2005 WJTA American Waterjet Conference
August 21-23, 2005 • Houston, Texas

Paper 5A-3

ON THE RESIDUAL ENERGY FOR CUTTING PLASTIC MATERIALS WITH ABRASIVE WATER INJECTION JET

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ABSTRACT

Compared with other cutting techniques, abrasive water injection jet cutting is a cool cutting technique that is suitable for cutting under dangerous conditions due to its unique advantages. Based on the theory of erosion, this paper studied the residual energy of abrasive water injection jet after it reaches the maximum cutting depth for plastic materials. It is found that the residual energy is related with various parameters, such as the flow rates of water and abrasive, the physical properties of materials, the nozzle diameter, and the size of abrasive particles. This result could be applied for evaluating the safety of cutting with abrasive water injection jet under certain dangerous environments.

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1. INTRODUCTION

The hot cutting methods use chemical reaction energy or electrical energy to cut materials. As a result, they are not suitable for cutting under dangerous environment and will have thermal effect on materials due to high temperature. The cutting method with abrasive water injection jet (AWIJ) has many advantages over hot cutting methods, such as low temperature, no thermal effect, no dust, and so on. For example, AWIJ can be used for cutting underground at coalmines where there are gases.

In order to evaluate the safety of cutting with AWIJ under certain dangerous circumstances, this paper will study the residual energy of AWIJ after cutting materials.

Song Yongzheng [1] found that the energy of materials resisting the impact of water jet depends on the destructive energy of the materials. Based on analyzing the relationship between parameters of jet and destructive energy of materials, he gave the destructive energy for plastic materials as follow [2]:

$$W = \frac{1}{2}(\sigma_b + \sigma_s)\varepsilon_\mu \tag{1}$$

where, W is the destructive energy for plastic materials; σ_s the yielding limit of material; σ_b the ultimate strength; ε_μ the destructive strain or failure limit at normal testing of strength. Figure 1 indicates the relationship between σ_s, σ_b, and ε_μ.

According to the study on erosion model with water jet by Xin Chengliang [3], there will be permanent deformation on the target material once the contacting stress reaches the yielding stress of the material.

Zhao Yongzan [4] analyzed the energy in cutting industrial ceramic with abrasive water jet. His study results indicated that ceramic material could not be removed before the total energy of the abrasive particles exceeds the volume energy of the ceramic material.

The studies mentioned above did not give the expression for residual energy of water jet. Based on the theory of erosion, this paper studied the residual energy of AWIJ after it reaches the maximum cutting depth for plastic materials.

2. PLASTIC MATERIALS CUTTING BY AWIJ

For plastic materials, any plastic deformation will be permanent. In the process of cutting with AWIJ, the energy of AWIJ decreases with the increasing of cutting depth. The maximum cutting depth means the AWIJ cannot cut any further, that is to say, the energy of AWIJ at that moment is not enough to produce plastic deformation on the target material. Only elastic deformation is produced after the maximum cutting depth. Therefore, it is assumed that the residual energy of

AWIJ after the maximum cutting depth is the energy just enough to produce elastic deformation on the target material.

For soft ductile materials, their weight often appears to increase at first when they are eroded by solid particles. After a period of continuous erosion, the weight of materials begins to reduce. The loss of weight is proportional to the quantity of the abrasive particles. With the increase in impacting speed of the particles, the period of weight increasing becomes shorter. Each impact of the abrasive particles will produce deformation, or strain, on the material surface. When the strain produced by numerous particles reaches the critical strain, the material will be removed, that is, cutting scraps are formed and separated from the material. This critical strain must be the performance of the material. It can be used to measure the plasticity of material under erosion. Similar to other performances of materials, the critical strain can be used as a criterion to determine the average plastic strain needed for removing the material by erosion.

3. RESIDUAL ENERGY OF AWIJ AFTER CUTTING

Considering the material is unequally impacted by numerous abrasive particles with the same speed. The same plastic deformation, or an average strain Δe_p, is formed at the target material with each impact. For simplification, it is assumed that each impact of abrasive particle produces a strain increase Δe_p. If N_f represents the average impacting number needed to remove material and we treat the impact erosion as low cyclic fatigue problems, then the equation

$$\Delta e_p N_f^b = \frac{1}{2}\varepsilon_\mu \tag{2}$$

is obtained, based on the Manson-Coffin laws. Where, ε_μ is the destructive strain or failure limit at normal testing of strength; *b* is a coefficient determined by testing, it is about 0.5 for most metals under single loading [5]. So that, the failure criterion will give

$$\Delta e_p N_f^{\frac{1}{2}} = e_c \tag{3}$$

Where, e_c is the critical strain.

