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Review Article

State-of-the-Art in Abrasive Water Jet Cutting Technology and the Promise for Micro- and Nano-Machining

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Abstract: A long time ago, nature proved that even the hardest engineering materials change their shape and form when water is applied to them. The new shape formed by this phenomenon can be both valuable and/or attractive. In modern industry, water cutting technology is divided into two groups. Water jet cutting technology, which is cutting with pure water and abrasive water jet cutting technology, which uses water embedded with fine abrasive particles. Clean water jet cutting technology is suitable for "soft engineering materials" for instance paper, wood, textiles, food and plastic. It is extensively used technology in industries to cut almost everything from frozen chickens to one-use diapers. On the other hand, when "hard engineering materials" need to be cut, the addition of fine abrasive particles such as garnet allows one to cut almost any engineering material whether it be marble (as used in Al-Masjid Al-Haram, The Holy Mosque, in Makkah, KSA) or tool steel, and in thickness up to 200 mm. In this review paper, the primary objective is to highlight the state-of-the-art of the abrasive water jet cutting technology and the promise for micro- and nano-machining in modern industry.

Keywords: Abrasive Water Jet Cutting, AWJC, Micro- and Nano-Machining

1. Introduction

The principle of liquid jet technology is that the technique involved in cutting the engineering materials by the use of very high-pressure in a liquid (mostly water, H_2O) with added abrasive slurry (such as garnet, natural resources, 80 mesh garnet is the optimum type and size in most cases) is used to cut almost every material including diamonds by means of controlled erosion [1, 2]. In 1968, the technique of using thin, high-pressure water for cutting materials was the first time patented as a pioneering breakthrough in the area of non-traditional processing technology by Norman Franz in the USA [3], but fast growth of the water jet cut method was starting in the early 80's as the ultra high pressure pumps become commercially available in the industry [4, 5]. Nowadays, it is a fast emerging technology, which is used in modern industry for processing a diversity of engineering materials and which has several benefits over other non-conventional cutting techniques [6]. Normally, to improve the process performance, abrasive particle grains of garnet are used, which allow the cutting of very hard engineering materials. So, the correct industrial name of this knowledge is called, water and stone, "Abrasive Water Jet Cutting (AWJC)" [7]. Figure 1 shows the schematic of the abrasive water jet cutting system with a view of a high-pressure water jet of 230 MPa. Indeed, no doubt, this idea came from watching rivers cut channels.

In general, industrial AWJC technology scheme includes four major elements: (1) an intensifier pump, which provides high-pressure water around 400 MPa; (2) an abrasive delivery system and a cutting head producing the abrasive water jet cutting; (3) a computer controlled display system, which provides the chosen cutting head motion; (4) and the simple storage tank system in which the remaining energy after cutting off the spent jet gets eventually dissipated.

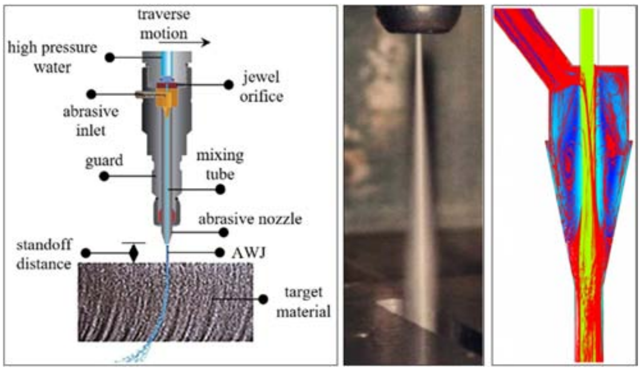

Figure 1. *Abrasive water jet cutting system and the vortex created inside the mixing chamber by water (yellow), air (rainbow) and abrasives (red).*

In AWJC technology, a stream of a few abrasive particles (around ~50 μm grit size and have sharp irregular edges) is introduced in the water jet cutting machine in this way that the momentum of the water jet machine is transferred to the abrasive particles. The water primary role is to accelerate huge amounts of abrasive particles to a thin and high velocity (up to 900 ms^{-1} [8]) and to produce a high coherent jet (converting pressure energy of carrier air or gas to kinetic energy [9] and hence to high velocity jet). Then, the jet (a tiny orifice, from 0.1 mm to 0.5 mm in diameter) is directed towards the working area (typically, 90°) to perform cutting procedure by micro-cutting action [10]. The water pressure is accelerated in the orifice as stated by the Bernoulli differential equation (Bernoulli's equation is the law of conservation of energy applied to an ideal fluid) to a high-velocity, v_j, as stated in Equation (1):

$$v_j = \mu\sqrt{\frac{2P}{\rho_w}} \quad (1)$$

where, P is the water pressure, ρ_w is the density of water (1 g/cm^3) and μ is the discharge coefficient (μ < 1.0, with a typical value of 0.86), which is a measure of the disagreement with the theoretical jet velocity [7]. Usually, nozzles are made from high wear resistant materials such as sapphire (lifetime: 300 hours) or tungsten carbide with either rectangular or circular geometry and can be straight to the target by 180°, or at a right angle by 90°. It is so designed that water pressure loss is the minimum possible because of friction, bends, etc. With the increase in wear behaviour of a abrasive nozzle during the process, the divergence of the jet stream rises resulting in a high degree of inaccuracy and stray cutting [11]. The tolerance level is tight as up to 0.1 mm of material, eliminating the need for other process sequences [12].

Typically, this requires a high-power motor connected to the intensifier pump with high intensification ratio. Most equipment for AWJC technology reaches high-pressures generation value using a multiplier system. The main principle of high-pressure generation lies in the combination of two closely linked pistons together [13-15]. Figure 2 shows the abrasive particle types that are available in modern industry.

