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Review Article

Comprehensive and essential review of advanced researches abrasive waterjet machining

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ABSTRACT

Abrasive Waterjet (AWJ) machining is a highly versatile non-conventional manufacturing technology, increasingly adopted across diverse industries due to its capability of processing a wide spectrum of materials, including metals, alloys, ceramics, composites, and polymers. Unlike conventional methods, AWJ utilizes high-pressure water mixed with abrasive particles to remove material by erosion, significantly reducing thermal effects, mechanical distortion, and material degradation. The performance and efficiency of AWJ machining are directly influenced by critical process parameters such as waterjet pressure, traverse speed, abrasive mass flow rate, stand-off distance, and nozzle geometry. Recent studies have shown that optimizing these parameters is essential to enhance surface finish, improve material removal rates, and reduce kerf defects such as taper angles and burr formation. This comprehensive review systematically synthesizes recent advancements and essential findings from the existing literature on AWJ machining. It emphasizes material-specific optimization strategies, explores critical interactions between machining parameters, and summarizes methodologies such as experimental designs, numerical modeling, response surface methodology, and artificial neural networks frequently used to optimize the AWJ process. Particular attention is given to identifying the underlying mechanisms influencing outcomes, such as material erosion phenomena, abrasive particle interactions with the material surface, crack initiation and propagation, as well as abrasive embedment. Furthermore, the review addresses current challenges, including achieving precision machining for hard-to-cut materials like superalloys (e.g., Inconel 718, Ti-6Al-4V) and fiber-reinforced polymer composites, highlighting recent solutions and future research directions. This extended synthesis provides valuable insights and standardized guidelines for industrial practitioners and researchers, facilitating broader adoption and continuous innovation within AWJ machining technology.

1. Introduction

Abrasive Waterjet (AWJ) machining is a prominent non-conventional manufacturing process distinguished by its capability to precisely machine complex, heat-sensitive, and advanced materials without generating substantial thermal stresses or inducing heat-affected zones (HAZ). Over the past decades, extensive research has underscored the importance and effectiveness of AWJ technology for machining applications in diverse industries, including aerospace, automotive, marine, biomedical, and energy sectors.

Numerous studies have examined AWJ processes and their applications across a wide variety of material classes. This includes machining advanced metallic alloys such as titanium (Ti-6Al-4V, gamma titanium aluminide): nickel-based superalloys (Inconel 718): aluminum alloys (AA6061, AA7075, AA2024-T3): and specialized high-strength steels. AWJ machining has also demonstrated excellent applicability in the processing of composites and polymer-based materials such as carbon fiber reinforced plastics (CFRP): Kevlar fiber-reinforced polymers, UHMWPE, wood-plastic composites, PP, PVC-U coated with polyurethane, acrylate coatings, jute-epoxy composites, and aluminum/silicon carbide composites.

The quality and effectiveness of the AWJ machining processes are highly dependent on careful selection and optimization of numerous parameters, which predominantly include waterjet pressure, abrasive mass flow rate, traverse speed, standoff distance, nozzle design

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and geometry, abrasive particle size and shape, and workpiece properties.

Parametric influences on AWJ machining outcomes are primarily reflected through key performance indicators such as surface roughness, kerf geometry, material removal rate, waviness, dimensional accuracy, surface contamination, grit embedment, and surface integrity.

Recent scientific explorations underline the importance of understanding the underlying mechanisms driving material removal in AWJ machining. Primary mechanisms include abrasive-induced micro-cutting, material erosion, plastic deformation, fracture propagation, brittle fracture, abrasive particle impact, and surface embedding. Detailed comprehension of these mechanisms is vital to explain precisely how selected parameters yield specific machining effects, thus guiding further process optimization and improved performance.

Moreover, extensive research has been dedicated to employing advanced analytical and numerical modeling approaches to simulate AWJ machining processes and predict outcomes more precisely. Techniques like finite element analysis (FEA): artificial neural networks (ANN): regression modeling, and response surface methodology (RSM) have become instrumental in modeling and predicting critical responses, optimizing parameters, and implementing adaptive process control.

Emerging trends also highlight the integration of AWJ with hybrid manufacturing processes, including additive manufacturing, milling, and turning operations, emphasizing their potential to achieve complex geometries, enhance surface quality, and expand the versatility of this machining technique

Considering the comprehensive analysis above, this review systematically assesses the recent advances in AWJ machining with particular emphasis on understanding the precise relationships between operational parameters, resulting effects, and underlying machining mechanisms. Additionally, this review synthesizes insights from an extensive range of contemporary studies, establishing a clear scientific foundation for future investigations, optimization strategies, and innovative AWJ machining applications.

2. Literature Survey

2.1. Materials

Ravi and Srinivasu [1] conducted a detailed parametric study on AWJ trepanation of Al-6061 alloy as shown in Figure 1. The experimental setup focuses on optimizing the process parameters such as water jet pressure, pass velocity and abrasive mass flow rate. They found that higher pressure and mass flow rates at lower speeds improved hole quality by minimizing form error and burr length. Optimal parameters included a pressure of 350 MPa, traverse speed of 50 mm/min, and mass flow rate of 0.55 kg/min, offering valuable insights for precise and high-quality machining of Al-6061.

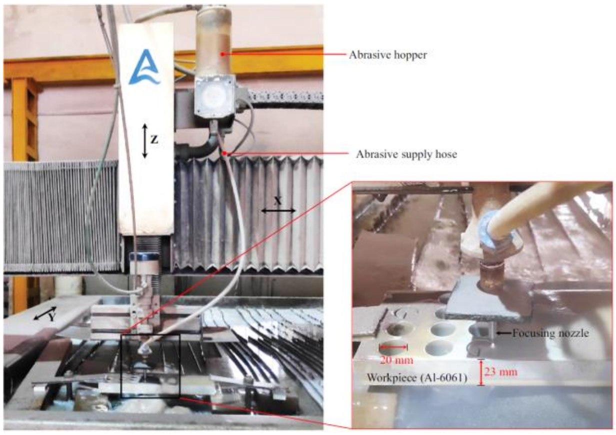


Figure 1. Experimental setup employed for AWJ trepanning [1].

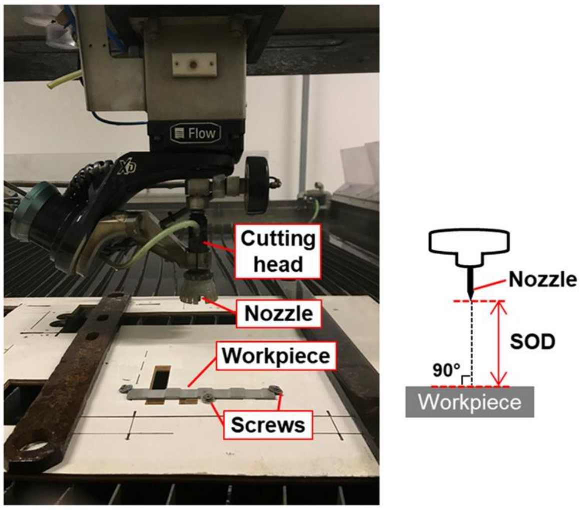


Figure 2. Experimental setup for AWJ and PWJ processes with a schematic showing the SOD process parameter and the impingement angle between the nozzle and the sample [2].

Cano-Salinas et al. [2] investigated AWJ milling of Inconel 718, focusing on finishing by plain waterjet (PWJ) cleaning as seen in Figure 2. Their study revealed that PWJ cleaning could remove up to 80% of embedded grit without altering surface texture or material properties, maintaining mechanical integrity. This combination of AWJ and PWJ proves effective for aerospace applications requiring high surface quality.

Płodzień et al. [3] studied AWJ cutting of Inconel 718, modeling kerf angle, surface roughness, and waviness. They found depth of cut significantly affected roughness and waviness, while sample height influenced kerf angle. Optimizing cutting speed and depth improved surface quality and dimensional accuracy, making AWJ a valuable method for machining high-strength, high-temperature materials.

Sourd et al. [4] examined PWJ cleaning of Ti6Al4V titanium alloy after AWJ milling, highlighting issues with abrasive embedment. They found PWJ cleaning reduced contamination by 65%, but deeply embedded particles remained (Figure 3).

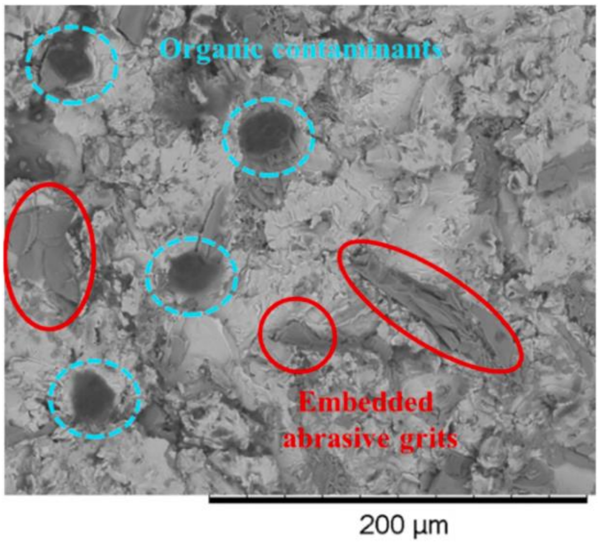


Figure 3. SEM image obtained from sensor in a specimen machined with water pressure of 118 MPa, scan step of 0.5 mm and jet traverse speed of 1 m/min [4].

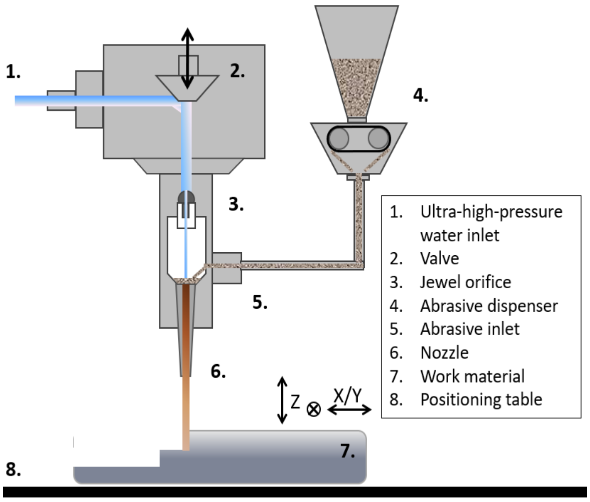


Figure 4. Schematic overview of the AWJ components [5].

