

Ashraf I. HASSAN, Jan KOSMOL

Katedra Budowy Maszyn, Politechnika Śląska, Gliwice

AN OVERVIEW OF ABRASIVE WATERJET MACHINING (AWJM)

Abstract: Abrasive waterjet machining (AWJM) is a new machining process, the advantages of which include low cutting temperatures, no heat damage to the material being cut, minimal dust, and low cutting forces. This paper presents a state of the art review of research in this new process. The main topics discussed are mechanics of material removal, productivity, cutting forces, surface quality and nozzle wear.

1. INTRODUCTION

Current design requirements have necessitated the need for a class of engineering materials that possess high stiffness and reduced weight, especially at elevated service temperatures. Due to the rapid developments in the aerospace and the automotive industries, traditional machining of ceramics and composite materials are becoming inadequate and inefficient because of the excessive tool wear, and the brittle nature of these materials.

Abrasive waterjet machining offers the potential for the development of a tool which is less sensitive to material properties, has virtually no thermal effects, and imposes minimal stresses [1]. This process was first introduced as a commercial system in 1983 for cutting of glass. Nowadays, this process is being widely used for machining of hard to machine materials like ceramics, ceramic composites, fiber-reinforced composites, and titanium alloys where conventional machining is often not technically or economically feasible [2]. The fact that it is a cold process has important implications where heat-affected zones are to be avoided [3].

The heart of the abrasive waterjet system is the abrasive jet nozzle as shown in Fig. 1. Water is pressurized up to 400 Mpa and expelled through a sapphire nozzle to form a coherent high-velocity jet. Abrasives are added into a specially shaped abrasive-jet nozzle

from separate feed ports. Part of the waterjet's momentum is transferred to the abrasives,

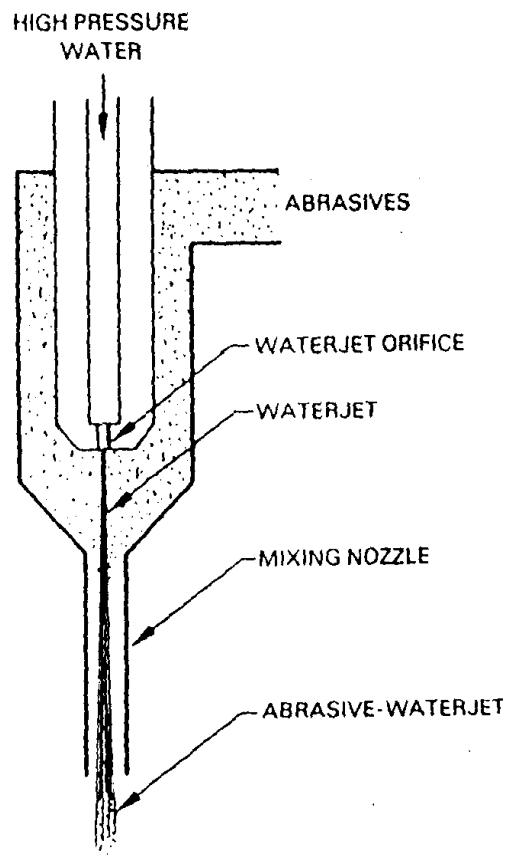


Fig.1 Schematic of abrasive waterjet nozzle [4]

whose velocities rapidly increase, as a result, a focused, high-velocity stream of abrasives exits the nozzle and performs the cutting action of the workpiece surface. The abrasive waterjet machining system is composed of the following components [1]: high pressure intensifier, waterjet, abrasive feed system, abrasive-jet nozzle, abrasive and water catcher, and supporting accessories such as hoses and control valves.

There are several parameters that affect the cutting performance of the abrasive waterjet [1]: hydraulic parameters; waterjet nozzle diameter and supply pressure, abrasive parameters; abrasive material, abrasive size and abrasive flow rate, mixing parameters; mixing tube dimensions and nozzle material, cutting parameters; traverse rate, stand off distance, impingement angle and depth of cut and material to be cut.

Advantages of the process include the following [1,4] : minimal dust specially when cutting of asbestos, less thermal or deformation stresses i.e. the workpiece is cold cut, decreased power consumption, striation is reduced, high accuracy due to little workpiece deformation, no fire hazards because water is inflammable, the ability to cut almost any material, deep kerfing capability, high edge surface quality, and no heavy clamping of workpiece is needed.

The following limitations are relevant to abrasive waterjet machining [1,5]: high capital investments are required, high cutting power is required, delamination occasionally occurs, the jet has only a limited stability perpendicular to its own axis, and the process is noisy and produces a great deal of spray.

The process has been extensively used in diverse fields of applications. An early study on practical applications of AWJM [1] provided a comprehensive list of potential candidate materials that were successfully machined. Examples of industrial applications of AWJM are found in [6-10]. Machine tools for AWJM have been extensively developed in several companies for the last two decades. Several machine tools' designs are found in [11-19].

This paper is a review of recent developments in AWJM research. An attempt will be made to assess the present situation; namely, to find out what new knowledge is available today, what is lacking in research and applications, and how the situation could be improved. The paper will concentrate on new research findings obtained during the last two decades, which had produced many useful theoretical as well as experimental findings. Much of the research has dealt with mechanisms of material removal in different work materials, productivity and surface quality and some reviews on AWJM have been conducted so far [20-25]. Comparison studies, especially between AWJM and laser, have also been conducted [5,26].

2. MECHANICS OF MATERIAL REMOVAL

The basic mechanisms of material removal were studied extensively and established through experimental as well as analytical work. The development of different wear mechanisms have pushed performance level of AWJM even further. An early erosion model by waterjets was developed by Hashish and Du Plessis [27] based on a control volume analysis to determine the hydrodynamic forces acting on the solid boundaries of the cutting slot. The coupled fluid-solid mechanics equations are simplified to yield a closed-form solution which satisfies all the limiting conditions of practical cutting applications. Different materials were characterized by friction, damping coefficient and compressive yield strength. The equation derived for jet penetration was later combined by the same authors [28] with empirical equation for jet spreading and velocity decay in air to predict the depth of cut and material removal for non-metallic materials such as wood, limestone and coal. A similar hydrodynamic model for pure waterjet was derived by Majka [29]. Another model was developed by Wilkins and Graham [30] for soft materials such as leather, wood, rubber and plastics based on the deflection of the jet within the material.

The process of erosion by solid particle impact has been investigated by several notable researchers since 1960. The early work of Finnie [31] is still regarded as the leading work, since then a number of researchers in AWJM have developed several cutting models on erosion. Mechanisms of erosion of ductile materials dominated the literature until 1970. It is well known that there is a dramatic difference in the response of ductile and brittle materials to erosion. Finnie's model for the prediction of material removal during erosion of ductile

materials was derived by solving the equation of motion of a single particle striking the surface at a shallow angle of impact in the same manner as a milling cutter or a grinding wheel. One of the drawbacks of the model was that particle rotation during cutting was neglected. Ductile behavior of some brittle materials was observed during erosive cutting when the abrasive size is very small [32]. Later, an intensive work in the field of erosion was conducted by Hashish [4,33-35]. A simplified model, based on Finnie's model, for cutting of ductile materials was suggested which divided the cutting zone into two regions : cutting wear and deformation wear [33]. This division is based on a visualization study of the AWJM process [34] using movie cameras at speeds of 64 and 1000 frames/s. This model uses cutting wear by single-particle abrasive impact. Figure 2 shows a schematic of the different cutting stages. A steady-state interface to a depth (h_c) exists at the top of the kerf. Below (h_c), a step of material exists and appears to move under the impact of the jet until it reaches the final depth (h). The kerf curvature at depth (h_c) changes suddenly, marking a transition from one material removal mode to another [36,37]. The abrasive waterjet material removal process is a complex erosion process where more than one mode contributes to the erosion results. Material removal takes place as a result of the erosive action of large number of impacts (10^3 /s) by the abrasive particles [38].

