Int J Adv Manuf Technol (2017) 88:495–505
DOI 10.1007/s00170-016-8777-z

ORIGINAL ARTICLE

A review of the current state of abrasive water-jet turning machining method

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Received: 10 December 2015 / Accepted: 12 April 2016 / Published online: 26 April 2016

Abstract Abrasive water-jet turning (AWJT) is one of these alternative methods and has gained an important status among others in a very short period of time. AWJT becomes prominent with its flexibility in cutting materials with almost any properties, with the elimination of thermal effects during the process, and with minimal stresses it imposes. It is widely preferred when heat-affected zones are to be avoided as it is a cold process. AWJT, on the other hand, is the replacement of a traditional cutter head of a turning testing apparatus with the AWJ in order to remove material turning the workpiece using a spindle testing apparatus while moving the nozzle on an axis with a specific distance from the workpiece. It is convenient to machine planar workpieces using the AWJ while it is harder to machine (turn) workpieces. However, there are scientific studies on the machinability of the planar workpieces, studies on the machinability of cylindrical materials are rarely found in the literature. Among the machining parameters for AWJT are nozzle feed rate, spindle speed, abrasive flow rate, pump pressure, abrasive size, and standoff distance. The studies available in the literature focus on the impact on *Ra* (μm), machining depth (mm), and material removal rate (mm^3 min^{-1}) as experiment outcomes. In this study, reviews of the research are available in the literature on the turning of workpieces using abrasive water jet. This study will also discuss the recommendations for the future research.

Keywords Abrasive water-jet turning · Average surface roughness · Material removal rate · Abrasives · Machining · Advanced manufacturing technology

Nomenclature

R_a	Surface roughness value (μm)
ASR	*Ra* (μm)
P	Pump pressure (MPa)
ND	Nozzle diameter (mm)
NFR	Nozzle feed rate (mm min^{-1})
SS	Spindle speed (min^{-1})
AFR	Abrasive flow rate (g min^{-1})
DOC	Depth of cut (mm)
SOD	Standoff distance (mm)
MRR	Material removal rate (mm^3 min^{-1})

1 Introduction

Manufacturing challenges are ever increasing with the technological developments leading to the development of high-performance materials such as advanced ceramics, composites, etc. As a result, traditional machining techniques are becoming insufficient for these materials to be effectively machined. Researchers need to further their studies focusing on the development in terms of the strength of industrial materials in order to meet the expectations of the modern world. Production of innovative and strong materials for the industrial purposes has led to the need for machinability of these materials. Alternative machining methods were needed in order to meet these requirements.

The purpose of the nontraditional manufacturing methods is to have metal and nonmetal material rendered in a specific

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profile and size using different energy forms [1–4]. In the recent years, miniaturized and hard-to-machine workpieces are needed to be processed as a result of the requirements of the advanced material needs, leading to traditional manufacturing methods to become insufficient [2–4]. Therefore, nontraditional machining methods are now making it possible to process miniature and hard-to-machine materials conveniently. Abrasive water-jet (AWJ) cutting, a cold-working process (involving no thermal effects), does not lead to increased heat at the cutting area during the material removal process employing the erosion property of the fluid on the workpiece [4–7]. Thus, no heat building in the cutting area is an important factor for the material removal process which has significant consequences for the machining performance and the surface quality of the workpiece [6–9]. Recent advancements in several fields of the industry due to the advanced technology have required some innovative steps to be taken in the manufacturing sector [7–11]. The AWJ technology has been commonly used in the metal cutting process [10, 11]. AWJ cutting is based on the principle of abrasion (erosion), applying high-pressure water on the material in order to cut it [9–11]. Pressurized water has a high level of kinetic energy expressed in terms of the Bernoulli equation when it is guided through a narrow container [11–13]. Having a high level of energy, the water leads to erosion and cutting of the material, obtaining high water flow speeds [13, 14]. The use of AWJ in the metal industry has led to several technologies and systemic advancements in terms of hardware and material structure. With these advancements, AWJ is now being preferred, commonly especially in the metal industry in order to work on hard-to-machine materials [10–14].

Increasing performance due to design has led to new areas of work thus increasing the industrial use of AWJ [1–11]. The use of multiple cutting heads has reduced the material machining time, increasing the efficiency [14–17].

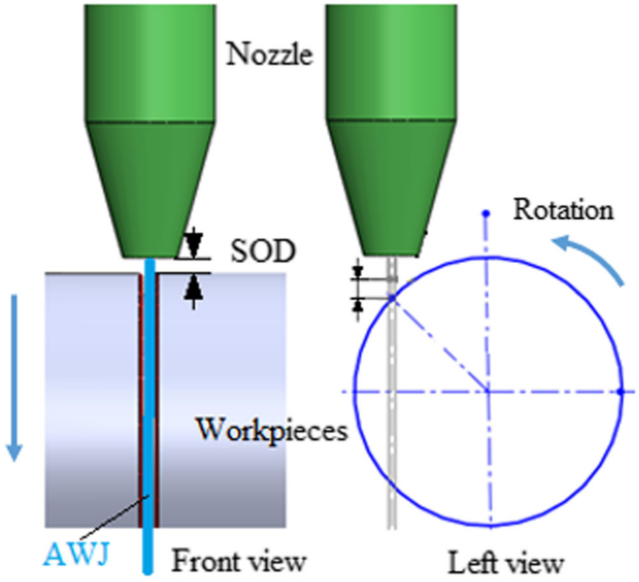


Fig. 1 Schematic presentation of AWJT process

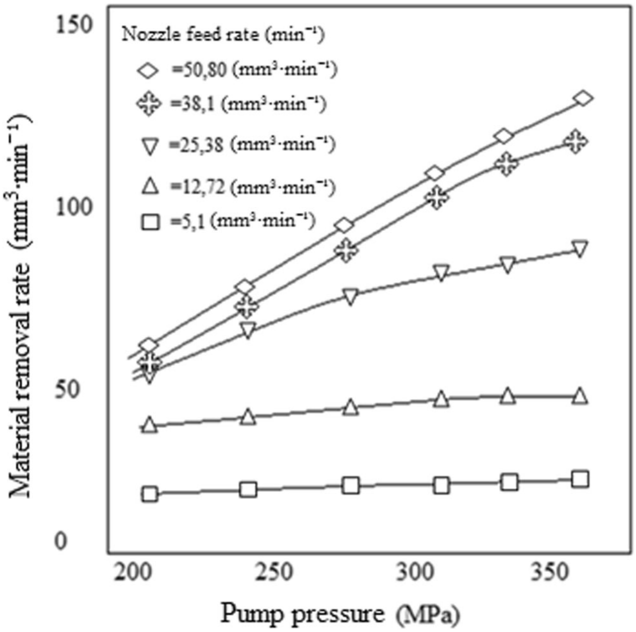


Fig. 2 Variations of pump pressure on the material removal rate [21]

