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Research on the Effect of Jet Angle on Pre-Mixed Abrasive Water Jet Erosion Process

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Abrasive water jet (AWJ) is a safe processing technology which can effectively machine almost any materials. However, due to excessive influence factors and micro-high-speed characteristics of the erosion process, traditional experiment methods have limitations in the research of the process, and the understanding of the abrasive water jet cutting (AWJC) process is not comprehensive. In this paper, the SPH coupled FEM method is used to establish the model of the pre-mixed AWJC process, and the effect of jet angle on the abrasive particle erosion process is analyzed deeply. The effect of jet angle on erosion crater sphericity is achieved from simulation results and the sphericity values are compared with the values observed in the experiments. Simulation results are in good agreement with results obtained from the experimental verification, which proves that the SPH coupled FEM method has better reliability and higher accuracy than single particle or multi-particle FEM erosion simulation. Based on the analysis of erosion crater morphology, the reason of jet angle change during AWJC process. This paper not only enriches the research method of abrasive water jet cutting process, but also contributes to the precise control of abrasive water jet cutting process.

1. Introduction

Water jet technology for cleaning, descaling, cutting, drilling and crushing has been developed around the world, becoming part of the rise of new technologies and new processes (Li et al., 2015). AWJ technology is a new type of processing technology developed on the basis of water jet. By adding abrasive particles to the water, it is possible to effectively cut various metal and non-metallic materials at lower pressure. AWJs are divided into pre-mixed AWJ and rear-mixed AWJ depending on the abrasive addition approach. These two kinds of AWJ are mixed in different ways, so the energy transfer process is different, but the cutting principle is high-frequency and high-speed impinging erosion of high-speed abrasive particles on the target materials (Narayanan et al., 2013). Due to the presence of a large amount of water during the AWJC process, there is no high temperature and flame so that the thermal damage and thermal stress are not obvious (Ahmed et al., 2016). In addition, the cutting products only include water, abrasive and target material debris, so it is considered as an environmentally friendly and safe cutting technology. Due to the high mobility and flexibility of its cutting systems, AWJC technology has a very wide range of engineering applications. It has been successfully applied in the fields of hard-material machining, waste treatment of energetic materials, defusing explosives, cutting under inflammable and explosive environment and other special industrial machining process (Li and Wang, 2015).

With the development of AWJ technology, the application scene becomes more and more special and complicated, and the understanding and manipulation of AWJC process also should meet higher requirements. The study of the influence of cutting parameters on cutting process is also the research hotspot. Although many scholars have researched the effect of various cutting parameters on the cutting performance and obtained the influence laws (Aich et al., 2014; Gupta et al., 2014). However, because the AWJC is a microscopic high-speed process which can be influenced by many nonlinear parameters, traditional

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experiment research methods present obvious limitations with the erosion process observation, so this erosion process and mechanism are still not clear up till now.

Because the simulation method can control cutting simulation conditions accurately and can study the influence of each parameter separately, more and more AWJC simulation research have been conducted. In the early years, the main methods of numerical simulation are finite element method (FEM) and arbitrary Lagrangian-Euler method (ALE). However, the FEM will produce grid distortion and cause calculation terminate and the ALE method divides too many Eulerian element grids so that the amount of computation increases significantly. Because the smoothed particle hydrodynamics (SPH) method does not need to generate the mesh, it can effectively avoid the problem of grid twist and grid reconstruction, which can be very convenient to simulate the large deformation problem of the mesh. In high-speed collision simulation, the explosion of high-energy explosives, underwater explosion shocks and other issues have been well applied. Yu et al. (2012) have adopted SPH method to analyze the high-speed nonlinearity problem of AWJC process and obtained good results. Later, through the SPH method, some scholars analyzed AWJ cutting speed and the acceleration process of abrasive in the nozzle.

In this paper, the SPH coupled FEM method is used to simulate the cutting process of pre-mixed AWJ erosion process under different jet angles. The uniform and random mixture of abrasive particles and water will be realized by MATLAB programming. The erosion crater sphericity values and the crater morphology features will be analyzed. Based on these research, the change law of jet angle and its effect on AWJC process will be discussed.

2. Pre-mixed AWJC modeling methods

2.1 Theoretical base of SPH method

SPH method can deal with partial differential equations based on Lagrange method. By discretizing the computation domain with a series of particles, SPH method can effectively solve the divergence and distortion problems in large deformation simulations. 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*.

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

When the interpolated function represents density, velocity, and energy field variables, respectively, the continuity equation, momentum equation and energy equation could be derived by time differential processing. All of these functions are written 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.

