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Effect of Process Parameters on Metal Cutting Using Abrasive Water Jet Machining (AWJM) Technology: A Review

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ABSTRACT

Abrasive water jet machining (AWJM) is a nonconventional eco-friendly machining method widely employed in many modern industrial applications. Among various process factors that influence the quality of machined surface cut using AWJM technology, water jet pressure, traverse speed, abrasive mass flow rate, stand-off distance, type of abrasive material, particle size, and work material are considered the key operating parameters. This paper reviews the findings of recent studies of the cutting of different workpiece materials using AWJM technology with regard to the impact of key process parameters on the machining responses such as surface roughness (Ra), kerf geometrical and dimensional accuracy, depth of cut, and material elimination rate (MRR), and makes recommendations for future research.

Keywords: *Abrasive water jet machining (AWJM), water jet pressure, traverse speed, abrasive mass flow rate, stand-off distance, kerf profile, kerf taper.*

1. Introduction

Advanced machining techniques are now commonly used to solve different problems in manufacturing such as the machining of refractory materials and the production of complex-shaped products with high accuracy and better surface quality. Among various advanced machining techniques, (AWJM) has received close attention from academics and production engineers in the manufacturing industry due to its flexibility, minimal thermal stress, and ability to cut hard and brittle materials with superior surface quality [1]. AWJM is a non-traditional machining process that utilises a high-pressure stream of water containing abrasive particles to cut or shape a wide range of materials, including ferrous and non-ferrous alloys, plastics, composites, ceramics, glass, and even stone. The basic process of material removal using AWJM technology is erosion caused by the impact of the abrasive particles on the surface of the workpiece material. AWJM is commonly used in the aerospace, automotive, electronics, and metalworking sectors, for example, in applications such as prototyping, part cutting, trimming, and deburring, while advances in the process continue to be made in terms of providing increased cutting speeds, higher jet pressure and cutting accuracy [2]. A standard abrasive water jet system contains primary four elements: a water filtering and storage system, a pumping system, a cutting head, and an abrasive delivery system and workpiece table (catcher) as presented below in Figure 1.

Water filtering and storage system

This system provides continuous pressure to the ultra-high-pressure pump. A standard AWJM system contains a cooling water tank as well as a cutting tank, as shown in Figure 1. In most cases, particles with size more than 90 μm need to be extracted from the water as they would generate carry on the important parts of the pump leading to pump failure. Water is used as a coolant for the oil pump [3].

Pumping system

This system is supplied with an intensifier and collector to respectively produce and store high-pressure water. The intensifier contains a double-action reciprocating pump controlled by oil pressure. The high-pressure pump contains two different circuits to produce high pressure water of up to 600 MPa.

AWJ cutting head

The cutting head is fitted with a focusing tube, orifice, nozzle, and mixing chamber. The focusing tube is usually made of high-grade anti-corrosion stainless steel less than 100 mm long with a diameter of 0.75 mm. Cutting head orifice is commonly made from sapphire, or diamond material with a diameter up to 0.85 mm. The high-pressure tube carries the pressurised water from the accumulator to the cutting head through a focusing tube. As the water passes through the orifice, the energy from the pressure of the water is converted into the kinetic energy of water particles due to the convergent shape of the orifice. The high-speed water jet then passes through a mixing chamber which is directly connected to the orifice. The water loses its pressure energy as it passes through the mixing chamber due to the Venturi phenomenon. In the mixing chamber, abrasive particles blend with water, and the high energy of the water particles is transported to the abrasive particles and then the mixture of water and abrasive particles passes through the nozzle and works like a saw to cut the material [3].

Abrasive supply system

The abrasive supply system contains abrasive hopper and a pneumatically controlled valve to control the abrasive mass flow rate. Categories of abrasive material commonly employed in industry are garnet, silicon carbide, and aluminium oxide, of different colours and with mesh sizes up to ≤90 μm [4,5]. A catcher or water sump is used to collect the pressurised water after cutting which is then returned to the cutting water tank. Figure 2 presents an image of the Model 160X JMC abrasive water jet machine, Figure 3 shows common nozzles used in AWJM operations, and Figure 4 displays samples of AWJ-machined 3D parts.

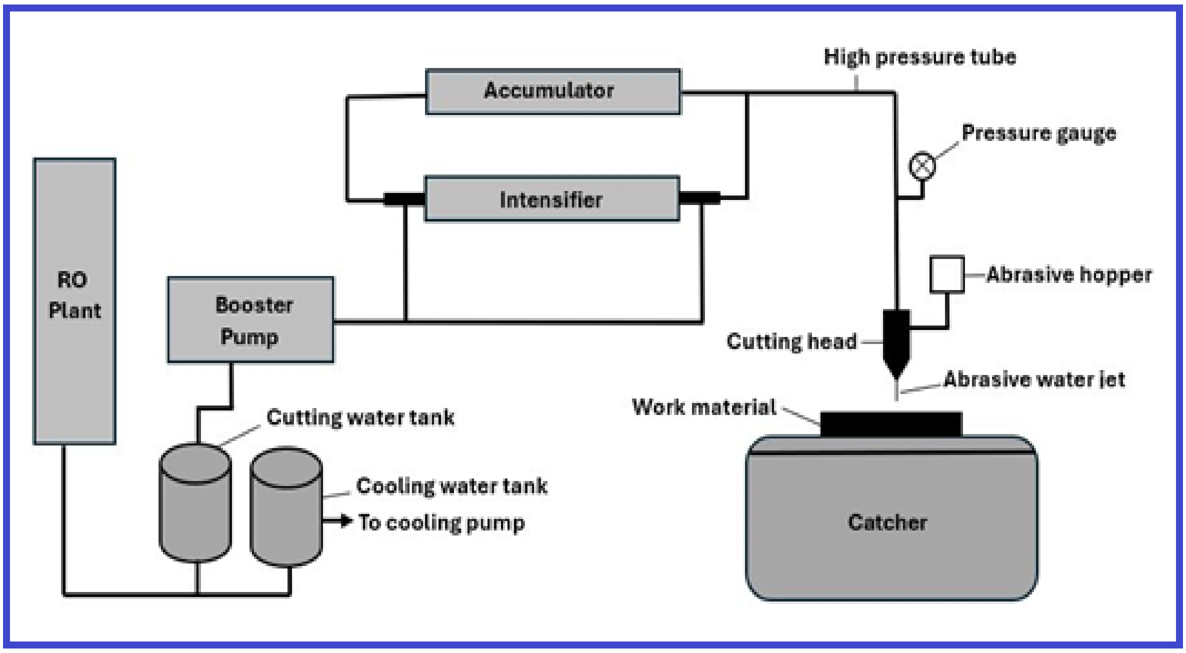

Figure 1: AWJM Design [3]

