ENERGY APPROACH OF THE TAPER AT ABRASIVE WATERJET CUTTING

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Abstract:
Accuracy of abrasive waterjet cutting mainly depends on the form of cutting gap. It is very difficult to keep in hand the taper of the gap and produce almost parallel cut surfaces. There are a lot of parameters having effect on the gap. Results of a complex investigation have not been published in the literature. Taper can be different at different materials and depends on the applied technological parameters (feed rate, pressure, abrasive flow rate etc.). Some results of research work carried out on Ti6Al4V alloy related to the taper of the cutting kerf are explained in this paper, mainly from point of view of the load energy which effect to the surface of the workpiece during abrasive waterjet cutting.

Keywords: abrasive waterjet cutting, form of the cutting gap, Ti6Al4V alloy

1. Introduction

Abrasive waterjet cutting has become popular in the last few years because the heat of cutting does not deform the material and the cut surface is of high quality. The fact that almost every type of material (both soft and hard) may be cut by the method and that the thickness of the cut is less limited, are two of the several important advantages of the abrasive water jet technology.

Comparing to thermal cutting processes, abrasive water jet cutting is a relatively clean technology. Nevertheless it consumes energy, water and abrasive powder. Choosing optimal cutting parameters abrasive water jet methods become a cleaner technology.

When investigating the accuracy of water jet cutting, the process can be characterised by different output parameters, like surface roughness of the machined surface, geometry of cutting gap (depth, width, tapering). Cutting tests were carried out on Ti6Al4V alloy for investigation of accuracy and quality of cutting gap. Some results of these investigations are summarised in this paper.

One of the barriers of the application of waterjet cutting is the accuracy problem of this machining method. Usually the form of the cutting gap causes difficulties in the assurance of the prescribed accuracy.
2. Accuracy and taper of the cutting gap

Accuracy of the waterjet cutting is mainly defined by the form of the cutting gap. Form of the kerf is always complex, cut surfaces are almost never parallel. In most cases the kerf is wider at the upper side then the lower side, where the jet goes out from the workpiece. This complex geometry is usually considered like a taper (Fig. 1.)

![Characteristics of the Taper of the Cutting Gap](image)

\[ w_t: \text{ top kerf width} \quad w_b: \text{ bottom kerf width} \]

**Figure 1. Characteristics of the Taper of the Cutting Gap**

Form of cutting kerf was investigated by several authors [2,3,4]. They noticed that kerf taper has close relation with material thickness and the material characteristics. At cutting depth greater than a given value, no single parameter clearly dominates the cutting gap taper as it is affected by a combination of all the independent variables. Öjmertz [2] establishes that form of the gap depends on a lot of cutting parameters, and gives the characteristics of them (Fig. 2.), but doesn’t give any mathematical relation for expressing their effects.

![Effect of cutting parameters on the form of cutting gap](image)

**Figure 2. Effect of cutting parameters on the form of cutting gap**
Elimination of this tapering error is very difficult because of the great number of effecting cutting parameters, especially if we consider the economy of the machining. Error caused by the taper can be reached the extent of 0.3 mm at cutting through a 10-15 mm thick steel workpiece, which value is a very hard limitation of application of this machining method.

Kerf taper is normally expressed by kerf taper angle as [1]:

\[
\alpha = \arctan\left(\frac{w_t - w_b}{2t_n}\right) \tag{1}
\]

where \(w_t\) is the top kerf width, \(w_b\) is bottom kerf width, \(t_n\) is workpiece thickness for through cuts.

Aim of recent research work was to get connections between the technological parameters and the taper of the kerf in order to find cutting parameters with which we can get parallel cut surface.

3. Cutting experiments on Ti6Al4V alloy

Cutting experiments were done on a two dimensional waterjet cutting machine type INNO PUMP-36HD. Main technical data of the devices are as follows: maximum water pressure: 360 MPa; working space: 2100x1900x210 mm; positioning accuracy: ±0.15 mm; type of abrasive feedrate: vibration; electric power: 30 kW; water flow rate: 1.5 l/min; control system: Messer-Griesheim. Abrasive powder was a Barton Garnet type #80 size powder, which 200μm average size abrasive grains.

Cutting tests were carried out for investigation of kerf taper on AlMgSi0.5 aluminium and Ti6Al4V titanium alloy (Fig. 2).

![Figure 3. Process and result of cut on Ti6Al4V alloy](image)

During the cutting experiments the water pressure (p), the abrasive mass flow rate (ma) and the feedrate (f) were changed in different levels. Applied technological parameters were as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pressure, MPa</td>
<td>300; 330; 360</td>
</tr>
<tr>
<td>Abrasive mass flow rate, g/s</td>
<td>4; 5; 6</td>
</tr>
<tr>
<td>Feedrate, mm/min</td>
<td>10; 20; 30; 40</td>
</tr>
</tbody>
</table>
Other parameters were kept constant as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of abrasive powder</td>
<td>Barton Garnet #80</td>
</tr>
<tr>
<td>Material thickness</td>
<td>25 mm</td>
</tr>
<tr>
<td>Diameter of primary nozzle</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Diameter of abrasive nozzle</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Length of abrasive nozzle</td>
<td>70 mm</td>
</tr>
<tr>
<td>Standoff distance</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

After the cutting experiments upper width \((w_t)\) and lower width \((w_b)\) were measured for determination of the taper of the gap, on Zeiss Discovery V8 stereo microscope (Fig. 4).