Figure 2. *Abrasive particles types.*

1.1. Parameters and Process

Currently, the need in the manufacturing sector for rapid prototyping and small production batches is increasing [16]. The manufacture of precision parts underlines the fact that the final quality appearance of the machining operations may account for approximately 15% of the total manufacturing costs estimation, thanks to the global economy. The AWJC technology process optimization has been accelerated because of the need for improvements in surface quality level [17]. The surface quality control is a very important part of the surface preparation in all types of technologies that are used for their creation. Besides, the process features change markedly with machining factors entering the AWJC technique. The quality level of AWJC technique is affected significantly by a great many process parameters [18, 19]. There are many connected parameters in this method yet they are precisely controllable. The process parameter which affects less or more on the quality of cutting in AWJC technology is shown in Figure 3.

There are numerous associated parameters in this technique. Generally, all the involved parameters can be classified into two categories: the input parameters and output parameters. Table 1 shows the input parameters and their examples classified into input parameter categories [20, 21]. The primary process quality measures include: (1) surface finish (2) depth of cut (3) kerf width geometry (4) material remove rate and (5) nozzle wear. More work is required to fully understand the influence of the important process parameters on surface roughness. Indeed, some techniques have been proposed for improving the surface finish and kerf quality [22, 23]. The mechanism and rate of material removal during AWJC depends on the range of process parameters and the type of abrasive particles. Using a thorough understanding of the AWJC mechanism, methods such as polishing [24], turning [25], drilling [26], milling [27] and surface finishing [28] have become possible to design and manufacture at even low costs.

Repeatability and reproducibility of direct examination of AWJC technology proposed that there are two methods of material removal: (1) erosion by cutting wear as a result of abrasive particle impact at a shallow angle on the top surface of the kerf width and (2) deformation wear because of uncontrolled plastic deformation of the material caused by the abrasive particle impact at the large angle deeper into the kerf width [10, 29].

As mentioned above, abrasive water jet cutting technology has almost no boundaries. The process parameter is mostly used for 2D and 3D cutting. There is no difference between cheap construction steel or stainless materials, both are cut equally well. So, if a quality cutting process is required, the parameters must be adjusted and the cutting process must be completed before entering the deformation abrasion section.

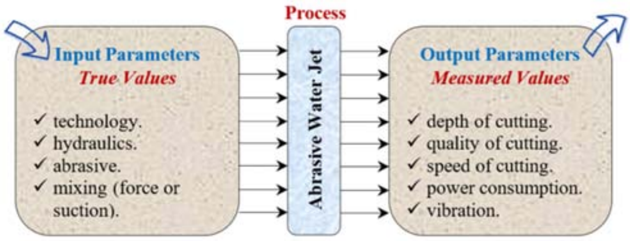

Figure 3. *AWJC process parameter.*

Table 1. *Input parameters and their examples.*

input parameters categories			
technology	***hydraulics***	***abrasive***	***mixing***
standoff distance, z, (mm)	water pressure, P, (MPa)	abrasive material type	focusing tube length, l_f, (mm)
traverse rate, v, (m.s^{-1})	orifice diameter, d_o, (mm)	abrasive material size	focusing tube diameter, d_f, (mm)
traverse direction, s (°)	orifice material	abrasive material shape	focusing tube material
impact angle, φ, (°)	-	particle diameter, d_p, (mm)	abrasive feeding direction, f_d, (°)
depth of cut, (mm)	-	abrasive feed rate, m_a, (kg.mm^{-1})	-
target material	-	-	-

1.2. Pros and Cons

AWJC technology has various distinct advantages over other non-traditional cutting techniques that are available in the market, such as the fact that there is no thermal distortion due to water (H_2O) acting as a coolant. It offers a wide-ranging flexibility for machining different types/shapes of components with high precision and accuracy level, minimum stresses acting on the workpiece, small force cutting and high flexibility and indeed AWJC technology has been verified to be an active technique for processing many engineering materials [30] and has found broad applications in modern industry [31]. Also, it is a cost-effective technique [32] and eco-friendly method that can be implemented for processing a number of engineering materials specifically “difficult-to-cut” engineering materials for instance ceramics (i.e., oxides: Al_2O_3 [33], MgO, ZrO_2, etc. and non-oxides: TiN, CrN, Si_3N_4, TiC, SiC, ZrC, etc.). [34]. Typically, it can be simply integrated with current CAD/CAM systems [35], thus, significantly optimizing the process of the cutting shape [36]. AWJC technology cuts in any direction, around tight corners, produces the final part with little or even no minor finishing, there is no airborne dust while cutting composites and aerospace composite can be drilled and cut without delamination. In general, the scheme produces no dust, thereby, significantly improving working conditions and benefiting the environment (in being non-toxic). However, AWJC technology has some limitations and drawbacks. It may create tapered edges on the kerf width, accurately when cutting at high traverse rates [37, 38]. It may also generate loud high-frequency noise (ranging from 85 to 95 dB in the sound level system so hearing protection kit is an essential as well as its personal room) and a messy working environment area. There can be higher abrasive wear. Also, one of the disadvantages that has prevented it from wide use in the machining industry is the long switching times by which it cannot rapidly stop and start again [39].

1.3. Applications

The potential applications of AWJC technology are numerous, but of course some uses are a better fit than others. The AWJC method cuts effectively almost all engineering materials and thicknesses such as aluminium [40], titanium alloys [41], glass [42], brass, pre-hardened steel, tool steel

[43], stainless steel, mild steel [44], copper, plastic, quartz, ceramic [45], laminates, composites [46], flammable materials, leather, stone [47], granite, marble [48], foam, Inconel, fish, meat, etc. [49]. Undoubtedly, however, AWJC plays its most important role in the following sectors [50]:

- Aerospace Industry:
  - engine components.
  - interior cabin parts.
- Automotive Industry:
  - interior trim (trunk, door panels, liners, headliners).
  - fiberglass body components and bumpers.
  - electronics industries.
  - circuit boards.
  - cable stripping.
- Oil and Gas Industry:
  - casing cutting for decommissioning of oil wells.
  - rescue operations.
  - platform cutting and repair.
  - underwater construction.
  - pipe cutting.
- Construction Industry:
  - sandblast and cut corroded rebar.
  - drill holes for bolting posts.
  - road and bridge repair.
  - underground work and pile cutting.
- Food Industry:
  - nutrition preparation.
  - cutting certain foods (bread and trimming fat from meats).

