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State of the Art of Research and Development in Abrasive Waterjet Machining

Thermodynamic analysis of material removal mechanisms indicates that an ideal tool for shaping of materials is a high energy beam, having infinitely small cross-section, precisely controlled depth, and direction of penetration, and does not cause any detrimental effects on the generated surface. The production of the beam should be relatively inexpensive and environmentally sound while the material removal rate should be reasonably high for the process to be viable. A narrow stream of high energy water mixed with abrasive particles comes close to meeting these requirements because abrasive waterjet machining has become one of the leading manufacturing technologies in a relatively short period of time. This paper gives an overview of the basic research and development activities in the area of abrasive waterjet machining in the 1990s in the United States.

1 Introduction

As we are poised toward the 21st century, it will be interesting to conduct a review of the state of the art of modern manufacturing processes, which were born in the last quarter of the 20th century. Among these processes, abrasive waterjet machining has offered certain unique capability to machine exotic and difficult-to-machine materials where conventional machining is often technically or economically not feasible. As a nontraditional machining method, this process is still evolving and undergoing sophistication day-by-day finding widespread applications in various areas, which can be expected to increase considerably in the 21st century.

Even though waterjet cutting machines started to operate in the early 1970s for cutting wood and plastics, abrasive waterjet (AWJ) machining was first introduced in 1983 as a commercial system for cutting glass. Currently, AWJ cutting finds application for machining a wide range of metals and nonmetals such as cast iron, stainless steel, mild steel, aluminum, copper, titanium and its alloys, high carbon steels, tool steels, concrete, ceramics, metal matrix composites, laminates, and fiber-reinforced composites. High speed and multidirectional cutting capability, high cutting efficiency, ability to cut complicated shapes of even nonflat 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.

Basic research and development in the area of abrasive waterjet machining in the United States are currently promoted by five university laboratories namely the University of Kentucky, University of Washington, University of Rhode Island, New Jersey Institute of Technology, and University of Missouri-Rolla, and one industry which is Quest Integrated, Inc. Organizations such as Boeing, NASA, Pratt & Whitney, U.S. Air Force, and manufacturers of waterjet cutting systems conduct research in this area which is of proprietary nature. Of the above universities, University of Missouri-Rolla is concentrating on research activities primarily in mining and rock cutting; whereas, others are involved in research and development related to manufacturing area. In this paper, state of the art of the research in AWJ cutting as a manufacturing activity is being discussed. Table 1 shows the different topics which are being investigated in AWJ machining in the above institutions.

The basic research activities in abrasive waterjet machining performed in the 1990s in U.S. can be broadly divided into four different areas such as,

- research dealing with understanding the physics of the process,
- research oriented toward operations of the process,
- research focused on systems, sensing, monitoring, and controlling, and
- development of new applications to broaden the scope of this technology.

Being a modern manufacturing process, abrasive waterjet machining is yet to undergo sufficient sophistication so that its fullest potential can be exploited. Thus, all the investigations are motivated toward enhancing the capability of the process. A brief discussion of the state of the art of the research activities in the AWJ machining area is given below.

2 Physics of The AWJ Machining Process

The research and development oriented toward understanding the physics of the AWJ machining process involve several aspects of the process such as wear mechanisms, erosion model-

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Table 1 Research areas in AWJ machining

Physics of the process	Wear mechanisms/erosion modeling	University of Kentucky University of Washington University of Rhode Island Quest Integrated, Inc.
	Energy dissipation phenomenon	University of Kentucky University of Washington
	Surface characterization of AWJ cutting	University of Kentucky Quest Integrated, Inc. University of Washington New Jersey Institute of Technology
Operations	Drilling with abrasive waterjet	University of Kentucky Quest Integrated. Inc. University of Washington
	Turning/threading with AWJ	University of Rhode Island Quest Integrated, Inc.
	3 dimensional machining	University of Kentucky Quest Integrated, Inc. University of Rhode Island University of Washington New Jersey Institute of Technology
Systems and sensing	Ultra-high pressure systems	Quest Integrated, Inc.
	Temperature sensing in AWJ cutting	University of Kentucky Quest Integrated, Inc.
	Studies on AWJ nozzle wear and orifice health monitoring	University of Kentucky University of Rhode Island Quest Integrated, Inc.
New applications	Smart nozzles	Quest Integrated, Inc.
	Ice jet machining	New Jersey Institute of Technology
	Cryogenic and abrasive cryogenic jets	Quest Integrated, Inc.
	Hybrid machining	University of Kentucky University of Missouri-Rolla Cleveland State University
	Polishing and cleaning with high pressure waterjet	University of Rhode Island New Jersey Institute of Technology

ing, energy dissipation phenomenon, and surface characterization. Salient features of these investigations are briefly given below.

