Controlled Experiment on the Cutting Depth of 7050 Aluminium Alloy Machined by High-pressure Abrasive Water Jet and Process Study

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ABSTRACT: As the new type of cutting technology, high pressure abrasive water jet (AWJ) has been used in more fields at present. The article aims at ultralumin material of 7050 aluminium alloy, takes advantage of the existing experiment equipment and adopts the high pressure abrasive water jet technology to conduct cutting experiment. On the basis of experimental data, the cutting experiment model is established; the pressure of jet has influences on the cutting depth of 7050 aluminium alloy material; the target distance and feeding speed of nozzle movement under different cutting conditions are obtained by adopting the method of orthogonal experiment; the prediction model of cutting depth (H) is established by adopting Matlab language and multiple regression analysis method when 7050 aluminium alloy material is machined by high pressure abrasive water jet. Finally, the analytical result of the cutting depth range has shown that the pressure of water jet has the most obvious influence on the cutting depth of aluminium alloy material, while the influence by the feeding speed of water jet ranks the second.

Keywords: high pressure abrasive water jet; cutting; 7050 aluminium alloy; the depth of cutting; orthogonal experiment; process study

1 INTRODUCTION

All kinds of hard and soft materials such as metal, marble, glass and rubber can be machined by the high pressure abrasive water jet (AWJ) technology. When the machining time is short, there is no poisonous gas, machining heat effect and deformation[1]. As the new type of non-traditional machining technology, cutting is the major machining method studying high pressure abrasive water cut because the diameter of machining flow is small (which is in the range of 0.8–1.8mm)[2]. In order to cut high-strength and high-hardness material, it can replace the traditional plasma cutting, laser cutting, wire-electrode cutting and metal saw blade milling processing. What’s more, this technology is more and more widely applied.

Super-strength aluminium alloy which is heat-treatable and reinforced is mainly dominated by Al-Zn-Mg-Cu series (for short of 7xxx series). Its advantages include high strength and hardness, good heat machinability and welding performance, better corrosion resistance and higher tenacity, and it is used for structural material with big bearing[3]. In the super-strength aluminium alloy, 7050 aluminium alloy developed by America ALCOA Company has the performance of very high strength, spalling corrosion resistance and stress corrosion cracking resistance. Meanwhile, owing to the advantages of low density and good breaking tenacity, it is widely used in the field of aerospace and shipbuilding and, it is suitable for manufacturing structural parts[4, 5]. The mechanical property of 7050 aluminium alloy is shown in Table 1[6]. High-pressure abrasive water jet is used for conducting cutting experiment on 7050 aluminium alloy, analyzing the influences on the cutting depth by the target distance and the pressure of the abrasive
water jet and feeding speed and proposing reasonable technology for cutting to provide theory and experi-

Table 1. Mechanical property of 7050 aluminium alloy.

<table>
<thead>
<tr>
<th>Strength of extension σb/MPa</th>
<th>Yield limit σ0.2/MPa</th>
<th>Ductility δ/%</th>
<th>Hardness (HB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥572</td>
<td>≥503</td>
<td>12</td>
<td>150</td>
</tr>
</tbody>
</table>

2 EXPERIMENT ON 7050 ALUMINIUM ALLOY VERTICALLY CUT BY HIGH PRESSURE ABRASIVE WATER JET

2.1 Formation of aluminium alloy scraps

In the process of high pressure abrasive water jet cutting, the flow velocity flowing through the nozzle is two to three times of velocity of sound \(^7\), thereby strong impact force can produce. Meanwhile, abrasive is brought in cutting head mixing chamber through conveying system, and ejected from the abrasive water nozzle after speeding up through high pressure water. Because there are certain corner angles on the abrasive, the abrasive can be used as impact pressure head, and the big impact \(F\) is produced on the surface of aluminium alloy by the abrasive which is driven by high speed water. The central crack and the transverse crack are produced at the front end of the abrasive pressure head. Under continuous impact of abrasive water, , scraps drop from the surface of aluminium alloy when crack continuously expands to the surface of workpiece, and plasticity crack is produced on the cutting surface as well as brittle fracture, so the modes of scraps include plasticity and brittleness.

