X. C. CHEN, S. S. DENG, M. CHEN, W. X. HUA, S. LIAO, S. YAO

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SIMULATION ANALYSIS OF STRIATION PHENOMENA IN ABRASIVE WATER JET CUTTING (AWJC) PROCESS OF AISI 304 STAINLESS STEEL

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Abrasive water jet cutting (AWJC) technology has been widely used in metal processing field. However, the generation of striations deteriorates cutting quality. In this paper, Smoothed particle hydrodynamics (SPH) coupled Finite element method (FEM) is used to simulate and analyze the cutting process of AISI 304 stainless steel. The results show that the declining jet angle will result in uneven erosion of abrasive particles, which is caused by the generation of striation phenomenon. The research can deepen the understanding of striation phenomena in metal machining process.

Key words: AISI 304 steel, abrasive water jet, metal damage mechanism, mesh free method, striation

INTRODUCTION

Abrasive water jet (AWJ) can effectively cut all kinds of metal materials [1]. Unlike other cutting methods, AWJC has no obvious thermal damage during metal cutting process [2].

The striation phenomenon is a common feature of beam-cutting process [3]. The striation is always along with AWJC process when particular material of certain thickness is cut at high traverse velocities [4]. Various investigations have reported the possible factors influencing the striation formation, which can be classified into nature of step formation during cutting process, dynamic characteristics of the AWJ, and vibration of jet machining system [5, 6]. These studies promotes the understanding about the striation, but the striation formation mechanisms is still equivocal.

Taking into account the limitations of the experimental study, this paper simulates the AWJC process by SPH coupled FEM method and analyzes the effect of the jet angle on the characteristics of erosion craters. According to the above mentioned, the mechanism of striation generation can be explored.

AWJC SIMULATION MODELING

SPH is a mesh free method based on Lagrange principle. By using a series of particles to discretize the computational domain, it can effectively exhibit the deformation process without the divergence and distortion problem [7, 8].

With the kernel function *W(x-y,h)*, the value of interpolated function *f(x)* at particle *i* can be expressed as the sum of the interpolated function values of other particles in the support domain *Ω* which has a radius of variable smoothing length *h*.

$$f\left(x_i\right)=\sum_{j=1}^{N}\frac{m_j}{\rho_j}f\left(x_j\right)W\left(x_i-x_j,h\right) \tag{1}$$

Where m_j is the mass of particle *j* / kg, and ρ_j is the density of particle *j* / kg/m³ .

When *f(x)* represents density ρ_i, velocity v_i, and energy e_i of particle *i*, the equations of continuity, momentum and energy could be derived by time *t* differential processing as follows.

$$\frac{\mathrm{d}\rho_i}{\mathrm{d}t}=\sum_{j=1}^{N}m_j\left(v_i-v_j\right)\nabla_i W\left(x_i-x_j,h\right) \tag{2}$$

$$\frac{\mathrm{d}v_i}{\mathrm{d}t}=\sum_{j=1}^{N}m_j\left(\frac{p_i}{\rho_i^2}+\frac{p_j}{\rho_j^2}+\Pi_{ij}\right)\nabla_i W\left(x_i-x_j,h\right) \tag{3}$$

$$\frac{\mathrm{d}e_i}{\mathrm{d}t}=\frac{1}{2}\sum_{j=1}^{N}m_j\left(\frac{p_i}{\rho_i^2}+\frac{p_j}{\rho_j^2}+\Pi_{ij}\right)v_{ij}\nabla_i W\left(x_i-x_j,h\right) \tag{4}$$

Where $v_{ij}=(v_i-v_j)$ and Π_{ij} is artificial viscosity.

MATERIAL MODELS

The water is defined as NULL material. The Mie-Gruneisen equation is adopted to describe water properties [9].

$$P=\frac{\rho_0 C^2\mu\left[1+\left(1-\frac{\gamma_0}{2}\right)\mu-\frac{a}{2}\mu^2\right]}{\left[1-\left(S_1-1\right)\mu-S_2\frac{\mu_2}{\mu+1}-S_3\frac{\mu^3}{\left(\mu+1\right)^2}\right]}+\left(\gamma_0+a\mu\right)Ea \tag{5}$$

The parameter values are shown in Table 1.

