A Machinability Study of Kevlar-Phenolic Composites Using Abrasive Waterjet Cutting Process

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Abstract

Abrasive waterjet cutting is one of the non-traditional cutting processes capable of cutting wide range of hard-to-cut materials. This paper assesses the influence of process parameters on depth of cut and surface roughness which are important cutting performance measures in abrasive waterjet cutting of Kevlar reinforced phenolic composites. Experiments were conducted in varying water pressure, nozzle traverse speed, abrasive mass flow rate and standoff distance for cutting Kevlar-phenolic composites using abrasive waterjet cutting process. The effects of these parameters on depth of cut and surface roughness have been studied based on the experimental results. In order to correctly select the process parameters, an empirical model for the prediction of depth of cut in abrasive waterjet cutting of Kevlar-phenolic composites is developed using regression analysis. This developed model has been verified with the experimental results that reveal a high applicability of the model within the experimental range used.

Key words—*abrasive waterjet, composites, empirical model, garnet, kevlar, phenolic, regression analysis.*

1. INTRODUCTION

Abrasive Waterjet Cutting [AWJC] has various distinct advantages over the other non-traditional cutting technologies, such as no thermal distortion, high machining versatility, minimum stresses on the work piece, high flexibility and small cutting forces and has been proven to be an effective technology for processing various engineering materials [1]. It is superior to many other cutting techniques in processing variety of materials and has found extensive applications in industry [2]. In this method, a stream of small abrasive particles is introduced in the waterjet in such a manner that waterjet's momentum is partly transferred to the abrasive particles. The main role of water is primarily to accelerate large quantities of abrasive particles to a high velocity and to produce a high coherent jet. This jet is then directed towards working area to perform cutting [3]. It is also a cost effective and environmentally friendly technique that can be adopted for processing number of engineering materials particularly difficult-to-cut materials such as ceramics [4], [5]. However, AWJC has some limitations and drawbacks. It may generate loud noise and a messy working environment. It may also create tapered edges on the kerf, especially when cutting at high traverse rates [6], [7].

As in the case of every machining process, the quality of AWJC process is significantly affected by the process tuning parameters [8], [9]. There are numerous associated parameters in this technique, among which water pressure, abrasive flow rate, jet traverse rate, standoff distance and diameter of focusing nozzle are of great importance but precisely controllable [10], [11]. The main process quality measures include attainable depth of cut, kerf width and surface finish. Number of techniques for improving kerf quality and surface finish has been proposed [10]-[13].

In this paper depth of cut is considered as the performance measure as in many industrial application it is the main constraint on the process applicability. In order to effectively control and optimize the AWJC process, predictive models for depth of cut have been already developed for ceramics, aluminum, stainless steel, brass, copper, titanium etc. [14]-[16]. But no such models have been developed for Kevlar-phenolic composites. More work is required to fully understand the influence of the important process parameters on depth of cut of Kevlar-phenolic composites. This paper assesses the influence of abrasive waterjet cutting process parameters on depth of cut of Kevlar reinforced phenolic composites. An empirical model for the prediction of depth of cut in AWJC process of Kevlar-phenolic composites is developed using regression analysis. The model is then experimentally verified when cutting Kevlar-phenolic composites within the practical range of process variables.

2. EXPERIMENTAL WORK

2.1 Material

Composite materials are formed by combining two or more materials in such a way that the constituents of the composite materials are still distinguishable, and not fully blended. Composite materials have excellent compressibility combined with good tensile strength, making them versatile in a wide range of situations. The composite material considered in this study is Kevlar 129 which is hand laminated in the prepreg form of modified phenolic resin. The aramid fibers which was readily available in a woven fabric and named for its manufacturer's style of 258 (2 x 2 basket weave) were used for the preparation of the laminates. The layers were properly stacked to have a laminate thickness of 13.8 mm. The orientation of fiber within the fabric was kept constant during the lay-up process hence they are considered as bidirectional laminates (0°/90°). The young's modulus of Kevlar 129 is 90000 MPa and the density is 1.45 g/cm3.

