A Review Paper on Current Research and Development in Abrasive Waterjet Machining

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Abstract
Abrasive waterjet machining, or AWJM for short, is a relatively new machining method that offers an alternative to standard machining procedures for cutting parts made of hard materials that are notoriously difficult to cut. A concentrated jet of water moving at a high speed through which abrasive particles have been suspended results in a production method that is relatively economical and kind to the environment, and it also has a high rate of material removal. As a result, abrasive waterjet machining has quickly become one of the most prominent industrial technologies. In the past decade, AWJM's inception and evolution have been studied extensively. It presents AWJM's research on improving performance measures, process monitoring and control, and variable optimization. Numerous AWJM industrial uses for various categories of material have been recorded, each with their own unique set of variants. The future direction of study in the same field is another topic that is covered in this paper.
Key words: Process parameter, process optimization, monitoring, control.

I. INTRODUCTION

Cutting by abrasive waterjet was first commercialised in the late 1980s. Cutting by abrasive waterjet was the first method of its sort to be commercialised in the early 1970s. AWJ machining was unviable in the start of the 1980s. Modern abrasive jet technology has matured into a reliable full-scale production method.

In AWJ machining, a high-velocity water jet combined with abrasive particles removes workpiece material. The water jet erodes the material it touches in this operation. AWJ is a cutting-edge industrial material-processing method. AWJ is versatile, has low cutting forces, excellent flexibility, and negligible thermal distortion. The workpiece doesn't produce a heat impacted zone, unlike other machining procedures (HAZ). This process's benefits make it a good candidate for automation. High speed and multidirectional cutting, high cutting efficiency, capacity to cut complicated forms of even non-flat surfaces successfully at close tolerances, minimal heat buildup, low deformation stresses inside the machined item, quick changeover of cutting patterns under computer control, etc. This cutting tool is also used for drilling, milling, turning, threading, cleaning, and hybrid machining. Its versatility facilitates all various machining procedures.

Processing materials such as titanium, steel, brass, aluminium, stone, inconel, and other types of glass and composites are common applications for AWJM's versatile capabilities. The abrasive waterjet machining technique is a relatively new manufacturing method, and as such, it has not yet undergone significant improvement to allow for the realisation of its full potential.

This paper reviews ten years of AWJM research. It begins by offering an overview of the technique based on high velocity erosion and then highlights some of its uses for diverse materials. The essay focuses on AWJM process modelling and optimization and process monitoring and control as the key academic subject areas. The report's final portion includes future research recommendations for AWJM.

2. Theory

1.1 The AWJM process

A water jet that includes some form of abrasive substance is referred to as an abrasive water jet. Abrasives are grain-sized particles of specific materials such as aluminium oxide, silicon carbide, sodium bicarbonate, dolomite, and/or glass beads. These materials are versatile. Water jet cutting is essentially erosion. Depending on the brittleness or ductility of the eroding material, two different methods are used. Water is blasted through a small hole at high pressure (4,000 bars) and driven into the mixing chamber at rapid speed (approximately 900 metres per second). Abrasive particles and a water jet are drawn into the nozzle simultaneously in the mixing chamber. The nozzle expels air, abrasive particles, and 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.

(a) 286.

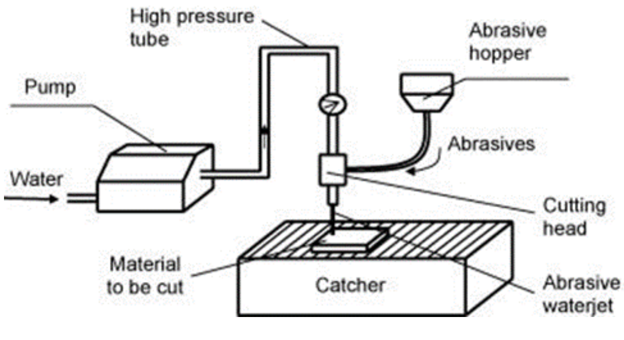

Fig -1: Schematic of an abrasive waterjet cutting system

II. AWJM VARIATIONS

Polishing, drilling, turning, milling, and three-dimensional machining are the operational facets that make up AWJ machining. Zhu and colleagues found that AWJ followed by lapping may provide precise surface machining with low pressure and a minor erosion angle. Modern materials are brittle and rigid, making solid drill bits difficult to use. Mechanical drilling has trouble creating holes smaller than 0.04 cm and at a shallow angle to the surface. Material properties pose further complications.

