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CUTTING CAPABILITY EQUATION OF ABRASIVE SUSPENSION JET

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ABSTRACT

The Abrasive Suspension Jet (ASJ) has great potential for cutting materials due to its high power, but its cutting capability is not very explicit. This paper explores the establishment of cutting capability equation of ASJ theoretically and experimentally. Firstly, based on fluid mechanics, the abrasive power of ASJ is deducted; secondly, based on Rittinger's theory, the debris surface area generation is directly proportional to the abrasive power of ASJ, the cutting capability equation of ASJ has been developed. Moreover, the paper presents a series of cutting tests using ASJ, the cutting capability equation is found to agree well with experimental results. The conclusions are drawn following: the cutting capability of ASJ is proportional to the abrasive power and abrasive size of ASJ; the cut depth increases with pressure, nozzle diameter, abrasive size and abrasive concentration; and decreases with traverse speed and standoff distance; the cutting capability and the cut depth is directly proportional to the pressure to the power of 1.5, the pressure is the most influential parameter in ASJ cutting.

1. INTRODUCTION

The Abrasive Suspension Jet (ASJ) has great potential for cutting materials in various applications due to its high power. The ASJ cutting is a complex process involving the interactions of several factors. However, the fundamental reasons behind the process have not been well established, the cutting capability of ASJ and what and how the factors in ASJ cutting process to influence the cutting capability have not been clear.

Many researchers tried to investigate the cutting capability of ASJ experimentally [1][2][3], few published papers or reports attempted to explore the cutting capability equation of ASJ both theoretically and experimentally. Miller [4][5] presented a procedure for predicting the cut surface area generation per minute by ASJ operating at pressures up to 1000 bar. Based on straight line cutting of stainless steel, the cut surface area generated per minute was given by:

$$CSA = 3D \times P \times MF \times QF \times ACF$$

Where: CSA is the cut surface area generated per minute, mm^2 /min.
D is the jet diameter, mm.
P is the water pressure, bar.
MF is the machine ability factor, 1 for stainless steel 304L.
QF is the quality factor, 1 for a good edge quality.
ACF is the abrasive concentration factor, 1 for 10 percent abrasive by weight.

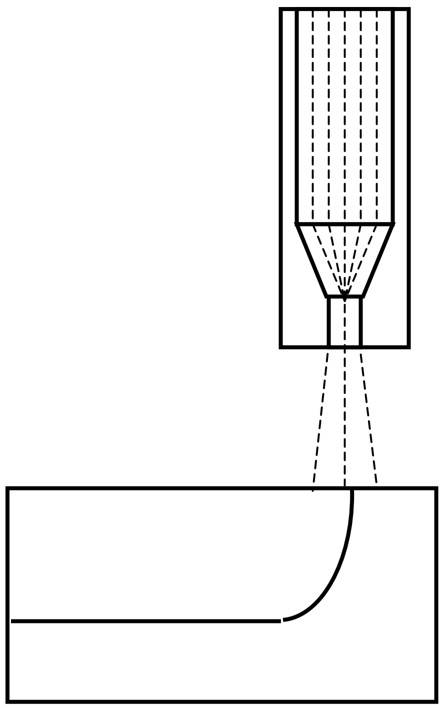
Above equation showed that the cut surface area generation is directly proportional to the pressure, nozzle diameter, and abrasive concentration, and is not related with the abrasive size.

We have applied ASJ for semiconductor industry successfully and developed a unique ASJ singulation. The ASJ singulations can cut substrate and wafer with width down to 0.05mm and speed up to 200mm/s, provide a cost-effective cutting process for any material with both straight line and curvilinear edges, make the highest quality cut. At same time, we could use the singulation to finish a series cutting experiments to achieve the object of exploring the cutting capability of ASJ.

This paper presents our efforts to explore the establishment of cutting capability equation of ASJ theoretically and experimentally. Firstly, based on fluid mechanics, the abrasive power of ASJ is deducted; secondly, based on Rittinger's theory, the debris surface area generation is directly proportional to the abrasive power of ASJ, the cutting capability equation of ASJ has been developed. Moreover, the paper presents a series of cutting tests using ASJ, the cutting capability equation is found to agree well with experimental results. The conclusions are drawn following: the cutting capability of ASJ is proportional to the abrasive power and abrasive size of ASJ; The cut depth increases with pressure, nozzle diameter, abrasive size and abrasive concentration; and decreases with traverse speed and standoff distance; The cut depth is directly proportional to the pressure to the power of 1.5, the pressure is the most influential parameter.