2.2 Equipment

The equipment used for machining the samples was Water Jet Sweden cutter which was equipped with KMT ultrahigh pressure pump with the designed pressure of 4000 bar. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a work piece table with dimension of 3000 mm x 1500 mm. Sapphire orifice was used to transform the high-pressure water into a collimated jet, with a carbide nozzle to form an abrasive waterjet. The schematic of an abrasive waterjet cutting process is shown in fig.1.

Throughout the experiments, the nozzle was frequently checked and replaced with a new one whenever the nozzle was worn out significantly. The abrasive waterjet cutting head is shown in fig.2.

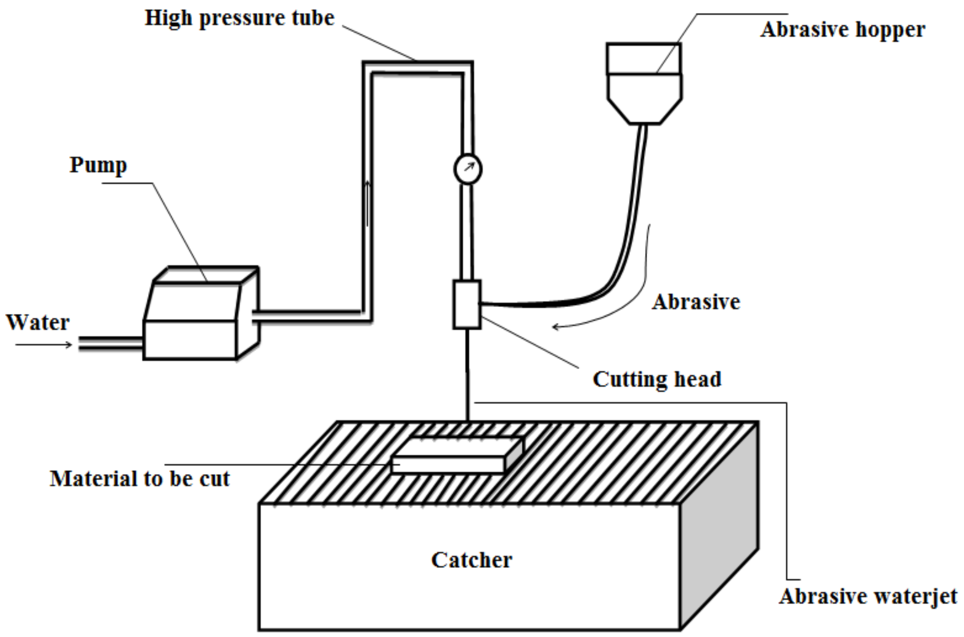


Fig 1. Schematic of an abrasive waterjet cutting process

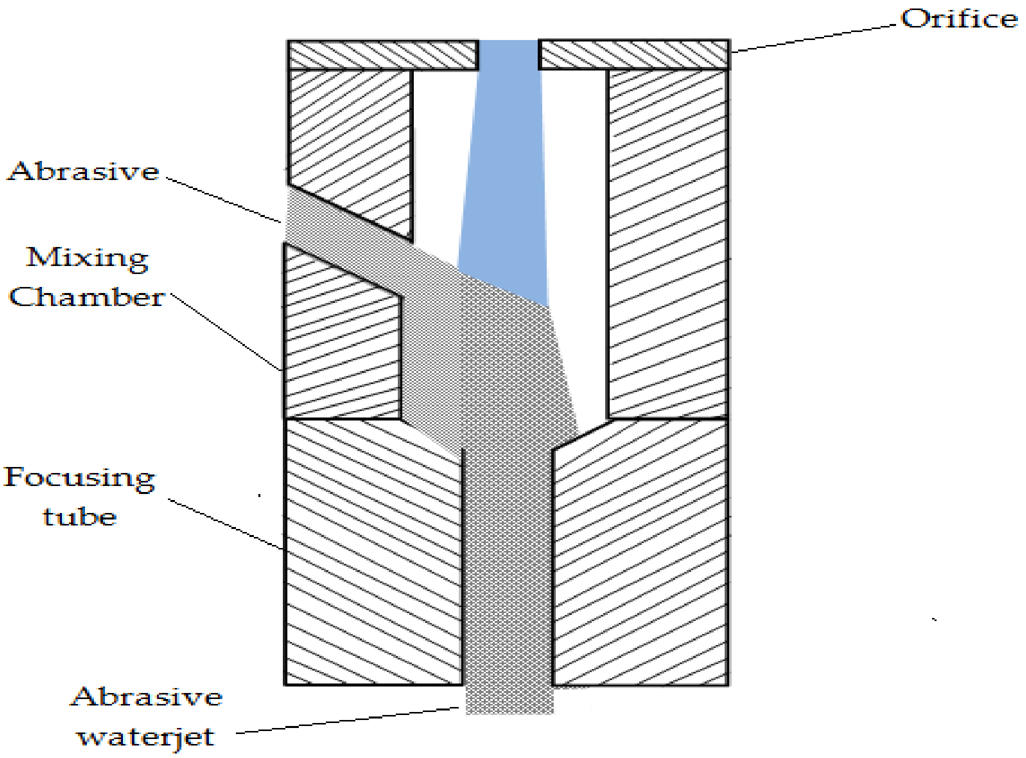


Fig. 2. Abrasive waterjet cutting head

The abrasives were delivered using compressed air from a hopper to the mixing chamber and were regulated using a metering disc. The abrasive waterjet pressure is manually controlled using the pressure gauge. The standoff distance is controlled through the controller in the operator control stand. The traverse speed was controlled automatically by the abrasive waterjet system programmed by NC code. The debris of material and the slurry were collected into a catcher tank.

2.3 Design of Experiments (DOE)

