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Developments in Abrasive Water Jet Machining of Nonmetals

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Abstract

Abrasive water jet machining (AWJM) is known for precise cutting of metals and nonmetals. In the past few years, this machining technology has undergone some important developments which possibly enhanced its capability and extended its applications. This article presents such important developments and related attempts on AWJM made by researchers in the recent past. The scope covers AWJM of important nonmetallic materials like rock, glass, rubber, composites and ceramics etc. The important developments have been in the form of utilizing abrasives like sugar particles, glass beads, ice particles, bone powder; water-less abrasive jet machining; process optimization; and acoustic emission monitoring etc. that enhanced the capability of the AWJM process towards cost reduction, quality enhancement, and sustainability. The article intends to amass such important information related to the recent developments in AWJM for nonmetal cutting and aims to facilitate scholars and researchers with this new knowledge.

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Introduction

Nonmetals like glass, composites, polymers, rubbers, and ceramics are not easy to machine and their machining requires technological interventions to make good products out of them. Abrasive water jet machining (AWJM) is a well-known and very old modern machining technique [1]. Since its inception, there have been several research attempts to make this machining process better. In the last 5-6 years, to machine various nonmetallic materials, researchers and engineers have made significant attempts for process capability enhancement, process control and monitoring, process sustainability, process optimization, and quality enhancement of nonmetallic products [2-4]. The history of this process is almost two hundred years long, where somewhere in 1850, water jet was first used to cut rocks, followed by cutting paper in 1950. After 1990, abrasive water jet machining was started to be used for cutting, polishing, and cleaning purposes. Today, abrasive water jet machining is being utilized in many micromachining, cutting, polishing, and finishing applications. Figure 1 presents the working principle of AWJM. The major components of an AWJM system consists of water storage and supply system, abrasive supply system, nozzle, and a catcher tank to collect used abrasives and eroded work material.

AWJM process mechanism is governed by cutting and deformation wear of the work material after a high velocity abrasive laden water jet is stroked to the surface of the workpiece whose cutting is to be performed [1, 2]. The action of high velocity abrasive particles erodes the material from the work surface. In case of brittle material like most of the nonmetals, the material from the work surface gets separated due to brittle fracture and plastic deformation [3-5]. Water jet pressure, abrasive mass flow rate, stand-off-distance, nozzle diameter, abrasive material type and particle size etc. are the important process parameters of an AWJM. The pressure of a water jet ranges from 150 to 450 MPa. It is the most important parameter responsible for the cutting to happen as it provides momentum to the abrasive particles to reach upto work surface. Low water jet pressure causes stray cutting and geometrical inaccuracy in the product. Extremely high pressure may cause damage on work surface. Abrasive type, size, and properties are important. Garnet is the most extensively utilized abrasive materials and it is hard enough. The other abrasives used in AWJM are glass beads, steel shots, silica, silicon carbide etc. Coarse abrasive particles are suitable for cutting, whereas fine are for polishing. Mass flow rate of abrasive particles is the magnitude of their mass flowing per unit time out of the nozzle. High mass flow rate is responsible for high material removal rate due to increased cut depth. The distance between nozzle and worksurface is known as the stand-off-distance (SOD) and its optimum value is desirable because low SOD imparts inefficient cutting due to bouncing back of abrasive particles and high SOD also causes jet expansion before striking and therefore inefficient cutting. Nozzle or jet traverse speed is yet another important parameter whose low value generates good surface properties but low material removal rate. Surface quality with roughness and geometric accuracy, and process productivity are the major categories of machinability indicators in any machining process. Surface roughness, kerf (width and angle), material removal rate, cut depth, and subsurface stresses are the major parameters of AWJM machinability investigated to determine the success of this process.