2.1 Wear Mechanisms/Erosion Modeling. Investigations into the mechanisms of hydro-abrasive wear during AWJ machining have focused on analytical modeling [1–3], visualization studies [4], and statistical analysis [5, 6]. Analytical models have been traditionally derived based on Finnie's [7] and Bitter's [8] models for dry erosive wear. Hashish [9] developed a particle erosion model to predict the smooth cutting region (cutting wear zone) and rough cutting region (deformation wear zone) depth. Raju and Ramulu [10, 11] derived governing equations for smooth cutting region (SCR) and rough cutting region (RCR) assuming steady-state cutting conditions by equating the material removal rate of individual abrasives on a local scale to the microscopic volume removal rate and combining with the momentum equation for the slurry stream in both regions. Simple fracture mechanical model and model of comminution were adopted by Momber and Kovacevic [12] to define secondary fragmentation in waterjet cutting of brittle multiphase materials. Investigations conducted [13] into the material removal mechanisms in refractory ceramics indicated that in the SCR material removal is through simultaneous cutting of the matrix and inclusion (transgranular), which could be due to the availability of higher specific jet energy at the top of the kerf, and in the RCR the material removal process is characterized by the removal of the binding matrix followed by a washing of the inclusion grains (intergranular). Investigations of Zeng and Kim [2, 3] indicated that the erosion mechanisms associated with AWJ cutting and milling of polycrystalline ceramics is characterized by plastic flow at the immediate impact site and intergranular network cracking at the interior due to impact induced stress waves. The qualitative predictions of the erosion models were verified with AWJ erosion experiments.

Through a novel approach, Yong and Kovacevic [14] suggested that the accuracy of the analytical models in predicting the hydro-abrasive behavior of AWJ can be considerably improved if the models are based on water-mixture film erosion, instead of dry erosion. This approach employed exact solutions for an inhomogeneous contact problem and the Hertz impact theory to determine the effects of water-mixture film adhering to solid materials on impact contact. Closed-form expressions were obtained for dry contact impact force, and film contact impact force. Through experimental verification of the analytical model it was concluded that in comparison with dry contact, the maximum impact force is significantly reduced by the presence of water-mixture film when impact energy of an object is low. The effect of the water-mixture film reduces with increase in impact energy up to a critical value and then it stabilizes.

2.2 Energy Dissipation Phenomenon. Energy dissipation processes play a key role in determining the technical and economical performance of AWJ machining. Understanding the components involved in the energy dissipation process and estimating the quantity of the energy dissipated provide useful information for optimization of the process. Figure 1 shows the simplified energy balance during cutting with abrasive waterjet. A physical model was developed by Momber et al. [15] to quantify the energy dissipated, during AWJ cutting. Different mechanisms of energy dissipation during AWJ machining such as erosion debris formation, friction, water-solid particle film damping, and workpiece heating were identified. Detailed experimental investigations were conducted [16, 17] to quantify the contributions of the different mechanisms involved in this dissipation process and the exit energy of the jet.

2.3 Surface Characterization of AWJ Cutting. In AWJ cutting, as the jet penetrates into the workpiece, it loses its kinetic energy continuously and starts deflecting. Thus, a typical AWJ generated surface has two distinct regions along the kerf wall; one is a relatively smooth region (cutting wear zone) at the top of the kerf and the other is a striated region (deformation wear zone) at the bottom of the kerf [18]. The investigations

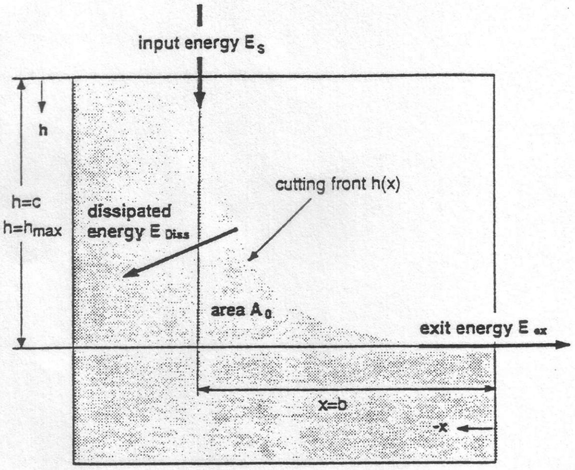

Fig. 1 Energy balance

in surface characterization of AWJ cutting are focused toward either understanding the profile generation mechanisms [19–21] or developing suitable strategy to monitor and control the surface finish [21, 22].

A physical model was developed by Hashish [19] to describe the waviness (striations) phenomenon associated with AWJ cutting. Investigations [20, 21] into surface profile characterization indicate that AWJ cut profile is predominantly random, Gaussian and isotropic in nature. Apart from the process parameters, the vibration of the AWJ machining system originating from the driving motors, plays a significant role [20] on the striation generating mechanisms of the machined surface. Wavelength decomposition of the ARMA models representing the surface profile signature indicate that [21] a typical AWJ cut profile is made up of two wavelengths namely primary and secondary. The primary and the secondary wavelengths at the smooth cutting zones are caused by the abrasive particles whereas in the rough cutting zone, the primary wavelength is caused by the jet diameter and the secondary wavelength is caused by the abrasive particles.

Investigations [22] into surface quality monitoring indicated that the static level of the workpiece normal force can be adopted as a suitable parameter for monitoring the surface finish in AWJ cutting. Through a separate analysis, Kovacevic et al. [21] demonstrated that the power spectrum density of the ARMA models representing the dynamic force is capable of providing a quantified measure of the surface finish at the RCR. Through a semi-empirical model, Raju and Ramulu [23] surmised that the total kinetic energy of the jet at the point of transition of SCR and RCR is a critical parameter which dictates the striation formation.

Scanning electron microscope studies conducted [24, 25] to investigate the surface and subsurface damages during AWJ machining indicate that abrasive shearing and brittle fracture mechanisms are predominant in composite materials with high interstitial integrity, and ductile shear induced by scooping and plowing action of abrasive particles predominate material removal in ductile material.

