Int. J. Adv. Res. in Water Resources and Hydraulic Engineering
Volume 6, Print Issue 1 - 2023, Pg. No. 13-19
Peer Reviewed Journal

Research Article

Advancements in Abrasive Waterjet Machining: A Comprehensive Review of Current Research and Development

Rashmi Pandey,[1] Payal Singh[2]

[1]Assistant Professor, Civil Engineering Department, Barkatullah University, MP, India.
[2]M.tech Student Civil Engineering Department, Barkatullah University, MP, India.

I N F O

Corresponding Author:
Rashmi Pandey, Assistant Professor, Civil Engineering Department, Barkatullah University, MP, India.
E-mail Id:
pandeydrrashmi3@gmail.com
How to cite this article:
Pandey R, Singh P. Advancements in Abrasive Waterjet Machining: A Comprehensive Review of Current Research and Development. *Int J Adv Res Wtr Resrs Hydr Engg* 2023*;* 6(1): 13-19.

Date of Submission: 2023-03-11
Date of Acceptance: 2023-04-21

A B S T R A C T

Cutting components composed of hard materials that are notoriously challenging to cut can be accomplished using a relatively recent machining technique known as abrasive waterjet machining, or AWJM. A production technique that is both reasonably inexpensive and environmentally friendly and has a high rate of material removal is produced by a concentrated jet of water travelling at a high speed through which abrasive particles have been suspended. Abrasive waterjet machining has consequently rapidly emerged as one of the most well-known industrial technologies. The origins and development of AWJM have been thoroughly investigated throughout the previous ten years. It summarises the findings of AWJM's research into process monitoring and control, variable optimisation, better performance metrics. There have been many AWJM industrial uses for different types of material documented, each with their own distinct set of variations. Another subject explored in this essay is the potential course of future research in the same area.

Keywords: Process Parameter, Process Optimization, Monitoring, Control

Introduction

The use of an abrasive waterjet for cutting became widely available in the late 1980s. The first technique of its kind to be commercialised was cutting using an abrasive waterjet in the early 1970s. At the start of the 1980s, AWJ machining was not economically viable. A reliable full-scale production technique has been developed using contemporary abrasive jet technology.

A high-velocity water jet and abrasive particles are used in AWJ machining to remove workpiece material. In this process, the water jet erodes the substance it comes into contact with. A modern industrial material-processing technique is AWJ. Low cutting forces, exceptional flexibility, barely perceptible thermal distortion are all characteristics of AWJ. In contrast to conventional machining techniques, the workpiece does not form a heat impacted zone (HAZ). The advantages of this procedure make it a strong candidate for automation.

High cutting speed and efficiency, ability to properly cut intricate shapes of even non-flat surfaces at tight tolerances, little heat accumulation, low deformation stresses inside the machined item, quick switching between cutting patterns under computer control, etc. Additionally to cutting, this tool is utilised for cleaning, threading, drilling, milling, turning, hybrid machining. Its adaptability makes all different machining processes easier.

Applications for AWJM's adaptable capabilities include processing materials including titanium, steel, brass, aluminium, stone, inconel, various varieties of glass and composites. As a relatively new manufacturing technique, abrasive waterjet machining has not yet undergone sufficient refinement to enable the achievement of its full potential. In this publication, ten years of AWJM research are reviewed. It starts by providing an overview of the high velocity erosion technique before highlighting some of its applications for various materials. The main academic topics of the study are AWJM process modelling and optimisation and process monitoring and control. The report's conclusion makes suggestions for AWJM's future research.