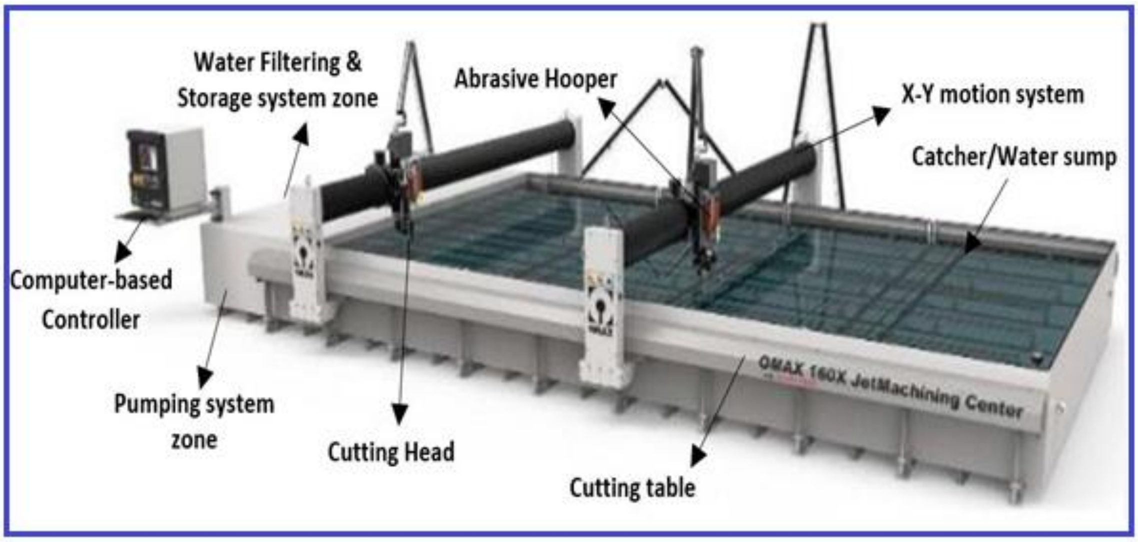

Figure 2 : Image of the Model 160X JMC AWJ Machine [6]

Figure 3 : AWJM Nozzles [6]

Figure 4 : Samples of AWJ machined 3D parts [6]

2. Process factors affecting AWJ machining

Various factors affecting AWJ machining operations can be classified into five main types involving hydraulics, cutting, abrasive material, work material, and mixing and acceleration factors [3,4], as shown in Figure 5. However, studies have demonstrated that some factors have a greater impact on the process than others, and this paper focuses on the key factors and their influence on AWJM operations when cutting different materials. Figure 6 shows the impact of the AWJ machining process on the workpiece material.

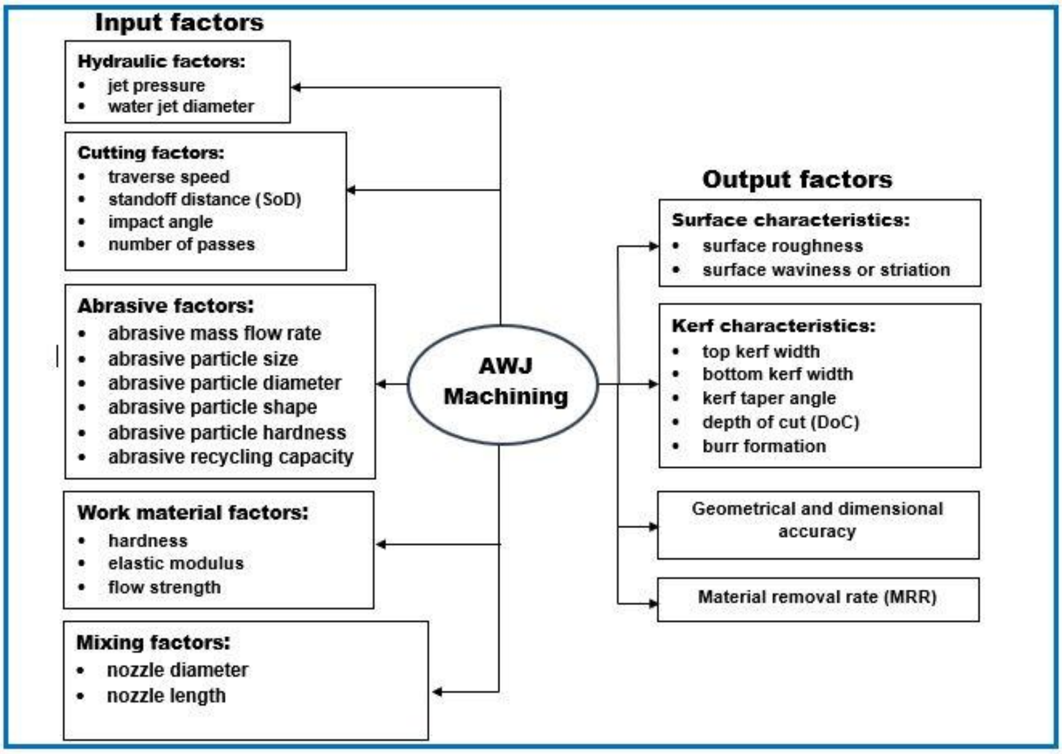

Figure 5: Influential factors in the AWJ machining process [3]

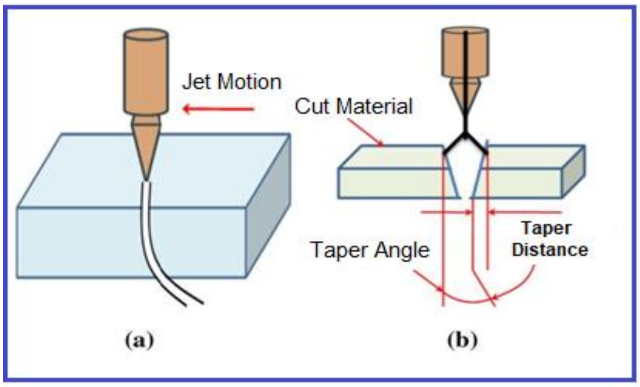

Figure 6 : Impact of the AWJM process on the workpiece material: (a) striation formation by deflection of the water jet stream during the cutting process; (b) taper formation [1]

3. Key factors influencing the AWJM process

1) **Water jet pressure (WJP)** is a critical parameter that determines the cutting power of the abrasive water jet. Higher water pressures of typically 200-600 MPa can achieve faster cutting rates and deeper penetration. Water jet pressure is directly proportional to penetration depth and the material removal rate (MRR) [7].

