RECENT ADVANCES IN ABRASIVE WATERJET MACHINING (AWJM)

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ABSTRACT

Abrasive waterjet machining (AWJM) has many advantages including 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 work in this new process. The main topics discussed are mechanics of material removal, productivity, cutting forces, surface quality, and nozzle wear.

KEYWORDS

Abrasive water jet – material removal – productivity – forces –temperatures – surface quality – nozzle wear

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1. INTRODUCTION

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 AWJ system is the abrasive jet nozzle as shown in Figure. 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, whose velocities

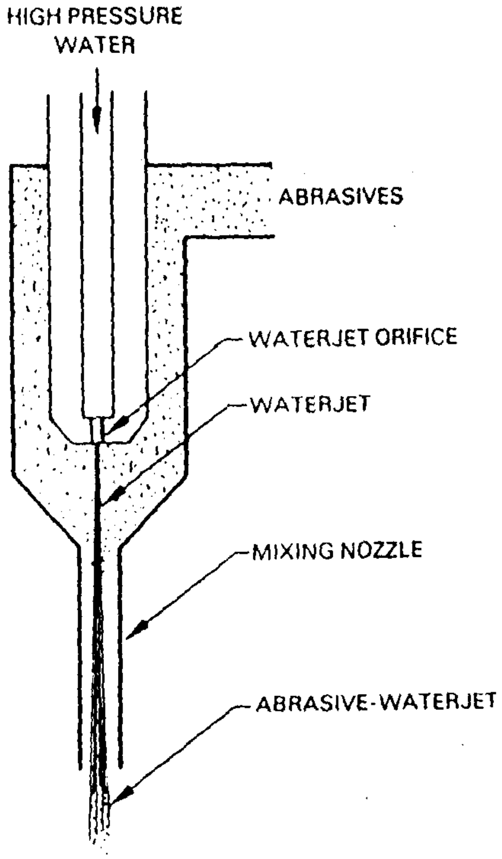


Figure.1 Schematic of AWJ nozzle [4]

rapidly increase, as a result, a focused, high-velocity stream of abrasives exits the nozzle and performs the cutting action of the workpiece surface.

There are several parameters that affect the cutting performance of the AWJ [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, 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 AWJ 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.

This paper is a review of recent developments in AWJM research. 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.

2. MECHANISMS OF MATERIAL REMOVAL

An early erosion model by waterjets was developed by Hashish and Du Plessis [6] based on a control volume analysis to determine the hydrodynamic forces acting on the solid boundaries of the cutting slot. The equation derived for jet penetration was later combined by the same authors [7] 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 [8]. Another model was developed by Wilkins and Graham [9] 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 [10] is still regarded as the leading work, since then a number of researchers in AWJM have developed several cutting models on erosion. 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 [11]. Later, an intensive work in the field of erosion was conducted by Hashish [4, 12-14]. 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 [12]. This division is based on a visualization study of the AWJM process [13] 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 [15, 16]. The AWJ 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 [17]. 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 relatively smooth due to cutting wear at a shallow angle of impact and it exists at the upper portion of the cutting kerf [14]. The material hardness is the most relevant material property

to this mode [15]. 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 [14].This wear mode results in an unsteady penetration process. The modulus of elasticity was found to correlate well with this mode of material removal [15, 16]. Recent studies in AWJM of graphite/epoxy composites pointed out the existence of a small initial

