Recent Advances in Abrasive Jet Machining: A Review of Materials, Techniques, and Industrial Applications

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Abstract — This literature review presents a comprehensive analysis of the advancements in Abrasive Jet Machining (AJM) for machining applications over the past decade (2015–2025). AJM has evolved from a coarse material removal method to a precision manufacturing process, driven by innovations in abrasive materials, nozzle designs, jet control strategies, and hybrid processing techniques. This review categorizes and synthesizes findings from peer-reviewed studies published in high-impact journals, focusing on developments in nano-structured and composite abrasives, functionally graded nozzle materials, and advanced carrier media. Processing advancements such as optimized nozzle geometries, pulsed and submerged jet techniques, and AI-driven control frameworks are critically examined. AJM's application spectrum is analyzed across aerospace, biomedical, microfabrication, and electronic domains, emphasizing its unique capabilities for machining hard, brittle, and thermally sensitive materials. Comparative assessments highlight AJM's advantages in material versatility, surface integrity, and sustainability over conventional and thermal-based machining techniques. The review also identifies existing challenges—such as nozzle wear, process standardization, and abrasive waste—and outlines future directions including smart AJM systems, green abrasives, and integration with additive manufacturing post-processing. Collectively, the findings position AJM as a versatile and strategic technology for precision, clean, and adaptive manufacturing.

Keywords: Abrasive Water Jet Machining (AWJM); Micro-Abrasive Jet Machining (μ-AJM); Non-traditional Machining; Nano-structured Abrasives; Nozzle Wear Resistance

I. Introduction

Abrasive Jet Machining (AJM) has steadily emerged as one of the most versatile non-traditional machining processes for intricate and precision-based material removal. Operating on the principle of high-velocity impact of abrasive particles suspended in a carrier medium, AJM enables the machining of materials that are brittle, heat-sensitive, or difficult to cut by conventional methods. Over the past decade (2015–2025), the landscape of AJM has evolved significantly due to technological advancements in abrasive materials, nozzle design, process modeling, and application-specific optimization. These developments have expanded AJM's usability across critical sectors such as aerospace, biomedical device fabrication, and microelectronics, where fine tolerances and thermal integrity are paramount.

While AJM has historically been employed for cleaning, etching, and deburring, its scope has widened considerably due to the integration of modern control strategies, miniaturized nozzle systems, and the development of new hybrid variants such as Abrasive Water Jet Machining (AWJM), Micro-Abrasive Jet Machining (μ-AJM), and Abrasive Suspension Jet Machining (ASJM). This shift from conventional macro-scale applications to micro- and meso-scale machining has been enabled largely by improvements in particle dynamics understanding, modeling of erosion mechanisms, and innovations in abrasive flow control.

The urgency to manufacture components with superior surface integrity, low thermal distortion, and high geometric precision has further accelerated research in AJM, positioning it as a critical process in modern manufacturing. Moreover, the environmental and energy-efficiency advantages of AJM—being a 'cold' process—have aligned with global sustainability goals, offering an edge over thermal-based techniques like laser or EDM.

Despite the progress, challenges remain. Nozzle wear, process stability, limited MRR, and abrasive recycling pose practical bottlenecks. Recent research efforts have attempted to address these by leveraging computational modeling (CFD, FEM), sensor-based feedback control, and high-performance materials for process-critical components. This review aims to provide a structured and critical overview of these developments, emphasizing the significant strides in AJM research over the past ten years.

II. Methodology

This review adopts a systematic and thematic approach to examine peer-reviewed research on Abrasive Jet Machining published between 2015 and 2025. The methodology involves three stages:

A. Literature Search Strategy

An exhaustive search was conducted in high-impact engineering and manufacturing science journals indexed in *Scopus*, *Web of Science*, and *ScienceDirect*. Only original research articles and comprehensive review papers published in peer-reviewed journals were considered. Search strings included:

- "Abrasive Jet Machining"
- "Abrasive Water Jet Machining"
- "Micro-Abrasive Jet Machining"
- "Abrasive nozzle wear"
- "Particle erosion modeling"
- "CFD in AJM"
- "Hybrid AJM processes"
- "Surface integrity abrasive jet"

Articles from conference proceedings, patents, theses, and grey literature were excluded to ensure academic rigor. Emphasis was placed on journals such as:

- Journal of Materials Processing Technology
- Wear

- International Journal of Advanced Manufacturing Technology
- CIRP Annals
- Precision Engineering
- Surface and Coatings Technology

B. *Selection and Categorization*

The initial corpus consisted of over 120 articles. After screening abstracts for relevance, approximately 75 core studies were retained for in-depth review. These studies were grouped into three thematic domains:

- Material advancements – covering abrasive types, nozzle materials, slurry formulations
- Processing techniques – including jet control, nozzle geometry, process optimization, and hybrid AJM approaches
- Applications and performance – assessing process outcomes in various industries and component-level case studies

Each selected paper was critically analyzed to extract quantitative results (e.g., MRR, surface roughness, kerf angle), experimental setups, computational insights, and theoretical contributions. Comparative studies, parametric analyses, and novel experimental configurations were given special attention.

III. DEVELOPMENT IN AWJM

Yuvaraj et al. 2015 investigated the optimization of abrasive water jet (AWJ) cutting processes using a Multi-Criteria Decision-Making (MCDM) approach, specifically the TOPSIS method, to enhance multiresponse characteristics. The study focused on key process parameters—water jet pressure, traverse rate, abrasive flow rate, and standoff distance—and their influence on performance metrics such as depth of penetration (DOP), cutting rate (CR), surface roughness (Ra), taper cut ratio (TCR), and top kerf width (TKW). The optimized AWJ parameters (300 MPa water jet pressure, 120 mm/min traverse rate, 360 g/min abrasive flow rate, and 1 mm standoff distance) yielded improved results, including higher DOP and CR alongside reduced Ra, TCR, and TKW. The study demonstrated the effectiveness of the TOPSIS method in balancing conflicting responses for the AA5083-H32 aluminum alloy. Additionally, analysis of variance (ANOVA) was employed to identify significant factors affecting the AWJ cutting process. This work provides valuable insights into parameter optimization for achieving superior machining performance in AWJ applications.

