve the inherent mechanical strength of composites. The process introduces negligible thermal damage, maintaining over 95% of the original tensile and flexural strength of CFRP and GFRP materials. Studies have reported that using a traverse speed between 40 and 80 mm/min, a water pressure of 300–400 MPa, and an abrasive flow rate of 300–350 g/min yields optimal results in terms of edge quality and strength retention [44]. At lower traverse speeds (40 mm/min), the jet interaction time increases, resulting in minimal delamination (typically below 0.2 mm) and smoother cut edges with surface roughness (Ra) values around 2.5–3.0 µm. Conversely, higher traverse speeds (above 150 mm/min) reduce cutting strength and increase roughness values to 5–6 µm, compromising the overall load-bearing capability of the material. Optimization studies have demonstrated that selecting appropriate parameters through multi-objective techniques can maintain 90–95% of the composite's baseline tensile strength, while simultaneously reducing material removal time by nearly 30% achieving a balance between machining efficiency, mechanical integrity, and cost-effectiveness.

4.3 Ceramics and Glass

Brittle materials such as ceramics and glass are notoriously difficult to machine due to their high hardness and low fracture toughness. Traditional machining methods often lead to chipping, cracking, and surface defects. AWJM offers a promising solution by using a high-velocity abrasive stream that erodes the surface without exerting excessive mechanical loads. The process parameters need to be meticulously controlled to ensure that the erosion occurs uniformly, thereby minimizing the risk of cracks and micro-fractures. Investigations into the machining of alumina, silicon carbide, and borosilicate glass have shown that careful regulation of abrasive grain size and pressure can lead to clean cuts with minimal subsurface damage. Some studies have also explored the use of pulsed water jets and hybrid processes to further refine the material removal process and improve surface characteristics [45]. Material-specific investigations in AWJM have significantly advanced the understanding of how different materials respond to the abrasive jet cutting mechanism. By tailoring process parameters to the unique properties of each material class, researchers have been able to expand the applicability of AWJM across diverse industrial sectors.

These insights contribute to the development of more efficient, sustainable, and high-precision machining strategies.

5. Recent Developments and Innovations

Recent research in abrasive water jet machining (AWJM) has focused on enhancing precision, efficiency, and material versatility as given in table 3. Advances include controlled-depth machining, multi-layer and hybrid composite cutting, and optimization of process parameters using experimental, statistical, and metaheuristic approaches. Studies highlight improved surface quality, reduced delamination, and minimal thermal impact across metals, composites, and natural-fiber laminates. Innovations such as additive-enhanced jets, neural network modeling, and hybrid optimization strategies have expanded AWJM applications in aerospace, automotive, and microfabrication, pushing the boundaries of sustainable and high-precision material processing.

Table 3. Studies on abrasive water jet machining (AWJM): materials, parameters, responses, and optimization approaches

Author (s), Year	Material/Workpiece	AWJM Parameters Studied	Responses/Outputs	Key Findings/Observations	Optimization/Modeling Approach
Anu Kuttan et al., [2]	Various materials	Mixing, hydraulic, cutting, abrasive parameters	Material removal, kerf quality	Survey of AWJM techniques; identified challenges like low material removal rate, low penetration	Review; dimensional, statistical, differential equation, neural network, numerical, analytical models
Ozcan et al., [87]	Free-form surfaces	Water pressure, traverse speed, abrasive rate, standoff distance	Kerf profile (width, depth, shape)	Developed analytical model using energy/momentum conservation; 3D in-process geometry predicted; 15% avg. error	Analytical modeling; IPW simulation with Signed Distance Field
Bańkowski et al., [89]	S235JR carbon steel	Cutting speed, abrasive consumption	Cutting temperature, microstructure, nano hardness	Local temps exceeded eutectoid temperature; phase changes observed; heat affects microstructure	Experimental: thermocouples, XRD, optical microscopy
Spadło et al., [88]	Steel	AWJM energy impact	Microstructure, indentation hardness	Local temp rise to 450°C+; plastic deformation and heat transfer affect microstructure	Optical metallography, SEM, hardness tests
Dahiya et al., [90]	Composites	Various AWJM parameters	Machining quality, morphology	AWJM efficient for composites; literature review; research gaps identified	Review; modeling & optimization methods tabulated
Arun et al., [91]	Silicon-filled epoxy glass fibre composites	Silicon content, water jet pressure, standoff	Kerf taper angle, surface roughness	5% Si filler gave optimal machining quality; 10% increased Ra and	Experimental investigation, SEM, process optimization