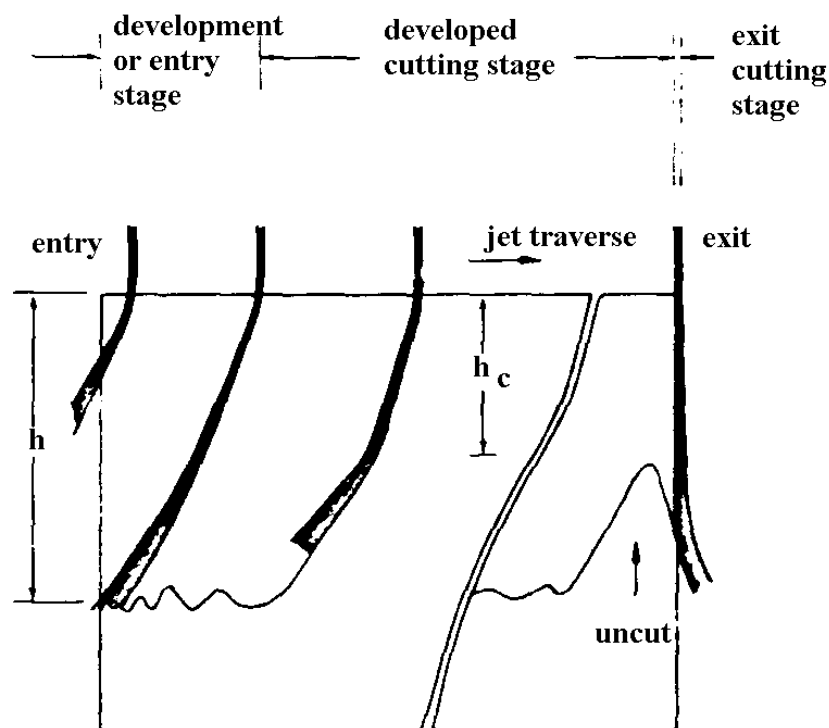


Fig. 2 Cutting zones of abrasive waterjet kerfs [36]

Two mechanisms have been identified as the dominant modes of material removal. These are the cutting wear mode and the deformation wear mode. The surface produced by the first mode is a relatively smooth due to a cutting wear at a shallow angle of impact and it exists at

the upper portion of the cutting kerf [35]. The material hardness is the most relevant material property to this mode [36]. The surface produced by the other mode is striated due to a deformation wear mode at large angles of impact which is characterized by material removal due to excessive plastic deformation [35]. This wear mode results in an unsteady penetration process. The modulus of elasticity was found to correlate well with this mode of material removal [36,37]. Recent studies in AWJM of graphite/epoxy composites pointed out the existence of a small initial damage zone near the jet entrance in addition to the previous two zones [39,40]. A recent study found that the depth of the cutting wear zone could be increased by 30 % by applying a small oscillation to the AWJ head [41]. Momber [42] reviewed the different formulas for the depth of cut obtained by different researchers.

The relative contribution of each mode to the total depth of cut depends on the traverse rate [4]. The depth over the cutting wear mode (h_c) is obtained by the following expression [35], see Fig.3:

$$h_c = \frac{(V_o / C_K) d_j}{[(\pi \rho_p u d_j^2 / 14 \dot{m})]^{2/5} + (V_e / C_K)} \quad (1)$$

where,

u	traverse rate
V_o	initial abrasive particle velocity
C_K	characteristic velocity
d_j	jet diameter
ρ_p	density of abrasive particle
$\dot{m}$	abrasive particle mass flow rate
V_e	threshold particle velocity

whereas the depth of cut by deformation wear mode (h_d) is calculated by the following equation [35] :

$$h_d = \frac{1}{[\pi d_j \sigma u / 2 C_1 \dot{m} (V_e - V_o)^2 + [C_f V_o / d_j (V_o - V_e)]} \quad (2)$$

where,

σ	workpiece flow stress
C_1	ratio of effective particle velocity
C_f	coefficient of friction on kerf wall

The developed model can be easily used for predictions. Two properties are needed for a specific material: flow stress and a critical velocity. These can be determined based on experimental results. The prediction accuracy of the model was found to be very adequate for cutting applications. The total depth of cut (h) can be expressed as:

$$h = h_c + h_d \quad (3)$$

The critical traverse rate (u_c) at which cutting wear terminates is [4] :

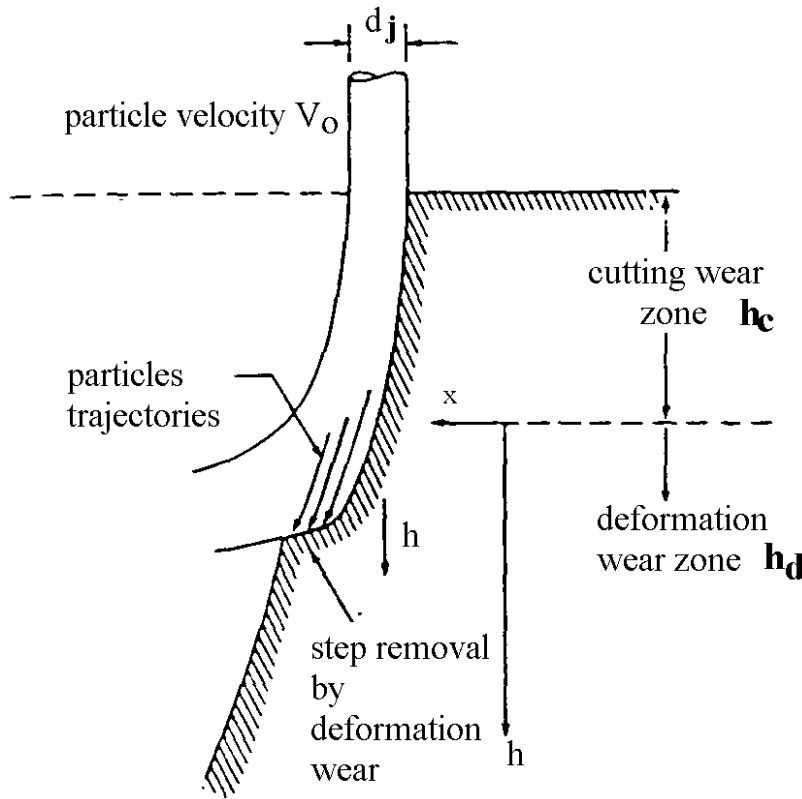


Fig. 3 Erosion zones in AWJM [35]

$$u_c = \frac{\dot{m} V^2}{20 \sigma d_j^2} \quad (4)$$

where, V particle velocity

It was noted that the erosion mechanism in silicon carbide-reinforced aluminium metal matrix composite differs slightly. The aluminium matrix is subject to microcutting, such as ductile materials, while the SiC particulates being removed by shovelling action of the incoming jet [43]. A recent work by Finnie [44] reviewed the research work of erosion by solid particles entrained in a liquid jet during the last four decades. Finnie confirmed again that the erosion mechanism dominating ductile materials is plastic deformation. Observations of scanning electron microscopy showed that some particles remove a chip as in metal cutting, others leave material piled up at the sides or the end of the crater. This raised material is presumably removed easily by subsequent particles. A recent study used a new approach for modeling the AWJM process of ductile materials, based on experimental results, in order to obtain metal removal rates as a function of particle velocity. It has been shown that the material is cut because a threshold water pressure is exceeded. A correlation relating material removal rate to the particle velocity was derived [45]. A more recent study modeled AWJM of ductile

materials on the basis of Finnie's and Hashish's models but modified by using the concept of generalised kerf shape i.e. accounting for the variations in the kerf width. The basic material property which determines the total depth of cut is suggested to be the melting specific energy rather than the elastic modulus as previous studies [46].