AWJ has a wide area of use ranging from soft and ductile materials to tough and brittle materials. It has become the state of the art in many branches of industry which are manufactured consumer products such as automotive and aeronautics [2–6, 18–20]. Among the studies involving AWJ machining are cutting long, but small-diameter workpieces and making grooves on the hard-to-machine materials such as ceramics, composites, glass, etc. [16–18].

It is inevitable to use an experimental turning testing apparatus for the abrasive water-jet turning (AWJT) process. The literature scan showed that there are several experimental studies which involve AWJT machining method. However,

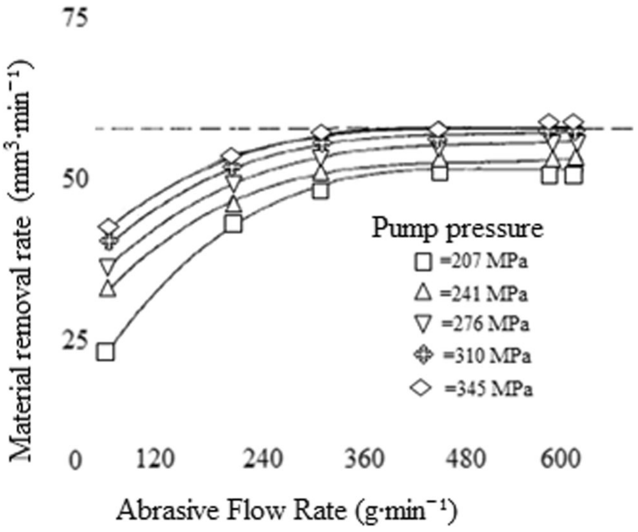


Fig. 3 Variations of abrasive flow rate on the material removal rate [21]

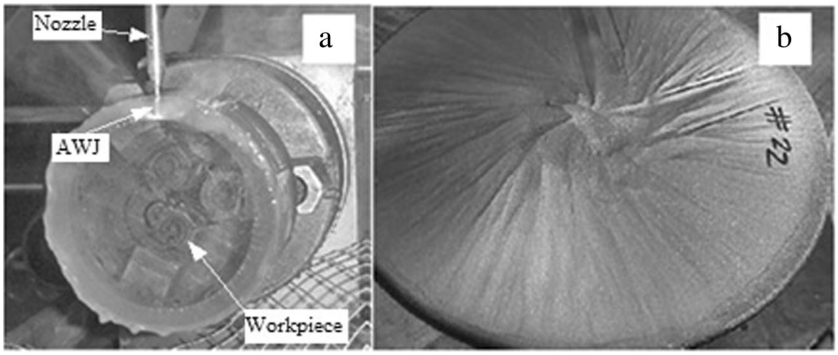


Fig. 4 **a** Image of the facing process, **b** image of the surface roughness created at the center of the workpiece after the facing process [22]

it was found that all the turning testing apparatus used in these studies were similar and that the experimental testing apparatus most of the times did not involve an enclosure for the spindle. AWJ, by turning an advanced manufacturing process, has been developed especially for turning too hard and brittle materials with any geometrical workpieces. AWJ is used in this process. There is a need for a testing apparatus to rotate the workpiece. A general principle of AWJT proses is shown in Fig. 1.

This study explored the literature scan and offers an evaluation in order to guide the further experimental studies which involve AWJT machining.

2 Literature survey of abrasive water-jet turning

Ansari and Hashish [21] studied the impact of AWJT parameters of the volume of material removed when machining the Al6061 alloy. The machining parameters of this study involve different pump pressures, abrasive flow rate, and nozzle feed rate as variables while spindle speed and abrasive size as constant. The material removal rate is increased when the pump pressure and abrasive flow rate were increased (Figs. 1, 2, and 3).

Hashish [22] investigated the trails created on the machined surface by the AWJT process under his study, macro-characteristics of AWJ turned surfaces. In his study, aluminum samples of 25-mm diameter were used. He observed that surface roughness was created on the workpiece after the material removal process. The image of facing process using AWJ on a workpiece is shown in Fig. 4a, while the image of surface roughness created by the increased nozzle feed rate is shown in Fig. 4b.

Macro images of the longitudinal turning study of an aluminum sample taking standoff distance as constant with different nozzle feed rates are shown in Fig. 5. As a result of the experiments, it was stated that material removal rate decreases and the efficiency of the jet suffers when the standoff distance from the workpiece is increased. It was reported that surface roughness increases with the increased nozzle feed rate [22].

Zhong and Han [23] developed the experimental turning testing apparatus shown in Fig. 6 and experimented on a glass material.

Experimental testing apparatus involves a direct connection of the electric motor to the spindle, and no intermediary transfer elements were used. The spindle was insulated against pressure water and abrasive particles. Cylindrical glass samples of 25 mm were used in the experiments. Among the machining parameters were spindle speed, standoff distance, pump pressure, nozzle feed rate, and abrasive flow rate. It was reported that surface roughness and waviness increase with

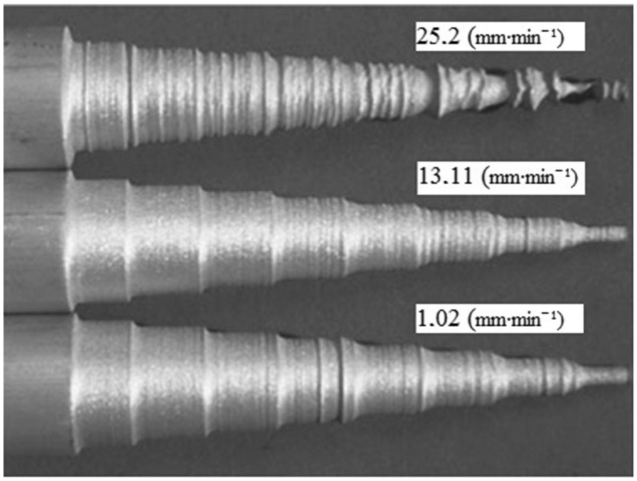


Fig. 5 Macro surface images resulting from different feed rates [22]

