Gas-Particle Two-Phase Jet Flow from Slot Nozzle and Micro-Blasting Process*

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Recently, the micro-blasting process has been widely used to process brittle material, and a conventional circular nozzle has been commonly used. But the cutting performance of a circular nozzle does not process a large area well, so the use of a slot nozzle is considered. In this study, in order to improve the cutting performance of the micro-blasting nozzle, a new slot nozzle with a large aspect ratio is proposed and the flow characteristics and cutting performance are examined precisely by experimental and numerical analyses. The main results show that (1) setting the circular vane in the slot nozzle perpendicular to the stream can diffuse particle flow uniformly at the nozzle exit, making the particle velocity distribution uniform, (2) expanding the nozzle outlet at an angle, uniform air and particle velocity distributions at the nozzle exit can be obtained, (3) in spite of setting obstacles at the nozzle, a fine cutting efficiency is obtained compared to the conventional micro-blasting circular nozzle.

Key Words: Multi-Phase Flow, Jet, Nozzle, Flow Control, Micro-Blasting

1. Introduction

The machining technology supporting the rapid growth industries, such as semiconductor, electrical and electronic industries, the fine processes of drilling, grooving, etc., with high accuracy and high efficiency have been desired moreover.

There are many methods for fine processes, such as wet and dry etching, laser, electronic discharge, ultra sonic or drilling, and so on. However, micro-blasting process by particle laden impinging air jet flow with the order of 10 μ m particles has been increasing in order to process brittle materials, such as glass or ceramic, as the fine process for high accuracy and productivity⁽¹⁾ (where the micro-blasting process, MBP, is the machining process that makes a micro fracture by impinging high speed gas-solid two phase flow with fine particle to work piece surface. This process proceeds as collection of micro fracture. Pattern accuracy is controlled by high accuracy pho-

tolithography resist masking).

In MBP, a circular nozzle is used commonly, yet it takes a large number of scanning times to process a wide area, and then a long machining time. On the other hand, setting a lot of circular ones to obtain high productivity causes high equipment cost and low maintenance ability because of its complexity.

Recently, use of a two-dimensional rectangular nozzle, slot nozzle, has been considered to process a large area with high efficiency⁽²⁾. However, it is difficult to obtain uniform and high accuracy for cutting depth over the nozzle width.

In this study, in order to improve the cutting performance of an MBP nozzle, a new rectangular nozzle with a large aspect ratio is proposed and the flow characteristics and cutting performance are examined precisely by experimental and numerical analyses. As a result, the new rectangular nozzle showed a high accuracy over the nozzle width and high cutting performance.

2. Experimental Apparatus and Procedure

2.1 Nozzle

Figure 1 shows the newly proposed nozzle and coordinate system. Figure 1 (a) represents the basic nozzle designed in reference to the diffuser⁽³⁾. It has a two-dimensional rectangular shape at the cross section of the

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Fig. 1 Details of new rectangular nozzle

nozzle outlet. Particle laden flow with a constant mass loading ratio in circular pipe ($\phi = 32$ mm) flows into the nozzle inlet (square cross section: 32×32 mm) and then it expands to 100 mm width in the y direction (expansion angle: $\alpha = 38^\circ$). The width of the nozzle outlet is constant at 100 mm. The depth of the nozzle (z direction) converges linearly to 1 mm (nozzle height, h) from nozzle inlet to 10 mm upstream of the nozzle outlet, and the 10 mm length from there to the nozzle outlet is parallel to the 1 mm depth (hereafter, it is called the 1st nozzle).

The other nozzles in Fig. 1 (b) and (c) with the vane, plate or circular shaped vane are also used in order to create uniform air flow and to diffuse the particle uniformly at the nozzle outlet.

Figure 1 (d) and (e) shows the new nozzles for uniforming more the flow at the nozzle exit. Figure 1 (d), the 2nd nozzle, shows the nozzle with 140 mm width at the outlet expands at a constant angle from nozzle inlet to outlet, and Fig. 1 (e), the 3rd nozzle, shows the nozzle with 160 mm outlet width which expands more linearly from the middle section of nozzle.