2) **Abrasive mass flow rate (AFR)**: The amount of abrasive material such as garnet, aluminum oxide or silicon carbide introduced into the water jet stream affects cutting performance. The optimal abrasive flow rate, usually measured in mm^3/min, depends on the desired cut quality [8].

3) **Stand-off distance (SoD)**, frequently denoted in mm, is the distance between the nozzle and the machined part, which affects the focus and coherence of the water jet and impacts the cut quality and taper [9].

4) **Traverse speed (TS)**, usually designated in mm/min, is the speed at which the water jet is moved across the workpiece, which influences the depth of cut and surface finish. Higher traverse speeds result in shallower cuts but better surface quality [10].

5) **Abrasive material and particle size (μm)**: Natural garnet and artificial abrasives such as silicon carbide and aluminum oxide are commonly used in AWJ machining. The size of the abrasive particles affects cutting efficiency and surface roughness, where smaller particles can achieve smoother finishes but may have lower cutting rates [11].

6) **Nozzle diameter (mm)**: The diameter of the water jet nozzle, typically in the range of 0.8-1.5 mm, impacts power density and the width of the cut [12].

7) **Work material parameters**: The hardness, flow strength, thickness, elastic modulus, and other material properties of the workpiece material influence the optimal process parameters required to achieve the desired cut quality [13].

The values of the above-mentioned parameters must be carefully selected and balanced in order to achieve the desired cutting performance, accuracy, and surface finish for any given AWJM application. Experimentation and process optimisation are often required to determine the ideal parameter settings. The next section reviews the current state of AWJM operations so as to understand the research issues and challenges that are faced in the use of this technology.

4. Review of literature relevant to the key factors influencing the AWJM process

Bhandarkar et al. [14] examined the dimensional accuracy and characteristics of the machined pocket of Inconel 718 using an OMAX 2652 AWJ machine with silica sand as the abrasive material. Key process parameters were traverse speed (TS) up to 1600 mm/min and water jet pressure (WJP) up to140 MPa. The responses measured included length, breadth, depth, and surface roughness. It was found that a WJP of 35 MPa produced optimal length and breadth at a TS of 1000 mm/min, whereas optimal depth was achieved at the same TS of 1000 mm/min but 140 MPa while lower Ra was attained at a TS of 1600 mm/min and WJP of 35 MPa. In addition, the surface characterisation by scanning electron microscopy (SEM) showed that the scratch depth was strongly affected by WJP, while TS had a significant impact on the scratch length. Ebeid et al. [15] evaluated the impact of key process parameters on the AWJ machining of aluminium alloy (Alumec 89) using abrasive material based on silicon dioxide and ferric oxide, with process parameters of jet traverse speed (1000 - 2000 mm/min), water jet pressure (20-100 MPa), stand-off distance (2-5 mm), and abrasive flow rate (100-250 g/min). It was found that an increase in jet traverse speed generated a lower Ra with a decreased depth of cut and MRR, whereas higher abrasive flow rate produced a better depth of cut and MRR with better surface finish. It was concluded that traverse speed and abrasive flow rate strongly affected the process, whereas stand-off distance and jet pressure had no significant impact on Ra, MRR and depth of cut in the machining tests. Figure 7 shows the impact of traverse speed and water jet pressure on surface roughness at different abrasive flow rates (AFR).

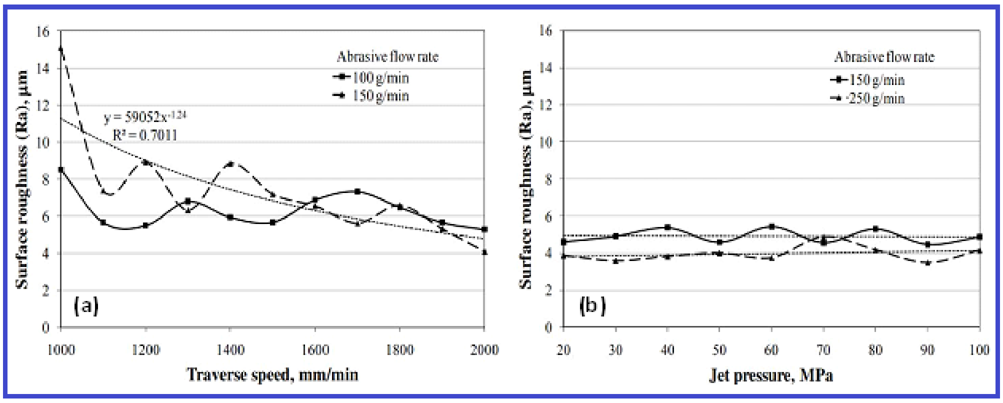

Figure 7 : Impact of (a) traverse speed and (b) jet pressure on surface roughness at different abrasive flow rates [15]

Hole roundness (RD) deviation and MRR have also been evaluated in the deep hole drilling of AISI 316L using AWJ drilling operation [16], with drilling tests performed at values of WJP, AFR and stand-off distance (SoD) of 260-360 MPa, 0.3-0.6 kg/min, and 1-2.5 mm respectively. Metal removal rate (MRR) and hole roundness (RD) were the key responses considered, and it was found that WJP and AFR directly affected MRR, which also decreased with increasing SoD due to the lower velocity of the abrasive particles. In addition, the RD of the drilled holes was strongly controlled by WJP, whereas increased SoD tended to increase the RD. The analysis of variance (ANOVA) demonstrated that WJP and AFR were the two most influential factors on MRR, while WJP and SoD had a considerable impact on RD. Vasudevan et. al. [17] explored the drilling concert of Yttrium Stabilized Zirconia (YSZ)-coated Inconel 718 superalloy using an Aquajet G3020 abrasive water jet machine, and the impacts of the key process factors of WJP, AFR, and SoD on the quality and efficiency of drilling YSZ-coated Inconel 718 were examined. Table 1 shows the process factors and corresponding levels, and the geometrical features of the resulting holes were measured, including entry diameter (EnD), exit diameter (ExD), and erosion diameter (ErD). The ANOVA results indicated that the SoD and AFR were more influential parameters affecting EnD, while WJP and AFR had a strong impact on ExD whereas SoD significantly affected ErD. Figures 8 and 9 show captured images of the entry and exit hole diameters of AWJ pierced holes at level I, II, III respectively.