If the jet's pressure-time profile and abrasive flow rate are precisely controlled, an AWJ can drill a nice hole. When drilling small holes with a large aspect ratio, AWJ is preferable to lasers and EDM, especially at shallow angles. The workpiece is rotated while the AWJ is moved axially and radially during the turning operation. Ansari and Hashish established that turning with an abrasive waterjet can manufacture hard materials.

Hashish studied jet pressure, abrasive flow rate, abrasive particle size, orifice size, and feed rate. Manu and Babu have devised a system that considers local impact angles during AWJ rotation to predict ultimate diameter.

According to the findings of Hashish's [18] preliminary milling studies, abrasive-waterjet milling has a significant amount of promise in the application, and it offers benefits that are not offered by any other milling process now in use. Researchers from a variety of institutions have shown that AWJ technology is capable of performing precision milling operations in a variety of materials, including ceramics, titanium, and aluminium, when a mask is used. According to Paul et a research, .'s depth variation control of 0.04 millimetres can be achieved with linear motion milling when working with carbon steel. By combining cutting, turning, and drilling into a single machine setup, three-dimensional machining of cylindrical items can be accomplished with comparatively little effort. AWJ can be combined with flame cutting (oxy-fuel cutting), routing, plasma cutting, or EDMing. Waterjet pre-drilling enhances EDM performance. Kalyan Sundaram et al. investigated a non-traditional hybrid laser/waterjet approach for cutting Y-PSZ substrates (LWJ). Combining CO2 laser with abrasive-free waterjet. The hybrid approach uses Y-weak PSZ's thermal shock resistance to control fracture growth throughout the cutting line. Laser and waterjet localise heat and quickly quench it.

III. AWJM APPLICATIONS

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

3.1 Ceramic high-tech materials

High hardness and strength make ceramics difficult to machine using typical methods. As a result, laser machining, ultrasonic machining, and electro discharge machining have been implemented in ceramics processing. Each of these technologies for machining ceramics has advantages and disadvantages. Plasma flame and laser cutting leave behind a thick, hard crust and cannot achieve the requisite level of accuracy on a 13mm plate.

AWJM improves EDM and laser cutting of reflective and non-conductive materials. Xu and Wang studied abrasive waterjet cutting of alumina ceramics, taking nozzle oscillation into account.

3.2 Composites

Standard manufacturing processes cannot successfully produce Particle Reinforced Metal Matrix Composites (PRMMCs) due to tool wear caused by the stiff reinforcement, despite their high strength potential.

Electro discharge machining, laser cutting, and abrasive water jet (AWJ) machining are being used to machine MMCs. Muller and Monaghan compared AWJM of PRMMC to LBM and EDM (EDM). AWJ cutting did not cause heat degradation or burr attachment, according to the study.

3.3 Stones made of marble and granite

Granite's unique features, including its durability and resistance to scratches, cracks, stains, spills, heat, cold, and moisture, have led to its extensive use as a dimensional stone in modern public and commercial applications. The new abrasive water jet (AWJ) can cut rocks and similar materials. This tool can cut, weaken, and drill rocks. The technology is a potential tool for manufacturing, civil, and mining engineering because to its exact shape cutting, superior surface polish, decreased kerf widths, prolonged tool life, sophisticated free-form cutting, process automation, no dust, and better working conditions and environment. These properties make the technology relevant to manufacturing, civil, and mining engineering. These properties make the technology more environmentally benign than circular sawing for natural stone milling and processing. Some examples:

3.4 Glass

Glass goods can solve several design engineering difficulties. These materials should be in a designer's toolbox because they can work where metals and plastics can't. MAJM provides for efficient and cost-effective micro-machining of fragile materials like glasses. Fan et al. developed predicted mathematical models for micro-channel cutting and micro-hole drilling on glasses using an abrasive air jet. Dadkhah pour et al. previously studied material removal during AWJ milling of anamorphous glass channels.