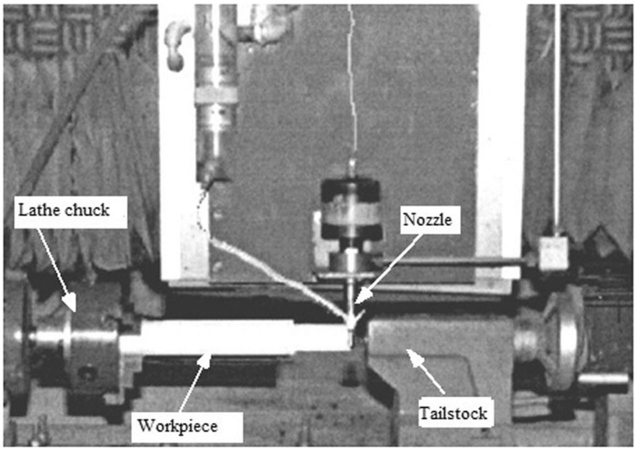


Fig. 6 Image of the AWJ turning the process on cylindrical glass material [23]

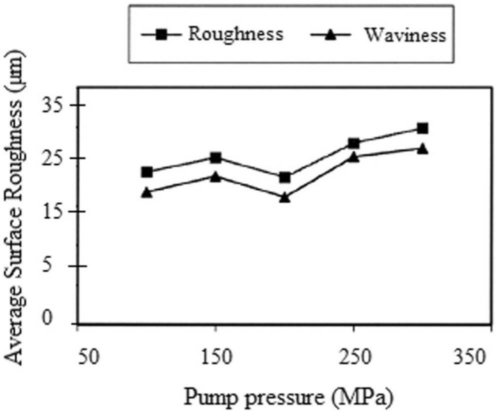


Fig. 7 Variations of pump pressure on surface roughness and surface waviness [23]

the increased nozzle feed rate. An improvement on the surface quality was observed due to increased workpiece rotation speed. The lowest surface roughness value was obtained with low nozzle feed rate and high rotation speed. Increasing the standoff distance resulted in high surface roughness values. It was reported that increased pump pressure leads to increased surface roughness and waviness (Fig. 7) [23].

Andersson et al. [24] compared the AWJ and traditional turning methods in a study exploring the preparation of a test sample using AWJ. Researchers have developed the experimental testing apparatus showed in Fig. 8 for the AWJT.

It was reported that no thermal effects were in place during the sample preparation process, and it was possible to machine several materials with different characteristics with reduced operating times and costs [24].

Uhlmann et al. [25] machined a titanium-aluminum alloy using both AWJ and traditional turning methods. A six-axis AWJ testing apparatus was used during the AWJT process. An experimental turning testing apparatus was developed for the AWJ machining. The schematic presentation of the AWJT process is shown in Fig. 9.

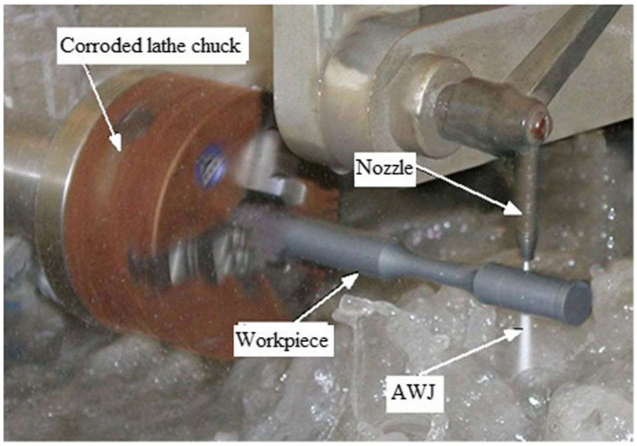


Fig. 8 Image of the AWJ testing apparatus and the machining process [24]

Researchers have taken the abrasive flow rates in a range between 100 and 600 g min^{-1}. A garnet of 80 mesh was used as the abrasive material. The nozzle feed rate was 10 mm min^{-1}, pump pressure was 550 MPa, standoff distance was 50 mm, and nozzle angle was 30° as constant parameters. The results of this study showed that traditional turning process leads to material accumulation on the cutter while causing thermal effects due to friction, and these results were documented. In terms of the volume of material removed, it was shown that AWJT was able to remove, the higher amount of material (13 cm^3). The Ra values obtained from the AWJ process were in a range between 5 and 20 μm [25]. Furthermore, the $Ra = 5$ μm gave a material removal rate (MRR) of 0.3 $\text{cm}^3\ \text{min}^{-1}$. Following a preliminary experiment which involved a final diameter of 4.98 mm and a depth of cut of 3.3 mm resulted in the same surface quality shown in Fig. 10 with an MRR of 0.8 $\text{cm}^3\ \text{min}^{-1}$.

Axinte et al. [26] have investigated the effects of machining parameters of the AWJ process on the grinding disk. The authors have designed an experimental turning testing apparatus in order to perform the turning process. The image of the experimental turning testing apparatus is shown in Fig. 11.