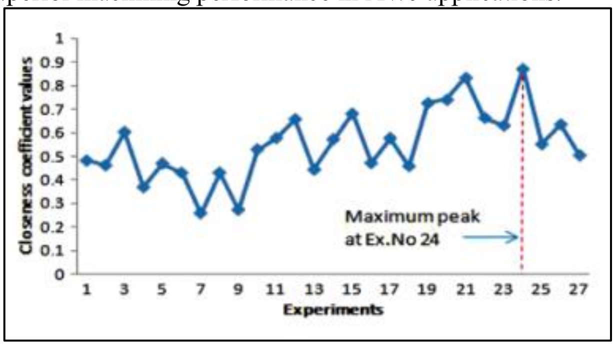


Fig. 1: Effect of process parameters in each experiment [1]

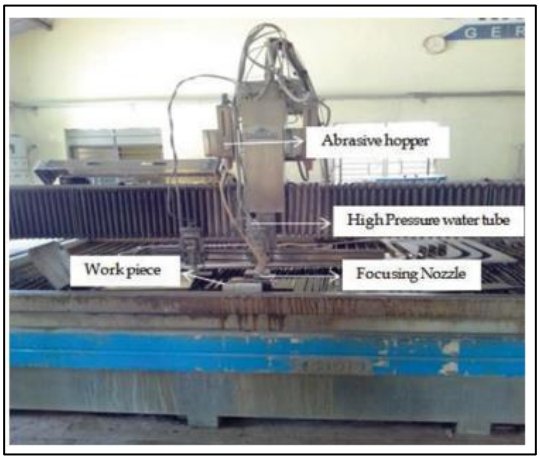


Fig. 2: Experimental setup [1]

Lu et al. 2015 investigated the rock erosion mechanisms under high-velocity water jet impingement, a process critical to applications like hydrodemolition, hydrodynamic fragmentation, and cavitating drilling. Through theoretical analysis and experimental studies with water jet velocities ranging from 157 ± 1 m/s to 774 ± 1 m/s, the authors identified three distinct failure patterns in sandstone: (i) a central broken pit with circumferential surface cracks at velocities exceeding a threshold (157–316 m/s), (ii) internal fractures comprising radial, circumferential, and conical cracks, and (iii) macrocracks on side surfaces transitioning from transverse to split-like cracks as velocity increased. Scanning electron microscopy (SEM) revealed detailed fracture morphology, providing insights into the damage mechanisms. This study advances the understanding of velocity-dependent rock fragmentation, offering practical implications for optimizing water jet-based cutting and drilling technologies.

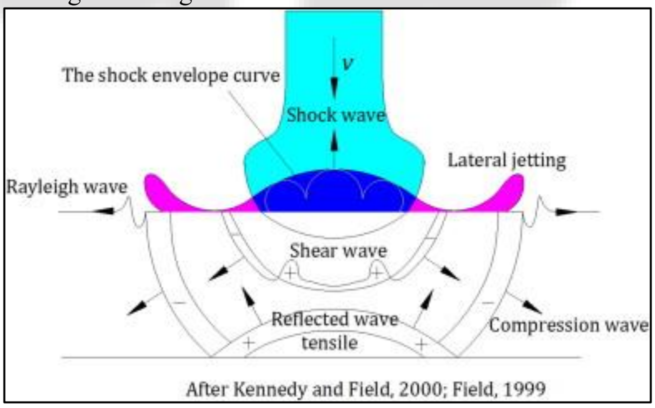


Fig. 3: The schematic of water jet impact on solid surface: stress and shock wave generation and propagation.[2]

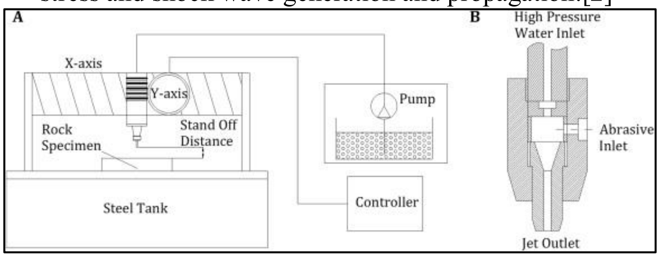


Fig. 4: Schematic diagram of water jet system and the nozzle profile.[2]

Ćojbašić et al. 2016 proposed a novel approach using an Extreme Learning Machine (ELM) to predict surface roughness in abrasive water jet (AWJ) machining, a critical quality indicator influenced by parameters such as workpiece thickness, abrasive flow rate, and cutting speed. Through extensive experimental trials under varying cutting conditions, the authors trained an ELM model and compared its performance with Genetic Programming (GP) and Artificial Neural Networks (ANNs). The results demonstrated that the ELM model outperformed GP and ANNs in predictive accuracy and generalization capability, offering a reliable tool for surface roughness estimation. The study concluded that ELM-based modeling presents a promising alternative for developing predictive strategies in AWJ machining, paving the way for optimized process control. This work highlights the potential of machine learning techniques in enhancing precision manufacturing.

