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A Review on Current Research and Development in Abrasive Waterjet Machining

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Abstract
Abrasive waterjet machining (AWJM) is an emerging machining technology option for hard material parts that are extremely difficult-to-machine by conventional machining processes. A narrow stream of high velocity water mixed with abrasive particles gives relatively inexpensive and environment friendly production with reasonably high material removal rate. Because of that abrasive waterjet machining has become one of the leading manufacturing technologies in a relatively short period of time. This paper reviews the research work carried out from the inception to the development of AWJM within the past decade. It reports on the AWJM research relating to improving performance measures, monitoring and control of process, optimizing the process variables. A wide range of AWJM industrial applications for different category of material are reported with variations. The paper also discusses the future trend of research work in the same area.
Index Terms: Abrasive waterjet machining, Process parameter, Process optimization, Monitoring, Control.

I. INTRODUCTION

Waterjet cutting machines started to operate in the early 1970s for cutting wood and plastics material [1] and cutting by abrasive waterjet was first commercialized in the late 1980s as a pioneering breakthrough in the area of unconventional processing technologies [2]. In the early 1980s, AWJ machining was considered as an impractical application. Today, state-of the art abrasive jet technology has grown into a full-scale production process with precise, consistent results [3].

In AWJ machining process, the work piece material is removed by the action of a high-velocity jet of water mixed with abrasive particles based on the principle of erosion of the material upon which the water jet hits [4]. AWJ is one of the most advanced modern methods used in manufacturing industry for material processing. AWJ has few advantages such as high machining versatility, small cutting forces, high flexibility and no thermal distortion [5]. Comparing with other complementary machining processes, no heat affected zone (HAZ) on the work piece is produced [6]. High speed and multidirectional cutting capability, high cutting efficiency, ability to cut complicated shapes of even non flat surfaces very effectively at close tolerances, minimal heat build-up, low deformation stresses within the machined part, easy accomplishment of changeover of cutting patterns under computer control, etc. are a few of the advantages offered by this process which make it ideal for automation. Due to its versatility, this cutting tool is finding application not only in contour cutting, but also in other machining methods such as drilling, milling, turning, threading, cleaning, and hybrid machining [1]. AWJM is widely used in the processing of materials such as titanium, steel, brass, aluminum, stone, inconel and any kind of glass and composites [7]. Being a modern manufacturing process, abrasive waterjet machining is yet to undergo sufficient superiority so that its fullest potential can be obtained.

This paper provides a review on the various research activities carried out in the past decade on AWJM. It first presents the process overview based on the widely accepted principle of high velocity erosion and highlights some of its applications for different category of material. The core of the paper identifies the major AWJM academic research area with the headings of AWJM process modeling and optimization, AWJM process monitoring and control. The final part of the paper suggests future direction for the AWJM research.

1.1 The AWJM process

An abrasive water jet is a jet of water that contains some abrasive material. Abrasives are particles of special materials like aluminum oxide, silicon carbide, sodium bicarbonate, dolomite and/or glass beads with varying grain sizes [8]. High pressure abrasive water jet cutting is essentially an erosion process which involves two distinct mechanisms depending upon whether the eroded material is brittle or ductile in nature [9]. In this process, water goes through the thin orifice with very high pressure (about 4,000 bars) and enters mixing chamber with a very high velocity (about 900 m/s). In mixing chamber, abrasive particles along with water jet are drawn into the nozzle. This mixture containing water, abrasive particles, and air leaves nozzle. Having received a lot of kinetic energy and velocity by water jet, the abrasive particles cause wearing and machining when they impact work piece surface [10]. The Schematic diagram of an abrasive waterjet cutting system is shown in Fig. 1 [11].