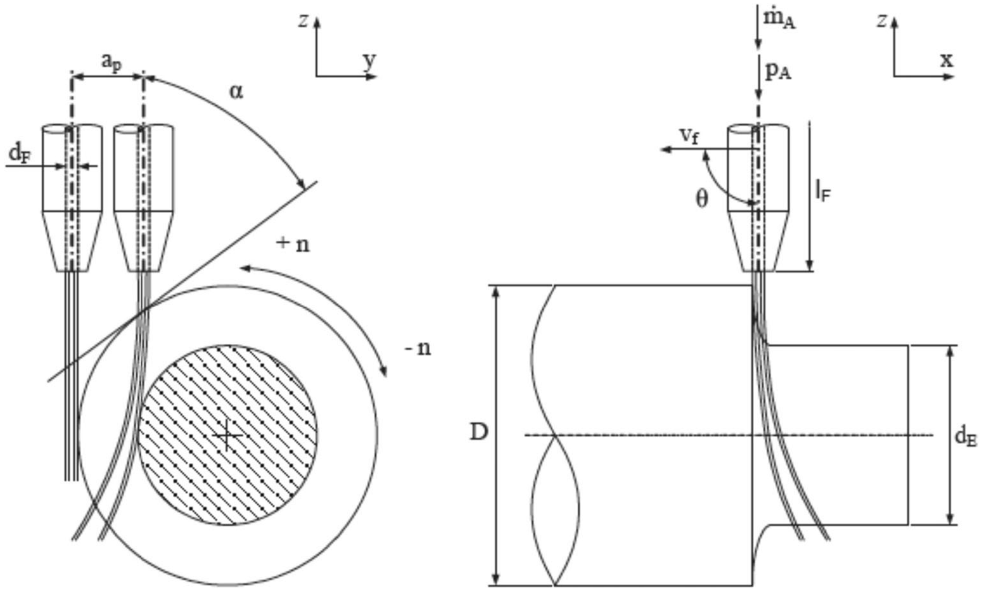
Convex and concave profile geometries were observed on the grinding disk. Researchers reported that AWJ is a new technique. Two different sizes of grinding disks made up of aluminum oxide with 50- and 140-mm diameters were used in the study. A five-axis KMT, 413-MPa ultra-high-pressure AWJ pump was used as the AWJ testing apparatus. The diameter of the orifice was 0.3 mm while the diameter of the nozzle was 1.1 mm. Among the machining parameters, spindle speed was 90–168 min^{-1}, nozzle feed rate on the z-axis was 1–120 mm min^{-1}, standoff distance was 5–60 mm, pump pressure was 69–415 MPa, and the abrasive material was garnet of 80 mesh in size. Results of the study showed that the machining width was reduced from 3.6 to 2.6 mm when the nozzle feed rate was increased to 30 from 10 mm min^{-1}, that the accuracy of the profile cross section of the grinding disk was corrupted with the increased standoff distance, that the accuracy depends on the diameter and focus of the jet, that better results will be obtained with scattered jet formation, and that the jet obtained with 285 g min^{-1} abrasive content results in linear and scattered jet formation [26].

Manu and Babu [27] developed a mathematical model building on the erosion model of Finnie in order to develop an erosion model for AWJT [27]. The model was developed taking the impact angle of the abrasive and water delivered from the nozzle as a function of the decreased diameter. Figure 12 shows the impact angle of the AWJ.

Their experimental study involved Al 6063 as the experiment sample. Researchers have designed the experimental turning testing apparatus showed in Fig. 13 for the AWJT [27].

Among the machining parameters were pump pressure (250 MPa), abrasive flow rate (5 g/s), abrasive size (80 mesh

Fig. 9 The schematic presentation of the AWJT process [25]



garnet), three different nozzle diameters (0.76, 1.2, and 1.6 mm), four different spindle speeds (13, 25, 37, and 50 min^{-1}), 12 different nozzle feed rates (1, 1.5, 2, 2.5, 3, 4, 5, 10, 20, 30, 40, 50 mm min^{-1}), and five different standoff distances (11.7, 10.7, 9.7, 8.7, 7.7 mm). It was reported that the values obtained from the experiments were similar to the ones estimated with the mathematical model [27].

Zohourkari and Zohoor [28] developed a mathematical model in order to estimate the final diameter of the ductile material after the material removal process using AWJ. Researchers have conducted an experimental study using AWJ in order to be able to compare the accuracy of their theoretical findings with actual manufacturing process. Researchers reported that the results of their theoretical model and results of the experiments were similar. According to the results, nozzle feed rate (2 mm min^{-1}), to investigate the effect of traverse speed and to check the efficiency of the propose model, the predicted diameters obtained by the proposed model and Manu model and the comparison with experimental data are shown graphically (Fig 14).

Kartal and Gokkaya [29] have developed a customized experimental turning testing apparatus for the machining of the cylindrical samples using AWJ as shown in Fig. 15. In their study, researchers have developed a safety cabinet for the driving motor and spindle which are affected by the abrasive and water during the AWJ machining. The unfavorable conditions occurring during the turning process were eliminated with the safety cabinet they have developed.

Kartal et al. [30] studied the impact of machining parameters on surface roughness for the turning of a copper alloy (Cu-Cr-Zr) using AWJ (Fig. 16). Pump pressure of 350 MPa, abrasive type of garnet and size of 80 mesh, and nozzle diameter of 1.2 mm are kept constant throughout their experiments. A copper alloy of ∅ 30 and 240 mm in size was used during the experiments. The sample was machined using AWJ for

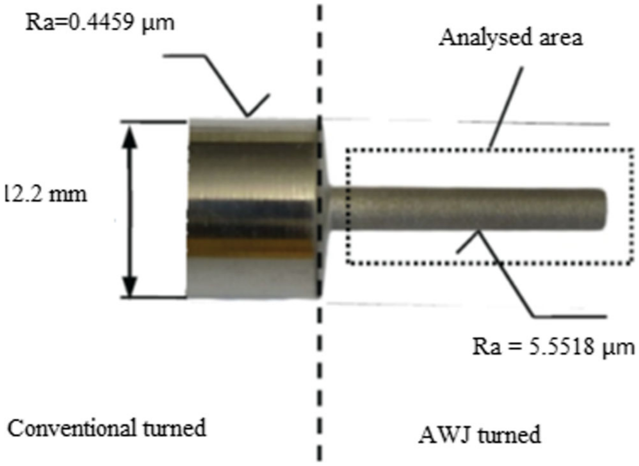


Fig. 10 Conventional and AWJ turning of TNBV5 specimen [25]