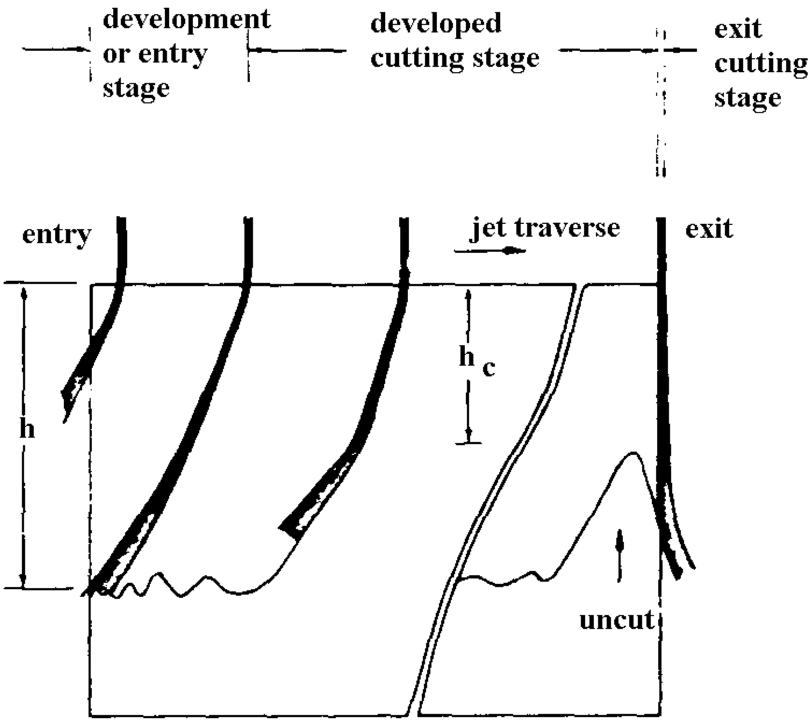


Figure. 2 Cutting zones of AWJ kerfs [15]

damage zone near the jet entrance in addition to the previous two zones [18,19]. 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 [20]. Momber [21] reviewed the different formulas for the depth of cut obtained by different researchers.

It was noted that the erosion mechanism in silicon carbide-reinforced aluminum metal matrix composite differs slightly. The aluminum matrix is subject to microcutting, such as ductile materials, while the SiC particulates being removed by shoveling action of the incoming jet [22]. A recent work by Finnie [23] confirmed again that the erosion mechanism dominating ductile materials is plastic deformation. A correlation relating material removal rate to the particle velocity was derived [24]. 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 generalized 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 [25]. 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 [10]. A model of AWJM of polycrystalline ceramics was initiated by Zeng and Kim [26, 27]. Erosion mechanisms include intergranular network cracking due to fractures caused by impact induced stress waves and plastic flow. 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 high-speed water [28, 29]. More recent studies [30,31] suggest erosion mechanisms for brittle materials on the basis of Finnie's [10] and Zeng's [26] models for brittle materials but taking

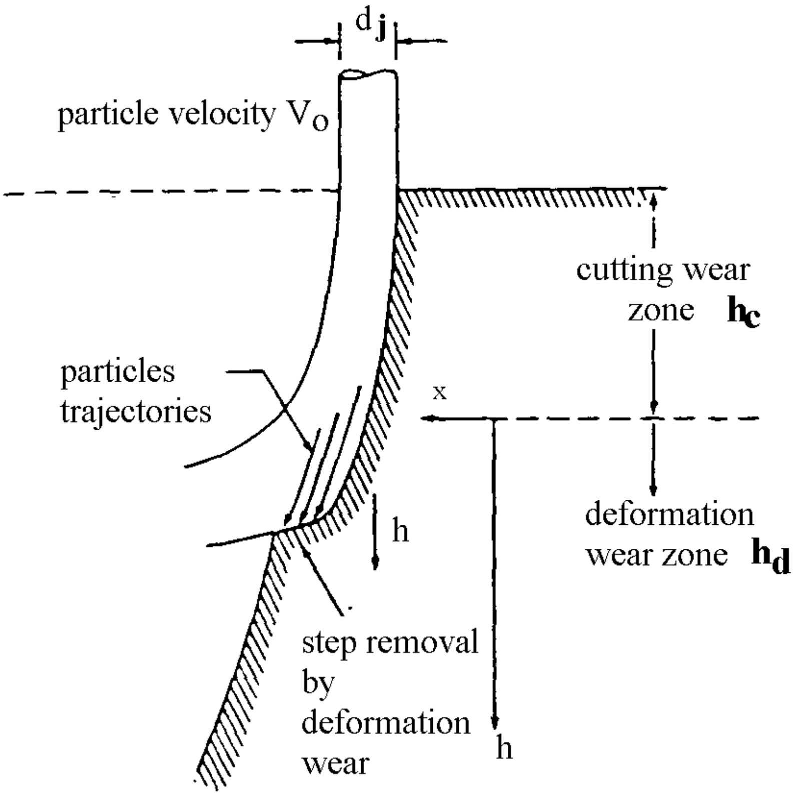


Figure. 3 Erosion zones in AWJM [14]

into account the size and shape of the abrasive particles. Turenne and Fiset [32] 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. 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 [33] who considered the rain erosion of aerospace vehicles which is similar to waterjet erosion.