		distance, traverse speed		KTA; high WP improves machinability	
Sreekumar et al., [93]	Various materials	AWJM with additives	Material removal rate, depth of cut, kerf-width, kerf-taper	Polymeric additives improve jet stability and cutting performance	Review; analysis of additive effects
Dahiya et al., [90]	Glass fibre reinforced polymer composite	Water pressure, stand-off distance, traverse rate, abrasive flow rate	Max delamination length, surface roughness, kerf taper	Max delamination decreases with higher AMFR & lower TR; optimal Ra, Kt, DLL obtained	RSM-based regression; multi-response optimization
Iyer & Arunkumar, [95]	Bismaleimide hybrid fiber composites	Water pressure, transverse speed, standoff distance, abrasive mass flow	Kerf taper, surface roughness	Plowing and abrasive embedment affect delamination; optimal parameters minimize kerf & Ra	CCD-based DoE; experimental analysis
Abouzaid et al., [96]	Brass	Stand-off distance, traverse speed	Kerf width, cutting quality, surface roughness	Lower SOD + higher TS improves cut quality; optimal Ra = 1.1 μm, KW = 1.706 mm	Experimental parameter study
Demiral Jagadish et al., [92]	Green composites	AWJM pressure, traverse speed, stand-off distance	Surface roughness, process time	Neural networks map multiple outputs; metaheuristics (SMO, GWO, TLBO) optimize AWJM parameters	Neural networks; genetic/metaheuristic optimization
Dahiya et al., [98]	GFRP composite	Water pressure, traverse rate, stand-off distance, abrasive flow rate	Delamination, fiber pull-out, abrasive embedment	Optimal SOD, WP, TR, AMFR minimizes delamination; SEM confirms surface integrity	RSM-based CCD; desirability function optimization
Dubey et al., [99]	Ti-6Al-4V alloy	Abrasive flow rate, stand-off distance, nozzle traverse speed	MRR, surface roughness, kerf taper	Stand-off distance most influential; Grey entropy weight method improved Grey relational grade	RSM-Box–Behnken; Grey Entropy Weight (GEW) method
Gariani & Altaher, [100]	Metals	Water pressure, traverse speed, abrasive mass flow, SOD,	Surface roughness, kerf accuracy, depth, MRR	Reviewed effect of key parameters on machining responses; future research suggested	Review

