Fluid Flow Analysis of Agitation Pipe in the Electroplated Diamond Wire Saw

**Derong Duan**¹,²,³, **Peiqi Ge**²*, **Zhigang Gong**³, **Fuli Huang**³ and **Guangzhou Cao**³

¹School of Mechanical Engineering, University of Jinan, Jinan, Shandong, 250022, China
²School of Mechanical Engineering, Shandong University, Jinan, Shandong, 250061, China
³Shantian Abrasive co., LTD, Linyi, Shandong, 276702, China
*Corresponding author’s e-mail: me_duandr@ujn.edu.cn

**Abstract.** Agitation pipe is the important part of the electroplated diamond wire saw in the suspension sanding process. The structure type and the sandblasting configuration in agitation pipe play a role on the flow uniformity. Fluid flow in the different structure forms of agitating pipe was studied and the influence of sandblasting angle and the diameter was also contrasted. Results found that the central water type of agitation pipe has the better performance, generating the flow field distribution in the middle part with high velocity and small velocity on both sides. The order of sandblasting in performance was 30°, 45° and 60°. The better flow uniformity occurred in the configuration of sandblasting with the diameter 7.5 mm, 7 mm and 7.5 mm.

**1. Introduction**

Monocrystalline silicon, polycrystalline silicon and other hard brittle materials are the important raw material in the integrated circuit and photovoltaic industry. With the rapid development of 5G market, the integrated circuit processing is developing in the direction of very large scale integrated circuit. The production efficiency of raw materials and processing quality will directly affect the subsequent development of semiconductor industry[1]. The high quality of hard materials such as monocrystalline silicon processing and the accuracy of semiconductor processing equipment are closely related to the mechanical parts geometry specifications, which directly affect the slice thickness, parallelism and the surface quality[2].

At present, the line width of integrated circuit process have been transition from 0.18 mm to 0.13 mm, even reached 0.1 mm[3]. Therefore, with the increase of the diameter in the silicon and the decreases in the line width, the more precise machining method is needed to realize the request of section geometric size and surface integrity. Owing to the small wire diameter, high cutting efficiency, and the advantages of wear-resisting, it has become the main component in the wire cutting process of the brittle hard materials[4]. According to the principle of composite electroplating, electroplated diamond wire saw wire is prepared by suspension method. In order to improve the processing efficiency of wire saw, the production equipment of one machine and multi wire is usually used, which can realize the production of multiple wire saws at the same time[5]. The production efficiency of wire saw can be greatly improved by adopting the suspension sand feeding process of one machine with multiple wires. Among them, the sanding quality of wire saw wire mainly depends on the dispersion degree of diamond fine powder in the sand tank fluid.
2. Research method setting

2.1. Basic governing equations
Fluid dynamics analysis software Fluent was used to analyse the fluid in the agitation pipe. Assuming that the fluid in the agitating pipe is incompressible fluid and the medium is water, the fluid movement in the agitating pipe can meet the fluid control equation

\[ \nabla \cdot u = 0 \]  
\[ \rho \frac{\partial u}{\partial t} = -\nabla P + \mu \nabla^2 u \]  

2.2. Agitating pipe
As shown in Figure 1, three kinds of agitation pipe were selected to analyse the influences of structure forms on the fluid flow. Figure 1.(A) displays the one end water type. Figure 1.(B) displays the central water type. The main difference in this two kinds of structure forms is the difference in water intake. The one end structure tube flow for the water sweep along the sand tube by side to the other end and the central water structure tube flow for central tube into the separate flow on both ends of the tube. Each agitating pipe length is 590 mm, the liquid import 28 mm in diameter.

Among them, the arrangement angles of sandblasting ports are inclined by 30°, 45° and 60°, respectively. There are 24 sandblasting orifices in two rows arranged on the agitating pipe. Staggered arrangement or parallel arrangement can be adopted. The diameter of sandblasting mouth is 7 mm, 7.5 mm and 8 mm respectively. In the calculation, the liquid inlet boundary is set as the velocity inlet, and the inlet velocity is 3.4 m/s. The pressure outlet boundary was set on each sandblasting port with pressure 0. The outer wall is smooth without sliding boundary condition.

3. Results and discussion

3.1. Fluid flow in agitating pipe
Figure 2 shows the fluid flow in the two kinds of agitating pipes. With the increase of the loss along the way, the fluid velocity decreases gradually. Similar to the flow in the tube when the sandblasting ports are staggered, the outlet velocity of the middle inlet structure is lower than that of the one end inlet structure due to the increase of the number of changes in the fluid flow direction. The backflow is formed
at the end of the agitating pipe. The size of the reflux is affected by the velocity of the incoming flow and reacts on the size and distribution of the mainstream velocity.

