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A predictive depth of penetration model for abrasive waterjet cutting of polymer matrix composites

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Abstract
A common defective phenomenon in abrasive waterjet (AWJ) cutting of layered materials such as polymer matrix composites is delamination which occurs only when the jet is unable to cut through the workpiece. It is therefore essential to predict the depth of penetration in order to achieve through cuts and to eliminate delamination. A semi-empirical model is developed for predicting the depth of jet penetration in AWJ cutting of polymer matrix composites. The plausibility of the model is then assessed by analysing the predicted trends of this performance measure and by comparing with the experimental results. It is shown that the model gives adequate predictions and can be used for process planning.

Keywords: Waterjet cutting; layered composites; depth of penetration; predictive model

Nomenclature

a_t total depth of jet penetration
d_j jet diameter
C, k, k_1, k_2, k_3, α_1, α_2, α_3 constants
K_e kinetic energy
m_a abrasive mass flow rate
m_w water flow rate
P_w waterjet pressure
U jet traverse rate
V volume of material removed
V_a slurry jet (or particle) velocity
V_j water velocity
W kerf width
ρ_w water density

1. Introduction

Abrasive waterjet (AWJ) cutting, due to its various distinct advantages over the other cutting technologies such as no thermal distortion, high machining versatility, high flexibility and small cutting forces [1], is being increasingly used in various industries. In the past decades, considerable research has been carried out to study this cutting technology from using relatively low to medium water pressures, to high water pressures available since late 1980's. This includes the topographical analysis of machined surfaces and the associated cutting mechanisms [2,3], as well as the analysis of kerf geometrical features to optimize the cutting processes [3,4]. It has been reported [5] that AWJ cutting can be described as an erosive process by abrasive particles entrained by a stream of ultrahigh pressure waterjet, and the

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erosive process for pure ductile and pure brittle materials have been found to exhibit similar mechanisms to those in the conventional erosive process [6,7]. In addition, a considerable amount of work has been reported on the modeling studies for brittle and ductile materials based on the erosive theory [2], energy approach [3,8] and fracture mechanics [9], although these studies essentially use semi-empirical approach with the constants in the models determined by cutting tests. Studies have also been reported on enhancing the AWJ cutting performance using techniques such as nozzle oscillation [8] and increasing machine capability [10].

By contrast, it seems that the research has been limited to "hard" or "difficult-to-cut" materials with little attention paid to AWJ cutting of "soft" materials such as polymer matrix composites. A study by the present author on the AWJ cutting of polymer matrix composites has shown that the kerf generated exhibits similar characteristics to those on ductile and brittle materials [11]. It is found that AWJ can produce good quality cuts with very high cutting rate. However, delamination defects may occur for some of the non-through cuts. If the cutting parameters can be selected such that the abrasive waterjet can penetrate the workpiece, kerfs with no delamination can be achieved. This paper presents a predictive depth of penetration model for AWJ cutting of polymer matrix composites. The plausibility and the predictive capability of the model is then assessed by analyzing the trends of the predicted depths of penetration and by comparing with the experimental results.

2. Predictive depth of penetration model

The erosive or cutting process for polymer matrix composites under an AWJ has been found to possess a unique mechanism [11,12]. The cutting of the matrix (resin) exhibits a combination of the erosive mechanisms for ductile and brittle materials, while the cutting of the fibers is predominated by shearing and pulling-out processes dependent on the level of the particle energy. Thus, it does not seem to be appropriate to use either the erosion theories [6,7] or the fracture mechanics approach to model the AWJ cutting process for polymer matrix composites. Consequently, an energy approach is used in the development of the depth of penetration model. It is assumed that the rate of material removed from the workpiece is proportional to the kinetic energy of the abrasive particles, i.e.

$$\frac{dV}{dt} = C\frac{dK_e}{dt} \tag{1}$$

where C is a proportionality factor to allow for the variation in material properties, and the other symbols are as defined in the Nomenclature. The material removal rate can be calculated by multiplying the cross-sectional area of the cutting front by the jet traverse rate U. By ignoring the variation of the kerf width along the depth, it can be given by