3 Operations

The operations aspect of AWJ machining consists of drilling, turning, threading, and 3D machining.

3.1 Drilling with Abrasive Waterjet. Investigations on drilling using AWJ are being conducted currently at the University of Kentucky, University of Washington, and Quest Integrated, Inc. Drilling difficult-to-machine materials such as ceramics, glass, high nickel alloys used as gas turbine materials, etc., pose a formidable challenge to drilling with conventional drill bits. Deep hole drilling using laser causes undesirable surface characteristics, considerable heating of the workpiece and need for additional processing. Drilling using AWJ is a viable alternative for this purpose. Emphasis of the research in drilling using AWJ in the University of Kentucky and University of Washington is primarily on drilling stationary workpiece with stationary jet whereas Quest Integrated, Inc. is focusing in AWJ deep hole drilling up to 2.5 m depth. Hashish demonstrated [26] that different techniques such as rectangular shaped AWJ with rotating workpiece, stationary workpiece with oscillating jet, or stationary workpiece with rotating jet can be adopted to produce high quality deep holes.

Depth monitoring in opaque materials during AWJ drilling of small diameter blind holes is very difficult to perform without interruptions. In order to control blind hole drilling process efficiently, depth monitoring is the primary issue, which is being addressed by the investigators. A semiempirical transient numerical model for prediction of the depth of AWJ drilling was developed by Raju and Ramulu [23] based on the principle of conservation of momentum. This drilling model was providing close correlation at medium drilling depths. Kwak et al. [27] adopted a different approach to address this issue. Their investigations demonstrated that acoustic emission signal generated during the AWJ drilling process can be used as an effective tool for monitoring the drilling depth. This investigation also showed that acoustic emission sensing technique provides critical information and more insight into the material removal mechanisms during the AWJ drilling process. Yong and Kovacevic [28] developed a theoretical model to construct arbitrary particle-laden jet flow by fractal point sets which was demonstrated for predicting AWJ drilling depth.

Two-dimensional dynamic photoelasticity method was developed by Ramulu [29] to record the photoelastic stress patterns associated with AWJ drilling and cutting. These fringe patterns were used to identify the transient stress fields adjacent to the drilled hole during the initial crater generation and crack propagation. A new approach using reflection interference optical method called photo-carrier wave method was developed by Yeh et al. [30] combining the laser holography and traditional photoelasticity to determine the principal stresses in the vicinity of the AWJ drilling zone.

3.2 Turning/Threading with AWJ. In turning with AWJ, the workpiece is rotated while the AWJ is traversed axially as well as radially to produce the required turned surface. Investigations on AWJ turning has addressed the volume removal rate, surface finish control, visualization, and modeling [31] of the turning process. Unlike conventional turning, AWJ turning is less sensitive to the original part shape. Its relative insensitivity to length-to-diameter ratio of the workpiece enables the process to turn long and small diameter parts to precise dimensions. This process is ideally suitable for machining difficult-to-machine materials such as ceramics, composites, glass, etc.

Detailed investigations conducted at University of Rhode Island [32, 33] demonstrated that composite screw threads machined using AWJ have a good potential as an alternative for adhesive bonding or bolted connections. They provide a fast and reliable method of obtaining good quality thread profiles. Numerical stress analysis of the joints indicate that the resulting threads have the potential to provide good joint strength as compared to adhesive bonded joints. Microstructural examination of machined threads reveal minimal structural damage. Mechanical characterization of threaded joints revealed a strong dependence of joint strength on composite fiber orientation.

3.3 Three-Dimensional Machining. Three-dimensional machining of cylindrical objects is relatively easy to perform by incorporating cutting, turning and drilling in the same setup. However, 3D machining of flat objects using AWJ has always been a challenge. Capability to monitor and control the depth

Table 2 Models for predicting depth of penetration in AWJ cutting

Hashish [1]	$\frac{cd_j}{2.5}\left(\frac{14m_a}{\pi u d_j^2 \rho_a}\right)^{2.5}\frac{V_a}{V_i}$	Ductile materials (SCR)
Hashish [1]	$\frac{1}{\frac{\pi d_j \sigma_f}{2(1-c)m_a(V_a-V_c)}+\frac{C_f}{d_f}\frac{V_a}{V_a-V_c}}$	Ductile materials (RCR)
Kovacevic Mohan & Hirscher [34]	$\frac{C\cdot p^{0.79}\cdot s^{0.0068}\cdot \dot{m}_P^{0.1844}}{v^{0.5671}}$	Concrete regression model
Zeng and Kim [35, 36]	$\frac{N_m P_w^{1.25}\dot{m}_w^{0.687}\dot{m}^{0.343}}{CD_{0.618}u^{0.866}}$	Brittle materials
Chung, Geskin & Singh [37]	$\frac{(p-p_c)\cdot \dot{m}_P^{0.6}}{v\cdot b_K}$	Ductile materials
Momber and Kovacevic [38]	$p^{\phi}\cdot\frac{d_f}{v}\cdot\int_{E_A}^{E_P} g(E_P)dE_p\cdot \dot{m}_P^n$	Ductile and brittle materials

of penetration in AWJ cutting and drilling determines the 3D machining effectiveness. Both analytical and empirical models have been developed for predicting the depth of penetration in AWJ cutting. These models are given in Table 2.