2. THEORETICAL ANALYSIS

The premixed abrasive suspension is pushed out through a nozzle by high pressure to form the powerful ASJ so to cut a kerf on the workpiece. **Figure 1** shows a schematic of cutting workpiece with ASJ and lists its parameters. There are three-group parameters in the ASJ cutting process, and the cutting capability of ASJ is determined mainly by the abrasive power of ASJ.



Abrasive Parameters:
- Abrasive size, S
- Abrasive concentration, C
- Abrasive density, ρ_a

Power Parameters:
- Pressure, P
- Nozzle diameter, D

Jet Parameters:
- Spreading angle, α
- Stand off distance, D_s

Cutting Capability:
- Traverse speed, u
- Cutting depth, h
- Cutting width, w
- Debris size, S_d

Figure 1. ASJ cutting workpiece and parameters involved

2.1 Abrasive Power of ASJ

Let us explore the relation between the abrasive power of ASJ and the ASJ parameters firstly. Supposing that the abrasive is premixed in the water; the density of abrasive suspension ρ is decided by the density of the abrasive ρ_a, the density of the water ρ_w, and the abrasive concentration C, and followed the equation:

$$\rho = \frac{1 + C}{1/\rho_w + C/\rho_a} \qquad (1)$$

The velocity v of ASJ is related strongly with the water pressure P and the density of abrasive suspension ρ complying the theory of fluid mechanics:

$$v^2 = 2P/\rho \qquad (2)$$

The abrasive flow rate $\dot{M}_a$ by mass though a nozzle equals to:

$$\dot{M}_a = \frac{\pi}{4} D^2 v \rho \frac{C}{1+C} = \frac{\pi}{4} D^2 \sqrt{2P\rho} \frac{C}{1+C} \tag{3}$$

Where, D is the nozzle diameter.
So, the abrasive power of ASJ N can be calculated as the following:

$$N = \dot{M}_a \bullet \frac{1}{2} v^2 = \dot{M}_a P / \rho = \frac{\pi}{4} D^2 P^{1.5} \sqrt{\frac{2}{\rho}} \frac{C}{1+C} \tag{4}$$

Equation (4) shows that the abrasive power of ASJ N is decided by the nozzle diameter, the pressure, the abrasive concentration and the density of abrasive suspension. The abrasive power of ASJ N is proportional to the pressure raised to exponent 1.5.

2.2 Debris Surface Area Generation

When ASJ is cutting the workpiece, the kerf material is impacted to a lot of fine debris by high power abrasive. Suppose that the debris size is S_d, the debris surface area is proportional to S_d^2 and the debris volume is proportional to S_d^3; the kerf volume generation equals to the multiplication of cut depth h, traverse speed u, and cut width w. Whole debris surface area generation A is proportional to the multiplication of the number of debris generation and the debris surface area S_d^2:

$$A \propto \frac{huw}{S_d^3} S_d^2 \propto \frac{huw}{S_d} \tag{5}$$

The debris size S_d is smaller than the abrasive size S and is proportional to the abrasive size,

$$S_d \propto S \tag{6}$$

So the debris surface area generation is proportional to the kerf volume generation huw and inversely proportional to the abrasive size S :

$$A \propto \frac{huw}{S_d} \propto \frac{huw}{S} \tag{7}$$

2.3 Cutting Capability of ASJ

The mechanism that the kerf material is impacted to fine debris by high power abrasive in ASJ cutting is very similar to the mechanism of comminuting fine particle with high pressure water. In fine particle comminuting with high pressure water jet, the energy required is proportional to the new surface area formed, which comply with Rittinger's Theory [6]. It is reasonable to deduce that the debris surface area generation A is directly proportional to the abrasive power N of ASJ:

$$A \propto N \tag{8}$$

Substituting Equation (4) and Equation (7) into Equation (8), we can get the equation of the cut kerf volume generation huw:

$$huw = KD^2 P^{1.5} \frac{1}{\sqrt{\rho}} \frac{C}{1+C} S \tag{9}$$

Where, K is a constant.