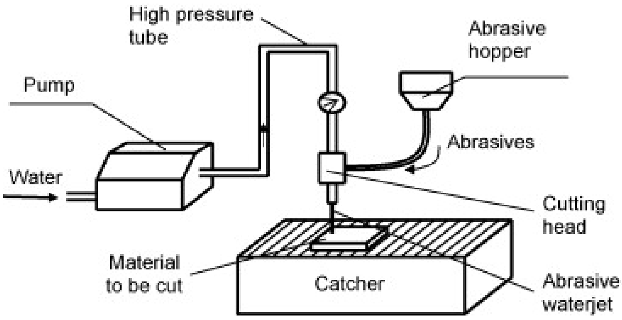

Fig -1: Schematic of an abrasive waterjet cutting system

II. AWJM VARIATIONS

The operation aspects of AWJ machining consist of polishing, drilling, turning, 3D machining and milling. Zhu et al. [12] found that by using ductile erosion method with low pressure and small erosion angle, the precision surface machining can be carried out by AWJ then lapping. Drilling advanced materials with solid drill bits is often not possible due to brittleness and hardness of material. In addition to material property constraints, mechanical drilling has difficulty in producing holes that are less than 0.04 cm in diameter and shallow angle to the surface [13]. By controlling the jet's pressure-time profile and the abrasive flow rate, it is proved that the hole of high quality can be drilled by AWJ [14]. For drilling small diameter and large aspect ratio holes, AWJ is superior to other fielded tools such as lasers and Electro Discharge Machining (EDM), particularly at shallow angle [13]. In turning with AWJ, the work piece is rotated while the AWJ is traversed axially as well as radially to produce the required turned surface. Turning with abrasive waterjet has been demonstrated as a viable process for difficult-to-machine materials by Ansari and Hashish [15]. Hashish [16] investigated the AWJ turning parameters such as jet pressure, the abrasive flow rate, the abrasive particle size, the orifice size and the feed rate. A different approach considering the varying local impact angle in AWJ turning presented to predict the final diameter by Manu and Babu [17]. The results of preliminary milling experiments by Hashish [18] indicated that abrasive-waterjet have great potential in milling application with advantages unmatched by existing techniques. Many researchers demonstrated the capability of AWJ technology for precision milling operations in different materials such as titanium, aluminum, and ceramics using a mask [19]. Paul et al. [20] reported that 0.04 mm depth variation control can be obtained for carbon steel using linear motion milling. Three-dimensional machining of cylindrical objects is relatively easy to perform by incorporating cutting, turning and drilling in the same setup [1]. AWJ can also be used to complement other cutting systems and it may be incorporated with flame cutting (Oxy-fuel cutting), routing, plasma cutting or EDMing. Pre drilling holes with a waterjet increases the performance of some EDM processes [21]. A non-traditional hybrid laser/waterjet process that combines CO_2 laser and abrasive-free waterjet (LWJ) has investigated by Kalyanasundaram et al. [22] for cutting of yttria-partially stabilized zirconia (Y-PSZ) substrates. The hybrid system exploits the low thermal shock resistance of Y-PSZ for controlled crack propagation along cutting path through localized heating and rapid quenching by laser and waterjet, respectively.

III. AWJM APPLICATIONS

This section discusses the viability of the AWJM process in the machining of the various materials used in industrial application.

3.1 Advanced ceramics materials

The high hardness and strength of ceramic materials make it very difficult for processing by the conventional technologies, leading to high machining costs [23]. As a result, non-traditional cutting technologies have been used for processing ceramics, such as lasers [24], ultrasonic machining [25], electro discharge machining [21]. Although these processes have been successfully used for machining ceramics, each is associated with its own disadvantages. Plasma flame and laser cutting leave behind a heavy crust that is extremely hard and these methods do not achieve the accuracy on a 13mm thick plate [3]. AWJM process extends the cutting capabilities of EDM and laser for reflective and non-conductive materials [26]. Xu and Wang [27] have carried out an extensive experimental study of abrasive waterjet cutting of alumina ceramics considering the effect of small nozzle oscillation on cutting performance.

3.2 Modern composites materials

Particle Reinforced Metal Matrix Composites (PRMMCs) have proved to be extremely difficult to machine using conventional manufacturing processes due to heavy tool wear caused by the presence of the hard reinforcement [28]. Nonconventional machining processes such as electro discharge machining [29], laser cutting [30] and abrasive water jet (AWJ) machining [4] techniques are increasingly being used for the machining of particle reinforced MMCs. Muller and Monaghan [28] compared the AWJM of particle reinforced metal matrix composite (PRMMC) with other non-conventional machining processes such as LBM and electro discharge machining (EDM). The results show that AWJ cutting is not resulted in any thermal damage within the composite and no burr attachment is observed.