Theory

The AWJM process

Abrasive water jets are defined as water jets that contain some sort of abrasive material. Abrasives are specialised materials, such as aluminium oxide, silicon carbide, sodium bicarbonate, dolomite,/or glass beads, in the form of grain-sized particles. These substances are adaptable. Erosion is basically what happens when water jets cut. Two alternative techniques are used, depending on whether the eroding material is brittle or ductile. High pressure (4,000 pressures) and high speed (about 900 metres per second) water jets are fired into the mixing chamber through a tiny aperture. Abrasive particles and a water jet are drawn into the nozzle simultaneously in the mixing chamber. The nozzle expels air, abrasive particles, water. When abrasive particles with a lot of kinetic energy and velocity hit a workpiece's surface, they wear and machine. Figure 1 shows how abrasive waterjet cutting works.

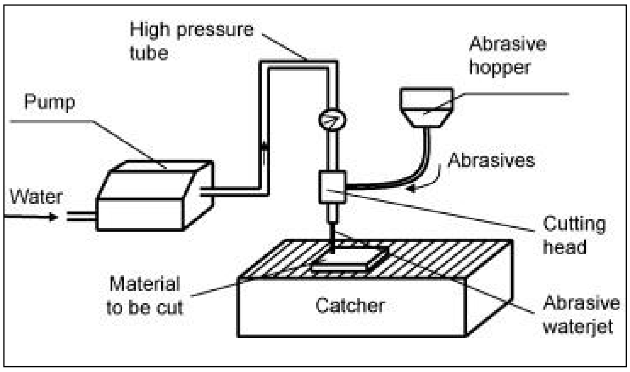

Figure 1.Schematic of an abrasive waterjet cutting system

The operational elements of AWJ machining include polishing, drilling, turning, milling, three-dimensional machining. According to research by Zhu and colleagues, AWJ followed by lapping may be able to produce precise surface machining with less pressure and little erosion angle. Solid drill bits are challenging to use since modern materials are hard and brittle. When the hole is smaller than 0.04 cm and is angled shallowly to the surface, mechanical drilling struggles. Additional difficulties are caused by material qualities.

An AWJ can drill a beautiful hole if the pressure-time profile and abrasive flow rate are carefully managed. AWJ is superior to lasers and EDM when drilling small holes with a large aspect ratio, especially at shallow angles. During the turning operation, the AWJ is moved axially and radially while the workpiece is rotated. Ansari and Hashish shown that hard materials can be produced by spinning with an abrasive waterjet.

Hashish researched feed rate, orifice size, abrasive flow rate, jet pressure, abrasive particle size. Manu and Babu have developed a technique to forecast the final diameter while taking into account local impact angles during AWJ rotation.

Abrasive-waterjet milling holds a lot of promise in the application and offers advantages that no other milling method now in use can match, according to the results of Hashish's[18] preliminary milling tests. A wide range of institutions' researchers have demonstrated that, when a mask is utilised, AWJ technology is capable of executing precision milling operations in a number of materials, including ceramics, titanium, aluminium. According to Paul et al.'s study, linear motion milling can produce carbon steel parts with a depth variation control of 0.04 millimetres. Cylindrical products can be machined in three dimensions with a minimum of effort by combining cutting, turning, drilling into a single machine setting.

AWJ can be used in conjunction with EDMing, plasma cutting, routing, flame cutting (oxy-fuel cutting). Pre-drilling with a waterjet improves EDM performance. For cutting Y-PSZ substrates (LWJ), Kalyan Sundaram et al. investigated an unconventional hybrid laser/waterjet method. combining a waterjet without abrasives with a CO2 laser. The thermal shock resistance of the Y-weak PSZ is used in the hybrid technique to limit fracture progression along the cutting line. Heat is immediately localised and quenched by laser and waterjet.

AWJM Applications

In this section, the applicability of AWJM in industrial applications is examined.

Ceramic High-Tech Materials

Ceramics are challenging to machine using conventional techniques because of their high hardness and strength. As a result, ceramics processing now includes the use of laser, ultrasonic, electro discharge machining. These technologies for machining ceramics each have benefits and drawbacks. On a 13mm plate, plasma flame and laser cutting cannot attain the necessary level of accuracy because they leave behind a thick, hard crust.