In brittle materials, erosion occurs by the propagation and intersection of cracks produced by impacting particles. At a threshold load a median crack will propagate downwards from the base of the plastic zone. This crack does not remove material but it does degrade strength [31]. A model of AWJM of polycrystalline ceramics was initiated by Zeng and Kim [47,48]. Erosion mechanisms observed include intergranular network cracking due to fractures caused by impact induced stress waves and plastic flow. Material removal due to network cracking was calculated with a crack network model which relates the fracture surface energy in forming the crack network to the energy of the impact induced stress waves, while plastic flow is evaluated with Finnie's model. It was found that an incident angle of 90° is optimum for maximum material removal to the contrast of metals where the maximum material removal is obtained at smaller incident angles as was previously pointed out by Finnie [31]. A semi-empirical model for grey cast iron was developed based on wear particle analysis because eroded particle size distribution may give information about the general erosion mechanism. The erosion mechanism does not depend significantly on pressure, but pressure was found to influence the efficiency of the material removal process. The erosion mechanism was suggested as microcrack network and the widening of the cracks by a high-speed water [49,50]. More recent studies [51,52] suggest erosion mechanisms for brittle materials on the basis of Finnie's [31] and Zeng's [47] models for brittle materials but taking into account the size and shape of the abrasive particles. Two zones of material removal exist, in the first the material is removed by microcutting and fracture because of the impact of abrasive particles at shallow angle of impact. In the second zone, material is removed by plastic deformation and fracture due to the orthogonal impact of abrasive particles. Meanwhile, variations in the width of cut has been neglected. It was pointed out that the use of spherical blunt abrasive particles will lead to more fracture.

Turenne and Fiset [53] modeled the abrasive particle trajectories during erosion by a slurry jet using an analysis based on potential and stream functions. This leads to the determination of the velocity components of the jet. It was shown that the predominant variable affecting the impact parameters is the particle size.

Up to date, there has been no attempt at analyzing abrasive water jet cutting using the powerful tool of finite element method. A preliminary effort of modeling the impact of a solid surface by a single water drop using a dynamic linear finite element model was carried out by Alder [54] who was concerned with rain erosion of aerospace vehicles which is similar to waterjet erosion.

3. PRODUCTIVITY

Significant experimental as well as analytical work on productivity has been reported. An early experimental work on productivity was reported by Hashish [55]. The important parameters affecting the productivity in AWJM are abrasive flow rate, pressure, stand off distance, traverse rate, abrasive material and abrasive particle size. The effect of these parameters on productivity will be discussed. The effect of abrasive flow rate on the depth of cut is shown in Fig. 4. A certain critical flow rate exists beyond which the

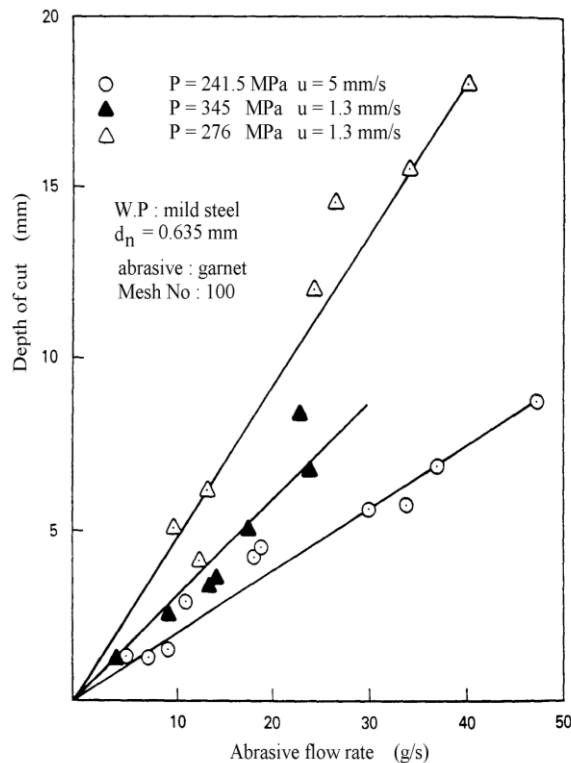


Fig. 4 Effect of abrasive flow rate on depth of cut [55]

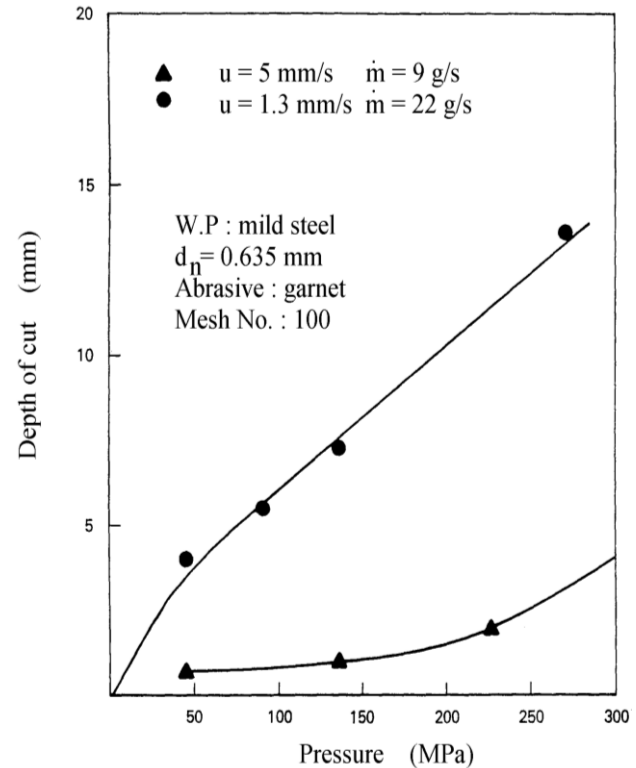


Fig. 5 Effect of pressure on depth of cut [55]

optimum abrasive flow rate exists at which the depth of cut peaks. The effect of pressure on the depth of cut is shown in Fig. 5. An optimum pressure should be determined to compromise between the rate of cutting and power requirements. High pressures result in deeper cuts and higher traverse rates. However, it was shown that higher pressures result also in lower hydraulic efficiency, more frequent maintenance, high wear rates of mixing tubes, and fragmentation of particles before they exit the nozzle. Consequently, hydraulic power is best utilized at an optimum pressure e.g. over 240 Mpa [56]. The effect of stand off distance on the depth of cut is shown in Fig. 6. The effect of stand off distance on material removal is shown in Fig. 7. It can be seen that there is an optimum stand off distance for maximum volume removal rate. An increased stand off distance is associated with a decrease in volume removal. However, increasing the abrasive flow rate does not significantly alter the trend of the

effect of stand off distance. Increasing the traverse rate will result in reduced depth of cut, see Fig. 8.