X. C. Chen, S. S. Deng, M. Chen, W. X. Hua, S. Liao, S. Yao, People's Liberation Army Logistical Engineering University, Chongqing, China (e-mail: cxccad@163.com)

Table 1 **Parameter values of the water**

Mie-Grueisen parameters	Values
Sonic velocity *C* / m/s	1 480
Grueisen coefficient γ_0	0,4934
Volume correction factor *a*	1,397
Fitting coefficient S_1	2,56
Fitting coefficient S_2	- 1,986
Fitting coefficient S_3	0,2268
Water density ρ_0 / kg/m^3	1 000

Table 2 **Abrasive material properties**

Parameters	Values
Abrasive density / kg/m^3	4 000
Elastic Modulus / GPa	248
Poisson's ratio	0,27

Table 3 **Properties of steel plane material**

Parameters	Values
Steel density / kg/m^3	8 030
Elastic Modulus / GPa	195
Poisson's ratio	0,27
Yield Strength / MPa	316
Tensile strength / MPa	623
Failure strain	0,55

Abrasive particle is 80# corundum. The linear elastic material model is used to reflect its performance, and the parameter settings are shown in Table 2.

A MATLAB software program is developed to realize the uniform distribution of abrasive particles. The number of abrasive particles depends on the volume concentration and the total number of particles.

In view of the hardening characteristics of metal material, a plastic hardening model is used to define the properties of the AISI 304 stainless steel. An equivalent failure strain is defined for the metal material, and when the strain rate of the element exceeds the equivalent failure strain, the target material elements fail and are deleted. The properties of the steel plane material are shown in Table 3.

Model description

The steel plate is modelled by finite element method. Due to the large deformation of AWJ during the impact process, the AWJ model is established by SPH method. The coupling between the finite element model of the steel plate and the abrasive water jet SPH model can be achieved by contact algorithm [10]. The contact type between steel and jet is "eroding_nodes_to_surface" in LS-DYNA.

As shown in Figure 1, two kinds of models are established in this paper. Figure 1a and Figure 1b are models for studying the erosion crater morphology evolution and the striation formation mechanism respectively. The steel plane is AISI 304 stainless steel.

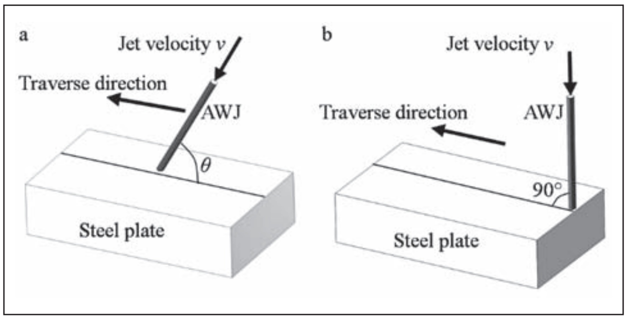

Figure 1 Schematic diagram of pre-mixed AWJ model a) erosion model of different jet angle; b) AWJC model for striation research

RESULTS AND ANALYSIS

Crater morphology of different jet angles

In order to analyze the effect of jet angle on the morphology of erosion craters, erosion models with angles of 50 °, 70 ° and 90 ° are established. The impact velocity of the jet is 150 m/s, and the AWJ beam length is 0,02 m. Figure 2 shows the characteristics of the erosion craters at different jet angles.