To achieve a thorough cut it was required that the combinations of the process variables give the jet enough energy to penetrate through the specimens. In the present study four process parameters were selected as control factors. The parameters and levels were selected based on the literature review of some studies that had been documented on AWJC on graphite/epoxy laminates [17], metallic coated sheet steels [18] and fiber-reinforced plastics [19]. Taguchi's experimental design was used to construct the design of experiments (DOE). Four process parameters, i.e. water pressure, nozzle traverse speed, mass flow rate of abrasive particles and standoff distance each varied at three levels as shown in table 1, an L_{81} (3^4) orthogonal arrays table with 81 rows corresponding to the number of experiments was selected for the experimentation.

Table 1 Levels of parameters used in experiment

Parameters	Unit	Level 1	Level 2	Level 3
Water pressure	MPa	275	334	393
Traverse speed	mm/s	4.6	5.6	6.6
Mass flow rate	g/s	4	6.9	9.8
Standoff distance	mm	1.8	3.4	5

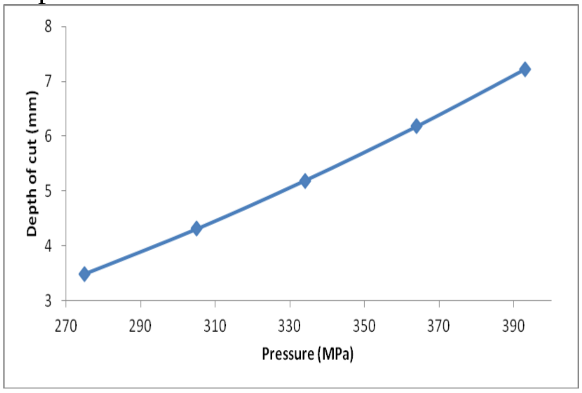
The parameters that were kept constant during tests included the jet impact angle at neutral nozzle position (90°), orifice diameter (0.35 mm), nozzle diameter (1.05 mm), abrasive material (garnet particles with the density of 4100 kg/m^3)
and average diameter of abrasive particles (0.18mm). For each experiment, the machining parameters were set to the pre-defined levels according to the orthogonal array. All machining procedures were done using a single pass cutting. For each cut, at least three measures were made and the average was taken as the final reading to minimize the error.

