INFLUENCE OF ABRASIVE WATERJET CUTTING CONDITIONS ON DEPTH OF CUT OF MILD STEEL

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ABSTRACT

Abrasive waterjet cutting is superior to many other non-traditional machining processes in processing variety of materials, particularly difficult-to-cut materials and has found extensive applications in industry. This paper assesses the influence of process parameters on depth of cut which is an important cutting performance measure in abrasive waterjet cutting of mild steel. Experiments were conducted in varying water pressure, nozzle traverse speed, abrasive mass flow rate and standoff distance for cutting mild steel using abrasive waterjet cutting process. The effects of these parameters on depth of cut 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 mild steel 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.

Keywords—abrasive waterjet, depth of cut, abrasive mass flow rate, mild steel, predictive model, regression analysis, standoff distance, traverse speed.

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 mild steel. More work is required to fully understand the influence of the important process parameters on depth of cut of mild steel. This paper assesses the influence of abrasive waterjet cutting process parameters on depth of cut of mild steel. An empirical model for the prediction of depth of cut in AWJC process of mild steel is developed using regression analysis. The model is then experimentally verified when cutting mild steel within the practical range of process variables.

II. EXPERIMENTAL WORK

A. Material

Mild steel is the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many applications. It is often used when large quantities of steel are needed, for example as structural steel. It is the most versatile form of steel. Mild steel - Grade 250 plates were used as the specimens in this study. The dimensions of these mild steel plates were 150 x 100 x 60 mm. It has the following properties: Density = 7.85 g/cm$^3$; Modulus of elasticity = 210,000 MPa.

B. 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 abrasive waterjet cutting equipment used for the experiments is shown in figure 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 figure 2.

C. 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]. 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, was selected to construct the design of experiment. When selecting the levels and ranges of these process variables, the machine system limitations and the ranges of practical applications were considered.

Table 1 Levels of parameters used in experiment

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pressure</td>
<td>MPa</td>
<td>270</td>
<td>335</td>
<td>400</td>
</tr>
<tr>
<td>Traverse speed</td>
<td>mm/s</td>
<td>0.42</td>
<td>1.46</td>
<td>2.5</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>g/s</td>
<td>8</td>
<td>11.5</td>
<td>15</td>
</tr>
<tr>
<td>Standoff distance</td>
<td>mm</td>
<td>1.8</td>
<td>3.4</td>
<td>5</td>
</tr>
</tbody>
</table>

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/m³) and average diameter of abrasive particles (0.18 mm). 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.

D. Data Collection

For each experiment, the machining parameters were set to the pre-defined levels. All machining procedures were done using a single pass cutting. The abrasives were delivered using compressed air from a hopper to the mixing chamber and were regulated using a metering disc. The abrasive flow rates were calibrated by measuring the time spent for a certain weight of abrasives to be completely consumed in the hopper. The supply pressure was manually controlled using a pressure gauge. The standoff distance is controlled through the controller in the operator control stand. The traverse speed and supply of abrasives were automatically controlled by the abrasive waterjet system programmed by NC code. The depth of cut for each test was measured by using a “SigmaScope 500” profile projector at a magnification of 10 times. With this magnification together with a large shadow screen on the projector and precision digital readouts, the measurement accuracy was expected to be more than adequate for the purpose of this study. For each cut, at least three measures were made and the average was taken as the final reading.

III. Experimental results

The effects of process parameters on depth of cut during cutting of mild steel are shown in figure 3.
Figure 3 (a) shows the effect of water pressure on depth of cut. In this experimental study, mass flow rate, traverse speed and standoff distance were kept 8 g/s, 0.42 mm/s and 5 mm respectively. The depth of cut gradually increases when the water pressure increases from 270 MPa to 390 MPa. Figure 3 (b) shows the trend in change in depth of cut with increase in mass flow rate. During the cutting process the water pressure was 270 MPa, traverse speed was 0.42 mm/s and standoff distance was 5 mm. As the mass flow rate is increased from 8 g/s to 15 g/s, the depth of cut is also increased. Figure 3 (c) shows the relationship between traverse speed and depth of cut. The other three process parameters namely; mass flow rate, water pressure and standoff distance were kept constant as 8 g/s, 270 MPa and 5 mm respectively. The general trend of the curve shows that increase in traverse speed from 0.42 mm/s to 2.5 mm/s results in decrease in depth of cut. Figure 3 (d) shows the relationship between standoff distance ranging from 1.8 mm to 5 mm and depth of cut. During the cutting process mass flow rate, water pressure and traverse speed were 8 g/s, 270 MPa and 0.42 mm/s respectively. There is a slight decrease in depth cut is seen when the standoff distance is increased.
IV. DISCUSSION ON EXPERIMENTAL RESULTS

By analyzing the experimental data of all the selected materials, it has been found that the optimum selection of the four basic parameters, i.e., water pressure, abrasive mass flow rate, nozzle traverse speed and nozzle standoff distance are very important on controlling process output such as depth of cut. Results show that the water pressure and abrasive mass flow rate positively affect the depth of cut in that an increase in these variables results in an increase in depth of cut, while standoff distance and nozzle traverse speed adversely influence the depth of cut, i.e. the increase in these two parameters is associated with a decrease in the depth of cut. Therefore it is recommended that a combination of high water pressure, more abrasive mass flow rate, low traverse speed and short standoff distance be used to produce more depth of cut. In general, the effect of water pressure and mass flow rate is pronounced higher compared to traverse speed with the standoff distance having minimal effect.