In addition to the applications mentioned, AWJC technology is used in manufacturing the micro-electro-mechanical systems (MEMS). Micro-module fabrication for electrical contact and semiconductor processing can also be carried out effectively. Deflashing small castings and engraving registration numbers on toughened glass used for car windows are common uses. Also, it is an excellent technique for small milled slots in hard metallic components and for deburring small holes similar to those in hypodermic needles. Besides, it is used for frosting and abrading glass economically as compared to any grinding or etching technique [51]. Based on the application, the cut-off thickness of materials can be typical of stainless steel as 100 mm, aluminium as 120 mm, glass as 100 mm and stone as 140 mm [52]. Figure 4 shows some samples of AWJC parts.

Figure 4. *Some samples of AWJC parts.*

1.4. Surface Roughness, R_a

The surface quality level is indeed one of the most specified client requirements for the final machine parts. The primary indication of the surface's quality level on the machined parts is the surface roughness, R_a, profile (peak-to-valley roughness) [33, 53-56]. The average surface roughness, R_a, value is defined in Equation (2) as

$$R_a = \frac{1}{L}\int_0^L |z|\,dx \tag{2}$$

where, L is the profile length being evaluated and $z = f(x)$ is the profile measured from the reference mean line. Based on the quality level and applications, cost will play the major part in the customer's satisfaction. Figure 5 shows the surface roughness appearance after AWJC procedure is accomplished. As can be seen, the surface appearance ranges from excellent down to poor, depending on the application's requirements. Also, cutting speed and edge quality are directly related. At high feed rates the jet has increased curvature as it passes through the cut. Reduced cutting speeds can result in a good edge finish of sub-micrometer level, having a ground appearance and minimal taper. High feed rates for separation cuts give striations through the full cut depth. Moreover, edge quality is defined with a scoring system from 5 down to 1. Naturally, the surface finishing profile cut by AWJC technology is striated (scratches on the surface). The striations zone is usually curved opposite to the cutting direction (traverse speed). Mostly, the thickness and curvature depend on the engineering material to be cut and the zone's (smooth or striation), cross-section area, cutting velocity and intensity. Material removal processes, which include solid particle erosion, e.g., AWJC machining, are very complex and theoretically very difficult to describe. Theoretically, it is impossible to eliminate the striation marks on the cutting surface. However, by selecting proper parameters, the surface quality could be controlled properly. [57]. Figure 6 illustrates the surface zone (smooth zone and striation zone) with the surface roughness profile during the cutting ranging from the top edge (kerf width) towards the bottom edge (kerf width). It can be clearly seen that the surface roughness, R_a, is affected during the cutting process and it is crucial to study all the parameters concerning the effect of each one on the R_a value.

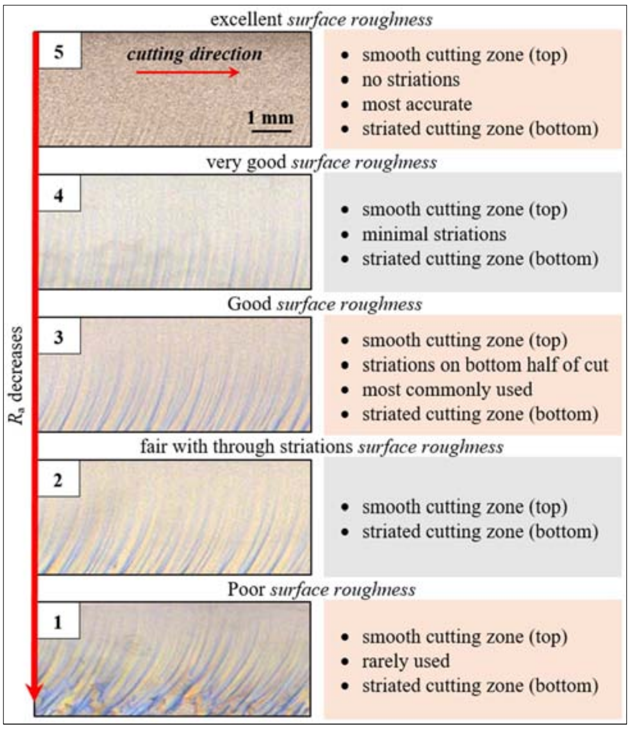

Figure 5. *AWJ cutting appearance.*

In the top edge (upper corner) of the cut surface, there is a small curve caused by the impact of the abrasive particles departing from the nozzle jet of the AWJC technology machine. Usually, this zone is the smoother surface and accepted as an ignorable edge impact caused by the abrasive particles hitting the surface at a low impact angle. Recently, R_a = 1.3 µm has proven the surface roughness quality can be obtained. The AWJ cutting capability is reduced as the kinetic energy (KE) of the abrasives decreases and the jet loses its regularity. This is a transition zone, where the second cutting mechanism prevails and the surface is formed by faults due to parallel jet deviations. In this zone mechanism, the impulse angle of the hitting particles against the surface is bigger and is defined as the deformation erosion. It is realized by the abrasive particles hitting the surface at a bigger angle [58].

Simply, depending on whether a contour is to be cut out of the material, or the workpiece should be with high-quality finishing, the operational cost can go up by as much as five times.