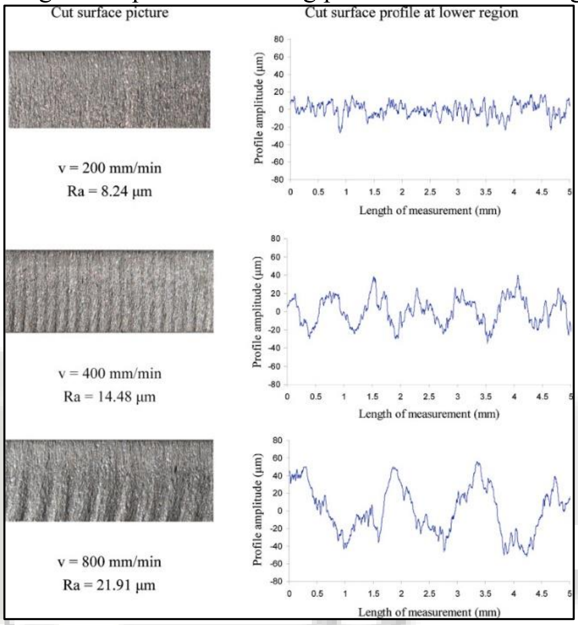


Fig. 5: Picture of the cut surface and the surface profile at lower region of the cut, for aluminium alloy sample with thickness of 6 mm. [3]

Tripathi et al. 2017 investigated the application of pulsating water jet technology for rock disintegration, addressing limitations of conventional high-pressure methods. The study focused on marble and granite erosion using a 20.20 kHz modulated water jet with specific parameters: 0.9 mm nozzle diameter, 6 mm standoff distance, 2-16 mm/s traverse speed, and 60 MPa pump pressure. The research demonstrated that pulsating jets achieve effective material disintegration at lower energy costs compared to continuous jets, while maintaining processing quality. Advanced monitoring techniques, including acoustic emission analysis and optical profilometry, revealed significant correlations between rock properties (physical and mechanical characteristics) and cutting performance (depth and surface quality). The real-time acoustic emission data provided insights into the dynamic interaction between pulsation frequency and rock fracture mechanisms. This work highlights the potential of pulsating water jets as an efficient alternative for hard rock processing in mining and quarrying applications, offering economic and operational advantages over traditional methods.

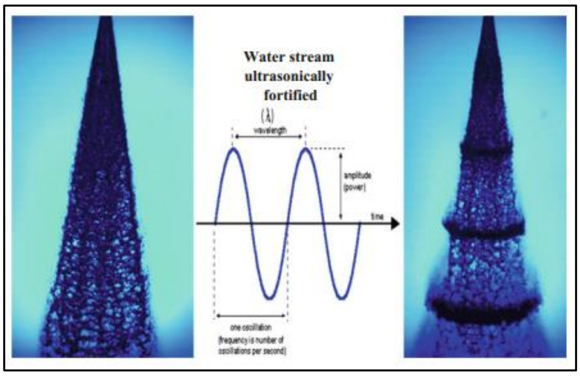


Fig. 6: Water stream ultrasonically fortified on the left—without pulsation, on the right—with pulsation 20 kHz [4]

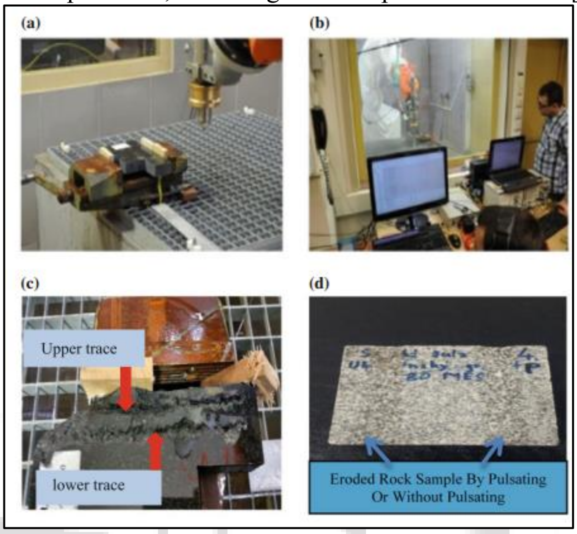


Fig. 7: An Experimental setup. b Monitoring the process. c Rock sample with black granite. d White marble [4]

Haldar et al. 2018 conducted a comprehensive review of abrasive jet systems, highlighting their versatility in manufacturing and R&D applications. Their study emphasized the system's effectiveness in machining brittle materials (e.g., cutting, drilling, engraving glass and marble), surface preparation for welding/coatings, and erosion testing of components like turbine blades. The authors also explored its use in shot peening for surface hardening. They designed an in-house abrasive jet system and experimentally validated its performance across machining, cleaning, and erosion applications. Notably, their work demonstrated that natural sand abrasives could efficiently cut brittle materials and remove rust from metal surfaces. Additionally, they successfully employed the system for erosion testing of metal matrix composite laser coatings. This study underscores the adaptability of abrasive jet technology and its potential for diverse industrial uses, providing a foundation for further optimization and application-specific research [5].

Melentiev et al. 2019 conducted a comprehensive investigation of particle velocity dynamics in micro-abrasive jet machining (AJM), a critical factor influencing the precision of micro-pattern fabrication on freeform surfaces. The study combined theoretical analysis with two-dimensional axisymmetric numerical simulations to examine velocity fields in micro-scale nozzles down to 100 µm diameter. Key findings revealed that viscous friction significantly reduces kinetic energy transfer efficiency in small nozzles, with particle velocity being strongly dependent on nozzle geometry (diameter and length), air pressure, and particle characteristics (size and density). The research developed predictive regression models for maximum particle velocity and its spatial distribution, providing practical tools for optimizing particle kinetic energy in micro-AJM applications. Notably, the numerical results demonstrated good agreement with experimental data, validating the proposed modeling approach. This work advances the fundamental understanding of energy transfer mechanisms in micro-AJM while offering practical guidelines for process control in precision microfabrication.