3.3 Marble and granite

Owing to its unique characteristics and attractive properties, such as high durability and resistance to scratches, cracks, stains, spills, heat, cold, and moisture, granite has been widely used as dimensional stone in public and commercial applications in today's life [31]. The abrasive water jet (AWJ) is a new innovative tool for cutting rocks and rocklike materials. It can be used for cutting, pre-weakening and drilling of rocks [32].The technology is a promising tool not only for manufacturing industries but also for the other industries including civil and mining engineering fields due to its distinctive features of precise shape cutting, a good surface finish, smaller kerf widths, extended tool life, complex free-form cutting, process automation, no dust, better working conditions, and environment. These features make the technology an environmentally friendly technique over other traditional cutting processes such as circular sawing in natural stone machining and processing applications [33].

3.4 Glass

Glass products have applications in design engineering, and they can solve many special problems. These materials can work in situations in which plastics and metals would fail and need to be part of designer's repertoire [34]. Micro abrasive jet machining (MAJM) is an economical and efficient technology for micro-machining of brittle material like glasses. Fan et al. [35] developed predictive mathematical models for the erosion rates in micro-hole drilling and micro-channel cutting on glasses with an abrasive air jet. A study on the material removal process in AWJ milling of channels on anamorphous glass had been presented by Dadkhahipour et al. [36].

IV. MAJOR AREAS OF AWJM RESEARCH

The authors have organized the various AWJM research into two major areas namely AWJM process modeling and optimization together with AWJM process monitoring and control.

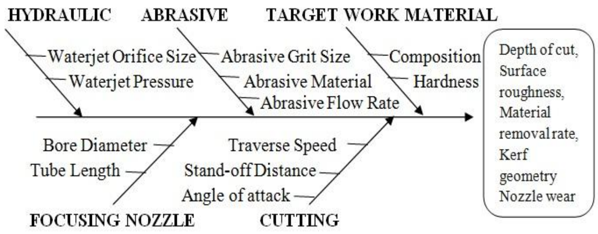

Fig -2: Process parameters influencing the AWJ cutting process

4.1 AWJM process modeling and optimization

Modeling in AWJM helps us to get a better understanding of this complex process. Modeling studies are the scientific ways to study the system behaviors. A mathematical model of a system is the relationship between input and output parameters in terms of mathematical equations. The literature found related to modeling and optimization of AWJM is mainly based on statistical design of experiments (DOE) such as Taguchi method and response surface method. Few researchers concentrated on modeling and optimization of AWJM through other techniques such as artificial neural network (ANN), fuzzy logic (FL), genetic algorithm, grey relational analysis, simulated annealing, artificial bee colony etc.

The intensity and the efficiency of the machining process depend on several AWJ process parameters. They are classified as hydraulic, work material, abrasive, and cutting parameters. Fig. 2 shows various parameters influencing the process [37]. Depth of cut, surface roughness, material removal rate, kerf geometry and nozzle wear are often used as target parameters [10]. The selection of appropriate machining conditions for the AWJM process is based on the analysis relating the various process parameters to different performance measures. The work carried out by researchers on effects of various process parameters on different performance measures are discussed below.

4.1.1 Effects of the process parameter on depth of cut

Aydin et al. [38] developed many models for the prediction of cut depth by using Taguchi method and regression analysis in AWJ machining of granitic rocks and verified. The results indicated that the cut depths decreased with increasing traverse speed and decreasing abrasive size. On the other hand, increase of the abrasive mass flow rate and water pressure lead to increase in the cut depths and standoff distance has no discernible effects on the cut depths. Several authors also work on the optimization of process parameters such as water pressure, nozzle traverse speed, abrasive flow rate, standoff distance and abrasive size by using Taguchi method and regression analysis for various materials such as glass [39], cast iron [40] and aluminum [41]. An experimental study of the depth of cut in multi pass abrasive waterjet (AWJ) cutting of alumina ceramics with controlled nozzle oscillation has been presented by using Taguchi method by Wang [42] and predictive models for the depth of cut have been developed. He has shown that the combined use of multi pass and nozzle oscillation cutting techniques can significantly increase the depth of cut by an average of 50.8% as compared to single pass cutting. Jegaraj and Babu [43] carried out experimental studies to investigate the influence of orifice and focusing tube bore variation on the performance of abrasive waterjet in terms of depth of cut for 6063-T6 aluminium alloy. They have used Taguchi's design of experiments and those experimental data have been used to build empirical models and also developed fuzzy model. Wang and Guo [44] developed a semi-empirical model for predicting the depth of jet penetration in AWJ cutting of polymer matrix composites by using full factorial experimental design. They have shown that the model gives adequate predictions and can be used for process planning. Chakravarthy and Babu [45] presented a new approach, based on the principles of fuzzy logic and Genetic Algorithm (GA) for selection of optimal process parameters in Abrasive Water Jet (AWJ) cutting of granite to any predetermined depth.