3. PRODUCTIVITY

Significant experimental as well as analytical work on productivity have been reported. An early experimental work on productivity was reported by Hashish [34]. The effect of abrasive flow rate on the depth of cut is shown in Figure. 4. A certain critical flow rate exists beyond which the optimum abrasive flow rate exists at which the depth of cut peaks. The effect of pressure on the depth of cut is shown in Figure. 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 [35]. The effect of stand off distance on the depth of cut is shown in Figure. 6. The effect of stand off distance on material removal is shown in Figure. 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 Figure. 8. However, volume removal rates may increase with increasing the traverse rate. Figure 9 shows a diagrammatic

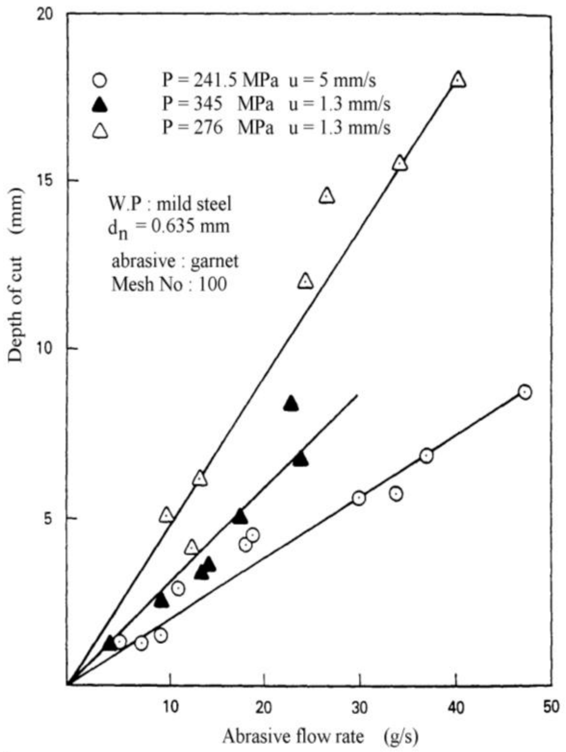


Figure. 4 Effect of abrasive flow rate on depth of cut [34]

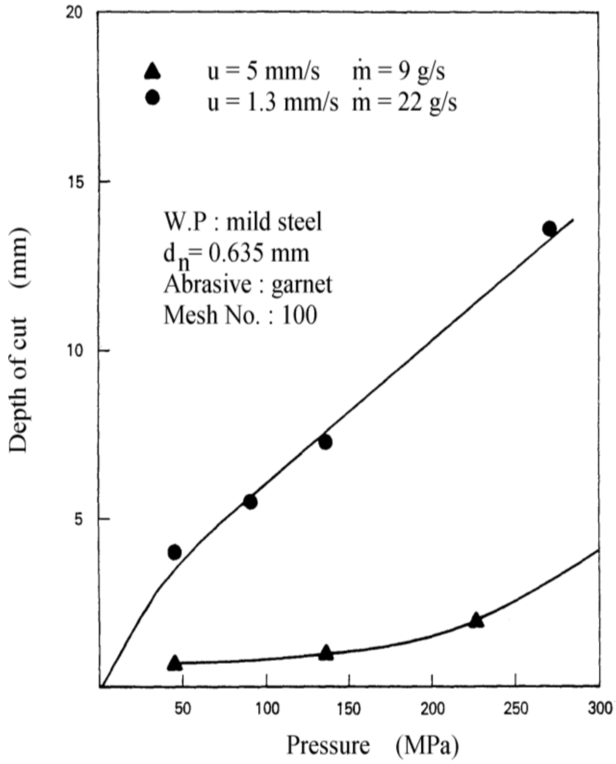


Figure. 5 Effect of pressure on depth of cut [34]