		abrasive type & size			
Abouhawa et al., [101]	Ti-6Al-4V/CFRP/Al7075 stacks	Jet pressure, SOD, nozzle speed	Kerf taper, surface roughness, MRR	ANN + NSGA-II + Entropy-TOPSIS optimized multi-layer cutting; water pressure had highest influence	Bayesian ANN; NSGA-II; Entropy-TOPSIS
Palanikumar et al., [102]	MWCNT/bamboo/Kenaf epoxy composites	Traverse speed, abrasive flow rate, SOD	Surface roughness, kerf width	Optimized with RSM & Firefly Algorithm; minimal error <6.27%	RSM Box-Behnken; Firefly Algorithm
Rahman et al., [103]	Various metals & composites	AWJ micromachining parameters	Material removal, precision, minimal thermal deformation	Review on AWJMM advancements; emphasizes automation, CFD, and precision manufacturing	Review; forward-looking technological perspective
Ravindran et al., [104]	Al2017A/hBN/ZrO2 hybrid composites	Water pressure, traverse speed, abrasive flow rate, SOD	Cylindricity, circularity, roundness, HDF	Medium WP + medium TS + high AFR + large SOD improves hole quality metrics	Taguchi L27; RSM; mean effect plots
Chaturvedi et al., [105]	Ti-6Al-4V alloy	Jet pressure, AFR, SOD, transverse speed	Machining time, hardness, surface roughness	Pressure most affects time & Ra; particle embedding changes hardness	L25(54) orthogonal matrix DoE; SEM
Qasem et al., [106]	Granite	Pump pressure, traverse speed, abrasive mass flow	Depth of cut	Fine-grained granite gives higher depth; optimal P, T, A calculated	Experimental analysis
Mogul et al., [107]	Ti-6Al-4V alloy	Water pressure, transverse speed, AFR, orifice size, nozzle diameter	Depth of cut	Backprop NN predicted depth with 95% accuracy; low depth predictions less accurate	Backpropagation neural network; Taguchi L27; K-fold validation
Veljković et al., [108]	Aluminum AlMg3	Operating pressure oscillations, traverse speed	Surface topography, waviness	Pressure oscillations directly affect surface striations; FFT analysis used	Experimental; FFT signal analysis
Buglioni et al., [109]	Steel/alloys	AWJM vs Milling	Ultimate tensile strength, elongation	AWJM samples show lower UTS, higher elongation; milling introduces stress concentrators	Experimental & simulated mechanical analysis

Wu et al., [110]	No. 45 steel	Abrasive particle size, operating pressure, abrasive feed rate	MRR, notch depth, nozzle wear rate	Multi-response optimization identified optimal conditions for max MRR, notch depth, min nozzle wear	Taguchi L16; Decision Engineering Analysis & Resolution; regression
Pendokhare et al., [111]	Lanthanum phosphate/Yttria & GFRP composites	AWJM process parameters	MRR, kerf angle, surface roughness, delamination	Foraging-based metaheuristic optimization; African Vultures Optimizer most efficient	Metaheuristic optimization; comparative analysis

The studies collectively demonstrate optimized AWJM parameters for diverse materials, leading to improved surface quality, kerf geometry, reduced delamination, and higher material removal rates. Advanced modeling, neural networks, and metaheuristic algorithms enhanced prediction accuracy, while innovations in hybrid, composite, and natural-fiber materials expanded AWJM applicability in aerospace, automotive, and precision engineering.

5.1 Hybrid AWJM

Hybrid AWJM has emerged as a transformative approach in precision machining, combining mechanical erosion with advanced energy inputs to address the limitations of conventional waterjet cutting such as striations, taper, and lower efficiency on hard or composite materials. Two prominent avenues in this hybridization are ultrasonic vibration-assisted AWJM and laser-assisted AWJM, each offering distinct benefits that, when integrated, yield synergistic advantages.

5.1.1 Ultrasonic Vibration–Assisted AWJM

Figure 3 shows that schematic of AWJM that applying high-frequency (>20 kHz) ultrasonic vibrations to the workpiece or nozzle assembly significantly improved material removal rate (MRR), hole quality, and decreased delamination [46]. Ultrasonic-vibration-assisted AWJM on materials like as quartz glass can drastically modify abrasive particle dynamics via cavitation and microjet effects, minimizing edge chipping and increasing surface integrity. Using ultrasonic vibration in waterjet drilling of CFRP laminates led to a 20% increase in MRR, an 85.6% reduction in delamination zone, and significantly improved hole-wall smoothness under optimized conditions (10 µm amplitude at 20 kHz, 900 m/s jet velocity). These findings demonstrate the capacity of ultrasonic aid to control cavitation intensity, promote cleaner erosion, and inhibit lateral water flow, which is often responsible for edge damage. Overall, this hybrid approach improves efficiency and quality, especially for brittle or multilayer composites.