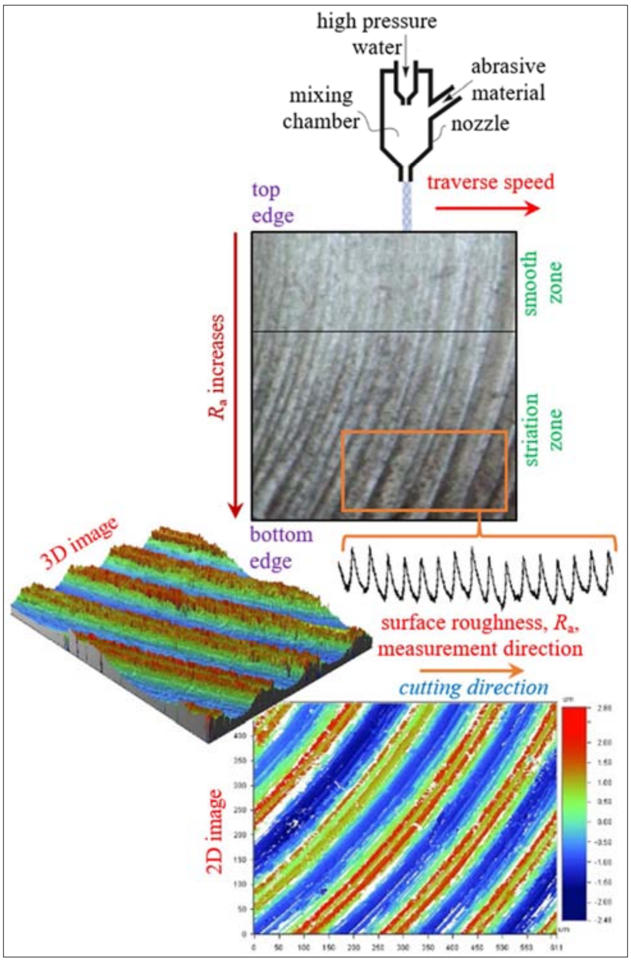

Figure 6. *Surface zone.*

2. The State-of-the-Art

As mentioned earlier, around the 1980s [5], AWJC technology was originally commercialized as a novel efficient technique for processing numerous engineering materials. After the introduction of this AWJC technology, much research and development has been conducted with the aim of exploring its applications in many fields. To advance AWJC technology, it is crucial to know what has been done from time to time on the different parameters optimization in AWJC and the solution techniques, (i.e., [59-73]). The following review papers represent a summary of such studies highlighting the decision variables and up-to-date concluding remarks.

2.1. Effect of Process Parameters on R_a

Alsoufi, M. S., *et al.* [44] recently studied the effect of two advanced modern technologies namely abrasive water jet (AWJ) and laser beam cutting (LBC) on the surface roughness, R_a, and micro-hardness, µ-HV of carbon steel material.

Experimental results indicate that better quality surface of the final cutting process was reached using abrasive water jet cutting technology for comparable working environments concerning surface roughness, R_a, and micro-hardness, μ-HV.

Li, R., *et al.* [74] studied the effects of pressure, feed rate and abrasive mass flow rate on the surface roughness, R_a, using advanced abrasive water jet cutting recombinant bamboo material. Different thicknesses were cut in the transversal and longitudinal directions. The results revealed that the average value of R_a increased with any rise in the feed rate and abrasive mass flow rate values however that it decreases with any increase in water pressure. The R_a average value was less when cutting recombinant bamboo in a longitudinal than in a transverse direction.

Monková, K., *et al.* [75] worked on the factors in AWJ cutting which affect the surface roughness, R_a, of the titanium, $_{22}$Ti, material. Transverse speed, abrasive mass flow rate, the angle of attack and depth of cut parameters were used for evaluation of the R_a. The design of experiments (DoE) as a full factorial design was used on different thicknesses of the engineering material. The results concluded that the variable independent factors affect the R_a morphology regarding micro cutting quality. They also showed that a higher value of R_a is caused by increasing the transverse speed.

Mutavgjic, V., *et al.* [76] carried out an experimental study of surface roughness, R_a, of stainless steel and aluminium samples obtained by AWJ cutting. Abrasive flow rate, standoff distance, water pressure and transverse rate were considered. The outcomes indicated that as the abrasive flow rate and water pressure increased, the mean value of the R_a improved dramatically. Also, it was observed that the R_a value is directly proportional to transverse speed.

Selvan, M. C. P., *et al.* [77] assessed the influence of process parameters on the surface roughness, R_a, in AWJ of cast iron material using Taguchi's method. The parameters on surface roughness such as water pressure, transverse speed, material feed rate and standoff distance were evaluated. The water pressure and mass flow rate showed an inversely proportional relation with R_a. Also, the results revealed that as nozzle transverse speed increases, the R_a value increased. Also, it shows that as the standoff distance decreases (very close to target), the surface smoothness increases.

Shanmughasundaram, P. [78] presented the influence of AWJC parameters for example traverse speed, water pressure, and standoff distance at three different random locations on the surface roughness, R_a, of the Al-graphite composites materials. Squeeze casting was used as a fabrication method and L9 Taguchi technique was used as experimental analysis. It was observed that the impact of water pressure on R_a was found to be more important than standoff distance and traverse speed. Alas, it was confirmed that mathematical modeling could be employed to predict the R_a of composites materials.

Doreswamy, D., *et al.* [79] carried out tests to find the effect of the feed rate and standoff distance on the (top/bottom) kerf width and surface roughness, R_a, for machining of D2 heat treated steel using AWJC technology. The results revealed that in single pass machining, for the same increase in standoff distance, the top edge of the kerf width increases by ~18%, while the bottom edge of the kerf width decreases by ~25%. Equally important, the increase in feed rate and standoff distance parameters increases the R_a value.

Begic-Hajdarevic, D., *et al.* [80] carried out a number of experiments on the effect of various process parameters on surface roughness, R_a, of the aluminium plate using AWJC technology. The experimental results demonstrate that traverse speed has a major influence on the R_a at the bottom edge of kerf width. Also, to reduce the overall manufacturing costs, the abrasive mass flow rate might be reduced to the manufacturer's suggested value, since the R_a values to some extent change by increasing the abrasive mass flow rate.

Patel, V. B. and V. A. Patel [81] studied the effect of AWJ process parameters on both material removal rate (MRR) and surface roughness, R_a, of EN8 medium carbon steel material. Taguchi's method and analysis of variance were used to improve the process parameters for cost-effective and time machining. The L25 orthogonal array was carried out using abrasive flow rate, traverse speed and standoff distance. The results show that traverse speed was the most significant factor for MRR. Standoff distance and abrasive flow rate are equally significant control factors for MRR. Besides, the standoff distance is the utmost major control factor on R_a value. The mixing ratio of water pressure and abrasive material is a most significant control factor for both.

