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Review Article

THE INFLUENCE OF ABRASIVE WATER JET MACHINING PARAMETERS ON VARIOUS RESPONSES—A REVIEW

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Composites materials are getting difficult to machine owing to its constituents properties, fiber orientation and relative volume fraction of matrix. Abrasive water jet machining is a recent non-traditional machining process, and widely used in many industrial applications. Abrasive water jet cutting of material involves the effect of a high pressure velocity jet of water with induced abrasive particle on to materials to be cut. The present paper collects the findings on influences of distinct parameters of AWJ machining of composite materials. The parameters such as hydraulic pressure, traverse speed, abrasive mass flow rate, standoff distance, types of abrasive materials, grit size, jet nozzle oscillation and cutting orientation are focused for kerf tapper angle, surface roughness and depth of cut. From the literature survey it was found that by increase of water pressure, kerf tapper angle and surface roughness gets decreased. However, traverse speed and standoff distance shows reverse effects.

Keywords: Abrasive water jet machining, Kerf tapper ratio, Surface roughness, Fiber reinforced composite materials, Abrasive materials

INTRODUCTION

Nature has taught that even the hardest rocks can be eroded by a stream of water and moved away from the area. Because this effect could be seen, it could also be adapted to man's use. In the late 1960s Franz found that very high pressure jets could be used to cut through wood products with little damage to the material on the outside of the cut surface and at relatively high cutting speed (Byran, 1963). The first equipment was installed at Alton Boxboard in 1972 and led to the development of a new tool for manufacturing industry (Walstad and Noecker, 1972). In the AWJ machining process, high pressure water is supplied by a pump at the orifice inside the cutting head from where it is converted into a high velocity jet. While passing through a mixing chamber, water creates a vacuum which draws the abrasive particles into a focusing tube where the Abrasive Water Jet (AWJ) mixture is

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formed (Momber, 1998). The jet plume (mixture of abrasives and water droplets) impacts the target surface it results in the generation of a unique footprint (kerf). As a result of this, the work-piece material removal is mainly caused by the impact of amultitude of high velocities abrasive particles as discussed by Momber and Kovacevic (1998). It has advantage over other machining process; such as (a) it can cut any material like titanium, diamond, glass, plastics and composite, etc. (b) Any 2-D profile can cut with high tolerance. (c) There is no direct contact between cutting tool and work material, so no heat generation, no wear of tool and no structural change in work material. (d) No special fixture or tooling is required for cutting. (e) It has minimum cutting force in jet direction so no special clamping is required.

A typical abrasive water jet system includes main four components: (1) the water purifying and storage system. (2) High pressure generating system. (3) Cutting head and (4) Abrasive delivery system and catcher as shown in Figure 1.

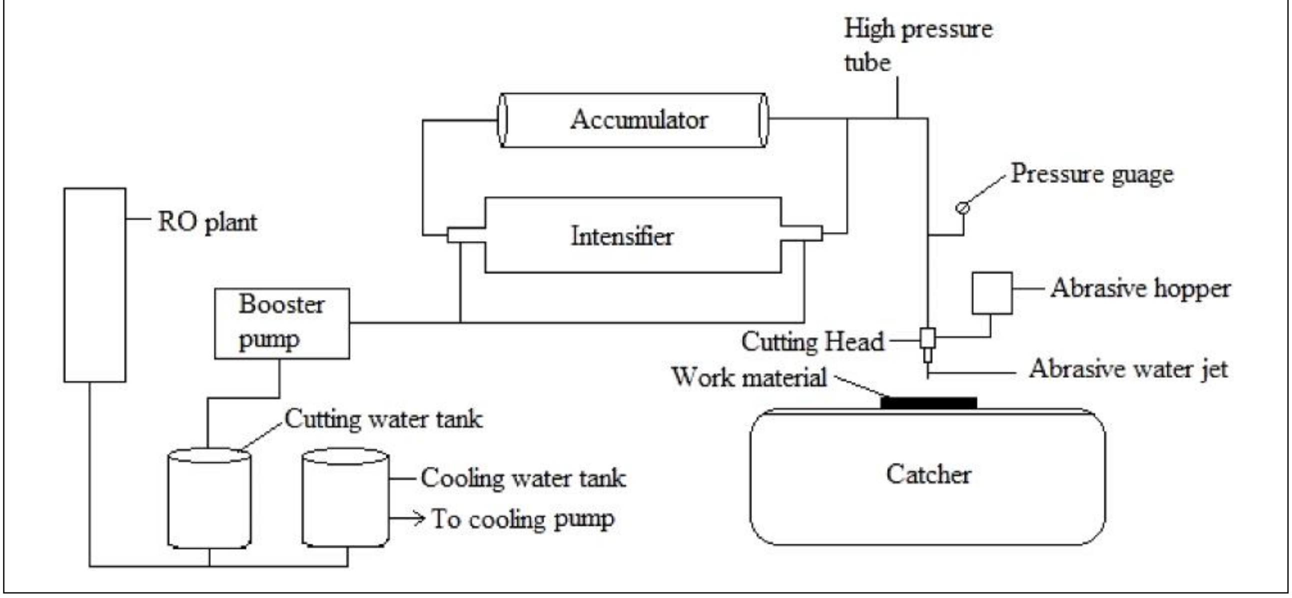
The Water Purifying and Storage System

The water purifying and storage system is used for supplying pressure to ultrahigh pressure pump continuously. Typical AWJ system includes two different storage tanks (i) cutting tank, and (ii) cooling water tank as shown in Figure 1. Generally, particle having size greater than 1 µm needs to be removed from the water as it creates wear of the critical part of pump, which leads to failure of pump. Cooling water is used to reduce the temperature of oil pump.

High Pressure Generating System

This system is equipped with intensifier and accumulator to generate high pressure and storage of high pressure water respectively. Intensifier includes double acting reciprocating pump which is operated by oil pressure. Ultra high pressure pump includes two different

Figure 1: Schematic Diagram of an Abrasive Water Jet Cutting System



circuits to generate high pressure up to 600 MPa. Accumulator stores the high pressure water energy to reduce the pressure loss in next stage.

Cutting Head

The cutting head equipped with focusing tube, orifice, nozzle and mixing chamber. Generally, focusing tube is made up of stainless steel having length of 76.2 mm and diameter 0.76 mm. Sapphire, ruby and diamond material can be used for orifice having diameter ranging from 0.08 to 0.8 mm. High pressure tube carries the pressured water from accumulator to cutting head through focusing tube. High pressure water passes through orifice which converts pressure energy of water into kinetic energy of water particle due to convergent shape of orifice. The high speed water jet then passes through a mixing chamber, which is directly connected to orifice. Water loses its pressure energy as it passes through mixing chamber due to venturi effect which creates vacuum in mixing chamber. Due to vacuum abrasive enters in mixing chamber mixes with water. In mixing chamber high energy of water particle transfers to abrasive particle then mixer of water and abrasive pass through nozzle with act as saw to cut the material.

Abrasive Delivery System and Catcher

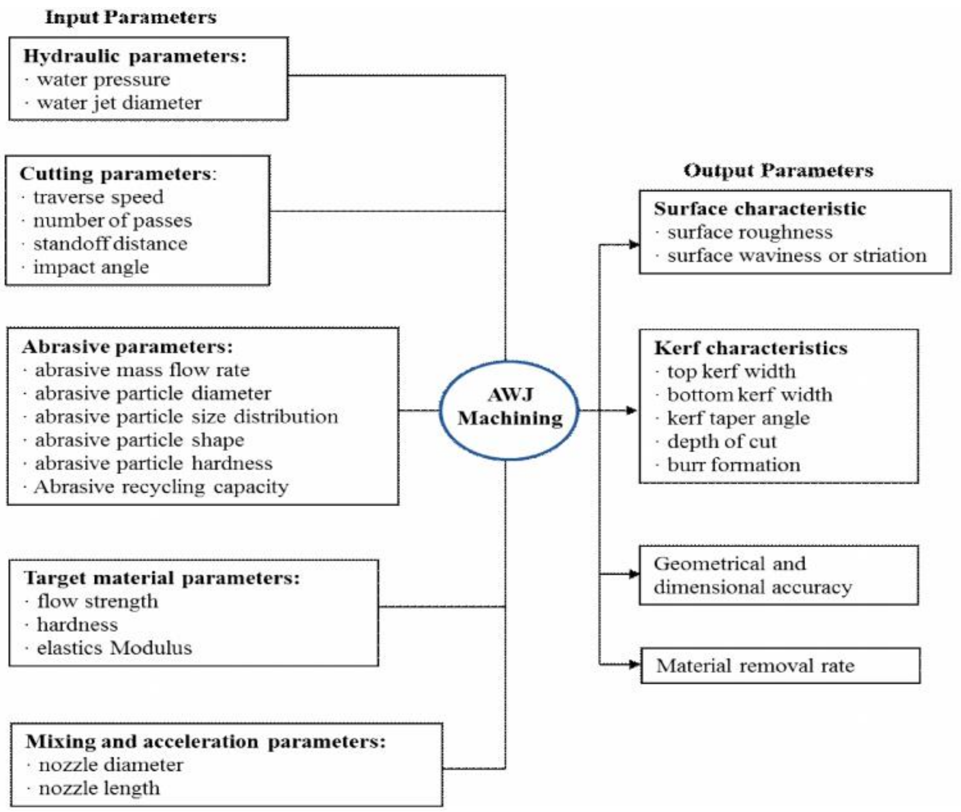
The abrasive delivery system includes abrasive hopper and pneumatically operated valve to control the abrasive mass flow rate. Generally, three different types of abrasive material used in industries such as garnet, aluminum oxide and silicon carbide with different mesh size ranging from 60 to 120 mesh. The target material is being cut by water, which contains large amount of energy needed to absorb before it can damage any part. Catcher is used to collect the pressurized water after cutting.