$$\frac{dV}{dt} = a_t W U \tag{2}$$

where W is the kerf width. It has been found [11] that W is not only dependent on the jet or water pressure, but also the jet diameter, nozzle traverse rate and abrasive mass flow rate. In general, kerf width is related to the "effective" jet diameter within which the particle energy is above the threshold value for removing the target material, this is in turn dependent on the jet energy (or water pressure) and energy distribution within the jet as well as the material destructive energy. Further, kerf width increases to some extent with an increase in the abrasive mass flow rate; however this increase is not in a linear form since the cutting efficiency of individual particles decreases with an increase in the mass flow rate owing to the increased interference between particles. Kerf width is also affected by the nozzle traverse rate stemming from the number of particles striking on a given exposed surface. However, this effect is not quite hyperbolic as a result of the effect of traverse rate on the energy loss (due to damping and friction on the jet) in the overall cutting process [13]. Thus, the kerf width may be expressed in the following empirical form:

$$W = k_1 d_j \frac{m_a^{\alpha_1} P_w^{\alpha_2}}{U^{\alpha_3}} \tag{3}$$

The rate of the kinetic energy of the abrasive particles in the jet stream can be expressed as

$$\frac{dK_e}{dt} = \frac{1}{2} m_a V_a^2 \tag{4}$$

Consequently, Eq. (1) becomes

$$k_1 a_t d_j m_a^{\alpha_1} P_w^{\alpha_2} U^{1-\alpha_3} = \tfrac{1}{2} C m_a V_a^2 \tag{5}$$

or

$$a_t = \frac{C m_a^{1-\alpha_1} V_a^2}{2 k_1 d_j P_w^{\alpha_2} U^{1-\alpha_3}} \tag{6}$$

The velocity of the particles V_a is assumed to be equal to the velocity of the slurry and can be approximated by the momentum transfer equation considering the incoming waterjet and the exit slurry jet momentum:

$$m_w V_j = k_2 (m_w + m_a) V_a \tag{7}$$

where k_2 is a factor allowing for momentum transfer efficiency. Thus, the velocity of the slurry jet can be found to be

$$V_a = k_2 \left(\frac{m_w}{m_w + m_a} \right) V_j \tag{8}$$

Solving Eq. (8) has resulted in a very complex V_a equation so that an attempt has been made to simplify this equation. It is assumed that the mass of the abrasives is only a very small proportion of the mass of the abrasive and water slurry so that the ratio term in the bracket is approximately a constant for a given water pressure and system configuration (i.e. the m_a variation is ignored). Thus,

$$V_a = k_2 k_3 V_j \tag{9}$$

For the cutting conditions given in the next section, this simplification only results in an error of less than 4% and an even smaller error may be expected for the final depth of penetration.

By assuming that the water is incompressible and the frictional loss in the system is negligible, the velocity of the waterjet may be approximated by using Bernoulli's equation and is given by

$$V_j = \left(2P_w / \rho_w\right)^{0.5} \tag{10}$$

Thus, substituting Eqs. (9) and (10) into Eq. (6) gives

$$a_t = \frac{C(k_2 k_3)^2 m_a^{1-\alpha_1} P_w^{1-\alpha_2}}{k_1 d_j U^{1-\alpha_3} \rho_w} \tag{11}$$

or

$$a_t = k \frac{m_a^{1-\alpha_1} P_w^{1-\alpha_2}}{d_j U^{1-\alpha_3} \rho_w} \tag{12}$$

where *k* generalizes all the constants in Eq. (11) and can be determined from the cutting tests for the work material under consideration.

3. Experimental work

In order to obtain the empirical constants in the depth of penetration model and to assess its plausibility, a set of experiments has been conducted on a Flow Systems International waterjet cutter to cut 300x300 mm test specimens of 16 mm thick. The waterjet 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. 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. This material finds extensive application in various industries and its major mechanical and physical properties are: impact strength = 11 MPa, compressive strength (flatwise) = 290 MPa, compressive strength (edgewise) = 210 MPa, shear strength = 100 MPa, and maximum working temperature = 130°C.

While AWJ cutting involves a large number of variables, only the major and easy-to-adjust dynamic variables were considered in the present study. These were the water pressure, the nozzle traverse speed or rate, and the abrasive mass flow rate. The water pressures were selected within the common ranges of application and the equipment limit, i.e. at 230, 280, 330 and 380 MPa. The traverse speeds tested were 0.0067, 0.0167, 0.0267 and 0.0367 m/s (or 400, 1000, 1600 and 2200 mm/min) and the abrasive mass flow rates were (0.017, 0.033, 0.050 and 0.067 kg/s (or 0.1, 0.2, 0.3 and 0.4 kg/min). For these tests, a 4 mm stand-off distance between the nozzle and the workpiece was used. It should be noted that the selection of the stand-off distance was to prevent contact between the nozzle and the specimen as delamination may occur. Thus, Based on four-level three-factor full factorial experimental design, 64 straight cuts of 60 mm long have been produced for evaluation.