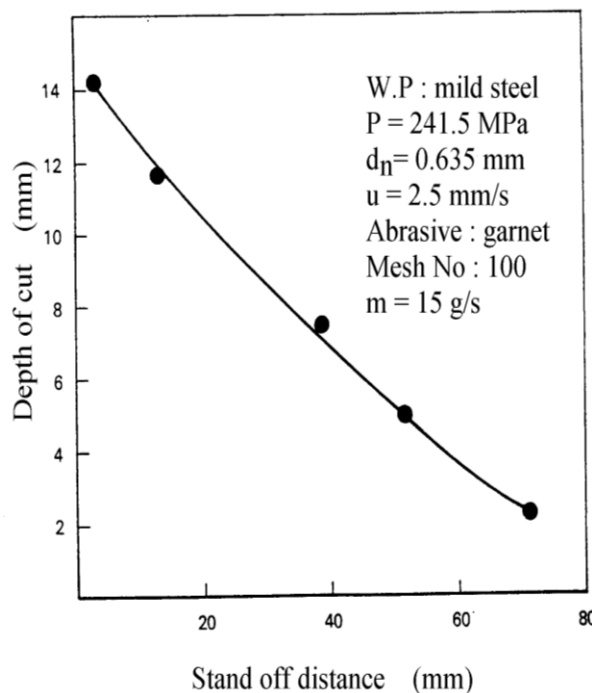


Fig. 6 Effect of stand off distance on depth of cut [55]

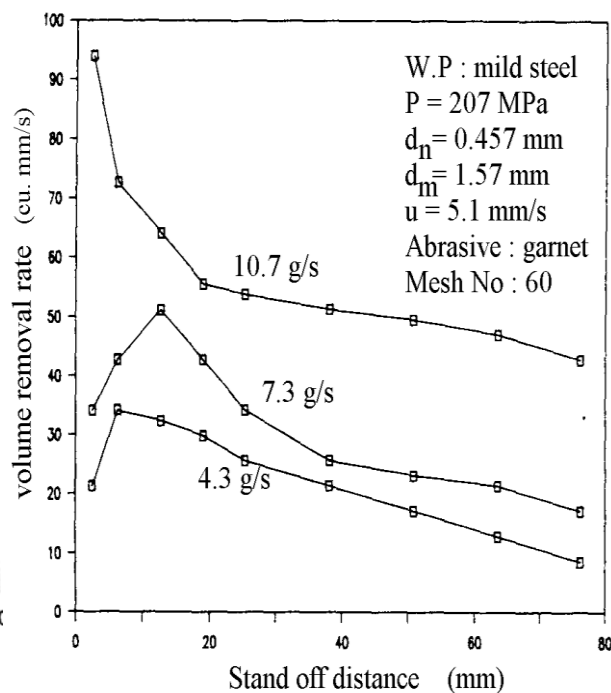


Fig. 7 Effect of stand off distance on volume removal [4]

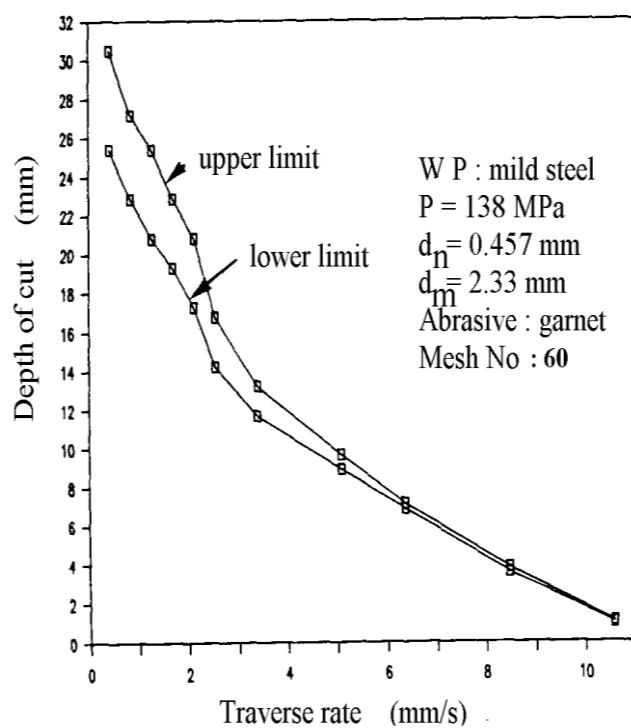


Fig. 8 Effect of traverse rate on depth and uniformity of cut [4]

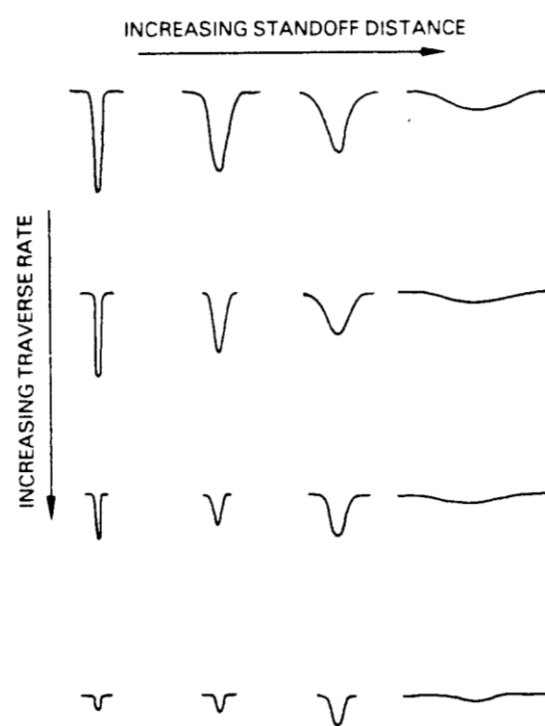


Fig. 9 Effect of stand off distance and traverse rate on shape of cut [4]

However, volume removal rates may increase with increasing the traverse rate. Figure 9 shows a diagrammatic representation of the effects of both stand off distance and traverse rate in the slot geometry. The use of hard abrasives would be suitable for fast material removal rates, whereas the use of soft, frangible abrasives may be suitable for finishing. Finer particles produce finer surfaces. However, reduced volume removal rates are associated with finer particles [4].

An early attempt to apply AWJ to milling was conducted by Hashish [4]. The preliminary results was encouraging in providing reasonable metal removal rates. But on the other hand, controlling the depth of cut was a difficult problem and an optimum machining strategy was needed to maximize metal removal rates and minimize the surface texture effects. Hashish [57] investigated the optimization of factors affecting AWJM due to the large number of parameters and factors involved. Significant improvements were found to be obtained. The relative significance of AWJM parameters on machining results were qualitatively summarized. Hashish [58] studied the effect of jet angle on productivity and found the same conclusion of Finnie [31] that there is an optimum angle for maximum depth of cut. He extended his study to milling, turning and drilling. It has been shown that metal removal rates can be increased by a factor of three when the jet is angled. The jet angle was also found to affect surface roughness and straightness of the machined surfaces. In a recent study on pocket milling using AWJ, Paul et al [59] developed empirical models using regression analysis. The depth of the pocket could be controlled to a value of 0.04 mm. A recent study on AWJ turning showed that the material removal rate trends are similar to those in linear cutting with AWJ [60]. The volume removal rates while machining modern ceramics were found to be primarily dependent on pressure and abrasive flow rate [61].

4. CUTTING FORCES AND TEMPERATURES

Few researchers were concerned with cutting forces and temperature. This may be attributed to the fact that AWJM is a cold cutting process and cutting forces are very low. The first study on thermal energy distributions in the workpiece during cutting with AWJ was conducted by Ohadi et al. [38]. From the results in Fig. 10, two important trends can be identified, where (y) is the distance from the cutting interface perpendicular to jet direction, (Z) is the depth in the workpiece parallel to jet direction, (t) is the workpiece thickness and (T_o) is the ambient temperature. First, it is seen that highest temperatures occur at the immediate vicinity of the cutting interface whereafter they experience a sharp decay with increasing distance from the cutting interface. However, increasing pressure increases temperature due to higher waterjet velocity, as shown in Fig. 11, where the numbers on the x-axis represent the positions of thermocouples. It was also observed that a material with higher thermal conductivity experiences higher temperatures during the cut. A more recent study on temperature distribution in the workpiece modeled the problem of temperature distribution

mathematically by feeding experimental temperature data to a heat conduction algorithm, which determines the heat flux in the workpiece. This heat flux is fed into a heat conduction model to calculate the corresponding temperature distribution in the workpiece [62]. One of the limitations of the model is its inability to predict temperatures accurately at the entry and exit zones. However, there is still a lack of understanding in this field.

