Modeling of cutting of stainless steel AISI 304 by abrasive water jet

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Abstract
Abrasive water jet (AWJ) has distinct advantages in machining stainless steel, titanium alloy and other metals because of its high machining ability and cold working characteristics. In this paper, the depth of cutting stainless steel AISI 304 by abrasive water jet was studied, so as to provide guidance for reasonable setting of process parameters. Firstly, the effect mechanism of main process parameters on cutting depth was analyzed. Then, the simulation model was built by the method of SPH coupled FEM to simulate the erosion process of abrasive water jet. Then, the material removal volume was studied from the micro and macro perspectives. Based on the essential equivalent relationship between the two aspects, the parametric model of cutting depth was deduced. Finally, the two models were compared and verified. The results show that the parametric model can be used to predict the cutting depth of AISI 304 and guide the setting of process parameters.

1. Introduction
Stainless steel AISI 304 has excellent corrosion resistance, heat resistance and toughness, which is widely used in all walks of life. However, AISI 304 has high high-temperature strength and high-temperature hardness, so the cutting force is large in the cutting process. Stainless steel has high plasticity and toughness, so it consumes more energy in cutting, which leads to elevated cutting temperature. Moreover, due to the low thermal conductivity of stainless steel, the heat dissipation condition is poor, which has a great impact on the tool life. Due to the strong oxidation resistance of stainless steel, plasma cutting is usually used to cut AISI 304. However, the heat effect of plasma cutting is high.

Abrasive water jet is formed by mixing abrasive particles on the basis of plain water jet. It has the advantages of no heat effect, strong processing ability, high flexibility and environmental protection [1, 2], which is very suitable for cutting various hard-to-cut materials [3]. As an important means of material processing, this technology is widely used in many fields such as aerospace, medical treatment, manufacturing and construction. In recent years, it has attracted extensive attention of manufacturing industry [4]. Many experts have done a lot of research on the cutting of steels by abrasive water jet. Hloh [5] analytically developed the real topographic function and maximal depth of neglected initial zones on stainless steel AISI 304, AISI 309 and aluminium to predict surface roughness on the top region of surfaces created by AWJ. On the basis of analysis and interpretation of data obtained from the surface, a topography function, which is necessary to be known for the subsequent prediction and control of AWJ cutting technology, was derived. Hreha et al [6] researched the determination of vibration emission frequency depending on the impact of abrasive particles during cutting of stainless steel AISI 309. The research results are useful for improving the quality of surface created by abrasive water jet, and they can encourage the on-line process control of abrasive water jet cutting with the minimum human intervention in case of a fault or error during the supply of abrasives to cutting head. Hashish [7, 8] analyzed the process of abrasive water jet cutting through the metal, believed that the material removal mechanism mainly includes cutting wear and deformation wear. The material removal of the upper part of the cross-section is mainly caused by cutting wear, and the material removal of the lower part of the cross-section is mainly caused by cutting wear. Tabatchikova et al [9, 10] studied the structure and microhardness in a near-surface layer of high-strength steel as well as the microstructure of welding joints of high-strength steel subjected...
to abrasive waterjet cutting. The results show that welding joints have satisfactory strength and toughness. Li et al [11, 12] studied the process of high-speed erosion of steel plate by single and multiple abrasive particles through simulation. He believed that the main material removal mechanism of abrasive particles erosion at normal angles is inertial fracture, while the main material removal mechanism of abrasive particles erosion at tilt angles is thermal instability-driven fracture, especially adiabatic shear fracture and tensile fracture. Filip et al [13] presented an experimental investigation on cutting hardox steel with abrasive water jet. The effects of traverse speed, material thickness and material type on surface roughness were experimented. Through the statistical analysis of the experimental data, the mathematical model was built. The model can be used for the process planning of abrasive water jet machining of the considered material in industrial environment. Zhu et al [14] made an experimental study on the cutting of coloring stainless steel by abrasive water jet. Through the analysis of the macroscopic features of kerfs, a damage model was built and a principle to optimize process parameters was put forward. Chaturvedi et al [15] carried out a study on cutting AISI 304 by abrasive water jet. The effects of traverse speed, standoff distance, abrasive flow rate and pressure on material removal rate and surface roughness were experimented. The optimum parameters of improving material removal rate and reducing surface roughness were predicted. Chen et al [16] used the method of SPH coupled FEM to simulate the cutting process of AISI 304. It is considered that the decrease of impact angle can lead to the uneven erosion of abrasive particles, which is caused by the generation of striation phenomenon.