Higher AWJ pressures improved cleaning effectiveness, though higher pressures might affect material integrity, suggesting further optimization for high-cleanliness applications.

Holmberg et al. [5] explored AWJ milling for superalloy gas turbine components, focusing on alloy 718 (Figure 4). They concluded AWJ milling effectively competed with semi/finish milling, excelling in machining complex geometries with minimal surface impact. However, post-processing was necessary to achieve surface quality comparable to traditional milling.

Armağan and Arıcı [6] studied AWJ machining of Fe-Cr-C based hardfacing wear plates, emphasizing surface quality and kerf properties. Material alignment direction significantly influenced surface roughness and kerf taper angle, with optimal parameters improving machining efficiency and quality. Detailed morphological analyses provided insights into material removal mechanisms.

Figure 5. UHMWPE plate production flow chart [7].

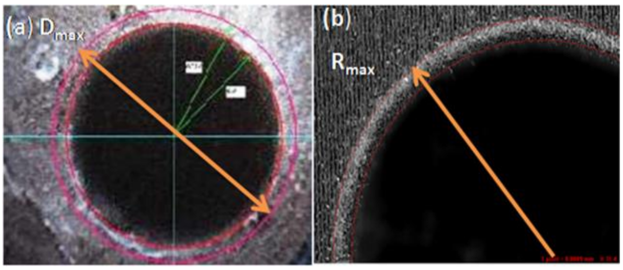


Figure 6. Measurement of maximum damage drilled hole diameter (Dmax): (a) Peel up at the entry hole and (b) Push out at the exithole [8].

Doğankaya et al. [7] investigated AWJ machining of UHMWPE (Figure 5): focusing on optimizing process parameters for trimming, pocketing, and hole-making. Using design of experiments and particle swarm optimization, they achieved a balance between surface roughness and dimensional accuracy. The study demonstrated AWJ's advantages, such as low cost and environmental friendliness, but noted challenges with delamination and dimensional errors.

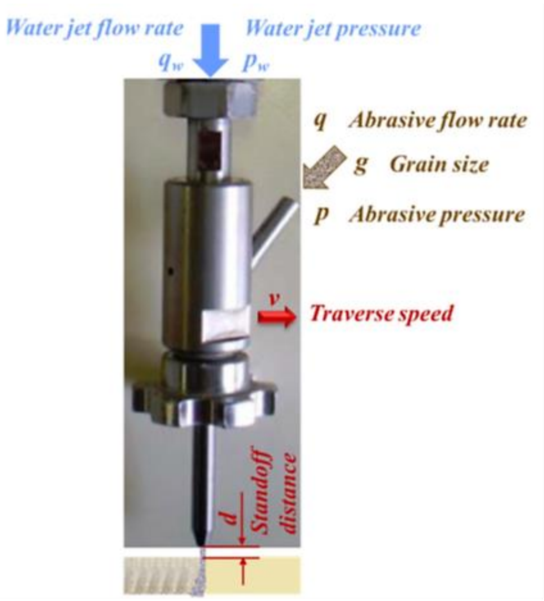
Ganesan et al. [8] optimized AWJ machining parameters for drilling onyx composites, fabricated via additive manufacturing. They used Taguchi analysis, genetic algorithms, and Moth-Flame Optimization to reduce delamination and surface roughness as seen in Figure 6. Optimal parameters significantly improved machining efficiency and quality, confirming the potential for high-precision component production.

Müller et al. [9] compared AWJ and WJ technologies for cutting PP and PVC-U materials coated with polyurethane and acrylate. AWJ achieved more uniform cuts with fewer burrs. Optimal cutting speeds and scanning electron microscope (SEM) analysis showed AWJ maintained coating integrity, highlighting its effectiveness for precise cutting of coated polymer materials.

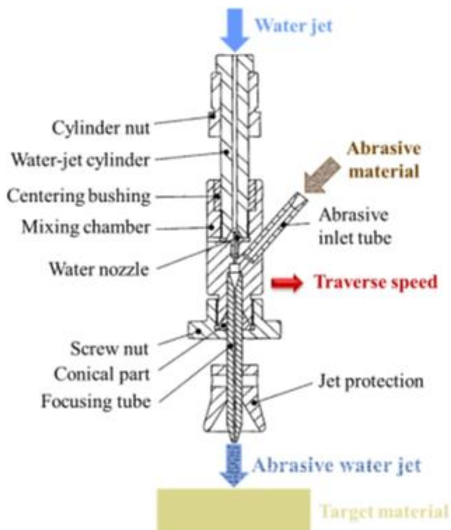
Ruiz-Garcia et al. [10] examined AWJ cutting and drilling of CFRP/UNS A97075 stacks. They identified optimal parameters to minimize defects like kerf taper and surface roughness, finding higher traverse feed rates and abrasive mass flow rates improved quality. AWJ provided better control over surface quality and dimensional accuracy compared to conventional methods.

Murthy et al. [11] optimized AWJ machining parameters for jute/epoxy composites with different fiber orientations. Using Taguchi and Response Surface Methodology, they identified optimal settings to minimize surface roughness. The study emphasized the impact of fiber orientation on machining outcomes, providing insights for industrial applications.

Gubencu et al. [12] analyzed kerf quality in AWJ cutting of Kevlar fiber-reinforced polymers. Figure 7 shows the process parameters and components of the cutter head. They found that higher abrasive flow rates and finer grains improved the surface roughness, while higher pass rates increased the kerf taper. Optimizing parameters enhanced cut quality, making AWJ suitable for high-precision applications.



(a)



(b)

Figure 7. Principle of AWJ machining: (a) process parameters (b) components of cutting head [12].

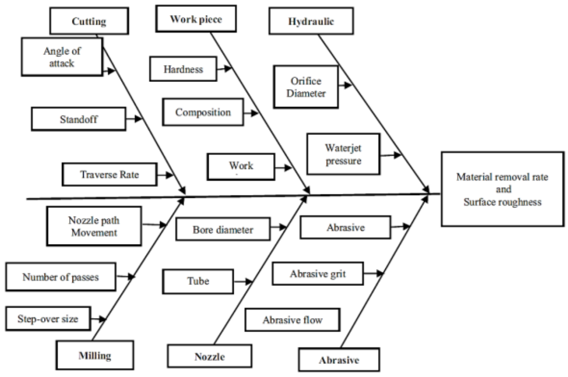


Figure 8. Process parameters involved in AWJ milling [13].

Gopichand and Sreenivasarao [13] studied AWJ milling of Hastelloy C-276, focusing on material removal rate and surface roughness. The process parameters in AWJ machining were examined using the fishbone method as seen in Figure 8. Using response surface methodology and grey relational analysis, they optimized parameters for high material removal rate (MRR) and smooth surfaces. The study highlighted the importance of balancing pressure, step over, traverse rate, and abrasive flow rate.

Qian et al. [14] investigated AWJ machining of cylindrical surfaces in AA7075 aluminum alloy. They found surface roughness increased with smaller cut radii, emphasizing the need for optimizing tangential velocity. The developed regression model accurately predicted surface roughness, enhancing machining precision for circular cuts.

Shi et al. [15] optimized AWJ drilling parameters for Al2024-T3 aluminum alloy. They identified stand-off distance, water jet pressure, and abrasive mass flow rate as critical factors influencing hole quality. They investigated the formations on the workpiece at different magnification ratios, as shown in Figure 9. Optimal settings significantly improved diameter, kerf angle, and surface roughness, providing guidelines for high-quality drilling in aerospace applications.

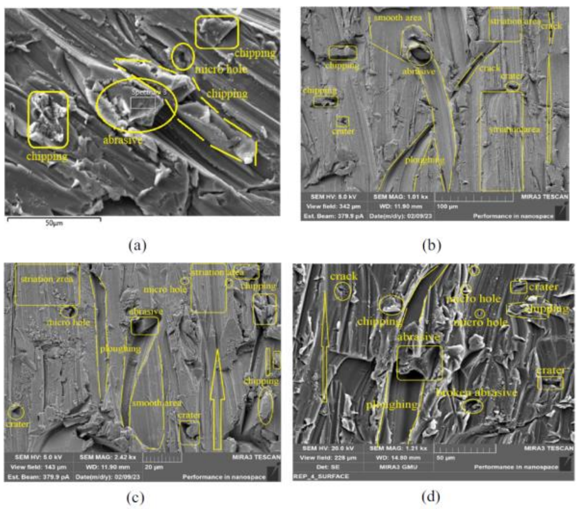


Figure 9. (a) Surface microstructure containing embedded abrasives at 1.81 kx, (b) 1.01 kx, (c) 2.42 kx magnification, (d) 1.21 kx [15].

Pal and Sharma [16] developed a strategy for fabricating complex-shaped micro-tools using AWJ milling. They addressed challenges with conventional methods, demonstrating AWJ's potential for creating high-quality micro-tools. The study highlighted the importance of parameter optimization for achieving desired geometries and surface finishes.

Karkalos and Karmiris-Obratański [17] studied PWJ post-treatment for AWJ milled Ti-6Al-4V titanium alloy. They found PWJ minimally impacted surface quality, emphasizing the need for optimized post-treatment strategies to enhance machining outcomes. The study provided insights into balancing PWJ conditions for improved surface finishes.

Li et al. [18] investigated AWJ cutting of (arbon Fiber Reinforced Polymer (CFRP) with a focus on surface morphology. They identified optimal parameters to extend the smooth cutting zone, enhancing surface quality. The study provided recommendations for process control to achieve high-quality cuts, emphasizing the importance of parameter selection.