2.2 Material models

During the simulation, different material models are assigned to the jet and steel plate.

2.2.1 Water and abrasive particle material models

The water is defined as NULL material, and the water equation is defined by setting the state equation. The equation of state satisfies the Mie-Grueisen equation (Campbell et al., 2000).

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

The value of each parameter is shown in table 1.

Table 1: Parameter values of the water

Mie-Grueisen equation Parameters	Values
Sonic velocity, C (m/s)	1480
Grueisen coefficient r0	0.4934
Volume correction factor a	1.397
Fitting coefficient S1	2.56
Fitting coefficient S2	-1.986
Fitting coefficient S3	0.2268
Water density ρ0 (kg/m^3)	1000

Table 2: Abrasive material properties

Parameters	Values
Abrasive density (kg/m^3)	4000
Elastic Modulus (GPa)	248
Poisson's ratio	0.27

Table 3: Properties of steel plane material

Parameters	Values
Steel type	AISI 304
Steel density(kg/m^3)	8030
Elastic Modulus(GPa)	195
Poisson's ratio	0.27
Yield Strength(MPa)	316
Tensile strength(MPa)	623
Failure strain	0.55

According to previous studies, corundum is selected as abrasive material in this paper (Wen et al., 2017). Abrasive particle is 80# corundum which belongs to the elastic-plastic. Linear elastic material model is adopted to reflect its properties. The parameters are set as shown in Table 2.

Abrasive particles and water particles have different material properties. In order to ensure the two kinds of SPH particles distributed evenly, a MATLAB software program is developed. The abrasive particle number is determined by its volume concentration and the total number of particles.

2.2.2 Steel plane material model

Because the target material is nonlinear plastic hardening body, the target metal material is defined by the plastic hardening model. By defining the equivalent failure strain, the definition of the erosion failure of the target material element is achieved. When the failure condition is satisfied, the failure units are no longer involved in the calculation and not shown in the post-processing. The properties of the steel plane material are shown in Table 3.

2.3 Coupling method of SPH-FEM model

During simulation, the steel plate is modelled by the finite element method, and the abrasive water jet is modelled by SPH method because of its larger deformation. The coupling between steel FEM model and AWJ SPH model can be realized by the contact algorithm (Liu et al., 2015). The contact type between the steel and AWJ is ‘eroding_nodes_to_surface’ in LS-DYNA.

According to the above modeling methods, the corresponding AWJ erosion model is established for different analysis contents.

2.4 Model description

As shown in figure 1, the models studied in this paper are mainly the pre-mixed AWJ erosion model. The erosion model is used to analyze the erosion crater features of different jet angles, and the cutting model is used to study the change laws of jet action direction during AWJC process and its effect on cutting results.

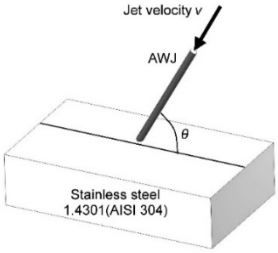

Figure 1: Schematic diagram of pre-mixed AWJ erosion model

3. Simulation results and analysis

3.1 Reliability analysis of AWJ erosion simulation

In order to verify the correctness of the simulation method, the AWJ erosion model was established according to the parameters in references (Junkar et al., 2006; Kumar et al., 2012). The values of the erosion parameters are shown in Table 4.

Table 4: Erosion experiment and simulation parameter values

Parameter	Values
Impact angle (°)	60 and 90
Impact velocity (m/s)	180, 200 and 220
Abrasive particle density (kg/m³)	4000
Abrasive particle size	200μm Garnet for simulation, 190μm Garnet for experiment
Target material	Stainless steel 1.4301(AISI 304)

The simulation results are shown in figure 2. The crater minor dimension d_1 and crater major dimension d_2 are measured and their ratio is defined as crater sphericity S_C.

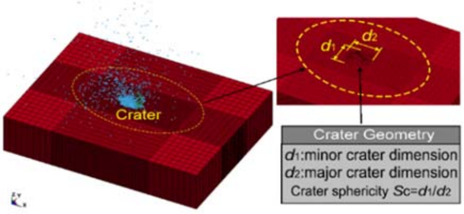

Figure 2: Schematic diagram of erosion simulation results

The simulation results are compared with corresponding experimental results, which are shown in Table 5.