2.2 Experiment condition

In the process of high-pressure abrasive water jet cutting, there are more than 20 technological parameters influencing machining quality \(^8, 9\). After analysis, the parameters can be divided into different types. One type is intrinsic parameter, such as the radius of water jet nozzle, the length and the radius of sand mixing tube, movement precision of nozzle and abrasive. The parameter is generally different owing to the equipment and basically not changes when cutting material. The second type is setup parameter, such as the target distance and feeding speed of water jet cutting. The parameter is set according to material before cutting. The third type is variable parameter which changes along with the changes of setting parameter, such as the changes of the pressure of abrasive water jet. Because the diameter of the water nozzle does not change, the abrasive flow and water flow rate of the water jet nozzle will change accordingly, and the machine tool water jet cutting system usually adjusts by itself \(^10, 11\).

By using five-axis intelligent water jet cutter LTJ1613-5A machine tool manufactured from Shanghai Lionstek science and technology Co., Ltd, premixed abrasive water jet is adopted, and garnet sand is used as abrasive to conduct vertical cutting. Because the shorter the target distance is, the smaller the water column diffusion of water jet is, the cutting force on workpiece is more concentrated, and the target distance is 1 – 6mm at the time of experiment. Owing to limitation of experiment condition, part of the technological parameters is adjusted and tested at the time of experiment. Technological parameters ensured on the experiment are shown in Table 2:

Table 2. Perpendicular cutting technological parameter of high pressure abrasive water jet.

<table>
<thead>
<tr>
<th>Performance</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjustment range of cutting pressure</td>
<td>0–420Mpa</td>
</tr>
<tr>
<td>Positional accuracy</td>
<td>±0.04mm/m</td>
</tr>
<tr>
<td>The maximum water discharge</td>
<td>3.7L/min</td>
</tr>
<tr>
<td>Diameter of water nozzle</td>
<td>0.33mm</td>
</tr>
<tr>
<td>Material of water nozzle</td>
<td>Sapphire</td>
</tr>
<tr>
<td>Diameter of abrasive nozzle</td>
<td>0.889mm</td>
</tr>
<tr>
<td>Particle size of abrasive</td>
<td>80μm</td>
</tr>
<tr>
<td>Flow of abrasive</td>
<td>0.5kg/min</td>
</tr>
</tbody>
</table>

2.3 Experimental result

In the process of experiment, because of not considering the factor of machining quality, the test cutting depth is the maximum actual cutting depth, the length of incision in the cut aluminium alloy is 30mm, and the depth is measured by probe and vernier caliper.

2.3.1 Influence on the cutting depth by the pressure of abrasive water jet

![Figure 1. Relationship between the speed of water jet and rigidity.](image)

The pressure of water jet is the major power source for abrasive water cutting; furthermore, it is the key factor influencing the cutting depth and the priority subject for studying of each country. When abrasive is added to the certain amount, the speed of abrasive water jet...
declines rapidly, the rigidity of the abrasive water jet diminishes on the contrary, and the elastic model is 
\[ E = \rho(c + v)^2 \] (in this formula, \( E \) is the rigidity of the jet, \( \rho \) is the density of water jet, \( c \) is propagation velocity of elastic waves in liquid, and \( v \) is the ejected speed after abrasive is added in water jet). The changes of rigidity are shown in Figure 1, which is, when abrasive water jet reaches the certain speed value, the rigidity of the abrasive water jet is bigger, and the abrasive water jet can effectively cut material [12].