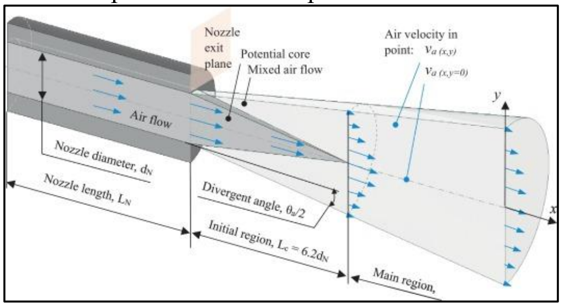


Fig. 8: Schema of air flow distribution [6]

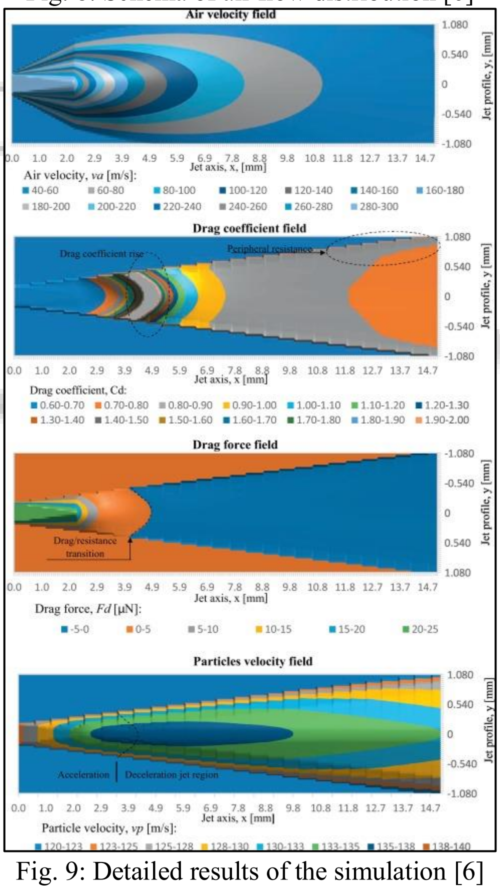


Fig. 9: Detailed results of the simulation [6]

Sabarinathan et al. 2020 presented an innovative approach to sustainable manufacturing by repurposing waste alumina grinding wheels as abrasive media in waterjet machining. The study systematically characterized the recycled alumina particles (0.92 shape factor, angular morphology via SEM/EDX) and evaluated their performance against conventional garnet abrasives in machining marble and aluminum. Results demonstrated superior efficiency of recycled alumina, with 43-63% higher material removal rates and enhanced cutting depth capabilities compared to garnet. While producing higher surface roughness, the recycled abrasives showed particular effectiveness in marble cutting, generating beneficial lateral cracks for efficient material removal - a valuable characteristic for stone processing industries. This research not only addresses environmental concerns through waste utilization but also identifies cost-effective alternatives for industrial rough cutting operations, particularly in granite and marble processing where surface finish requirements are less critical than material removal rates.

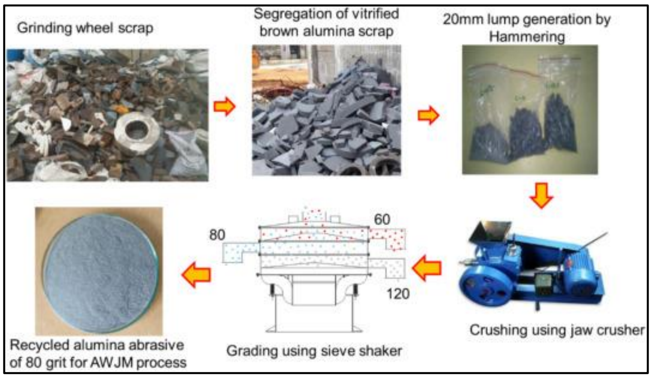


Fig. 10: Schematic layout of recycling and grain generation process [7]

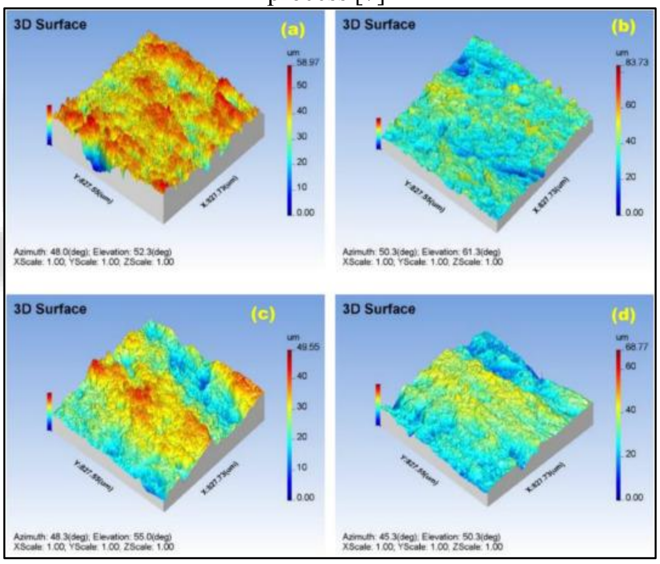


Fig. 11 3D surface topography of the striation zone of cut down surface (a) aluminium @ garnet, (b) aluminium @ recycled alumina, (c) marble @ garnet and (d) marble @ recycled alumina [7]

Schüler et al. 2021 conducted a fundamental investigation into the abrasive-particle interaction mechanisms governing the erosion process in abrasive waterjet (AWJ) machining, a critical yet poorly understood aspect of this otherwise well-established non-conventional manufacturing technology. The study systematically examined how individual abrasive grit characteristics (shape and mechanical properties) influence machining outcomes through comprehensive experimental analysis combining visual inspection of machined surfaces with residual stress measurements. This work provides valuable insights into the micro-mechanisms of material removal in AWJ processes, establishing a foundation for more accurate process modeling and control. By elucidating the relationship between abrasive particle properties and machining results, the research addresses a key challenge in AWJ technology - the precise control of erosion factors - while enhancing the fundamental understanding needed to optimize this flexible machining method for hard-to-machine materials.