Table 5: Crater sphericity values of simulation and experiment

Jet velocity (m/s)	Crater sphericity values	
	Impact angle of 60°	Impact angle of 90°
180	0.603 (Experiment)	0.759 (Experiment)
	0.905 (Junkar et al., 2006)	1.000 (Junkar et al., 2006)
	0.792 (Kumar et al., 2012)	1.000 (Kumar et al., 2012)
	0.724 (Present simulation)	0.947 (Present simulation)
200	0.623 (Experiment)	0.793 (Experiment)
	0.905 (Junkar et al., 2006)	1.000 (Junkar et al., 2006)
	0.808 (Kumar et al., 2012)	1.000 (Kumar et al., 2012)
	0.792 (Present simulation)	0.895 (Present simulation)
220	0.637 (Experiment)	0.825 (Experiment)
	0.924 (Junkar et al., 2006)	1.000 (Junkar et al., 2006)
	0.830 (Kumar et al., 2012)	1.000 (Kumar et al., 2012)
	0.826 (Present simulation)	0.947 (Present simulation)

It can be seen from Table 5 that the simulation results of AWJ erosion process are in good agreement with the experimental results. Compared with conventional FEM simulation of single abrasive particle or multiple abrasive particles impinging process, the SPH coupled FEM simulation get closer to the actual results, which shows that the AWJ beam model established by SPH method can effectively simulate the random scattering of a large amount of abrasive particles in the water and can more truly reflect realistic AWJ erosion characteristics.

3.2 Erosion crater morphology evolution feature analysis of different jet angles

In order to analyze the influence of jet angle on the erosion process, SPH method was used to establish the erosion model under different inclination angles. The impact velocity of AWJ is 150 m/s and the jet particle column has a length of 2cm. The impact angles are 50°, 70° and 90°. When the angle is 90°, the AWJ impacts the target material vertically. Figure 3 shows the erosion crater features of different jet angles.

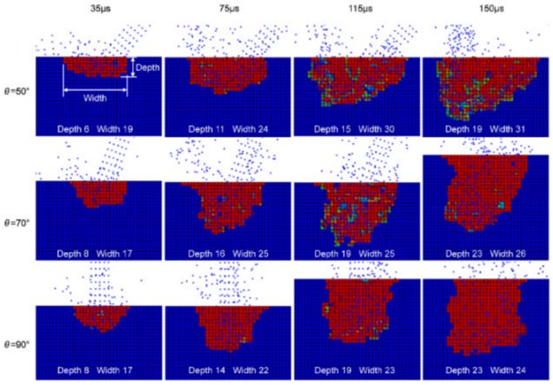

Figure 3: Erosion crater morphologies of different jet angles

As can be seen from figure 3, the AWJ angle has a large effect on the shape of the erosion crater morphology. Crater shape change from V type to U type under vertical impact, but the declining impact has different features. The jet not only has the normal kinetic energy perpendicular to the surface of the target, which can produce a certain depth of erosion crater, but also has a horizontal kinetic energy parallel to the surface of the target, which can cause the crater deviation. When the jet impinges on the target material, the horizontal kinetic energy makes the development direction of the erosion crater gradually deflect along the direction of the jet. This deflection causes that the contact of the jet with the material and the characteristics of the second erosion are changed. Abrasive particle having second erosion capacity no longer evenly act on the around wall of erosion crater, but with a certain level of kinetic energy. So that the second erosion of the inner wall of the erosion crater along the jet direction is more serious, and the material deviated from the jet direction is subjected to less second erosion, thus forming an inclined erosion crater.

In figure 3, comparison between the erosion craters of 50° and 70° shows that the smaller impact angle increases the kinetic energy in the horizontal direction and reduces the kinetic energy perpendicular to the target surface, resulting in an increase of the crater width and a decrease in crater depth. However, when jet is perpendicular to the material surface, the depth and width of the impact crater are not greater than the 70° angle inclination impact crater, because the jet is not easy to discharge from the bottom of the erosion crater and a thicker water cushion layer hinders the continuous jet impinging although the jet has a large vertical kinetic energy. Compared with vertical impact, 70° angle inclination jet has a horizontal kinetic energy so that the discharge of the abrasive water jet is smoother and the water layer at the crater bottom is thinner, which is conducive to the increase in the depth of the target although the normal kinetic energy is less than that of vertical impact.

Through the above research, it is found that the jet angle will affect the material removal efficiency of the abrasive water jet, which directly influences the cutting effect of the abrasive water jet. In the actual cutting process, the relationship between the slope position, the direction of the nozzle movement and the direction of the jet has a great influence on jet rebound and the water cushion layer, which directly affects the cutting effect.