Alberdi, A., *et al.* [82] conducted a number of experiments on composite material cutting with AWJ cutting technology. The machinability index for many composite materials with different thicknesses was found experimentally. A study of the influence of the abrasive water jet cutting technology parameters on the quality of cut samples (taper and surface roughness, R_a) was carried out. The kerf taper angle in a function of absolute transverse feed rates is more than a function respective of separation.

Folkes, J. [83] presented a literature review on different engineering materials also their geometric to form a component using AWJC technology. It concludes that the AWJ cutting technology is the most suitable tool in the manufacturing process such as cutting, drilling, milling, forming and removing engineering materials. Also, the study suggested that using AWJC technology can machine almost any engineering materials having benefits such as the fact that minimal force is required, there is no heat affected zone working area and that it is indeed an eco-friendly procedure.

Aultrin, K. S. J. and M. D. Anand [84] investigated work on optimization of machining parameters in AWJC technology for copper iron alloy material using surface methodology (RSM) and regression analysis. Abrasive flow rate, water pressure, focusing nozzle diameter, orifice diameter and standoff distance were considered as the process parameters during the investigation.

2.2. Process Parameters Optimization Using Taguchi's Approach

Deng, J. L. [85] presented the Gray Relational Analysis (GRA) technique for calculating the degree of relationship between sequences of experiments having multi-output parameters. In Taguchi's technique, the orthogonal array offers a set of well-balanced experimentations, and a signal-to-noise ratio (SN Ratio), which is a logarithmic function of the output and serves as an objective function for optimization. It aids the study of the entire parameters with some minimum experimental runs. It replaces the full factorial experiments with a clean, less expensive, faster partial factorial experiment. For more details regarding Taguchi's approach (design, concept, process and levels parameters and method), see [86-90].

Nagdeve, L., *et al.* [91] performed an experiment on AWJ to find out the optimum process parameter for supreme material removal rate (MRR) and quality surface finish after cutting an aluminum sample. Taguchi's method and analysis of variance (ANOVA) were used to optimize and predict the optimal choice for each process parameter such as standoff distance, traverse rate, abrasive flow rate and water pressure. The analysis reveals that the standoff distance significantly affects the metal removal rate (MRR) while, abrasive flow rate affects the surface roughness. Tests are carried out using L9 orthogonal array by varying pressure, standoff distance, abrasive flow rate and traverse rate.

Ramprasad, *et al.* [92] carried out work to optimize the metal removal rate (MRR) of stainless steel 403 in AWJC technology using Taguchi's method and ANOVA analysis. The MRR is optimized using three parameters namely water pressure, abrasive flow rate and standoff distance. It concluded that the water pressure was the most influential factor for stainless steel 403 work material followed by standoff distance and abrasive flow rate.

Gupta, V., *et al.* [93] investigated minimization of kerf width and kerf taper angle using Taguchi's method in AWJ of marble material. Parameters like water pressure, nozzle transverse speed and abrasive flow rate were considered. It was determined that the nozzle transverse speed was the most vital aspect affecting the kerf taper angle and the top kerf width.

Reddy, D. S., *et al.* [94] studied the optimization of the process parameters on AWJ using Taguchi's method, variance analysis (ANOVA) and signal-to-noise ratio (SN Ratio) for Inconel 800H material to optimize process parameters for surface roughness, R_a, and material removal rate (MRR). The results confirmed that the determined optimal combination of AWJ cutting technology parameters satisfies the real need for machining the Inconel 800H material.

Rao, M. S., *et al.* [95] examined the impact of process parameters such as traverse speed, water pressure and a standoff distance of AWJC technology for mild steel material on surface roughness, R_a. Taguchi's method, variance analysis (ANOVA), signal-to-noise ratio (SN Ratio) and F-test were used to optimize the selected parameters of AWJ process. Taguchi's design of experimentation (DoE) and the L9 orthogonal array is formulated and it was concluded that the water pressure and transverse speed were the most significant parameters and that standoff distance is a less important parameter.

Chauhan, D. K. and K. K. Chauhan [96] carried out a number of experiments on titanium alloy material to find out at what parameter levels the physical vapor disposition coated cemented carbide tool could get maximum lifetime on a milling machine. Taguchi's method and signal-to-noise ratio (SN Ratio) were used. Results showed that parameters such as cutting speed, feed rate, depth of cut and coolant flow rate could be considered as the tool lifetime maximum level.

Raval, M. A. and C. P. Patel [97] performed experimentation on AWJC technology parameter optimization on steel material using the design of experiment (DoE) Taguchi's orthogonal array L9. Gray relation analysis (GRA) technique was also used to reach a conclusion about at what machine parameters the process is optimum and efficient. The controllable variables were abrasive grain size, pressure, tip distance and pole distance. The results revealed that the magnetic abrasive in water jet machining is a feasible alternative to aluminium oxide and other abrasives.

Preeti, *et al.* [98] conducted a series of the experimental research of process parameters effect on material removal rate (MRR) of the machined component Makrana white marble material. Analysis of variance (ANOVA) and F-test were used to analyze process parameters such as water pressure, abrasive flow rate and standoff distance. Results revealed that the water pressure and abrasive flow rate plays a significant role in impelling material removable rate (MRR).

2.3. Mathematical Modeling Approach

According to [99], genetic algorithm (GA) is one of the greatest techniques ever employed. GA technique has been used by several investigators in order to find out the optimal surface roughness modern machining. An overview of GA method to optimize the R_a and previous work can be found below [100].

Jain N. K., *et al.* [101] worked on genetic algorithm (GA) for optimizing four parameters of the advanced manufacturing process using water jet machine (WJM), abrasive water jet machine (AWJM), abrasive jet machine (AJW) and ultrasonic machine (USM). It was concluded that the maximum value of material removal rate (MRR) in AWJM increases as water pressure at nozzle exit increases with increase in power consumption. MRR increases as an increase in the feed rate of the nozzle and abrasive water jet nozzle diameter. Also, it increases in mass flow rate of water pressure simultaneously MRR and power consumption.