Figure 1 (f) shows some symbols and the coordinate

system used. The origin o is located on the nozzle center at the outlet, x , y and z coordinates are taken as in the downstream, width and height directions, respectively. The velocity of the x direction is u , the maximum velocity at the nozzle outlet is u_0 and the centerline air and particle velocity are u_c and $u_{p,c}$, respectively. p_0 and p_∞ are supplied air pressure and ambient pressure, respectively.

For the purpose of comparison of the process efficiency, conventional MBP nozzles having a circular outlet appearing in Fig. 2 are also used. The suction and pressure type nozzles supply the particle by injected air flow from the opened particle tank and closed pressurized particle tank, respectively.

2.2 Experimental apparatus

The air from the air compressor is introduced into the nozzle after adjusting the flow rate by inverter and air valves and then issued into the atmosphere from the nozzle exit. The jet temperature T_a was measured by thermocouples set at the inner pipe wall surface located in upstream of the nozzle.

The jet velocity u was measured by a Pitot tube with 0.8 mm inner diameter, and the effect of compressibility

Fig. 2 Conventional nozzles

of air was considered because the nozzle exit velocity was a little large, almost 200 m/sec in most cases. The tuft was used to measure jet direction for reference since the velocity has a y direction component.

The MBP experiment was carried out as follows. First, the glass plate as a work-piece was set normal to the mainstream of the nozzle-plate distance $H/h = 15 = \text{const.}$ Second, the screw type particle feeder fed the particle constantly within $\pm 5\%$ of feeding accuracy into the upstream flow of nozzle, and then the particle laden jet with a uniform concentration impinged on a work-piece after passing through in the nozzle. Particle was collected in a dust collector after being issued to the workpiece. The nozzle was fixed and the work-piece was transferred in the z direction at 3 mm/sec speed. The cutting depth was obtained by measuring the cutting cross section by surface roughness measurements (Tokyo-Seimitsu, Surfcom-1400D). In this study, the accuracy of cutting depth was defined by the rate of difference between maximum and minimum cutting depths, $d_{\max}$ and $d_{\min}$, in the area of 80% length l_i of cutting width.

$$\zeta = \pm \left(\frac{d_{\max} - d_{\min}}{2d} \right) \times 100 \quad (1)$$

Removal weight of the work-piece was measured by electrical precision balance (A&D, GR-200).

The behavior and velocity of the particle was measured by PIV (TSI, 2D-PIV System) to analyze image data from a CCD camera. The Nd-Pb YAG laser (New Wave Research, Solo-I-15 Hz, 15 mJ/cm²) was used as a light source for flow visualization. The laser-light, which expands like a sheet by cylindrical lens exposed the flow field at time interval of 3.0 μsec , and the CCD camera could take the flow region of 200 $\times$ 260 mm. The velocity vector was analyzed in a small fragment divided into a 1.0 $\times$ 1.0 mm area. The average value of the velocity vector for 50 times measurements (100 frames) was used as the

Table 1 Test condition

Item	Data
Particle (abrasive)	JIS-GC#600 (Ave. dia. 25 μm) Specific gravity : 3 170 kg/m ³
Loading ratio, LR	0.06 $\sim$ 0.38
Impinging distance, H	15 mm ($H/h=15$)
Supplied pressure, ($p_0 - p_\infty$)	0.025 $\sim$ 0.200 MPa
Workpiece transfer speed	3 mm/sec
Workpiece material	Soda lime glass ($\text{Na}_2\text{CaO}5\text{SiO}_2$)

experimental value. The errors of particle velocity measured by PIV were within 15%. In order to visualize the particle concentration, the reflection light from the particle was also taken by the CCD camera.