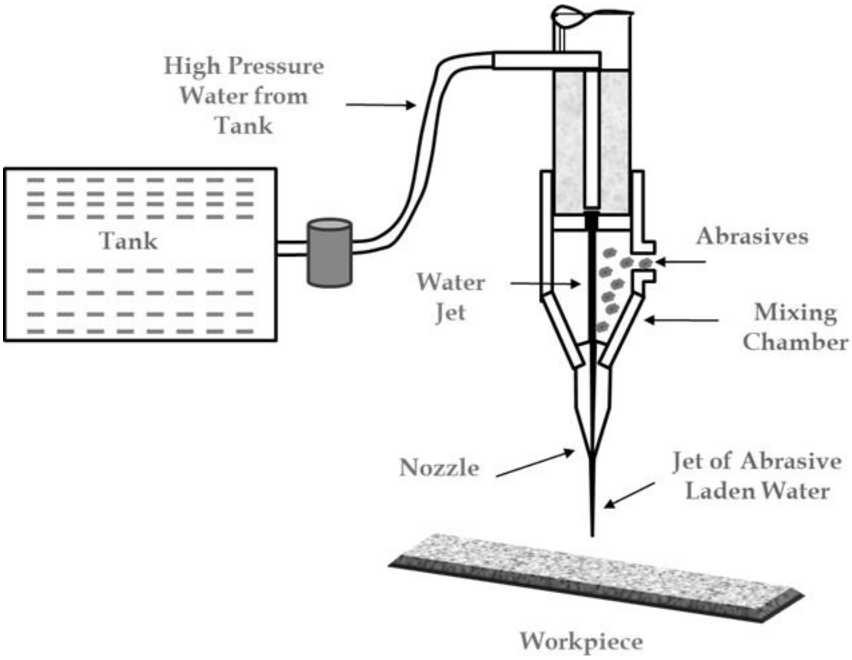

Figure 1: Working principle of abrasive water jet machining

Accumulation of abrasive particles on worksurface, stacking faults, stray cutting, ineffective and shallow erosion, nozzle clogging, delamination of composites, surface and subsurface cracks, and other surface irregularities, are some of the most important and major challenges in AWJM of nonmetals [1, 4]. Table 1 enlists some important information related to AWJM of nonmetals.

TABLE 1. SOME IMPORTANT DETAILS RELATED TO AWJM OF NONMETALS

Materials	Challenges	AWJM Technique Applied	Application areas
Glasses and other Ceramics Soda lime, Quartz, Optical, Borosilicate Glasses; Silicon Carbide	-Abrasive contamination -Crack and failure -Shallow cutting -Surface quality deterioration (poor finish and high kerf width & angle)	-Sequential smoothening -No water machining -fluidized bed chamber for mixing of abrasives	-Lenses and scientific & laboratory instrument -Containers -Jewellery
Polymer Composites Carbon fibre reinforced, glass fibre reinforced, neem wood, thermoplastics, biocomposites	-Stray cutting -Delamination and other subsurface damage -Burrs and microstructural damage	-Using nanoabrasives -Combined machining and finishing -Modifying nozzle design -Cutting in suspension jet and oscillation fluid	-Knee joints -Wind turbine -Hydrogen tanks -Automotive door panels -Packaging -Electronic and electrical devices
Granites and Marbles	-Extremely difficult to cut due to high hardness, insufficient penetration, stray cutting, and low productivity	-Cutting at high speed -Cutting in two passes -hybridization with disc cutting -Using steel shots as abrasives	-Construction and infrastructure development

In the last six years, the field of AWJM has witnessed some important innovations and developments related to the development of machine tools, hybridization, use of novel abrasives, process optimization, etc. to overcome the limitations of AWJM of nonmetals. Some of the important developments are highlighted in Fig. 2 and covered in the below section.