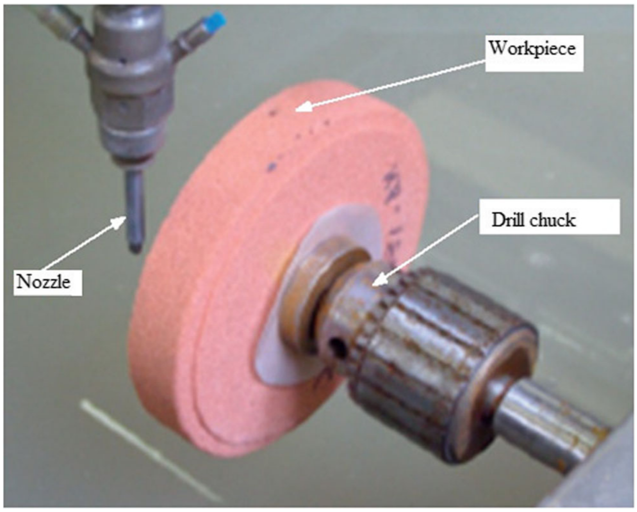
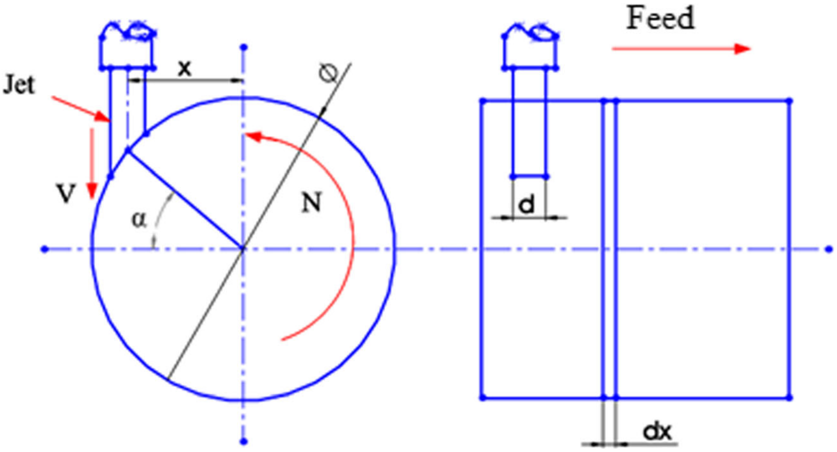


Fig. 11 Image of the experimental turning of the grinding disk [26]

Fig. 12 Image of the impact angle of AWJ [27]



four experiment parameters of nozzle feed rate (10, 15, 20, and 25 mm min^{-1}), abrasive flow rate (50, 150, 250, and 350 g min^{-1}), spindle speed (25, 50, 75, and 100 min^{-1}), and nozzle distance (2, 5, 8, and 11 mm). According to the empirical results, nozzle feed rate and nozzle approach distance led to an increase in *Ra*, giving an *Ra* value of 2.5–5.5 μm.

Kartal et al. [31] processed low-density polyethylene material using AWJT processing parameters with L_{18} orthogonal array. In their study, researchers have conducted material removal work on a polyethylene workpiece using a traditional turning setup. They have reported that the surface roughness of the polyethylene workpiece was rather high and that the material removed tends to stick to the finished surface. However, they have reported that the AWJT process did not involve the unfavorable conditions commonly encountered with the traditional turning process and that the machining area was not exposed to thermal deformation and therefore melting when machining with AWJ. Figure 17a shows the low-density polyethylene material machined with traditional turning method while Fig. 17b shows the low-density polyethylene material machined with AWJ.

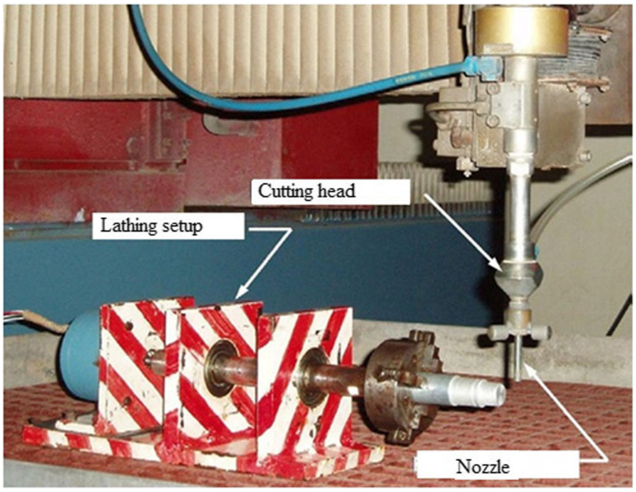


Fig. 13 Image of the experimental testing apparatus for AWJ turning [27]

Kartal and Gökkaya [32] studied the impact of AWJ parameters on both volume of the material removed and the machining depth of AISI 1040 steel. It was reported that spindle speed, nozzle feed rate, abrasive flow rate, and standoff distance have an impact on the material removal volume and machining depth (Fig. 18).

Hloch et al. [33] have experimented on the titanium material of Ø 55 mm for AWJT [33] Garnet of 60 mesh was used as the abrasive material. Among the machining parameters were pump pressure (400 MPa), spindle speed (60 min^{-1}), standoff distance (10 mm), and abrasive flow rate (400 g min^{-1}) which were kept constant while five different nozzle feed rates (1.5, 3, 4.5, 6, and 7.5 mm min^{-1}) were variable. Figures 19a and 20 show the machining conditions of the titanium material while Fig. 19b and 20 shows the titanium material machined with AWJ.

It was stated that the workpiece shown in Fig. 18 was attached to the experimental turning testing apparatus directly without any safety material and then was machined. The results of the AWJT of the titanium material showed that the nozzle feed rate of 1.5 mm min^{-1} given *Ra* of 6.984 μm, while the highest nozzle feed rate gives *Ra* of 8.308 μm. It was reported that the material removal rate was reduced while the *Ra* was increased with the increased nozzle feed rate. Nevertheless, it was stated that AWJT offers significant advantages when it comes to materials which are hard to machine using traditional turning methods [33].