Composites

Despite their great strength potential, conventional manufacturing procedures cannot successfully make Particle Reinforced Metal Matrix Composites (PRMMCs) due to tool wear brought on by the stiff reinforcement.

MMCs are being machined via abrasive water jet (AWJ) machining, laser cutting, electro discharge machining. AWJM of PRMMC was compared by Muller and Monaghan to LBM and EDM (EDM). According to the investigation, AWJ cutting did not result in heat deterioration or burr attachment.

Stones Made of Marble and Granite

Due to the special qualities of granite, such as its resilience and resistance to heat, cold, dampness, fractures, stains, scratches, it is widely used as a dimensional stone in contemporary public and commercial applications. Rocks and other comparable materials can be chopped using the new abrasive water jet (AWJ). This device can drill, weaken, cut rocks. Due to its precise shape cutting, greater surface polish, reduced kerf widths, increased tool life, complex free-form cutting, process automation, lack of dust, better working conditions and environment, the technology has the potential to be used in manufacturing, civil, mining engineering. The technology is applicable to manufacturing, civil, mining engineering because of these characteristics. For the milling and processing of natural stone, these characteristics make the technology more environmentally friendly than circular sawing. Some Examples:

Glass

Glass products can help with a number of design and technical issues. A designer should have these materials on hand since they can be used in situations where metals and plastics cannot. MAJM enables the efficient and affordable micro-machining of delicate materials, such as glasses. Fan et al. created anticipated mathematical models for employing an abrasive air jet to drill tiny holes and cut tiny channels in glasses. In a prior study, Dadkhah Pour et al. examined the removal of debris during AWJ milling of anamorphous glass channels.

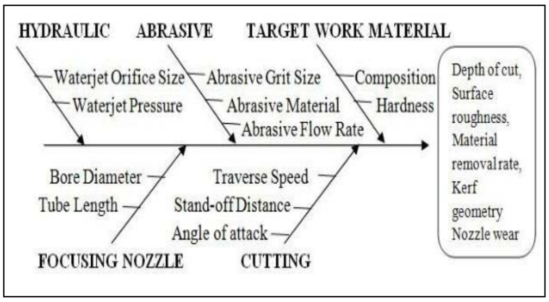

Figure 2.Process parameters influencing the AWJ cutting process

Major Areas of AWJM Research

The authors divided the many AWJM investigations into two categories: modelling and optimization, monitoring and control.

Process modelling and optimization with AWJM software

AWJM models assist us in comprehending this intricate procedure. Studies using modelling examine system behaviours. A system's input and output parameters are connected by a set of equations in a mathematical model of the system. To simulate and optimise AWJM, the majority of the study used statistical Design of Experiments (DOE) techniques such the Taguchi method and the response surface approach. Few scholars have modelled and optimised AWJM using techniques including simulated annealing, artificial bee colonies, fuzzy logic, genetic algorithms, grey relational analysis, artificial neural networks (ANN).

The efficiency and effort of machining are determined by AWJ process parameters. Included are hydraulic, material, abrasive, cutting parameters. Numerous process parameters are shown in Figure 2. Cut depth, surface roughness, material removal rate, kerf shape, nozzle wear are examples of target parameters. The selection of AWJM machining settings is based on an analysis of the connections between process parameters and performance measures. The impact of process factors on performance metrics is covered in the next section.