Bañon et al. [19] explored AWJ machining for surface texturing of thin aluminum alloy UNS A92024. They optimized parameters for better wettability and adhesive bonding performance, demonstrating the potential for creating hydrophilic or hydrophobic surfaces. The study highlighted industrial applications in the aerospace sector.

Hashish [20] investigated AWJ milling, revealing significant potential for various materials. The study highlighted AWJ's advantages, such as minimal thermal effects and efficiency in material removal. The need for improved prediction models and economic analysis for broader application was emphasized.

Wan et al. [21] proposed an analytical model and optimization algorithm for AWJ milling of Ti6Al4V titanium alloy. The model achieved high accuracy in predicting milling depth, erosion rate, and surface roughness. Optimized parameters improved machining efficiency, making AWJ suitable for high-precision industries.

Chen et al. [22] developed a model to predict the effective depth of cut in ductile materials during AWJ machining by making an experimental setup as shown in Figure 10. The model, validated experimentally, provided accurate predictions and enhanced AWJ machining performance. It offered significant industrial value for high-quality surface finishes in materials like Ti-6Al-4V.

Wan et al. [23] developed an analytical model and optimization algorithm for AWJ milling of Ti6Al4V titanium alloy. The model's high accuracy and optimized parameters improved milling quality and efficiency, providing practical applications in aerospace and high-precision industries.

Dekster et al. [24] investigated multipass AWJ machining of Ti-6Al-4V alloy, focusing on kerf characteristics and material removal rates. The study highlighted the potential of multipass strategies to improve kerf quality and machining performance for aerospace applications. They revealed the effect of the multiple pass strategy on the penetration depth as seen in Figure 11.

Ramesh and Mani [25] used machine learning to predict surface roughness in AWJ milling of alumina ceramic. The support vector regression model outperformed traditional models, achieving high prediction accuracy. The study demonstrated the potential of machine learning for optimizing AWJ processes.

Bui et al. [26] proposed an adaptive speed control method for AWJ milling of thin titanium alloy workpieces. Their model effectively corrected depth variations in pocket corners, ensuring consistent milling depths. The study provided insights for improving AWJ milling accuracy and efficiency.

Gowthama et al. [27] characterized and optimized AWJ machining parameters for Al/SiC composites. They found optimal settings for surface roughness, material removal rate, and kerf angle. The study highlighted AWJ's potential for precise and efficient machining of metal matrix composites.

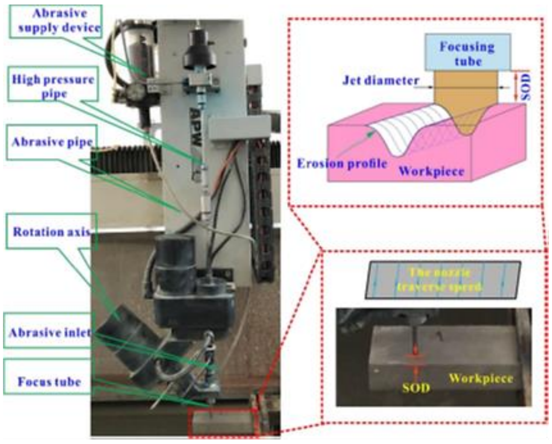


Figure 10. Experimental setup for visualization of abrasive waterjet cutting [22].

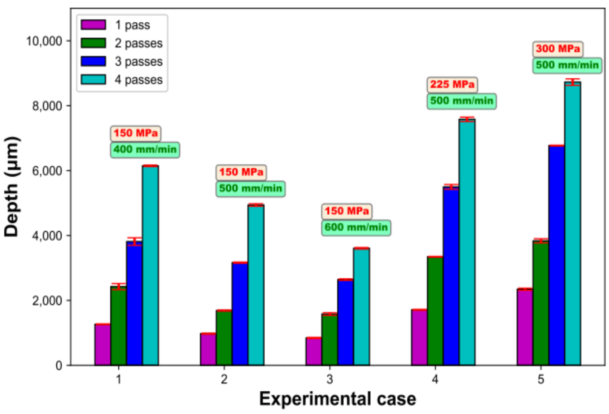


Figure 11. Influence of multipass strategy on the depth of penetration [24].

Ozcan et al. [28] developed a model for controlled depth AWJ milling of free-form surfaces. The model accurately predicted kerf profiles and improved machining efficiency. The study demonstrated AWJ's potential for high-precision roughing passes in aerospace and automotive industries.

Shukla [29] examined AWJ milling, particularly for titanium alloys. The study highlighted process modeling, experimental studies, and optimization strategies to improve AWJ efficiency and surface quality. The research underscored AWJ's advantages over traditional methods.

Arun et al. [30] optimized AWJ machining parameters for Monel 400 alloy. Using the Taguchi method, they identified optimal settings to minimize surface roughness and kerf taper angle. The study demonstrated AWJ's superior machining quality and efficiency compared to conventional methods.

Rammohan et al. [31] developed a numerical model for predicting kerf generation in AWJ machining of military-grade armor steel. The hybrid model integrated Smoothed Particle Hydrodynamics (SPH): discrete element approach (DEA): and Finite Element Model (FEM) to enhance simulation accuracy. The study highlighted the importance of optimizing key parameters for improved cutting performance.

Uhlmann et al. [32] enhanced AWJ milling for near-net-shape fabrication of titanium aluminide. The study introduced a method involving intersecting kerfs to increase material removal rates, identifying significant differences in kerf profiles. The research provided insights for optimizing AWJ milling for complex geometries.

Gowthama et al. [33] optimized AWJ machining parameters for Al/SiC composites, focusing on surface roughness, material removal rate, and kerf angle. The study demonstrated the potential of AWJ for precise and efficient machining of metal matrix composites, offering valuable insights for industrial applications.

Duspara et al. [34] optimized AWJ machining parameters for cutting AISI 316L stainless steel. Using a central composite design and ANOVA analysis, they identified significant parameters affecting surface roughness. The study concluded that AWJ can replace conventional methods for high-quality machining of stainless steel.

Kesharwani [35] investigated AWJ milling of Ti-6Al-4V alloy using non-spherical abrasive particles. The study found that a modified abrasive feed system improved machining efficiency and surface quality. The research provided insights into optimizing AWJ processes for precision machining of titanium alloys.

Hocheng et al. [36] explored AWJ milling of fiber-reinforced plastics, focusing on material removal mechanisms. They identified optimal conditions for maximum efficiency and minimal surface damage, demonstrating AWJ's advantages over traditional milling processes for composite materials.

Ramkumar and Gupta [37] combined AWJ machining with conventional milling for machining hard materials. They highlighted the benefits of a hybrid approach, leveraging AWJ for roughing and conventional milling for finishing. The study demonstrated significant improvements in machining efficiency and surface quality.

Patel and Shaikh [38] reviewed the impact of AWJ machining parameters on composite materials. They emphasized optimizing water pressure, traverse speed, abrasive flow rate, and standoff distance to enhance kerf taper angle, surface roughness, and depth of cut. The study provided practical insights for improving AWJ performance.

Escobar-Palafox et al. [39] characterized AWJ pocket milling of Inconel 718, developing models to predict pocket geometry based on process parameters. They found optimal parameter combinations for stable milling conditions, enhancing efficiency and precision in machining aerospace materials.

Hashish [40] investigated AWJ milling of gamma titanium aluminide, achieving high accuracy and fine surface finishes. The study emphasized the importance of stress relief and cleaning processes to prevent deformation and abrasive embedment. The research highlighted AWJ's cost-effectiveness and industrial applicability.

Hutyrová et al. [41] examined AWJ and WJ turning of wood plastic composites. They found AWJ significantly improved material removal rates and surface quality compared to WJ. The study provided insights for optimizing AWJ parameters to overcome challenges associated with conventional turning of composite materials.

Ting et al. [42] compared prediction models for surface roughness in AWJ machining of titanium alloys. The Artificial Neural Networks (ANN) model outperformed support vector machine (SVM) and regression analysis (RA) models, achieving the highest prediction accuracy. The study highlighted the effectiveness of ANN in optimizing machining parameters for improved surface quality.

Goutham et al. [43] investigated AWJ pocket milling of Inconel 825, analyzing process parameters like step over, traverse speed, pressure, and abrasive flow rate. They found the spiral strategy yielded better outcomes, demonstrating AWJ's potential for machining high-performance materials with minimal thermal distortion.

Hussien et al. [44] evaluated AWJ cutting of CFRP, focusing on surface roughness and kerf angle. They identified optimal parameters to enhance cutting performance, providing a viable alternative to traditional methods. The study presented regression models for accurate prediction of machining outcomes.

Murthy et al. [45] optimized AWJ machining parameters for jute-polymer composites, achieving significant improvements in surface roughness and delamination. Using grey relational analysis, they identified optimal settings for high-quality machining, offering valuable insights for industrial applications.

Fowler et al. [46] studied grit embedment in AWJ milling of Ti6Al4V, finding high-speed milling at low impingement angles minimized grit embedment. The study provided insights for achieving better surface quality and enhancing AWJ applicability in precision machining.

Yuan et al. [47] investigated AWJ milling of circular pockets in Ti6Al4V, developing a material removal model. They identified optimal parameters to improve milling depth and surface roughness, enhancing AWJ's suitability for precision applications in high-performance industries.

Fowler et al. [48] examined the impact of particle hardness and shape on AWJ milling of Ti6Al4V. Harder, angular particles increased material removal rates but also roughened surfaces. Optimizing abrasive selection and traverse speed was crucial for balancing efficiency and surface quality.

Ebeid et al. [49] developed an ANN model to predict AWJ milling parameters for aluminum alloys. The model showed high accuracy in predicting surface roughness, depth of cut, and material removal rate, offering a tool for optimizing AWJ performance and improving machining outcomes.

Kumar et al. [50] optimized AWJ cutting parameters for GFRP composites, achieving better material removal rates, kerf width, and taper angle. The study emphasized the importance of balancing water jet pressure, abrasive flow rate, stand-off distance, and traverse rate for optimal performance.