Li et al. [34] studied on the SWJ machining of the high-strength AISI 4340 steel samples. Researchers investigated the impact of machining parameters of the AWJT on the *Ra* and the material removal rate of AISI 4340 steel [34]. Among the machining parameters were nozzle feed rate (3, 6, 12, and 24 mm min^{-1}), pump pressure (200, 260, 320, and 380 MPa), abrasive flow rate (228, 333, 420, and 498 g min^{-1}), nozzle angle (45°, 60°, 75°, and 90°) and spindle speed (97,194, 389, and 777 min^{-1}). Researchers have developed a mathematical

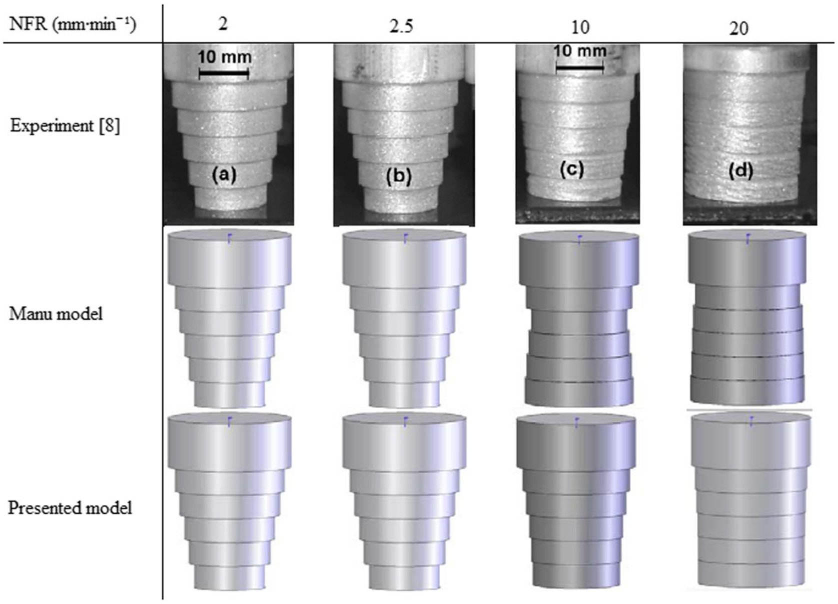


Fig. 14 Image of the comparison between the model of Manu and the experiment results [28]

model building on the Bernoulli equation in order to be able to estimate the *Ra* and material removal rate. The error rate between the mathematical model developed, and the results obtained from the experiments was 2 %. Researchers used the experimental turning testing apparatus showed in Fig. 22 for the AWJT.

The Li et al. [34] have concluded that the nozzle feed rate of 6 mm min^{-1}, pump pressure of 380 MPa, abrasive flow rate of 498 g min^{-1}, AWJ impact angle of 90°, and spindle speed 777 min^{-1} are required for optimal material removal. They have found an increase in the machining depth when the spindle speed is increased. Radial mode (Fig. 21a) and offset (Fig. 21b) mode were compared for the AWJT experiments in order to identify which one is advantageous for the surface roughness and material removal rate. It was found that the radial mode resulted in a rougher surface when compared to the offset mode, and it was stated that the offset mode must be preferred in order to obtain surfaces with reduced roughness.

Zohourkari et al. [35] have investigated the impact of AWJT parameters on the material removal rate. Among the AWJT parameters were pump pressure (130, 200, 250, 300, and 370 MPa), abrasive flow rate (106, 230, 324, 422, and 557 g min^{-1}), nozzle feed rate (3, 5, 7, and 9.8 mm min^{-1}), and spindle spin (160, 300, 400, 500, and 640 min^{-1}). AA 2011-T4 aluminum alloy of Ø 30 mm was selected as the workpiece. Researchers have used the experimental turning testing apparatus showed in Fig. 21 for the AWJT of the AA 2011-T4 aluminum alloy.

Researchers have conducted variance analysis, response surface methodology (RSM), and multiple regression analyses in order to define the impact of the machining parameters on the material removal rate. It was reported that any parameter other than the spindle speed had a statistically significant impact on the material removal rate and that the nozzle feed rate is the most significant parameter among the others [35].

Kartal and Gökkaya [36] developed a custom experimental turning machine in order to investigate the machinability of

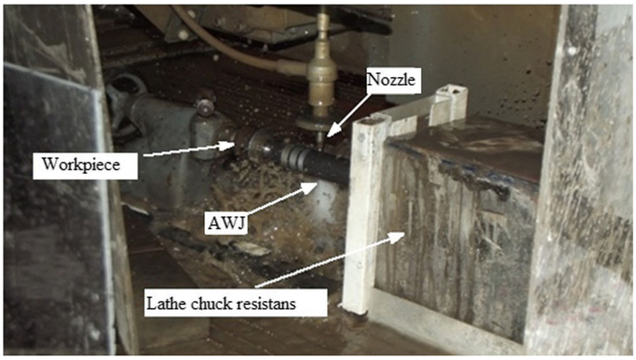


Fig. 15 Image of the experimental turning testing apparatus developed for AWJ turning [29]

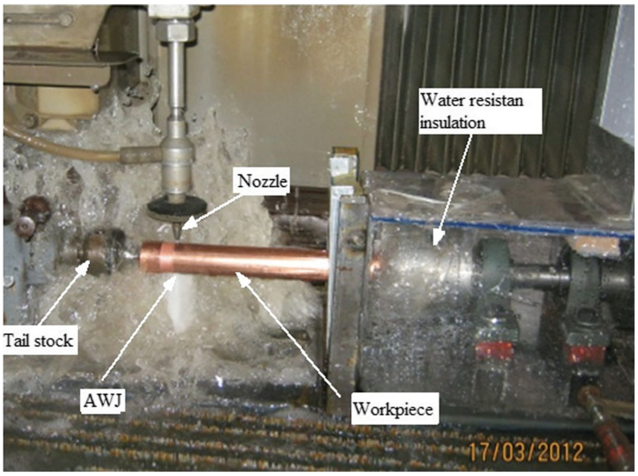


Fig. 16 Image of the AWJ turning process on copper alloy [30]