4.1.2 Effects of the process parameter on surface roughness

Azmir and Ahsan [46] studied effect of machining parameters such as abrasive types, hydraulic pressure, standoff distance, abrasive flow rate, traverse rate, cutting orientation on surface roughness (Ra) by using Taguchi's design of experiments and analysis of variance for glass/epoxy composite laminate. Zohoor and Nourian [10] determined the effect of parameters on nozzle diameter wear and effect of it on surface roughness and developed regression equations by using response surface methodology. Several researchers also work on different parameters by using Taguchi method and regression analysis for the optimization of surface roughness on different materials such as granite [47], polymer matrix composite [48]. Yusup et al. [49] employed artificial bee colony (ABC) algorithm to optimize the machining control parameters such as traverse speed, waterjet pressure, standoff distance, abrasive grit size and abrasive flow rate for surface roughness. They have compared the results of ABC with the actual machining, regression, artificial neural network (ANN), genetic algorithm (GA) and simulated annealing (SA). Ashanira et al. [50] presented a hybridization model of support vector machine (SVM) and grey relational analysis (GRA) in predicting surface roughness value. They have found that traverse speed is the most influential factor that affects surface roughness while standoff distance is the least influential factor that affects surface roughness. Yuyong et al. [51] calculated cutting speed by ANN model based on water pressure, abrasive flow rate, work piece thickness and expecting surface quality grade. They have found that surface quality of the part can be indirectly controlled by adjusting the cutting speed of water jet. Zain et al. [52] compared the surface roughness value for the experimental, regression analysis, genetic algorithm and simulated annealing. In that study they have selected traverse speed, waterjet pressure, standoff distance, abrasive grit size, abrasive flow rate as process parameters and AA 7075 aluminum alloy as work material. Iqbal et al. [53] developed full factorial design of experiments in order to investigate the effects of different parameters on surface finish for AISI 4340 (high strength low alloy steel, hardened to 49HRc) and Aluminum 2219.

4.1.3 Effects of the process parameter on kerf geometry

Ramulu and Arol [54] determined the influence of cutting parameters such as jet traverse speed, abrasive flow rate, water pressure, abrasive grain size, grit flow rate on the surface roughness and kerf taper of an abrasive waterjet machined graphite/epoxy laminate by using Taguchi method and also developed mathematical model based on regression techniques. Wang and Wong [55] performed regression analysis to provide empirical models for the prediction and optimization of productivity and kerf quality by considering different parameters. Experimental techniques based on statistical experimental design principles and theoretical investigations have been conducted by Chen et al. [56] to study AWJ cutting of alumina-based ceramics. They have determined equations for the prediction and optimization of Kerf characteristics of the AWJ. Wang [48] presented an experimental investigation of the machinability and kerf characteristics of polymer matrix composite sheets under abrasive waterjet. He has developed regression equation for top kerf width and kerf taper angle in terms of water pressure, nozzle traverse speed, standoff distance. Cosansu and Cogun [57] investigated experimentally the cutting performance outputs (kerf taper angle) of colemanite powder as abrasive in abrasive waterjet cutting (AWJC) with varying traverse rate and abrasive flow rate and compared it with the garnet for Al7075 material, marble, glass, Ti6Al4V and a composite material. Karakurt et al. [58] worked on effects of process parameters such as traverse speed, abrasive flow rate, standoff distance water pressure and the material properties (i.e. textural properties) of the granites on the kerf angle by using Taguchi method. The most significant process factors influencing the kerf angle of the granites have been statistically determined as the traverse speed and the standoff distance. Shanmugam and Masood [11] presented an investigation on the kerf taper angle generated by abrasive waterjet (AWJ) technique to machine two types of composites: epoxy pre-impregnated graphite woven fabric and glass epoxy. For industrial application they have shown that the kerf taper can be predicted and can be compensated during the design and process planning stage.