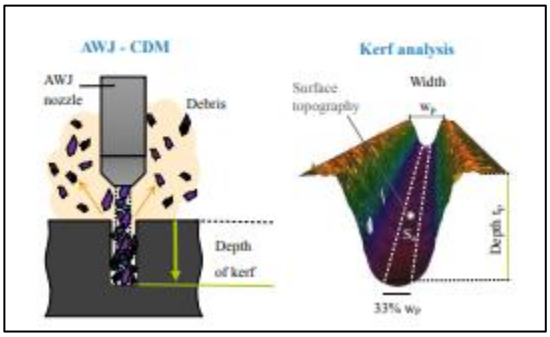


Fig. 12 Schematic of AWJ controlled-depth machining (left) and analysis of the machined kerf.[8]

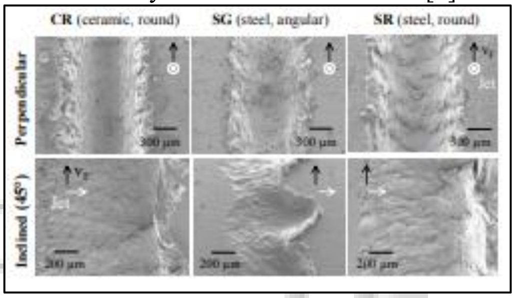


Fig. 13: Macroscopic evaluation of the annealed specimen machined perpendicular and at inclination by different abrasive grit [8]

Pradhan et al. 2022 investigated the emerging technology of hot abrasive jet machining (HAJM) to address precision machining challenges in modern manufacturing. The study focused on developing an indigenous fluidized-bed HAJM system capable of processing abrasives at elevated temperatures to enhance cutting performance and target surface erosion. Through a combination of experimental analysis and computational fluid dynamics (CFD) simulations, the research examined erosive footprint prediction and tapered hole generation capabilities. The work demonstrated that temperature-controlled abrasives significantly improve machining efficiency while maintaining environmental sustainability. Notably, the study encompassed the complete design-fabrication-implementation cycle of a HAJM system using commercial hardware/software, along with comprehensive sustainability assessments. These developments offer promising solutions for achieving geometrical accuracy, particularly in critical hole-making operations, while addressing time-efficiency and environmental concerns in precision manufacturing.[9]

Vijay kumar et al. 2023 investigated the optimization of abrasive aqua jet machining (AAJM) for producing precision blind holes in Inconel-625, a challenging aerospace alloy known for its high strength and corrosion resistance. The study employed desirability analysis to optimize four key process parameters: abrasive jet pressure (AJP, up to 300 MPa), gap distance (1-3 mm), traverse speed (96-192 mm/min), and abrasive mixture composition (garnet vs. silicon carbide). Results demonstrated significant improvements at maximum pressure - 27.35% reduction in surface roughness, 56.23% and 42.56% improvements in circularity and cylindricity respectively, along with a 32.83% increase in erosion rate. The optimal parameter combination (300 MPa AJP, 1 mm gap, 96 mm/min speed, 100% SiC abrasive) was identified through comprehensive analysis, with ANOVA confirming AJP as the most influential factor. Advanced characterization using SEM and 3D topography provided insights into surface quality enhancements. This work establishes AAJM as a viable solution for machining high-performance alloys, addressing critical challenges in aerospace component manufacturing.

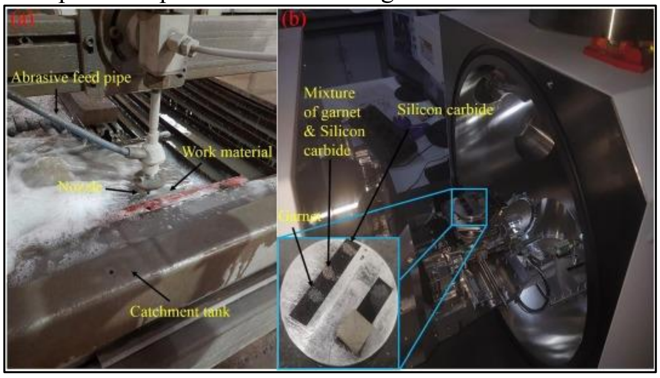


Fig. 14: (a) AAJHM Setup (b) Processing of Garnet, silicon carbide and a mixture of garnet with silicon carbide.[10]

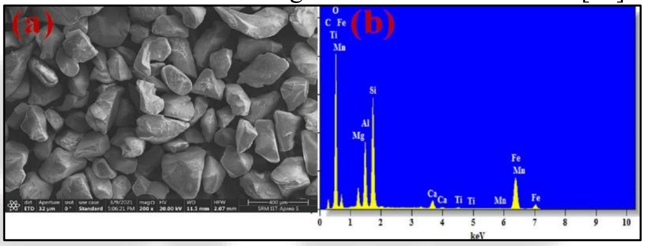


Fig. 15: (a) SEM of garnet and (b) EDX of garnet.[10]

Meijer et al. 2024 explored the novel application of pressurized air wet abrasive jet machining (PAWAJM) for creating asymmetric microgeometries on filigree micromilling tools, addressing a gap in cutting edge preparation technology. The study demonstrated that PAWAJM can effectively produce controlled asymmetric geometries with specific characteristics (average cutting edge rounding and form-factor K > 1.2) on AISI M3:2 high-speed steel tools. Subsequent machining tests revealed significant performance benefits, including reduced process forces, improved surface quality, and enhanced tool life compared to conventional symmetric edge preparations. The research provides valuable insights into the relationship between asymmetric microgeometry design and machining performance in hard micromilling applications. These findings advance the understanding of precision tool conditioning methods and their impact on micromachining operations, offering practical solutions for optimizing tool performance in demanding applications.

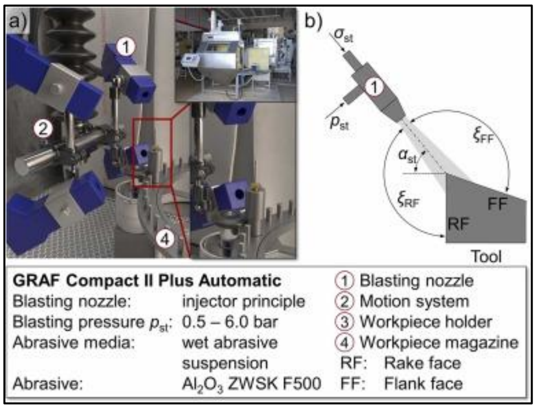


Fig. 16 a) Experimental setup for in the PAWAJM system and b) schematic illustration of the blasting situation [11]