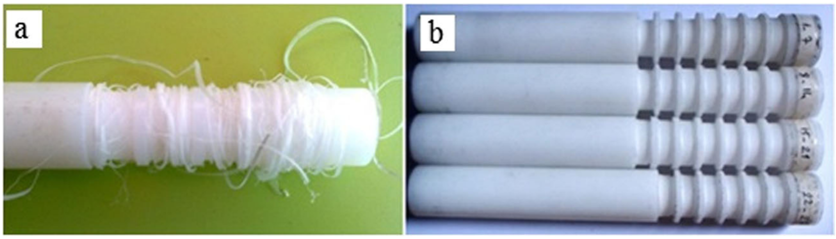


Fig. 17 Polyethylene material **a** machined with classical lathe, **b** machined with AWJT [31]

the AISI 1050 steel material using AWJT. Among the machining parameters were nozzle diameter (0.7 and 1.3 mm) nozzle feed rate (5, 25, and 45 mm $\min^{-1}$), abrasive flow rate (50, 200, and 350 g $\min^{-1}$), spindle speed (500, 1500, and 2500 $\min^{-1}$), and standoff distance (2, 10, and 18 mm). Experiment design followed Taguchi L_{18} and was conducted accordingly. The impact on the machining depth of the AWJ parameters was explored using the variance analysis. A linear regression model was presented, utilizing the interaction between factors found to affect machining depth in this study. The study concluded that high levels of material removal are possible with AWJT process in a single pass with no production defects. The most significant effects on the machining depth were observed with nozzle feed rate, abrasive flow rate, and spindle speed, respectively. Nozzle feed rate and abrasive flow rate had an impact on the machining depth by 75 and 14 %, respectively, according to the variance impact percentages. Using the factors affecting the machining depth, a linear regression model was proposed and the data obtained from the regression model was compared with the data obtained from the experiments (Fig. 23) [36].

3 Discussions and the future status of AWJT

Several experimental attempts were made in the AWJT machining, design, and applications since the day it was first developed. Researchers have been contributing to the development of this technology yet this field is open to research on many different levels due to its complex structure. AWJT offers a suitable option for the needs of today's applications. Several experiments were conducted on the materials such as modern composites, glass, and ceramics which receive growing attention in many engineering applications. AWJT is replacing traditional machining methods such as ultrasonic machining, laser beam machining, and electro-discharge machining which are used for hard-to-machine and firm materials for it offers a faster process which does not damage the surface integrity of the material. Additionally, the options for combined use of other material removal methods with AWJT were studied in order to expand the application and machining characteristics of AWJT. One of the main focuses of the AWJT research is the optimization of the process variables. Researchers have excluded several important factors such as nozzle size and nozzle diameter, which play an important role in the performance characteristics. Literature review shows that the studies available on this subject focus on a single factor when working on AWJT optimization. There are no studies on a multi-objective optimization of the AWJT, and it is believed that this will be the focus of the future experiments. Nevertheless, several experimental tools currently used for optimization (Taguchi method, artificial neural networks, genetic algorithms, response surface methodology (RSM), etc.) may be combined in order for us to be able to make use of the advantages of these tools simultaneously. Moreover, the literature review revealed that there are no studies for the multiple response optimization of process variables which calls for future research on this field. A limited amount of studies available in the literature took machining parameters such as nozzle feed rate, abrasive flow rate, abrasive size, spindle speed, nozzle diameter, and standoff distance into account while a combined study on parameters such as pump pressure, abrasive material, and cutting depth is still missing. Therefore, this field calls for further investigation. Several new techniques are reported in order to improve cutting performance. Among these techniques are forward angling, controlled nozzle oscillation, and multi-pass cutting which also require further investigation. As studies focusing on cutting depth will be important for ductile material applications,

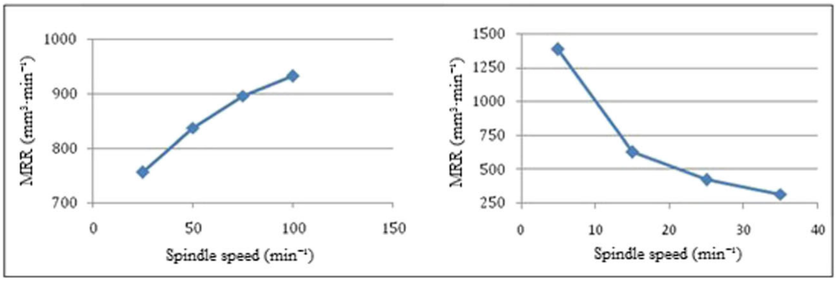


Fig. 18 Graphic representation of the impact of spindle speed and nozzle feed rate on the material removal rate [32]

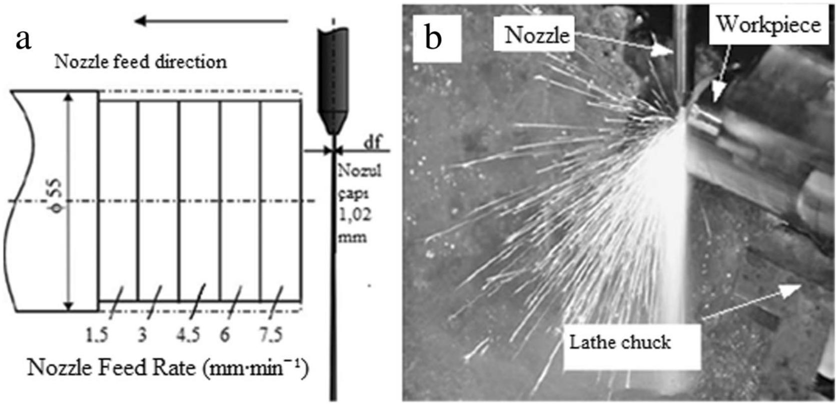


Fig. 19 **a** The theoretical display of the machining conditions, (**b**) the titanium material being machined with AWJT [33]

application angle needs to be included in these studies. Modern machines are now able to cut from different angles (3D, multi-axial machines, etc.). It is of utmost importance to evaluate the possibility to cut a free-form object as it is the case for traditional machining. Alternative technologies need to be investigated in order to overcome grit contamination and dirt accumulation. As a versatile machining technique, AWJT requires a fully automated monitoring solution if it is to be used in many more industrial applications. However, there are not enough research on the automated monitoring of AWJT process which aims to develop a closed-cycle control strategy. Nevertheless, there is a need for advanced experimental testing apparatus which eliminates the ripples in the water-jet pool, which are resistant against abrasive particles and corrosion, and which will operate underwater for silent operation. Development studies are continuing in order to make AWJT process more economic and standardized. Combining process modeling studies for several materials with detailed experimental studies will bring convenience to these efforts. With micro-AWJ, a material can be tried turning. AWJ turning processes work done under the water level. Five-axis turning operations can be done with AWJ. A turning of cylindrical parts with hole-punching operation can be performed.