Process Parameter's Effect on Cut Depth

Models were developed and validated by Aydin et al. for AWJ machining of granitic rocks. Regression analysis and Taguchi were employed in these models. When traverse speed and abrasive size were increased, cut depths decreased. Cut depths grow as abrasive mass flow rate and water pressure rise, although standoff distance has little of an impact. Several writers tune process variables for glass, cast iron, aluminium using the Taguchi technique and regression analysis, including water pressure, nozzle traverse speed, abrasive flow rate, standoff distance, abrasive size. When cutting alumina ceramics with controlled nozzle oscillation using a multipass abrasive waterjet (AWJ), Wang employed the Taguchi technique to examine the depth of cut. For the depth of cut, predictive models were created. Ceramics made of alumina were examined. When compared to single-pass cutting, multi-pass cutting with nozzle oscillation cutting can enhance cut depth by 50.8%. Jegaraj and Babu investigated how changing the orifice and focusing tube bore might affect the effectiveness of an abrasive waterjet for cutting 6063-T6 aluminium. These investigations found. Empirical and fuzzy models were developed using Taguchi's experimental design. Also employed is fuzzy logic. Using a full factorial experimental approach, Wang and Guo developed a semi-empirical model for predicting jet penetration in AWJ cutting of polymer matrix composites. Modelling the penetration of jets. They demonstrated how the model can deliver accurate forecasts for process planning. A novel method for cutting granite utilising fuzzy logic and the Genetic Algorithm (GA) was reported by Chakravarthy and Babu.[45] The ideal process parameters for AWJ granite cutting are found using this technique.

Variable Impacts on Surface Roughness

Azmir and Ahsan[46] investigated the impact of machining settings on surface roughness (Ra) of a glass/epoxy composite laminate using Taguchi's design of experiments and analysis of variance. A machine's settings can alter surface roughness. Response surface techniques were utilised by Zohoor and Nourian to investigate nozzle wear and surface roughness. They created regression models to take their results into consideration. The surface roughness of composites made of granite and polymer matrix is optimised by several studies using the Taguchi approach and regression analysis. Surface roughness was improved by Yusup et al. using the artificial bee colony (ABC) technology. Control parameters were traverse speed, waterjet pressure, standoff distance, grit size, flow rate. They contrasted real machining, regression, ANN, GA, ABC (SA) with simulated annealing. SVM and GRA were used by Ashanira et al. to forecast surface roughness. Surface roughness is most affected by traversal speed, which has the least effect on standoff distance. Utilising an ANN model, Yuyong et al. computed cutting speed while accounting for water pressure, abrasive flow rate, work piece thickness, expected surface quality grade. They discovered that altering the water jet's cutting speed can have an indirect impact on the surface quality of the component. Experimental, regression analysis, genetic algorithm, simulated annealing surface roughness were compared by Zain et al. In that investigation, the researchers employed the aluminium alloy AA 7075 and determined the process parameters traverse speed, waterjet pressure, standoff distance, abrasive grit size, abrasive flow rate. In order to investigate the impact of various parameters on the surface finish of AISI 4340 and Aluminium 2219, Iqbal et al. created a thorough factorial design of testing. These studies looked at how various traits affected surface polish.

Process Parameter's Effect on Kerf Geometry

Ramulu and Arol evaluated the impact of jet traverse speed, abrasive flow rate, water pressure, abrasive grain size, grit flow rate on a graphite/epoxy laminate's surface roughness and kerf taper using the Taguchi technique. They created a mathematical model based on regression to take this influence into account. To develop empirical models for predicting and optimising productivity and kerf quality, Wang and Wong carried out a regression study. Chen investigated AWJ cutting of ceramics with an alumina base utilising statistical and theoretical techniques. To forecast and optimise AWJ kerf characteristics, they have created formulas. Wang researched the waterjet-cut polymer matrix composite sheets' machinability and kerf characteristics. To forecast top kerf width, taper angle, water pressure, nozzle traverse speed, standoff distance, he developed a regression equation. Colemanite powder was put to the test by Cosansu and Cogun in abrasive waterjet cutting (AWJC) with varying traverse rates and abrasive flow rates. Comparisons were made between garnet for Al7075, marble, glass, Ti6Al4V, a composite. The effects of traverse speed, abrasive flow rate, standoff distance, water pressure, granite texture on kerf angle were studied by Karakurt et al. using the Taguchi technique. According to a statistical analysis, standoff distance and traverse speed have the biggest effects on granite kerf angle. Research on the AWJ kerf taper angle utilised to create two different composites was presented by Shanmugam and Masood. Both glass epoxy and graphite cloth impregnated with epoxy were employed. They demonstrated how industrial kerf taper might be anticipated and taken into account when planning designs and processes.