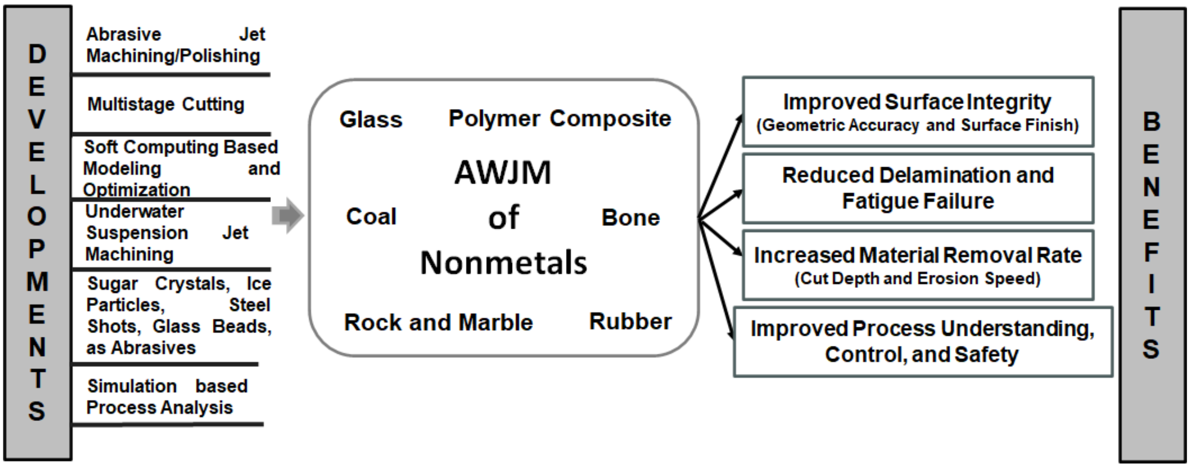

Figure 2: Illustration of some developments and their benefits in AWJM of nonmetals

Analysis of Important Developments

Figure 3 is a fishbone diagram that maps the developments related to abrasives, machine tools, process parameters, and other areas, made to address various challenges encountered during AWJM of nonmetals. Following that, Table 2 presents a summary of all the related important recent developments in AWJM of nonmetals namely glass, rubber, composites, and ceramics.