To control the uniformity of the AWJ penetration into the workpiece, it is necessary to devise a sensing system that can sense the depth of AWJ penetration on-line. Kovacevic [39] demonstrated that workpiece normal force generated by AWJ could be used as an indicator of the depth of jet penetration. A suitable optimization strategy was developed by Kovacevic and Fang [40] by applying the principles of Fuzzy set theory to select the optimal process parameters for achieving a required depth of cut in a given material. The advantage of this approach is the elimination of the need for extensive experimentation. Acoustic emission was used as a parameter by Mohan et al. [41] to monitor the depth of penetration on-line in AWJ cutting. The peak of the power spectrum density of the ARMA model representing the AE signal exhibits a linear relationship with kerf depth. A suitable control strategy was proposed using this approach.

Two general approaches are adopted for performing three-dimensional machining of flat objects with AWJ. The first approach involves the usage of templates or masks to machine complex patterns such as isogrid structures [42] where selective pocketing is needed. Even though this method is relatively straight forward, the entrapment of AWJ mixture between the template and the workpiece should be avoided to prevent any damage of the workpiece surface. Most of the complicated shapes cannot be produced by the template method alone. The second approach of 3D machining is by controlling the exposure time through manipulation of traverse rate and the number of passes. Due to its versatility, the potential of 3D machining by controlling the exposure time needs to be exploited.

Kovacevic and Yong [43, 44] have developed a robust model for simulating 3D AWJ machining process. This model combines two fundamental issues together, namely kinematics of the particles and the constitutive equation for the erosion rate of a particle. The theoretical framework consists of two parts. One part quantifies the particle motion, including velocities and locations, on the cross-section of an arbitrarily shaped nozzle by using fractal point sets generated by nonlinear iterative equations. The other part ascertains the constitutive equation for estimating the penetrating ability of a particle experiencing cutting (or fracture) wear and deformation wear. Based on the developed model, a quantitative simulation of AWJ machining was performed for local and global machining parameters such as the average depth of cut or drill, surface waviness and roughness. The validity of the 3D features of the surfaces generated through the model for different processes such as drilling and cutting was verified through diverse experiments with glass, titanium and other metals, and they were found to be in good agreement. Due to the universality of this model, it could be used for exploring new functions of AWJ as a machining tool reducing expensive and time consuming tests. Figure 2 shows the 3D configuration of kerfs produced by a triangular nozzle for different orientations as an example.

4 Systems and Sensing

Investigations into the systems and sensing in AWJ machining consists of Ultra-high pressure systems, temperature sensing, AWJ nozzle wear monitoring, and smart nozzles.

4.1 Ultra-High Pressure Systems. Commercially available, high pressure intensifier pumps provide reliable operations up to 380 MPa. The cutting of metals and composites without using abrasives is limited at these pressures. To overcome these limitations, tests were conducted at Quest Integrated, Inc. by increasing the waterjet pressures up to 690 MPa with significantly improved results. It was found that 0.025 mm diameter jet at 690 MPa is feasible in making thin cuts and small diameter holes in thin sheet metals [45]. Addition of abrasives to the super pressure jets has also been explored. The premise is to increase the particle velocity. A special vacuum assist line has been developed [45] to entrain the abrasive to the nozzle. Preliminary investigations indicate that reducing the waterjet diameter improves the efficiency of cutting.

High pressure continuous abrasive suspension jets (ASJ) are being developed at Quest Integrated, Inc. [45]. Figure 3 shows the schematics of this system. Three basic critical components are under investigation for developing reliable high pressure ASJ systems namely nozzle, valves, and isolator. The isolator was selected to eliminate the need for slurry seal development. This concept showed increased reliability and flexibility in controlling effective stroke length and pressure fluctuations without the need for an accumulator. Nozzle material made out of molybdenum carbide and diamond composite show good promise for reliable operation up to 4 hours. However, there is still a need for improved nozzle material. It has been observed ASJ cut up to 5 times faster than AWJ.

4.2 Temperature Sensing in AWJ Cutting. Contrary to the traditional manufacturing processes, the absence of thermal effects and heat affected zone in AWJ cutting process have