3. EXPERIMENTAL RESULTS AND DISCUSSION

By analyzing the experimental data, it has been found that the effects of the four basic parameters, i.e., water pressure, abrasive mass flow rate, nozzle traverse speed and nozzle standoff distance on depth of cut and surface roughness are in the same fashion as reported in previous studies for other materials [20]-[22]. The effect of each of these parameters is studied while keeping the other parameters considered in this study as constant.

3.1 Effect of Water Pressure on Depth of Cut

The influence of water pressure on the depth of cut is shown in fig. 3. Results indicate that, within the operating range selected, increase of water pressure results in increase of depth of cut when mass flow rate, traverse speed and standoff distance were kept constant. When water pressure is increased, the jet kinetic energy increases that leads to more depth of cut.

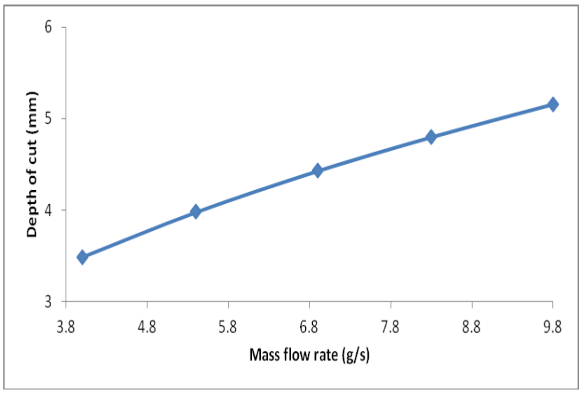


m_a = 4 g/s
u = 6.6 mm/s
s = 5 mm

Fig. 3. Water pressure versus depth of cut

3.2 Effect of Mass Flow Rate on Depth of Cut

Increase in abrasive mass flow rate also increases the depth of cut as shown in fig. 4. This is found while keeping the pressure, traverse speed and standoff distance as constant. The impact between the abrasive particle and the material determines the ability of the abrasive waterjet to cut the material. Since cutting is a cumulative process, the speed of the abrasive particle and the frequency of particle impacts are both important. The speed of the particle determines the impulsive loading on the material and the potential energy transfer from the particle to the material. The frequency of the impact determines the rate of energy transfer and hence, the rate of cut depth growth. The mass flow rate of the abrasive particles partially determines the frequency of the impacting particles and partially determines the speed at which they hit. In addition, with the greater mass flow rates, the kinetic energy of the water must be spread over more particles. Therefore, the depth of cut goes down with the increased mass flow rate.



p = 275
MPa
u = 6.6

Fig. 4. Abrasive mass flow rate versus depth of cut

3.3 Effect of Traverse Speed on Depth of Cut

Traverse speed is the advance rate of nozzle on horizontal plane per unit time during cutting operation. Results indicate that increase of traverse speed decreases the depth of cut within the operating range selected, by keeping the other parameters considered in this study as constant. The longer the abrasive waterjet stays at a particular location, the deeper the cut will be because the stream of abrasive particles has more time to erode the material. This effect is due to two reasons. First the longer the dwell time the greater the number of impacting abrasive particles hit the material and the greater the micro damage, which starts the erosion process.