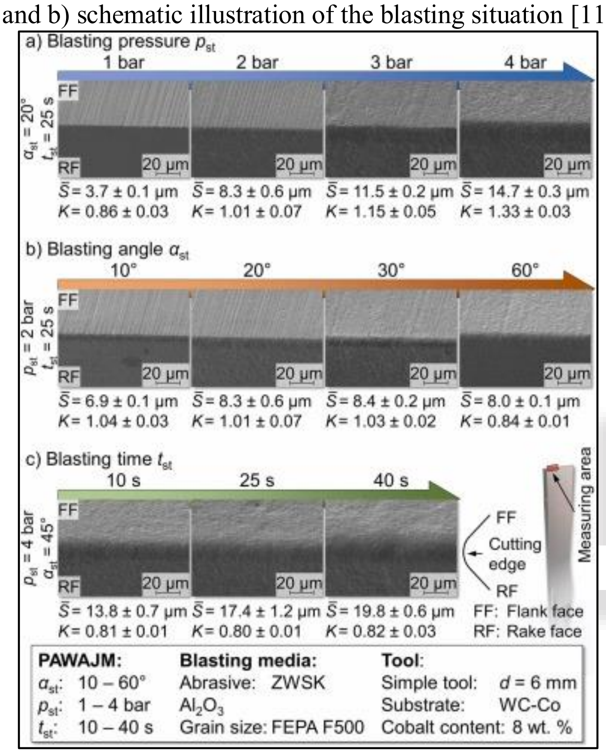


Fig. 17: Change of the microgeometry of the simple tools by the choice of a) the blasting pressure p_{st}, b) the blasting angle α_{st}, and c) the blasting time t_{st} [11]

Zhuang et al. 2024 presented a comparative study on abrasive jet post-processing of tool coatings, evaluating both elastic abrasive jet machining (EAJM) and conventional hard abrasive (Al2O3) jet machining (HAJM). The research demonstrated that EAJM effectively reduced coating surface roughness and improved tool wear resistance across broad parameter ranges without coating damage, while HAJM offered more significant enhancements in coating hardness, elastic modulus, and residual stress - albeit requiring precise parameter control to avoid performance degradation. The study established a mathematical model relating jet pressure and time to tool life, identifying optimal processing windows (326-4870 kPa·s for HAJM and 1061-17,780 kPa·s for EAJM). Significantly, the work revealed that tool life improvement correlates strongly with coating physical properties, explaining the superior performance of HAJM-treated tools when properly optimized. These findings provide valuable guidelines for selecting and optimizing abrasive jet processes based on specific coating performance requirements.

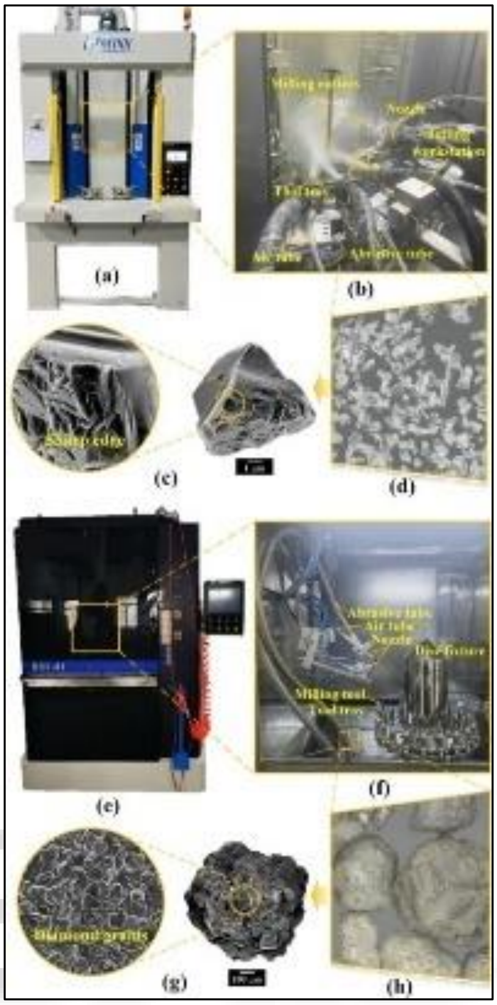
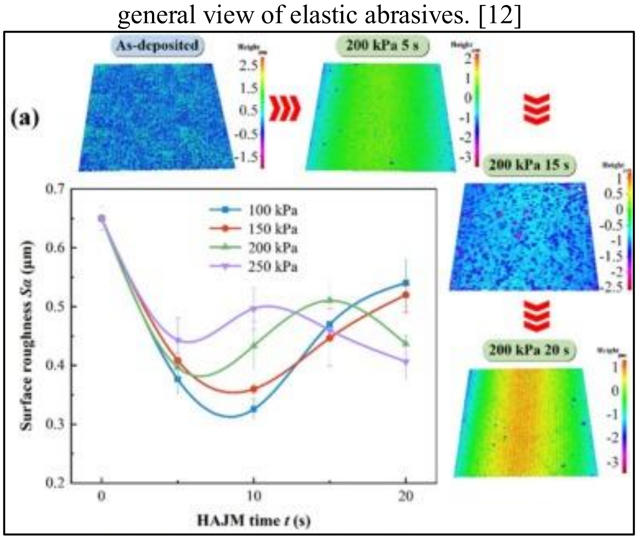


Fig. 18: Equipment and abrasives of two jet machining methods: (a) HAJM equipment appearance; (b) internal structure of HAJM equipment; (c) topography of a single Al_2O_3 particle; (d) general view of Al_2O_3 abrasives; (e) EAJM equipment appearance; (f) internal structure of EAJM equipment; (g) topography of a single elastic particle; (h) general view of elastic abrasives. [12]