For all the tests, the other parameters were kept constant using the system standard configuration, i.e. the orifice diameter = 0.33 mm, the mixing tube diameter = 1.02 mm, the length of mixing tube = 76.2 mm. The abrasives used was 80 mesh almandine garnet sand.

For each cut, the depth of jet penetration was obtained from the specimens. Based on the experimental data, the constants *k*, α_1, α_2 and α_3 in Eq. (12) have been statistically determined at a 95% confidence level and the predictive equation for the material under investigation becomes

$$a_t = 12.406 \frac{m_a^{0.429} P_w^{1.215}}{d_j U^{0.668} \rho_w} \tag{13}$$

where a_t is in mm (or 10^{-3}m), m_a is in kg/s, P_w is in MPa (or 10^6Pa), d_j is in mm (or 10^{-3}m), U is in m/s and ρ_w is in kg/m^3.

4. Assessment of the model

In order to check the adequacy of the model, a comparison has been carried out based on the percentage deviation of the model predicted value with respect to the corresponding experimental result. This is shown in the histogram in Fig. 1. This comparison shows that the model's prediction yields an average percentage deviation of 0.59% with the standard deviation of 3.37%. A statistical analysis has found the coefficient of determination (R^2) to be 0.94. Consequently, this model can give adequate prediction of the depth of jet penetration for the test conditions in this study.

The generality and plausibility of the model is further studied by examining the predicted trends with respect to the process parameters, as shown in Fig. 2, where the solid lines represent the predicted trends by the model, while the symbols represent the experimental data which are plotted for comparison. Again, the predicted and experimental values are in good agreement both in terms of the trends and the quantitative values. In general, the depth of penetration increases with the water pressure and abrasive mass flow rate, but decreases as the jet traverse rate increases. This is consistent with the earlier studies [11].

Figs. 2(a) and (b) show that the depth of penetration decreases with an increase in jet traverse rate in an exponential form. This is attributed to a number of factors. Firstly, 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. Secondly, Momber et al. [13] have found that the damping and friction effect on the jet decreases as the jet exposure time decreases (or the jet traverse rate increases). Thus, an increase in the jet traverse speed will reduce the energy loss of the particles and improve the material removal rate. Thirdly, it has been reported [11] 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.

The trend of depth of penetration with respect to the water pressure is shown in Figs. 2 (c) and (d). In general, the depth of penetration increases with water pressure, as more energy will be able to remove more material. Studies [11] have found that this increase is almost in a linear form initially; as the water pressure further increases, the rate of increase declines. 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 according to Eq. (2). In addition, particle fragmentation increases with water pressure, which reduces the cutting effectiveness of the particles. The developed model appears to be able to represent this trend very well at water pressure of up to 330 MPa. It also shows a good agreement with the experiment at the water pressure of 380 MPa though in some cases it overestimates the depth of penetration. Thus, the model can be considered to be valid for water pressure of up to 380 MPa, the pressure limit in most systems used in practice.

Figs 2 (e) and (f) show that the depth of penetration increases with the abrasive mass flow rate; however, the rate of increase decreases as the abrasive flow rate increases. This trend is in line with the earlier findings in many investigations [4,8,11], 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 (according to Eq. (2)) and contributes to the reduced rate of increase in the depth of penetration. Consequently, the model's prediction is plausible and reasonable in representing the cutting process both qualitatively and quantitatively.

5. Conclusions

A predictive depth of penetration model for AWJ cutting of polymer matrix composites has been developed using an energy approach. Based on the test data, the model has been shown to be able to provide adequate estimation of this cutting performance measure and may be used for process control to eliminate the delamination defects that can occur in layered material processing. An analysis of the predicted trends for the depth of penetration and a numerical comparison between the predicted and experimental results have confirmed the plausibility of the model.

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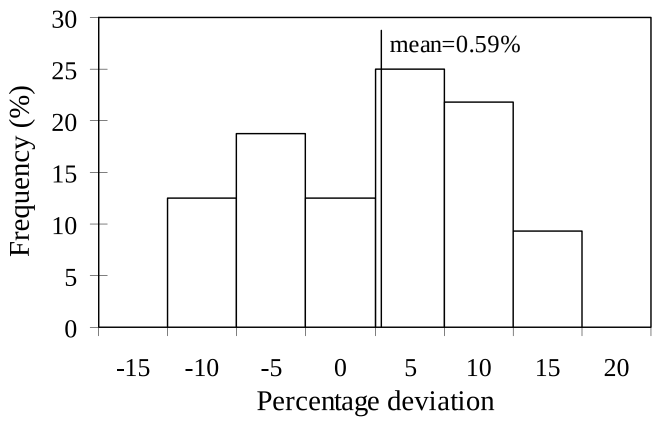

Fig. 1. Percentage deviations of model prediction from the experimental a_t values.