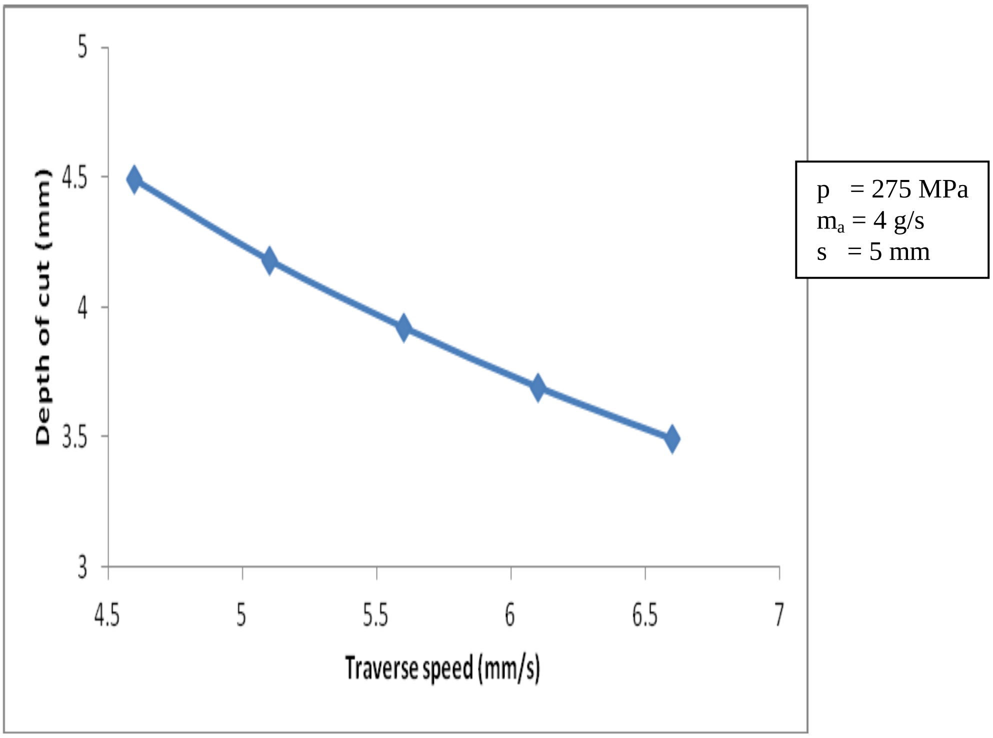
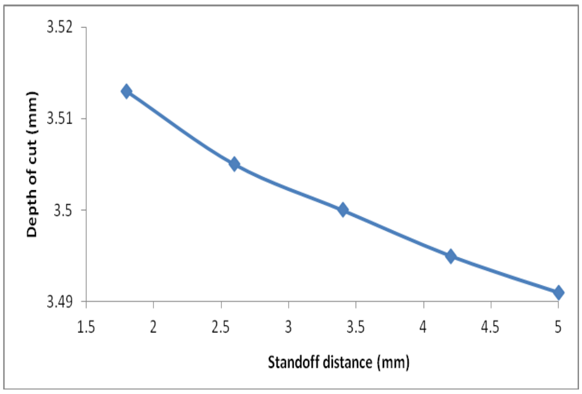


Fig. 5. Traverse speed versus depth of cut

Secondly, the water from the jet does have a tendency to get into the micro cracks and because of the resulting hydrodynamic pressure, the crack growth results. When the micro cracks grow and connect, the included material will break loose from the parent material and the depth of cut increases. For this reason, it seems reasonable to expect an inverse relationship between the traverse speed and the depth of cut as shown in fig. 5.

3.4 Effect of Standoff distance on Depth of Cut

Standoff distance is the distance between the nozzle and the work piece during cutting operation. If we keep other operational parameters constant, when standoff distance increases, depth of cut decreases as shown in fig. 6. However standoff distance on depth of cut is not much influential when compared to the other parameters considered in this study.