2.3 Experimental condition

Table 1 shows the particle properties and experimental conditions. For the experiment of air single-phase flow characteristics, the supplied air pressure at upstream of nozzle is $(p_0 - p_\infty) = 0.025 \text{ MPa}$ ($u_0 \approx 200 \text{ m/sec}$) for the measurements of velocity and pressure distributions. For the MBP experiment, $(p_0 - p_\infty) = 0.100 \text{ MPa}$ ($u_0 \approx 360 \text{ m/sec}$), and the experiment of machining efficiency ($p_0 - p_\infty$) was changed from 0.050 to 0.200 MPa. The particle presented was silicon-carbide abrasive (mean particle diameter: 25 μm), and for the measurement of particle velocity vector, the mass loading ratio was $LR = 0.06 = \text{const.}$, for the MBP experiment, $LR = 0.10 = \text{const.}$, and for the machining efficiency, the mass flow rate was $m = 1000 \text{ g/min} = \text{const.}$ ($LR = 0.15$ to 0.38).

3. Numerical Analysis

In this study, in order to estimate the effect of various parameters on the flow characteristics in nozzle and jet flow, two-dimensional numerical analysis by the software (Fluid technology, CFD-2000) was introduced, which consisted of mass and energy conservation, and the standard turbulence $k-\varepsilon$ model (k : turbulence kinetic energy, ε : turbulence dissipation rate) was used.

Figure 3 shows the computational domain and coordinate system. The computational domain for the $x-z$ plane at $y = 0$ is the area of $x/h = 500 \times z/h = 200$, and it divides into non-uniform fragments of 150×100 . The pressure gives $(p_0 - p_\infty) = 0.025 \text{ MPa} = \text{const.}$ at the nozzle inlet and gives atmospheric pressure at the nozzle outlet as a boundary condition.

Velocity distribution of particle was obtained as following condition, a unit spherical particle flow down without particle-particle and particle-nozzle wall collision, also interaction between particle and fluid is not considered (one way method).

Fig. 3 Computational domain

Fig. 4 Cutting cross section by MBP (1st nozzle)

Fig. 5 Velocity distribution of air free jet (1st nozzle)

4. Result and Discussion

4.1 Cutting performance of the 1st nozzle

Figure 4 shows the cutting cross section of the 1st nozzle by MBP. The cutting depth d takes a maximum value at the center of nozzle ($y/h = 0$), and the cross section is a concave shape almost symmetric with the center.

Figure 5 shows the velocity distribution of the air free jet. Air distribution u/u_0 shows the saddle shaped distribution which appears large at the outer edge of the distribution. Also uniformity velocity width at each cross section of x becomes small toward downstream as shown by the dotted line in Fig. 5 since it declines by shearing with ambient fluid.

Figure 6 shows a particle concentration and particle velocity vector of the 1st nozzle, in the half of left and right respectively, because the profiles were symmetric with the center.

The particle concentration becomes maximum at the center and decreases to the nozzle edge, with almost no particle in the area of $y/h < -35$. The particle can't spread in the y direction because of a large inertia force of par-

Fig. 6 Particle concentration and velocity vector of gas-solid free jet (1st nozzle)

ticle. The particle velocity distribution shows a convex shape with a minimum at the center and a maximum at the nozzle edge. The particle velocity decreases at around the center of the nozzle by particle-particle and particle-wall interactions.

As a result, it is considered that the cutting accuracy depends on the particle concentration and velocity. Therefore, in order to improve the cutting accuracy, a uniform particle concentration and velocity distribution in the y direction are needed.

4.2 Uniformity of particle concentration

In order to diffuse the particle in $\pm y$ direction, the plate and circular shaped vanes shown in Fig. 1 (b) and (c) was used. There is no difference in the characteristics of single air jet flow (average and variable velocity distribution) by setting some vane.

Figure 7 (a) and (b) shows the particle velocity vector and particle concentration for the 1st nozzle with plate and circular vanes, respectively. For the plate vane, the particle concentration decreases at the downstream of vane but it spreads in the y direction a little more than the basic nozzle without vane. The velocity distribution corresponds with particle concentration, that is particle velocity becomes large at the thin region and small at the dense region from the difference of particle interaction by non-uniformity of particle concentration.