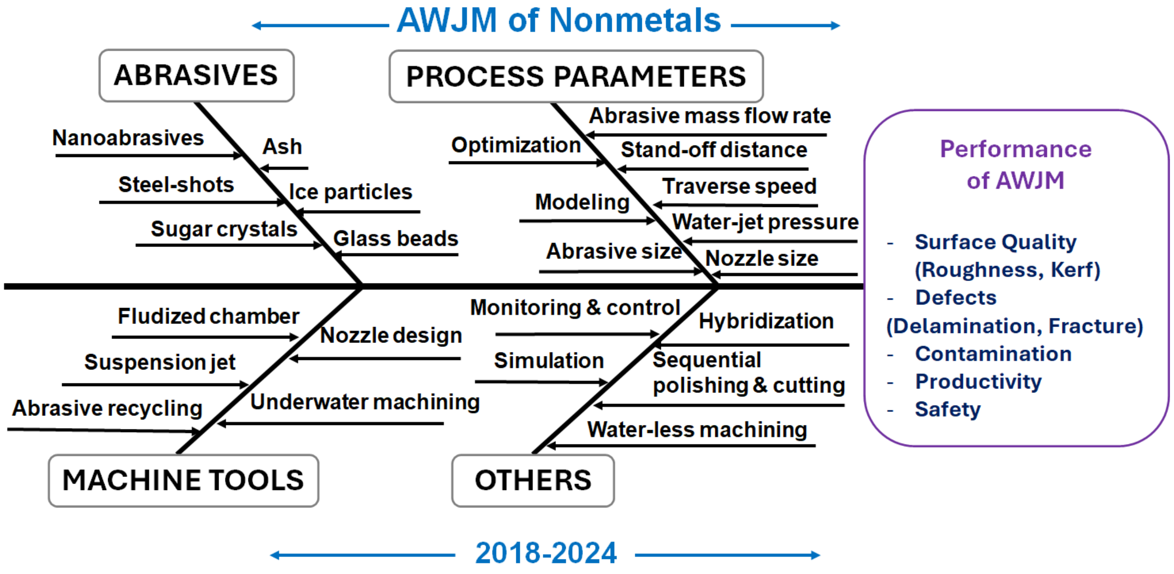

Figure 3: Fish-bone diagram on category wise developments made in last six years

Cutting granite-based rocks is an arduous task and can be very well accomplished using AWJM [7]. A recent investigation highlights the importance of cutting rocks on two passes at high speed for a better penetration and reduction in cutting time [7]. Cutting of marbles has also been accomplished by researchers using AWJM [8]. An interesting study has made use of steel shots as abrasive to cut granite by AWJM [9]. Recycled steel shots also performed well and cuts made by them were much deeper than garnets. On of the latest developments highlights the synchronization of AWJM and disc cutting for early breaking of rocks [10]. Cutting of coal has also been attempted by AWJM [11]. A comprehensive study compared ice as abrasives, water jet an abrasive laden water jet and found that ice particles are the better alternate and safer and energy efficient. For glass material, not only machining, but also smoothing and polishing type operations have been conducted using AWJM [12, 13]. In the past few years, different strategies have been incorporated. One of the important research projects indicates the highly improved surface texture, with 1.9-micron surface roughness of area, of soda-lime glass by smoothening it immediately after AWJM [13]. A study reveals the development of fluidized bed mixing chamber and normal pressurized bed mixing chamber based abrasive jet machining process to enhance the machinability of a borosilicate glass [14]. Fluidized bed mixing chamber AWJ outperformed with high productivity and better geometrical accuracy of machined glass. The nitrile rubber is a lightweight material and unlike metals and other nonmetals its machining is challenging [16]. An investigation reported on its cutting highlights the capability of AWJM with a suspension mixture of garnet abrasives, water, and polymer additive to make slots and other geometries in rubber. A unique study made use of bone powder and sugar particles (separately) for AWJM of bones [17]. Sugar particles were identified as superior compared to bone powder to obtain better surface characteristics on bone. Developments in AWJM could possibly extend its application in agriculture and food industry as well [18-20]. Although the capability of waterjet for cutting crop residue was identified before [18], but important research conducted on cutting wheat straws highlights the fact that cutting capability of water jet is higher when abrasives are mixed in there [19].

AWJM of polymer composites and ceramics, has also faced recent technological interventions and many sincere attempts have been made [21-30]. In a novel investigation on abrasive water jet cutting of biocomposite, the application of nanoabrasives has successfully reduced surface roughness [21]. A novel multistage machining of zirconia was attempted in two passes i.e. machining and finishing [23]. In this work, fused alumina during machining and soda during finishing were used as abrasive materials. The finishing pass was able to remove contamination and improve surface quality. While making holes on glass fibre polymer composite, effect of nozzle design was researched [25]. Novel internally threaded nozzle was designed which due to whirling effect of abrasive particles produced better finish i.e. 0.531 µm than a plain nozzle. Cutting of orthopedic implants from carbon fiber-reinforced polymer composite underwater abrasive water suspension jet found performing better than plain abrasive water jet cutting [26]. An injection molded composite made of a mixture of neem wood saw powder and polypropylene has also been cut by AWJM [27]. A cutting-edge research investigation reported that to enhance the polishing of carbides such as silicon carbides, self-excited oscillating fluids can be provisioned in abrasive water jet machining [28]. Such polishing technique can effectively improve the polishing depth and smoothening ability. 3D printed PLA and ABS materials have also been successfully machined by AWJM [29]. One of the latest investigations encourages integrating acoustic emission-based monitoring method to monitor abrasive flow and wear etc. at the cutting head and workpiece in abrasive water jet machining of carbon fibre reinforced composites [30]. The study of the effect of parameters on acoustic emission signals can further lead to monitor malfunctions in AWJM.