Table 1. Process factors and corresponding levels [17]

Factor	Unit	Level I	Level II	Level III
(WJP)	MPa	175	225	275
(AFR)	g/min	250	300	350
(SoD)	mm	1	2	3

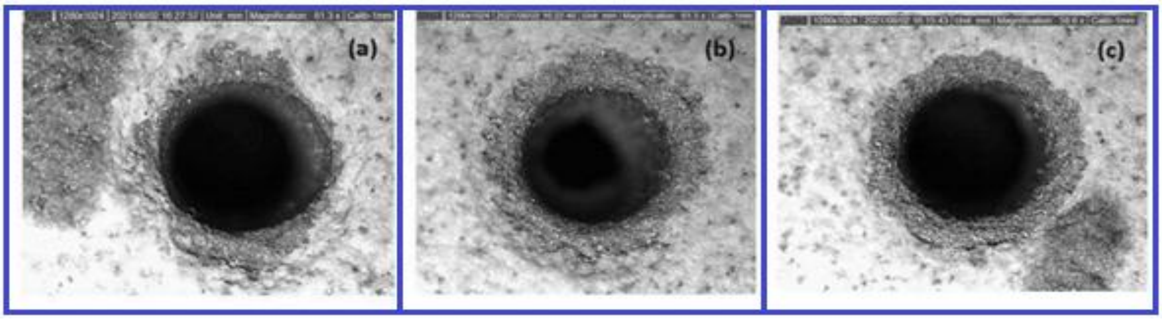

Figure 8 : Captured images of the entry holes of AWJ-pierced holes at (a) level I, (b) level II, and (c) level III [17]

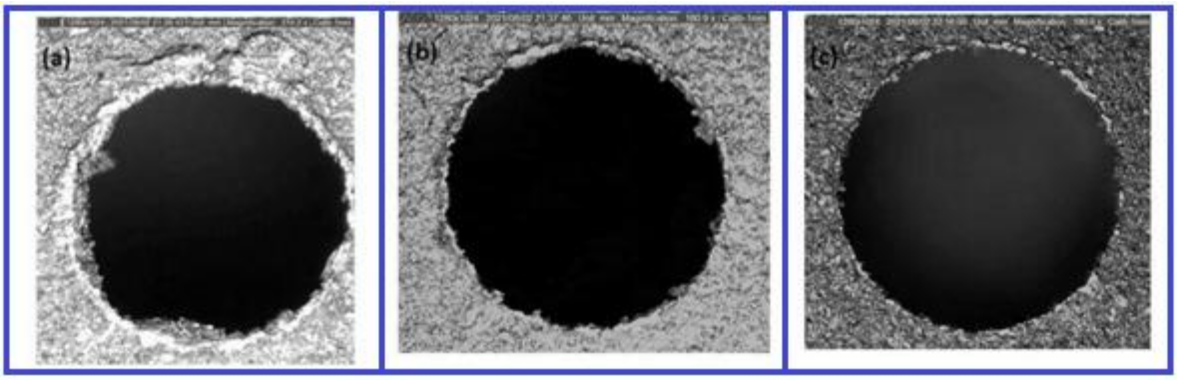

Figure 9 : Captured images of the exit holes of AWJ-pierced holes at (a) level I, (b) level II, and (c) level III [17]

An experimental study was conducted by Perec [18] aiming to optimise the accuracy of (AWJ) machining process when cutting 18CrNiMo7-6 steel using almandine garnet J80A abrasive material. The Taguchi method L_9 was utilised to optimise the key process parameters of TS, AFR, and WJP with values up to 250 mm/min, 450 g/min, and 400 MPa respectively. The output parameters measured were taper angle (δ) and surface roughness (Ra). The results showed that a lower Ra of 21.27 µm and minimal taper angle (δ) of 3.22° were achieved at values of AFR of 350 g/min, WJP of 400 MPa and TS of100 mm/min. It was observed that the accuracy of the process was most significantly sensitive to traverse speed, followed by AFR and then WJP as shown in Figure 10.

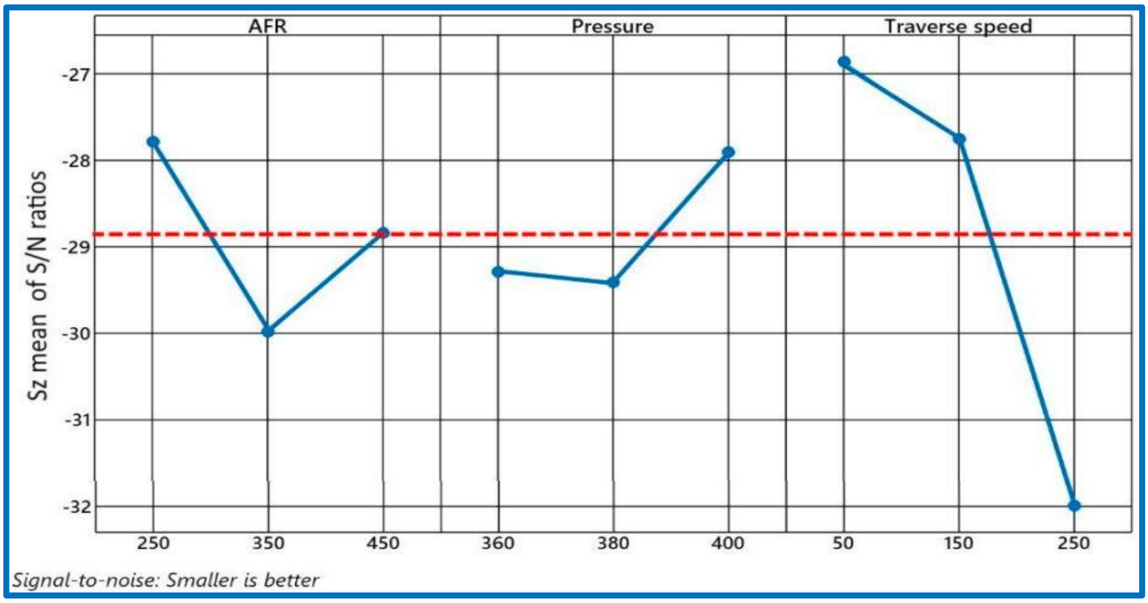

Figure 10 : S/N ratio plot for surface roughness [18]

Wan et al. [19] examined the cylindrical surface characteristics of material machined by AWJ with different radii (Rc) of circular cuts applied to AA7075 aluminium alloy, using an analysis of variance (ANOVA) to investigate the effects of the input process parameters water jet pressure, tangential velocity, and (SoD) on surface roughness (Ra) with maximum values up to 320 MPa, 250 mm/min, and 10 mm respectively. It was observed that striations on the cut surface of the workpiece become more obvious and occurred earlier in the process with a smaller value of Rc. The final results showed that the parameters most strongly affecting cylindrical surface quality were tangential velocity followed by circular cut radius, then WJP, and finally SoD. Figure 11 shows values of Ra at different locations on the cylindrical surface.