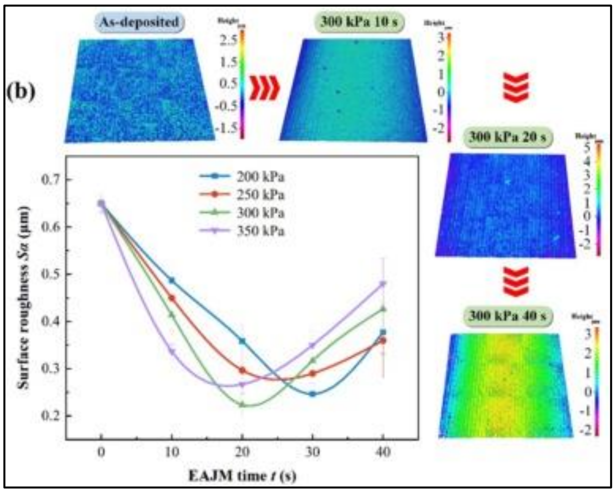


Fig. 17: Variations in surface roughness and morphology of coating under (a) HAJM and (b) EAJM for post-treatment. [12]

Zhuang et al. 2025 Zhuang et al. 2025 developed an eco-friendly approach to valorize grinding wheel waste by repurposing alumina stubs as abrasives in waterjet machining. Through mechanical crushing and comprehensive characterization (SEM/EDX analysis revealing 0.92 shape factor with sharp edges), the study demonstrated that recycled alumina outperformed conventional garnet abrasives, achieving 43% and 63% higher material removal rates for aluminum and marble respectively. While producing rougher surfaces, the angular recycled particles proved particularly effective for stone cutting, generating beneficial lateral cracks that enhanced material removal - making them ideal for granite and marble industries where rapid stock removal outweighs surface finish requirements. This research provides both a sustainable waste solution and a cost-effective alternative for industrial roughing operations.

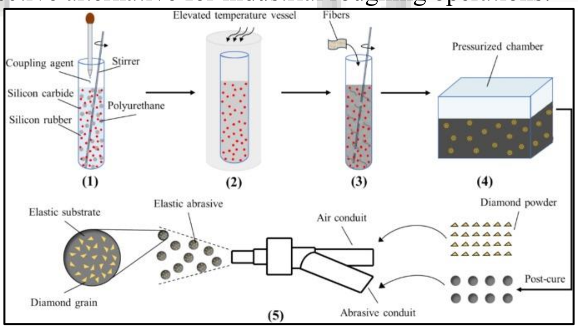


Fig. 18: Production processes of the novel elastic abrasive. [13]

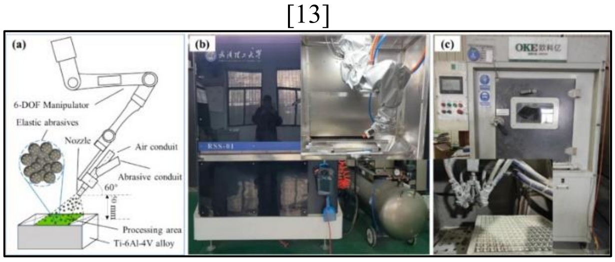


Fig. 19: Experimental setup for abrasive jet machining: (a) model of EAJM, (b) robot-based surface strengthening machine and (c) hard abrasive jet machining device. [13]

IV. Summary of Application Trends

The last decade has firmly established AJM as a multi-sectoral, precision machining platform capable of delivering thermally benign and geometrically accurate results. Table 3 (to be included later) summarizes notable application studies with key metrics.

Key industrial advantages driving AJM adoption include:

- Superior surface quality without recast layers or HAZ
- Compatibility with delicate and hard materials alike
- Scalable process configurations (from micro to macro)
- Safer and more sustainable alternatives to conventional techniques

These strengths position AJM as a strategic enabler of next-generation manufacturing, particularly where surface integrity, material diversity, and process sustainability are prioritized.

V. Discussion

Over the past ten years, Abrasive Jet Machining (AJM) has undergone a remarkable transformation from a coarse material removal technique into a nuanced, multi-scale, and multi-material machining solution. As evidenced by the literature, this evolution has been fueled by advances in materials engineering, process optimization, hybridization strategies, and domain-specific adaptation. This discussion distills key cross-cutting insights, evaluates process trade-offs, identifies current limitations, and outlines avenues for future research and industrial deployment.

A. Synergistic Advances Across Materials, Processing, and Applications

Perhaps the most evident trend in AJM research has been the mutual reinforcement between material innovations and process enhancements. The development of high-performance abrasives—such as nano-structured particles, composite grit, and spherical polymeric media—has enabled more controlled erosion, finer surface finishes, and expanded compatibility with soft and brittle materials alike. Simultaneously, advances in nozzle materials, such as functionally graded ceramics and diamond-tipped micro-nozzles, have extended tool life while preserving dimensional accuracy.

These innovations have found immediate application in micro-electromechanical systems (MEMS), biomedical implants, aerospace components, and optical devices, where tolerances are tight and thermal safety is essential. AJM's ability to machine difficult-to-cut materials like Inconel, zirconia, and CFRPs—without introducing residual stresses or heat-affected zones—has validated its industrial relevance. Moreover, its non-contact nature and environmental adaptability (e.g., submerged operation) make AJM a uniquely scalable process, usable from cleanroom labs to heavy-duty fabrication plants.

B. Comparative Strengths and Positioning Among Machining Technologies

In a comparative landscape, AJM offers several unrivaled capabilities that distinguish it from both traditional and other non-traditional machining processes:

Feature	Conventional Machining	Laser Cutting	EDM	AJM / AWJM
Thermal Influence	High	High	High	Negligible
Suitable for Brittle Materials	Poor	Moderate	Moderate	Excellent
Minimum Feature Size	~200 µm	~30 µm	~50 µm	<50 µm (with µ-AJM)
Tool Wear	Significant	N/A	Electrode erosion	Low (with optimized nozzles)
Multi-material Machinability	Limited	Poor (reflective materials)	Good	Excellent
Environmental Emissions	Coolants, Swarf	Fumes	Debris, Dielectrics	Minimal (especially submerged)

This comparative matrix shows that AJM is uniquely positioned as a cold, clean, multi-material machining platform with high adaptability and precision potential. While it may not yet compete with EDM or laser in deep 3D contouring or sub-micron patterning, it excels in applications where material safety, surface integrity, and machining of composites or ceramics are critical.