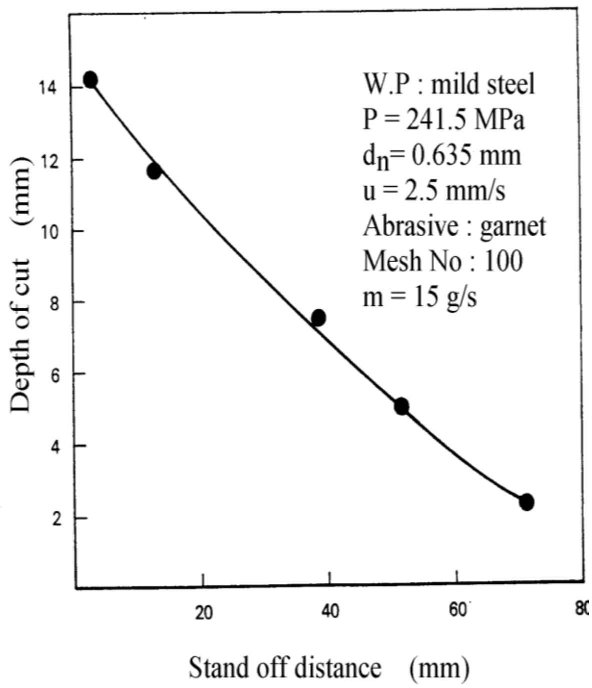


Figure. 6 Effect of stand off distance on

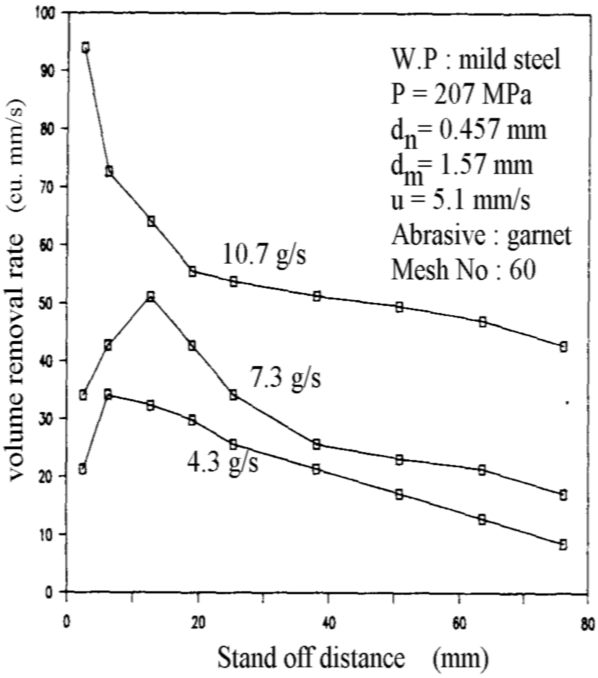


Figure. 7 Effect of stand off distance on

depth of cut [34] volume removal [4]

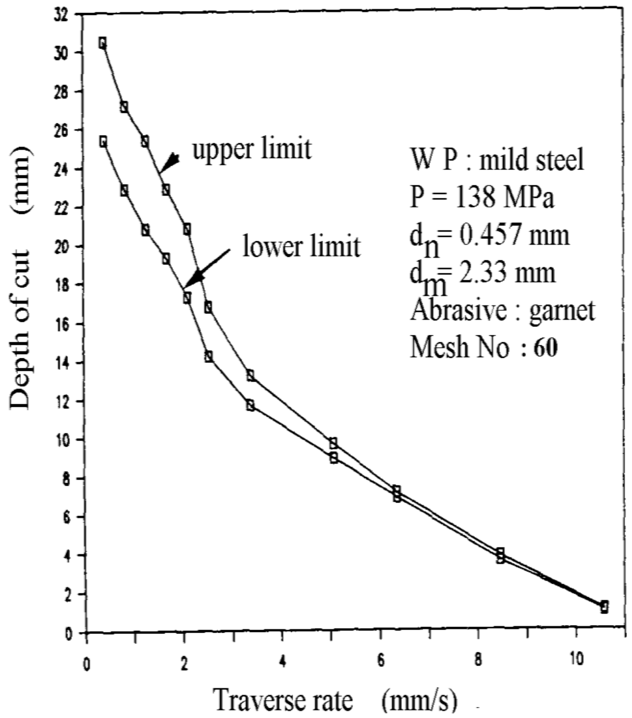


Figure. 8 Effect of traverse rate on depth and uniformity of cut [4]