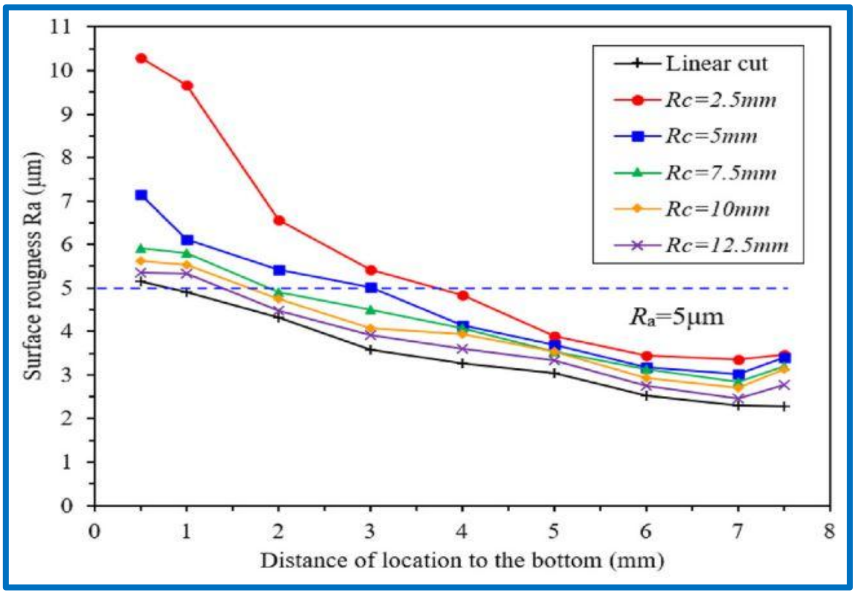

Figure 11 : Surface roughness at different locations of the cylindrical surface [19]

The effects of WJP, TS, and SoD on the AWJ cutting process of AISI 304 and Ti-6Al-4V alloys using garnet abrasive particles with a mesh size of 80μm have also been investigated [20] in an experimental study which focused on enhancing the material removal rate (MRR) and examining the depth of the kerf profile in the specimens cut. The WJP, TS, and SoD had maximum values of 240 MPa, 1000 mm/min, and 10 mm respectively, and the results showed that the kerf shape and quality of the surface were significantly influenced by SoD. In addition, it was concluded that the WJP had a strong impact on the highest depth of the kerf profile and affecting the MRR by controlling the velocity of the abrasive particles. Figure 12 shows the impact of WJP on the kerf profiles obtained.

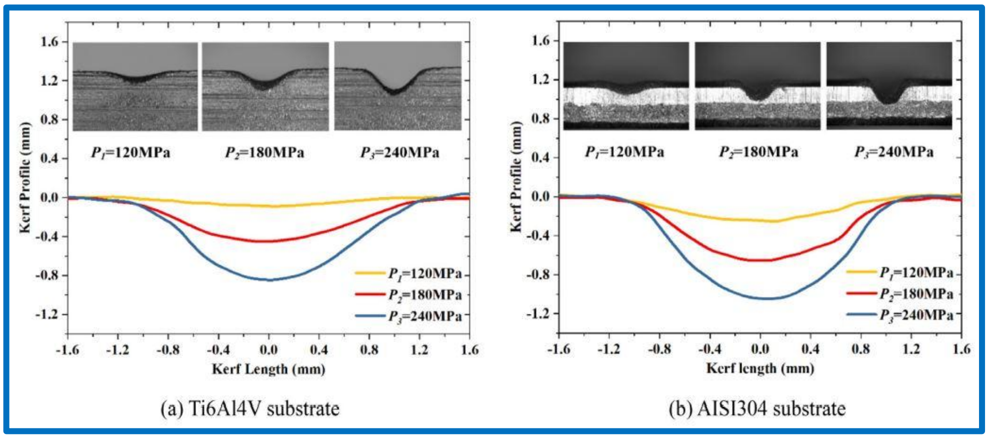

Figure 12: Comparisons of kerf profiles obtained in the cutting Ti-6Al-4V and AISI 304 substrates with different water jet pressures [20]

Jakub et al. [21] investigated the effects of SoD on the erosion of 316L stainless steel, 6082 Aluminium and Ti-6Al-4V alloys when applying a stream of pulsating (intermittent) abrasive water jet at various SoD values of 15 - 39 mm at a constant water jet pressure and traverse speed of 40 MPa and 0.25 mm/s respectively. The results showed that the deepest eroded path in the 6082 Aluminium alloy was achieved with an optimal SoD of 17 mm, while the Ti-6Al-4V alloy was found to be a more resistant material when using pulsating abrasive water jet technology. In a related experimental study [22], the effect of a pulsating abrasive water jet applied to CW004A copper was investigated using (SEM) to evaluate the material's surface topography. The tests conducted at a traverse speed of 0.1 mm/s, circular nozzle diameter of 1.321 mm, and water pressure of 39 MPa. The results indicated that a low traverse speed rate had catastrophic effects on the material with significant losses in volume and weight, and the surface topography was characterised by the formation of depressions, protrusions, and craters while subsurface material failure was detected at up to 200 μm. Figure 13 shows SEM images of the cross-cut CW004A copper sample.

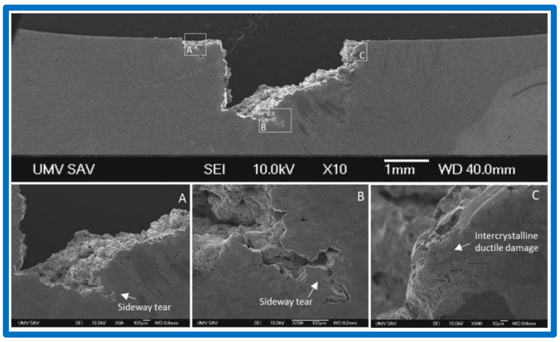

Figure 13 : SEM images of a cross-cut CW004A copper sample [22]

An experimental study was performed to investigate the impact of operating parameters on kerf taper during AWJ of aluminium alloy 6061-T6 [23]. Control parameters were water jet pressure, traverse cutting speed (expressed by AWJ cutting quality), material thickness, and abrasive flow rate. The findings suggested that the traverse speed and material thickness had the greatest impact on kerf taper, while the effects of WJP and AFR were not significant. It was concluded that the kerf taper was very sensitive to traverse cutting speed, whereas increased material thickness resulted in reduced taper. Figures 14 and 15 respectively show the impact on taper angle of material thickness and cutting traverse speed as opposed to WJP and AFR.