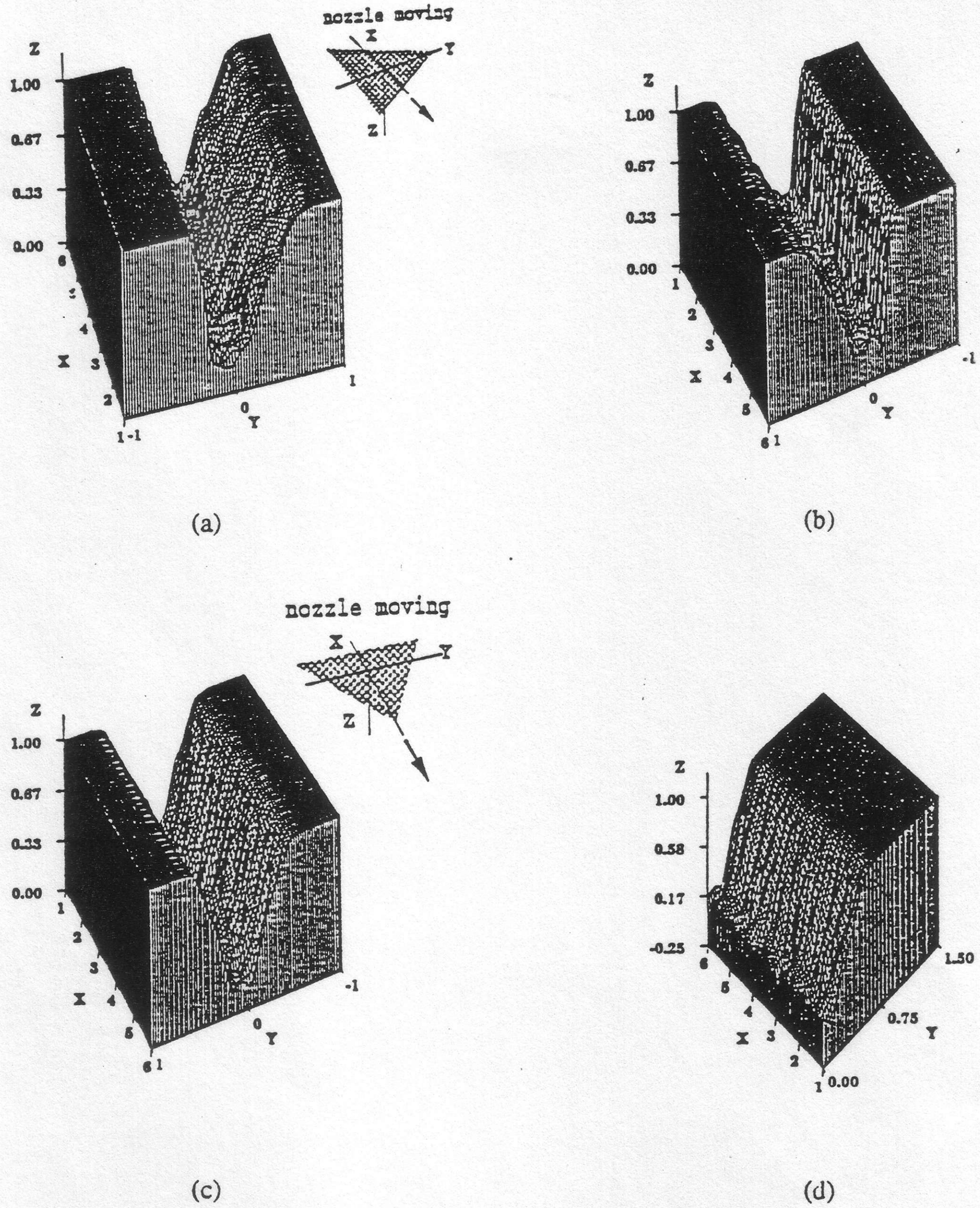

Fig. 2 3D configurations of kerfs produced by a triangular nozzle (*a–b*) different views of a kerf to show the variation of waviness and roughness (*c*) comparison with (*a–b*) when the orientation of the nozzle is changed (*d*). A section view of (*c*) to show details of lateral waviness and bottom roughness

tempted one to often refer to this technique as a cold-jet cutting process. However, cutting of materials like titanium yields spark showers and water vapor at the cutting zone indicating the presence of highly localized heating effects. Thermal sensitive materials like certain polycarbonates, plastics, glass, certain composite materials, and biomaterials like bones are subjected to structural deformation and crack formation when exposed to temperature rise of even a few degrees. Apart from the workpiece, the cutting nozzle is also subjected to temperature rise due to erosive wear and turbulent mixing. Hence, there is a need to investigate the source of heat generation and its distribution in the workpiece as well as the abrasive waterjet nozzle.

Investigations performed to monitor the temperature distribution involved both analytical modeling and experimental studies. Two-dimensional moving line heat source model was used as the basis for the analytical model to monitor the thermal energy distribution. As heat flux could not be determined directly (due to the complexity of the problem), a suitably defined inverse heat conduction problem through a parameter estimation approach which uses the experimentally determined temperature histories at various points in the workpiece, was adopted. Even though the analytical approaches were similar, Ohadi et al. [46] used thermocouples for workpiece temperature measurement whereas Kovacevic et al. [47] adopted infrared (IR) sensing technique. Different workpiece materials such as aluminum, stainless steel and titanium alloy were used for the investigations. Apart from being a simpler tool for workpiece temperature monitoring, infrared sensing offers to be a feasible technique for visualization of AWJ cutting mechanisms in opaque materials. It was also demonstrated [47] that IR sensing technique could be used as a viable method for monitoring the nozzle wear using the temperature distribution in the AWJ cutting nozzle.

4.3 Studies on AWJ Nozzle Wear and Orifice Health Monitoring. The role of the nozzle in AWJ machining can be considered to be analogous to that of the cutting tool in traditional machining; the difference being that there is no tool-