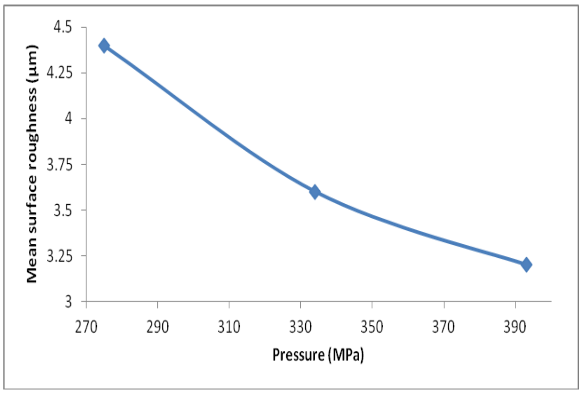


p = 275 MPa
m_a = 4 g/s
u = 6.6 mm/s

Fig. 6. Standoff distance versus depth of cut

3.5 Effect of Water Pressure on Surface Roughness

The influence of water pressure on the surface roughness is shown in fig. 7. Jet pressure plays an important role in surface finish. As the jet pressure increases, surface becomes smoother. With increase in jet pressure, brittle abrasives break down into smaller ones. As a result of reduction of size of the abrasives the surface becomes smoother. Again, due to increase in jet pressure, the kinetic energy of the particles increases which results in smoother machined surface.



m_a = 4 g/s
u = 6.6 mm/s
s = 5 mm

Fig. 7 Water pressure versus surface roughness

3.6 Effect of Mass Flow Rate on Surface Roughness

It needs a large number of impacts per unit area under a certain pressure to overcome the bonding strength of any material. With the increase in abrasive flow rate, surface roughness decreases. This is because of more number of impacts and cutting edges available per unit area with a higher abrasive flow rate. Abrasive flow rate determines the number of impacting abrasive particles as well as total kinetic energy available. Therefore, higher abrasive flow rate, higher should be the cutting ability of the jet. But for higher abrasive flow rate, abrasives collide among themselves and loose their kinetic energy. It is evident that the surface is smoother near the jet entrance and gradually the surface roughness increases towards the jet exit. The effect of abrasive mass flow rate on surface roughness is shown in fig. 8.

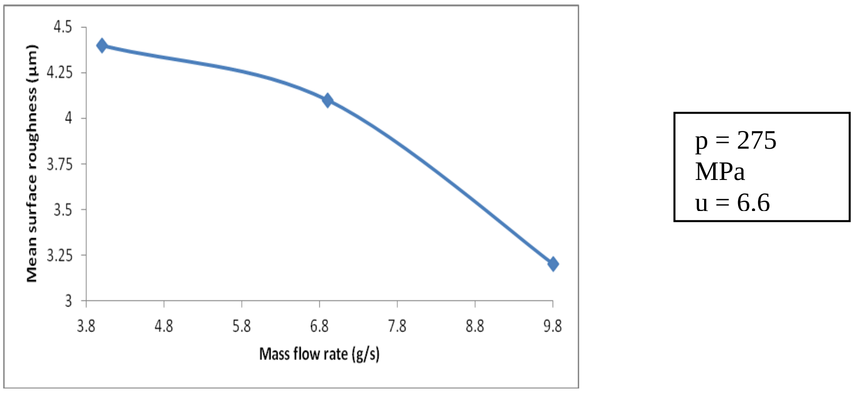


Fig. 8. Abrasive mass flow rate versus surface roughness

3.7 Effect of Traverse Speed on Surface Roughness

Traverse speed didn't show a prominent influence on surface roughness. But with increase in work feed rate the surface roughness increased. This is due to the fact that as the work moves faster, less number of particles are available that pass through a unit area. Therefore, less number of impacts and cutting edges are available per unit area, which results a rougher surface.The relationship between the traverse speed and the surface roughness is shown in fig. 9.