2. Materials and methods

The depth of cutting is a very important index for cutting. If the cutting depth is less than the thickness of the material, the material is not cut off and the cutting fails. However, if the cutting depth is far greater than the thickness of the material, it means that a large part of the jet energy is redundant, resulting in a waste of energy and increasing the cost. From another point of view, when the erosion ability of abrasive water jet is determined, if the cutting depth can be effectively controlled, the traverse speed can be increased to the greatest level. The increase of traverse speed means the improvement of cutting efficiency. It can be seen that the control of cutting depth is what the factories aspire to achieve. The process parameters have great effect on the cutting depth. Therefore, on the basis of studying the effects of process parameters on cutting depth, this paper built prediction models of cutting depth from different ways, so as to guide the setting of process parameters and realize the control of cutting depth.

In the processing of AISI 304, the removal ability of water is limited, and abrasive particles undertake the most important task of material removal. Therefore, the properties of abrasive particles have great influence on the processing ability, efficiency and quality of abrasive water jet. There are many kinds of abrasives, such as olivine and garnet [17]. They differ with the shape, performance and price. In real machining, the choice of abrasives needs to consider both the properties and cost. Garnet, as a kind of natural abrasive, not only has the characteristics of high hardness, high strength and environmental protection, but also has low price. It is an ideal choice for abrasive water jet machining and has become one of the most widely used abrasives. Therefore, in this paper, garnet (mesh 80) was selected as abrasive to carry out cutting experiment. The composition and main properties of garnet are shown in tables 1 and 2. Figure 1 shows the morphology of garnet under Olympus microscope at 200 times magnification. It can be seen from the figure that the shape of abrasive particles is irregular, and most of them have sharp edges and corners. The existence of these sharp edges and corners is particularly conducive to the removal of materials.

The main properties of AISI 304 are shown in table 3. In this paper, the effects of process parameters on cutting depth were experimented. The selection and setting of process parameters were shown in table 4. Then, the prediction models of cutting depth were built from two aspects of simulation and parametric modeling.

| Table 1. Composition of garnet. |
|-------------------------------|
| Composition | wt% |
| SiO₂ | 34~43 |
| Al₂O₃ | 18~28 |
| FeO | 21~36.5 |
| MgO | 6~12 |
| Fe₂O₃ | 6~12 |
| CaO | 2~3 |
| MnO | 1 |
The simulation was realized by LS-DYNA. The method of smoothed particle hydrodynamics (SPH) coupled finite element method (FEM) was used. Water was transformed into water particles, which were randomly mixed with abrasive particles in a certain proportion to form a particle beam impacting on the material. Water and abrasives adopted the material model of NULL and defined by the state equation of Gruneisen. The constitutive model adopted the material model of Johnson-Cook. The abrasive is garnet and the workpiece is AISI 304. The total number of abrasive and water particles was automatically determined by software based on model data. The random mixing of two kinds of particles was realized by random sampling assignment of Excel.

There are few researches on the parametric model of cutting depth of AWJ. Wang [18, 19] built the parametric model of cutting depth based on the method of dimensional analysis. The idea of modeling in this paper is quite different from his. The parametric model built in this paper is based on the material removal volume of abrasive water jet. The removal volume was analyzed from micro and macro perspectives. The parametric model of cutting depth was built by the essential equivalent relationship between micro removal volume and macro removal volume. According to the material (AISI 304) and abrasive (garnet) studied in this paper, the coefficient of the model was determined by undetermined coefficient method, and the parametric model was specified.