Process Parameter Influence on Material Removed Per Unit of Time

To ascertain the effects of orifice and nozzle diameter on the rate of an abrasive water jet's ability to cut 6063-T6 aluminium alloy, Jegaraj and Babu carried a full factorial testing. A 0.4 mm aperture considerably slows material elimination, which is slowed down by larger orifice sizes. Conventional research techniques were used to examine surface roughness and material clearing rate. The quantity of abrasive particles implanted in pure titanium surfaces was quantified by Arola and Hall using energy dispersive X-ray analysis. Hocheng and Chang talked about the kerf and material lost during the waterjet cutting of the ceramic plate. The crucial hydraulic pressure, abrasive flow rate, traverse speed for through-cutting were determined. They also demonstrated that the primary waterjet element that influences the rate of material removal is particle speed. The factors that affect the rate of material removal, such as waterjet pressure, abrasive flow rate, traverse rate, standoff distance, number of passes, have been extensively studied.

Process Parameter affects Nozzle Wear

In an abrasive water jet environment, nozzle wear is affected by the AWJ system's parameters as well as the nozzle's geometric and material parameters. Hashish has tested soft (steel) mixing tubes with a mild abrasive (garnet sand) and hard (tungsten carbide) tubes with a tougher abrasive. Both tube types were abrasion-tested (aluminum oxide). Using actual machining settings, he's assessed a range of tool materials, including carbides and ceramics. Nanduri used waterjet abrasion to study nozzle wear. Wear is influenced by the bore eccentricity, nozzle eccentricity, inlet depth, inlet angle, nozzle diameters. Nanduri measured the length, inlet angle, diameter, orifice diameter, abrasive flow rate, water pressure in order to study nozzle wear. He developed an empirical model to calculate the weight loss of the ROCTEC R100 and REXP nozzles based on these results.

Process monitoring at AWJM

A wear sensor system developed by Kovacevic allows for almost real-time monitoring of abrasive waterjet (AWJ) nozzle wear. In order to account for the increase in the internal diameter of the AWJ nozzle, the CPU is programmed to analyse wear data, determine the direction of wear propagation, relay that information to the controller. Kovacevic and Mohan

Using isotherms and line scans, the thermal energy distribution in an AWJ-cut workpiece was examined. The wear of the AWJ nozzle was observed using infrared thermography. Kovacevic and Zhang developed a fuzzy method based on work piece force and nozzle diameter to identify wear. This hazy approach determined whether the nozzle was functional. Kovacevic demonstrated how to measure the depth of penetration of an abrasive waterjet using the work piece normal force, how force-feedback control may be used to modulate the depth of penetration. Kovacevic also demonstrated how normal force may be used to calculate the depth of a jet penetration. A method for monitoring and compensating for waterjet wear was proposed by Mohan and Kovacevic. This method takes frequency-domain acoustic data from the jet as input. The artificial neural network used by this system was created utilising the back-propagation method. During AWJ machining, Jurisevic discovered a connection between stand-off distance and straight-cut sound. To measure the standoff distance, they have developed a strategy and monitoring system. A system with adaptive-control constraints and AWJ was able to successfully implement some of the ideas that were proposed. Jegaraj and Babu looked at how changing the orifice and focusing tube bore would affect the performance of an abrasive waterjet on aluminium alloy 6063-T6. The performance of an abrasive waterjet was investigated in this study in relation to differences.