LITERATURE OVERVIEW

Abrasive Water Jet Machining (AWJM) is a new non-conventional material removal technology which is increasingly used in industry (Ciglar *et al.*, 2009). The AWJM process has a high-potential and is applicable to both metals and non-metals (Jain, 2008). Thus, AWJM offers a productive alternative to conventional techniques. In AWJM process material removal occurs through erosion and results from the interaction between an abrasive laden water jet and target (Arola and Ramulu, 1997). In this section an extensive review of the current state of research and development in AWJM conducted. AWJ cutting involves a large number of variables, and virtually all these variables affect the cutting results, only the major and easy-to-adjust variables were considered. The performance of AWJM depends upon number of process parameters and can be classified into two categories: the input parameters and output parameters. The abrasive water jet machining process is characterized by large number of process parameters that determine efficiency, economy and quality of the whole process. Figure 2 demonstrates the factors influencing AWJ machining process.

Shanmugam and Masood (2009) have made an investigation on the kerf taper angle, generated by Abrasive Water Jet (AWJ) machining of two kinds of composite materials (i) epoxy pre-impregnated graphite woven fabric and (ii) glass epoxy. The experiments

Figure 2: Process Parameters Influencing the AWJ Machining



have been conducted on a flow water jet system with sapphire orifice having diameter of 0.254 mm and abrasive garnets with a mesh size of #80. Taguchi experiments design was used to construct the design of experiments for the process parameters. Effect of different four process parameters were studied namely water pressure, traverse speed, standoff distance and abrasive mass flow rate on kerf taper angle. They concluded that, increase of water pressure and traverse speed shows the opposite effect on kerf taper angles as shown in Figures 3a and 6a. With increasing standoff distance the kerf taper angle increases as demonstrated in Figure 9a. As increase in abrasive mass flow rate kerf taper angle is decreases insignificantly as illustrated in Figure 11a.

Wang (1999) investigated the machinability and kerf characteristics of polymer matrix composite sheets under abrasive water jet machining. Experiments were conducted on a Flow Systems International water jet cutter equipped with a model 20X dual intensifier high output pump (up to 380 MPa) and a five axis robot positioning system to cut 300 x 300 mm test specimens. The specimens were prepared from Teflon and phenolic resin. Three major parameters have been studied mainly, water pressure, the nozzle traverse speed and the standoff distance. It can be noted from Figure 3b that both the top and bottom kerf widths increase approximately linearly with the water pressure. The kerf taper angle also increases with the water pressure. The effect of traverse speed on the top kerf width, bottom kerf width and kerf taper is shown in Figure 6b. As shown in Figure 9b, that the top and bottom kerf widths increase with an increase in the standoff distance.

Azmir and Ahsan (2009) explained the influence of six machining parameters on surface roughness (R_a) and kerf taper ratio (T_R) characteristics during an abrasive water jet machining of glass/epoxy laminated composite. Taguchi's design of experiments and analysis of variance were used to determine the effect of machining parameters on Ra and T_R. In this case, six machining parameters abrasive types, hydraulic pressure, standoff distance, abrasive mass flow rate, traverse rate and cutting orientation were selected as control factors. The equipment used for machining the samples was Excel-CNC abrasive water jet cutting machine equipped with Ingersold Rand model of water jet pump with the designed pressure of 345 MPa. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system. For the nozzle assembly, it has an orifice of 0.25 mm diameter of sapphire jewel and a focusing tube of 0.76 mm internal diameter of carbide with a focus length of 70 mm. The effect of hydraulic pressure, traverse speed, standoff distance, abrasive mass flow rate, types of abrasive and cutting orientation on mean kerf taper ratio and mean surface roughness as shown in Figures 3c, 6c, 9c, 12b, 14a,15a and 4a, 7a, 10a, 13a, 14a and 15a respectively.

Ramulu and Arola (1994) examined the influence of cutting parameters on the surface roughness and kerf taper of an abrasive water jet machined graphite/epoxy laminate. All the experiments were performed with a PowerJet model water jet, driven by a Model 20-35 water jet pump. The material used for the experiments was graphite/epoxy (Gr/Ep) laminated sheets with 16 mm thickness. Three series of cutting tests were performed each constructed using a Taguchi's experimental design array. Five independent variables associated with AWJ cutting process were varied including jet pressure, standoff distance, traverse speed, grit size and abrasive mass flow rate. Surface roughness parameters including R_a, R_q, R_y, and R_z were obtained with SurfAnalyzer 4000 profilometer using a 5µ diameter probe. Measurements were reduced using analysis of variance (ANOVA) techniques of Taguchi to designate the effects and interaction effects of the process parameters on cut quality. Kerf taper (T_R) was defined as the ratio of the jet entrance kerf width to th exit kerf width. Taper (T_R) measurements were obtained by recording the entrance and exit kerf widths an optical microscope and calculating the ratio of the measurements.

Azmir *et al.* (2009) investigated the effect of Abrasive Water Jet Machining (AWJM) process parameters on kerf taper ratio (T_R) and surface roughness (R_a) of Aramid Fiber Reinforced Plastics (AFRP) composite. Taguchi's design of experiment was used as the experimental approach. The equipment used for machining the samples was Excel-CNC abrasive water jet cutting machine equipped with Ingersold Rand model of water jet pump with a designed pressure of 345 MPa. In that study, Kevlar 129 was used and hand laminated in the prepreg form of modified phenolic resin having its real weight of 410 g/m^2. The aramid fibres which was readily available in a woven fabric and named for its manufacture's style of 258 (2 × 2 basket weave) were used for the preparation of the laminates Through analysis of variance (ANOVA), it was found that the traverse rate was considered to be the most significant factor in both T_R and R_a quality criteria. T_R and R_a were reduced as increasing the hydraulic pressure as shown in Figures 3e and 4b. T_R and R_a were increases as the traverse rate and standoff distance increases, as demonstrated in Figures 6e, 7b, 9d and 10b respectively. However, there was no clear pattern for abrasive mass flow rate on both R_a and T_R as shown in Figures 12c and 13b.

Wang and Guo (2002) developed semi-empirical model to predict the depth of jet penetration in abrasive water jet cutting of polymer matrix composites. All the experiments have been conducted on a Flow Systems International water jet cutter to cut 300 X 300 mm^2 test specimens of 16 mm thick. The water jet cutter was equipped with a model 20X dual intensifier high output pump (up to 380 MPa) and a five-axis robot manipulator for positioning and moving the nozzle. All the specimens were Phenolic Fabric Polymer Matrix Composites which are non-metallic laminated sheets made by impregnated layers of fiber (cotton) reinforcement with resin matrix. They have studied the effect of three parameters likely, water pressure, nozzle traverse speed, and abrasive mass flow rate on depth penetration while kept all other parameters as constant. As shown in Figure 5 and Figure 11, depth of penetration is increases as water pressure and abrasive mass flow rate increases. While jet traverse rate shows the opposite effect on depth of penetration as given in Figure 8.

Xu and Wang have been presented and discussed an experimental investigation of Abrasive Water Jet (AWJ) cutting of alumina ceramics with controlled nozzle oscillation. In that experiment, the specimens used were 87% alumina ceramic plates with a thickness of 12.7 mm, to represent brittle materials. The abrasive water jet cutting system employed was the Flow International Water jet Cutter driven by a "Model 20X" dual intensifier pumping system, with an operating pressure of up to 380 MPa. A Taguchi experimental design array was used to construct the cutting tests. They found that, larger oscillation angles increase the overlap cutting action and the number of scanning actions on a given part of surface, so that the scanning action was dominant and thus reduces the surface roughness. It has been found that oscillation angle have a similar effect on kerf taper and surface roughness.