**Table 2. Main properties of garnet.**

| Properties                  | Values |
|-----------------------------|--------|
| Density (g cm\(^{-3}\))    | 3.96~4.10 |
| Hardness (HM)               | 7.49~9.00 |
| Elastic modulus (GPa)       | 248    |
| Poisson’s ratio             | 0.27   |

**Table 3. Main properties of AISI 304.**

| Properties                  | Values |
|-----------------------------|--------|
| Density (g cm\(^{-3}\))    | 7.93   |
| Tensile strength (MPa)      | 515    |
| Elastic modulus (GPa)       | 194    |
| Fracture toughness (MPa m\(^{0.5}\)) | 170 |
| Vickers hardness (HV)       | 210    |
| Poisson’s ratio             | 0.275  |

**Table 4. Setting of parameters.**

| Parameters                  | Values |
|-----------------------------|--------|
| Nozzle diameter (mm)        | 0.7    |
| Standoff distance (mm)      | 2~18   |
| Traverse speed (mm min\(^{-1}\)) | 250~650 |
| Abrasive flow rate (kg min\(^{-1}\)) | 0~0.8 |
| Impact angle (deg)          | 90     |
| Pressure (MPa)              | 100~300 |

Figure 1. Morphology of garnets.
3. Results and discussion

3.1. Effect mechanism of parameters

Figure 2 shows the effects of process parameters on cutting depth. The workpiece is AISI 304 and the abrasive is garnet. It can be seen from the figure that pressure, abrasive flow rate, standoff distance and traverse speed have great effect on cutting depth. With the increase of pressure, the cutting depth increases gradually, but the increase rate decreases. With the increase of abrasive flow rate, the cutting depth increases first and then decreases. With the increase of standoff distance, the cutting depth decreases in a certain range, but the decrease rate is small. While when the standoff distance exceeds the range, the cutting depth decreases rapidly. With the increase of traverse speed, the cutting depth decreases sharply at first, and then stabilizes to a small value.

The total energy of all abrasive particles determines the removal ability of abrasive water jet. The total energy is determined by two factors: one is the total amount of abrasive particles; the other is the velocity of abrasive particles. The total amount of abrasive particles is related to abrasive flow rate, while the velocity of abrasive particles is related to pressure. Therefore, the pressure reflects the erosion energy and the abrasive flow rate reflects the erosion ability of the AWJ. Theoretically, the greater the pressure and abrasive flow rate, the deeper the cutting depth. However, it can be found from the experimental results that although the cutting depth increases with the increase of pressure, the increasing rate is decreasing. In addition, the cutting depth does not increase continuously with the increase of abrasive flow rate, but decreases after reaching a peak value. Although the increase of pressure and abrasive flow rate helps to improve the erosion kinetic energy of AWJ, it also causes greater instability of AWJ and intensifies the interaction between abrasive particles. To a certain extent, it weakens the space for improving the erosion ability of materials by pressure and abrasive flow rate.

The standoff distance determines in which section the jet impacts on the material. It reflects the actual erosion energy of AWJ. The application of abrasive water jet to different requirements can be realized by setting the standoff distance flexibly. For cutting, high energy is needed to cut off the material. The velocity of AWJ is the maximum in the zone nearest to the nozzle exit, so this zone is the best choice of standoff distance for cutting. If the standoff distance is large, the energy attenuation of AWJ is serious, and the cutting depth that can be realized
will decrease rapidly. The traverse speed determines the interaction time between AWJ and material. The traverse speed corresponds not only to the final depth of cutting, but also to the time required for cutting. Therefore, ensuring a certain cutting depth and making the cutting time as small as possible is an important principle for setting the traverse speed. This reflects the trade-off between cutting depth and cutting efficiency. That is to say, in the premise of not considering the cutting quality, the traverse speed should be set as far as possible to make the material just cut off.