4. Conclusion

In this paper, the AWJC process model is established by SPH coupled FEM method. By measuring the erosion crater sphericity values, the influence of jet angle on the crater shape is obtained, and the simulation results are verified by comparison with the experiment results. Based on the above analysis, the effect of jet angle on the erosion process of pre-mixed AWJ is analyzed. The conclusions of this paper are as follows.

(1) Compared with traditional FEM erosion simulations of single abrasive particle and multi-particle abrasive particles, the results obtained from SPH coupled FEM simulation are closer to the experimental values, which indicates that the FEM coupled SPH method can more truly reflect the AWJ erosion process and its characteristics.

(2) The erosion of AWJ is mainly caused by the first erosion and the second erosion of abrasive particles. The first erosion is mainly responsible for the crater depth increase. The second erosion mainly damages the wall material around the erosion crater, which changes the crater morphology from V type to U type.

(3) The changes of jet angle will affect the second erosion characteristics. When the jet angle is small, the horizontal momentum of abrasive particles increases, resulting in increased damage to the material in the direction of the jet, which will cause the crater morphology to tilt.

(4) When the jet angle is small, increased jet angle can increase the normal momentum of the abrasive particles, so that the depth of the erosion crater increases. When the jet angle increases to a certain value, the jet cannot be smoothly discharged from the erosion crater, making more water gather at the bottom of the crater and weakening the erosion capacity of subsequent jet.

This paper can promote the understanding of the AWJC process as well as enrich the application of mesh-free method in AWJC simulation. However, the AWJC model established by SPH method in this study does not take into account the shape of the abrasive particles, so there is a certain error in the AWJ erosion process simulation. Therefore, the further study on the mesh-free method improvement is necessary.

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References

Ahmed D.H., Naser J., Deam R.T., 2016, Particles impact characteristics on cutting surface during the abrasive water jet machining: numerical study, Journal of Materials Processing Technology, 232, 116–130, DOI: 10.1016/j.jmatprotec.2016.01.032.

Aich U., Banerjee S., Bandyopadhyay A., Das P.K., 2014, Abrasive water jet cutting of borosilicate glass, Procedia Materials Science, 6, 775-785.

Campbell J., Vignjevic R., Libersky L, 2000, A contact algorithm for smoothed particle hydrodynamics, Computer Methods in Applied Mechanics and Engineering, 184(1), 49-65.

Gupta V., Pandey P.M., Garg M.P., Khanna R., Batra N.K., 2014, Minimization of kerf taper angle and kerf width using Taguchi's method in abrasive water jet machining of marble, Procedia Materials Science, 6, 140–149.

Junkar M., Jurisevic B., Fajdiga M., Grah M., 2006, Finite element analysis of single-particle impact in abrasive water jet machining, International Journal of Impact Engineering, 32(7), 1095-1112, DOI: 10.1016/j.ijimpeng.2004.09.006.

Kumar N., Shukla M., 2012, Finite element analysis of multi-particle impact on erosion in abrasive water jet machining of titanium alloy, Journal of Computational & Applied Mathematics, 236(18), 4600–4610, DOI: 10.1016/j.cam.2012.04.022.

Li H.Z., Wang J., 2015, An experimental study of abrasive waterjet machining of Ti-6Al-4V, The International Journal of Advanced Manufacturing Technology, 81(1), 361–369, DOI: 10.1007/s00170-015-7245-5.

Li G.R., Ge Y.F., Zheng Y., Xue X.Q. (2015). The research of stress theoretical analysis and structural parameters of sprayer fluid of rotating conical abrasive jet, International Journal of Heat and Technology, 33(4), 33-40, DOI:10.18280/ijht.330405.

Liu X.H., Liu S.Y., Ji H.F., 2015, Numerical research on rock breaking performance of water jet based on SPH, Powder Technology, 286, 181-192.

Narayanan C., Balz R., Weiss D.A., Heiniger K.C., 2013, Modelling of abrasive particle energy in water jet machining, Journal of Materials Processing Technology, 213(12), 2201–2210, DOI: 10.1016/j.jmatprotec.2013.06.020.

Wen Z.H., Liu Y., Liu X.T., Liang B. (2017). Experimental research into the effects of abrasive characteristics on abrasive gas jet coal-breaking performance, International Journal of Heat and Technology, 35(1), 32-36, DOI: 10.18280/ijht.350105.

Yu F., Wang J.M., Liu F.H., 2012, Numerical simulation of single particle acceleration process by SPH coupled FEM for abrasive waterjet cutting, The International Journal of Advanced Manufacturing Technology, 59(1), 193-200, DOI: 10.1007/s00170-011-3495-z.