IV. MAJOR AREAS OF AWJM RESEARCH

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

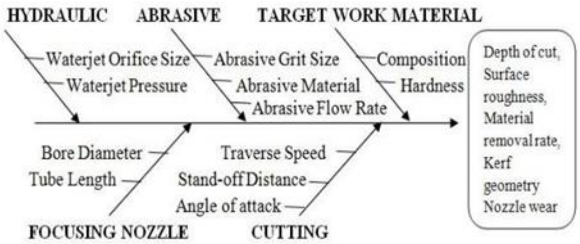

Fig -2: Process parameters influencing the AWJ cutting process

4.1 Process modelling and optimization with AWJM software

AWJM models help us understand this complex process. Modeling studies explore system behaviours. A mathematical model of a system links input and output parameters using a set of equations. Most of the study used statistical design of experiments (DOE) methodologies such the Taguchi method and the response surface approach to model and optimise AWJM.

Only a few academics modelled and optimised AWJM utilising artificial neural networks (ANN), fuzzy logic (FL), genetic algorithms, grey relational analysis, simulated annealing, artificial bee colonies, etc.

AWJ process parameters determine machining effort and effectiveness. Hydraulic, material, abrasive, and cutting parameters are included. Figure 2 shows numerous process parameters. Target parameters include cut depth, surface roughness, material removal rate, kerf shape, and nozzle wear. The examination of the relationships between process parameters and performance metrics forms the basis for selecting AWJM machining conditions. The next part discusses how process factors affect performance measurements.

4.1.1 Process parameter's effect on cut depth

Aydin et al. created and confirmed models for AWJ machining of granitic rocks. These models used Taguchi and regression analysis. Cut depths reduced when traverse speed and abrasive size were increased. Increases in abrasive mass flow rate and water pressure increase cut depths, whereas standoff distance has little effect. Using the Taguchi technique and regression analysis, several authors optimise process parameters such as water pressure, nozzle traverse speed, abrasive flow rate, standoff distance, and abrasive size for glass, cast iron, and aluminium. Wang used the Taguchi technique to analyse the depth of cut in multipass abrasive waterjet (AWJ) cutting of alumina ceramics with controlled nozzle oscillation. Predictive models for the depth of cut were established. Alumina ceramics were studied. Multi-pass cutting with nozzle oscillation cutting can increase the depth of cut by 50.8% compared to single-pass cutting. Jegaraj and Babu tested the effect of orifice and focusing tube bore modification on abrasive waterjet performance in cutting 6063-T6 aluminium. These studies determined. Taguchi's experimental design was utilised to create empirical and fuzzy models. Fuzzy logic is also used. Wang and Guo built a semi-empirical model for forecasting jet penetration in AWJ cutting of polymer matrix composites using a full factorial experimental methodology. This model estimated jet penetration. They showed that the model can provide reliable predictions for process planning. Chakravarthy and Babu [45] presented a new approach for cutting granite using fuzzy logic and the Genetic Algorithm (GA). This method identifies the best process parameters for AWJ granite cutting.

4.1.2 Variable impacts on surface roughness

Azmir and Ahsan [46] used Taguchi's design of experiments and analysis of variance to study the effect of machining settings on glass/epoxy composite laminate surface roughness (Ra). Surface roughness is affected by machining settings. Zohoor and Nourian used response surface methods to study nozzle wear and surface roughness. To account for their findings, they built regression models. Several researchers use the Taguchi technique and regression analysis to optimise the surface roughness of granite and polymer matrix composites. Yusup et al. used the artificial bee colony (ABC) technology to improve surface roughness. Traverse speed, waterjet pressure, standoff distance, grit size, and flow rate were control parameters. They compared simulated annealing with actual machining, regression, ANN, GA, and ABC (SA). Ashanira et al. coupled SVM and GRA to predict surface roughness. Standoff distance has the least impact on surface roughness, whereas traversal speed has the highest. Yuyong et calculated cutting speed using an ANN model, taking into consideration water pressure, abrasive flow rate, work piece thickness, and projected surface quality grade. They found that changing the water jet's cutting speed can indirectly affect the component's surface quality. Zain et al. compared experimental, regression analysis, genetic algorithm, and simulated annealing surface roughness. In that study, they used AA 7075 aluminium alloy and selected traverse speed, waterjet pressure, standoff distance, abrasive grit size, and abrasive flow rate as process parameters. Iqbal et al. constructed a comprehensive factorial design of tests to explore the effects of various parameters on the surface finish of AISI 4340 and Aluminum 2219. These investigations tested how different characteristics affected surface polish.