In short, the pressure and abrasive flow rate determine the erosion ability of AWJ, while the standoff distance and traverse speed determine the actual erosion energy of AWJ. These four main process parameters are closely linked, which jointly determine the effective erosion energy of AWJ. The greater the effective erosion energy is, the deeper the cutting depth is. Therefore, the process parameters affect the cutting depth by affecting the effective erosion energy of abrasive water jet.

3.2. Simulation model
The simulation results at different times were shown in figure 3. The red particles are abrasive particles and the green particles are water particles. It can be seen from the figure that abrasive water jet erodes materials in the form of particle beam, which conforms to the characteristics of high-energy beam of abrasive water jet. Water and abrasive particles are randomly distributed. With the passage of time, the cutting depth deepens rapidly. It removes material in a very short time. With the increase of cutting depth, the kerf width also increases. The increase of kerf width is mainly related to the reflection and reflux of particles. The particles reflect after the impact, and the particles that reach the bottom will flow back. The reflected and refluxed particles also erode the material, which plays a role in removing the material to a certain extent.

Although the time required to reach the maximum cutting depth is extremely short, due to the existence of traverse speed, there is always a small area at the entrance of the material, in which the cutting depth is less than the maximum cutting depth. The range of this area is
Where, $L$ is the length of incomplete cutting area, $t_m$ is the time required for cutting depth to reach maximum or material thickness, $U$ is traverse speed.

According to equation (1), if the maximum cutting depth is far deeper than the material thickness, it means that the energy of abrasive water jet is large, so the time required for material cutting is extremely short. Therefore, the range of incomplete cutting area is very small under the condition of constant traverse speed. If the maximum cutting depth is less than the material thickness, it means that the energy of abrasive water jet is insufficient. Therefore, the range of incomplete cutting area is relatively large under the condition of constant traverse speed. The bottom of the kerf in this area has an appearance of downhill, as shown in figure 4. If the maximum cutting depth is slightly deeper than the material thickness, theoretically, a considerable part of the material in this area has not been completely cut. However, the existence of the reflection and backflow of abrasive water jet will remove the material that is not completely removed. Therefore, the incomplete cutting area at the entrance is rarely seen in actual processing.

3.3. Parametric model

In the process of abrasive water jet cutting AISI 304, abrasive particles undertake the most important task of material removal. Therefore, the total amount of material removal caused by all abrasive particles should be very close to the volume of material removed. In this paper, the material removal volume was analyzed from micro and macro perspectives. Then, based on the essential equivalent relationship between them, the parametric model of cutting depth was deduced.

In order to calculate the removal volume of abrasive water jet on macro scale conveniently, several assumptions were made: (1) The taper of the kerf is 0; (2) the width of the kerf is equal to the diameter of the nozzle; (3) the standoff distance is small.

Assumptions (1) and (2) are made to obtain the ideal kerf profile $C_1D_1D_2C_2$ in figure 5 so as to facilitate the calculation of the removal volume of the material. Since the jet gradually diverges after it is ejected from the nozzle, the diameter of the initial interaction between the jet and the material ($A_1A_2$ in figure 5) is larger than that of the nozzle outlet. However, due to the low energy, it is difficult for the jet at the boundary to remove the material, so the initial effective erosion diameter of the jet to the material (width of upper kerf, $B_1B_2$ in figure 5) is generally smaller than the initial effective diameter. Even so, the initial effective erosion diameter is generally larger than the nozzle outlet diameter ($C_1C_2$ in figure 5). The energy of AWJ decreases gradually with the increase
of cutting depth, and the removal ability of AWJ to the bottom material decreases. The harder the material is to
be cut and the lower the effective erosion energy is, the higher the convergence degree of the kerf profile is. For
AISI 304, the kerf profile is always convergent. Therefore, the material removal volume corresponding to the
ideal kerf \((C_1D_1D_2C_2)\) in figure 5 is very close to that corresponding to the actual kerf \((B_1E_1E_2B_2)\) in figure 5. To
sum up, in the calculation of material removal volume of AISI 304, assumptions (1) and (2) are reasonable.