Zaina, A. M., *et al.* [102] worked on the integration of two software computing techniques; (1) simulated annealing (SA) and (2) genetic algorithm (GA) to estimate the optimal process parameters that lead to a minimum value of machining performance. Transverse speed, water jet pressure and standoff distance were considered as the process parameters for evaluating the surface roughness R_a. The machining performance and process parameters were considered with the real experimental data in AWJ. The results showed that both proposed integration systems managed to estimate the ideal process parameters of AWJ, leading to the minimum value of machining performance when the output results were compared to real data results.

Venkata Rao, R., *et al.* [103] developed a newly advanced algorithm called the “teaching-learning-based optimization (TLBO) algorithm” for optimization of the process parameter. The process was applied to obtain the optimum process parameter in ultrasonic machine (USM), abrasive jet machining (AJW) and wired electric discharge machining (WEDM). The teaching-learning-based process inspires the algorithm and it works on the influence outcome of an instructor on the learner's output in a classroom. In the case of USM, the TLBO algorithm improved by ~12% over genetic algorithm (GA). In the case of AJM for brittle and ductile material, the TLBO algorithm improved by ~8% and ~12% respectively, over simulated annealing (SA) and GA. By using the TLBO algorithm for the WEDM process, it shows measurable improvement over the artificial bee colony algorithm (ABC) results. It concluded that the TLBO algorithm can be used for multi-objective manufacturing optimization problems.

Zain, A. M., *et al.* [104] performed experimentation on AWJ cutting technology to find out which optimization methods were more efficient and precise to determine the optimum solution for surface roughness, R_a, Aluminum Al 7075 alloy material was performed using genetic algorithm (GA), regression modeling (RM), simulated annealing (SA), experimental data (ED) and integration GA-SA type 1 and type 2. The results showed that the integration of GA-SA type 1 and SA-GA type 2 methods are very efficient and give a correct optimum solution.

Vundavilli, P. R., *et al.* [105] deals with identifying the depth of cut in AWJ cutting technology using the fuzzy logic (FL) system. Water pressure, abrasive mass flow rate, the diameter of focusing nozzle and jet transverse speed were proposed as dependent parameters for the depth of cut. Three designed methods were developed to find the prediction accuracy of the depth of cut of any engineering materials. Strategy 1 worked with the construction of a Mamdani-based fuzzy logic system, which relies on its knowledge-based only. Strategy 2 depends on database and a rule-based FL system. Strategy 3 generates automatically for getting the optimum value binary coded genetic algorithm (GA). The estimation accuracy of the automatic FL system (i.e. Strategy 3) is found to be better than the other two Strategies.

Aultrin, K. S. J., *et al.* [106] presented a fuzzy logic (FL) modeling of AWJ cutting technology and optimization of its rule base, database and consequent part utilizing a genetic algorithm (GA), along with a binary coded GA. Though modeling with fuzzy logic, the output parameters, namely surface roughness, R_a, and MRR have been predicted for different combinations of AWJ process parameters, such as water pressure at the nozzle exit diameter of abrasive water jet nozzle traverse or feed rate of the nozzle mass flow rate of water and mass flow rate of abrasive particles between the jet nozzle and the target.

Kesharwani, E. G. S. [107] investigated using non-spherical (Triangular & Trapezoidal) sharp edge shaped ceramics abrasive particles as the abrasive for cutting surface material. Titanium based super alloy (Ti-6Al-4V) was used during the experiments as the material is used extensively in the aerospace industry. It was observed that the traverse speed is an important parameter in the case of controlled depth milling (CDM) for AWJ cutting technology. The results found that with the new set-up of the abrasive feed system, a reduction in time was reached by roughly 20% for milling the Ti-6Al-4V sample. Also, it is confirmed that the surface waviness can be decreased as traverse speed is increased by using the newly set-up abrasive inlet system.

Liu, D., *et al.* [108] identified the effect of process parameters (water pressure, transverse speed, tilt angle, abrasive flow rate, surface speed and standoff distance) on the depth of penetration (DoP) and surface roughness, R_a, for aluminium ceramics in AWJ turning. Two mixed methods were used for analysis namely response surface methodology (RSM) with Box-Behnken Design (BBD). The results showed that the transverse speed is a crucial factor on DoP along with water pressure, abrasive flow rate and tilt angle.

Ibraheem, H. M. A. *et al.* [109] deals with identifying the effect of operation parameters while making a hole in glass fiber-reinforced plastic (GFRP) ceramic material. The design of experiments (DoE) was used as a statistical approach to this research. The operational parameters were nominal hole diameter, metal thickness, cutting feed, fiber density, abrasive flow rate, jet pressure and standoff distance. The results revealed that the appropriate level of cutting feed, the level of jet pressure, abrasive mass flow rate and standoff distance were responsible for the high quality of finishing, high quality of dimension accuracy, high rate of productivity and low cost.

Aich, U., *et al.* [110] calculated the depth of cut (DoC) for borosilicate glass material using AWJC technology with different process parameters such as water pressure, abrasive flow rate, transverse speed and standoff distance. One model was introduced to find out the different effect of process parameter on DoC and gives optimum parameter in the cutting process. It includes optimized parameter by particle swarm optimization (PSO). Scanning electron microscopic (SEM) image reveals the nature of the erosion and cutting surface of amorphous material qualitatively.

Dittrich, M., *et al.* [111] described how the process design is executed regarding productivity and machining precision using the design of experiments (DoE) for aluminium oxide Al_2O_3 material. Water pressure, impact angle, abrasive flow rate, nozzle transverse speed and standoff distance were the processing parameters. The investigations show a high degree of repeatability and reproducibility of the results using appropriate process parameters. It also shows that the use of the water abrasive injector fine jet allows extremely precise efficient insertion of surface structures into the Al_2O_3.

Selvan, M. C. P., *et al.* [112] studied the effects of process parameters on the depth of cut (DoC) in the AWJ cutting technology of cast iron material. Water pressure, traverse speed, abrasive mass flow rate and standoff distance on the depth of cut (DoC) were studied. It is observed that the selected parameters have a direct effect on DoC. Statistical regression analysis was employed to develop an experiential model relating these process parameters of AWJC to the DoC.