Hydraulic Pressure

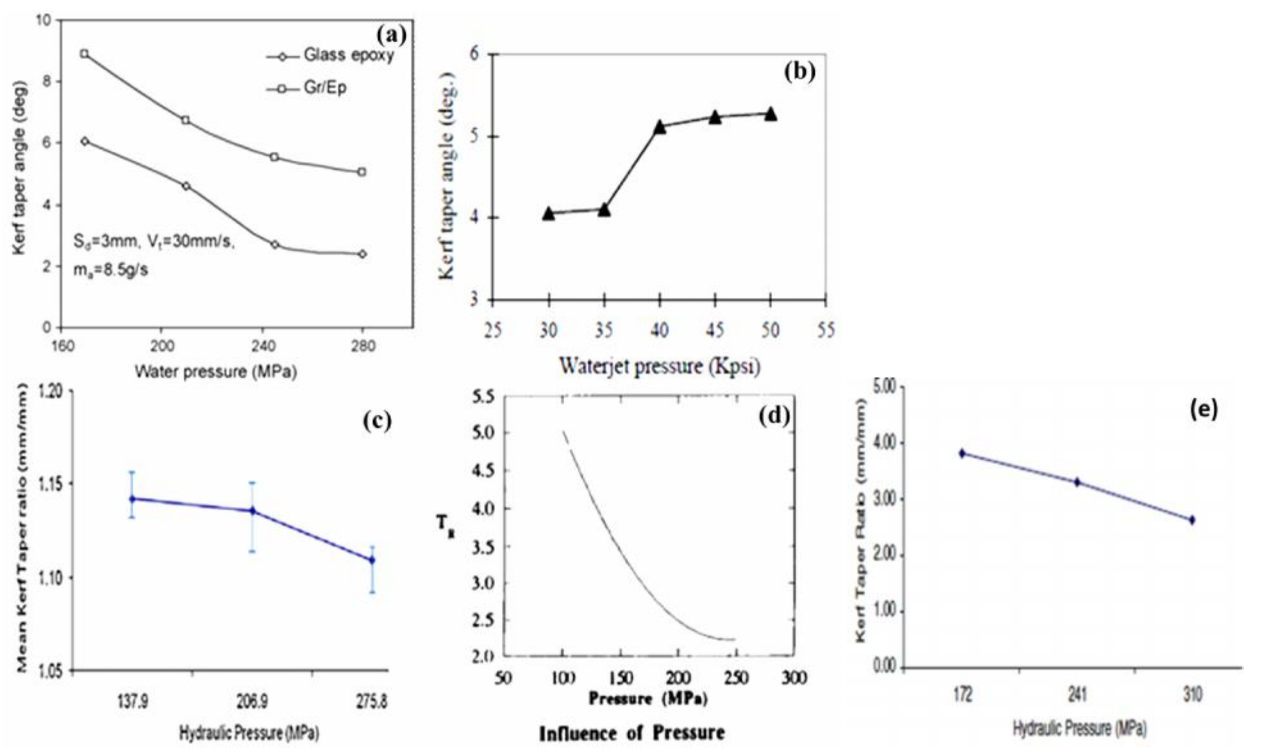
Effect of Hydraulic Pressure on Kerf Geometry

Shanmugam and Masood have been made an investigation on AWJ machining of graphite woven fabric and glass epoxy and studied the influence of hydraulic pressure on kerf geometry. Figure 3a shows the influence of water pressure on the kerf taper angles. They concluded that, within the operating range selected, increase of water pressure results in decrease of kerf taper angles. When water pressure is increased, the jet kinetic energy increases that lead to a high momentum transfer of the abrasive particles, generating a wider-bottom kerf. Therefore, the difference in top and bottom kerf width is reduced, leading to a decrease in kerf taper angle.

Jun Wang studied the effect of hydraulic pressure on kerf taper angle on AWJ machining of polymer matrix composite. As shown in Figure 3b that both the top and bottom kerf widths increase approximately linearly with the water pressure, as higher water pressure results in greater jet kinetic energy impinging onto the material and opens a wider slot. The kerf taper angle also increases with the water pressure. This is because the bottom kerf width is not increased in the same order as the top kerf width, as indicated in the figure. It follows that as the jet loses its kinetic energy, it cannot remove the material adequately at the lower section, resulting in a narrow bottom kerf. It is interesting to note that the characteristics of the taper angle in terms of water pressure and traverse speed discussed above are opposite to those reported in glass/epoxy cutting. This may stem from the different types of materials processed, different pressure and speed ranges selected as well as different ratios of jet energy used to the energy required to cut the materials.

Azmir and Ahsan have been made an investigation on AWJ machining glass/epoxy and studied the influence of hydraulic pressure on kerf geometry. Higher hydraulic pressure results in greater jet kinetic energy and opens a wider slot on the work-piece on both of the top and bottom widths. Consequently, the kerf taper ratio calculated as the ratio of top to the bottom width is reduced with further increase of supply hydraulic pressure due to the more rapidly increasing of top kerf width compared to the bottom kerf width. This is clearly illustrated in Figure 3c.

Figure 3: Effect of Hydraulic Pressure on Kerf Taper Ratio



Ramulu and Arola studied the effect of hydraulic pressure on kerf taper ratio of AWJ machining of graphite/epoxy laminated composite. The influence of pressure on kerf taper is shown in Figure 3d. High supply pressures increase the kinetic energy of the abrasive particles and retain their capacity for material removal. As expected, higher supply pressures reduce the kerf taper over the cutting depth. Further increases in the supply pressure would reduce the kerf taper.

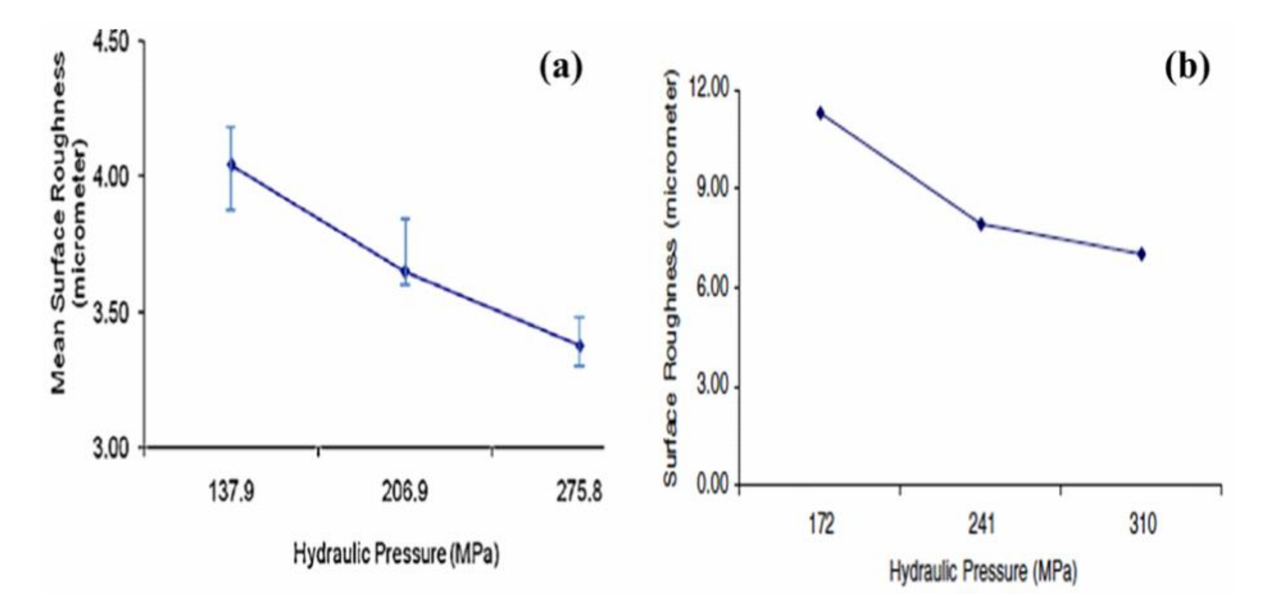
Azmir *et al.* have been made an investigation on AWJ machining aramid fiber reinforced plastics and studied the influence of hydraulic pressure on kerf geometry. Higher hydraulic pressure results in greater jet kinetic energy and opens a wider slot on the work-piece on both of the top and bottom widths. T_R is reduced with further increase of supply hydraulic pressure due to the more rapidly increasing of top kerf width compared to the bottom kerf width. This is clearly illustrated in Figure 3e.

Effect of Hydraulic Pressure on Surface Roughness

Azmir and Ahsan studied the effect of hydraulic pressure on surface roughness of AWJ machining of glass/epoxy laminated composite. While, in case of hydraulic pressure, a higher hydraulic pressure increases the kinetic energy of the abrasive particles and enhances their capability for material removal. As a result, the surface roughness decreases as illustrated in Figure 4a.