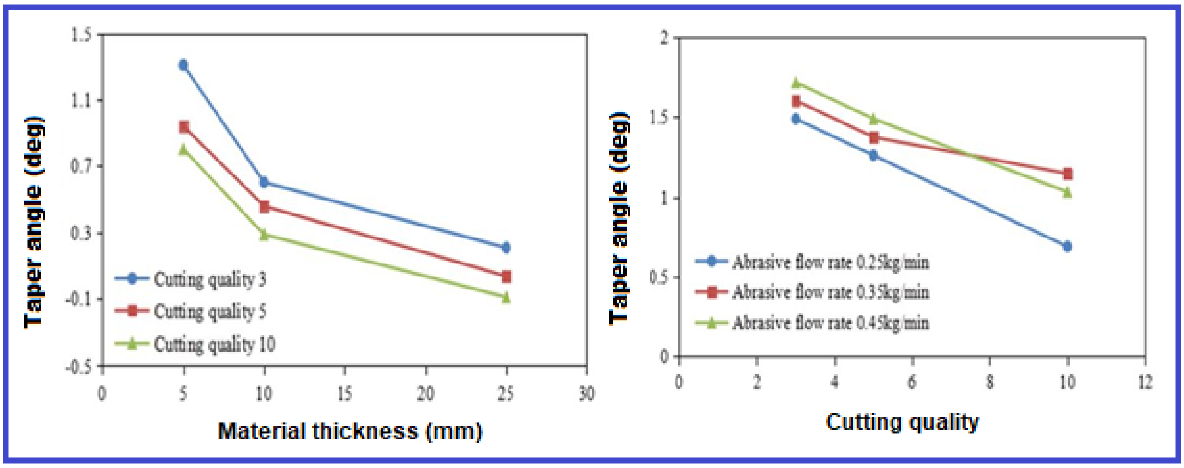

Figure 14 : Effect of material thickness and cutting traverse speed (cutting quality) on taper angle [23]

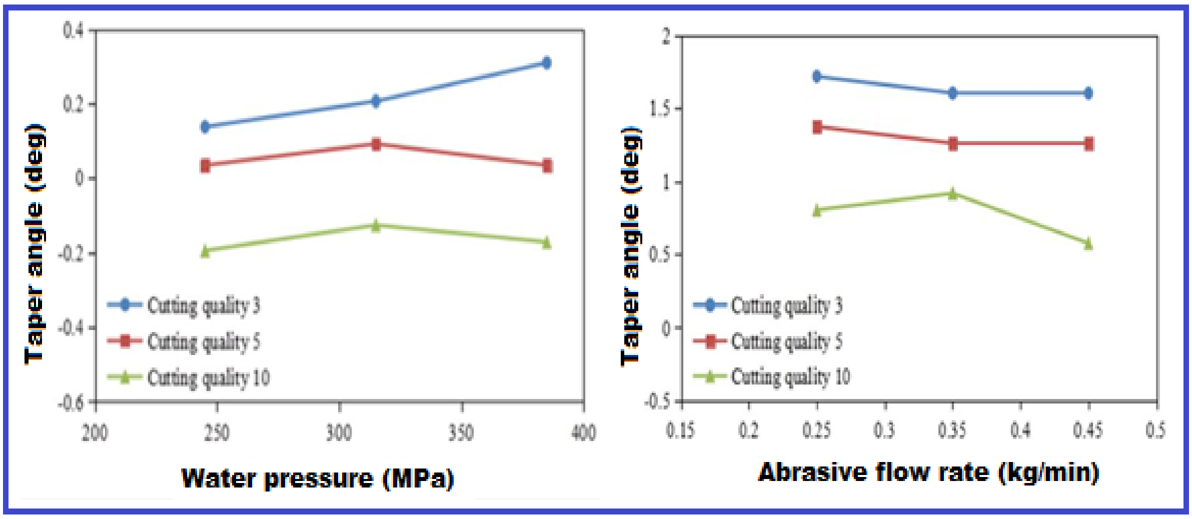

Figure 15 : Influence of WJP and AFR on taper angle [23]

Research by Karthik et al. [24] investigated the impact of WJP, TS, and AFR on MRR and kerf top width from the abrasive water jet cutting of stainless steel 304 using an L_{27} orthogonal array. The results show that the most influential factors for kerf top width are TS and AFR, while MRR is more strongly influenced by WJP and TS. The impact of AWJM on the surface quality of Ti-6Al-4V alloy was investigated by Elsheikh et al. [25], in a study aiming to optimise the key process parameters of WJP, AFR, TS, and SoD in order to accomplish the desired surface finish. A Taguchi L9 orthogonal array, analysis of means (ANOMS), and analysis of variance (ANOVA) were utilised for the optimization of the process, and it was found that the optimal value of surface roughness (Ra) was 0.54 μm, which was significantly affected by SoD and AFR Ra with a percentage contribution ratio (PCR) of 61.77 % and 29.32 % respectively. Moreover, the optimised process parameters resulting in the minimum of Ra were a WJP of 2000 bar, AFR of 500 mm3/min, TS of 1000 mm/min, and SoD of 2.5 mm. Figure 16 shows the analysis of means (ANOMS) results for surface roughness (Ra).

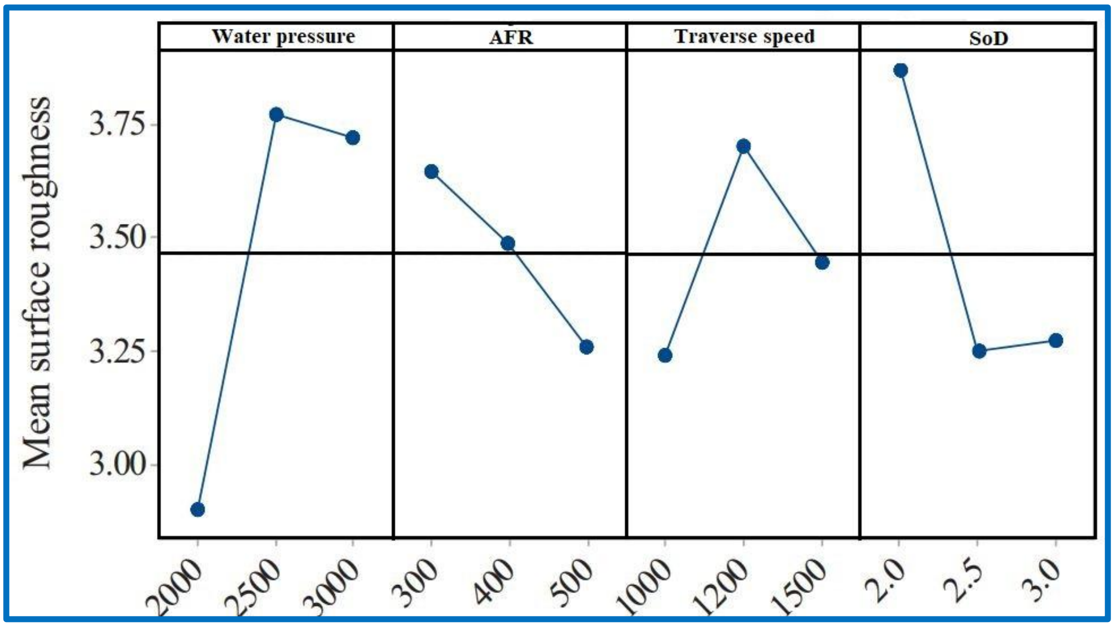

Figure 16 : ANOMS results for surface roughness (Ra) [25]