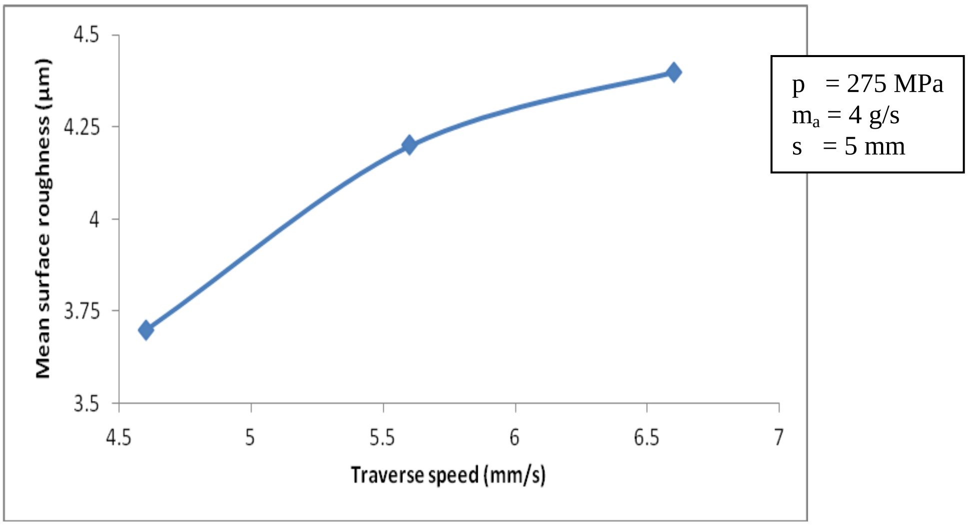


Fig. 9. Traverse speed versus surface roughness

3.8 Effect of Standoff distance on Surface Roughness

Surface roughness increase with increase in standoff distance. This is shown in fig. 10.

The machined surface is smoother near the top of the surface and becomes rougher at greater depths from the top surface.

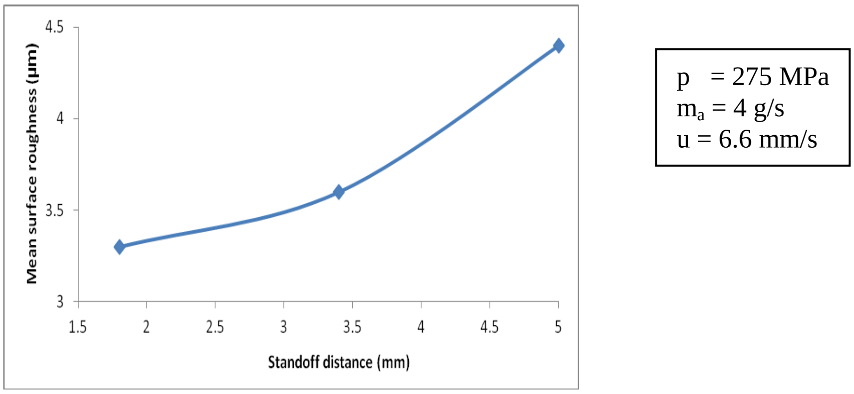


Fig. 10. Standoff distance versus surface roughness

4. EMPIRICAL MODEL FOR DEPTH OF CUT

Mathematical model for the depth of cut is empirically developed based on the experimental data set by using regression analysis technique as shown in (1). This model relate the depth of cut to four process variables, namely water pressure, nozzle traverse speed, nozzle standoff distance and abrasive mass flow rate.

$$D_c = 2.003\times10^4 \times \frac{m_a}{\rho_w d_j u}\times(\frac{p}{E})^{1.903}\times(\frac{s}{d_p})^{0.559}\times(\frac{s\,m_a}{d_p^3\rho_p u})^{-0.565}\times(\frac{\rho_p u^2}{p})^{-0.132} ---(1)$$

Where D_c, d_j, d_p and s are in meters, m_a is in kg/s, u is in m/s, ρ_p and ρ_w are in kg/m^3, p and E are in MPa. The above model is valid for the operating parameters in the following range for practical purposes and machine limitations:

275 MPa < p < 393 MPa; 4.6 mm/s < u < 6.6 mm/s; 1.8 mm < s < 5 mm and 4 g/s < m_a < 9.8 g/s

To facilitate the understanding of the effect of the process parameters, the above equation may be re-arranged as in (2).