Azmir *et al.* have been made an investigation on AWJ machining aramid fiber reinforced plastics and studied the influence of hydraulic pressure on surface roughness. Looking to case of hydraulic pressure, a higher hydraulic pressure increases the kinetic energy of the abrasive particles and enhances their ability for material removal. Whenever the supply pressure provides sufficiently high energy to the abrasives, the cutting process is enabled to be carried out without severe jet

Figure 4: Effect of Hydraulic Pressure on Surface Roughness

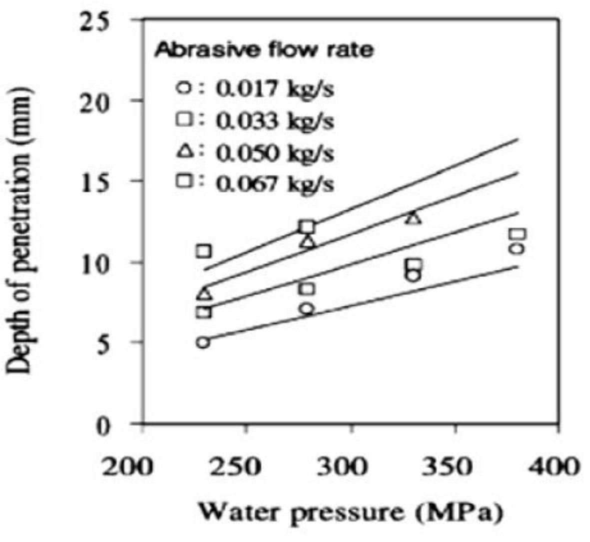


deflection which in turn minimizes the waviness pattern. As a result, the R_a decreases as illustrated in Figure 4b. In the AWJM of AFRP laminate, higher degrees of waviness were generally noted on the specimens that were machined with low jet pressure.

Effect of Hydraulic Pressure on Depth Penetration

Wang and Guo have been made an investigation on AWJ machining of Phenolic fabric polymer matrix composites and studied the influence of hydraulic pressure on depth penetration. The trend of depth of penetration with respect to the water pressure is shown in Figure 5. In general, the depth of penetration increases with water pressure, as more energy will be able to remove more material. This is due to the fact that a higher water pressure tends to open a wider kerf which will have a negative effect on the depth of penetration. In addition, particle fragmentation increases with water pressure, which reduces the cutting effectiveness of the particles.

Figure 5: Effect of Hydraulic Pressure on Depth of Penetration



Traverse Speed

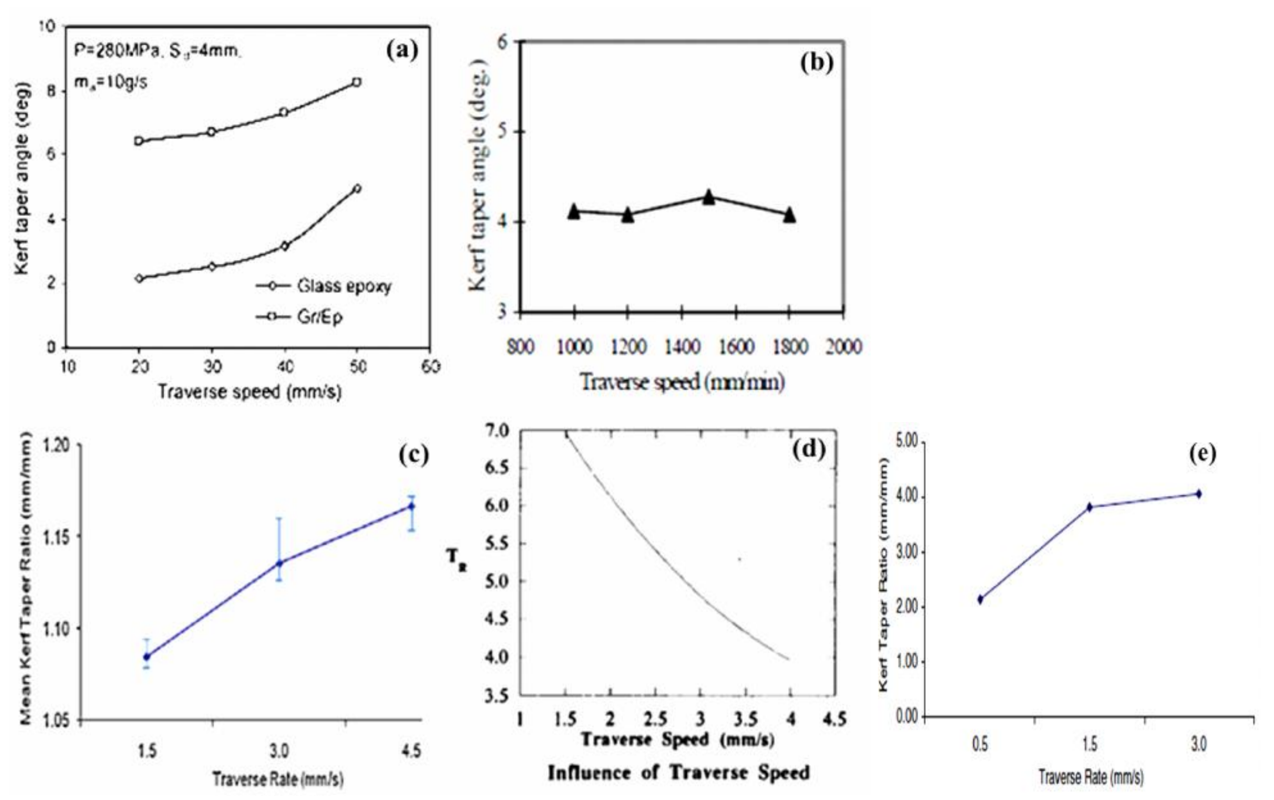
Effect of Traverse Speed on Kerf Geometry

Shanmugam and Masood have been made an investigation on AWJ machining of graphite woven fabric and glass epoxy and studied the influence of traverse speed on kerf geometry. Increase of traverse speed increases kerf taper angle as shown in Figure 6a. The increase in kerf taper angle is a direct result of the exposure time because at higher traverse, less time is available for cutting, leading to less overlapping of the jet on the target material.

Jun Wang studied the effect of traverse speed on the top kerf width, bottom kerf width and kerf taper is shown in Figure 6b. It can be seen from the figure that the traverse speed has a negative effect on both the top and bottom kerf widths. Taper angle decreases slightly with an increase in the traverse speed. The negative effect of the traverse speed on both the top and bottom kerf widths is due to the fact that a faster passing of abrasive water jet allows fewer abrasives to strike on the jet target and hence generates a narrower slot. It is interesting to note that the characteristics of the taper angle in terms of water pressure and traverse speed discussed above are opposite to those reported in glass/epoxy cutting.

Azmir and Ahsan examined the effect of traverse rate on the kerf taper as shown in Figure 6c. It could be concluded that the negative effect of traverse rate on the kerf width is due to the fact that a faster passing of abrasive water jet allows fewer particles to strike on the target material and, hence, generates a narrower slot. In other words, the

Figure 6: Effect of Traverse Speed on Kerf Taper Angle



decrease in the exposure time that was caused by increasing the traverse rate resulted to the reduction in both of the kerf top and bottom width. Whereas, the increasing trend of the kerf taper ratio is the result of the more rapidly decreasing kerf width at the bottom than at the top as the traverse rate increases.

Ramulu and Arola studied the influence of traverse speed on the taper of the laminated material at the aforementioned cutting conditions. This trend resulted from the reduction in kerf entrance width with increasing traverse speed due to the decrease in exposure time. Kerf exit width was nearly independent of the traverse speed used for cutting in this scenario and, therefore, did not influence the taper ratio. At lower jet pressures, kerf taper generally increases with an increase in traverse speed, which is attributed to an increase in jet deflection as shown in Figure 6d.

Azmir *et al.* investigated the effect of traverse rate on the kerf taper ratio as shown in Figure 6e. It is concluded that the negative effect of traverse rate on the kerf width is due to the fact that a faster passing of abrasive water jet allows fewer particles to strike on the target material and, hence, generates a narrower slot. In other words, the decrease in the exposure time that was caused by increasing the traverse rate resulted to the reduction in both of the kerf top and bottom width. Whereas, the increasing trend of the T_R is the result of the more rapidly decreasing kerf width at the bottom than at the top as the traverse rate increases.

Effect of Traverse Speed on Surface Roughness

Azmir and Ahsan investigated the influence of traverse speed on prediction of the kerf profile shape under different traverse speed in AWJM of glass/epoxy, it was found that the roughness of the cut profiles changes with traverse rate and it is more obvious at the highest traverse rate. In this case, a lower traverse rate is desirable to produce a better surface finish as shown in Figure 7a.

Azmir *et al.* in case of traverse rate, it can be anticipated as increasing the traverse rate allows less overlap machining action and fewer abrasive particles to impinge the surface, increasing the roughness of the surface. Also, a faster traverse rate increases the jet deflection which results to a higher magnitude of surface roughness. The roughness of the cut profiles changes with traverse rate and it is more obvious at the highest traverse rate. In this case, a lower traverse rate is desirable to produce a better surface finish as shown in Figure 7b.