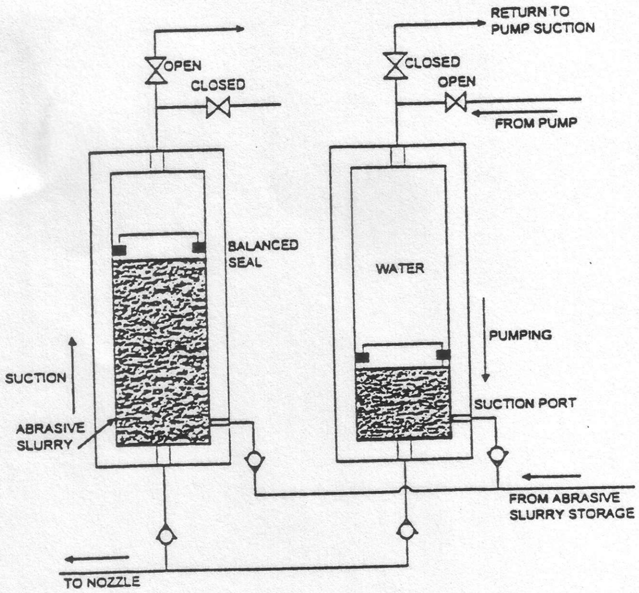

Fig. 3 Schematics of high pressure continuous abrasive suspension jet

workpiece contact here. However, like a conventional tool, AWJ nozzle is also subjected to constant wear as machining progresses. One of the most critical parts that influences the technical and economical performance of the AWJ system is the AWJ nozzle. The increased wear of the AWJ nozzle makes the clearance between the abrasive mixture and the nozzle larger. This causes incomplete mixing of the abrasive particles with the high velocity waterjet which results in deterioration in cutting ability, poor surface quality, and affects the precision of machining causing undesirable changes in workpiece geometry. Hence suitable methods need to be devised to ensure uniform product quality at desirable levels by replacement or compensating for the worn nozzle at the right time.

Both direct and indirect sensing techniques have been adopted for nozzle wear monitoring. These sensing techniques are given in Table 3. Investigations conducted by Kim et al. [54] indicated that polycarbonate plastic tubing is an excellent material for accelerated nozzle wear simulation. Detailed wear rate investigations indicate that aluminum oxide abrasive has higher erosion capability than garnet for brittle nozzles and workpieces, but is equal or even less effective for eroding ductile nozzles and workpieces. Investigations of the effects of offset inner diameter (ID) on AWJ machining process [55] indicate that offset ID adversely affects the nozzle wear and hence nozzle performance, only when the measured offset is greater than 0.2 mm.

Quest Integrated, Inc. has developed [45] a suitable strategy for monitoring the orifice health. This is based on monitoring the vacuum level in the mixing chamber, located just below the sapphire orifice. A schematics of the orifice health sensor is shown in Fig. 4. As a worn out orifice will affect the coherence length of the jet exiting from the orifice, it is used as a measure of the orifice health. Lower coherence length of the jet which is indicative of a worn nozzle was showing a higher pressure in the sensor. Higher vacuum is accompanied by a more coherent jet indicating a healthy orifice.

4.4 Smart Nozzles. To automate the AWJ machining process, a quick change nozzle was developed by Quest Integrated, Inc. [56]. This nozzle (as shown in Fig. 5) consists of a nozzle body that attaches to the end effector and cartridges that represent AWJ tools. A cartridge contains the orifice and the nozzle in an alignable assembly. The alignment of the cartridge was provided to allow the user to select the proper combinations of waterjet orifices and nozzle and also to be able to reuse the cartridge for several applications. The challenge of reliable cartridge operation was to design a small-size, non-metal-to-metal, high pressure quick-connect seal with minimal maintenance. Another critical design criteria was positioning accuracy of the nozzle tip. Significant reduction in downtime was observed in operations requiring multiple machining operations when quick-change nozzle was used [56].

5 New Applications

Feasibility of several innovative applications related to high pressure waterjet machining area such as ice-jet machining, cryogenic and abrasive cryogenic jets, hybrid maching, polishing, and cleaning have been investigated with high success.

5.1 Ice Jet Machining. In AWJ machining, abrasives such as garnet, aluminum oxide, quartz, etc. are added to a thin stream of high velocity waterjet in order to improve the cutting effectiveness. However, addition of abrasive particles lead to increase in the cost of production, undesirable environmental impact, and minimal usable jet diameter. It would be highly desirable to enhance the productivity of waterjet and yet use abrasives. This objective can be achieved by replacement of abrasives by ice particles and formation of ice-jet (IJ). As the hardness of ice is less than that of the abrasives used in conventional AWJ, IJ may not be as highly productive as AWJ. However, cost reduction and elimination of the negative environmental effects could overweigh the reduction in productivity. The most important advantage is the feasibility of IJ usage for shaping of materials in food, electronics, space, and other branches of industry where any contamination in the course of processing should be completely eliminated. One of the potential applications of IJ is medicine.

Ice-Jet machining technology has been developed [57] at New Jersey Institute of Technology in which a narrow stream of high velocity waterjet entrained with ice particles is used as the machining tool. A study was conducted to establish the feasibility of formation of high speed water-ice slurry and evaluate the ability of this jet to machine materials. This slurry can be generated in two ways. One method is to mix the small ice particles into water stream in the mixing chamber similar to mixing abrasive particle. In this case, the abrasive supply system should be modified to prevent ice melting. This type of IJ can be used for shaping of a wide variety of materials when the jet diameter of 500 plus micron is acceptable. If the jet particles should be less than 500 microns, IJ should be formed by partial freezing of water during and after acceleration. Two critical factors to be considered for this type are the drop in the freezing point of water at higher pressures and need for additional heat removal after the isenthalpic expansion through the waterjet orifice. Schematic of the ice-jet machining by ice particle injection is shown in Fig. 6.

In the second type of IJ system where the ice particles are generated within the stream, the carbide nozzle is replaced by a finned copper tube submerged in a liquid bath. Water is initially cooled prior to the booster pump. The high velocity water exiting from the nozzle was partially frozen in the copper tube, and the ice jet stream exiting the copper tube was used for machining.