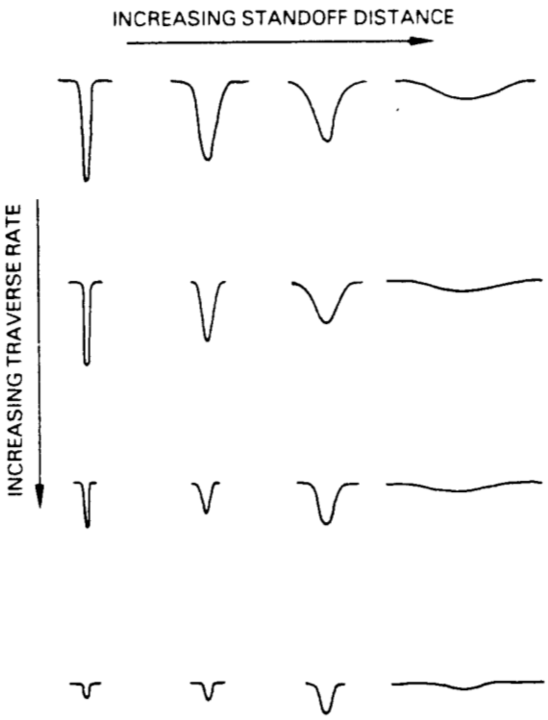


Figure. 9 Effect of stand off distance and traverse rate on shape of cut [4]

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].

Hashish [36] 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 was qualitatively summarized. Hashish [37] studied the effect of jet angle on productivity and found the same conclusion of Finnie [10] 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. [38] 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 [39]. The volume removal rates while machining modern ceramics were found to be primarily dependent on pressure and abrasive flow rate [40].

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. [17]. The highest temperatures were found to occur at the immediate vicinity of the cutting interface where they experience a sharp decay with increasing distance from the cutting interface. However, increasing pressure increases temperature due to higher waterjet velocity. It was also observed that a material with higher thermal conductivity experiences higher temperatures during the cut. A more recent study on

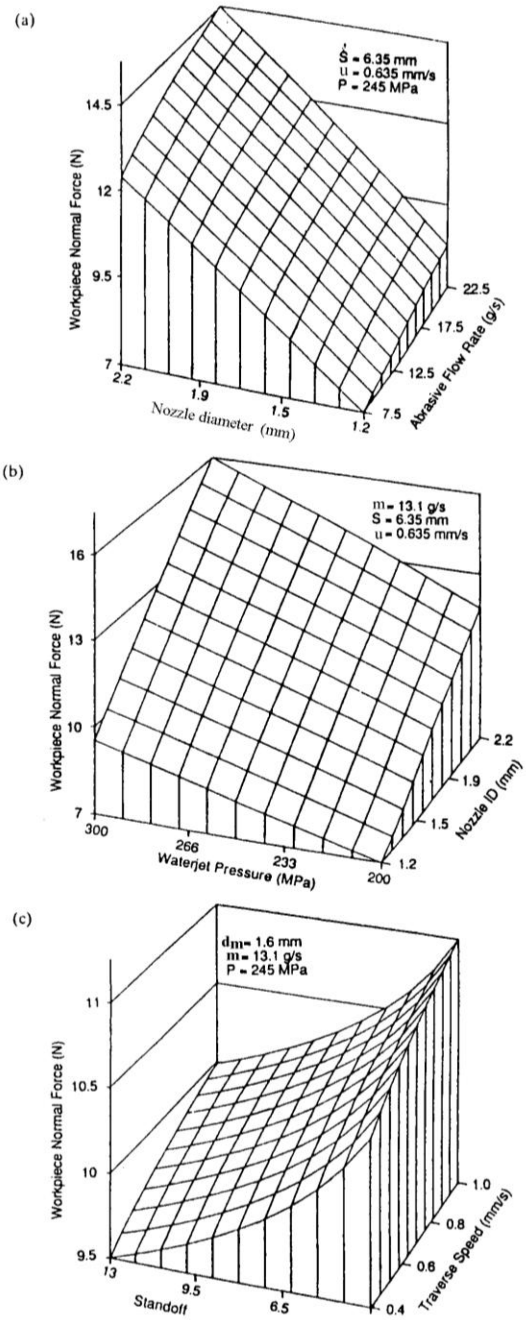


Figure. 10 Effect of AWJ cutting conditions on workpiece normal force [43]