Effect of Traverse Speed on Depth Penetration

Wang and Guo Figure 8 shows that, the depth of penetration decreases with an increase in jet traverse rate in an exponential form. As the traverse speed increases, the number of particles impinging on a given exposed target area decreases, which in turn reduces the material removal rate. They have found that the damping and friction effect on the jet decreases as the jet exposure time decreases. Thus, an increase in the jet traverse speed will reduce the energy loss of the particles and improve the material removal rate. It has been reported that with a faster travel of the jet, fewer particles will be able to strike on the target material and open a narrower slot. Consequently, as a result of the reduced energy loss and the narrowing kerf width at a high traverse speed, the rate of decrease in the depth of penetration is reducing and the curves tend to flattening in the graphs as the traverse speed increases.

Figure 7: Effect of Traverse Speed on Surface Roughness

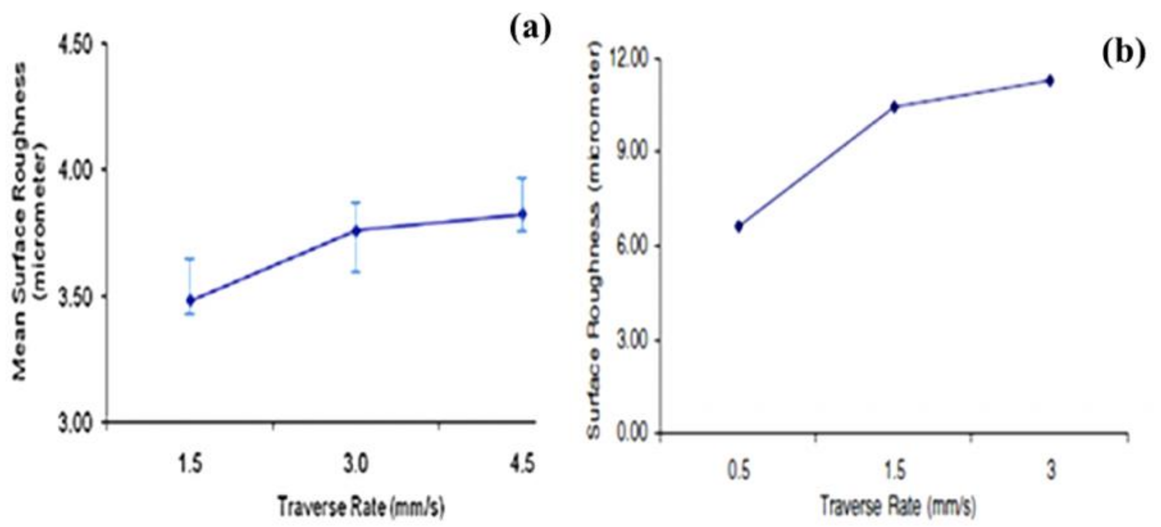
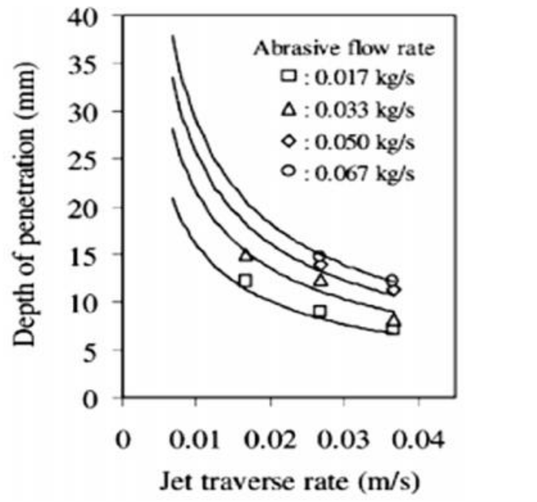


Figure 8: Effect of Traverse Speed on Depth Penetration



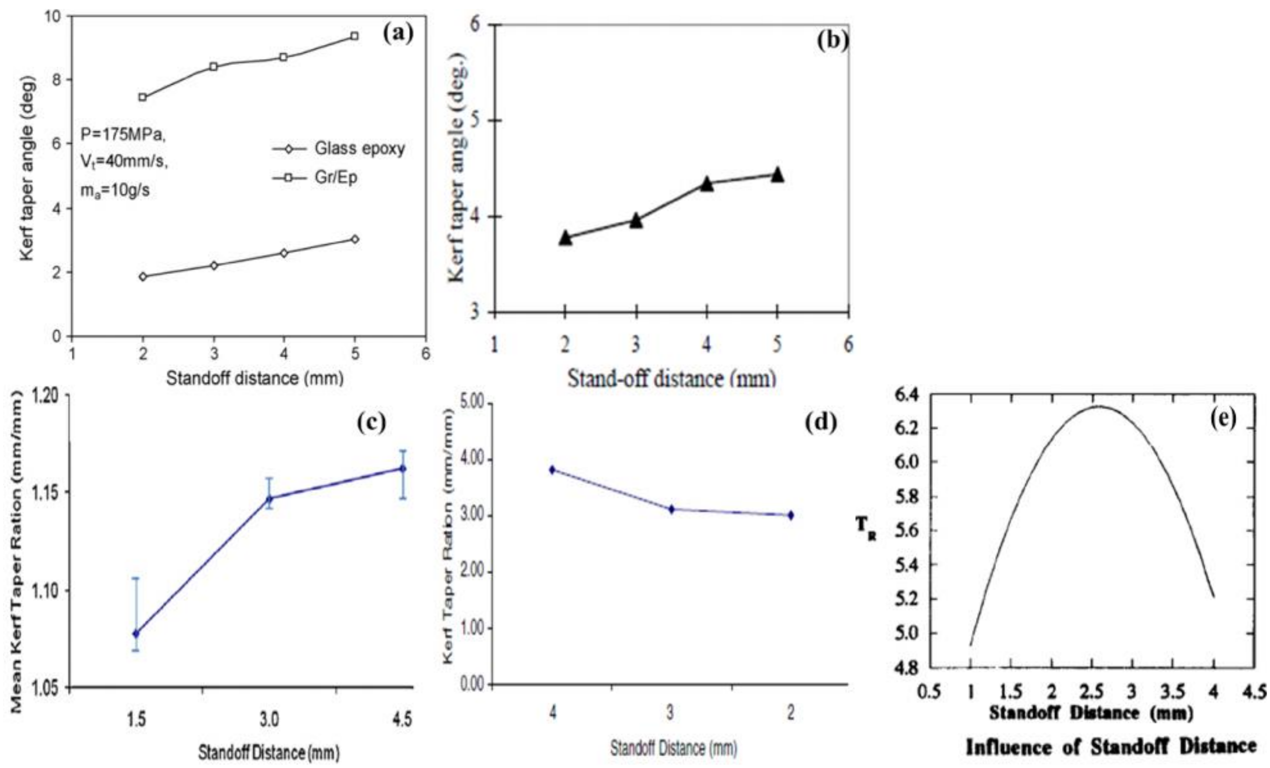
Standoff Distance

Effect of Standoff Distance on Kerf Geometry

Shanmugam and Masood With increase in standoff distance, the kerf taper increases within the range 2-5 mm as shown in Figure 9a. By increasing the standoff distance the material surface is exposed to the downstream of the jet. At downstream, the jet starts to diverge losing its coherence thereby reducing the effective cutting area that directly affects the kerf taper angle.

Jun Wang Figure 9b shows that the top and bottom kerf widths increase with an increase in the standoff distance although a smaller rate associated with the bottom kerf width is observed. This may be explained as the result of jet divergence when high-velocity water jets spread out (at different angles) as they exit from the mixing tube. Since the jet is losing its kinetic energy as it penetrates into the work material, the outer rim of the diverged jet will not take effect as it approaches the lower part

Figure 9: Effect of Standoff Distance on Kerf Taper Angle



of the kerf. As such, the stand-off distance has a lesser effect on the bottom kerf width than the top kerf width. As a consequence of this effect, the kerf taper angle is increasing with the stand-off distance, as shown in Figure 9b.

Azmir and Ahsan Figure 9c, the kerf taper ratio increases with the increase in standoff distance. It was found that higher standoff distance allows the jet to expand before impingement and lowers the densities of abrasive particles in the outer perimeter of the expanding jet. This generally results in lower penetration depth as well as a higher surface roughness. Thus, increasing the standoff distance between the nozzle and work-piece is expected to result in higher difference between top and bottom kerf widths which eventually gives higher kerf taper ratio.

Ramulu and Arola the influence of standoff distance on kerf taper is shown in Figure 9e. At this combination of parametric levels, the kerf taper increases with an increase in standoff distance to 2.75 mm. Beyond this standoff distance the kerf taper begins to decrease, most likely due to the reduced effects of jet expansion at the jet entrance with little change of kerf width at the jet exit. Although jet expansion increases with higher standoff distance, as the standoff distance surpasses 2.75 mm the energy of the exterior of the jet decreases to levels which are below those necessary to create macro-damage. For this reason, the kerf taper decreases with an increase in standoff distance. Generally, when cutting with higher jet pressures or larger grit sizes, kerf taper increases with an increase in standoff distance.