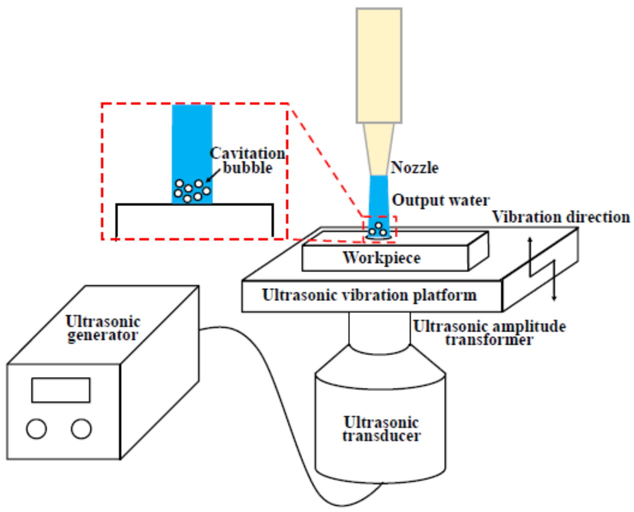


Fig. 3. Schematic of ultrasonic-vibration-assisted AWJM[86]

5.1.2 Laser–Assisted AWJM

In laser-assisted AWJM, a laser beam preheats or softens the workpiece surface ahead of the abrasive jet, facilitating easier material erosion without generating a heat-affected zone. Springer's research explains that integration of femtosecond or CO_2 lasers with AWJM enables localized heating that alleviates jet resistance, improves ablation efficiency, and enhances micro-machining accuracy particularly for ceramics and polymers while avoiding typical laser-induced thermal damage [47]. Additional studies show the method achieves up to a 20 % improvement in drilling depth-to-diameter ratio and significantly reduces debris re-deposition, thanks to the laser's interaction in a liquid medium combined with ultrasound, which improves cavitation suppression.

5.1.3 Dual-Mode Hybrid

The most advanced frontier marries ultrasonic and laser energies within AWJM, yielding a hybrid process that capitalizes on the advantages of both approaches. Although most work in this vein is in turning/milling contexts, the underlying principles extend naturally to AWJM. For instance, documented hybrid turning of aluminum and magnesium alloys, demonstrating substantial reductions in cutting forces, improved surface finishes, and tool wear abatement when ultrasonic vibration and laser heating were combined. These findings underscore the potential of combined energy modalities to enhance thermoplastic behavior, reduce mechanical resistance, and improve machining stability. Adapting this approach to AWJM involves synchronizing ultrasonic oscillations with a laser preheat of the material just ahead of the waterjet. Ultrasonic cavitation then agitates the softened zone, promoting more efficient and uniform abrasion. Preliminary models and experimental frameworks (inspired by turning/milling hybrids) predict enhanced MRR, sharper kerf profiles, minimal taper, and controlled micro-cracking especially in refractory ceramics or functionally graded materials. While ultrasonic and laser-assisted AWJM have individually matured, integrating both in a coordinated system requires sophisticated synchronization control, precise alignment of laser and jet, and real-time process monitoring [48-49]. Moreover, optimizing parameters such as laser power, vibration amplitude, jet pressure, and nozzle dynamics is non-trivial, demanding coupled multi-physics modelling and in-depth experimental validation. Nonetheless, early academic interest and promising preliminary results suggest this dual-mode hybrid AWJM represents a compelling direction for future research. It holds the promise of achieving unprecedented precision, efficiency, and surface integrity in machining of hard, brittle, or composite materials pushing AWJM closer to the performance of traditional high-precision processes but with the added benefit of being cold, clean, and ecologically friendly

5.2 Abrasive Recycling

The increasing demand for sustainable manufacturing practices has led to significant developments in abrasive recycling, particularly in processes like Abrasive Water Jet Machining (AWJM) and other surface finishing operations. Traditionally, abrasive materials such as garnet, aluminum oxide, and silicon carbide were discarded after a single use, contributing to both environmental and economic concerns. However, recent innovations have focused on recovering and reusing these abrasives without compromising machining efficiency. One of the key advancements in this domain is the development of specialized abrasive recycling systems that incorporate multi-stage sieving, washing, and drying mechanisms. These systems effectively remove contaminants such as metal fragments, oil residues, and broken particles, thereby restoring the abrasive to near-original quality. Studies have shown that recycled abrasives can retain up to 85–90% of their cutting performance, making them viable for multiple reuse cycles [50-51]. Furthermore, improvements in material characterization techniques, including scanning electron microscopy (SEM) and particle size analysis, help in assessing the integrity of recycled abrasives more precisely.