**Figure 4. Measurement of width of the gap on Zeiss Discovery V8 stereo microscope**

Taper of the cutting gap can be calculated from the measured upper width \((w_t)\) and lower width \((w_b)\) of the gap according to (1).

4. **Width and taper of the gap**

Measured values of the width of the cutting gap can be seen on Figure 5.

**Figure 5. Width of the gap in function of the feed-rate**
From Fig. 5 it can be seen that the increase of the feed-rate decreases the width of the gap both the upper and lower side of the workpiece. Decrease is higher at the bottom side, which means, that the taper is increasing as function of the feed-rate.

Calculated taper of the cutting gap can be seen on Figure 6.

![Figure 6. Change of the taper angle of the gap in function of the feedrate at different water pressure](image)

The taper angle increases clearly in function of the feed-rate (Fig. 6). It follows from Fig 5 from changing of the width. The effect of the pressure from this figure cannot be defined. Unequivocal effect of the pressure can be seen on Fig 7, where the taper angle is described in function of the water pressure at different feed-rates.

![Figure 7. Change of the taper angle of the cutting kerf in function of the water pressure at different feed-rates](image)
On Fig. 7 there are feed-rate values, on which by increasing the pressure the taper angle is decreasing, but not in all case. This phenomenon could be explained that at high pressures the particles of the jet have enough kinetic energy for material removal even at the bottom side of the cut.

5. Energy of the cutting jet

In order to define the load energy at first the theoretical kinematic energy of the jet at the upper side of the workpiece shall be determined. This theoretical energy can be determined like this [5]:

\[ E_m = \frac{m_a \cdot v^2}{2} \]  

(2)

where \( m_a \): mass of the abrasive, kg
\( v \): speed of the particles in the jet, m/s

Real energy of the jet naturally is not equal with this value – because a lot of other factors effect on it- but clearly is proportional with this.

From the simplified Bernoulli equation for the flowing water particles speed we can get:

\[ v = \sqrt{\frac{2p}{\rho}} \]  

(3)

where: \( p \): applied pressure, Pa
\( \rho \): density of the water (1000 kg/m3)

Mass of the abrasive material can be calculated:

\[ m_a = \dot{m} \cdot t_a \]  

(4)

where \( \dot{m} \): abrasive mass flow rate, kg/s;
\( t_a \): loading time, s

Considering that the loading time:

\[ t_a = \frac{d}{f} \]  

(5)

where \( d \): diameter of abrasive nozzle, m
\( f \): feed-rate of the head, m/s
From (2)-(5) we get:

\[ E_m = \frac{\dot{m} \cdot d \cdot p}{\rho \cdot f} \]  \hspace{1cm} (6)

This theoretical value of the waterjet energy can be defined for all of applied cutting test parameters. Theoretical value of the waterjet energy can be calculated.

Figure 8 shows the change of the top and bottom width of the kerf as function of the theoretical load energy calculated in (6). An interesting connection can be recognised between the load energy and the width of the kerf.

On the base of Fig 8 it can be said that taper of the cutting gap – i.e. accuracy of waterjet cutting – mainly depends on the load energy of the cutting jet and the material of the workpiece. From the figure directly can be read the energy value, with which we can get parallel machined surfaces (in case of this Ti6Al4V alloy now it is about 10 J load energy). This point is at the section of two lines. At this point the upper and lower width of the gap are equal, i.e. the surfaces of the gap are parallel [6].

The same load energy of course can be adjusted with different combinations of technological parameters, so the user has the possibility for choosing the most economical parameter combination. This usually means the choice of pressure and abrasive flow related to the maximum possible value of the feed-rate.
6. Conclusions of the research work

As summary of the results my research work the following statements can be drawn up:

- Accuracy of the waterjet cutting is mainly defined by the extent and form of cutting gap.
- Form of the cutting gap is always taper, direction of the taper depends on the target material. At metals taper is decreasing up-to-down, ie. the gap is wider at the upper side then the lower. For soft materials the orientation can be divergent as well.
- Width of the cutting gap depends on the technological parameters, but control of it has many difficulties. Results, published in the literature are not always complete in this field, they have sometimes contradictions.
- The feed-rate \( f \) clearly increases the taper angle. The effect of the water pressure \( p \) and the abrasive mass flow rate \( m_a \) are not unequivocal.
- On base of accomplished research work can be established, that taper of the gap mainly depends on the load energy of the jet, and can be controlled with it.
- At 25 mm thick Ti6Al4V alloy the parallel cut was reached about at 10 J load energy.

Generally it can be underscored, that parallel cut can be reached theoretically in all cases of cut, when the top and the bottom width of the kerf are equal so parallel cut can be achieved through an appropriate choice of the technological parameters. At given load energy for economical cut the pressure and the abrasive flow should be chosen for the maximum possible feed-rate.

7. Acknowledgement

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References