For the circular vane, the particle concentration shows a uniform profile except for the nozzle edge area. The particle velocity distribution also shows a uniform profile from uniformity of particle interaction.

Figure 8 (a) and (b) shows the profile of cutting cross section ($z = 0$) by MBP with plate and circular vanes, respectively. Each cutting cross-section shows non-uniform shape corresponds with particle concentration, the thin particle concentration region shows shallow, and the dense region shows deep. For the circular vane, the cutting accuracy shows $\zeta = \pm 7.5\%$ at $-40 < y/h < 40$, although for the plate vane, it shows $\zeta = \pm 60\%$ in the same region. It is clear that the circular vane has an advantage for diffusing

(a) 1st nozzle with plate vane

(b) 1st nozzle with circular vane

Fig. 7 Particle concentration and velocity vector of gas-solid free jet (1st nozzle with plate or circular vane)

Fig. 8 Cutting cross section for each vane (1st nozzle)

the particle in the y direction and cutting accuracy.

Next, the cutting efficiency of each nozzle by MBP was examined. Figure 9 shows the cutting weight of glass by a nozzle without a vane, with plate and circular vanes. Supplied power W is defined as the product of flow rate and loss of fluid at nozzle ($p_0 - p_\infty$).

The nozzle with circular vane shows the largest cutting weight, and the cutting weight of the other nozzle almost the same. For example, the nozzle with circular vane shows a 30% advantage compared to the other nozzles at $W = 5$ kW. It results from decreasing of particle-particle interaction and smooth discharging of particle from work surface after cutting by particle diffusion and uniformity.

Thus, particle diffusion and uniformity contribute not

Fig. 9 Cutting efficiency for each vanes (1st nozzle)

Fig. 10 Velocity distribution, u/u_0 ($x-y$ plane, $z=0$)

only improvement of cutting accuracy but also to improvement of cutting efficiency.

4.3 Uniformity of air velocity distribution and cutting performance

In this section, the relationship between uniformity of air velocity distribution and MBP characteristics by the 2nd and 3rd new nozzles appearing in Fig. 1 (d) and (e) is examined.

4.3.1 Velocity distribution ($x-y$ plane, $z=0$)

Figure 10 shows the experimental results of velocity distribution ($x-y$ plane, $z=0$) of the air free jet for each nozzle. The velocity distribution for each nozzle shows a uniform one over the nozzle width at the nozzle outlet, but it does not keep in the outsides of jet at downstream.

The 1st nozzle shows a saddle-shaped velocity distribution that is known as the general characteristics of a rectangular jet. Therefore, the uniform region of the velocity distribution is small.

For the 2nd nozzle, the velocity distribution does not show a saddle-shaped one, and it has a wide uniform profile since it is extended at a constant angle from nozzle inlet to outlet. The velocity near the edge of the jet decreases gradually compared to the 1st nozzle since it has

the y direction component.

For the 3rd nozzle, the maximum velocity appears again near the edge of the jet. It depends on the separation of flow from the extended nozzle wall, but the most wide uniform-profile is obtained. The 2nd and 3rd nozzles can give the uniform velocity distribution at $0 < x/h < 15$ and $30 < x/h$, respectively.

Next, velocity distribution of the air free jet at x - z plane ($y=0$) is examined precisely to reveal the flow characteristics of each nozzle in detail.

4.3.2 Velocity distribution (x - z plane, $y=0$)

Figure 11 shows the experimental results and calculation of velocity distribution of the air free jet. It is shown a half region since the distribution is symmetric with the center. Jet issued from the nozzle exit indicates rectangular air velocity distribution at the nozzle exit, and it expands to the z direction downstream with a decrease of centerline velocity. All of the air velocity distributions for each nozzle show almost the same on each cross section of x . The calculation value fits well.