4.1.3 Process parameter's effect on kerf geometry.

Ramulu and Arol used the Taguchi technique to assess the effect of jet traverse speed, abrasive flow rate, water pressure, abrasive grain size, and grit flow rate on the surface roughness and kerf taper of a graphite/epoxy laminate. To account for this influence, they devised a regression-based mathematical model. Wang and Wong conducted a regression research to provide empirical models for predicting and optimising productivity and kerf quality. Chen explored AWJ cutting of alumina-based ceramics using statistical and theoretical methods. They've developed formulas to forecast and optimise AWJ kerf characteristics. Wang studied the machinability and kerf parameters of polymer matrix composite sheets when cut with an abrasive waterjet. He created a regression equation to predict top kerf width, taper angle, water pressure, nozzle traverse speed, and standoff distance. Cosansu and Cogun tested colemanite powder as an abrasive in abrasive waterjet cutting (AWJC) with varied traverse rate and abrasive flow rate. Garnet for Al7075, marble, glass, Ti6Al4V, and a composite were compared. Karakurt et al. used the Taguchi technique to determine the effects of traverse speed, abrasive flow rate, standoff distance, water pressure, and granite texture on kerf angle. Traverse speed and standoff distance have the largest impact on granite kerf angle, according to statistical study. Shanmugam and Masood presented research on the AWJ kerf taper angle used to make two types of composites. Epoxy-impregnated graphite cloth and glass epoxy were used. They showed that industrial kerf taper may be predicted and accounted for during design and process planning.

4.1.4 Process parameter influence on material removed per unit of time

Jegaraj and Babu conducted full factorial testing to determine how orifice and nozzle diameter affect the rate at which an abrasive water jet cuts 6063-T6 aluminium alloy. Increasing the orifice size slows material elimination, and a 0.4 mm aperture slows it significantly. Surface roughness and material clearance rate were studied using conventional methods. Arola and Hall used energy dispersive X-ray analysis to determine the amount of abrasive particles implanted in pure titanium surfaces. Hocheng and Chang discussed the kerf and material removed when a waterjet sliced a ceramic plate. They identified the critical hydraulic pressure, abrasive flow rate, and traverse speed for through-cutting. They also showed that particle speed is the main waterjet component that affects material removal rate. Considerable effort has gone into studying the elements that impact material removal rate, including waterjet pressure, abrasive flow rate, traverse rate, standoff distance, and number of passes.

4.1.5 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 studied nozzle wear via waterjet abrasion. The bore eccentricity, nozzle length, inlet depth, inlet angle, and nozzle diameters affect wear. Nanduri studied nozzle wear by measuring length, inlet angle, diameter, orifice diameter, abrasive flow rate, and water pressure. Based on such observations, he built an empirical model to estimate ROCTEC R100 and REXP nozzle weight loss.

4.2 Process monitoring at AWJM

Kovacevic invented a wear sensor system that tracks abrasive waterjet (AWJ) nozzle wear virtually in real time. The CPU is configured to analyse wear data to determine the direction of wear propagation and transmit that information to the controller to correct for the increase in the AWJ nozzle's interior diameter. Mohan and Kovacevic