Assumption (3) is made to minimize the influence of standoff distance. In a short distance from the nozzle
outlet, the velocity of the jet at the axis remains basically unchanged and has the maximal energy. Therefore, for
cutting, generally set a very small standoff distance to make full use of AWJ energy to achieve cutting operation.
Thus, assumption (3) is in line with the actual working conditions.

In summary, the three assumptions are reasonable in the calculation of the material removal volume of
AISI 304.

Based on the above three assumptions, it is easy to calculate the removal volume of abrasive water jet from a
macroscopic point of view. That is

\[ V = h d_j U T \]  \hspace{1cm} (2)

Where, \( V \) is the volume of material removal, \( h \) is cutting depth, \( d_j \) is the diameter of nozzle outlet, \( T \) is
cutting time.

If the standoff distance is very small, the energy of abrasive particles is basically the same. On this premise, it
can be assumed that all abrasive particles cause the same removal of material. The material removal volume of
abrasive water jet is approximately equal to the product of the material removal volume of a single abrasive
particle and the total number of abrasive particles. That is

\[ V = \frac{m_a}{m} V_0 T \]  \hspace{1cm} (3)

Where, \( m_a \) is abrasive flow rate, \( m \) is the weight of single abrasive particle, \( V_0 \) is the volume of material
removal by single abrasive particle.

Substituting equation (3) into equation (2) gives

\[ h d_j U = \frac{m_a}{m} V_0 \]  \hspace{1cm} (4)

That is

\[ h = \frac{m_a}{md_j U} V_0 \]  \hspace{1cm} (5)

According to the study of Zhu \cite{20}, the volume of material removal by single abrasive particle is

\[ V_a = f_1 \frac{E^2 U_m^2 C^2}{K IC H^2} \left( 1 - f_2 \frac{E^2 K IC}{H^2 U_m^2 C^2} \right) \]  \hspace{1cm} (6)

Where, \( f_1 \) and \( f_2 \) are constants, \( E \) is the elastic modulus, \( K IC \) is the fracture toughness, \( H \) is the hardness, \( U_m^2 C^2 \) is the kinetic energy of a particle that causes the fracture of the material.

If the impact angle is 90°, then

\[ U_m^2 C^2 = U_M \]  \hspace{1cm} (7)

Where, \( U_M \) is the effective erosion kinetic energy.

According to the study of Marshall \cite{21}, the effective erosion kinetic energy can be derived to be

\[ U_M = \frac{U_k}{1 + \frac{H a}{U_k}} \]  \hspace{1cm} (8)

Where, \( U_k \) is the erosion kinetic energy, \( H a \) is the hardness of abrasive particles.

According to the kinetic energy theorem, the erosion kinetic energy is

\[ U_k = \frac{1}{2} m_v^2 \]  \hspace{1cm} (9)

Where, \( v_o \) is the velocity of the particles.

Assuming that the velocity of abrasive particles is the same as that of water and remains unchanged during
the cutting process, then

\[ m_w v_w = a(m_w + m_a) v_o \]  \hspace{1cm} (10)
That is

\[ v_a = \frac{m_w v_w}{a(m_u + m_v)} \]  

(11)

Where, \( a \) is for momentum transfer efficiency, \( m_w \) is the flow of water, \( v_w \) is the velocity of the water.

Assuming that water is incompressible, then

\[ v_w = \sqrt{\frac{2P}{\rho_w}} \]  

(12)

Substituting equation (6)–(12) into equation (5) gives

\[ h = \frac{m_a f_1 E^+ \bar{m}^2 p^*}{d_j U \rho_w \bar{m}^2} \left(1 + \frac{m_u}{m_v}\right) \frac{K_{IC} H \bar{m}}{1 + \sqrt{\frac{H}{H_{IC}}}} \]

\[ \times \left(1 - \frac{f_2 \rho_w \bar{m}^2}{H H_{IC}^2 m^2 p^*} \left(1 + \frac{m_u}{m_v}\right)^2 \right)^{\frac{1}{2}} \]  

(13)

When the workpiece and abrasive are determined, the material parameters are determined.