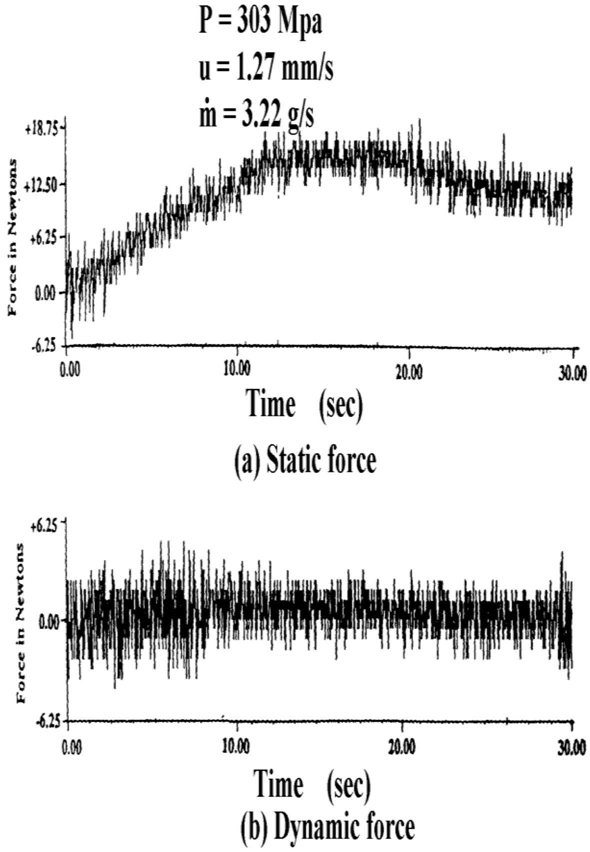


Figure.11 Typical cutting force signals [2] (a) static force (b) dynamic force

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 [41].

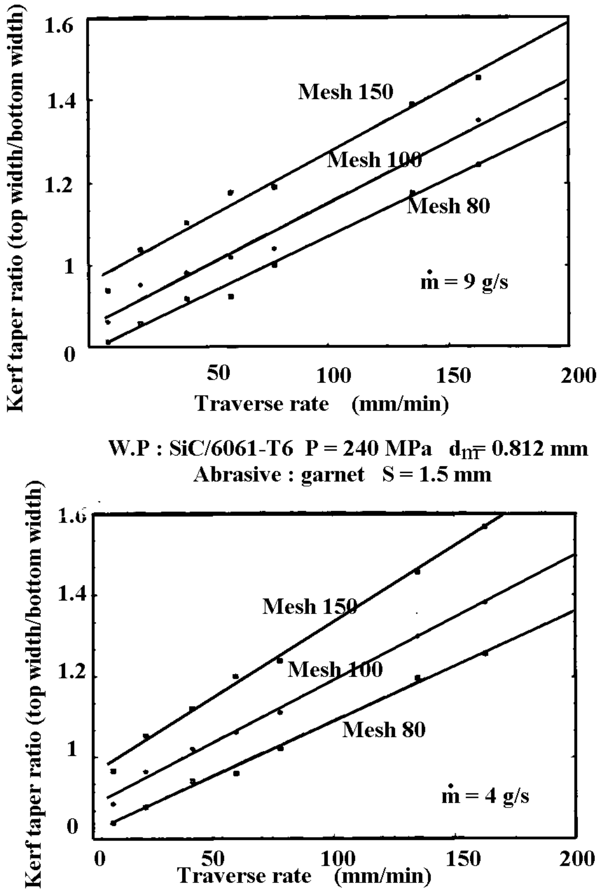
In an early study on cutting forces in pure waterjet cutting, Decker et al [42] suggested a model for jet forces based on jet energy. It was found that the jet force increases with an increase in pressure and waterjet nozzle diameter and it is affected by nozzle geometry. Kovacevic [43] modeled cutting forces in AWJM process. The effects of AWJ nozzle diameter, abrasive flow rate, waterjet pressure, stand off distance and traverse rate are shown in Figure. 10. 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. Typical static cutting force signal and the corresponding dynamic force signal are given in Figure.11 [2]. Based on Decker's model, a recent study [44] 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 [45, 46], while others concentrate on ceramics [20], composite materials [21, 47-50], titanium alloys [45] and amorphous alloys [51].