The model was calculated using the experimental data and it was found to be able to give an acceptable estimation of the DoC with average deviations of less than 3%.

2.4. Correlation

AWJC technology is obtained by applying even an ultra high water pressure ranging from 300 MPa to 900 MPa forcing water through a thin and small diameter orifice at an extremely high speed of about 300 m/s to 1000 m/s [113]. Figure 7 shows the increase of water pressure level for plunger pumps from the middle of the 1950s (around 6 MPa) to recent time with expected value until 2030, which will be what is most promising for micro-, nano- machining technology. By analyzing the experimental data based on what is available in the literature, 1400 MPa could be possible and if this happened, then the R_a performance will reach the sub-nanometer level leading to a new and promising trend for the industrial future.

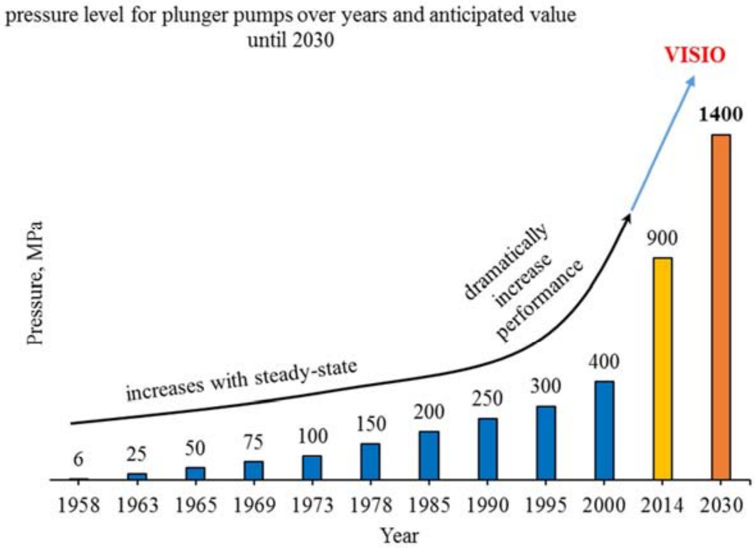

Figure 7. *Water pressure level for plunger pumps from middle of the 1950s (around 6 MPa) to recent time and the anticipated value until 2030.*

Based on the literature review listed in this paper, surface roughness, R_a, represents the most significant parameter that is involved in the last piece of product that directly engages with the customer. Indeed, this is also in agreement with the following publications [114-118]. So, the following graphs were made by the author based on statistical and analytical regularity evaluation of the relationship between input and output data. Figure 8 shows the relationship between the input data (traverse speed, abrasive mass flow rate, water pressure and standoff distance) and the output data (surface roughness, depth of cut, surface waviness and kerf taper ratio).

Based on the trend represented in Figure 8, traverse speed did not show any notable effect on the surface roughness, R_a. For reducing machining costs, every worker tries to set the feed rate cutting value as high as possible, nevertheless raising the traverse speed leads to an increase in the surface roughness, R_a, and inaccurate measurements. However, with an increase in feed rate, the surface roughness, R_a, value increased. This is because only a small quantity of abrasive particles remain that permit over a unit area on the surface. Hence, a smaller number of cutting edges and impacts are available per unit area on the surface, which results in a high value of the surface roughness (rougher surface). Basically, the speed is related to thickness in a nonlinear manner, for half the thickness, the speed increases twofolf. With the increase in abrasive flow rate, the surface roughness, R_a, declines. This is because of the remains effects and cutting edges existing per unit area producing a high value of abrasive flow rate. The abrasive flow rate calculates the total kinetic energy (KE) and the number of affecting abrasive particles. This then increases the abrasive flow rate and increases the cutting ability of the jet in the AWJ cutting machine. Nonetheless, for a higher abrasive flow rate value, abrasive particles crash among themselves and finally lose their kinetic energy (KE). Indeed, it is obvious that the surface roughness, R_a, is smoother near the jet entrance (top edge) and regularly the surface roughness, R_a, rises towards the jet exit (bottom edge). Jet pressure plays a very important role in the surface finish. As the jet pressure rises, the surface roughness becomes smoother. As the jet pressure is increased, brittle abrasive particles break down into small sizes. Because of this drop in the abrasive particles' size, the surface roughness again becomes smoother. Yet again, because of the rise in jet pressure, the kinetic energy (KE) of the abrasive particles rises, which results in the smoother machined surface. Surface roughness, R_a, value rises with an increase in the standoff distance. Commonly, a higher standoff distance allows the jet to expand before impingement which might increase vulnerability to external drag from the atmosphere area. Thus, increasing the standoff distance results in an increased jet diameter as cutting is started and it decreases the KE of the jet at impingement. Accordingly, surface roughness, R_a, increases with a rise in standoff distance. It is required to have low value of the standoff distance which might lead to a smooth surface finishing value due to an increase in KE. The machined surface is smoother at the top edge of the kerf width and becomes rougher at the bottom edge of the kerf width.

In the case of depth of cut, an increase of the traverse speed decreases the DoC. The drop-in DoC is a direct effect of the exposure time, a higher traverse speed leads to less time for cutting the sample, also leading to less jet overlapping on the material to be cut. Besides, an increase in abrasive mass flow rate also increases the DoC. It is understood that a critical KE transfer from the jet to abrasive particles is required to crack the material. Consequently, higher mass flow rate leads to more material being removed, which results in more DoC. Additionally, when water pressure is increased, the jet kinetic energy increases that leads to greater DoC. Lastly, an increase in nozzle standoff distance reduces the DoC. However, the standoff distance on the DoC is not very influential when compared to the traverse rate.