From equation (9), we can get the equation of the cut kerf area generation hu:

$$hu = KD^2 P^{1.5} \frac{1}{\sqrt{\rho}} \frac{C}{1+C} S \frac{1}{w} \tag{10}$$

Since the ASJ will spread with a spreading angle α after pushed out from the nozzle, the cut width w at top of kerf has a relation with the nozzle diameter, the spreading angle α and the stand off distance D_s:

$$w = D + \tan(\alpha) \times D_s \tag{11}$$

Substituting Equation (11) into Equation (10), we have:

$$hu = KDP^{1.5} \frac{1}{\sqrt{\rho}} \frac{C}{1+C} S \frac{1}{1+\tan(\alpha) D_s / D} \tag{12}$$

Equation (12) can be called as the cutting capability equation of ASJ. It shows that the cutting capability hu of ASJ is proportional to the pressure raised to exponent 1.5, the nozzle diameter, the abrasive size and abrasive concentration.

When the traverse speed is fixed, we can use the cut depth to represent the cutting capability of ASJ. From equation (12), the cut depth h of ASJ:

$$h = KDP^{1.5} \frac{1}{\sqrt{\rho}} \frac{C}{1+C} S \frac{1}{(1+\tan(\alpha) D_s / D) u} \tag{13}$$

If the nozzle standoff distance D_s is short, the $w \approx D$, then the cut depth is:

$$h \approx KDP^{1.5} \frac{1}{\sqrt{\rho}} \frac{C}{1+C} S \frac{1}{u} \tag{14}$$

Equation (14) shows that the cut depth is proportional to the pressure raised to exponent 1.5, the nozzle diameter, the abrasive size and abrasive concentration, inversely proportional to the traverse speed.

3. EXPERIMENTAL STUDY

We have looked at the factors influencing the cut depth in ASJ cutting process theoretically. In this section, we will show a series experiment results and look at the actual effect of parameters in ASJ cutting process.

3.1 Pressure

Pressure experiments were finished with pressure ranged between 0 to 10 KPSI. **Figure 2** shows the results of the pressure experiments conducted using parameter settings listed. Increased water pressure is without doubt beneficial to ASJ cutting capability and to the cut depth. Furthermore, the experiment data collected show that the cut depth is directly proportional to the pressure to the power of 1.5, which is good agreement with the theoretical analysis, Equation (14).

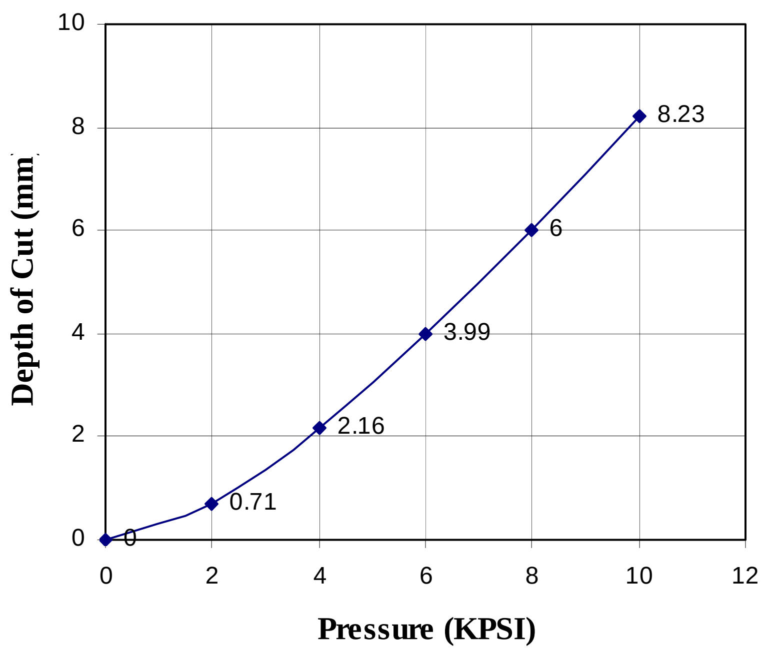


Figure 2. Effect of Pressure on depth of cut
(D=0.22mm, S=0.063mm Aluminum Oxide, C=30%,
D_s = 0.15mm, u=5mm/s, Workpiece=Aluminum Plate)

3.2 Nozzle Diameter

The exponent of nozzle diameter is 1 in the Equation (14) of cut depth. **Figure 3** depicts the linear relationship between the nozzle diameter and the cut depth got from the experiments, which is good agreement with the theoretical analysis, Equation (14). This confirms that larger nozzles cause much increase in cut depth under fixed pressure and abrasive concentration conditions.