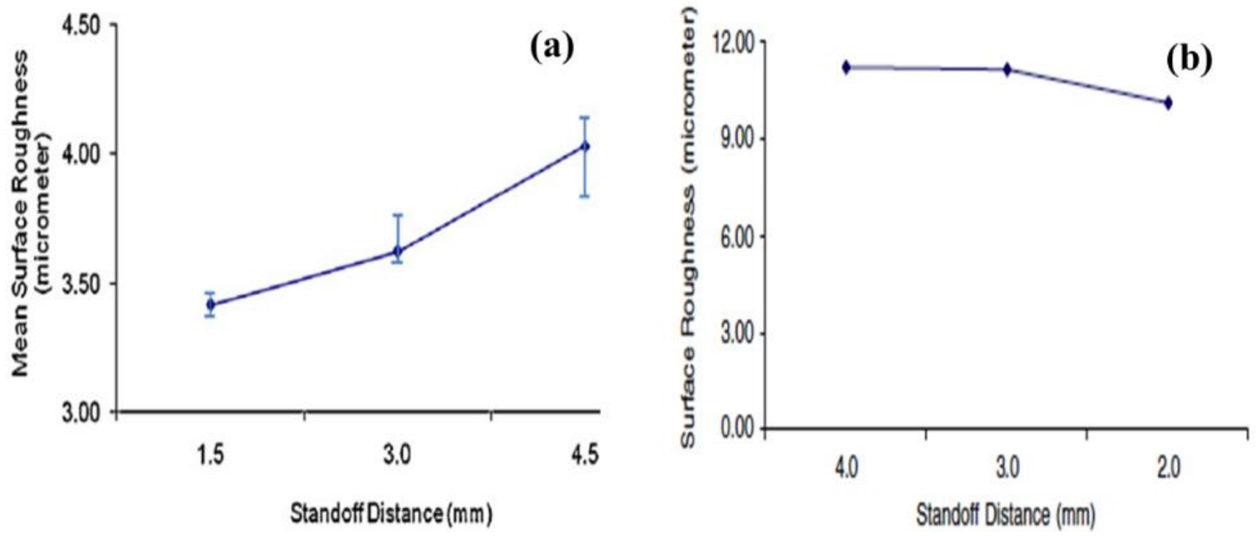
Azmir *et al.* Referring to Figure 9d, the T_R increases with the increase in standoff distance. Higher standoff distance allows the jet to expand before impingement and lowers the densities of abrasive particles in the outer perimeter of the expanding jet. Thus, increasing the standoff distance between the nozzle and work-piece is expected to result in higher difference between top and bottom kerf widths which eventually gives higher T_R.

Effect of Standoff Distance on Surface Roughness

Azmir and Ahsan in case of standoff distance, generally, higher standoff distance allows the jet to expand before impingement which may increase vulnerability to external drag from the surrounding environment. Therefore, increase in the standoff distance results an increased jet diameter as cutting is initiated and in turn, reduces the kinetic energy density of the jet at impingement. It is desirable to have a lower standoff distance which may produce a smoother surface due to increased kinetic energy as shown in Figure 10a.

Azmir *et al.* in case of standoff distance increasing the standoff distance results an increase in jet diameter as cutting is initiated and in turn, reduces the kinetic energy density of the jet due to impingement. It is desirable to have a lower standoff distance which may produce a smoother surface due to increased kinetic energy. As shown in Figure 10b, decreasing the standoff distance reduces the surface roughness slightly. However, it is believed that the surface of the machined laminate may not be optimized with minimum standoff distance. If the standoff distance is too small, the abrasive water flow is damped or decelerated by the target surface that generates shallower depths of cut.

Figure 10: Effect of Standoff Distance on Surface Roughness

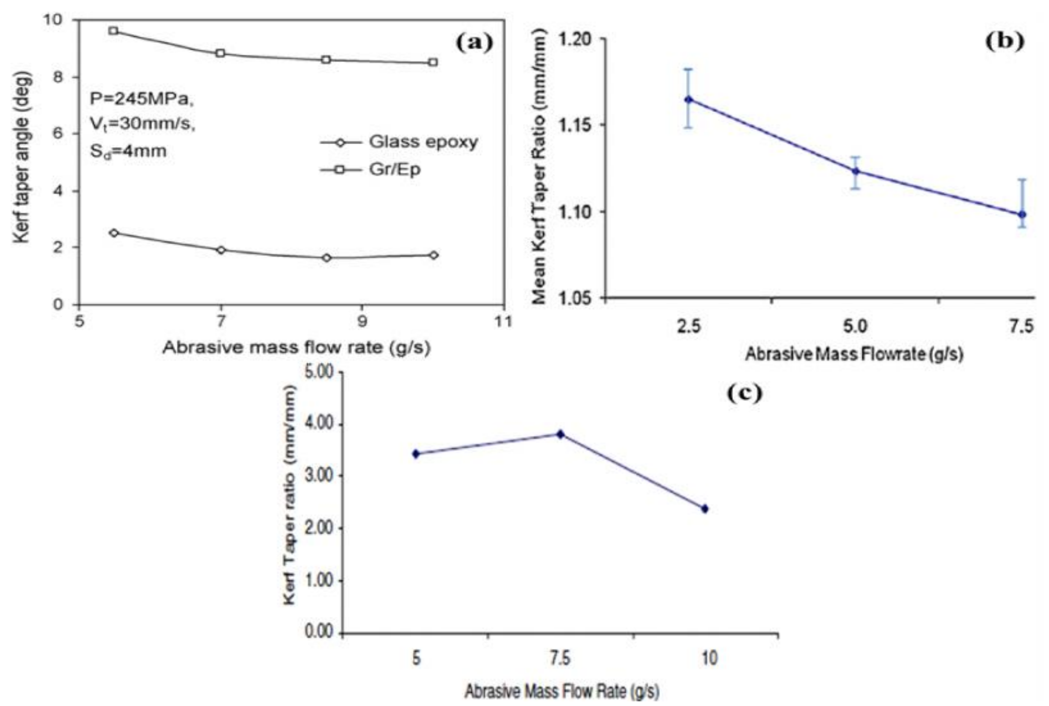


Abrasive Mass Flow Rate

Effect of Abrasive Mass Flow Rate on Kerf Geometry

Shanmugam and Masood with an increase in the abrasive mass flow rate the kerf taper angle seems to decrease insignificantly, as shown in Figure 11a. It is implicit that a critical energy transfer from the jet to the particles is needed to fracture the material, below which any increase in abrasive mass flow rate does not have an effect on the kerf taper angle. In

Figure 11: Effect of Abrasive Mass Flow Rate on Kerf Taper Angle



general, the effect of traverse speed and water pressure is pronounced higher compared to standoff distance with the abrasive mass flow rate having minimal effect. It is recommended that a combination of high water pressure, low traverse speed and short standoff distance are used to produce more vertical kerf wall.

Azmir and Ahsan the higher the abrasive mass flow rate, the higher the number of particles involved in the mixing and cutting processes. Every increase in the abrasive mass flow rate leads to a proportional increase in the depth of cut. Therefore, the jet will have higher kinetic energy and consequently will gain higher capability to penetrate the workpiece. As a result, there will be a relatively wider width for both top and bottom kerf widths. With the increase in penetration capability, the bottom width tends to be equal to the top width resulting in kerf taper ratio approximating to 1. As shown in Figure 11b, with the increase in abrasive mass flow rate consequently the kerf taper ratio is approaching to 1 as the penetration capability increases.

Azmir *et al.* the higher the abrasive mass flow rate, the higher the number of particles involved in the mixing and cutting processes. Every increase in the abrasive mass flow rate leads to a proportional increase in the depth of cut. Therefore, the jet will have higher kinetic energy and consequently will gain higher ability to penetrate the work-piece. As a result, there will be a relatively wider width for both top and bottom kerf widths. The increase in both top and bottom kerf widths does not give a higher or lower value in TR as it is calculated as the ratio of top kerf width to the bottom kerf width. Figure 11c shows no clear trend on the effect of abrasive mass flow rate on the TR.