Additionally, manufacturers are investing in closed-loop abrasive recycling systems that integrate directly with machining setups, reducing the need for external waste management. These closed systems enhance operational efficiency and support environmental compliance by minimizing disposal and raw material consumption. Research is also exploring the blending of fresh and recycled abrasives in optimal ratios to balance cost savings and machining performance [52-53].

Abrasive recycling has emerged as a critical strategy in advancing sustainable manufacturing, promoting resource efficiency, and lowering the ecological footprint of machining processes

5.3 Simulation and Modelling

Recent developments in simulation and modelling have significantly advanced the understanding and optimization of abrasive water jet machining (AWJM), particularly concerning kerf characteristics and nozzle performance. Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) have emerged as powerful tools to simulate the complex interactions between high-pressure abrasive jets and workpiece materials. These techniques enable researchers to visualize and analyze material removal mechanisms, predict stress and deformation patterns, and assess the thermal and mechanical effects involved in the cutting process. FEM is commonly used to model the mechanical response of the workpiece under jet impact, providing detailed insights into kerf geometry, material fracture behavior, and surface integrity [54-55]. By incorporating material properties, boundary conditions, and dynamic loading, FEM helps in predicting kerf taper, width, and depth with improved accuracy. On the other hand, CFD focuses on modeling the fluid dynamics of the abrasive jet, simulating the velocity, pressure distribution, turbulence, and abrasive particle trajectories within and outside the nozzle.

Recent innovations have combined FEM and CFD techniques in a coupled manner to achieve a comprehensive understanding of AWJM processes. These integrated models are increasingly employed to optimize nozzle geometry, including diameter, convergence angle, and material, which directly affect jet coherence, energy delivery, and erosion efficiency. The use of advanced simulation not only reduces experimental costs and time but also enables virtual prototyping of new designs. As a result, simulation-driven approaches are now essential in improving process performance, enhancing cut quality, and extending nozzle life in modern AWJM systems

5.4 Multi-Objective Optimization

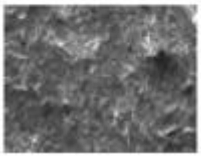
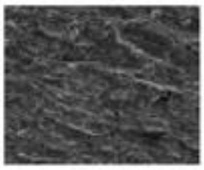
In recent years, multi-objective optimization (MOO) has emerged as a critical approach in advanced manufacturing processes to simultaneously enhance multiple conflicting performance parameters such as material removal rate (MRR), surface roughness, and kerf taper. Traditional single-objective techniques often fall short in addressing the trade-offs among these parameters. Consequently, researchers have increasingly adopted sophisticated optimization strategies, including the Taguchi method, Response Surface Methodology (RSM), and evolutionary algorithms. The Taguchi method, widely recognized for its robustness and simplicity, focuses on signal-to-noise ratio analysis to improve quality characteristics. Although it primarily emphasizes single-objective optimization, it has been modified and combined with other techniques to address multiple objectives effectively. On the other hand, RSM, a statistical and mathematical technique, facilitates the development of empirical models that describe the relationship between input variables and output responses [56-57]. This method is particularly useful for identifying optimal process conditions with minimal experimental trials. Evolutionary algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Non-dominated Sorting Genetic Algorithm II (NSGA-II) have shown significant promise in handling complex, nonlinear, and multi-modal optimization problems. These algorithms mimic natural selection and swarm intelligence to generate a set of Pareto-optimal solutions, allowing decision-makers to choose the most suitable trade-off based on specific requirements [58-59]. The integration of these MOO techniques has led to significant process improvements in non-traditional machining and advanced manufacturing, contributing to enhanced productivity, superior surface integrity, and minimized machining errors. These developments underscore the growing importance of intelligent optimization tools in achieving sustainable and high-performance manufacturing outcomes.