5.1 Kerf width and taper

Hamatani and Ramulu [50] studied the effect of traverse rate and stand off distance on the kerf width and taper. The surface quality of AWJ piercing is evaluated in terms of hole taper as a function of stand off distance, while for the AWJ slotting both kerf width taper and surface roughness are reported as a function of machining conditions. Figure 12 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. Figure 13 shows the taper results in the case of piercing of metal matrix composite (MMC), Figure. 13(a), and ceramic matrix



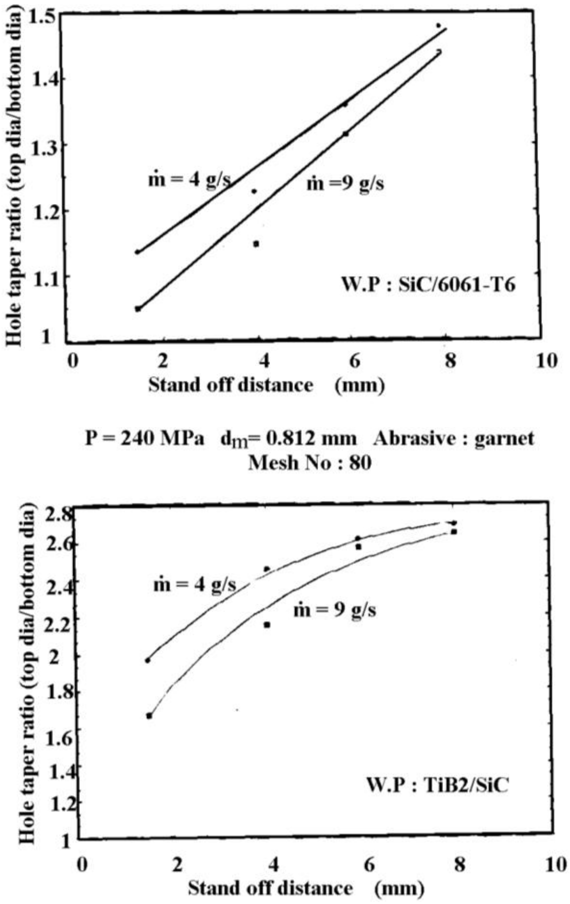


Figure. 12 Kerf taper ratio versus traverse rate [50]

Figure. 13 Hole taper ratio versus stand off distance [50]

composite, Figure. 13(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.

5.2 Surface texture

Hashish [45, 47] showed that the surface texture that may be associated with AWJ machining include: surface waviness, surface finish and lay. The finish of a surface machined by AWJ 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 [52]. 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 Figure. 14(a) [50, 53]. It is clear that an increase in the abrasive flow rate produces better surface finish, Figure. 14(b). Blickwedel et al [54] developed a semi-empirical equation for

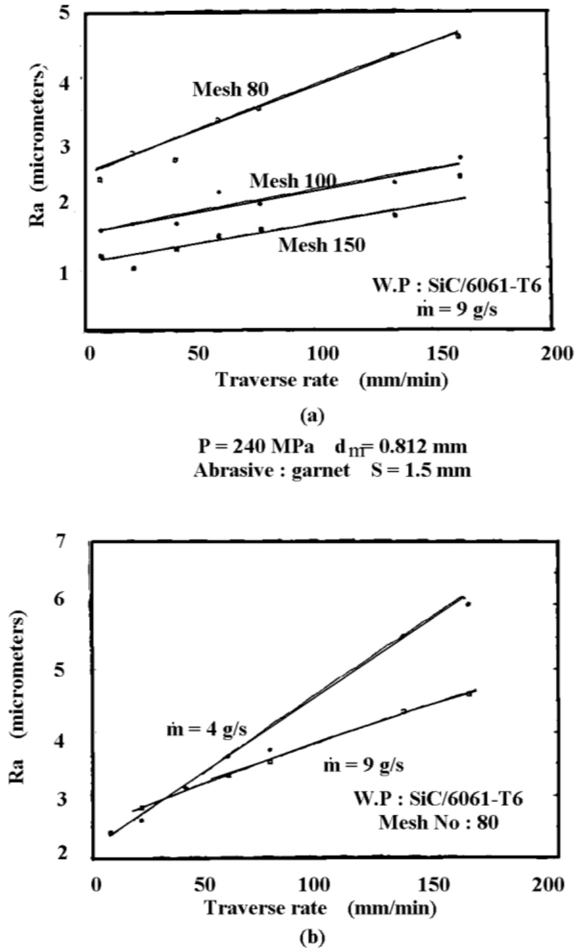


Figure. 14 Surface roughness versus traverse rate [50]

