MODELING AND ANALYSIS OF DEPTH OF CUT IN ABRASIVE WATERJET CUTTING OF TITANIUM

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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 which is an important cutting performance measure in abrasive waterjet cutting of titanium. Experiments were conducted in varying water pressure, nozzle traverse speed, abrasive mass flow rate and standoff distance for cutting titanium using abrasive waterjet cutting process. In order to correctly select the process parameters, an empirical model for the prediction of depth of cut in abrasive waterjet cutting of titanium is developed using regression analysis. The effects of these parameters on depth of cut have been studied based on the experimental results. 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; garnet; titanium; empirical model; 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, aluminium etc. [14-16]. But no such models have been developed for titanium. More work is required to fully understand the influence of the important process parameters on depth of cut of titanium. This paper assesses the influence of abrasive waterjet cutting process parameters on depth of cut of titanium. An empirical model for the prediction of depth of cut in AWJC process of titanium is developed using regression analysis. The model is then experimentally verified when cutting titanium within the practical range of process variables.

2. EXPERIMENTAL WORK

2.1. Material

Titanium has a low density and is a strong, lustrous, corrosion resistant transition metal with a silver colour. It is an important pigment for industrial, domestic and artistic applications. Due to excellent resistance to sea water, it is used to make propeller shafts and rigging and in the heat exchangers of desalination plants and in heater-chillers for salt water aquariums. Owing to its high stiffness it is favoured in place of steel in high performance model sailplane wing join rods.

Commercially pure titanium (ASTM Grade 3) plates of thickness 75 mm were used as the specimens. It has the following mechanical properties: Density = 4500 kg/m$^3$; Modulus of elasticity = 103,400 MPa; Shear Modulus = 45,000 MPa.

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. Figure 1 shows the schematic of the abrasive waterjet cutting process. 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. A 0.35 mm diameter sapphire orifice was used to transform the high-pressure water into a collimated jet, with a carbide nozzle of 1.05 mm diameter to form an abrasive waterjet. Throughout the experiments, the nozzle was frequently checked and replaced with a new one whenever the nozzle was worn out significantly. The abrasives used were 80 mesh garnet particles with the average diameter of 0.18 mm and density of 4100 kg/m$^3$. 


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. Experimental procedures

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. The four variables in AWJC which was varied are as follows: water pressure 270 MPa to 400 MPa, nozzle traverse speed from 0.5 mm/s to 20 mm/s, standoff distance 1.8 mm to 5 mm and mass flow rate of abrasive particles from 8 g/s to 15 g/s. Readings were taken with various combinations of process parameters to gather the required data. Three different readings were taken at each sample and the average readings were calculated as to minimize the error.

3. EMPIRICAL MODEL FOR DEPTH OF CUT

Based on the experimental data set, mathematical model for the depth of cut is empirically developed by using regression analysis technique as shown in Eq. (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.

$$D_c = 62 \times \frac{m_a}{\rho_w} d_j \times \left( \frac{p}{E} \right)^{1.229} \times \left( \frac{s}{d_p} \right)^{0.431} \times \left( \frac{sm_a}{d_p^3 \rho_p u} \right)^{-0.437} \times \left( \frac{\rho_p u^2}{p} \right)^{-0.159}$$  \hspace{1cm} (1)

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/m$^3$ and $p$ 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
- 0.5 mm/s < $u$ < 20 mm/s
- 1.8 mm < $s$ < 5 mm
and
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 below:

\[ D_c = 6.2 \times \frac{p \cdot 1.388 \cdot m_a \cdot 0.563 \cdot d_p \cdot 0.88 \cdot \rho_p \cdot 0.278}{u \cdot 0.881 \cdot s \cdot 0.006 \cdot \rho_w \cdot d_j} - - - (2) \]

For the material under consideration, it can be given by

\[ D_c = 4.261 \times 10^{-5} \times \frac{p \cdot 1.388 \cdot m_a \cdot 0.563 \cdot d_p \cdot 0.88 \cdot \rho_p \cdot 0.278}{u \cdot 0.881 \cdot s \cdot 0.006 \cdot \rho_w \cdot d_j} - - - (3) \]

4. EXPERIMENTAL RESULTS AND DISCUSSION

By analysing 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 the depth of cut are in the same fashion as reported in previous studies for other materials [17-20]. The effect of each of these parameters is studied while keeping the other parameters considered in this study as constant.

4.1. Effect of water pressure on depth of cut

The influence of water pressure on the depth of cut is shown in figure 2. 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.

4.2. Effect of abrasive mass flow rate on depth of cut

Increase in abrasive mass flow rate also increases the depth of cut as shown in figure 3. 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.

**Figure 3.** Effect of abrasive mass flow rate on depth of cut

### 4.3. 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. 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 figure 4.

**Figure 4.** Effect of traverse speed on depth of cut
4.4. 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. This is shown in figure 5. However standoff distance on depth of cut is not much influential when compared to the other parameters considered in this study.

![Figure 5. Effect of standoff distance on depth of cut](image)

5. MODEL ASSESSMENT

The above developed model in eq. (3) 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 5%.

![Figure 6. Comparision of experimental and predicted values of depth of cut](image)

There is reasonable correlation between the experimental and predicted values for depth of cut as shown in figure 6. Thus, it may be stated that the developed model can give adequate predictions for the depth of cut for the conditions considered in this study.
6. CONCLUSION

Experimental investigations have been carried for the depth of cut in abrasive waterjet cutting of titanium. From the experimental results an empirical model for the prediction of depth of cut in AWJC process of titanium has been developed using regression analysis. 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. Verification of the 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)
\(\rho_p\) density of particle (kg/m\(^3\))
\(\rho_w\) 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