Preliminary experimental results demonstrated the feasibility of Ice-jet machining of different materials such as aluminum, steel, titanium, plastic, and plexiglass. IJ cutting results in the formation of a clean surface with minimal material removal, lower kerf width and improved cutting and drilling effectiveness.

5.2 Cryogenic and Abrasive Cryogenic Jets. The use of liquid nitrogen jets has been demonstrated by the Air Force Armstrong Laboratory [63] for explosive washout. Also it was reported by Idaho Energy National Laboratory (INEL) that liquid nitrogen jets have been used to cut several relatively soft

Table 3 Studies on AWJ nozzle wear monitoring

Direct sensing methods		
Ultrasonic gauging	Operates on ultrasonic pulse-echo technique	Kovacevic and Evizi [48]
AWJ nozzle wear probe	Wear sensor embedded on nozzle tip made of conductive loops on ceramic substrate	Kovacevic [49]
Indirect sensing methods		
Opto-electric sensing of AWJ stream diameter	Using machine vision system consisting of CCD camera and laser light source	Kovacevic [50]
Optical tracking of kerf width	Monitoring kerf width using CCD camera	Kovacevic and Evizi [48]
Vibration monitoring	Detecting the change in nozzle vibration using accelerometer	Kovacevic and Evizi [48]
Workpiece normal force	Amplitude of static workpiece reactive force quantified wear in AWJ turning	Kovacevic and Evizi [48]
Acoustic signature analysis	Sound generated during the flow of WJ and AWJ was proportional to Nozzle ID	Kovacevic, Wang & Zhang [51]
Infrared sensing technique	Radial and axial wear of AWJ nozzle based on peak temperature measurement	Kovacevic, Mohan & Beardsley [47]
Real-time control strategies		
Time series analysis	ARMA Modeling of dynamic workpiece normal force in AWJ cutting	Kovacevic [50]
Fuzzy recognition	Algorithm based on fuzzy set theory using static force	Kovacevic and Zhang [52]
Artificial neural networks	Based on backpropagation algorithm using Frequency domain sound signals	Mohan, Kovacevic and Damarla [53]

materials. Dunsky and Hashish [64] generated liquefied CO_2 jets to explore the potential of cryogenic cutting and to identify the requirements for cryogenic jet development. A 345 MPa CO_2 jet was found to perform comparably to a waterjet at the same pressure and flow rate. Investigations are underway to develop abrasive cryogenic jets by entraining palletized CO_2. It was observed that the resulting jet improved cleaning power but not cutting power which could be due to disintegration of CO_2 particles at the highly erosive environment during the mixing process.

5.3 Hybrid Machining. Since inception, metal machining processes have always focused on performance improvement in terms of better surface quality, reduced cutting forces, enhanced tool life and improved chip shape. This objective can be better achieved if the thermal/frictional conditions existing at the cutting zone can be controlled effectively. Application of cutting fluids is an external means to reduce the frictional forces and dissipate the undesirable heat produced at the cutting zone. Location of placement, speed and direction of application of cutting fluids are critical factors which determine their effectiveness. Hybrid machining processes are developed at the University of Kentucky [58–60], University of Missouri-Rolla [61], and Cleveland State University [62] by the application of high pressure waterjet in order to achieve the above objectives.

5.4 Polishing and Cleaning With High Pressure Waterjet. One of the recent applications of high pressure waterjet is in precision polishing and cleaning technology. New Jersey