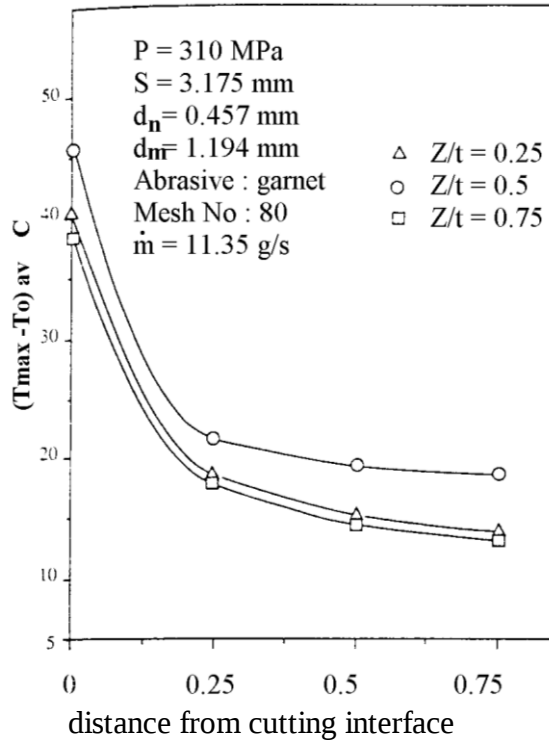


Fig. 10 Variation of averaged maximum temperatures with respect to distance from interface [38]

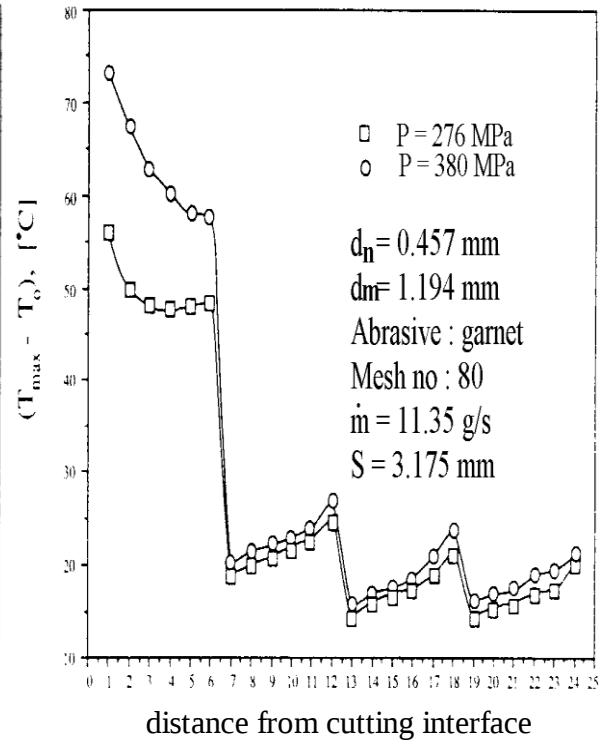


Fig. 11 Effect of pressure on temperature distributions in the workpiece [38]

In an early study on cutting forces in pure waterjet cutting, Decker et al [63] suggested a model for jet forces based on jet energy. It was found that the jet force increases with an increase in pressure and waterjet nozzle diameter and it is affected by nozzle geometry. Kovacevic [64] modeled cutting forces in AWJM process. The effects of abrasive waterjet nozzle diameter, abrasive flow rate, waterjet pressure, stand off distance and traverse rate are shown in Fig. 12. It could be concluded that the workpiece normal force will increase with increasing waterjet pressure, abrasive flow rate and nozzle diameter. Whereas, it will decrease with increasing stand off distance and will be only slightly affected by traverse rate. A large increase in the magnitude of the normal force will indicate the presence of nozzle wear and show that the depth of cut is exceeding the acceptable limit [64]. Typical static cutting force signal and the corresponding dynamic force signal are given in Fig.13 [2]. Based on Decker's

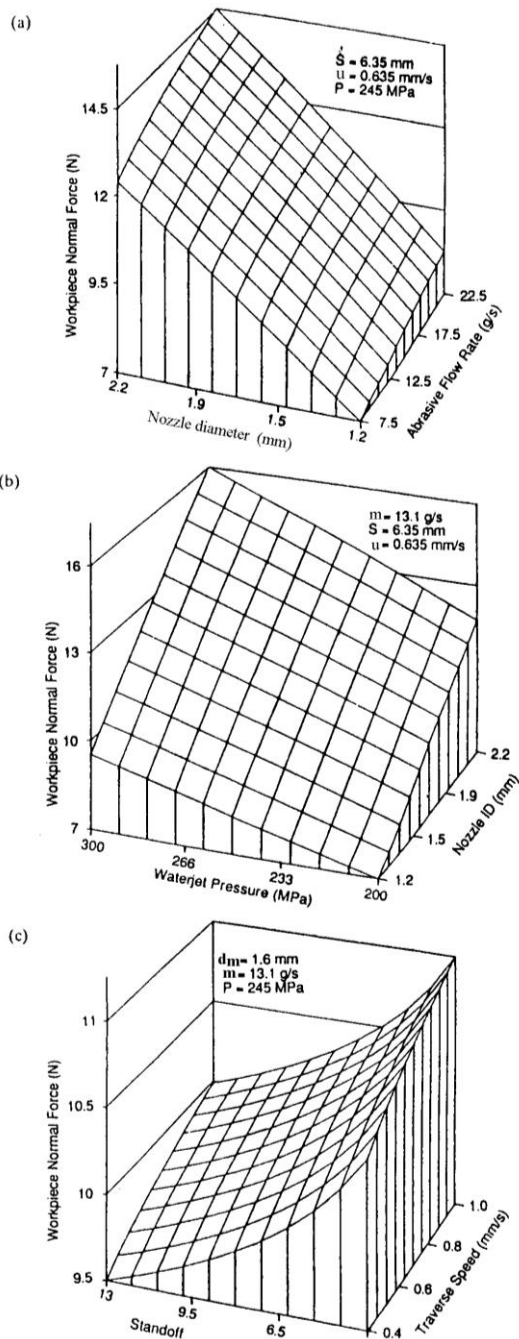


Fig. 12 Effect of AWJ cutting conditions on workpiece normal force [64]

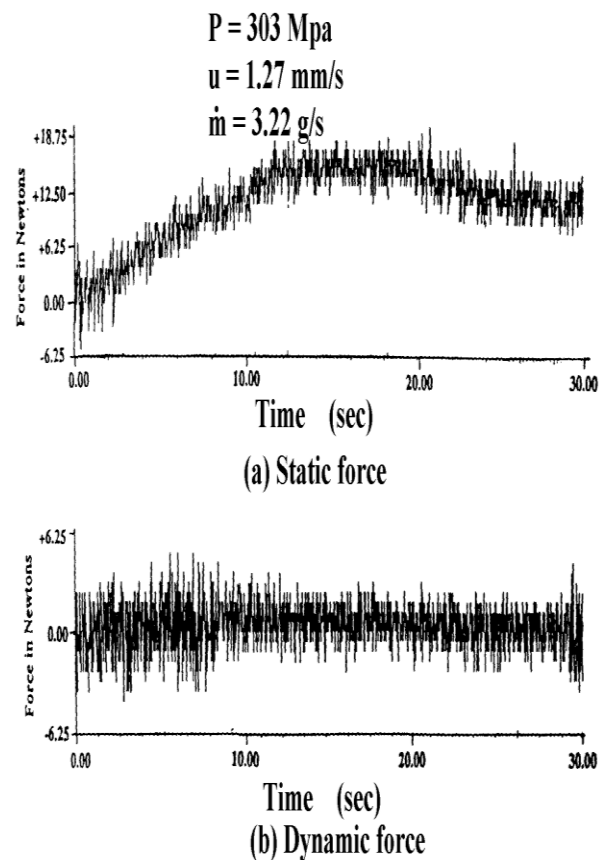


Fig.13 Typical cutting force signals [2] (a) static force (b) dynamic force

model, a recent study [65] showed the importance of the ratio of abrasive mass flow rate to water mass flow rate in affecting jet forces.