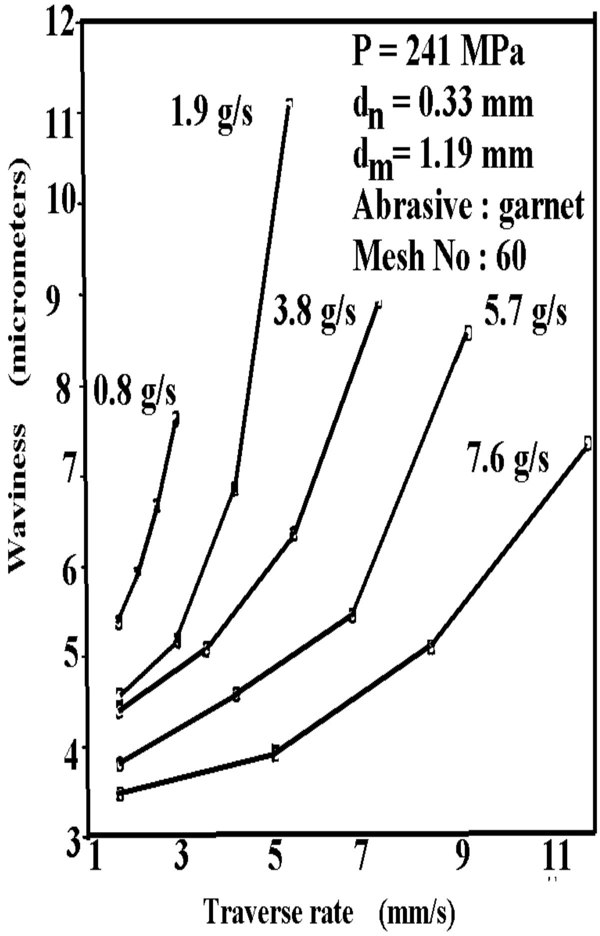


Figure. 15 Effect of traverse rate on surface waviness [45]

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 [19] using ANOVA regression techniques and can be used for determining cutting parameters for tailored surface quality.

The surface waviness was found to depend primarily on the dynamic parameters, i.e. pressure, abrasive flow rate, and traverse rate. Figure 15 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.

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 [55].

Strains occurring in erosion must be very large, and in addition, the surface will become work-hardened by the eroding particle [23]. Erosion also involves very high strain rates. This tends to increase the flow stress [10]. In a recent research work, Tönshoff et al [56] 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.

6. NOZZLE WEAR

The mixing tube is the component of the AWJ that receives the greatest wear. Hashish [57, 58] found that 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 shows a 50 % increase in the nozzle diameter after only 80 minutes of operation as observed by König and Schmelzer [59]. 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. A recent work showed the superiority of a new nozzle material, composite carbide over tungsten carbide and boron carbide, due to its particular combination of hardness and toughness [60]. Schwetz et al [61] 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.

It was also found that [62] the root mean square of the acoustic emission energy (AErms) increases linearly with an increase in the depth of cut and could be used for its on-line monitoring. The AE is the most suitable technique for AWJ monitoring, as the AE signal has high sensitivity to the variation in the depth of cut

CONCLUSIONS

AWJM is a comparatively recent machining process. As a result of the present review, the following conclusions could be drawn:

1. AWJ material removal process is a complex erosion process where more than one mode contributes to the erosion results. Two mechanisms for ductile materials are the dominant modes for material removal; cutting wear mode and deformation wear mode.
2. High surface quality was obtained with AWJ cutting by using high pressures and low traverse rates. The process does not generally affect the integrity of the surface.
3. 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. The maximum temperature occurs in the immediate vicinity of the cutting interface and decays rapidly thereafter with increasing distance from the cutting interface.
5. Hardness and toughness of the AWJ nozzle material should both exceed certain threshold values for effective performance.

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