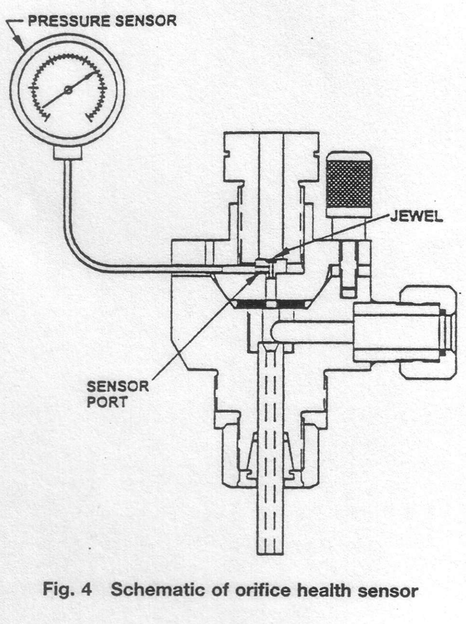

Fig. 4 Schematic of orifice health sensor

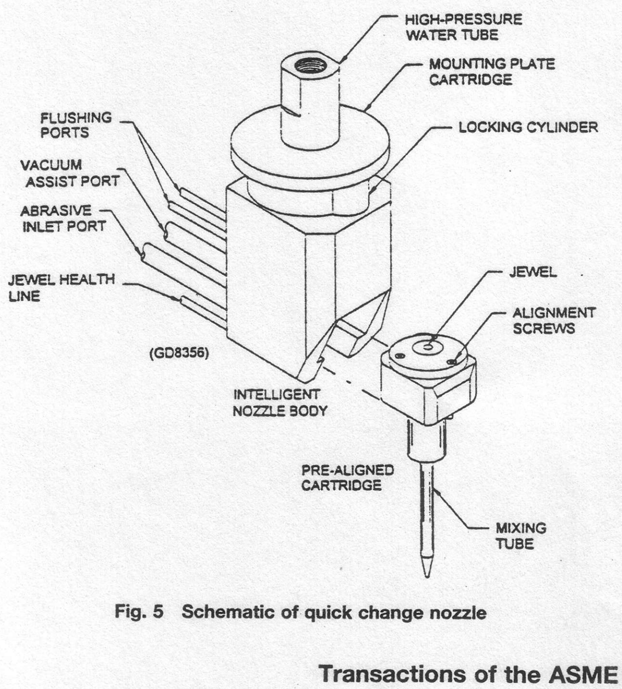

Fig. 5 Schematic of quick change nozzle

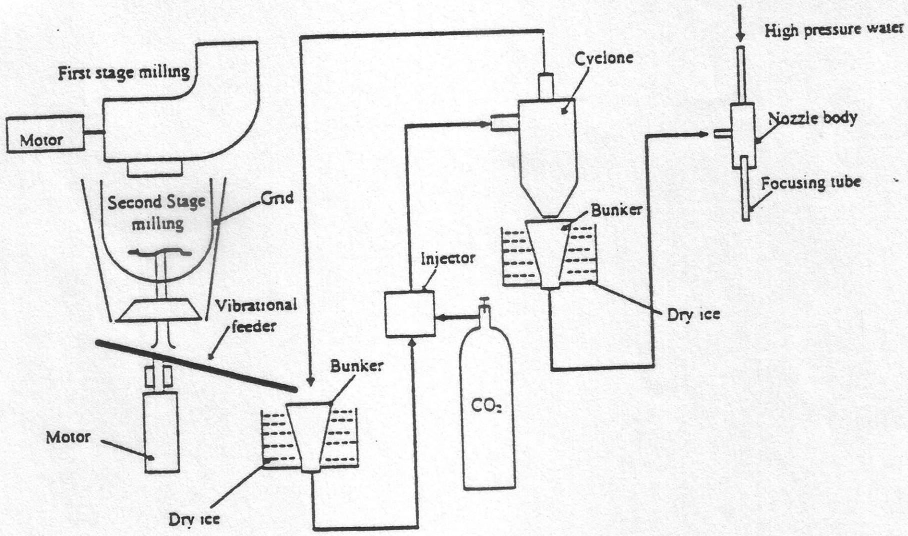

Fig. 6 Ice particle injection ice jet machining

Institute of Technology [65] is currently involved in developing the technology of polishing difficult-to-machine materials such as ceramics and high alloy steels using high pressure waterjet. Polishing using AWJ is performed by impingement of the jet at very shallow (near zero) angles. Experimental investigations demonstrate that compared to other finishing operations like grinding, AWJ as a polishing tool is capable of achieving ten fold improvement in surface finish with very little surface/subsurface damage or any induced stresses at impingement angles less than 20 deg. Investigations performed [66] by University of Rhode Island in application of waterjet in coating removal process indicate that process optimization can be achieved through understanding of coating material properties, their removal mechanisms and careful selection of process parameters.

The established precision cleaning technologies are based on the use of special chemical compounds for surface decontamination and soil removal from vessels and nuclear reactors. Tightening environmental regulations make this approach to surface processing illegal and too expensive due to the usage of chlorofluorocarbons (CFC) and ozone depleting solvents (ODS). New Jersey Institute of Technology has developed a robotic waterjet cleaning system [67, 68] which uses a spiral nozzle for precision cleaning applications. Experimental investigations show that stand-off distance is a critical parameter for cleaning using modified nipple block nozzle where the waterjet impingement is at a direction perpendicular to the cleaning surface. The feasibility of both approaches have been established and the results indicate that high pressure waterjet cleaning is a viable and desirable technique as it eliminates debris contamination, workpiece surface/subsurface damage and has the potential for recycling water and off-products.

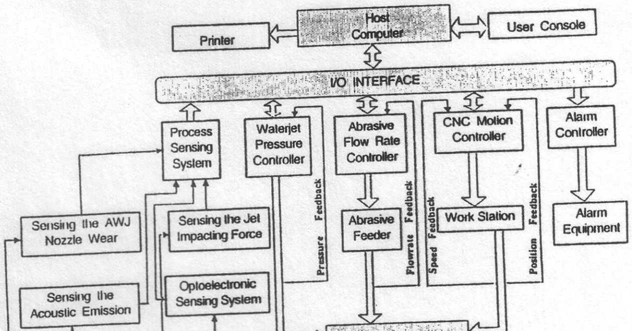

Fig. 7 Block diagram of new generation of AWJ cutting system

6 Conclusions

All the investigations described above and their predecessors are the vital and critical driving force behind the rapid progress of AWJ machining and related fields in the past decade and a half in the U.S. The research oriented toward understanding the physics of the process have been very vital for the operations and systems study. Also, the progress made in the operations, systems and sensing area enlarge the scope of understanding of the mechanisms of machining. The new applications developed in the high pressure abrasive waterjet area are complementary to the basic research and enhance the need to explore further possibilities. Toward the realization of an effective and optimum control of the AWJ process performance, the relationship between the AWJ process parameters and the process output needs to be understood clearly. The block diagram of the new generation of abrasive waterjet cutting system equipped with different levels of closed-loop feedback control systems is shown in Fig. 7 as a vision for the future. Even though few of these controllers such as position controller and speed controller have been developed and pressure controller is being developed, the challenge for the future lies in integrating the total system. Once this objective is met, AWJ could be ideal for a flexible manufacturing environment.

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