5. SURFACE QUALITY

Valuable contributions have already been made in the past two decades in this field. Several authors studied particularly the effect of AWJM on the surface quality of ductile materials such

as steels [66,67], while others concentrate on ceramics [41], composite materials [42,68-71], titanium alloys [66] and amorphous alloys [72].

5.1 Kerf width and taper

Hamatani and Ramulu [71] studied the effect of traverse rate and stand off distance on the kerf width and taper. The surface quality of abrasive waterjet piercing is evaluated in terms of hole taper as a function of stand off distance, while for the abrasive waterjet slotting both kerf width taper and surface roughness are reported as a function of machining conditions. Figure 14 shows the taper results for the slot cutting of metal matrix composites for three different mesh sizes of garnet. There appears to be an optimum traverse rate for a given abrasive particle size and flow rate that produces a slot that is not tapered. It is also interesting to note

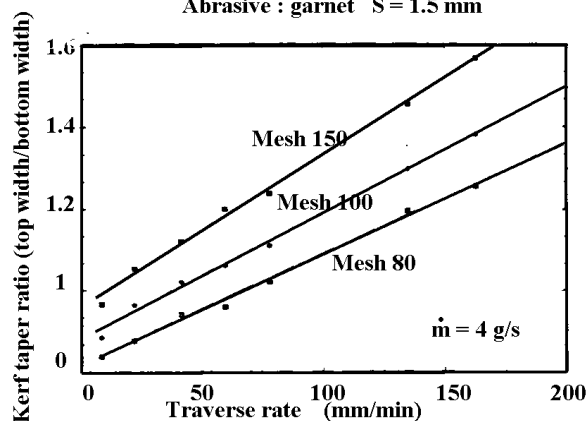
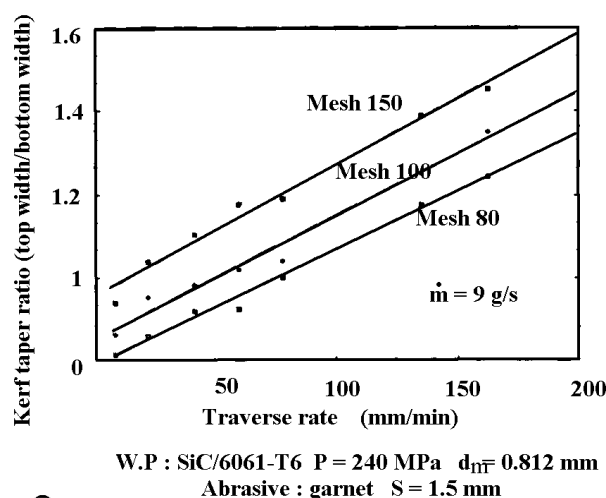


Fig. 14 Kerf taper ratio versus traverse rate [71]

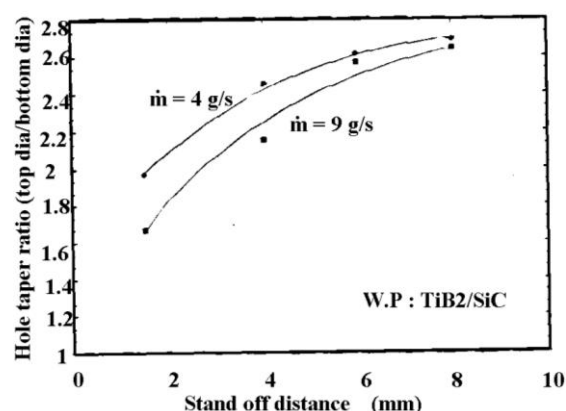
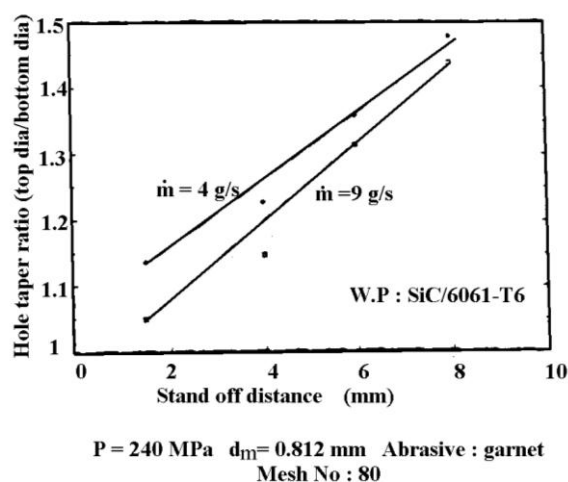


Fig. 15 Hole taper ratio versus stand off distance [71]

that at extremely slow traverse rates (less than 50 mm/min) the kerf width of the top surface was less than the kerf width of the bottom surface. A possible reason for this is the relatively long jet exposure times. Figure 15 shows the taper results in the case of piercing of metal

matrix composite (MMC), Fig. 15 (a) and ceramic matrix composite, Fig. 15 (b). A linear relationship apparently exists between stand off distance and hole taper in the case of MMC, while the variation in case of ceramic matrix composite is nonlinear. A model for predicting the kerf taper in graphite/epoxy composite was recently developed by Ramulu and Arola [40]. Afterwards, it was extended for kerf profile prediction and the effect of cutting parameters on kerf characteristics could be obtained using ANOVA techniques [39].

5.2 Surface texture

Hashish [66,68] was pioneer in exploring the effects of AWJM on the surface quality of the produced surfaces, hence helped to obtain better surface quality than ten years ago. The surface texture that may be associated with abrasive waterjet machining include: surface waviness, burr formation, surface finish and lay. The finish of a surface machined by abrasive waterjet exhibits two distinct contributions from the process: roughing occurring at the upper portion of the kerf, due to the micro effects of each impacting particle and waviness or striation, occurring at the lower portion of the kerf, due to jet penetration and loss of stability as the cutting depth increases. A smooth cut can be obtained by extending the cutting wear over the entire thickness of the material. This can be achieved by increasing the jet cutting power or by reducing the traverse rate [73]. The surface roughness was found to depend on the micromachining process of particle-material interaction. As the traverse rate and abrasive particle size increase, the surface roughness increases as shown in Fig. 16(a) [71,74]. It is clear that an increase in the abrasive flow rate produces better surface finish, Fig. 16 (b). In a study on AWJM of metal and ceramic matrix composite materials using scanning electron microscopy, Savrun and Taya [70] obtained relatively smooth surfaces with minimum subsurface microstructural damage. Blickwedel et al [75] developed a semi-empirical equation for the prediction of surface roughness as a function of both traverse rate and pressure using regression analysis. Another mathematical model for the prediction of surface roughness of graphite/epoxy composite was developed by Ramulu and Arola [40] using ANOVA regression techniques and can be used for determining cutting parameters for tailored surface quality. Chao et al [67] evaluated generated surfaces using surface topography analysis. It was found that the smooth zone has a random, moderately isotropic texture. The extent of the smooth zone depends on the cutting conditions e.g. traverse rate, depth of cut and cutting direction. Surface roughness was shown to strongly depend on depth of cut and traverse rate in the

striation zone. An oscillation applied to the abrasive waterjet nozzle head was found to

