Effect of Slurry Temperature on Kerf Taper Angle in Abrasive Water Jet Machining

Vandana Jain, and Puneet Tandon

Abstract—Abrasive water jet machining is categorized under modern machining process because of its capability to machine the different shape and materials. It uses the high pressurized mixture of air, abrasive and water particles to cut the work piece. Here, high pressure water jet accelerates the abrasive particles. The current research work presents the experimental investigation of the use of slurry in combination with abrasive and water to improve the kerf characteristics. It also shows the effect of slurry temperature on the taper angle of walls and kerf taper angle.

Keywords—Abrasive water jet machining, Abrasive water slurry jet machining, Kerf taper angle and Work piece inclination angle.

I. INTRODUCTION

ABRASIVE water jet is a more recent and rapidly growing machining process. Its flexibility, great advantages and grasp over a wide range of material make it easily adaptable for different cutting operations. Its applications have been spread in various fields such as medical, aerospace industry, automobile industry, etc. especially for customized parts production. It uses an ultra high pressurized jet of water and abrasive particles to cut the material through the erosion process [1] and micro chipping processes. In the last two decades, this technology is passed through the several advancements. These advancements results in the development of multi axis abrasive water jet machining, hybrid abrasive water jet machining processes, ice blast machining, cryogenic assisted machining, use of slurry (abrasive water slurry jet machining) in combination with water to increase process characteristics [2], etc.

Till the date, a lot of work has been done to improve and estimate the actual cutting characteristics. D.K. Shanmugam et al [3] introduced a unique technique to tilt the nozzle, i.e. compensation technique for reducing the kerf taper angle in abrasive water jet milled channel. With this technique taper angle can be reduced up to 0°. He developed a model for predicting the kerf taper angle by using dynamic analysis approach as well as shown that the kerf taper decrease linearly with increase in compensation angle. E. Siores et al [4] explored a new head oscillation technique and concluded that with the head oscillation technique the smooth zone depth is increased by 30% as compared to that without oscillation. Along with this striation drag angle and frequency in the striation zone decreased. A. W. Momber and R. Kovacevic [5] proposed a model to estimate the energy dissipation in work pieces. This model is developed as a function of eroded depth and expressed by a second-order polynomial approximation. Z. Maros [6] presented an experimental study and showed that the “Taper can be different at different materials and depends on the applied technological parameters (feed rate, pressure, abrasive flow rate etc.) with the help of machining on Ti6Al4V alloy. He also showed the effect of various input parameters on kerf and concluded that “Form of the cutting gap is always taper; direction of the taper depends on the target material”. D.K. Shanmugam et al [7] in his study presented an investigation on kerf characteristics in two difficult-to-machine composite materials (epoxy pre-impregnated graphite woven fabric and glass epoxy) and developed a predictive model for kerf taper angle by using energy conservation approach and dimensional analysis technique. After validation of the model he concluded that the kerf taper can be minimized within the allowable range but cannot be completely eliminated. T. Nguyen et al [8] studied the effect of liquid properties on the stability of jet and demonstrated that the jet disintegration is a result of the jet internal disturbances, associated with the fluid properties and the external air friction acting upon the jet surface. Furthermore, on addition of polymer additives jet becomes more stable due to increase in jet cohesion. He developed a model to predict the length of the jet of stable region. Palleda Mahabalesh [9] showcased the effect of different chemicals on taper angle in drilled hole and result of comparison of different chemicals at different concentration was more MMR in presence of chemically active liquids such as acetone and highest MMR was identified in case of abrasive water slurry jet machining and hole taper angle was almost 0° in case of polymer.

Present work explores the effect of slurry temperature on the kerf geometry (kerf taper angle) along with three other variables parameters, i.e. Stand-off distance, slurry viscosity and work piece inclination angle. Design of experiments is supported by MINITAB 14 software and followed by L27 array of Taguchi method.

Vandana Jain, and Puneet Tandon, are with PDPM Indian Institute of Information Technology, Design and Manufacturing, Jabalpur, India.

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II. EXPERIMENTAL SETUP

All the experiments are performed on abrasive water jet machine, designed by OMAX cooperation. This AWJM setup is integrated with direct drive type high pressure pump, which can produce pressure up to 400 MPa. Abrasive is supplied through the gravity feed abrasive hopper, which is attached to the machine setup. Nozzle of the setup is designed in such a way that abrasive is mixed with high pressure water jet in mixing chamber, just before passing through the nozzle tip. Sapphire orifice is here to produce collimating water jet with maximum speed 760 m/s and inside diameter of the nozzle is 0.765 mm.

Available setup is abrasive water jet machining set up. To perform the present work and maintain the slurry temperature, some modifications are carried out in existing setup. A thermally isolated reservoir is attached to machine set up and located at 2.1 meter height. This reservoir is connected to the nozzle through a T-shape joint. Slurry is fed under gravitational force and vacuum; created in the T-shape joint because of high pressure water jet.