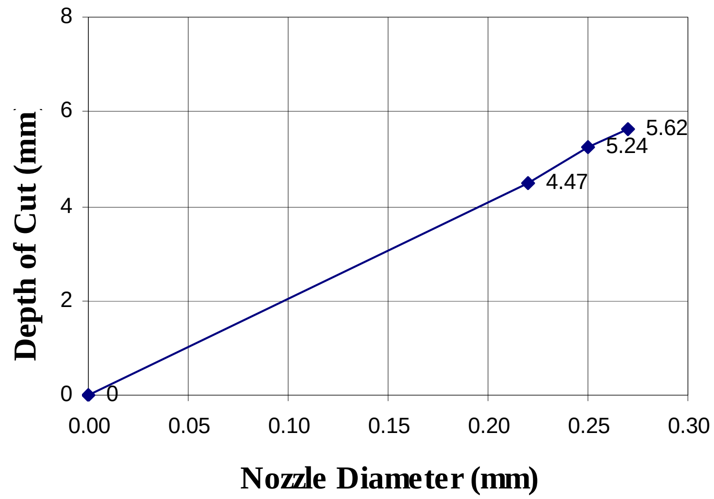


Figure 3. Effect of waterjet nozzle diameter on depth of cut (P=10KPSI, S=0.063mm Aluminum Oxide, C=30%, D_s = 0.15mm, u=10mm/s, Workpiece=Aluminum Plate)

3.3 Abrasive Size

Figure 4 show that there exists an optimum abrasive size for the maximum cut depth for a given nozzle diameter, the optimum abrasive size is 0.35 mm in the experiment.

Within the optimum abrasive size, increasing abrasive size led to an increase in cut depth, because larger particle sizes are more beneficial in ASJ cutting if they are sized to freely pass trough nozzle. There is a nearly linear relationship between the abrasive size and the cut depth got from the experiments, which is consistent with the theoretical analysis, Equation (14).

Beyond the optimum abrasive size, increasing abrasive size led to a decrease in the cut depth. From an energy transfer point of view there are a number of aspects to this phenomenon. Generally bigger sizes can carry more energy; but the same abrasive concentration carries a lower number of particles. Bigger abrasives can create bigger debris; but bigger abrasive cannot accelerate as fast as smaller ones because of their higher drag coefficient.

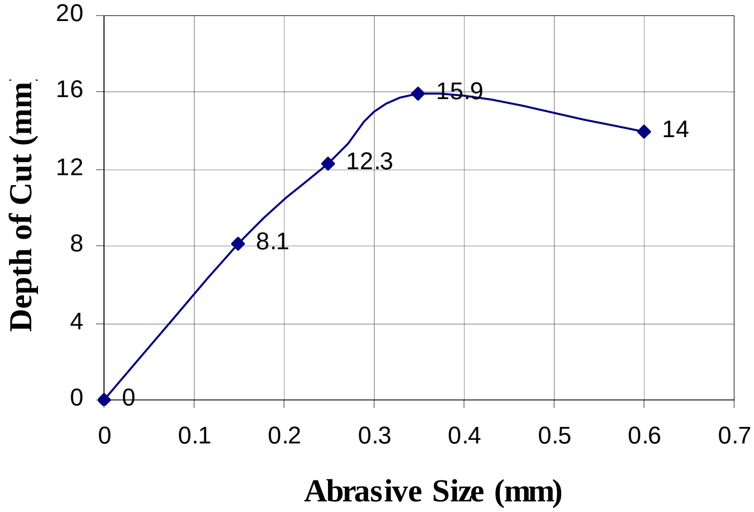


Figure 4. Effect of abrasive size on depth of cut [2]
(*P* = 8.9 MPa, D=2.5mm, C= 10%, D_s = 10mm, *u* = 2.5mm/s)

3.4 Abrasive Concentration

The effect of abrasive concentration was tested by cutting silicon carbide, alumina-reinforced silicon carbide, aluminum oxide, and alumina [3]. **Figure 5** show that there exists an optimum abrasive concentration for the maximum cut depth. When the value of abrasive concentration is ranged from 5% to 25%, increase in abrasive concentration increases the depth of cut. As observed with other metals, the maximum cut depth occurred at abrasive concentration 25%. This indicates that abrasives may be interfering with each other during cutting or crowding in the nozzle and gaining less velocity. Also, the increase in abrasive mass with associated increase in suspension density will result in a slower jet.