In order to attain the desired cutting performance while taking orifice and focusing tube bore into consideration, they created a fuzzy model utilising Taguchi's design of trials after analysing the AWJ's cutting efficacy. The focusing nozzle's bore diameter was monitored by machine vision, process parameters were changed using a neuro-genetic approach by Srinivasu and Babu. Two methods are listed below. An integrated strategy for adaptive AWJ cutting control is produced by combining monitoring and control methodologies. For waterjet monitoring, Axinte and Kong employ multiple acoustic emission sensors. The method increases the precision and calibre of machined surfaces by modifying cutting conditions (such as feed speed). A fuzzy logic (FL) expert system for AWJM depth of cut was developed by Vundavilli et al. Nozzle diameter, water pressure, abrasive mass flow rate, jet traverse speed all affect the cut depth. A control algorithm was proposed by Zohoor and Nourian to take nozzle diameter's effect on cut quality and kerf width into consideration. The desired nozzle offset is generated using this programme. The input jet energy that resulted in part erosion was measured by Rabani et al. using an online machine axis encoder and an aural emission sensor on the target work piece surface.

Future AWJM Research

Most of AWJM's primary research areas have been covered in this article. More research is required because the process is so complicated. A useful machining technique for modern applications is AWJM. Engineering applications are on the rise, according to experiments on AWJM of modern ceramic, glass, composite materials. It has taken the place of labor-intensive processes including ultrasonic, laser beam, electro discharge machining that damage the material's surface integrity. In order to increase the scope of its application and enhance its machining properties, AWJM has also investigated combining with other material removal techniques. The main goal of AWJM is to optimise process variables. Many important details were overlooked by the researchers during the analysis, including the orifice width and nozzle size, both of which would have had an impact on the findings. The overwhelming majority of this field's research demonstrates that, in order to maximise AWJM, researchers have concentrated on a single quality factor. The best process parameter value for one quality attribute may degrade the quality of other quality attributes and the final product as a whole. The authors acknowledged multi-objective AWJM optimisation as a possible study area but could not find any literature on it.It is possible to combine several experimental optimisation techniques (such the Taguchi method and RSM) to make advantage of both. There is no published literature on multi-response optimisation of process variables; more research is required.

Orifice and focusing tube bore variation has been addressed utilising a variety of monitoring and control techniques. These formulas are based on mathematical models, professional knowledge, or artificial intelligence. Very few studies demonstrate the ideal standoff distance during

AWJ cutting by only listening to the sound and ignoring other aspects. More personnel are needed in this industry.

Conclusions

1. Recent developments in AWJM and available research opportunities are discussed in this article. According to what has been said, we can say:
2. The AWJM method is becoming more popular in machining, particularly for materials that are challenging to cut. Due to its advantages over conventional and unconventional procedures, the machining industry is thinking about adopting it.
3. AWJM is suitable for milling, turning, drilling, polishing, cutting. In order to expand its applicability, AWJM has researched the advantages of combining its operations with those of other material removal techniques.
4. During AWJ cutting, monitoring and control rarely identify the appropriate standoff distance. There is no proof that similar research was conducted on other features. More personnel are needed in this industry.
5. Traverse speed, waterjet pressure, standoff distance, abrasive grit size, abrasive flow rate have received the most attention in research. Orifice diameter and nozzle size have not been the subject of many investigations.
6. The majority of optimisation studies have concentrated on enhancing a specific quality parameter, such as cut depth, surface roughness, material removal rate, kerf shape, nozzle wear. This study enhances one desirable quality. The optimisation of AWJM for power consumption, dimension accuracy, or multi-objective optimisation has not been studied. Sooner or later, more investigation is required.