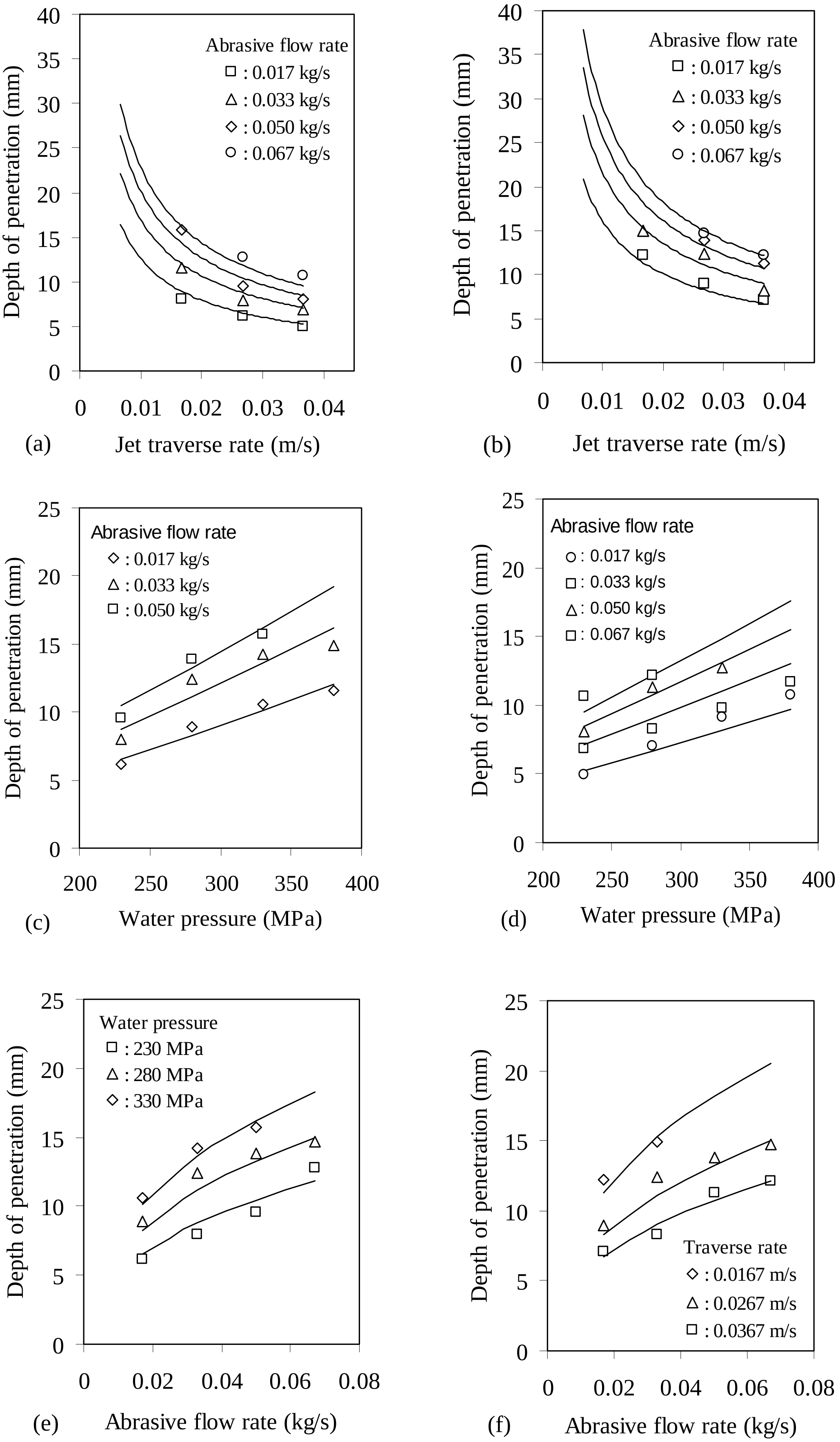

Fig. 2. Predicted trends of depth of penetration: (a) P_w = 230 MPa, (b) P_w = 280 MPa, (c) U = 0.0267 m/s, (d) U = 0.0367 m/s, (e) U = 0.0267 m/s, (f) P_w = 280 MPa.