Furthermore, the reservoir is made up of pure high-density polyethylene plastic having stuffing of thermally isolative material between the inner and outer walls of container. This stuffing prevents the flow of heat in environment through the container’s wall. It can withstand the slurry of temperature range of 0-100 °C. Schematic representation and experimental setup for controlling the slurry temperature in abrasive water jet machining is shown in Fig. 1 and 2 respectively.

Summary

slurry is prepared with water of temperature of 80-90 °C, to maintain the temperature 30, 50 and 70 °C; it has been kept for some time. Temperature of slurry is maintained manually and measured by non-contact inferred or LASER thermometer. This thermometer is capable of measuring the temperature between (-) 20 to (+) 3000°C.

III. SETUP FOR WORK PIECE INCLINATION ANGLE

Available abrasive water jet machining setup has no facility to incline either work piece or nozzle. For this purpose tilting and swelling vise has been used. It allows the angular moment about two axis, i.e. about X and Z axis while Y axis is fixed. Before performing the experiment, work piece is fixed in vise jaws and ensures that Z axis is set at zero. Angle is provided about Z axis. Fig. 3 shows the setup for swiveling and tilting vise.

IV. EXPERIMENTAL INVESTIGATION

All the experiments are performed on A36 mild steel plate of 10 mm thickness. Technical specifications of work piece are given in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mild Steel A36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of work piece</td>
<td>10 mm</td>
</tr>
<tr>
<td>Yield strength</td>
<td>250 MPa</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>400-550 MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>20.0 %</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>1350 °C</td>
</tr>
</tbody>
</table>

Details of fixed and variable parameters are given in Tables 2 and 3 respectively.
TABLE II
DETAILS OF FIXED PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive type</td>
<td>Garnet</td>
</tr>
<tr>
<td>Abrasive size</td>
<td>Mesh 80</td>
</tr>
<tr>
<td>Abrasive flow rate</td>
<td>0.35 kg/min</td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>0.761 mm</td>
</tr>
<tr>
<td>Slurry material</td>
<td>Gelatin</td>
</tr>
<tr>
<td>Tool offset</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Length of cut</td>
<td>40 mm</td>
</tr>
<tr>
<td>Abrasive index</td>
<td>0.94</td>
</tr>
<tr>
<td>Jet velocity</td>
<td>760 m/s</td>
</tr>
<tr>
<td>Traverse speed</td>
<td>1.18 mm/s</td>
</tr>
<tr>
<td>Pressure</td>
<td>275.79 MPa (40 Ksi)</td>
</tr>
</tbody>
</table>

TABLE III
DETAILS OF VARIABLE PARAMETERS

<table>
<thead>
<tr>
<th>Level</th>
<th>Slurry temperature (°C)</th>
<th>Stand-off distance (mm)</th>
<th>Work piece inclination angle (°)</th>
<th>Slurry Viscosity (N.s/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>1.18</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>1.38</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>1.58</td>
<td>3</td>
<td>18</td>
</tr>
</tbody>
</table>

Experiments are performed to observe the effect of slurry temperature along with some other variable parameters, i.e. slurry viscosity, work piece inclination angle and stand-off distance on kerf taper angle (defined as \(\tan^{-1}\left(\frac{W_u-W_l}{2t}\right)\)), where \(W_u\) is the upper width, \(W_l\) is lower width of the channel and \(t\) is the thickness of the work material) as well as taper of the two individual walls of the kerf. Fig. 6 and 7 demonstrate the relative positions of nozzle releasing AWSJ and workpiece, when the workpiece is not inclined and when the workpiece is inclined at an angle with respect to the machine table / nozzle respectively. Fig. 8 shows the schematic and microscopic images of the wall’s angle.

Cut channels are analyzed with the help of AXIO optical microscope to measure the upper channel width, lower channel width and inclination angle of walls. Principle of microscope is; to use a system of lenses to magnify the images (make: ZEISS) and to analyze the channel and has objective to provide magnified real images. Magnification of optical microscope is 50X with eyepiece magnification 10X and nose piece magnification 5X. Fig. 4 and 5 show the schematic representation of optical microscope and microscopic images. Specimens are washed with plain water in order to make it oil free and dust free before putting on measuring table.
(A) Effect of variable parameters on taper angle of walls

Fig. 9 shows the effect of slurry viscosity on the inclination angle of the two walls, when the work piece is inclined. Taper angle of one wall (here, Wall 1) decreases with increase in viscosity up to a threshold value. Further increase in viscosity, taper angle starts increasing. As per Fig. 9, the second wall (Wall 2) has just the opposite effect as on Wall 1, which has maximum value of the taper angle at viscosity of 10 N.s/m$^2$ while minimum at 18 N.s/m$^2$. This effect is due to jet orientation. As work piece is inclined to the jet i.e. instead of jet hitting the workpiece in the perpendicular direction, it strikes at some angle, one wall would interact more with jet in comparison to the other. The effect on two walls is opposite to each other.