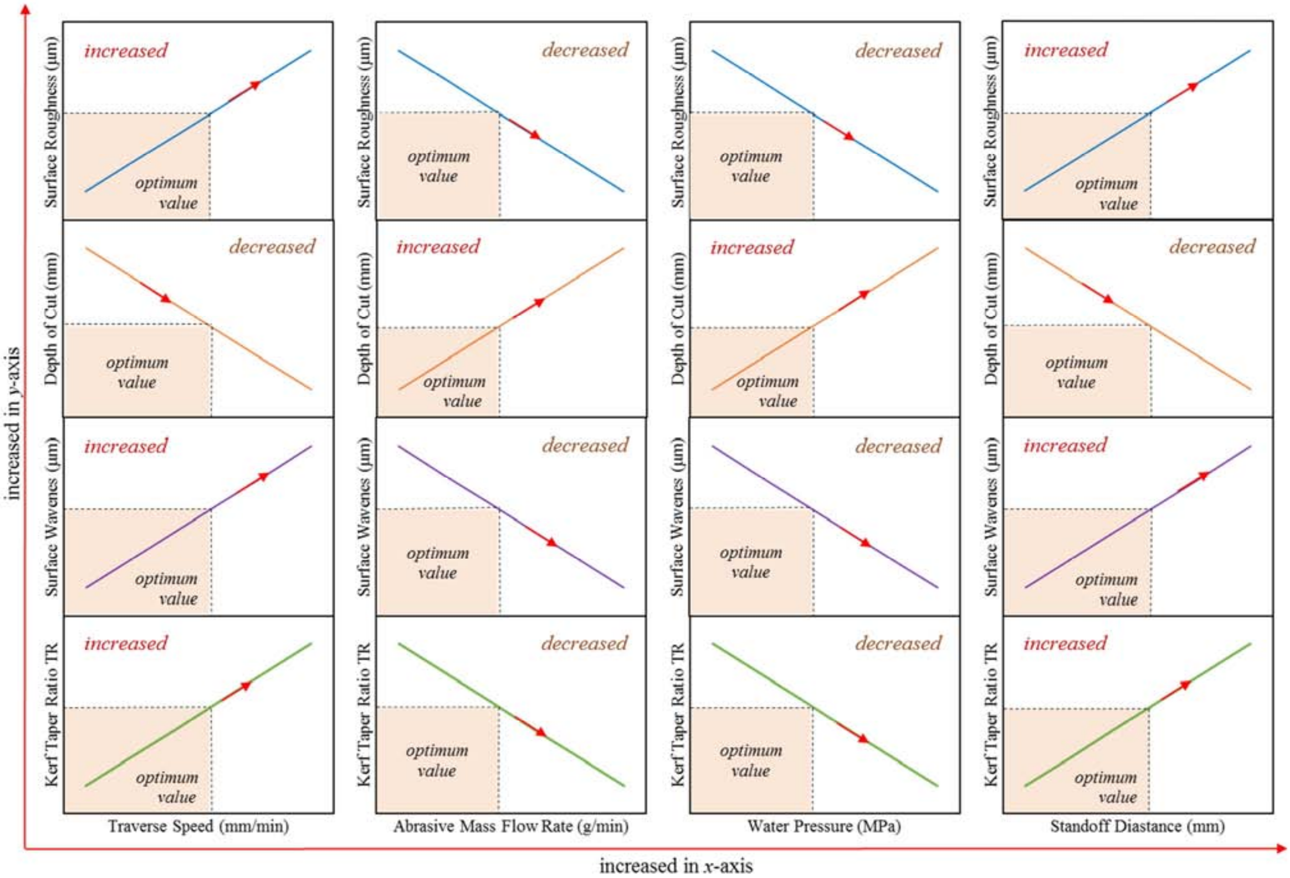

Figure 8. *Relationship between the input data (traverse speed, abrasive mass flow rate, water pressure and standoff distance) and the output data (surface roughness, depth of cut, surface waviness and kerf taper ratio).*

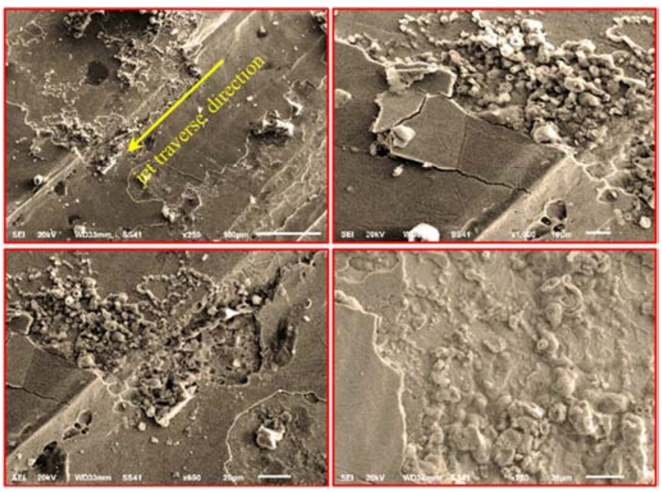

Figure 9. *SEM images after cutting process, adapted from [44].*

2.5. Morphology

The morphological study has been carried out using scanning electronic microscopy (SEM). Figure 9 shows the SEM images of steel sample, adapted from [44], after the cutting process has been accomplished using AWJC technology. It shows the morphology of cut surface when materials are oriented at 90° and are parallel to jet traverse. From the morphological analysis, a great many conclusions can be drawn such as surface roughness, crack length, abrasive embedment, delamination, pits, destruction level, wear, etc.

3. Conclusions

As is well-known, with almost every demand on the most-used natural supply, water and stone, nearly every material can be cut into the desired target. This makes abrasive water jet cutting technology a very effective machining method for processing a range of hard and brittle objects and which has a variety of distinctive advantages over the additional non-traditional cutting technology.

Abrasive water jet cutting (AWJC) technology is a very simple, environmentally friendly, fast processing, and reliable technology, and therefore it becomes an alternative to other methods. AWJ has proved to be a fascinating manufacturing process for the space, aircraft, boat and automotive sectors due to its specific advantages when machining almost all engineering materials.

This review paper is based on the literature review from time to time in understanding the influence of the important process parameters in AWJ on the final product quality. It will undoubtedly help researchers, manufacturers and strategy makers across a broad spectrum.

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