According to this model, the material will not be removed during erosion before the critical strain is reached. Assuming that the particle is a rigid ball with a radius *r* and density ρ_b, as shown in Figure 2, then its mass will be

$$m = \frac{4}{3}\pi r^3 \rho_b \tag{4}$$

In Figure 2, the double-dot chain lines show the shape before collision, while the solid line is the shape after deformation. When the plastic material is impacted by particles, it will produce a resistance or a constant stress P to prevent the particles from getting into the material. This resistance or stress can be seen as a hardness of the material. And because it is related with impacting velocity, it can be seen as the dynamic hardness of the material. In consideration of energy equilibrium, all the kinematic energy of particles is consumed on the plastic deformation. Then, the volume of deformation will be

$$V = \frac{mv^2}{2P} \tag{5}$$

Where, v is the impact speed of particles.

The initial kinematic energy of particles is equal to the work done by pressing, then the radius of pressing is

$$a = \sqrt{2}rv^{0.5}(\frac{2\rho_b}{3P})^{0.25} \tag{6}$$

The surface area affected by one impact is πa^2. Then the particle number needed for the area A to be impacted N_f times is $N_f \cdot \frac{A}{\pi a^2}$. The amount of abrasive needed before removing material is

$$M_f = m \cdot N_f \cdot \frac{A}{\pi a^2} \approx \frac{4}{3}\pi r^3 \rho_b N_f \frac{A}{\pi a^2} \tag{7}$$

Sun Jiashu showed that the average strain caused by pressing is about $0.2a/r$, that is, $\Delta e_p = 0.2a/r$. [5] Then from equation (3), we have

$$N_f \approx \frac{1}{0.04} \cdot \frac{e_c{}^2 r^2}{a^2} \tag{8}$$

Substituting (8) into (7), then

$$M_f \approx \frac{1}{0.03} r^5 e_c^2 A \frac{\rho_b}{a^4} \tag{9}$$

Substituting (6) into (9), then

$$M_f \approx 12.5 e_c^2 AP \frac{r}{v^2} \tag{10}$$

The above equation indicates that the amount of abrasive needed to remove material is proportional to the dynamic hardness of material.

Assuming that the abrasive water jet does not diffuse during cutting, then the contact area of particle with target material is

$$A = 2r_j V_n t \tag{11}$$

Where, r_j is the radius of nozzle; V_n the traverse rate of the nozzle; t the impacting time.

The amount of abrasive can be calculated by the flow rate of abrasive m_a:

$$M_f = m_a t \tag{12}$$

From (10), (11) and (12), it can be followed that the velocity of abrasive particles after the maximum cutting depth will be

$$v = \left(\frac{25 e_c^2 r_j P\, r V_n}{m_a} \right)^{0.5} \tag{13}$$

In AWIJ, the velocities of abrasive and water are almost the same. The residual energy of AWIJ is mainly the kinematic energy of abrasive and water after cutting. After the maximum cutting depth, the residual energy per unit time is

$$E_{sl} = \frac{1}{2}(m_a + \rho Q) v^2 \tag{14}$$

Where, Q is the flow rate of water, ρ the density of water.

Substituting (13) into (14), then

$$E_{sl} = 12.5(m_a + \rho Q) \cdot \frac{e_c^2 r_j P\ r V_n}{m_a} \tag{15}$$

4. CONCLUSION

With various advantages over other hot cutting tools, abrasive water jet is a possible tool for cutting under dangerous environments, such as coalmines. Although sparks may be produced during cutting with AWIJ, the energy of these sparks may not be large enough to ignite gases and cause explosion.

Based on the theory of erosion, this paper studied the residual energy of AWIJ after it reaches the maximum cutting depth for plastic materials. It is followed that the residual energy can be expressed as

$$E_{sl} = 12.5(m_a + \rho Q) \cdot \frac{e_c^2 r_j P \; r V_n}{m_a} \tag{16}$$

It is can be seen from equation (16) that the residual energy is related with various parameters, such as the flow rates of water and abrasive, the physical properties of materials, the nozzle diameter, and the size of abrasive particles. This result could be applied for evaluating the safety of cutting with AWIJ under dangerous environments. It will provide theoretical basis for designing cutting system applying at dangerous environments.

5. ACKNOWLEDGMENTS

This research is partially supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Scientific Research, 15510141, 2003-2006.