The influence of (AWJM) process parameters on surface roughness (Ra), and micro-hardness evolution on Ti-6Al-4V alloy has been investigated by Ramakrishnan et al. [26]. Key process parameter ranges were WJP from 150 to 250 MPa, AFR of 0.24 to 0.44 kg/min, and stand-off distance of 2 to 4mm, and the optimal Ra value was obtained at the cutting condition of 200 MPa WJP, 0.34 kg/min AFR, and 2mm SoD. The ANOVA results indicated that WJP most substantially reduced Ra, followed by stand-off distance and then AFR, and it was found that the micro-hardness of the AWJM sample was very sensitive to WJP and stand-off distance. An experimental study was performed by Perec [27] to optimise the cutting control parameters using the response surface method (RSM) to achieve high cutting depth and low Ra in the abrasive water jet (AWJ) machining of Hardox 500 alloy steel using crushed rock garnet J80A. Control parameter ranges were: WJP from 350 to 400MPa, AFR 250 to 450 g/min, and TS 100 to 300 mm/min. The parameter values which gave the best combination of lower Ra and higher cutting depth were WJP at 385 MPa, AFR 416 g/min, and TS 100 mm/min. Wang et al. [28] examined the quality of cutting surface during machining tungsten alloy using AWJM technique. The machining tests were conducted at values of WJP from 30 to 45MPa, TS from 2.5 to 7.5 mm/min, and constant SoD of 3 mm. The results showed that the optimal surface quality was achieved at a WJP of 45 MPa and TS of 2.5 mm/min as shown in Figure 17. It was observed that the quality of cutting tungsten alloys is significantly affected by the motion characteristics of the abrasive particles. The authors concluded that an increase in water jet pressure would minimise morphological damage of characteristics of tungsten alloy.

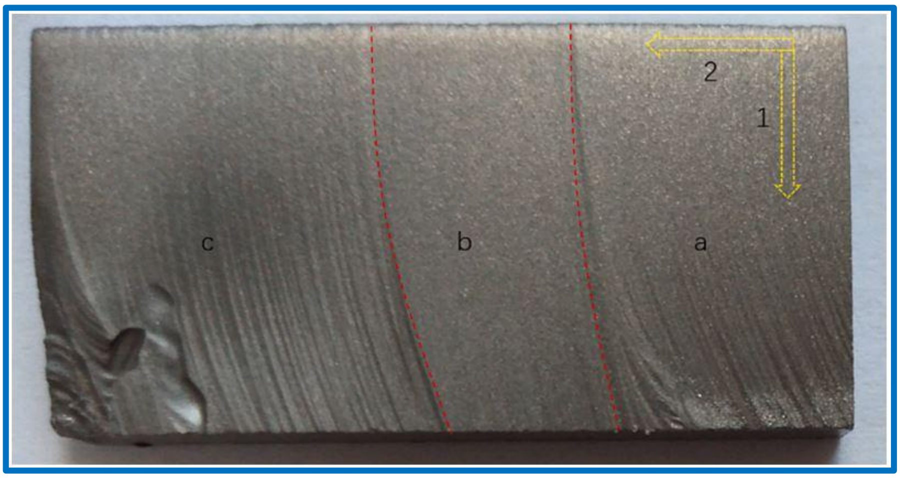

Figure 17: Image of surface profile of tungsten alloy at various traverse speeds of (a) 5 mm/min, (b) 2.5 mm/min, and (c) 7.5 mm/min at the optimal WJP of 45 MPa. Arrows 1 and 2 show the directions of the water jet and traverse speed respectively [28]

In addition, Radovanovic [29] studied the cutting performance of S235 carbon steel using AWJM. The optimisation process was performed to simultaneously maximise productivity and operating costs by varying the three key process parameters of AFR, TS, and SoD in ranges of values of 300 to 420 g/min, 81 to 127 mm/min, and 1 to 5 mm respectively. The optimal cutting conditions which achieved higher productivity with low operating costs were a TS of 127 mm/min, AFR of 300 g/min, and SoD of 1 mm at a constant WJP of 150 MPa. The impact of process parameters such as SoD, WJP and TS on surface topography during the submerged and unsubmerged abrasive water jet cutting of Ti-6Al-4V alloy has also been investigated [30]. It was found that Ra increases, and the depth of the smooth zone decreases with increases in SoD and TS and decreases in WJP in both submerged and unsubmerged conditions. Figure 18 shows the impact of the process parameters on Ra and the depth of the smooth zone under various cutting conditions.