TABLE 2. SUMMARY OF IMPORTANT DEVELOPMENTS IN AWJM FOR MACHINING OF NONMETALS

Material Type	**AWJM Development detail**	**Findings**	**Reference**
Granite Rocks	High speed two pass cutting	Ease of cutting with speed and accuracy	[7]
White Marble	Taguchi DoE with Delta	Successful cutting of Marbel and identification of nozzle traverse speed and water jet pressure as the most influential parameters	[8]
Granite Rocks	Use of steel shots as abrasives	Upto 50% deeper cutting than garnet abrasives has been achieved.	[9]
Granite Rocks	Combination of abrasive water jet and disc cutting	Improved cutting efficiency	[10]
Coal	Cutting by ice jet, water jet, abrasive water jet machining	Ice particles as abrasives found better than water and abrasive laden water.	[11]
Optical Glass	AAJP	Development of analytical model for a better understanding of polishing and parameter modeling and optimization	[12]
Soda-Lime Glass	AWJM with Sequential smoothening	Significant reduction in surface roughness	[13]
Borosilicate Glass	Water less Abrasive jet machining	Improved depth of cut and material removal rate	[14]
Quartz Glass	AJM	Successful polishing with upto 300 nm surface finish	[15]
Nitrile Rubber	Suspension type AWJM	Successful cutting of through slot with improved dimensional accuracy	[16]
Bone	Sugar particles and bone powder as abrasives	Best cut quality obtained using sugar with 3.87 microns average surface roughness.	[17]
Wheat straws	AWJM for Agriculture	Abrasive laden water jet is more capable	[18]

		than plain water jet	
Biocomposite	Nanoabrasives and GA-based optimization	Improvement in surface finish	[21]
Reaction bonded Silicon carbide	Study of effect of different abrasives	Diamond found the most suitable from productivity and surface quality point of view	[22]
Zirconia	Multistage machining (Roughing and Finishing)	Improved surface integrity	[23]
CFRPC	Application of different piercing methods	High quality cutting is possible at low pressure in the beginning and then at high pressure during entire machining.	[24]
GFRPC	Nozzle design modification	Nozzle with internal thread helped to achieve better surface finish	[25]
CFRPC	Underwater abrasive water suspension jet	Underwater cutting outperformed free-air cutting with achieving 0.89 mm- kerf width and 9.25 µm roughness.	[26]
Neem Wood plastic composite	AWJM	Low percentage of Neem wood powder enhances surface quality. Table traveling speed and water jet pressure are the influential parameters.	[27]
SiC	Abrasive water jet polishing with self-excited oscillation pulse fluid	Increased material removal depth	[28]
3D printed thermoplastics	Submerged abrasive water jet turning	Successful cutting	[29]
CFRPC	Acoustic emission monitoring	Operational efficiency and quality control enhancement	[30]
AJM- Abrasive jet machining AWJM- Abrasive water jet machining AAJP- Abrasive air jet polishing FRPC- Fibre reinforced polymer composite CFRPC- Carbon fiber-reinforced polymer composite GFRPC- Glass fibre reinforced polymer composite			

In the last six years, AWJM of various nonmetals has also been transformed with regards to modeling and optimization of its parameters [31-33]. There have been some significant attempts where researchers innovatively applied statistical as well as soft computing techniques in AWJM of nonmetal cutting [34-43]. Artificial neural network (ANN) integrated AWJM of granite successfully predicted responses in a close match with the experimental values [32]. During machining of glass fibre reinforced polymer composites, to optimize AWJM parameters, desirability-based response surface methodology technique was found effective to achieve least values of roughness- 2.91 µm, kerf taper- 0.4590, and delamination- 0.426 mm [33]. The statistical optimization technique i.e. grey relational analysis was used in a study to optimize AWJM process parameters to minimize roughness and delamination of polymer composites reinforced with jute [34]. A study reported on abrasive water drilling of onyx composite material, made successful use of genetic algorithm and Moth Flame Optimization algorithm for solving multiobjective problem and obtaining optimum process parameters for surface roughness and delamination factor [35]. To predict the drilling quality of AWJM, an artificial neural network was also implemented by a group of researchers [36]. In that work, cut quality of marble, with surface roughness and geometric accuracy, was accurately predicted by ANN and models were developed for ease of future reference. An integrated approach of ANN and multi-objective bonobo optimizer was used to predict AWJM parameters and further optimize them, with mass flow rate of abrasive- 430 g/min, traverse speed- 140–180 mm/min, pressure-280 MPa, standoff distance- 1.5 mm, for an optimum machining of composite laminates, with the best values of kerf taper angle and average roughness [37]. A grasshopper algorithm was successfully used in AWJM of polymer composite reinforced with bamboo and obtained highest MRR 58.442 g/s and lowest roughness 0.169 µm [38]. During optimization of AWJM of Marble cutting, researchers could successfully secure increased cut depth (87.3 mm) for improved productivity at feed- 2mm/s, abrasive concentration- 19.3%, nozzle inner diameter- 0.33 mm [39]. The ceramic tile manufacturing by abrasive water jet fabrication was also undergone optimization using crow search algorithm technique to secure the least roughness with 1.45 µm value [40]. A very recent study highlights the importance of machine learning (ML) for modeling and optimization of AWJM of banana fiber-reinforced composites [41]. ML based optimization helped to achieve the best values of machinability in terms of 2.170 kerf angle, 2.93 average roughness, 936 mm3/min material removal rate. A significant reduction in material failure was achieved in AWJM of Glass-carbon fiber reinforced polymer composite after adopting hybrid optimization [42]. A successful process optimization using Grey relational analysis and Response surface methodology of AWJM of AA6061/B4C/hBN Hybrid Composites was also achieved for the lowest kerf and roughness [43].