6. REFERENCES

[1] Song Yongzheng, Wen Xiaokang, Liang Zhiqiang, Comparison of abrasive cutting with laser and plasma cutting, China Mechanical Engineering, 1994; 5: 8-10

[2] Song Yongzheng, Wen Xiaokang, Liang Zhiqiang, Mechanical property and its model of high pressure abrasive water jet cutting, Forge Machinery, 1995; 3: 37-39

[3] Zhao Yongzan, Wang Jun, Zhao Min, Experimental study on mechanism of cutting materials with abrasive water jet, Journal of Harbin University of Commerce (Natural Sciences Edition), 2002; 18(3): 298-302

[4] Xin Chengliang, Prospects of water jet technology and discussion on technological innovation in the field of safety engineering projects, China Safety Science Journal, 2000; 10: 48-52

[5] Sun Jiashu, Erosion of metal, Press of Metallurgy Industry, 1992

[6] Liu Lang, Guo Chuwen, et al, Discussion on abrasive water jet cutting in dangerous environment of coal mine, Coal Mine Machinery, 2003; 4: 29-31

[7] Liu Lang, Guo Chuwen, et al, Design of experimental system on abrasive water jet cutting in dangerous environment at coal mines, Coal Mine Machinery, 2003; 8: 4-5

7. NOMENCLATURE

A	the contact area of particle with target material
a	the radius of pressing

b	a coefficient determined by testing
e_c	the critical strain
m_a	the flow rate of abrasive
M_f	the amount of abrasive needed before removing material
N	times of impacts
N_f	the average impacting number needed to remove material
P	the dynamic hardness of the material
Q	the flow rate of water
r	the radius of particle
r_j	the radius of nozzle
t	the impacting time.
v	the impact speed of particles
V_n	the traverse rate of the nozzle
W	the destructive energy for plastic materials
ε_μ	the failure limit or destructive strain at normal testing of strength
Δe_p	the average strain
σ_s	the yielding limit of material
σ_b	the ultimate strength
ρ	the density of water
ρ_b	the density of particle

8. GRAPHICS

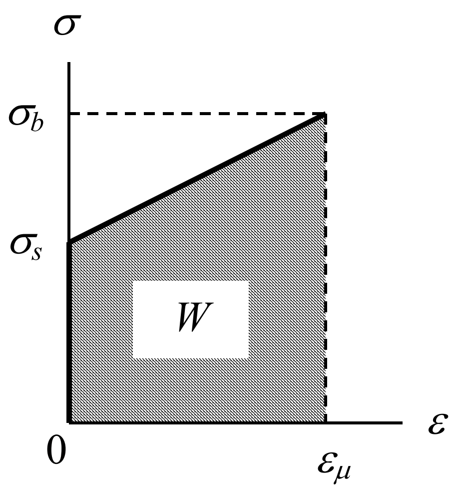

Figure 1 The relationship between σ_s, σ_b, and ε_μ.

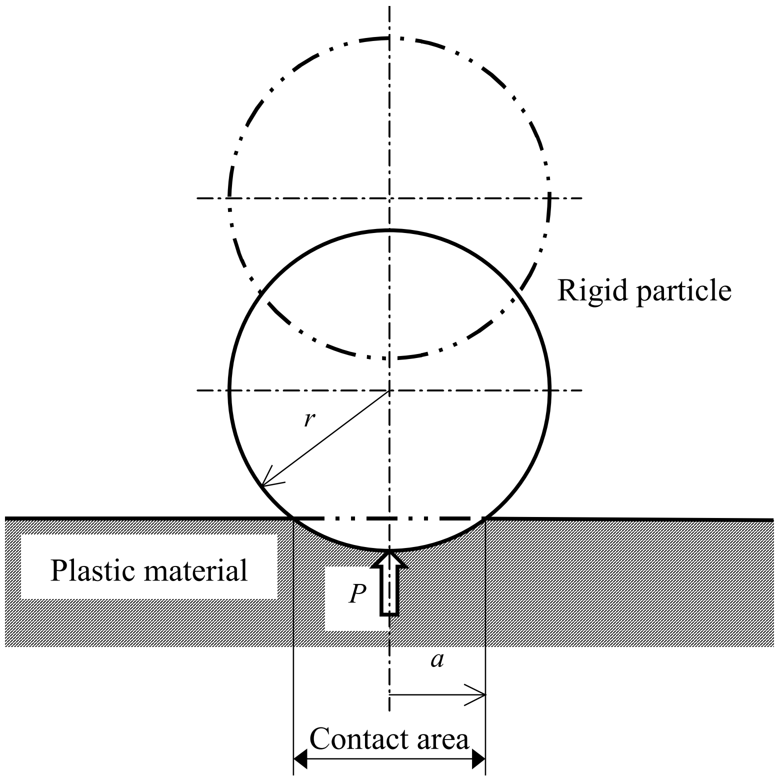

Figure 2 Deformation model of an abrasive particle