Alberdi et al. [51] developed a model to predict kerf profiles in AWJ slot milling of aluminum 7075-T651. They identified optimal parameter combinations for stable milling conditions, ensuring consistent quality and productivity. The study provided insights for enhancing AWJ milling processes.

Srinivasu and Axinte [52] optimized PWJ milling for advanced engineering composite materials. They developed a novel milling strategy to minimize surface damage and improve quality. The study highlighted PWJ's advantages for high-performance applications, reducing thermal stresses and tool wear.

Chithirai Pon Selvan [53] developed an empirical model for predicting depth of cut in AWJ cutting of titanium. The model, validated experimentally, provided reliable predictions and helped optimize process parameters, enhancing machining performance and precision.

Gokul et al. [54] investigated AWJ pocket milling in acrylic, optimizing parameters like standoff distance, step-over size, traverse speed, and abrasive flow rate. They identified significant factors affecting depth of cut and material removal rate, demonstrating AWJ's potential for efficient machining of acrylic.

Shipway et al. [55] studied surface characteristics of Ti6Al4V after AWJ milling, focusing on roughness, waviness, and grit embedment. They identified optimal parameters to balance material removal rate and surface quality, providing insights for improving AWJ processes.

Cenac et al. [56] optimized AWJ milling of aeronautic aluminum 2024-T3, developing models to predict milled depth. They identified optimal abrasive mass flow rates and provided insights into micro-cutting and lateral cracking mechanisms, enhancing process efficiency and precision.

Dittrich et al. [57] optimized water abrasive fine jet machining for structuring ceramic surfaces. They identified critical parameters like water pressure and abrasive flow rate, demonstrating the technique's potential for precise and reproducible machining of ceramics.

Gupta et al. [58] applied ANN to predict micro-channel characteristics in AWJ machining of SS304. The model achieved high accuracy, demonstrating ANN's capability to optimize AWJ processes and improve machining performance and dimensional accuracy.

Kanthababu et al. [59] optimized AWJ pocket milling parameters for Ti6Al4V, focusing on depth of cut and surface roughness. They identified step-over and traverse rate as significant factors, emphasizing the need for careful optimization to achieve desired machining outcomes.

Gong and Kim [60] developed an erosion model for AWJ milling of polycrystalline ceramics, identifying a 90° incidence angle as optimal for maximum erosion. The model, validated experimentally, provided insights into material removal mechanisms, enhancing AWJ efficiency for ceramics.

Paul et al. [61] optimized rectangular pocket milling in AWJ, reducing depth variation and improving material removal rate. The study developed empirical models for predicting outcomes, demonstrating AWJ's potential for precise and efficient material removal.

Ebeid et al. [62] optimized PWJ milling parameters for aluminum alloy, identifying the effects of jet traverse speed, water jet pressure, stand-off distance, and abrasive flow rate on milling performance. The study provided insights for improving PWJ machining efficiency and surface quality.

Siddiqui and Shukla [63] developed a model for predicting depth of cut in AWJ cutting of thick Kevlar-epoxy composites. The model, validated experimentally, offered precise predictions and optimization guidelines, ensuring effective cutting and high-quality finishes.

Fowler et al. [64] studied the impact of jet traverse speed and abrasive grit size on AWJ milling of Ti6Al4V. They identified optimal parameters for balancing material removal rate, surface roughness, and waviness, providing crucial insights for optimizing AWJ processes.

Pal and Tandon [65] examined the effects of milling depth and material characteristics on machining time in AWJ milling. They identified material properties and machining parameters influencing outcomes, offering insights for optimizing AWJ processes for different materials.

Feng et al. [66] investigated AWJ milling of Al2O3 ceramics, finding higher nozzle traverse speeds improved surface quality, while higher feeds reduced it. They provided insights for balancing efficiency and surface quality in AWJ milling of ceramics.

Müller et al. [67] compared AWJ and WJ techniques for cutting coated PP and PVC-U materials, as seen in Figure 12. AWJ achieved more uniform cuts without delamination, highlighting its effectiveness for precise cutting of coated polymer materials.

Figure 12. AWAC CNC waterjet cutting machine AWJ CT 0806: waterjet cutting process [67].

Chen et al. [68] developed a model to predict effective depth of cut in ductile materials during AWJ machining. The model, validated experimentally, provided accurate predictions and enhanced AWJ machining performance, offering significant industrial value.

Vishnu and Saleeshya [69] optimized AWJ machining parameters for Inconel 718, achieving better surface quality and minimal kerf taper. The study provided guidelines for machining complex profiles in hard-to-machine materials like Inconel 718.

Begic-Hajdarevic et al. [70] evaluated surface roughness in AWJ cutting of various materials, highlighting the importance of optimizing parameters like water pressure, abrasive flow rate, and traverse speed to achieve desired machining outcomes. The study provided practical insights for improving AWJ processes across different materials and applications.

In Table A.1 (in Appendix), the author, focus of the study, examined material, input-output parameters and key findings are categorized.

Figure 13 the bar chart highlights the extensive research conducted on various materials using AWJ machining, with key observations and interpretations revealing significant trends. Ti6Al4V titanium alloy, with five studies, emerges as the most frequently examined material, likely due to its critical applications in aerospace and biomedical fields where precision is paramount. The grouping of various materials, with three studies, indicates comparative analyses or general applicability of AWJ techniques. Inconel 718, a high-strength superalloy, with two studies, is a focus due to its challenging machining properties and usage in high-temperature environments like jet engines. AA7075 aluminum alloy, also with two studies, is significant in aerospace and automotive industries, prompting research into AWJ parameter optimization. AA CFRP is similarly studied for its high-performance structural applications. The repeated mention of Ti-6Al-4V suggests exploration of different aspects or methodologies in AWJ machining for the same material. Al2024-T3 aluminum alloy, known for high strength and fatigue resistance, is another focus due to its use in aerospace structures. Al2O3 ceramics, noted for their hardness and brittleness, are studied for precise machining techniques. Aluminides, with high temperature and corrosion resistance, are critical in aerospace and industrial applications, warranting two studies. Composite materials drive research interest due to their diverse industrial applications. Other materials, each represented by a single study, indicate broader but less frequent research interest across a wide range of materials. General observations highlight a focus on high-performance materials commonly used in high-stress, high-temperature applications, reflecting the diversity in material research and the versatility of AWJ machining. There is a notable interest in composites and advanced materials, underlining ongoing efforts to enhance AWJ machining techniques. In conclusion, the bar chart underscores the extensive research aimed at optimizing AWJ machining for critical materials, particularly high-performance alloys and composites, demonstrating the technology's broad applicability and versatility in modern manufacturing.

Figure 14 this chart illustrates the methodologies used in AWJ machining studies, highlighting the frequency of various methodologies applied in the research. A detailed analysis of the graph reveals several key insights. The most commonly used methodology is experimental, employed in 20 studies, indicating that many AWJ machining studies rely heavily on collecting and analyzing experimental data. Numerical modeling, used in 15 studies, is the second most common methodology, suggesting that computer-based models are widely utilized to simulate and understand

AWJ processes. Optimization algorithms, employed in 10 studies, underscore their importance in adjusting parameters and improving processes. The design of experiments, utilized in 9 studies, is crucial for systematically designing experiments and statistically analyzing collected data. Artificial neural networks, used in 8 studies, highlight their application in modeling complex and nonlinear processes. Response surface methodology, applied in 7 studies, is used to model and optimize the effects of independent variables. The finite element method, found in 5 studies, is significant for solving mechanical problems and detailed process analysis. The Taguchi method, used in 3 studies, is employed in experiment design and quality improvement studies. From the chart, it is evident that the most commonly used methodologies in AWJ machining studies are experimental approaches and numerical modeling, suggesting that researchers are extensively using both practical experiments and theoretical models to optimize and understand AWJ processes. Advanced methodologies such as optimization algorithms and artificial neural networks also play a crucial role, highlighting the complexity and need for optimization in AWJ technology. Figure 15 this chart visualizes the scope of studies in AWJ machining research, displaying the number of studies focused on different aspects.

The highest number of studies, with 19, focus on surface quality analysis, indicating that improving surface finish is a major area of concern in AWJ machining. This suggests a significant emphasis on achieving the desired surface characteristics, which are critical for the functionality and aesthetics of machined parts. Process parameter optimization, with 16 studies, is the second most common scope, highlighting the importance of optimizing parameters such as pressure, abrasive flow rate, and traverse speed to enhance machining performance and achieve desired outcomes efficiently.

Kerf analysis, addressed in 12 studies, is also a significant research area. Understanding kerf characteristics is crucial for achieving precise cuts and minimizing material waste, which is essential for high-precision applications. Material optimization, with 11 studies, focuses on selecting and optimizing materials used in AWJ machining to improve efficiency and performance, reflecting the diverse range of materials that can be machined with AWJ and the need to tailor processes to specific material properties.

Tool wear analysis, with 7 studies, reflects its importance in extending tool life and reducing operational costs. Prolonging tool life and maintaining consistent performance are key for economic and practical reasons in industrial applications. Multi-response optimization, covered in 9 studies, involves optimizing multiple responses simultaneously, which is crucial for achieving a balance in performance metrics and improving overall process outcomes.

Environmental impact, with only 3 studies, is the least frequently studied aspect. This indicates that while environmental concerns are acknowledged, they are less prioritized compared to other research scopes in AWJ machining. This could be due to the current focus on improving immediate machining outcomes over long-term environmental considerations.

Overall, the chart shows that most research in AWJ machining focuses on improving surface quality and optimizing process parameters, underscoring the importance of these factors in achieving high-quality and efficient machining. Kerf analysis and material optimization are also key areas, reflecting the importance of precision and material performance. Tool wear analysis and multi-response optimization are less frequently studied, while environmental impact, though recognized as important, has the least focus in current research, suggesting an area for potential future exploration.