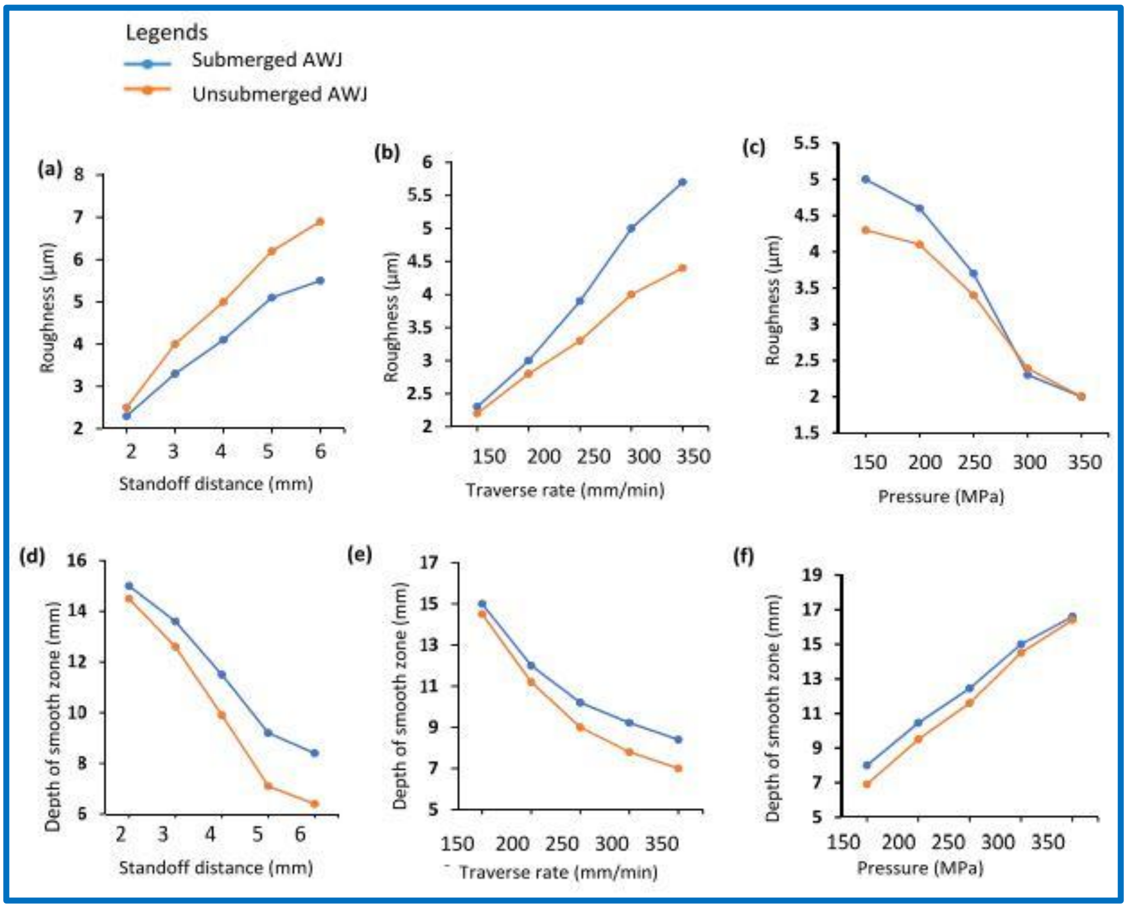

Figure 18: Effects of various process parameters on Ra and depth of the smooth zone during the submerged and unsubmerged abrasive water jet cutting of Ti-6Al-4V alloy under different cutting conditions [30]

Redžić et al. [31] investigated the influence of the abrasive material on the cutting-tip formation of carbide punching tools for sheet metal fabrication using AWJM technology. A garnet sand with a particle size between 63-90 µm as the abrasive material was utilised. The results showed that applying finer garnet sand ≤ 63 µm could produce better cutting -edge surface quality compared to the garnet sand > 63 µm. Arun et. al. [32] examined the optimal machining features for abrasive water jet cutting of Monel 400 alloy. In this experimental inspection, the (WJP), the nozzle jet traverse speed (TS), and the abrasive flow rate (AFR) were employed to explore the kerf taper angle (δ) and surface roughness (Ra) response variables. It was found that WJP and AFR, were determined to have the most substantial effects on kerf taper angle (δ) and surface roughness (Ra).

To recapitulate the main findings of the present literature in terms of the outcome of the key progression parameters of TS, AFR, WJP and SoD on surface quality and kerf profile and depth as well as the metal removal rate (MRR), research has consistently demonstrated that traverse speed (TS) is the most significant factor affecting surface quality during AWJM operations. However, while many studies conclude that a better surface finish is obtained at lower TS values, others emphasise that higher TS positively affects surface quality. This apparent contradiction could be attributed to the type of metal used and cutting conditions investigated. Similarly, although water jet pressure (WJP) is always found to have a considerable influence on the surface finish, there are disagreements among researchers concern the extent of its impact on surface roughness (Ra) and in some studies it is concluded that WJP has no effect on Ra, metal removal rate (MRR), and depth of cut when cutting aluminium alloy using AWJM technique. Meanwhile, all studies have shown that higher values of abrasive mass flow rate (AFR) produce better surface finish. Lower values of standoff distance (SoD) also have a positive impact on surface quality, again except when cutting aluminium alloys where SoD has no impact on Ra. In the same vein, kerf profile and the quality of the kerf surface are also significantly influenced by SoD. Additionally, WJP has a substantial impact on the maximum depth of the kerf profile and, although traverse speed and material thickness have a great impact on kerf taper, WJP and AFR have a negligible effect. Furthermore, several studies have pointed out that finer garnet sand has a positive impact on surface quality during AWJM operations. All relevant investigations have reported that the metal removal rate (MRR) is sensitive to TS, AFR and WJP, with optimal MRR values obtained at the highest values of those variables tested, whereas standoff distance (SoD) has only a minimal effect on MRR.

5. Conclusion

This survey has considered studies in which different kinds of materials were cut using abrasive water jet machining (AWJM) technology, and the effects of the key parameters of abrasive mass flow rate (AFR), traverse speed (TS), water jet pressure (WJP) and standoff distance (SoD) on the process responses such as surface roughness (Ra), kerf profile and its depth and metal removal rate (MRR) have been examined. The following conclusions can be drawn:

- TS and AFR are generally the most significant factors affecting surface quality, and WJP and SoD also have a considerable impact on the surface finish of machined parts.
- MRR is sensitive to TS, AFR and WJP.
- The optimal MRR is achieved at the higher values of WJP, TS, and AFR tested,

whereas SoD has only a marginal impact on MRR.

- The micro-hardness of machined samples is strongly influenced by WJP and SoD.
- Lower particle size of garnet sand ≤ 63 μm leads to better surface quality compared to larger particles.
- The kerf profile and value of the kerf surface are significantly influenced by SoD.
- WJP has a substantial impact on the maximum depth of the kerf profile, whereas TS and material thickness have a strong impact on kerf taper.
- The influence of WJP and AFR on kerf taper is negligible.
- WJP and AFR are the most significant factors affecting MRR, while SoD has a considerable impact on hole roundness (RD).

Finally, various apparently contradictory findings have been identified in this review, which indicates that further investigation is needed regarding the impact of the key process parameters mentioned above, in particular on surface quality. In addition, it is also suggested that future work should investigate the effect of nozzle diameter and the properties of workpiece materials on the process responses when cutting metals using AWJM technology.

Nomenclature

Symbol		**Unit**
AFR	Abrasive mass flow rate	g/min
TS	Cutting traverse speed	mm/min
WJP	Water jet pressure	MPa
SoD	Stand-off distance	mm
Ra	Surface roughness	μm
MRR	Metal removal rate	mm^3/min
RD	Hole roundness	mm
EnD	Entry diameter	mm
ExD	Exit diameter	mm
δ	kerf taper angle	degree

Abbreviations

AWJM	Abrasive water jet machining
ANOVA	Analysis of variance
ANOMS	Analysis of means
SEM	Scanning electron microscopy analysis
YSZ	Yttrium stabilized zirconia
Ti-6Al-4V	Titanium alloy

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