Figure 12 shows the non-dimensional velocity distribution by half width $z_{0.5}$ and centerline velocity u_c in the

Fig. 11 Velocity distribution, u/u_0 (x - z plane, $y=0$)

Fig. 12 Velocity distribution, u/u_0 (x - z plane, $y=0$) (3rd nozzle)

z direction with the theoretical value of a two-dimensional turbulent jet flow (Tollmien)⁽⁴⁾. Both of experimental and theoretical curves fit well except for the potential core and outer edge region. As a result, it is clear that jets issued from these nozzles have the same flow characteristic as two-dimensional turbulent free jet.

4.3.3 Jet width

Figure 13 (a) shows the jet width δ_y and half width $\delta_{y0.5}$ in the y direction. The jet width δ_y was defined as the jet edge is on $u=0.1u_c$. For the 1st nozzle, the jet does not extend in the y direction because of the straight nozzle outlet, but for the 2nd and 3rd nozzles δ_y is much larger because of the extended nozzle outlet.

The jet width of the 3rd nozzle is larger than the 2nd nozzle at the nozzle outlet. However, the spread of jet of the 3rd nozzle is smaller than the 2nd nozzle downstream since the loss of kinetic energy for the 3rd nozzle is larger. The half width of the 1st nozzle is in $\delta_{y0.5}/w < 1$, and it becomes smaller toward downstream, that is, the area of uniform velocity is narrow compare to the other nozzles.

Figure 13 (b) shows the jet width δ_z and half width $\delta_{z0.5}$ in the z direction. Both widths increase linearly toward downstream, and their relations can be expressed by

(a) $\delta_y/w, \delta_{y0.5}/w$ (x - y plane, $z=0$)

(b) $\delta_z/h, \delta_{z0.5}/h$ (x - z plane, $y=0$)

Fig. 13 Spread of jet

$$\begin{aligned}\delta_z/h &= 0.3(x/h) + 1.0 & (x/h \leq 30) \\ &= 0.4(x/h) - 2.0 & (x/h \geq 30)\end{aligned}\quad (2)$$

$$\begin{aligned}\delta_{z0.5}/h &= 0.16(x/h) + 0.85 & (x/h \leq 30) \\ &= 0.22(x/h) - 0.58 & (x/h \geq 30)\end{aligned}\quad (3)$$

4.3.4 Particle behavior Figure 14 shows the particle concentration and particle velocity vector for the 2nd and 3rd nozzles. The uniform particle concentration can be seen over the nozzle width for the two nozzles since the circular vane was set in the nozzle. It is thought that the high concentration area near the nozzle edge shown in Fig. 7 (b) is diffused in the y direction by the extended nozzle outlet.

For the 2nd and 3rd nozzles, the magnitude of particle velocity vector shows a uniform distribution results from uniform particle concentration the same as the case of the 1st nozzle, and the direction indicates outer direction. However, the 1st nozzle has inner direction.

4.3.5 Flow characteristics of particle laden free jet Figure 15 shows the velocity distributions in the $x-y$ plane ($z=0$) of particle and air for the 3rd nozzle. The velocity distribution of air is the result of a single-phase air jet flow at the same mass flow rate as the particle laden free jet. The spread of particle corresponds to the air, and it has a wide and uniform velocity profile in the y

Fig. 14 Particle concentration and velocity vector of gas-solid free jet

direction.

Figure 16(a) shows the centerline velocity distribution of air u_c and particle $u_{p,c}$ obtained by the experimental and numerical analyses. u_c expanded and accelerated rapidly to the nozzle outlet iso-entropically in the nozzle, and after being issued from the nozzle it decreased. The

Fig. 15 Particle velocity distribution of 3rd nozzle

(a) Velocity distribution

(b) Velocity distribution, logarithmic plot

Fig. 16 Centerline air and particle velocity distributions of 3rd nozzle

Fig. 17 Cutting cross section of 2nd and 3rd nozzles

experimental value of u_c fit well with the calculation. On the other hand, $u_{p,c}$ is only 20% of the air at the nozzle outlet since the particle has a large specific gravity compared to the air. After being issued from the nozzle outlet, particle accelerated by high speed air which have relatively higher velocity than particle, and it takes the maximum velocity at $x/h = 40$ and decreases gradually with the decrease of air velocity. The particle velocities obtained by the numerical and experimental analyses were considerably different. It results from the particle-nozzle wall and particle-particle interactions in the actual flow.