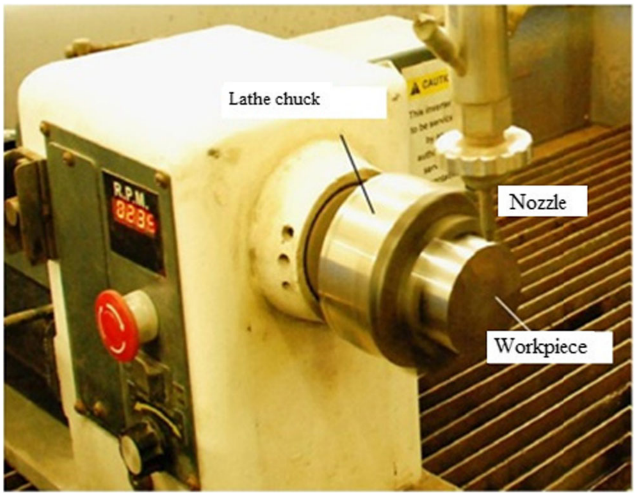


Fig. 20 The experimental testing apparatus for AWJ turning [34]

4 Conclusions

A review of the effects of AWJT process parameters has shown that

- The literature scan showed that there are several experimental studies which involve cutting and erosion using a turning device. All the turning testing apparatuses used in these studies were similar and that the testing apparatus most of the times did not involve an enclosure in order to protect against pressure water and abrasive particles.
- Using a lathe chuck without any enclosure makes the turning process even harder to perform.
- During the machining process, parameters such as spindle speed, nozzle feed rate, standoff distance, abrasive type and size, nozzle diameter, abrasive flow rate, and pump pressure have an impact on the surface roughness and waviness of the workpiece and material removal rate.
- AWJ machining is a cold-working process and does not lead to increased heat at the cutting area employing the erosion property of the fluid on the workpiece. Thus, no heat building in the cutting area is an important factor for the material removal process, which has significant consequences for the machining performance and the surface quality of the workpiece.
- It is possible to conveniently machine materials such as miniature metals or nonmetals which are otherwise hard to machine using AWJT.
- Garnet, silicon carbide dust, and aluminum oxide are most commonly used as abrasive materials.
- Most commonly, garnet of 80 mesh was used as the abrasive material. Increased pump pressure leads to increased surface roughness and waviness.

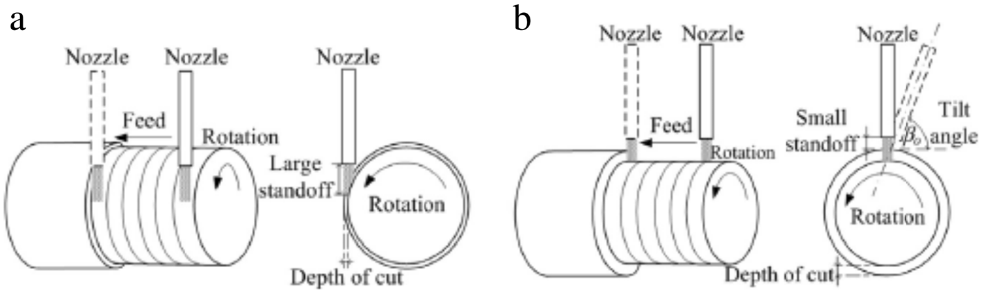


Fig. 21 AWJT techniques: **a** offset mode, **b** radial mode [34]

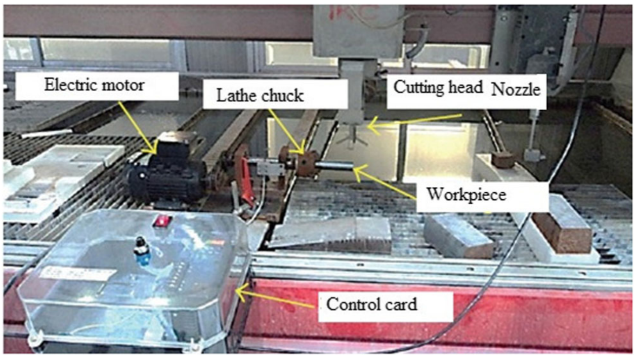


Fig. 22 Image of the experimental turning testing apparatus for AWJ turning [35]

- Increasing the nozzle feed rate and standoff distance results in increased average surface roughness, while increasing pump pressure and abrasive flow rate results in increased material removal rate.
- The spindle speed, nozzle feed rate, abrasive flow rate, and standoff distance have an impact on the material removal volume and the machining depth during the AWJT.
- It is possible to use offset mode and radial mode as AWJT techniques, and it was found that offset mode has a more significant effect on the surface roughness and waviness.
- It is possible to reduce the noise level at the AWJ machining process.

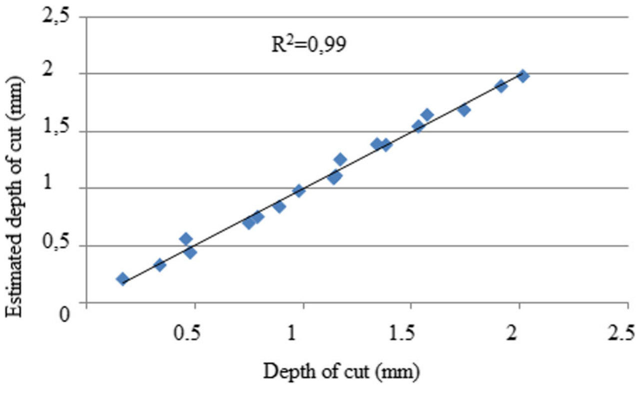


Fig. 23 Graph of the comparison between experimental and estimated machining depth values in terms of their impact on the machining depth when machining AISI 1050 steel material using AWJ [36]

Acknowledgments The authors are deeply grateful for the financial support of Kastamonu University Scientific Research Fund, Grant No: KUBAP-04/2015–01

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