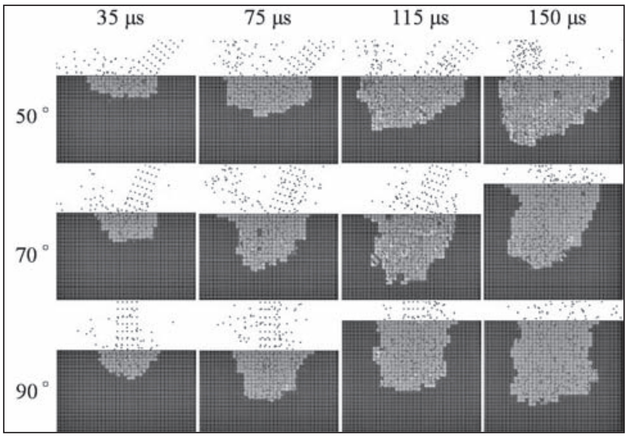

Figure 2 Erosion crater morphologies

As can be seen from Figure 2, jet angle has a great influence on erosion craters. Under the vertical impact, the jet has the kinetic energy perpendicular to the surface of the material, but the motion direction of abrasive particles changes after the first erosion because of the continuous exclusions by the follower AWJ. Therefore, the abrasive particles are squeezed to the around wall of the erosion craters and have horizontal kinetic energies, which will aggravate the secondary erosion of the abrasive particles around the erosion crater and result in the crater morphology change from V shape to U shape.

When AWJ has an inclination angle, the abrasive particles have large horizontal kinetic energies. At this time, the horizontal motion of the abrasive particles exacerbates the failure of the material on one side of the erosion crater. But the offset angles of the erosion craters are not linear. From Figure 2, it can be seen that the offset of the erosive craters to the non-material side gradually increases. With the increase of the depth of the erosion craters, the offset of the erosion craters grad-

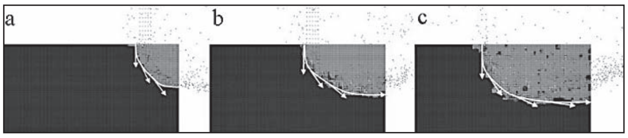

Figure 3 Simulation of AWJC process a) initial cutting moment; b) intermediate cutting moment; c) final cutting moment

ually increases. It is because the offset of the erosion crater changes the secondary erosion characteristics of the abrasive particles. The abrasive particles with secondary erosion do not erode the surrounding walls of the erosion craters evenly. The secondary erosion is more serious in the direction of the jet, and the material deviated from the jet direction is subjected to less secondary erosion, which leads to form a sloping craters.

Abrasive water jet erosion process analysis

In order to analyze the causes of striation, a SPH coupled FEM model is analyzed as shown in Figure 1b. The AWJ impact speed is 150 m/s, and the nozzle traverse speed is 220 mm/min. Figure 3 shows the AWJC process.

It can be seen from Figure 3 that the erosion angle of AWJ decreases gradually with the increase of jet erosion depth in AWJC process. When jet contacts with material, the jet that finishes the first erosive action is discharged from the right side due to the absence of the material on the right side and the exclusion movement of the follow-up jet, resulting in a decreased secondary erosion action on the left side material, which causes the jet erosion front surface to deflect to the right. This is similar to the mechanism in Figure 2.

On the one hand, with the increase of jet erosion depth, the deflection of jet erosion angle increases gradually. The gradually decreasing erosion angle weakens the erosion performance of the jet. On the other hand, with the increase of the jet depth, the erosion kinetic energy of the jet decreases. The combined effect of the two factors makes the erosion performance of the jet decrease rapidly. Therefore, the inclination angle of cutting front surface is not linear or constant as the erosion depth increases, but presents an exponential change.

According to the above analysis, the striation is mainly caused by uneven abrasive erosion. If the AWJC operators want to improve the abrasive striation phenomenon, several methods can be adopted. Such as, the nozzle can move forward with swinging motion in the moving plane, or multiple cutting can be carried out. These two methods can further improve the uneven AWJ erosion.

CONCLUSIONS

In this paper, the AWJ erosion and cutting models are established by SPH coupling FEM method. The influence of jet angle on erosion crater morphological and the cause of striation are simulated and analyzed. The conclusions of this paper are as follows.

(1) The impact angle of AWJ has a significant effect on the morphology of the erosion craters. The change of impact angle has a decisive effect on this non-uniform erosion characteristic.

(2) Similar to the uneven erosion principle of AWJ erosion process under inclined erosion conditions, non-uniform erosion also occurs during AWJC process, resulting in the phenomenon of cutting striation.

(3) AWJC is mainly caused by the first erosion of abrasive particles. The secondary erosion of the particles will improve the kerf quality.

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Note: The responsible translator for English language is Qiong Wu, Beijing Foreign studies University, China