AWJM process modeling and analysis using simulation tools based on finite element analysis (FEA) and computational fluid dynamics (CFD), for nonmetals, have been conducted by researchers in the recent past [44-48]. This development is mainly associated with FEA prediction of stress and strain on glass surface after impingement of abrasive particles [44], CFD study of erosion dynamics in hot abrasive water jet machining of zirconia [45], FEA for residual stress analysis in fibre composites [46]. In an important study, the piercing of CFRPC by AWJM was simulated using FEA [47]. The outcomes of that work indicate that water jet pressure should be kept at lower levels for lower delamination as the stress and deformation are more with high pressure levels. Table 3 summarizes the above discussed important recent attempts on modeling, optimization, and simulation on AWJM of nonmetals.

TABLE 3. SUMMARY OF SOME RECENT ATTEMPTS ON MODELING, OPTIMIZATION, AND SIMULATION OF AWJM OF NONMETALS

Reference	**Material Type**	**Modeling, Optimization, Simulation Technique applied**	**Outcomes**
[32]	Granite	Back propagation ANN	ANN predicted results for MRR were very close to experimental results
[33]	GFRPC	RSM based Desirability	Optimum based best machinability indicators: Roughness- 2.91 µm, KT- 0.4590, and D- 0.426 mm
[34]	Jute polymer composites	GRA	Optimum AWJM parameters: TS- 25 mm/min, SOD- 2 mm AMFR- 0.25% kg/min For least roughness and delamination
[35]	Onyx composite	GA and MFO	Optimum AWJD parameters: DD- 12 mm, TS- 30 mm/min, and AMFR- 450 g/min Optimum machinability indicators: SR- 2.344 µm, PU- 0.696, PO- 0.685.
[36]	Marble	ANN	High accuracy model developed for SR, HCi, HCy, HLE, and HT
[37]	Composite laminates	ANN and multi-objective bonobo optimizer	-Development of highly accurate prediction models for KT and SR. - Optimum AWJM parameters: AMFR- 430 g/min, TS- 140–180 mm/min, WJP- 280 MPa, and SOD- 1.5 mm.
[38]	Bamboo reinforced polymer composite	Grasshopper algorithm	Optimum AWJM parameters: SOD- 1.5 mm, WJP- 150 MPa, NS- 150 mm/min Optimum responses: MRR- 58.442 g/s, SR- 0.169 µm
[39]	Marble	Response Surface Methodology	Optimum AWJM parameters: ND- 0.33 mm, AC- 19.3%, and TS- 2 mm/s. Response: DoC- 87.3 mm
[40]	Ceramic tile	Crow search algorithm	Optimum AWJM parameters: WJP- 3997.19 bar, TS- 152.05 mm/min, AMFR- 381.08 g/min, and SOD-1.62mm. Response: SR- 1.456 µm.
[41]	Banana fiber-reinforced composite	Machine learning	Development of robust prediction models. Optimum responses: SR- 2.93 µm, MRR- 936 mm^3/min.
[42]	Glass-carbon fiber reinforced polymer composite	Hybrid GRA-PCA	Optimum AWJM parameters: AMFR- 230 gm/min, WJP- 75 MPa, SOD- 2 mm, and TS- 600 mm/min. Upto 33.9% reduction in delamination damage and failure.
[43]	AA6061/B4C/hBN Hybrid Composites	GRA-RSM	Optimum AWJM parameters: AMFR- 340 g/min, WJP- 200 MPa, TS- 60.06 mm/min, RP- 5.01% and MS- 80.
[44]	Laminated Glass	FEA	Prediction of stress and strain