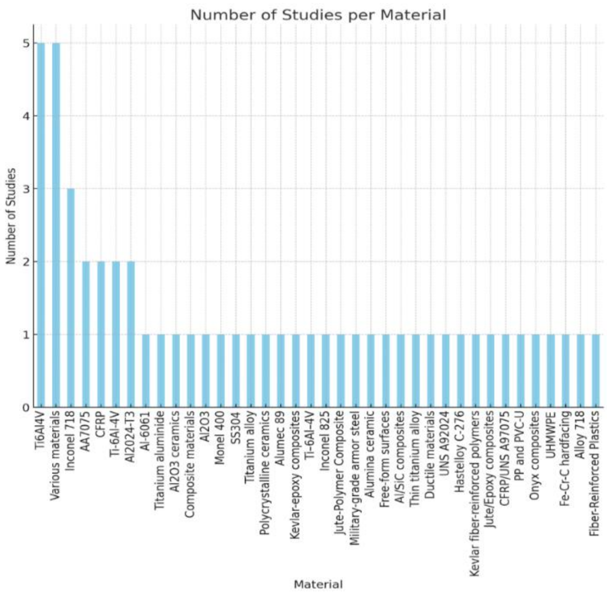


Figure 13. Research conducted on various materials using AWJ machining.

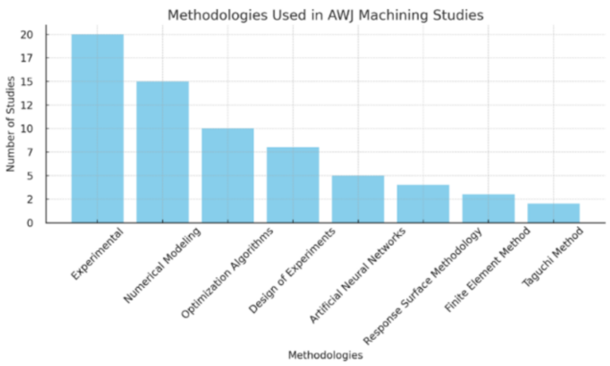


Figure 14. Methodologies used in AWJ machining studies

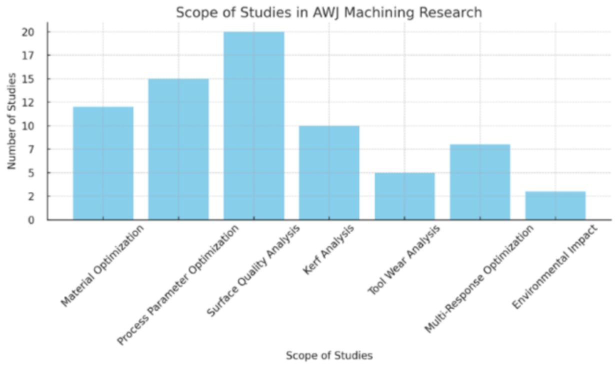


Figure 15. Scope of studies in AWJ machining research

Figure 16 the chart depicting the interactions of various parameters with key output metrics in AWJ machining reveals that water pressure has the most significant impact on both surface roughness (80%) and material removal rate (70%): underscoring its crucial role in the AWJ process. Traverse speed also critically affects surface roughness (70%) and material removal rate (60%): highlighting the need for precise control. Abrasive mass flow rate and stand-off distance have moderate impacts across all metrics, with intensities around 50-60%, suggesting their balanced influence in fine-tuning the process. Jet impingement angle and nozzle diameter, while having the least overall impact (30-50%): still contribute to optimizing specific applications. This analysis emphasizes the importance of optimizing water pressure and traverse speed to achieve desired machining outcomes, while also considering the moderate influences of other parameters for comprehensive process optimization.

Figure 17 the chart depicting the frequency distribution of various parameters in AWJ machining studies shows that abrasive flow rate, with a frequency of 25, is the most frequently investigated parameter, underscoring its crucial role in determining the efficiency and quality of the machining process. Waterjet pressure, with a frequency of around 22, is also a commonly studied parameter, indicating its importance in AWJ machining. Traverse speed, with a frequency of around 19, is another significant parameter, highlighting its impact on machining outcomes. Stand-off distance, with a frequency of 16, is moderately studied, reflecting its relevance in controlling the machining process. Nozzle diameter, with a frequency of around 13, is the least frequently investigated but still holds importance in overall process control. These insights emphasize that while abrasive flow rate, waterjet pressure, and traverse speed are the most critical parameters, stand-off distance and nozzle diameter are also significant in achieving optimal AWJ machining performance. The frequency distribution highlights the focus of researchers on these parameters to optimize the AWJ machining process for improved efficiency and quality.

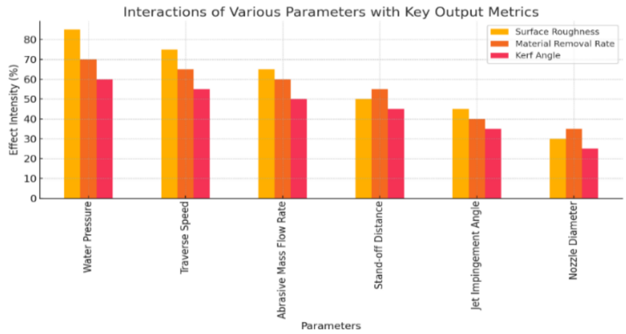


Figure 16. Intersections of various parameters with key output metrics

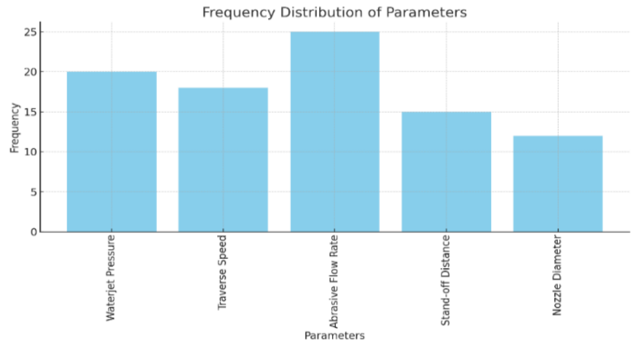


Figure 17. Frequency distribution of parameters

Figure 18 the "Number of Studies by Year" chart illustrates the research trends in AWJ machining, showing low annual studies from 1989-2005, indicating initial research phases. From 2006-2014, there's a noticeable increase, peaking in 2005 and 2014 with about four studies each year, reflecting growing interest and expansion. A slight decline occurs from 2015-2018, with 1-2 studies per year, suggesting a temporary shift in focus. A resurgence appears in 2019-2020, peaking in 2020 with eight studies, showing renewed interest and advancements. The period from 2021-2023 sees a significant increase, particularly in 2023 with twelve studies, indicating strong contemporary focus and innovation. In 2024, the number of studies slightly decreases to four but remains substantial, showing sustained interest. Overall, the chart highlights fluctuating but growing interest in AWJ machining, with notable peaks and a strong emphasis on recent advancements and ongoing research.

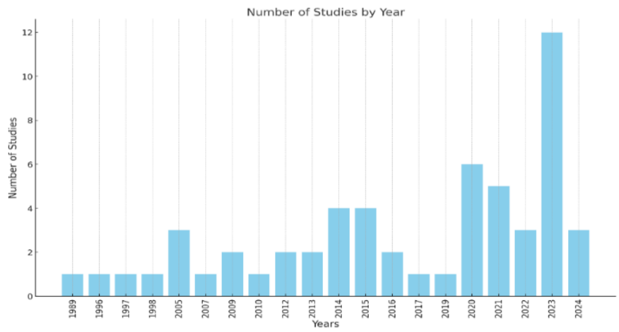


Figure 18. Number of studies by year.

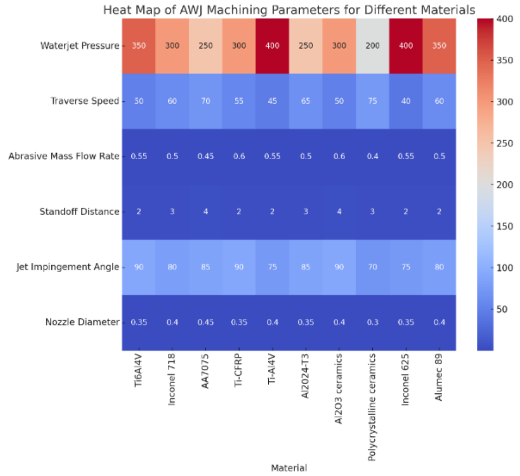


Figure 19. Heat map of AWJ machining parameters for different materials.

Figure 19 the chart shows the frequency of studies conducted on various materials using AWJ machining. Ti6Al4V has the highest number of studies (5): indicating a significant research focus on this titanium alloy, likely due to its extensive use in aerospace and biomedical applications. Inconel 718 and AA7075 follow with 3 studies each, reflecting their high strength and common use in aerospace and automotive industries. Other materials such as Ti-6Al-4V, Al-6061, and composite materials also have multiple studies, underscoring their industrial importance. A variety of materials, including Monel 400, S304, and polycrystalline ceramics, have fewer studies, indicating emerging interest or niche applications.

In terms of methodologies used in AWJ machining studies, experimental studies dominate the field with 20 studies, emphasizing the importance of empirical data in understanding and optimizing AWJ processes. Numerical modeling and optimization algorithms are also prominent, with significant efforts to predict and enhance AWJ performance through simulations and mathematical approaches. Design of Experiments (DoE) and ANN are increasingly used, showing the integration of statistical and machine learning methods in AWJ research. FEM and Taguchi Method are less common but still significant, indicating specialized applications in process optimization and quality control.

The scope of studies in AWJ machining research reveals that surface quality analysis is the most common focus, with 19 studies, highlighting the critical importance of surface finish in AWJ applications. Process parameter optimization (16 studies) and kerf analysis (12 studies) are also significant, as optimizing these parameters is crucial for improving efficiency and precision. Material optimization (11 studies) and tool wear analysis (7 studies) indicate ongoing efforts to enhance the durability and performance of both materials and cutting tools. Environmental impact (3 studies) shows emerging interest in the sustainability aspects of AWJ machining.