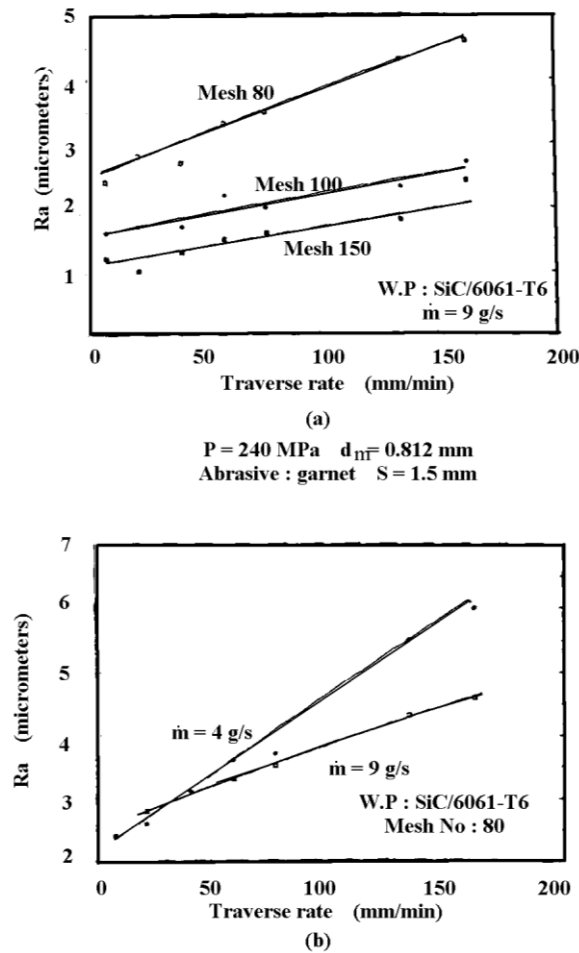


Fig. 16 Surface roughness versus traverse rate [71]

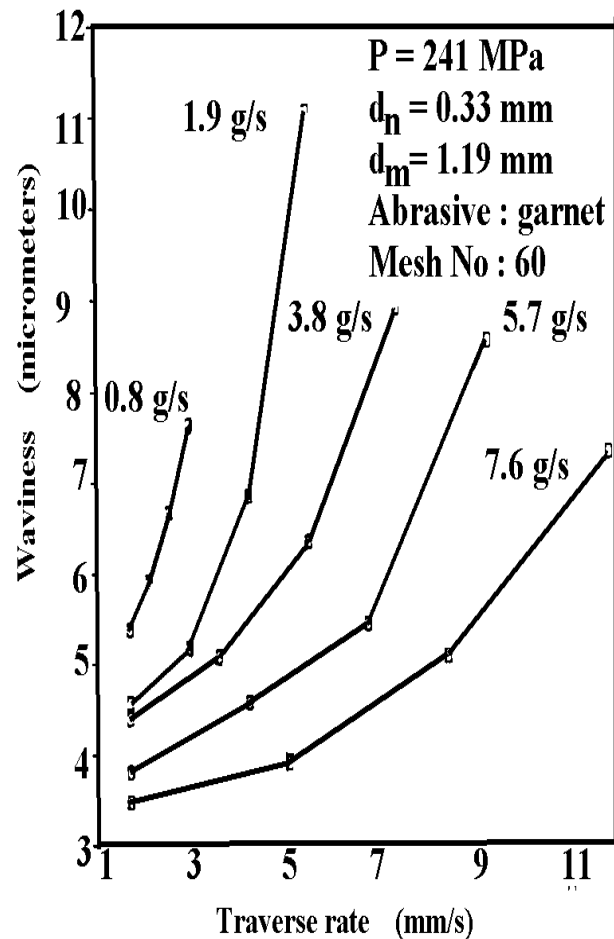


Fig. 17 Effect of traverse rate on surface waviness [66]

produce superior surface texture results for cutting of ceramics. The smooth zone depth increased by more than 30% as compared to that without oscillation. Also the striations were observed to decrease [41].

The surface waviness was found to depend primarily on the dynamic parameters, i.e. pressure, abrasive flow rate, and traverse rate. Figure 17 shows the effect of traverse rate and abrasive flow rate on surface waviness. As can be seen, the surface waviness is critically dependent on the traverse rate.

Burrs may form at the exit side of thin sheet metal cut with an abrasive waterjet. Figure 18 shows data on the height of burrs formed at different traverse rates and abrasive flow rates. The mechanism causing burr formation is similar to that in mechanical sawing, i.e. the material at the bottom of cut is bent rather than removed.

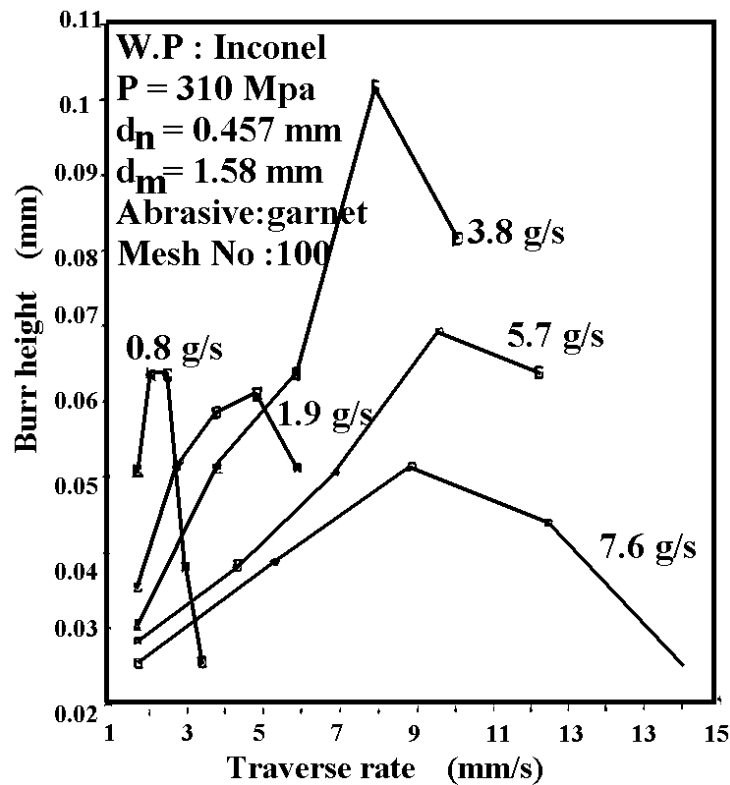


Fig. 18 Burr height produced by abrasive waterjet cutting [66]

5.3 Surface integrity

The surface integrity effects are defined as particle deposition, delamination, gouging, cracking, work hardening and heat affected zones. Particle deposition increases with increasing angle of attack and decreasing particle velocities. A recommended practice in using abrasive waterjet is that the abrasive supply be turned off after a surface has been generated by linear cutting, turning and milling, so that the waterjet alone can be used to clean the surface of particles that may have been imbedded.

Delamination may be observed when machining layered materials such as graphite epoxy composites and kevlar. Delamination occurs only if the deformation wear mode of erosion exists [66]. On the other hand, delamination is a major concern in AWJM of composite materials. The mechanism of delamination was studied using fracture mechanics and the optimum waterjet pressure for no delamination is now predictable [76].

Gouging are dimples about 10 microns in diameter observed microscopically. These dimples are particles pulled from the surface. The surfaces produced with abrasive waterjet are free from microstructural distortion.