In the experiment, the movement feeding speed \( V \) is 500mm/min, and the target distance \( S \) is 1mm. By changing the pressure of jet, the speed of abrasive water jet changes, and the cutting depth experiment are conducted on aluminium alloy material. The experimental results are shown in Figure 2 and Figure 3. When 7050 aluminium alloy material is vertically cut by high pressure abrasive water jet, the higher the pressure of jet is, the cutting action force of jet impacting and kinetic energy of abrasive will increase, and the cut degree of material obviously deepens. When the pressure reaches to the certain value, the pressure continuously increases, collision among abrasive will increase, the effective cutting action force cancels each other out, and the depth of cutting process increases slightly.

2.3.2 Influence on the cutting depth by the pressure of abrasive water jet

In the process of high pressure abrasive water jet cutting, feeding speed directly influences the action time of aluminium alloy material, especially the impact effect of abrasive on the same position of material, and the influences on the cutting depth is great. In the experiment, the jet pressure \( P \) is 350Mpa, the target distance \( S \) is 1mm, and the feeding speed is changed [13]. The test result of the cutting depth of aluminium alloy material is shown in Figure 4 and Figure 5. And it shows that the lower the movement feeding speed of nozzle is, the longer the action time of repeatedly impacting material by abrasive is, and the more material removes, the deeper the cutting depth is.

2.3.3 Influence on the cutting depth by the target distance

Because water cutting achieves on the basis of high pressure water jet, the target distance will influence water column diffusion of high pressure water jet. In the experiment, the pressure of jet \( P \) is 350Mpa, the feeding speed \( V \) is 500mm/min, and the target distance is respectively changed to cut aluminium alloy material. The experimental results are shown in Figure 6 and Figure 7, namely, within certain limits, the target distance increases, and the depth of cutting section is in the state of the optimal value.
3 PROCESS STUDY ON 7050 ALUMINIUM ALLOY VERTICALLY CUT BY HIGH PRESSURE ABRASIVE WATER JET

3.1 Optimal experiment design of cutting parameter of high pressure abrasive water jet

As the processing method for cutting new materials, the applied range of abrasive water jet cutting is very wide. In the process of cutting through abrasive water jet, there are many factors influencing cutting process quality, wherein, the major controlled technological parameters such as jet pressure, the target distance and movement speed of nozzle directly decide the depth of machining and analysis of micro-abrasive water jet [14].

On the premise of allowable experiment and by adopting the orthogonal experiment method, the cutting depth is the optimal for objective function, the influences on the cutting depth of 7050 aluminium alloy material by the above three parameters are selectively analyzed, then the cutting parameter is optimized. Moreover, the cutting efficiency is improved on the premise of guaranteeing the cutting quality.

3.1.1 Establishing related data for experiment

In order to complete the orthogonal experiment, four major factors, including jet pressure, movement speed of nozzle, target distance and cutting depth, are analyzed on the experiment [15]. Level factor set of each major machining technology parameter is shown in Table 3:

<table>
<thead>
<tr>
<th>Influence factor</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure of water jet</td>
<td>350</td>
<td>300</td>
<td>250</td>
</tr>
<tr>
<td>Target distance</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Feeding speed</td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
</tbody>
</table>

3.1.2 Establishing orthogonal table of technological parameter optimization

The experiment selects three influence factors, and three level values are selected from each factor. According to the characteristic of orthogonal experiment, related experiments shall be conducted for 9 times and denoted by L9(3^3). The detailed cutting orthogonal experiment table is shown in Table 4:

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Pressure of water jet</th>
<th>Target distance</th>
<th>Feeding speed</th>
<th>Depth of cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>350</td>
<td>1</td>
<td>200</td>
<td>28.1</td>
</tr>
<tr>
<td>2</td>
<td>350</td>
<td>2</td>
<td>300</td>
<td>22.8</td>
</tr>
<tr>
<td>3</td>
<td>350</td>
<td>3</td>
<td>400</td>
<td>18.6</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>1</td>
<td>300</td>
<td>18.2</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>2</td>
<td>400</td>
<td>14.6</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>3</td>
<td>200</td>
<td>24.2</td>
</tr>
<tr>
<td>7</td>
<td>250</td>
<td>1</td>
<td>400</td>
<td>12.4</td>
</tr>
<tr>
<td>8</td>
<td>250</td>
<td>2</td>
<td>200</td>
<td>17.2</td>
</tr>
<tr>
<td>9</td>
<td>250</td>
<td>3</td>
<td>300</td>
<td>14.8</td>
</tr>
</tbody>
</table>