Figure 16 (b) shows the logarithmic plot of Fig. 16 (a) around the nozzle exit. u_c decreases toward downstream after the potential core region ($0 < x/h < 5$). The transition region is in ($5 < x/h < 9$), and the developed region is in ($9 < x/h$). In the developed region, u_c can be expressed by

$$u_c/u_0 \propto (x/h)^{-0.5} \quad (4)$$

It corresponds to the two-dimensional free jet⁽⁵⁾.

Both profiles are similar, and the transition of particle velocity $u_{p,c}$ can be divided into the gradual accelerating region with the nearly constant gradient ($0 < x/h < 30$), the transition region ($30 < x/h < 70$), and the decreasing region ($70 < x/h$). The decreasing rate in the decreasing region corresponds to the air.

4.3.6 Cutting performance Figure 17 shows the cutting cross section by MBP using the 2nd and 3rd nozzles. As the nozzle outlet becomes wider, the large cutting region of the nozzle edge shown in Fig. 8 (b) decreases, and then high flatness and cutting accuracy can be obtained. The cutting accuracy shows a high quality of $\zeta = \pm 8.9\%$ at $-70 < y/h < 70$ for the 3rd nozzle. The high cutting accuracy in a wide range results from the uniform particle diffusion and uniform air velocity.

4.3.7 Cutting efficiency Figure 18 shows the relation between supplied power and removal weight for the conventional nozzle (Fig. 2) and the 3rd nozzle which was newly proposed.

The 3rd nozzle takes the largest removal weight compared to the conventional nozzles, for example, cutting efficiency of the 3rd nozzle improves by 15% of the pressure type nozzle (Fig. 2 (b)) at the supplied power of $W = 10$ kW.

Fig. 18 MBP efficiency

Removal of the particle and cutting material after the particle-laden jet impinges on the work-piece is a significant factor in order to improve the cutting efficiency of MBP. If the particle and cutting material remain on and around the work-piece after the particle impinges on the work-piece, a newly coming particle impinges on the remaining particle, and then the energy of the particle is spent only on interaction between the particle and particle remaining on the work-piece. Removal of the particle and cutting material for the conventional nozzle is not enough because the particle converges on one area, but the 3rd nozzle has a narrow impingement width and it makes easy removal of the particle and cutting material. As a result, cutting efficiency of the 3rd nozzle is improved considerably compared to the conventional nozzle.

5. Conclusion

In this study, in order to process the work-piece with high accuracy and high efficiency with the micro-blasting process, a new rectangular two-dimensional nozzle with high aspect ratio was proposed, and flow characteristics of particle laden high speed air jet flow, behavior of fine particles and cutting were examined by experimental and numerical analyses.

Main results are as follows.

(1) The circular vane of the nozzle shows uniform particle concentration and velocity distributions. As a result, high cutting accuracy can be obtained by MBP, also cutting efficiency can be improved by reduction of particle interaction and improvement of particle discharge from the impinging point.

(2) The second and third nozzles show uniform velocity distribution over a wide area, yet the first nozzle shows a saddle-shaped distribution. The cutting accuracy shows a high quality of $\zeta = \pm 8.9\%$ at $-70 < y/h < 70$ for the 3rd nozzle. The high cutting accuracy in a wide range results from the uniform particle diffusion and uniform air by MBP.

(3) The particle velocity shows a maximum at $y/h =$

40 since it has a large inertia force compared to the air. The particle is accelerated only by 20% of air velocity at the nozzle outlet.

(4) The 3rd nozzle takes the largest removal weight compared to the conventional nozzles. For example, cutting efficiency of the 3rd nozzle improves by 15% of the pressure type nozzle at the supplied power of $W = 10 \text{ kW}$.

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