4.1.4 Effects of the process parameter on material removal rate

Jegaraj and Babu [37] studied the influence of orifice and focusing nozzle diameter variation on the material removal rate of abrasive water jet in cutting 6063-T6 aluminum alloy by full factorial experiments. They have observed that rate of material removed decreases with an increase in the size of orifice and have found to be substantially low with an orifice size of 0.4 mm. The surface texture and material removal rate have been analyzed using conventional techniques whereas the quantity of abrasive particles embedded within the pure titanium surfaces has been determined using energy dispersive X-ray analysis in Abrasive Waterjet Surface Treatments by Arola and Hall [59]. Hocheng and Chang [60] discussed the kerf formation and material removal of a ceramic plate cut by an abrasive waterjet. Critical combination of hydraulic pressure, abrasive flow rate and traverse speed for through-cut has been found by them. They have also shown that the particle speed is the major factor of the waterjet system determining the material removal rate. Considerable efforts have been made in understanding the influence of dynamic variables such as waterjet pressure, abrasive flow rate, traverse rate, standoff distance, and number of passes on material removal rate [61].

4.1.5 Effects of the process parameter on nozzle wear

Nozzle wear in the abrasive water jet environment is affected by nozzle geometric and material parameters as well as AWJ system parameters [62]. Accelerated wear tests have been conducted by Hashish [63] on relatively soft (steel) mixing tubes using a typical soft abrasive (garnet sand) and on harder (tungsten carbide) tubes by using a harder abrasive material (aluminum oxide). A wide range of candidate tool materials, including several carbides and ceramics, have been also tested by him using actual machining parameters. Nanduri et al. [64] studied the phenomenon of nozzle wear in the abrasive waterjet environment. The effect of nozzle geometry such as bore eccentricity, nozzle length, inlet depth, inlet angle and nozzle diameters on wear have been investigated. Nanduri et al. [65] investigated experimentally nozzle wear for change in nozzle length, inlet angle, diameter, orifice diameter, abrasive flow rate, and water pressure and developed an empirical model for nozzle weight loss rate for ROCTEC nozzle materials - R100 and REXP.

4.2 AWJM process monitoring and control

A wear sensor system for direct and almost on-line tracking the wear of an abrasive waterjet (AWJ) nozzle has been proposed by Kovacevic [66]. The CPU has been programmed to analyze collected wear data in order to determine the direction of the wear propagation and to provide the information to the controller to compensate for the increase in the AWJ nozzle inside diameter. Mohan and Kovacevic [67] analyzed thermal energy distribution in the work piece cut with abrasive waterjet (AWJ) using the technique of infrared thermography through isotherms and line scans and proposed technique of AWJ nozzle wear monitoring through infrared thermography. Kovacevic and Zhang [68] developed a fuzzy algorithm for the recognition of the wear state based upon a relationship between the inside diameter of the nozzle and the normal work piece force. Kovacevic [69] shown that the work piece normal force generated by an abrasive waterjet can be used as the indicator of the depth of jet penetration and that force-feedback control holds promise as an effective way to regulate the depth of jet penetration. Mohan and Kovacevic [70] proposed an abrasive waterjet nozzle wear monitoring and compensating mechanism using the frequency domain acoustic signals generated by the jet exiting the nozzle, as input and also an artificial neural network which forms the critical part of this system developed using the back-propagation algorithm. Jurisevic et al. [6] found an evident connection between the stand-off distance and the sound generated during the straight-cut operation in the AWJ machining process. They have developed a methodology and create a system for the monitor the standoff distance in it. Some results of the presented research are successfully applied for an adaptive- control constraint AWJ system. Jegaraj and Babu [43] carried out experimental studies to investigate the influence of orifice and focusing tube bore variation on the performance of abrasive waterjet in terms of different parameters such as depth of cut, kerf width and surface roughness for 6063-T6 aluminium alloy. They have used Taguchi's design of experiments to analyze the performance of AWJ in cutting and have also developed fuzzy model for achieving desired cutting performance considering the variation in orifice and focusing tube bore. Srinivasu and Babu [71] developed a machine-vision-based monitoring approach to obtain the bore diameter of the focusing nozzle from time to time and a neuro-genetic approach is employed as a control strategy to modify the process parameters. By combining the monitoring and control strategies, an integrated approach for adaptive control of AWJ cutting process is realized. Relying on multiple acoustic emission sensors, the monitoring solution is implemented by Axinte and kong [72] on the harsh waterjet environment to detect process malfunctions (e.g. jet penetration, nozzle clogging) and by adjusting cutting conditions (e.g. feed speed) to result in improved accuracy and quality of machined surfaces. Vundavilli et al.[33] developed the expert system by using fuzzy logic (FL) for the performance of AWJM in terms of depth of cut which depends on various process parameters, such as diameter of focusing nozzle, water pressure, abrasive mass flow rate and jet traverse speed. Zohoor and Nourian [10] suggested a control program algorithm to compensate the effect of increase in nozzle diameter on cut surface quality and kerf width. This control program creates an offset with required amount in nozzle path. Rabani et al. [73] monitored the input jet energy that produces the part erosion using an acoustic emission sensor mounted on the target work piece surface while the jet feed velocity is acquired online from the machine axis encoders.