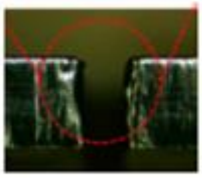
6. Challenges and Limitations

The performance of AWJM has to be improved because it is frequently utilized for cutting operations. AWJ cutting processes continue to face challenges in terms of quality and productivity performance, with metallic materials being regarded as among the most difficult to cut due to their low machinability. There have been complaints of cutting problems while using an abrasive waterjet machine. Damage might also vary depending on the material to be machined [60]. The issue of material reaction to AWJM in terms of its behavior, i.e., burr growth, high surface roughness, striation marks, changed kerf geometry, and delamination, has been explored from the beginning of AWJM applications in the 1980s [61-64]. Table 4 displays frequent AWJ cutting challenges that have been restudied by researchers, notably for metallic materials.

According to Table 3, earlier research has found comparable common problems with using this machine for materials that are challenging to cut, particularly metals [65–68]. Several studies have found that AWJ cutting is commonly employed on metallic materials of varying thicknesses. The AWJ cutting process has also been demonstrated to exhibit analogous defects, such as kerf taper, roughness, and metal breaking while cutting, regardless of thickness. Table 4 summarizes current research that employed AWJ cutting on metals of varying thicknesses. As shown in Table 4, the kerf taper angle and surface roughness are important quality problems identified in the AWJ cutting of metallic materials of varying thicknesses. Consequently, [69–71] carried out machinability studies that looked at how well AWJM performed when cutting low alloy steel of different thicknesses (5, 10, 15, and 20 mm). Their research found that material thickness influences machine performance in terms of material removal rate, surface roughness, and kerf wall inclination. As a result, it is critical to investigate the effect of material thickness on precise AWJM, as cutting operations in fabrication industries include varied product thicknesses. The issues described above impede AWJ cutting performance [72–75]. However, these issues have lately been reinvestigated, and it has been determined that AWJM performance is dependent on process factors. To improve AWJ cutting performance, it is necessary to undertake ongoing detailed investigations of process parameters, as indicated in the following section.

Table 4. AWJ cutting defects in materials [61-68]

Defects	Material	Images	Findings
Pahuja et al. [61] Surface Roughness	Ti- 6AAI-4V		Ti-6Al-4V was cut using AWJ by Gnanavebabu et al., who discovered striations and roughness in the cut surfaces. They discovered that the cut surface polish changes with the depth at which the abrasive jet reaches the surface.
Selvan et al. [62] & Gnanavelbabu et al. [68] Material removal rate, Kerf taper angle	Inconel 600		When employing an abrasive waterjet machine to cut super nickel alloy, Uhtayakumar et al. observed quality issues such kerf form and a low material removal rate. They achieved a considerable occurrence of erroneous kerf geometry by using a large quantity of water pressure and raising the transverse speed.
Wang et al. [63] Cutting rate and roughness	AISI 304		In AISI 304, Miao et al. used AWJM to find quality defects including kerf and cutting rate. These defects are created by lowering the energy of the jet.
Ramulu et al. [64] Depth of Cut	S 304		According to Supriya et al., achieving a high depth of cut is one of the challenges associated with cutting stainless steel due to its restricted machinability. They found that using an abrasive waterjet machine with a high-pressure setting increased the depth of cut.

Chen, M et al. [65] & Miaoet al. [66] Miao et al. [67] Kerf taper angle	ASI1090		The kerf taper angle is an intrinsic characteristic of AWJ cutting of AISI 1090 MS, according to Mohamad et al. They discovered that changing the kerf top width and bottom shape resulted in a higher kerf taper angle.