The thermal energy distribution in an AWJ-cut workpiece was analysed using isotherms and line scans. Infrared thermography was used to monitor AWJ nozzle wear. Kovacevic and Zhang established a fuzzy approach for recognising wear based on nozzle diameter and work piece force. This fuzzy method determined if the nozzle was working. Kovacevic showed that the work piece normal force created by an abrasive waterjet may be utilised to measure jet penetration, and force-feedback control shows promise for regulating jet penetration. Kovacevic also showed that normal force can indicate jet penetration depth. Mohan and Kovacevic suggested a waterjet wear monitoring and compensation method. This technique uses the jet's frequency-domain acoustic data as input. This system uses an artificial neural network constructed using the back-propagation technique. Jurisevic found a link between stand-off distance and straight-cut sound during AWJ machining. They've created a plan and monitoring system to track standoff distance. Some of the suggested ideas were successfully implemented in an adaptive-control constraint AWJ system. Jegaraj and Babu investigated the effect of orifice and focusing tube bore modification on abrasive waterjet performance for 6063-T6 aluminium alloy. This research determined how differences affect an abrasive waterjet's performance.

They analysed the AWJ's cutting effectiveness using Taguchi's design of trials and came to the following conclusion: they constructed a fuzzy model to achieve the desired cutting performance while considering orifice and focusing tube bore. Srinivasu and Babu used machine vision to monitor the focusing nozzle's bore diameter and a neuro-genetic technique to alter process parameters. Below are two approaches. Combining monitoring and control methodologies yields an integrated strategy for adaptive AWJ cutting control. Axinte and

Kong use numerous acoustic emission sensors for waterjet monitoring. By altering cutting circumstances (such as feed speed), the solution improves the accuracy and quality of machined surfaces. Vundavilli et al. created a fuzzy logic (FL) expert system for AWJM depth of cut. This cut depth is determined by nozzle diameter, water pressure, abrasive mass flow rate, and jet traverse speed. Zohoor and Nourian suggested a control algorithm to account for the impact of nozzle diameter on cut quality and kerf width. This programme generates the desired nozzle offset. Rabani et al. evaluated the input jet energy that caused part erosion using an auditory emission sensor on the target work piece surface and online machine axis encoders.

Future AWJM research

This article has addressed AWJM's most major research areas. Due to the complexity of the process, more research is needed. AWJM is a good machining method for current applications. Experiments on AWJM of composite, glass, and advanced ceramic materials show a trend in engineering applications. It has replaced ultrasonic, laser beam, and electro discharge machining, which take a long time and impair the material's surface integrity. AWJM has also researched combining with other material removal procedures to widen its application reach and improve machining characteristics.

AWJM focuses on optimising process variables. During the investigation, the researchers ignored a lot of crucial information, such as the nozzle size and orifice width, both of which would have affected the results. The vast bulk of research in this sector shows that, to optimise AWJM, researchers have focused on a single quality attribute. The ideal value of a process parameter for one quality characteristic could lower the quality of other quality characteristics and the product overall. The authors found no literature on multi-objective AWJM optimization and recognised it as a potential research direction. Various experimental optimization approaches (such as the Taguchi method and RSM) can be combined to take use of both. Multi-response optimization of process variables has no published literature; more research is needed.

Several monitoring and control strategies have been described to address orifice and focusing tube bore variation. These algorithms use mathematical models, expert knowledge, or intelligent systems. Very little study shows the appropriate standoff distance during AWJ cutting by merely monitoring sound and not considering for other factors. This sector needs more workers.

CONCLUSIONS

This article describes recent advancements in AWJM and research opportunities. From what has been mentioned, we can conclude:

1. The AWJM method is gaining popularity in machining, especially for hard-to-cut materials. The machining sector is considering adopting it due to its advantages over traditional and nonconventional methods.

2. AWJM can be used for cutting, polishing, drilling, turning, and milling. AWJM has studied the benefits of integrating its operations with those of other material removal procedures to widen its applicability.

3. Monitoring and control rarely reveal the ideal standoff distance during AWJ cutting. There's no evidence that this kind of work was done for other traits. This sector needs more workers.

4. Most study has focused on traverse speed, waterjet pressure, standoff distance, abrasive grit size, and abrasive flow rate. Few studies have been done on nozzle size and orifice diameter.

5. Most optimization research has focused on improving a particular quality attribute, such as cut depth, surface roughness, material removal rate, kerf shape, and nozzle wear. This research improves one quality attribute. There was no research on optimising AWJM for power consumption, dimension accuracy, or multi-objective optimization. Further research is needed soon.

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