The bar chart showing the interactions of various parameters with key output metrics (surface roughness, material removal rate, kerf angle) reveals that water pressure has the highest impact on all three metrics, particularly on material removal rate and surface roughness, indicating its critical role in AWJ machining. Traverse speed also significantly affects all metrics, especially kerf angle, showing its importance in controlling machining precision. Abrasive mass flow rate and stand-off distance have moderate effects, essential for fine-tuning the process. Jet impingement angle and nozzle diameter have lower but still significant impacts, particularly on surface roughness and kerf angle.

The frequency distribution of parameters shows that abrasive flow rate is the most frequently studied parameter (25 studies): highlighting its importance in controlling cutting efficiency and quality. Waterjet pressure and traverse speed follow closely, reflecting their critical roles in AWJ machining. Stand-off distance and nozzle diameter are studied less frequently, indicating more specialized or secondary roles in the process.

The chart tracking the number of studies by year shows a noticeable increase in studies in recent years, particularly in 2023, reflecting growing interest and advancements in AWJ machining technology. The early years (1989-2000) show sporadic studies, indicating the nascent stage of AWJ research during that period. A consistent increase from 2005 onwards suggests the maturation and expansion of AWJ applications in various industries.

In conclusion, the visualizations provide a comprehensive overview of AWJ machining research, highlighting key materials, methodologies, and parameters. The increasing trend in recent studies underscores ongoing advancements and interest in optimizing AWJ processes for various industrial applications. The detailed breakdown of parameter effects and research scopes offers valuable insights for future research directions, emphasizing the importance of empirical, modeling, and optimization approaches in enhancing AWJ machining performance.

3. Discussions

3.1. Methodological approaches

The diverse methodological approaches used across the reviewed studies highlight the versatility and complexity of AWJ machining. Techniques such as DoE, response surface methodology (RSM): Taguchi analysis, and ANN were frequently employed to optimize process parameters and predict outcomes. The choice of methodology often depended on the material being machined and the specific quality attributes of interest, such as surface roughness, MRR, and kerf angle. The widespread use of advanced statistical and machine learning methods underscores the necessity for robust, data-driven approaches to enhance AWJ machining processes.

3.2. Scope of studies

The scope of the reviewed studies varied significantly, covering a wide range of materials including metals, composites, polymers, and ceramics. This variety demonstrates the broad applicability of AWJ machining in different industrial sectors. Studies focused on optimizing parameters for specific materials, such as Al-6061 alloy, Inconel 718, Ti6Al4V titanium alloy, and UHMWPE, reveal the tailored strategies required for different materials. For instance, the high-strength, high-temperature resistance of Inconel 718 necessitated distinct optimization strategies compared to the softer and more ductile Al-6061 alloy.

3.3. Parameter interactions

The interactions between various AWJ machining parameters—such as waterjet pressure, traverse speed, abrasive flow rate, and standoff distance—were critical in determining machining outcomes. Higher waterjet pressures and abrasive flow rates generally improved material removal rates but could negatively impact surface roughness if not balanced with appropriate traverse speeds. Studies consistently highlighted the non-linear and interactive effects of these parameters, emphasizing the need for comprehensive optimization to achieve desired machining qualities. The interaction effects were often visualized using response surface plots and ANOVA analyses, providing clear insights into optimal parameter settings.

3.4. Distribution of optimal parameters

Optimal parameter settings identified across the studies showed considerable variation, reflecting the specific material properties and machining objectives. For example, optimal waterjet pressures ranged from 190 MPa to 350 MPa depending on the material and desired outcomes. Traverse speeds varied widely, from 25 mm/min to 1500 mm/min, illustrating the importance of balancing speed with material removal efficiency and surface quality. The diversity in optimal settings underscores the need for tailored approaches in AWJ machining, rather than one-size-fits-all solutions.

3.5. Frequency distribution of parameters

The frequency distribution of AWJ parameters used in the studies revealed trends and common practices within the field. High-frequency settings included waterjet pressures around 300 MPa, traverse speeds between 50 and 500 mm/min, and abrasive flow rates around 0.4 kg/min. These common settings provide a baseline for future studies and practical applications, suggesting standard operational ranges that balance efficiency with quality.

3.6. Yearly trends in studies

The distribution of studies by year indicated a growing interest and advancement in AWJ machining research. The number of studies has generally increased over the years, reflecting ongoing innovations and the expanding application of AWJ technology in various industries. This trend suggests a sustained and growing interest in optimizing AWJ processes, driven by the technology's advantages in machining complex geometries, minimizing thermal effects, and improving surface quality.

3.7. Practical implications

The practical implications of these findings are significant for industries utilizing AWJ machining. The optimization of process parameters can lead to substantial improvements in machining efficiency, surface quality, and material integrity, which are crucial for applications in aerospace, automotive, medical devices, and other high-precision fields. The insights gained from these studies provide a foundation for developing standardized guidelines and best practices, enhancing the reliability and predictability of AWJ machining outcomes.

3.8. Future research directions

Future research should continue to explore the interactions between AWJ parameters using advanced modeling and optimization techniques. There is a need for further studies on new and emerging materials, especially those with unique properties that pose challenges for conventional machining methods. Additionally, the integration of real-time monitoring and adaptive control systems in AWJ machining can further enhance process efficiency and quality. Exploring the environmental impacts and sustainability of AWJ machining, particularly in terms of water and abrasive consumption, is also a critical area for future investigation.

The reviewed studies provide comprehensive insights into the optimization of AWJ machining processes, highlighting the critical role of parameter interactions and the necessity for tailored approaches based on material properties and machining objectives. These findings offer valuable guidance for both academic research and industrial practice, promoting the continued advancement and application of AWJ technology.

4. Conclusions

The comprehensive review of AWJ machining studies reveals the technology's significant potential and versatility across various industrial applications. Several key conclusions can be drawn from the analysis of the methodologies, scope, parameter interactions, and trends observed in the literature:

Versatility of AWJ Machining: AWJ machining has been effectively applied to a wide range of materials, including metals, composites, polymers, and ceramics. This versatility makes it a valuable technology in industries such as aerospace, automotive, medical devices, and manufacturing, where precision and surface quality are paramount.

Optimization of Process Parameters: The studies consistently highlight the importance of optimizing process parameters such as waterjet pressure, traverse speed, abrasive mass flow rate, and standoff distance. Optimal parameter settings are crucial for achieving desired machining outcomes, including minimal surface roughness, high material removal rates, and precise kerf angles. Advanced optimization techniques, including DoE, RSM, and ANN, have proven effective in identifying these optimal settings.

Non-linear and Interactive Effects: The interactions between AWJ machining parameters are complex and often non-linear. Understanding these interactions is critical for optimizing the machining process. Studies employing response surface plots and ANOVA analyses provide valuable insights into these interactions, enabling the development of more effective machining strategies.

Material-Specific Strategies: Different materials require tailored optimization strategies due to their unique properties. For instance, high-strength materials like Inconel 718 and Ti6Al4V titanium alloy necessitate specific parameter adjustments compared to more ductile materials like Al-6061 alloy. The ability to customize the AWJ process for different materials enhances its applicability across diverse sectors.

Growing Research Interest: The increasing number of studies over the years indicates a growing interest and continuous advancements in AWJ machining. This trend underscores the technology's evolving nature and its expanding role in modern manufacturing processes. Continuous research and innovation are essential to further enhance the efficiency and capabilities of AWJ machining.

Practical Applications and Industrial Relevance: The findings from these studies have significant practical implications. Optimizing AWJ process parameters can lead to improved machining efficiency, better surface quality, and enhanced material integrity, which are critical for high-precision applications. The insights gained provide a foundation for developing standardized guidelines and best practices, benefiting both academic research and industrial operations.

Future Research Directions: Future research should focus on exploring the interactions between AWJ parameters using more advanced modeling and optimization techniques. Investigating new and emerging materials, real-time monitoring, and adaptive control systems will further enhance process efficiency and quality. Additionally, addressing environmental impacts and sustainability concerns, particularly regarding water and abrasive consumption, is essential for the continued advancement of AWJ technology.

In conclusion, abrasive waterjet machining is a versatile and powerful technology that offers significant advantages in precision machining. The continuous optimization of process parameters and the application of advanced analytical techniques will further unlock its potential, ensuring its relevance and effectiveness in various high-demand industrial applications. The insights from this review provide a comprehensive understanding of AWJ machining, guiding future research and practical implementations to enhance its capabilities and applications.

Declaration

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Author Contributions

Fuat Kartal: Conceptualization, Methodology, Software, Visualization, Investigation. Arslan Kaptan: Investigation, Resources, Data curation, Writing – original draft and supervision.