Apart from this, during the experiments it has been observed that at low viscosity there is more flaring of jet, which leads to further increase in kerf taper angle. At high values of viscosity, the pressure requirement also increases to fully develop the jet and for efficient penetration of workpiece, which leads increases in the value of kerf taper angle for Wall 1 and decrease for Wall 2.

During the experiments, it has been observed that as slurry temperature decreases, its viscosity increases. At lower temperature gelatin becomes very sticky (i.e. there is an increase in viscosity) and there is more flaring of jet at higher temperature due to reduced viscosity. Fig. 10 shows the effect of slurry temperature on taper angle of walls. Taper angle for Wall 1 decreases with increase in SOD and it increases for Wall 2 up to a threshold value. After the threshold value, taper angle starts increasing for Wall 1 and decreasing for Wall 2. As per reported literature and experimental observations, at low SOD, AWS jet is not found capable to deliver its whole energy and thus, to completely penetrate the workpiece and at higher values of SOD, there is more flaring of jet.

Fig. 11 illustrates the effect of stand-off-distance (SOD) on the taper of the walls of the workpiece. Taper angle for Wall 1 decreases with increase in SOD and it increases for Wall 2 up to a threshold value. After the threshold value, taper angle starts increasing for Wall 1 and decreasing for Wall 2. As per reported literature and experimental observations, at low SOD, AWS jet is not found capable to deliver its whole energy and thus, to completely penetrate the workpiece and at higher values of SOD, there is more flaring of jet.
Fig. 12 demonstrates the effect of workpiece inclination angle on the taper angle of walls. Taper angle decreases with increase in inclination angle for Wall 1, and has opposite effect on the other wall, i.e. taper angle of Wall 2 increases with workpiece inclination angle. This increasing and decreasing of taper angle is due to the jet orientation. On inclining the work piece, as relative position of jet and work piece change, orientation of kerf formation also changes, which results in opposite effect for Wall 1 and 2.

Effect of variable parameters on kerf taper angle

Fig. 13 presents the effect of slurry viscosity on kerf taper angle. The literature also reports that the jet cohesion and stability increases with increase in slurry viscosity. Due to the improved stability of the jet, it becomes more compact, and there is less flaring of the jet, which reduces the kerf taper angle. Apart from this, jet stability simultaneously affects the depth of cut also [11], which decreases with increase in slurry viscosity. As viscosity increases, the bottom width of kerf decreases and channel width becomes narrower at the bottom. Furthermore, upper width is not that much affected with increase in viscosity. The combined effect from Fig. 13 is observed as increase in kerf taper angle with increase in slurry viscosity.

Fig. 14 demonstrates the effect of temperature on kerf taper angle. As per experimental investigation, it has been observed that the viscosity of slurry is a function of temperature which increases with decrease in temperature. At lower temperature jet posses more stability due to which kerf taper reduces with decrease in temperature.

Fig. 15 showcases the effect of stand-off-distance on kerf taper angle. As per the observations, kerf taper angle has its minimum value at SOD of 2 mm, while it is slightly more at 1 mm and maximum at SOD of 3 mm. After the critical value, with further increase in SOD, jet diameter also increases, which directly affects the upper width of channel. In other words, upper width increases with increase in SOD while lower width decreases, as the velocity of radial component of the jet decreases with increased SOD. The overall effect results in increase in kerf taper angle with increase in SOD after a threshold value.

As per the Fig. 16, taper angle of the kerf decreases with increase in workpiece inclination angle. On inclining the work piece, one wall would be closer to the axial velocity component of the jet velocity in comparison to the other wall and for this wall, the major material removal is due to axial velocity component, while the other wall is primarily eroded due to radial velocity component of the jet. It has been discussed earlier also that axial velocity component is greater than radial component and upper width of the cut is dependent on of the nozzle diameter [10].
VI. COMPARISON OF RESULT

Fig. 17 shows the values of kerf taper at three different temperatures i.e. 30°C, 50 ºC and 70°C. The graph is plotted by separating the results of all the three temperatures. After fitting the best trend line the value of correlation factors are (R²) 0.86, 0.9365 and 0.7058 for 30°C, 50°C and 70°C temperature respectively. These high values of correlation factors show goodness of fit. It is cleared from the Fig. 18, that kerf taper has minimum value at 30°C temperature with correlation value of 0.86. Minimum value of kerf taper at this temperature is 0.3093°. While at 50°C and 70°C temperature, there is not much difference and the minimum values of kerf taper are 0.7192° and 0.6446° for 50 ºC and 70 ºC respectively.

VII. CONCLUSION

After experimental investigation, it is inferred that kerf taper angle depends on viscosity of slurry, which is a function of temperature. Hence, kerf taper can be reduced by lowering the slurry temperature. On analyzing individual walls, it has been found the taper angle of one wall is reduced with inclination angle of work piece while angle of another wall increases due to the jet orientation. For further understanding, it can be concluded that on inclining the work piece one wall interact more with jet and thereby get eroded by axial velocity components of jet while other, with the help of radial component. It is worthy to note that the axial velocity component is greater than radial component.

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