For brittle materials such as glass, cracks may be evident on the kerf edge. It was observed that microcracks less than one micron deep may form when abrasive particles less than 10 microns in size are used.

Changes in hardness due to abrasive waterjet machining are insignificant. Also abrasive waterjet process does not affect the mechanical characteristics of the material.

Strains occurring in erosion must be very large, and in addition, the surface will become work-hardened by the eroding particle [44]. Erosion also involves very high strain rates. This tends to increase the flow stress [31]. In a recent research work, Tönshoff et al [77] observed that the high-frequency impact of pure waterjet on the surface of steel, using pressures up to 100 Mpa, causes local plastic deformation. As a result, high compressive residual stresses are induced in the surface-near layers. Fatigue strength was also shown to increase. The effect on the depth only reaches the surface-near material within distances from the surface of up to approximately 30 microns.

The inspection of abrasive waterjet machined surfaces indicated that no heat affected zones are associated with the cutting process. Even if high temperatures occur for very short periods of time upon the impact, these are removed as the kerf is generated.

6. NOZZLE WEAR

The mixing tube, where the abrasives are mixed, accelerated and focused with the high-pressure waterjet, is the component of the abrasive waterjet that receives the greatest wear. Hashish [78,79] tested a wide range of candidate nozzle materials. The tungsten carbide grades exhibited more longevity than the hard ceramics such as boron carbide, when garnet abrasives were used. The reverse trend was observed with aluminum oxide abrasives. Wear mechanisms along the mixing tube change from erosion at the upstream to abrasion at the downstream sections. The development of nozzle wear as a function of operating time shows a 50 % increase in the nozzle diameter after only 80 minutes of operation as observed by König and Schmelzer [80]. A slight increase in the nozzle wear is also observed when the pressure increases from 200 Mpa to 300 Mpa. On the other hand, surface roughness and kerf taper progressively increase as the nozzle wear increases. The effect of mixing tube length on nozzle wear is shown in Fig. 19. The longer the mixing tube, the slower the wear rate. The reason is that the velocity vectors of the particles become parallel to the wall when the tube length increases and only the abrasion mode exists. Figure 20 shows the effect of mixing tube material on wear. The boron carbide tube exhibited a faster wear rate than the tungsten carbide tube. The reverse trend is observed when using aluminium oxide abrasives. A recent research work on the wear of mixing tube materials has shown the superiority of a new nozzle material, composite carbide over tungsten carbide and boron carbide, due to its particular combination of hardness and toughness [81]. Schwetz et al [82] suggest the use of boron carbide nozzles with hard abrasives such as aluminum oxide for machining of very hard and tough workpieces such as ceramics and cermets.

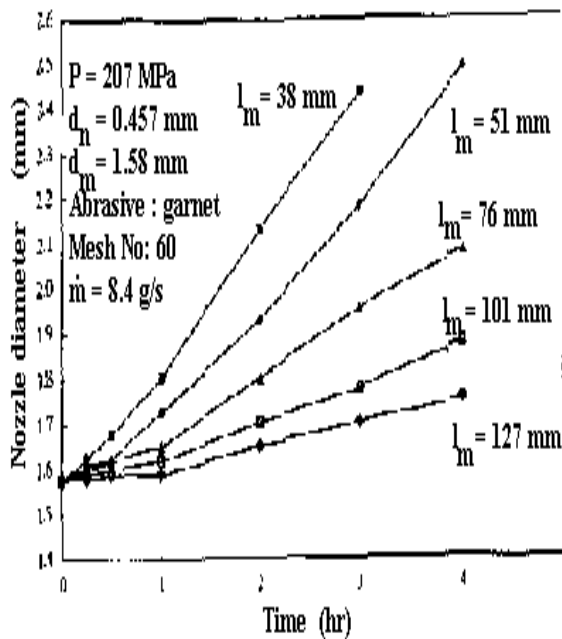


Fig. 19 Reduced wear rates with increased nozzle length [78]

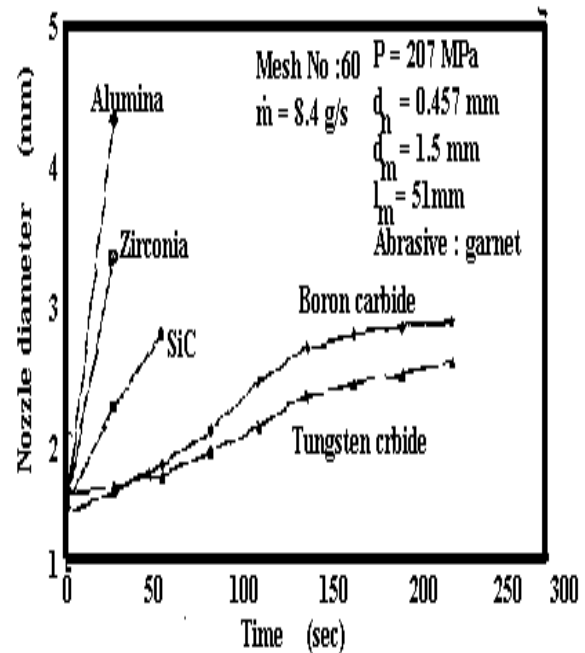


Fig. 20 Wear of different nozzle materials using garnet abrasives [78]

7. CONTROL AND MONITORING

Researchers have been becoming more interested and active in this field. Kovacevic [83] developed a wear sensor system for on line tracking of abrasive water jet nozzle wear based on conductive loops placed on ceramic substrate and embedded in the tip of the nozzle. Hence, compensation for the increase in AWJ nozzle diameter could be made. Afterwards, he [64] showed that the workpiece normal force generated by the abrasive water jet could be used as an indicator of the jet penetration, and that a force-feed back control holds a promise as an effective way to regulate the depth of jet penetration. A correlation between depth of cut and process variables, based on experimentation, was derived using multiple regression analysis. Another monitoring system for the AWJ nozzle wear based on acoustic signals generated by the AWJ was derived by Kovacevic et al. [84]. This model has the possibility of monitoring and compensating nozzle wear using the frequency domain acoustic signals generated by the jet exiting the nozzle. An artificial neural network is capable of determining the nozzle diameter corresponding to any unknown sound signal [85]. Kovacevic and Fang [86] showed that fuzzy rules could be applied in AWJM to determine WJ cutting parameters for milling instead of the tedious and time consuming experimentation. A more recent study [87] derived a mathematical model for the estimation of the energy absorption capability of materials during AWJM based on the energy balance inside the workpiece. It is shown that the energy absorption depends on the depth of cut.

CONCLUSIONS

AWJM is a comparatively recent machining process. It is mainly used for machining of high strength and difficult-to-cut materials due to its low cutting temperature, no heat damage to the surface, and low cutting forces. In recent years the process has been applied to different materials such as ceramics, composites, titanium alloys and even amorphous alloys. As a result of the present review, the following conclusions could be drawn :

1. The abrasive waterjet material removal process is a complex erosion process where more than one mode contributes to the erosion results. Two mechanisms have been identified for ductile materials as the dominant modes for material removal, cutting wear mode and deformation wear mode.
2. High surface quality was obtained with abrasive waterjet cutting by using high pressures and low traverse rates. The process does not generally affect the integrity of the surface.
3. The depth of cut varies linearly with the abrasive flow rate and pressure. Low traverse rates are more efficient for deep cuts. The smaller the stand off distance, the deeper the cut.
4. It was shown that the maximum temperature occurs in the immediate vicinity of the cutting interface and decays rapidly thereafter with increasing distance from the cutting interface.
5. The hardness and toughness of the abrasive waterjet nozzle material should both exceed certain threshold values for effective performance.

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