3.1.3 Optimization results and range analysis

The experiment data is calculated in the mode of range analysis to obtain the size of influences on cutting depth by each factor and ensure the optimal level combination of each factor. The cutting depth range analysis table of cutting process depth is shown in Table 5:

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Pressure of water jet</th>
<th>Target distance</th>
<th>Feeding speed</th>
<th>Depth of cutting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69.5</td>
<td>58.7</td>
<td>69.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>57</td>
<td>54.6</td>
<td>55.8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>44.4</td>
<td>57.6</td>
<td>45.6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>23.2</td>
<td>19.6</td>
<td>23.2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>18.2</td>
<td>18.6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>14.8</td>
<td>19.2</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8.4</td>
<td>0.4</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Optimization level P, S, V

Table 5 illustrates that the important order of the three factors influencing the cutting depth is successively the jet pressure P, the feeding speed of water jet V and the target distance S. In order to enable the cutting depth of 7050 aluminium alloy machined by high pressure abrasive water jet to be deeper and better under certain conditions, level P1, level S1 and
level \( V_1 \) are selected. The obtained optimal level combination through comprehensive selection is: the pressure of water jet \( P_x = 350 \text{MPa} \), the target distance \( S_1 = 1 \text{mm} \) and the movement speed of nozzle \( V_1 = 200 \text{mm/min} \).

3.1.4 General model analysis of high pressure abrasive water jet cutting depth

According to experiment data, when 7050 aluminun alloy material is cut by high pressure abrasive water jet, the related factors of the prediction model for cutting depth mainly include cutting depth \( H \) (mm), jet pressure \( P \) (Mpa), feeding movement speed of nozzle \( V \) (mm/min), and the target distance \( S \) (mm). And the mathematical expression of the cutting depth is shown as follows:

\[
H = KP^x S^y V^z
\]  
(1)

Wherein \( K \) is the correlation coefficient related to abrasive and 7050 aluminun alloy material; \( x \), \( y \) and \( z \) are undetermined coefficients.

3.1.5 Regression model of high pressure abrasive water jet cutting depth

Taking the logarithm for two sides of formula (1), we can obtain:

\[
\ln H = \ln K + x_1 \ln P + x_2 \ln S + x_3 \ln V
\]  
(2)

Enable \( x = \ln H \cdot \quad A_1 = \ln K \cdot \quad A_2 = \ln P \cdot \quad B_1 = \ln S \quad B_2 = \ln V \). Then formula (2) is transformed to:

\[
X = A_0 + A_1 x_1 + A_2 x_2 + A_3 x_3 + \varepsilon
\]  
(3)

Thereby we obtain a multiple linear regression equation set as follows:

\[
\begin{align*}
X_1 &= A_0 + A_1 x_1 + A_2 x_2 + A_3 x_3 + \varepsilon_1 \\
X_2 &= A_0 + A_1 x_1 + A_2 x_2 + A_3 x_3 + \varepsilon_2 \\
&\quad \vdots \\
X_9 &= A_0 + A_1 x_1 + A_2 x_2 + A_3 x_3 + \varepsilon_9
\end{align*}
\]  
(4)

Wherein, \( \varepsilon_i \) is random vector \((i = 1,2,3 \cdots 9)\), wherein \( E(\varepsilon) = 0 \).