			generated due to the strike of single abrasive grain of silicon carbide
[45]	Zirconia	CFD	Understanding of abrasive selection and hole making in hot abrasive jet machining
[46]	Composite	FEA	Analysis of relation between AWJM parameters and residual stress generation in the materials being machined
[47]	CFRPC	FEA	Finding the stresses and deformation during material piercing by AWJM
[48]	FRPC	SPH-FEA	Understanding the hole piercing mechanism by abrasives action
TS- Traverse speed, AMFR- Abrasive mass flow rate, SOD- Stand-off-distance, GRA- Grey relational analysis, PCA- Principal component analysis, GA- Genetic algorithm, MFO- Moth Flame Optimization algorithm, MRR- Material removal rate, RSM- Response surface methodology, ANN- Artificial neural network, FEA- Finite element analysis, CFD- Computational fluid dynamics, SPH- Smoothed Particle Hydrodynamic, AWJM- Abrasive water jet machining, AWJD- Abrasive water jet drilling, SR- Surface roughness, PU- Delamination peel up, PO- Delamination pushout, KT- Kerf Taper, D- delamination, DD- drilling diameter, HCi- Hole circularity, HCy- Hole cylindricity, HLE- Hole location error, WJP- Water jet pressure, NS- Nozzle speed, ND- Nozzle diameter, AC- Abrasive concentration, DoC- Depth of cut, RP- Reinforcement percentage, MS- Mesh size.			

Sustainability interventions as developments in AWJM technology are also being considered to obtain cost benefits, societal safety, and environment protection [49-51]. Selection of abrasives from waste like walnut shell and ash, and replacement with ice particles, sugar crystals, and glass beads; recycling of abrasives; life cycle engineering and analysis of AWJM process; environmental impacts quantification etc. are some of the strategies being adopted these days [52, 53]. Even for the cleaning and removal of unwanted materials from structures and products, AWJM has been found an efficient technique [54, 55]. Although most of the attempts in this direction have been made towards AWJM of metals, yet with the technological maturity, it is hoped that they will possibly be extended to the machining of nonmetals as well.

Conclusions

This paper has presented a review of some important developments that took place in the last six years in AWJM of nonmetals. Many technological interventions have been attempted to facilitate the machining of various nonmetals. The following points highlight some important conclusions of this review: Cutting of rocks and marbles can be accomplished using AWJM with strategies like cutting with steel shots as abrasives, process optimization, machining in multiple passes, etc., Machining of hard materials like coal and soft like rubber, is also possible using AWJM, AWJM of glass type brittle material requires interventions such as water-less cutting, sequential smoothening, optimization of process parameters etc., Carbon fibre reinforced and other composites and ceramics can efficiently be machined by adopting nozzle design modifications, using suspension jets, making use of nano abrasives in AWJM, for predicting AWJM parameters, ANN was found appropriate. For solving multiobjective optimization problems in AWJM of nonmetals, Grey relational analysis and desirability type statistical techniques and soft computing techniques such as Genetic algorithm, Moth Flame Optimization algorithm, and Crow Search algorithm, have been found very effective, Machine learning based interventions for modeling and optimization in AWJM still seeks more future work to establish the field, Finite element analysis and computational fluid dynamics type process simulation techniques have also complimented with a better understanding of the mechanism of AWJM of nonmetals, and sustainability attempts such as life cycle analysis and carbon footprint calculation of the AWJM of nonmetals, recycling of abrasives, and resource efficiency, etc. need sincere future investigations.

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