References

1. Kovacevic, R.; Hashish, M.; Mohan, R.; Ramulu, M.; Kim, T.J.; Geskin, E.S. (1997) State of the art of research and development in abrasive waterjet machining. Transactions of ASME. Journal of Manufacturing Science and Engineering, 119: 765-785.
2. Selvan, M.C.; Raju, N.M.; Sachidananda, H.K. (2012) Effects of process parameters on surface roughness in abrasive waterjet cutting of aluminum. Frontiers of Mechanical Engineering 7(4): 439–444.
3. Akkurt, A.; Mustafa, K. K.; Ulvi, S.C.; Fevzi, E. (2004) Effect of feed rate on surface roughness in abrasive water jet cutting applications. Journal of Materials Processing Technology, 147: 389–396.
4. Metin, K.; Erdogan, K.; Omer, E. (2011) Prediction of surface roughness in abrasive waterjet machining of particle reinforced
5. MMCs using genetic expression programming. The International Journal of Advanced Manufacturing Technology, 55: 955–968.
6. Caydas, U.; Hascalik, A. (2008) A study on surface roughness in abrasive waterjet machining process using artificial neural networks and regression analysis method. Journal of Materials Processing Technology, 202: 574–582.
7. Jurisevic, B.; Brissaud, D.; Junkar, M. (2004) Monitoring of abrasive water jet (AWJ) cutting using sound detection. The International Journal of Advanced Manufacturing Technology, 24: 733–737.
8. Kechagias, J.; Petropoulos, G.; Vaxevanidis, N. (2012) Application of Taguchi design for quality characterization of abrasive water jet machining of TRIP sheet steels. The International Journal of Advanced Manufacturing Technology, 62: 635–643.
9. Parikh, P.J.; Lam, S.S. (2009) Parameter estimation for abrasive waterjet machining process using neural networks. The International Journal of Advanced Manufacturing Technology, 40: 497–502.
10. Chen, F.L.; Siores, E. (2003) The effect of cutting jet variation on surface striation formation in abrasive water jet cutting. Journal of Materials Processing Technology, 135: 1-5.
11. Zohoor, M.; Nourian, S.H. (2012) Development of an algorithm for optimum control process to compensate the nozzle wear effect in cutting the hard and tough material using abrasive water jet cutting process. The International Journal of Advanced Manufacturing Technology, 61: 1019–1028.
12. Shanmugam, D.K.; Masood, S.H. (2009) An investigation on kerf characteristics in abrasive waterjet cutting of layered composites. Journal of Materials Processing Technology, 209: 3887–3893.
13. Zhu, H.T.; Huang, C.Z.; Wang, J.; Li, Q.L.; Che, C.L. (2009) Experimental study on abrasive waterjet polishing for hard–brittle materials. International Journal of Machine Tools and Manufacture, 49: 569–578.
14. Liu, H. T. (2007) Hole drilling with abrasive fluid jets. The International Journal of Advanced Manufacturing Technology, 32(9-10): 942-957.
15. Hashish, M.; Whalen, J. (1993) Precision drilling of ceramic-coated components with abrasive-waterjets. Transactions of ASME. Journal of Engineering for Gas Turbines and Power 115(1): 148–154.
16. Ansari, A.I.; Hashish, M. (1992) On the modeling of abrasive waterjet turning. Jet Cutting Technology, Fluid Mechanics and Its Applications, 13: 555-576.
17. Hashish, M. (1987) Turning with abrasive waterjets - a first investigation. Transactions of ASME. Journal of Engineering for Industry, 109(4): 281-290.
18. Manu, R.; Babu, N.R. (2009) An erosion-based model for abrasive waterjet turning of ductile materials. Wear,

266: 1091–1097.
19. Hashish, M. (1989) An investigation of milling with abrasive-waterjets. Transactions of ASME. Journal of Engineering for Industry, 111(2): 158–166.
20. Alberdi, A.; Rivero, A. (2011) Experimental study of the slot overlapping and tool path variation effect in abrasive waterjet milling. Transactions of ASME. Journal of Manufacturing Science and Engineering, 133: 034502-1-4.
21. Paul, S.; Hoogstrate, A.M.; Luttervel, C.A.; Kals, H.J. (1998) An experimental investigation of rectangular pocket milling