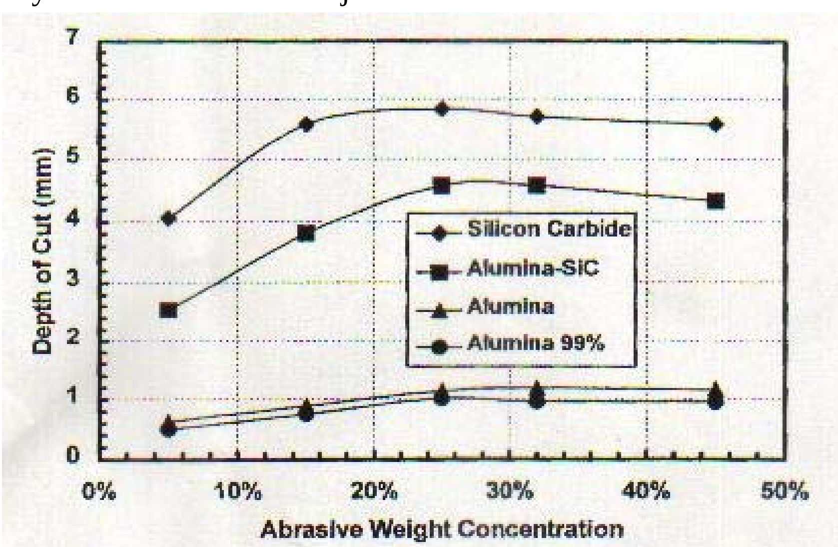


Figure 5. Effect of Abrasive Concentration on Ceramic Cutting [3]
(*P* = 207 MPa, D=0.23mm, S=220 mesh garnet,
u = 0.9mm/s, D_s = 2.54mm, *C2* = 0.9% SUPER-WATER,)

3.5 Traverse Speed

Figure 6 presents a plot of cut depth vs. nozzle traverse speed obtained in ASJ cutting of an aluminum plate at 10 KPSI pressure. As a result, the experimental data is similar to the result of our theoretical analysis, an increase in traverse speed generally reduce the cut depth. But the exponent of traverse speed is around -0.86 experimentally not –1 theoretically. The reason is that abrasives may be interfering with each other during cutting when the traverse speed is slow, which results in the cut depth reducing. Another reason is that the debris size may be smaller when the traverse speed is slower, which causes the more energy needed so to decrease the cut depth.

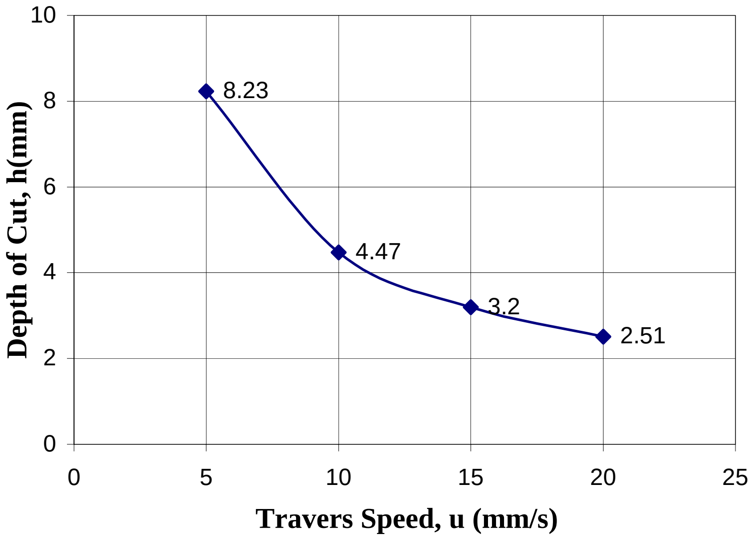


Figure 6. Effect of Traverse rate on depth of cut
(P = 10KPSI, D=0.22mm, S=0.063mm Aluminum Oxide, C=30%,
D_s = 0.15mm, Aluminum Plate)

3.6 Stand Off Distance

Since the ASJ will spread with a spreading angle α, the cut width w with the nozzle diameter, the spreading angle α and the stand off distance D_s, Equation (11). As the stand off distance was raised, the cut width would be increased, so that the cut depth would be decreased. **Figure 7** shows a trend for a decreasing cut depth as the standoff distance increases in our experiments. The exponent of standoff distance is around -1 experimentally, which is consistent with the theoretical analysis, Equation (13). The cut depth and the cut quality is the biggest as the standoff distance is 0.15mm in our experiments.