Order

\[ k_1 = \frac{f_1 E^+ \bar{m}^2}{\rho_w \bar{m}^2 K_{IC} H \bar{m}^2} \left(1 + \sqrt{\frac{H}{H_{IC}}}ight) \]

\[ k_2 = \frac{f_2 \rho_w \bar{m}^2}{H H_{IC}^2 m^2 p^*} \left(1 + \frac{m_u}{m_v}\right)^2 \]  

\[ k_1 \quad k_2 \]  

(14)

\( k_1 \) and \( k_2 \) in equation (14) are related to material properties of workpieces and types of abrasives. Their values can be obtained not only by specific parameters, but also by undetermined coefficient method based on some experimental data. It should be noted that once the values of \( k_1 \) and \( k_2 \) are determined, equation (14) is no longer universal. After determining the values of \( k_1 \) and \( k_2 \), it is only applicable to the processing of specific materials with specific abrasive particles.

In this paper, the values of \( k_1 \) and \( k_2 \) for AISI 304 and garnet abrasives were calculated by the undetermined coefficient method. According to the characteristics of the model, a group of \( k_1 \) and \( k_2 \) can be calculated by two groups of experimental data. Through the experimental data, the values of several pairs of \( k_1 \) and \( k_2 \) were calculated. The average values of \( k_1 \) and \( k_2 \) are 13.5361 and 1.2257, respectively. Thus, the parametric model for AISI 304 and garnet abrasives can be obtained by substituting the values into equation (14).

That is

\[ h = 13.5361 \frac{m_a \bar{m}^2 p^*}{d_j U \left(1 + \frac{m_u}{m_v}\right)^2} \left(1 - 1.2257 \left(1 + \frac{m_u}{m_v}\right)^2 \right)^{\frac{1}{2}} \]  

(15)

Equation (15) is the specified form of the parametric model, which is only applicable to the case of AISI 304 and garnet.

3.4. Comparison and verification

With AISI 304 as workpiece and garnet as abrasive, the cutting depth was predicted by simulation model and parametric model, and the predicted results were verified by cutting experiments. The setting of process parameters is shown in table 5, and the comparison of predicted and experimental results is shown in figure 6.

From figure 6, it can be found that the simulation results are generally 25% elevated than the true values. The method of converting water into water particles changed the interaction between water and abrasive particles, which has a great influence on the erosion effects. The results of the parametric model are more in line with the true situation. The relative error of one case is only 1.7%. It can be seen that the parametric model is reliable. Although the model can only be applied to the case of small standoff distance because of the idealization of the
kerf profile, the setting of small standoff distance accords with the true working conditions of abrasive water jet cutting. Therefore, the model is practical.

4. Conclusions

In this paper, the cutting depth of stainless steel AISI 304 by abrasive water jet was studied by building simulation model and parametric model. The simulation model was built based on the method of SPH coupled FEM. The parametric model was built by analyzing the equivalent relationship between material removal volumes from macro and micro perspectives. These two models can predict the cutting depth and guide the setting of process parameters.
(1) The process parameters jointly determine the effective erosion energy of AWJ. Therefore, the process parameters affect the cutting depth by affecting the effective erosion energy of abrasive water jet.

(2) It was found through the simulation that the material is not completely cut in a very short time after the initial contact between the AWJ and the material. The incomplete cutting area exists in theory. However, the existence of the reflection and backflow of abrasive water jet will remove the material that is not completely removed. Therefore, the incomplete cutting area at the entrance is rarely seen in real processing.

(3) The prediction accuracy of the parametric model is high. Although the model can only be applied to the case of small standoff distance because of the idealization of the kerf profile, the setting of small standoff distance accords with the true working conditions of abrasive water jet cutting. Therefore, the model is in line with the practical application.

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