Effect of Abrasive Mass Flow Rate on Surface Roughness

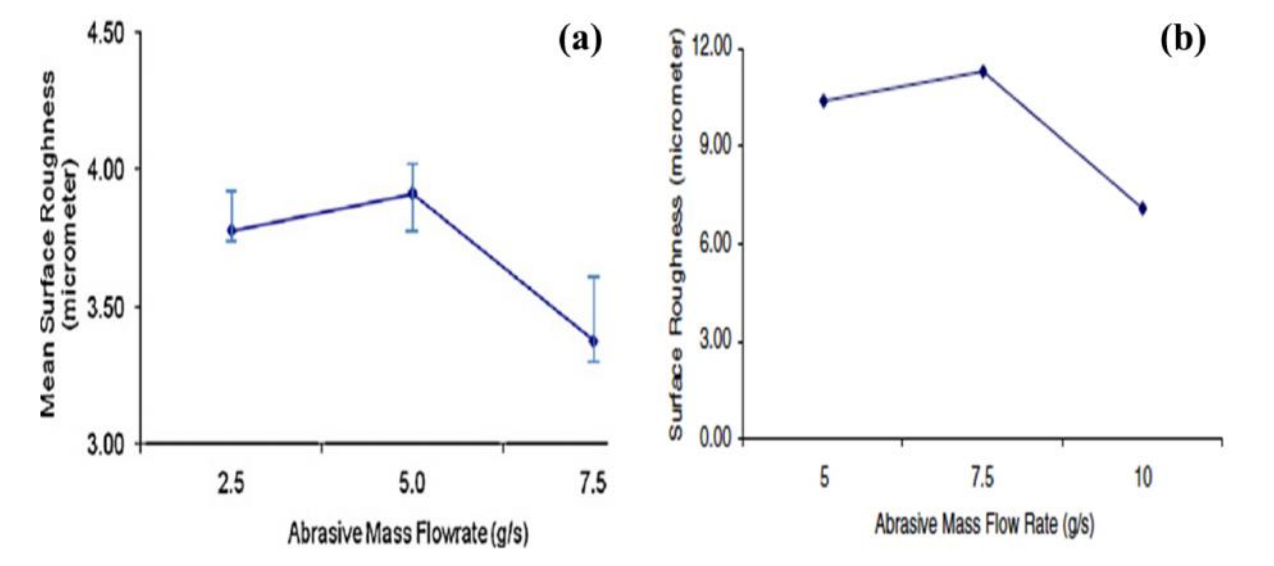
Azmir and Ahsan have been made an investigation on AWJ machining glass/epoxy and studied the influence of abrasive mass flow rate on surface roughness. In case of abrasive mass flow rate, the higher the abrasive mass flow rate, the higher the number of particles involved in the mixing and cutting processes. An increase in abrasive mass flow rate leads to a proportional increase in the depth of cut. When the abrasive mass flow rate is increased, the jet can cut through the laminate easily and as a result, the cut surface becomes smoother. However, the roughness increases with an increase in abrasive mass flow rate up to a certain limit and beyond that limit it was found to decrease as illustrated in Figure 12a. This is due to the fact that an increase in mass of abrasive particles results in inter-collision of particles among themselves and hence causes a loss of kinetic energy.

Azmir *et al.* have reported that, in case of abrasive mass flow rate, the higher the abrasive mass flow rate, the higher the number of particles involved in the mixing and cutting processes. An increase in abrasive mass flow rate leads to a proportional increase in the depth of cut. When the abrasive mass flow rate is increased, the jet can cut through the laminate easily and as a result, the cut surface becomes smoother. However, the roughness increases with an increase in abrasive mass flow rate up to a certain limit and beyond that limit it was found to decrease as illustrated in Figure 12b.

Effect of Abrasive Mass flow rate on Depth Penetration

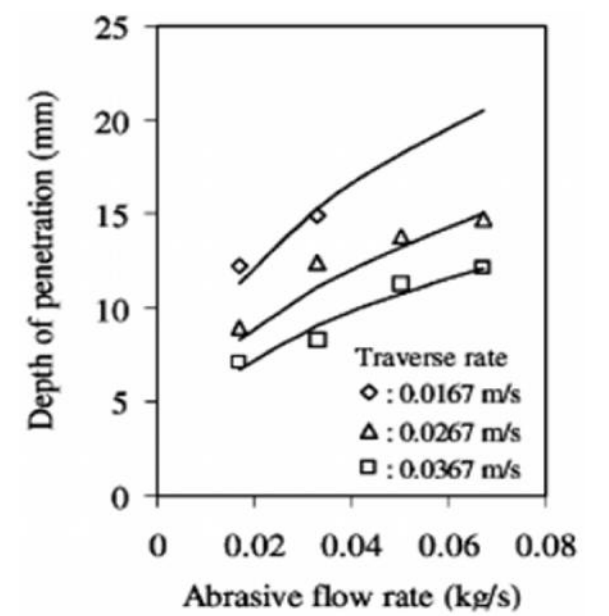
Wang and Guo Figure 13 show that the depth of penetration increases with the abrasive

Figure 12: Effect of Abrasive Mass Flow Rate on Surface Roughness



mass flow rate This trend is in line with the earlier findings in many investigations, and the predicted trend and values are in good agreement with those from the experiments. It is apparent that more particles tend to remove more materials and increase the depth of penetration. However, not all the abrasive particles in the jet will strike the target material or at least not remove the material in the same efficiency. This is due to the interference between particles which reduces the particle energy as well as the effectiveness of individual particles in cutting the material. An increase in the number of particles (or mass flow rate) in the jet will increase the chance of particle interference. Thus the overall cutting performance in terms of the depth of penetration does not increase linearly with abrasive mass flow rate. In addition, the kerf width also increases to some extent with the abrasive mass flow rate, which has a reduced effect on the depth of penetration and contributes to the reduced rate of increase in the depth of penetration.

Figure 13: Effect of Standoff Distance on Depth Penetration



Types of Abrasive

Effect of Types of Abrasive on Kerf Geometry

Azmir and Ahsan have been made an investigation on AWJ machining glass/epoxy and studied the influence of types of abrasive on kerf geometry. It shows clearly that at higher hardness of abrasive particles tends to produce lower taper ratio as shown in Figure 14a. It is believed that with the higher hardness of abrasive particles increases the kinetic energy of the water jet. Thus, results in higher capability of jet penetration into the target materials. As a result the top kerf width will be bigger and the bottom also may have relatively bigger width giving a lower taper as it is calculated based on the ratio of top and bottom kerf widths.

Effect of Types of Abrasive on Surface Roughness

Azmir and Ahsan have been made an investigation on AWJ machining glass/epoxy and studied the influence of types of abrasive on surface roughness. It was found that higher hardness of abrasive material which was aluminium oxide gave better surface finish compared to lower hardness of abrasive material such as garnet. The abrasive material hardness influences the fracture behavior of the abrasive particles. The harder the material, the higher the probability of particle fractures. The use of the harder aluminium oxide substantially reduces the surface roughness. It was found that the use of harder abrasive material such as silicon carbide and aluminium oxide resulted in retaining its cutting capability. Consequently, the surface of cuts became smoother as seen in Figure 14b.

Cutting Orientation

Azmir and Ahsan have been made an investigation on AWJ machining glass/epoxy and studied the influence of cutting orientation on kerf geometry and surface roughness. Surface roughness may be influenced by the kinetic energy of the jet. It also depends on the architecture of the fibres. As pointed out earlier, cutting orientation is relatively significant in influencing the surface roughness as illustrated in Figure 15b. However in present study, there is no clear trend on the effect of fibre's cutting orientation on surface roughness. It is believed that both constituents