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Appendix

Table A.1. Summary of Research Studies on AWJ Machining

Authors (Year)	Study Focus	Material	Input Parameters	Output Parameters	Key Findings
Ravi and Srinivasu (2023) [1]	AWJ trepanning optimization	Al-6061 alloy	Waterjet pressure, Traverse speed, Abrasive mass flow rate	Form error, Burr length, Hole quality	Higher pressure and mass flow rates at lower speeds improved hole quality. Optimal parameters: 350 MPa, 50 mm/min, 0.55 kg/min.
Cano-Salinas et al. (2023) [2]	AWJ milling with PWJ cleaning	Inconel 718	Water pressure, Traverse speed, Step-over distance	Surface texture, Grit embedment, Microhardness	PWJ cleaning removed up to 80% of embedded grit without altering surface texture or material properties.
Płodzień et al. (2023) [3]	AWJ cutting process modeling	Inconel 718	Depth of cut, Sample height, Cutting speed	Kerf angle, Surface roughness, Waviness	Depth of cut affected roughness and waviness, while sample height influenced kerf angle. Optimal cutting speed and depth improved surface quality and dimensional accuracy.
Sourd et al. (2021) [4]	PWJ cleaning post-AWJ milling	Ti6Al4V titanium alloy	Water pressure, Traverse speed, Scan step	Surface contamination, Crater volume	PWJ cleaning reduced contamination by 65%, but deeply embedded particles remained. Higher AWJ pressures improved cleaning effectiveness.
Holmberg et al. (2022) [5]	AWJ milling for superalloy turbine components	Alloy 718	Single and multi-pass AWJ milling	MRR, Surface integrity	AWJ milling competed with semi/finish milling, excelling in complex geometries but requiring post-processing for comparable surface quality.
Armağan and Arıcı (2024) [6]	AWJ machining of hardfacing wear plates	Fe-Cr-C based wear plates	Material alignment direction, Abrasive mass flow rate, Traverse speed	Surface roughness, Kerf taper angle	Material alignment direction significantly influenced surface roughness and kerf taper angle. Detailed morphological analyses provided insights into material removal mechanisms.
Doğankaya et al. (2020) [7]	AWJ machining optimization	UHMWPE	Water pressure, Abrasive flow rate, Standoff distance, Traverse speed	Surface roughness, Dimensional accuracy	Optimized parameters balanced surface roughness and dimensional accuracy. Challenges included delamination and dimensional errors.
Ganesan et al. (2023) [8]	AWJ drilling optimization	Onyx composites	Traverse speed, Abrasive mass flow rate, Drilling diameter	Delamination, Surface roughness	Higher abrasive mass flow rates and lower traverse speeds reduced delamination and surface roughness. Optimal parameters improved machining efficiency and quality.
Müller et al. (2021) [9]	AWJ vs. WJ cutting comparison	PP and PVC-U materials	Traverse speed	Kerf width, Taper angle, Burrs	AWJ achieved more uniform cuts with fewer burrs compared to WJ. SEM analysis confirmed no coating delamination.
Ruiz-Garcia et al. (2021) [10]	AWJ cutting and drilling optimization	CFRP/UNS A97075 stacks	Water pressure, Traverse feed rate, Abrasive mass flow rate	Kerf taper, Surface roughness, Macrogeometric deviations	Higher traverse feed rates and abrasive mass flow rates improved quality, providing better control over surface quality and dimensional accuracy compared to conventional methods.
Murthy et al. (2023) [11]	AWJ machining of jute/epoxy composites	Jute/epoxy composites	Traverse speed, Standoff distance, Abrasive mass flow rate	Surface roughness	Optimal settings to minimize surface roughness identified. Fiber orientation significantly impacted machining outcomes.

Gubencu et al. (2023) [12]	AWJ cutting of Kevlar fiber-reinforced polymers	Kevlar fiber-reinforced polymers	Traverse speed, Focusing tube diameter, Abrasive flow rate, Abrasive grain size	Surface roughness, Kerf taper angle	Higher abrasive flow rates and finer grains improved surface roughness. Higher traverse speeds increased kerf taper.
Gopichand and Sreenivasarao (2020) [13]	AWJ milling optimization	Hastelloy C-276	Waterjet pressure, Step over, Traverse rate, Abrasive flow rate	MRR, Surface roughness (Ra)	Optimized parameters for high MRR and smooth surfaces identified. Importance of balancing pressure, step over, traverse rate, and abrasive flow rate highlighted.
Qian et al. (2023) [14]	AWJ machining of cylindrical surfaces	AA7075 aluminum alloy	Tangential velocity, Circular cut radius, Working pressure, Standoff distance	Surface roughness	Surface roughness increased with smaller cut radii. Optimizing tangential velocity enhanced machining precision for circular cuts.
Shi et al. (2024) [15]	AWJ drilling optimization	Al2024-T3 aluminum alloy	Stand-off distance, Water jet pressure, Abrasive mass flow rate	Diameter, Kerf angle, Surface roughness	Optimal settings significantly improved diameter, kerf angle, and surface roughness. Guidelines provided for high-quality drilling in aerospace applications.
Pal and Sharma (2022) [16]	AWJ milling for micro-tool fabrication	Various materials	Step-over distance, Traverse speed	Geometry, Surface finish	Developed strategy for creating high-quality micro-tools, emphasizing the importance of parameter optimization for achieving desired geometries and surface finishes.
Karkalos and Karmiris-Obratański (2024) [17]	PWJ post-treatment optimization	Ti-6Al-4V titanium alloy	Number of PWJ passes, PWJ conditions	Surface roughness, Waviness, Form deviations	PWJ minimally impacted surface quality, emphasizing the need for optimized post-treatment strategies.
Li et al. (2020) [18]	AWJ cutting of CFRP with focus on surface morphology	CFRP	Traverse speed, Abrasive mass flow rate, Water jet pressure, Standoff distance	Surface roughness, Material removal rate	Identified optimal parameters to extend smooth cutting zone. Recommendations provided for process control to achieve high-quality cuts.
Bañon et al. (2023) [19]	AWJ machining for surface texturing	Thin aluminum alloy UNS A92024	Hydraulic pressure, Traverse speed, Abrasive flow rate, Spacing	Surface quality, Wettability, Adhesive bonding performance	Optimized parameters for better wettability and adhesive bonding. Demonstrated potential for creating hydrophilic or hydrophobic surfaces in aerospace applications.
Hashish (1989) [20]	Feasibility of AWJ milling	Various materials	Water pressure, Traverse speed, Abrasive mass flow rate	Material removal rate, Surface finish	Highlighted AWJ's advantages like minimal thermal effects and efficiency in material removal. Emphasized need for improved prediction models and economic analysis for broader application.
Wan et al. (2023) [21]	AWJ milling optimization	Ti6Al4V titanium alloy	Jet pressure, Abrasive flow rate, Standoff distance, Jet angle, Traverse speed, Feed rate	Milling depth, Erosion rate, Surface roughness	High accuracy in predicting milling depth, erosion rate, and surface roughness. Optimized parameters improved machining efficiency, suitable for high-precision industries.
Chen et al. (2023) [22]	AWJ machining performance model	Ductile materials	Water pressure, Abrasive flow rate, Standoff distance, Traverse speed	Effective depth of cut	Accurate predictions enhanced AWJ machining performance, offering significant industrial value for high-quality surface finishes in materials like Ti-6Al-4V.
Wan et al. (2022) [23]	AWJ milling optimization	Ti6Al4V titanium alloy	Jet pressure, Abrasive flow rate, Standoff distance, Jet angle, Traverse speed, Feed rate	Milling depth, Material erosion rate, Surface roughness	High accuracy in predicting milling outcomes. Optimized parameters improved milling quality and efficiency, providing practical applications in aerospace and high-precision industries.
Dekster et al. (2023) [24]	Multipass AWJ machining optimization	Ti-6Al-4V alloy	Jet pressure, Traverse feed rates, Number of passes	Kerf taper angle, Depth of penetration, Material removal rate	Multipass strategies improved kerf quality and machining performance for aerospace applications.
Ramesh and Mani (2021) [25]	Machine learning in AWJ milling	Alumina ceramic	Water pressure, Step over, Abrasive flow rate, Traverse rate	Surface roughness	Support vector regression model outperformed traditional models, achieving high prediction accuracy. Demonstrated potential of machine learning for optimizing AWJ processes.

Bui et al. (2019) [26]	Adaptive speed control in AWJ milling	Thin titanium alloy	Traverse speed, Depth of cut, Water pressure, Abrasive flow rate	Consistent milling depths	Adaptive speed control model effectively corrected depth variations in pocket corners, improving milling accuracy and efficiency.
Gowthama et al. (2023) [27]	AWJ machining optimization	Al/SiC composites	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Surface roughness, Material removal rate, Kerf angle	Optimized settings improved machining precision and efficiency. Highlighted AWJ's potential for precise and efficient machining of metal matrix composites.
Ozcan et al. (2021) [28]	Controlled depth AWJ milling for free-form surfaces	Various materials	Traverse speed, Water pressure, Abrasive flow rate, Standoff distance	Kerf profiles, Material removal rate	Model accurately predicted kerf profiles and improved machining efficiency. Demonstrated AWJ's potential for high-precision roughing passes in aerospace and automotive industries.
Shukla (2013) [29]	AWJ milling process optimization	Titanium alloys	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Material removal rate, Surface finish	Highlighted AWJ's advantages over traditional methods. Focused on process modeling, experimental studies, and optimization strategies to improve efficiency and surface quality.
Arun et al. (2024) [30]	AWJ machining optimization	Monel 400 alloy	Traverse speed, Water pressure, Abrasive flow rate, Standoff distance	Surface roughness, Kerf taper angle	Optimized parameters significantly improved machining quality and efficiency compared to conventional methods. Demonstrated superior surface quality and reduced kerf taper angle.
Rammohan et al. (2023) [31]	Numerical model for kerf generation in AWJ machining	Military-grade armor steel	Water pressure, Traverse speed, Abrasive flow rate, Jet angle	Kerf geometry, Material removal rate	Hybrid model integrating SPH, DEA, and FEM enhanced simulation accuracy. Emphasized importance of optimizing key parameters for improved cutting performance.
Uhlmann et al. (2020) [32]	Near-net-shape fabrication via AWJ milling	Titanium aluminide	Jet pressure, Traverse speed, Abrasive flow rate, Step over	Kerf profiles, Material removal rates	Introduced intersecting kerfs method to increase material removal rates. Identified significant differences in kerf profiles, providing insights for optimizing AWJ milling for complex geometries.
Gowthama et al. (2023) [33]	AWJ machining optimization	Al/SiC composites	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Surface roughness, Material removal rate, Kerf angle	Demonstrated AWJ's potential for precise and efficient machining of metal matrix composites. Optimal settings improved surface roughness, material removal rate, and kerf angle.
Duspara et al. (2017) [34]	AWJ machining optimization for stainless steel	AISI 316L stainless steel	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Surface roughness	Central composite design and ANOVA analysis identified significant parameters affecting surface roughness. Concluded AWJ can replace conventional methods for high-quality machining of stainless steel.
Kesharwani (2015) [35]	AWJ milling with non-spherical abrasive particles	Ti-6Al-4V alloy	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Material removal rate, Surface quality	Modified abrasive feed system improved machining efficiency and surface quality. Provided insights into optimizing AWJ processes for precision machining of titanium alloys.
Hocheng et al. (1997) [36]	AWJ milling of fiber-reinforced plastics	Fiber-reinforced plastics	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Material removal rate, Surface damage	Identified optimal conditions for maximum efficiency and minimal surface damage. Demonstrated AWJ's advantages over traditional milling processes for composite materials.
Ramkumar and Gupta (2020) [37]	Hybrid AWJ and conventional milling	Hard materials	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Material removal rate, Surface quality	Highlighted benefits of hybrid approach, leveraging AWJ for roughing and conventional milling for finishing. Significant improvements in machining efficiency and surface quality.
Patel and Shaikh (2015) [38]	Impact of AWJ machining parameters on composites	Composite materials	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Kerf taper angle, Surface roughness, Depth of cut	Emphasized optimizing parameters to enhance kerf taper angle, surface roughness, and depth of cut. Provided practical insights for improving AWJ performance.
Escobar-Palafox et al. (2012) [39]	AWJ pocket milling characterization	Inconel 718	Water pressure, Traverse speed, Abrasive flow rate, Step over	Pocket geometry, Milling depth	Developed models to predict pocket geometry based on process parameters. Identified optimal parameter combinations for stable milling conditions.
Hashish (2009) [40]	AWJ milling of gamma titanium aluminide	Gamma titanium aluminide	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Surface finish, Material removal rate	Achieved high accuracy and fine surface finishes. Emphasized importance of stress relief and cleaning processes to prevent deformation and abrasive embedment.