A. Water Pressure on Depth of Cut

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. Abrasive particles gain higher velocity, and hence higher energy, under an increased water pressure and as a result, removing more materials. Increasing the water pressure is a most effective method of increasing the cutting ability. The main reason for this is that the transfer rate of momentum and the velocity from the jet to the particles at the nozzle exit is increased in accordance with the water pressure, thus resulting in increased impact energy and accordingly the depth of cut.

B. Abrasive Mass Flow Rate on Depth of Cut

Increase in abrasive mass flow rate also increases the depth of cut. 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.

C. 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. 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.

D. Standoff Distance on Depth of Cut

Standoff distance is the distance between the nozzle and the work piece during cutting operation. The study showed that width of cut increases as the stand-off distance of the nozzle from the work is increased which is due to divergence shape of the abrasive water-jet. If we keep other operational parameters constant, when standoff distance increases, depth of cut decreases. However standoff distance on depth of cut is not much influential when compared to the other parameters considered in this study. The decrease of the depth of cut with an increase in standoff distance, although in a small rate, may be attributed to the fact that the particle velocity is reduced as the jet flows away from the nozzle when the standoff distance is increased. This results in less material to be removed and a reduced depth of cut.

V. Predictive Model for Depth of Cut

The general model for cutting mild steel in the straight-slit cutting mode is developed by dimensional analysis technique. The constants in the model were obtained using regression analysis of the experimental data using Data Fit 7.0 software 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.

\[
D_c = 461 \frac{m_a}{\rho_p d_j u} \times \left( \frac{p}{E} \right)^{0.207} \times \left( \frac{s}{d_p} \right)^{0.873} \times \left( \frac{s m_a}{d_p \rho_p u} \right)^{-0.881} \times \left( \frac{p u^2}{\rho} \right)^{-0.014}
\]  

where \( D_c, d_j, d_p, \) and \( s \) are in meters, \( m_a \) is in kg/s, \( u \) is in m/s, \( \rho_p \) and \( \rho_w \) are in kg/m³, \( p \) and \( E \) are in MPa. The above model is valid for the operating parameters in the following range for practical purposes and machine limitations:

- 270 MPa \( < p < 400 \) MPa
- 0.42 mm/s \( < u < 2.5 \) mm/s
- 1.8 mm \( < s < 5 \) mm
- 8 g/s \( < m_a < 15 \) g/s

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

\[
D_c = 461 \times \frac{p^{0.311}}{E^{0.297}} \times \frac{m_a^{0.119}}{u^{0.147}} \times \frac{d_j^{1.77}}{d_p^{0.008}} \times \frac{\rho_p^{0.867}}{\rho_w d_j}
\]  

For the material under consideration, it can be given as in (3).
The results predicted from above model in Equation (3) are compared with experimental measurements. Figure 4 shows the comparison of predicted and experimental values of depth of cut where the line indicates the ideal case. It is shown that the models predictions are in good agreement with the experimental data with the deviations of about 0.2% to 2%.

\[ D_c = 12.106 \times \frac{p^{0.311} m_a^{0.119} d_p^{1.77} \rho_p^{0.867}}{u^{0.147} s^{0.008} \rho_a d_j} \]  

(3)

Figure 4 Comparision of predicted and experimental values of depth of cut for mild steel

VI. Conclusions

Experimental investigations have been carried for the depth of cut in abrasive waterjet cutting of mild steel. The effects of different operational parameters such as: pressure, abrasive mass flow rate, traverse speed and nozzle standoff distance on depth of cut have been investigated. As a result of this study, it is observed that these operational parameters have direct effect on depth of cut. It has been found that water pressure has the most effect on the depth of cut. An increase in water pressure is associated with an increase in depth of cut. These findings indicate that the use of high water pressure is preferred to obtain overall good cutting performance. Depth of cut constantly increases as mass flow rate increases. It is recommended to use more mass flow rate to increase depth of cut. Among the process parameters considered in this study water pressure and abrasive mass flow rate have the similar effect on depth of cut. As nozzle traverse speed increase, depth of cut decreases. This means that low traverse speed should be used to have more depth of cut but is at the cost of sacrificing productivity. This experimental study has resulted that standoff distance has no apparent effect on depth of cut.

From the experimental results an empirical model for the prediction of depth of cut in AWJC process of mild steel has been developed using regression analysis. Also verification of the developed model for using it as a practical guideline for selecting the parameters has been found to agree with the experiments.
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)

REFERENCES