Enable:

\[
X = \begin{bmatrix} X_1 \\ \vdots \\ X_9 \end{bmatrix}, \quad A = \begin{bmatrix} A_0 \\ A_1 \\ \vdots \\ A_3 \end{bmatrix}, \quad \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_9 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & B_1 & \cdots & B_{13} \\ 1 & B_2 & \cdots & B_{12} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & B_9 & \cdots & B_9 \end{bmatrix}
\]

Then we obtain:

\[
X = BA + \varepsilon
\]  
(5)

Estimating according to least square method, then we can obtain experience regression formula as follows:

\[
\hat{A} = (B^T B)^{-1} B^T X
\]  
(6)

Substituting it into formula (1) to obtain the cutting model of 7050 aluminium alloy cut by high pressure water jet, the orthogonal experimental data is analyzed in the mode of multivariate regression by Matlab language to obtain prediction model equation as follows:

\[
H = KP^{x_1} S^{x_2} V^{x_3}
\]

\[
= 0.29553 P^{1.315803} S^{0.008042} V^{-0.594243}
\]  
(7)

3.1.6 Error analysis of the cutting equation of high pressure abrasive water jet

In order to verify the error of the regression equation for cutting aluminium alloy by high pressure abrasive water jet, the equation calculation result is contrasted with the measuring result of cutting experiment, and the error is shown in Table 6.

Through calculation, the maximum relative error is 7.48\%, and the minimum relative error is 0.46\%. There are many reasons influencing the error, including material uniformity, experiment equipment, experiment time and measuring method. The primary causes of the model to produce error are machine tool system error, measuring error and so on. According to the data of Table 6, the average relative error of the cutting depth \( H \) is shown as follows:

\[
\bar{\varepsilon}_{rel} = \frac{\varepsilon_{11} + \varepsilon_{12} + \cdots + \varepsilon_{19}}{9} \times 100\% = 2.96\%
\]  
(8)

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>True value mm</th>
<th>Predicated value mm</th>
<th>Absolute error mm</th>
<th>Relative error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.1</td>
<td>28.23</td>
<td>0.13</td>
<td>0.46%</td>
</tr>
<tr>
<td>2</td>
<td>18.6</td>
<td>18.86</td>
<td>0.26</td>
<td>1.4%</td>
</tr>
<tr>
<td>3</td>
<td>22.8</td>
<td>22.31</td>
<td>0.49</td>
<td>2.15%</td>
</tr>
<tr>
<td>4</td>
<td>23.8</td>
<td>23.09</td>
<td>0.71</td>
<td>2.98%</td>
</tr>
<tr>
<td>5</td>
<td>18.2</td>
<td>18.11</td>
<td>0.09</td>
<td>0.5%</td>
</tr>
<tr>
<td>6</td>
<td>14.6</td>
<td>15.35</td>
<td>0.75</td>
<td>5.14%</td>
</tr>
<tr>
<td>7</td>
<td>17.2</td>
<td>18.23</td>
<td>1.03</td>
<td>5.99%</td>
</tr>
<tr>
<td>8</td>
<td>15.1</td>
<td>14.25</td>
<td>0.85</td>
<td>5.06%</td>
</tr>
<tr>
<td>9</td>
<td>13.1</td>
<td>12.12</td>
<td>1.78</td>
<td>7.48%</td>
</tr>
</tbody>
</table>

Table 6. Comparison between the predicated value and measured value of the cutting depth.

4 EPILOGUE

The article takes advantage of the experiment and orthogonal experiment to conduct analysis. The re-
gression model equation is obtained through calculation and analysis by Matlab language to draw a conclusion. When 7050 aluminium alloy material is cut by high pressure abrasive water jet, the influences on the cutting depth $H$ by cutting jet pressure $P$ are the most obvious, and the influences by the movement feeding speed $V$ of nozzle and the target distance $S$ are the second. In addition, the cutting depth of 7050 aluminium alloy machined by high pressure abrasive water jet is analyzed in the mode of error, and the error is relatively small within the controllable range. For the convenience of practical operation, the optimal control of water jet cutting system can be achieved by optimizing the cutting speed on the premise of guaranteeing the cutting depth. The expert database of speed corresponding to the cutting time is established, and the corresponding cutting speed is optimized.

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**REFERENCES**