V. FUTURE DIRECTION OF AWJM RESEARCH

The major research areas in AWJM are discussed in previous sections. Researchers have contributed in different directions but due to complex nature of the process a lot of works are still required to be done.

The AWJM process is a suitable machining option in meeting the demands of today's modern applications. The AWJM of the modern composite, glass and advanced ceramic materials, which is showing a growing trend in many engineering applications, has also been experimented. It has replaced the conventional means of machining hard and difficult to cut material, namely the ultrasonic machining, laser beam machining and electro discharge machining, which are not only slow to machining but damage the surface integrity of the material. In addition, the AWJM process has sought the benefits of combining with other material removal methods to further expand its applications and improve the machining characteristics.

The optimization of process variables is a major area of research in AWJM. Researchers have excluded many important factors such as nozzle size and orifice diameter during study which otherwise would affect the performance characteristics differently. Most of the literature available in this area shows that researchers have concentrated on a single quality characteristic as objective during optimization of AWJM. Optimum value of process parameters for one quality characteristic may deteriorate other quality characteristics and hence the overall quality. No literature is available on multi-objective optimization of AWJM process and present authors found it as the main direction of future research. Also, various experimental tools used for optimization (such as Taguchi method and RSM) can be integrated together to incorporate the advantages of both simultaneously. No literature available so far for multi response optimization of process variables and more work is required to be done in this area.
Several monitoring and control algorithms based on the explicit mathematical models, expert's knowledge or intelligent systems have been reported to reduce the inaccuracy caused by the variation in orifice and focusing tube bore. Very little literature available so far shows the standoff distance at the optimal value during the AWJ cutting process using the generated sound monitoring and not for any other parameters. So, more work is required to be done in this area.

CONCLUSIONS

The work presented here is an overview of recent developments of AWJM and future research directions. From above discussion it can be concluded that:

1. It was shown that AWJM process is receiving more and more attention in the machining areas particularly for the processing of difficult-to-cut materials. Its unique advantages over other conventional and unconventional methods make it a new choice in the machining industry.
2. Apart from cutting, AWJM is also suitable for precise machining such as polishing, drilling, turning and milling. The AWJM process has sought the benefits of combining with other material removal methods to further expand its applications.
3. Very little literature available so far shows the standoff distance at the optimal value during the AWJ cutting process by monitoring and control. This kind of work has not been reported for any other parameters. So, more work is required to be done in this area.
4. In most of research work, mainly traverse speed, waterjet pressure, standoff distance, abrasive grit size and abrasive flow rate have been taken into account. Very little work has been reported on effect of nozzle size and orifice diameter.

5. Most of the research on optimization work has been carried out on process parameters for improvement of a single quality characteristic such as depth of cut, surface roughness, material removal rate, kerf geometry and nozzle wear. There is no any research paper found based on the optimization for the power consumption, dimension accuracy and multi-objective optimization of AWJM process. So, this area is still open for future research work.

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