Figure 14: Effect of Types of Abrasive on Surface Roughness

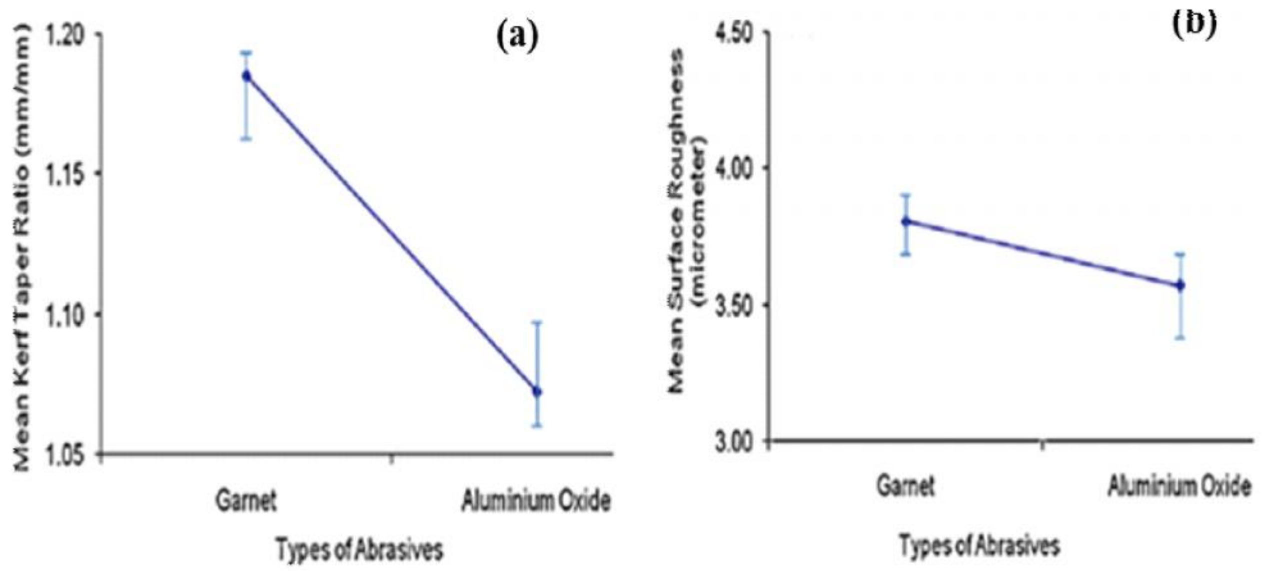
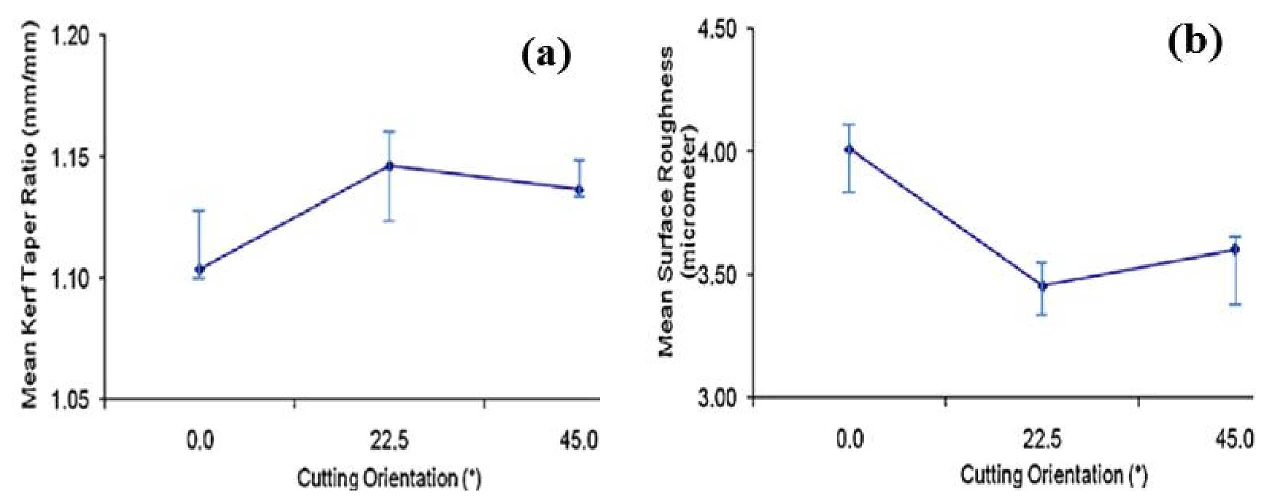


Figure 15: Effect of Cutting Orientation on Kerf Characteristics and Surface Roughness

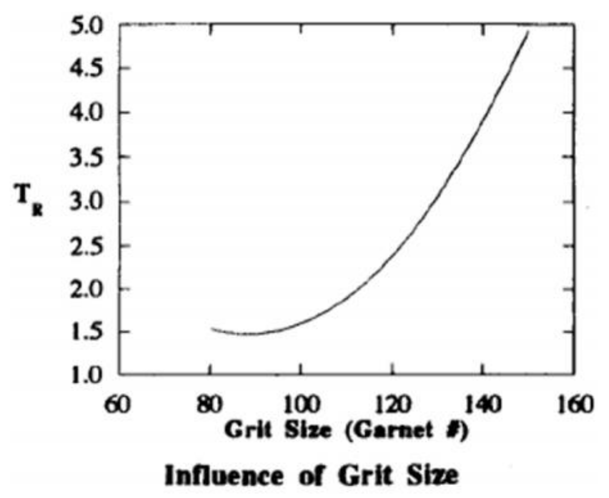


of fibres and interstitial matrix experienced independent shear fracture during material removal process. Based on Figure 15b, surface roughness is lowest at cutting orientation 22.50. However, the real effect of cutting orientation is very much a subject for discussion where it may well depend on the nature of fibres, mechanics fracture of fibres and cohesiveness of matrix. Actually, the effect of traverse rate on the kerf taper was also found to be similar to that observed on the surface roughness as shown in Figure 15a.

Grit Size

Ramulu and Arola have been made an investigation on AWJ machining of graphite/epoxy and studied the influence of grit size on kerf taper ratio. The influence of grit size on kerf taper ratio at these cutting conditions is shown in Figure 16. As shown, generally smaller grit sizes result in an increase in taper of the kerf when machining graphite/epoxy. It is also illustrated that a greater kerf taper results when using #80 garnet at this parametric combination. This phenomenon is most likely due to the rate of material removal

Figure 16: Effect of Grit Size on Kerf Taper Ratio

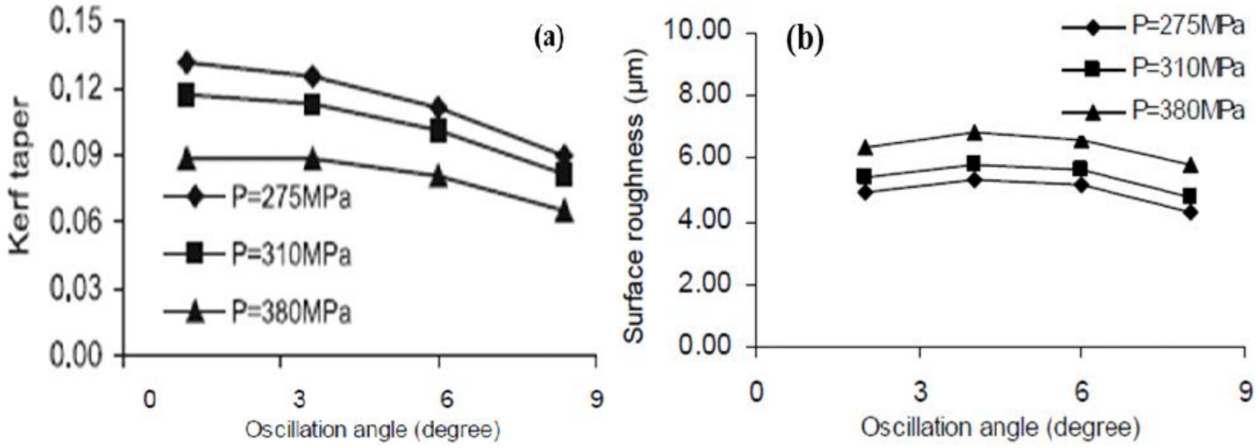


at the jet entrance when using large abrasives. Note that the kerf taper reaches a minimum at these cutting conditions and is increased with larger grit sizes. This phenomenon is attributed to the effect of larger abrasives on the entrance kerf width. Large abrasives increase the initial impact zone which results in a wide, r entrance kerf and in turn, a larger taper ratio.

Controlled Nozzle Oscillation

Xu and Wang have been made an

Figure 17: Effect of Jet Oscillation Angle on (a) Kerf Taper Ratio and (b) Surface Roughness



investigation on AWJ machining of alumina ceramic and studied the influence of jet oscillation on kerf taper ratio and surface roughness. It has been found oscillation angle have a similar effect on kerf taper and surface roughness. This is shown in Figures 17a and 17b. This trend is consistent for cutting under various conditions. Figure 17b shows the effect of oscillation angle on surface roughness. Here, it can be seen that initially, surface roughness increases slightly with an increase in oscillation angle, and reaches a maximum turning point. As the oscillation angle further increases, surface roughness starts to decrease. This may be a result of the scanning action of the jet on the cutting front. There appears to be an optimum scanning scope corresponding to a set of cutting parameters, similar to the above discussion about the effect of standoff distance. As the oscillation angle increases in the lower region, the jet scanning action cannot effectively cut off the "peaks" left on the cut surface, thus causing jet turbulence or instability and system vibration that increase the surface roughness. Larger oscillation angles increase the overlap cutting action and the number of scanning actions on a given part of surface, so that the scanning action is dominant and thus reduces the surface roughness.

CONCLUSION

Abrasive water jet machining process includes large number of process parameters, which affects the quality of cutting surface. Process parameter which affect less or more on quality of cutting in abrasive water jet machining are hydraulic pressure, traverse speed, stand-off distance, abrasive mass flow rate, abrasive materials, nozzle length and diameter, orifice diameter, abrasive shape, size and hardness. Characteristics of cutting surface is measured inform of surface roughness, surface waviness, material removal rate, kerf top width, kerf bottom width and kerf taper angle. It was concluded from literature (i) Hydraulic pressure (MPa) and type of abrasive materials were considered as the most significant control factor in influencing surface roughness and taper ratio respectively. (ii) High traverse speeds result in lower material removal rates as material. (iii) Garnet abrasives produce a larger taper of cut followed by Al_2O_3. This is due to higher hardness of Al_2O_3 compared to garnet. (iv) Decreasing the standoff distance and traverse rate may improve both criteria of machining performance. Cutting orientation does not influence the machining performance in both cases. (v) Small oscillation angles of cutting nozzle can improve the various cutting performance measures like surface roughness. Proper selection of orifice and nozzle length and diameter can improve the kerf quality.

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