$$D_c = 2.003\times10^4 \times \frac{p^{2.035} m_a^{0.435} d_p^{1.136}\rho_p^{0.433}}{E^{1.903}u^{0.699}s^{0.006}\rho_w d_j} ---(2)$$

5. MODEL ASSESSMENT

The above developed model in eq. (2) has been assessed both qualitatively and quantitatively with the experimental results. It is shown that the model predictions are in good agreement with the experimental data with the average deviations of about 4%.

6. CONCLUSION

Experimental investigations have been carried for the depth of cut and surface roughness in abrasive waterjet cutting of kevlar-phenolic composite. The effects of different operational parameters such as: pressure, abrasive mass flow rate, traverse speed and nozzle standoff distance on depth of cut and surface roughness have been investigated.

As a result of this study, it is observed that these operational parameters have direct effect on depth of cut and surface roughness. It has been found that water pressure has the most effect on the depth of cut and surface roughness. An increase in water pressure is associated with an increase in depth of cut but a decrease in surface roughness. These findings indicate that the use of high water pressure is preferred to obtain overall good cutting performance. Depth of cut constantly increases and surface roughness decreases as mass flow rate increases. It is recommended to use more mass flow rate to increase depth of cut and to decrease surface roughness. Among the process parameters considered in this study water pressure and abrasive mass flow rate have the similar effect on depth of cut and surface roughness. As nozzle traverse speed increase, surface roughness increases but depth of cut decreases. This means that low traverse speed should be used to have more depth of cut and surface smoothness but is at the cost of sacrificing productivity. This experimental study has resulted that standoff distance has no apparent effect on depth of cut. Nevertheless, surface smoothness increase as standoff distance decreases. Therefore to achieve an overall cutting performance, low standoff distance should be selected.

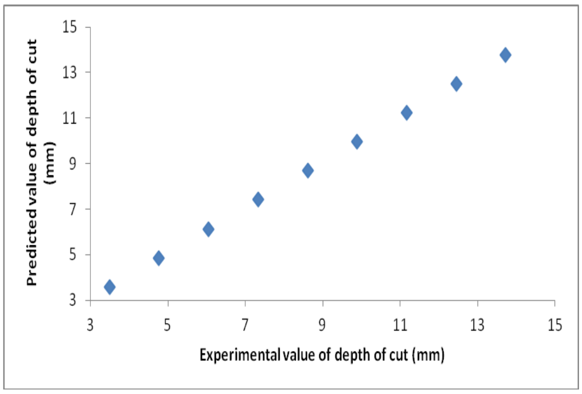


Fig. 11. Comparision of experimental and predicted values of depth of cut

From the experimental results an empirical model for the prediction of depth of cut in AWJC process of kevlar-phenolic composites has been developed using regression analysis. Also verification of the developed model for using it as a practical guideline for selecting the parameters have been found to agree with the experiments. Therefore the need for extensive experimental work in order to select the magnitudes of the most influential abrasive waterjet cutting parameters on depth of cut of kevlar-phenolic composites can be eliminated. However, other cutting performances such as kerf taper combined with the material removal mechanism are needed to establish generic models.

NOMENCLATURE

D_c	depth of cut (mm)
m_a	mass flow rate of abrasive particles (g/s)
ρ_P	density of particle (kg/m^3)
ρ_W	density of water (kg/m^3)
d_j	diameter of jet (mm)
d_p	average diameter of particle (mm)
u	traverse speed of nozzle (mm/s)
p	water pressure (MPa)
E	modulus of elasticity of material (MPa)
s	standoff distance (mm)

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He has published more than 25 papers in National and International Journals and conferences. At present he is guiding 7 Ph.D research scholars in India. He is currently in the position of Head of the Institute in Mahendra Institute of Technology, Tamil Nadu, India.