7. Future Research Directions

Abrasive Water Jet Machining (AWJM) has evolved significantly over the past decades, becoming a preferred method for machining difficult-to-cut materials without thermal distortion. However, as industries continue to demand higher precision, sustainability, and cost-effective solutions, the scope for further research in AWJM remains vast. The future of AWJM research is expected to address current limitations while expanding its capabilities through interdisciplinary approaches and advanced technologies. One of the primary areas requiring attention is the integration of advanced materials. The increased use of composites, high-strength alloys, and brittle ceramics in aerospace, biomedical, and automotive applications calls for deeper investigations into material-specific machining responses. Each material class exhibits unique behaviors under high-pressure jet impact, and current process parameters may not always yield optimal results [76-78]. Future studies should aim to develop customized abrasive types and jet conditions tailored to these materials. Additionally, the formulation of innovative abrasives designed specifically for hard or brittle materials can greatly enhance cutting efficiency and surface quality. Another major research direction is process optimization through Artificial Intelligence (AI) and Machine Learning (ML). Traditional parameter optimization techniques, while effective, often require extensive experimentation. In contrast, AI-based approaches can learn from historical data and identify optimal process windows in real-time. Predictive models that adjust AWJM parameters dynamically during operation could significantly reduce trial-and-error methods, improve consistency, and minimize waste [79-80]. Intelligent process control systems with real-time feedback loops could lead to fully automated AWJM setups with adaptive capabilities.

Sustainability and environmental impact are becoming increasingly important in manufacturing research. Although AWJM is inherently a cold process with minimal thermal damage, the consumption of abrasive materials and water needs careful evaluation. Life cycle assessment (LCA) studies can provide valuable insights into the environmental footprint of AWJM compared to conventional techniques. Future research should explore the use of eco-friendly abrasives, such as biodegradable particles or recycled materials, and water recycling systems to reduce overall resource consumption [81-83]. Exploring hybrid machining processes presents another promising research avenue. By integrating AWJM with complementary techniques such as laser machining, ultrasonic vibration, or traditional milling, researchers can overcome individual limitations and unlock new functionalities. Hybrid systems may allow for processing of complex geometries or multi-material structures, providing both high precision and efficiency. Moreover, the development of advanced modeling and simulation frameworks is essential to predict process outcomes more accurately. Incorporating multi-physics simulations that consider abrasive flow dynamics, material deformation, erosion mechanics, and heat generation will offer a more comprehensive understanding of the AWJ process [84-85]. Lastly, innovations in nozzle design and jet configuration, along with real-time monitoring and quality control, will define the next generation of AWJM. Smart sensing systems, machine vision, and acoustic emission monitoring can provide live feedback during machining, allowing for on-the-fly corrections and improved process reliability. Such advancements will ensure the continued relevance and growth of AWJM in high-precision and high-demand manufacturing sectors.

8. Conclusion

Abrasive Water Jet Machining (AWJM) has firmly established itself as a versatile and efficient non-traditional machining technique, particularly suited for processing hard-to-machine and thermally sensitive materials. This review has provided a comprehensive overview of the current research landscape, highlighting the advancements in process parameter optimization, material-specific investigations, and technological integrations. It is evident that AWJM offers numerous advantages, including minimal thermal distortion, high machining flexibility, and suitability across a wide range of materials. However, challenges such as limited surface finish, abrasive consumption, and nozzle wear continue to demand focused research efforts. Future directions are anticipated to revolve around the integration of intelligent control systems, machine learning-based optimization, sustainable abrasive materials, and hybrid machining approaches. These advancements will enhance process efficiency, precision, and eco-friendliness. As industries seek more adaptive and environmentally responsible manufacturing solutions, AWJM stands out as a compelling candidate for further development. By bridging current gaps and leveraging emerging technologies, researchers and practitioners can unlock the full potential of AWJM, making it a critical component in modern and future manufacturing systems.

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