Hutyrová et al. (2015) [41]	AWJ and WJ turning of wood plastic composites	Wood plastic composites	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Material removal rate, Surface quality	Found AWJ significantly improved material removal rates and surface quality compared to WJ. Provided insights for optimizing AWJ parameters to overcome challenges associated with conventional turning.
Ting et al. (2022) [42]	Prediction models for AWJ machining	Titanium alloys	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Surface roughness	ANN model outperformed SVM and RA models, achieving highest prediction accuracy. Highlighted effectiveness of ANN in optimizing machining parameters for improved surface quality.
Goutham et al. (2016) [43]	AWJ pocket milling optimization	Inconel 825	Step over, Traverse speed, Pressure, Abrasive flow rate	Material removal rate, Surface roughness	Spiral strategy yielded better outcomes, demonstrating AWJ's potential for machining high-performance materials with minimal thermal distortion.
Hussien et al. (2021) [44]	AWJ cutting performance evaluation	CFRP	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Surface roughness, Kerf angle	Identified optimal parameters to enhance cutting performance. Presented regression models for accurate prediction of machining outcomes.
Murthy et al. (2024) [45]	AWJ machining of jute-polymer composites	Jute-polymer composites	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Surface roughness, Delamination	Optimized parameters achieved significant improvements in surface roughness and delamination. Provided insights for high-quality machining of jute-polymer composites.
Fowler et al. (2005) [46]	Grit embedment in AWJ milling	Ti6Al4V	Water pressure, Traverse speed, Abrasive grit size, Standoff distance	Grit embedment, Surface quality	High-speed milling at low impingement angles minimized grit embedment. Provided insights for achieving better surface quality and enhancing AWJ applicability in precision machining.
Yuan et al. (2020) [47]	AWJ milling of circular pockets	Ti6Al4V	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Milling depth, Surface roughness	Developed material removal model. Identified optimal parameters to improve milling depth and surface roughness. Enhanced AWJ's suitability for precision applications in high-performance industries.
Fowler et al. (2009) [48]	Impact of particle hardness and shape on AWJ milling	Ti6Al4V	Particle hardness, Particle shape, Traverse speed, Standoff distance	Material removal rate, Surface roughness	Harder, angular particles increased material removal rates but also roughened surfaces. Optimizing abrasive selection and traverse speed crucial for balancing efficiency and surface quality.
Ebeid et al. (2014) [49]	ANN model for predicting AWJ milling parameters	Aluminum alloys	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Surface roughness, Depth of cut, Material removal rate	High accuracy in predicting surface roughness, depth of cut, and material removal rate. Offered tool for optimizing AWJ performance and improving machining outcomes.
Kumar et al. (2020) [50]	AWJ cutting optimization for GFRP composites	GFRP composites	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Material removal rate, Kerf width, Taper angle	Emphasized importance of balancing parameters for optimal performance. Achieved better material removal rates, kerf width, and taper angle.
Alberdi et al. (2010) [51]	AWJ slot milling prediction model	Aluminum 7075-T651	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Kerf profiles, Material removal rate	Developed model to predict kerf profiles in AWJ slot milling. Identified optimal parameter combinations for stable milling conditions, ensuring consistent quality and productivity.
Srinivasu and Axinte (2014) [52]	PWJ milling strategy development	Advanced engineering composite materials	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Surface damage, Material removal rate	Developed novel milling strategy to minimize surface damage and improve quality. Highlighted PWJ's advantages for high-performance applications, reducing thermal stresses and tool wear.
Chithirai Pon Selvan (2014) [53]	Empirical model for predicting depth of cut in AWJ cutting	Titanium	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Depth of cut	Validated model provided reliable predictions, helping optimize process parameters. Enhanced machining performance and precision.
Gokul et al. (2015) [54]	AWJ pocket milling optimization	Acrylic	Standoff distance, Step-over size, Traverse speed, Abrasive flow rate	Depth of cut, Material removal rate	Identified significant factors affecting depth of cut and material removal rate. Demonstrated AWJ's potential for efficient machining of acrylic.
Shipway et al. (2005) [55]	Surface characteristics of Ti6Al4V post-AWJ milling	Ti6Al4V	Water pressure, Traverse speed, Abrasive flow	Surface roughness, Waviness, Grit embedment	Identified optimal parameters to balance material removal rate and surface quality. Provided insights for improving AWJ processes.

			rate, Standoff distance		
Cenac et al. (2013) [56]	AWJ milling optimization for aeronautic aluminum	Aluminum 2024-T3	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Milled depth, Abrasive mass flow rate	Developed models to predict milled depth. Identified optimal abrasive mass flow rates and provided insights into micro-cutting and lateral cracking mechanisms.
Dittrich et al. (2014) [57]	Water abrasive fine jet machining for ceramics	Ceramic surfaces	Water pressure, Abrasive flow rate, Traverse speed, Standoff distance	Surface structure, Material removal rate	Identified critical parameters like water pressure and abrasive flow rate. Demonstrated potential for precise and reproducible machining of ceramics.
Gupta et al. (2015) [58]	ANN model for predicting micro-channel characteristics	SS304	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Micro-channel geometry	High accuracy in predicting micro-channel characteristics. Demonstrated ANN's capability to optimize AWJ processes and improve machining performance and dimensional accuracy.
Kanthababu et al. (2016) [59]	AWJ pocket milling optimization	Ti6Al4V	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Depth of cut, Surface roughness	Identified step-over and traverse rate as significant factors. Emphasized need for careful optimization to achieve desired machining outcomes.
Gong and Kim (1996) [60]	Erosion model for AWJ milling	Polycrystalline ceramics	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Material removal rate, Erosion profile	Identified 90° incidence angle as optimal for maximum erosion. Model provided insights into material removal mechanisms, enhancing AWJ efficiency for ceramics.
Paul et al. (1998) [61]	AWJ rectangular pocket milling optimization	Various materials	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Depth variation, Material removal rate	Developed empirical models for predicting outcomes. Reduced depth variation and improved material removal rate. Demonstrated AWJ's potential for precise and efficient material removal.
Ebeid et al. (2023) [62]	PWJ milling parameter optimization	Aluminum alloy	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Milling performance, Surface quality	Identified effects of key parameters on milling performance. Provided insights for improving PWJ machining efficiency and surface quality.
Siddiqui and Shukla (2023) [63]	AWJ depth of cut prediction model	Thick Kevlar-epoxy composites	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Depth of cut, Surface quality	Validated model offered precise predictions and optimization guidelines. Ensured effective cutting and high-quality finishes.
Fowler et al. (2005) [64]	AWJ milling parameter optimization	Ti6Al4V	Water pressure, Traverse speed, Abrasive grit size, Standoff distance	Material removal rate, Surface roughness, Waviness	Identified optimal parameters for balancing material removal rate, surface roughness, and waviness. Provided crucial insights for optimizing AWJ processes.
Pal and Tandon (2012) [65]	AWJ milling depth and material characteristics analysis	Various materials	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Machining time, Material removal rate	Identified material properties and machining parameters influencing outcomes. Offered insights for optimizing AWJ processes for different materials.
Feng et al. (2007) [66]	AWJ milling optimization for Al2O3 ceramics	Al2O3 ceramics	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Surface quality, Material removal rate	Higher nozzle traverse speeds improved surface quality, while higher feeds reduced it. Provided insights for balancing efficiency and surface quality in AWJ milling of ceramics.
Müller et al. (2021) [67]	AWJ vs. WJ cutting comparison	PP and PVC-U materials	Traverse speed	Kerf width, Taper angle, Burrs	AWJ achieved more uniform cuts without delamination, highlighting its effectiveness for precise cutting of coated polymer materials.
Chen et al. (2023) [68]	AWJ machining performance model	Ductile materials	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Effective depth of cut	Accurate predictions enhanced AWJ machining performance, offering significant industrial value for high-quality surface finishes in materials like Ti-6Al-4V.
Vishnu and Saleeshya (2021) [69]	AWJ machining parameter optimization	Inconel 718	Water pressure, Traverse speed, Abrasive flow rate, Standoff distance	Surface quality, Kerf taper	Optimized parameters achieved better surface quality and minimal kerf taper. Provided guidelines for machining complex profiles in hard-to-machine materials like Inconel 718.
Begic-Hajdarevic et al. (2015) [70]	AWJ cutting parameter optimization for various materials	Various materials	Water pressure, Traverse speed, Abrasive flow rate, Stand-off distance	Surface roughness	Highlighted importance of optimizing parameters to achieve desired machining outcomes. Provided practical insights for improving AWJ processes across different materials and applications.