Figure 7 also shows a trend for an increasing cut width as the standoff distance increases in our experiments. We observe that the cut width is substantially larger than the nozzle diameter of 0.22 mm. This deviation is of course due to jet spreading. We also observe that the cut width at the top of kerf is substantially larger than the cut width at the middle of kerf, there is a significant taper in the cut kerf.

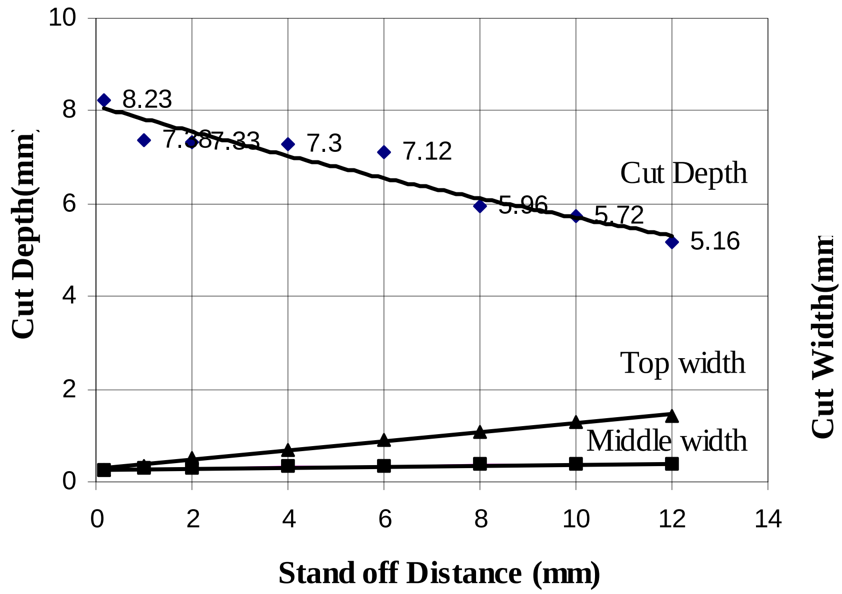


Figure 7. Effect of standoff distance on depth of cut
(P = 10KPSI, D=0.22mm, S=0.063mm Aluminum Oxide, C=30%, u=5mm/s, Aluminum Plate)

4. CONCLUSIONS

The following conclusion can be drawn from this paper:

- The cutting capability of ASJ is proportional to the abrasive power and the abrasive size of ASJ.
- The cutting capability and the cut depth are directly proportional to the pressure to the power of 1.5. Pressure is the most influential parameter which control the cut capability of ASJ.
- The cut depth is directly proportional to the nozzle diameter.
- There exists an optimum abrasive size for a given nozzle diameter. Within the optimum abrasive size, the cut depth is directly proportional to the abrasive size; beyond the optimum abrasive size, increasing abrasive size led to a decrease in the cut depth.
- There exists an optimum abrasive concentration. The cut depth is initially proportional to the abrasive size; beyond the optimum abrasive concentration, increasing abrasive concentration led to a decrease in the cut depth.
- An increase in traverse speed generally reduces the cut depth. But the exponent of traverse speed is around -0.86 experimentally not –1 theoretically.
- As the stand off distance was raised, the cut width would be increased approximately linear, the cut depth would be decreased approximately linear.

5. REFERENCES

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6. NOMENCLATURE

A — the debris surface area generation
C — the abrasive concentration with water by weight
D — the nozzle diameter, mm
D_s — the stand off distance between the nozzle and workpiece, mm
h — the cut kerf depth, mm
hu — the cut kerf area generation, the cut capability
huw — the cut kerf volume generation
K — the constant
$\dot{M}_a$ — the abrasive flow rate by mass
N — the abrasive power in ASJ, J
P — the water pressure, bar
S — the abrasive size, mm
S_d — the debris size, mm
u — the cut traverse speed, mm/s
v — the ASJ speed, mm/s
w — the cut kerf width, mm
ρ — the density of the abrasives suspension
ρ_a — the density of the abrasive
ρ_w — the density of the water
α — the spreading angle of ASJ