C. Persistent Challenges and Limitations

Despite these strengths, several persistent limitations continue to restrict AJM's full-scale industrial deployment:

1) Nozzle Wear and Dimensional Drift

Even with advances in wear-resistant nozzle materials, erosion-induced geometric drift remains a challenge, especially in long-cycle production. Minor changes in nozzle internal diameter or exit geometry can lead to variations in particle velocity and erosion profile. While modular nozzle inserts mitigate this, real-time wear compensation systems are still rare in commercial setups.

2) Process Repeatability and Standardization

AJM remains highly parameter-sensitive. Minor fluctuations in air pressure, abrasive feed rate, or standoff distance can significantly impact MRR and kerf geometry. Unlike CNC milling or turning, AJM lacks widespread industrial standards for process parameters, leading to variability across operators, equipment vendors, and material combinations.

3) Abrasive Recovery and Environmental Management

Though less pollutive than EDM or chemical machining, AJM generates spent abrasive waste, especially in dry and air-based configurations. The collection, separation, and recycling of abrasive particles remain an economic and environmental concern. The adoption of submerged AJM and closed-loop media systems has mitigated this, but comprehensive solutions are needed for widespread use.

4) Limited Integration with Smart Manufacturing

AJM systems are only beginning to adopt Industry 4.0 features, such as sensor-based feedback, remote control, and machine learning integration. Compared to CNC systems, which often come equipped with digital twins and predictive analytics, AJM still operates largely in a semi-open-loop configuration. This gap hinders its automation potential in smart factories.

5) Research Trends and Emerging Directions

The past decade's progress in AJM sets a foundation for future exploration along several strategic axes:

6) Intelligent AJM Systems

Incorporating real-time sensors, vision systems, and adaptive control algorithms could transform AJM into a self-correcting process. For example, integrating depth sensors or acoustic emission monitoring to dynamically adjust abrasive feed or traverse speed could enhance repeatability and reduce over-processing.

7) Green and Sustainable AJM

There is a growing need for eco-compatible abrasives, such as recycled glass, biodegradable polymer grit, or inert mineral particles. Concurrently, research into abrasive reusability, fluid filtration, and media lifecycle analysis is essential to position AJM as an environmentally responsible process.

8) AJM for Additive Manufacturing Post-processing

As 3D printing proliferates, there is an emerging role for AJM in post-processing of additive-manufactured components. Particularly in powder bed fusion and metal sintering, AJM could help remove support structures, smooth layer steps, or clean internal channels, where conventional tools cannot reach.

9) Biomedical Micromachining and Surface Engineering

Micro-AJM is expected to grow in the biomedical sector, enabling precision stent patterning, biodegradable implant texturing, and antimicrobial surface structuring. Combining AJM with plasma treatments or bioactive coatings could yield synergistic surface modifications.

10) Hybrid Multiphysics AJM Processes

Hybrid configurations—such as laser-AJM, ultrasonic-AJM, and electrochemical-AJM—will likely evolve into mainstream techniques. By combining complementary removal mechanisms, these systems can address limitations of individual processes while expanding material compatibility and process range.

D. Towards Standardization and Industrial Integration

For AJM to realize its full industrial potential, efforts must also focus on:

- Developing open databases of material–process–performance correlations
- Creating standardized test protocols for nozzle life, surface roughness, and kerf accuracy

- Benchmarking AJM vs. competing technologies under common manufacturing scenarios
- Designing AJM-compatible CAD/CAM platforms for streamlined process planning

Such developments would encourage cross-sector adoption, facilitate operator training, and enable AJM integration into flexible manufacturing systems (FMS) and cyber-physical production environments.

VI. CONCLUDING REFLECTIONS

The literature reviewed from 2015 to 2025 reflects a period of maturation and multidimensional expansion for AJM. The technology is no longer confined to niche operations but is increasingly recognized as a core manufacturing process in precision, sustainable, and high-performance domains. The synthesis of materials science, computational modeling, environmental engineering, and systems integration in AJM research signals a broader shift toward interdisciplinary innovation in non-traditional machining.

As global manufacturing pivots toward low-impact, high-integrity production, AJM stands out as a promising candidate for broader adoption—provided that its remaining limitations are addressed through targeted research, industrial partnerships, and policy support.

VII. CONCLUSION

Abrasive Jet Machining (AJM) has matured into a dynamic, flexible, and increasingly indispensable manufacturing process, addressing longstanding challenges in machining of hard, brittle, heat-sensitive, and composite materials. Over the last decade (2015–2025), peer-reviewed research has significantly advanced our understanding of AJM at both the material and process levels. These developments have elevated AJM from a niche capability to a platform technology supporting precision, micro, and hybrid manufacturing domains.

Key takeaways from this review include:

- Material Innovation: Development of high-performance abrasives (e.g., nano-structured, composite, and hybrid media), functionally graded and modular nozzle materials, and advanced carrier fluids (suspension and polymer-based) has enabled higher MRR, precision, and tool life across applications.
- Process Engineering: Optimized nozzle geometries (Venturi, swirl, micro), jet modulation techniques (pulsed, submerged), and AI-based control systems have greatly improved process stability, repeatability, and efficiency.
- Applications: AJM has found critical application in aerospace (cutting superalloys and CFRPs), biomedical (machining implants, micro-texturing), microfabrication (MEMS, wafers), ceramics (optical components), and even in decorative industries, thanks to its cold, non-contact nature.
- Performance Advantages: Unique strengths such as absence of HAZ, low tool wear, material flexibility, and compatibility with smart manufacturing objectives make AJM a robust choice for advanced manufacturing ecosystems.
- Challenges and Future Directions: Key challenges such as nozzle wear, process variability, lack of standardization, and abrasive waste management still limit full-scale deployment. However, research is actively addressing these through smart process integration, hybrid techniques, and sustainability-focused innovations.

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