As shown in figure 3, the velocity distribution at each sandblasting port of the two types of agitating pipes is roughly the same as that when the sandblasting ports are staggered. In the middle water inlet structure, the outlet velocity distribution of two rows of sandblasting ports is quite different. In structure B, there are no sandblasting ports at both ends, and the velocity of sandblasting ports of row II is relatively large and evenly distributed at No.4-9 outlet, and then the velocity gradually decreases. In row I, the exit velocity of No.6-7 in the middle is larger, and the outlet velocity distribution on both sides is more uniform. In the C structure, there are sandblasting ports at both ends, so the speed of sandblasting mouth on the agitating pipe is reduced. In row I, the outlet velocity of sandblasting port No.3-10 is more uniform, and the outlet velocity of both sides is reduced. The velocity of No.6-7 sandblasting mouth in row II was larger, and then gradually decreased along both sides.

Each row of 12 sandblasting ports is divided into three groups according to the serial number. The velocity treatment of sandblasting mouth is shown in table 1. The velocity standard deviation of sandblasting mouth with middle water inlet structure is larger than that of one end water inlet type, that is, the speed of middle sandblasting port is greater than that of both ends. In one end water inlet structure, the average velocity of No.1-4 sandblasting ports near the inlet end is 7.4% higher than that of the far inlet No.9-12 sandblasting ports. In the middle water inlet type B structure, the velocity of sandblasting mouth No.5-8 in the middle is 10.5% higher than that in No.1-4.

| Analysis object                  | Position of sandblasting mouth |
|----------------------------------|-------------------------------|
|                                 | AI   | AII  | BI   | BII  |
| Average velocity                | 4.16 | 4.23 | 3.94 | 4.17 |
| Maximum speed                   | 4.29 | 4.45 | 4.61 | 4.5  |
| Minimum speed                   | 3.96 | 3.91 | 3.58 | 3.69 |
| Standard deviation              | 0.14 | 0.21 |      |      |
| No.1-4 exit average speed       | 4.25 | 4.36 | 3.80 | 4.00 |
| No.5-8 exit average speed       | 4.20 | 4.32 | 4.19 | 4.43 |
| No.9-12 exit average speed      | 4.02 | 4.00 | 3.83 | 4.07 |
3.2. Effect of sandblasting mouth angle on the flow in tube

The fluid in the tube flows into the upper sand tank through the sandblasting port, and the direction of fluid erosion varies with the angle of sandblasting mouth. As shown in figure 4, the fluid flow on the XZ section of the agitating pipe at three angles is shown. It can be seen that the angle of sandblasting port has little effect on the fluid velocity distribution on the neutral surface of the tube. The fluid velocity gradually decreases with the flow of fluid. Finally, the bottom of the agitating pipe will be impacted by the "back stroke" phenomenon of fluid. The effect of reflux and mainstream in the tube will improve the fluid velocity at the corresponding position of sandblasting port. Because the fluid flows out gradually along the agitating pipe, that is, the fluid impacting the bottom of the agitating pipe is less and less. Therefore, the difference of fluid velocity distribution is mainly at the bottom of the agitating pipe. When the angle of sandblasting mouth is 30°, the fluid flows out of each sandblasting port. Therefore, the reflux area formed at the bottom of the agitating pipe is small, and the velocity value is small. When the angle of sandblasting mouth is 45°, the fluid outflow along the agitating pipe decreases, so the bottom reflux area increases and the velocity value increases. When the angle of sandblasting mouth is 60°, the fluid outflow along the agitating pipe further decreases, the bottom reflux area further increases, and the velocity value increases again.

Figure 4. Fluid velocity distribution in agitating pipe with different sandblasting mouth angles

As shown in table 2, the fluid velocity of each sandblasting mouth under three kinds of sandblasting mouth angles is shown. With the sandblasting mouth angle increasing, the standard deviation of fluid velocity at the outlet of each structure is 0.092, 0.097 and 0.11 respectively, which indicates that the dispersion of jet fluid velocity is increasing, that is, the uniformity of fluid velocity value of each sandblasting port is poor. On the whole, the average velocity of sandblasting mouth is 3.92 m/s when the angle of sandblasting mouth is 30° and 45° and 3.86 m/s when the angle of sandblasting mouth is 60°. The expansion of sandblasting angle affects the flow of mainstream in the tube, resulting in the decrease of average velocity at 60° and poor uniformity. The 12 outlets were divided into three groups. On the whole, the fluid velocity of outlet No.5-8 is the largest, and that of outlet No.1-4 near the inlet is the second. With the decrease of pressure drop and flow rate, the velocity of outlet No.9-12 at the bottom is the lowest. The results show that the outlet velocity of the agitating pipe with one end into the water is small at both ends and large in the middle. The outlet fluid of this distribution pattern impacts the sand sweeping pool, which makes the fluid fluidity in the middle area of the pool better, while the fluid fluidity on both sides of the pool is poor.
Table 2. Comparison of fluid velocity at sandblasting port

| Analysis object | 30I | 30II | 45I | 45II | 60I | 60II |
|------------------|-----|------|-----|------|-----|------|
| Average velocity | 3.92| 3.92 | 3.91| 3.93 | 3.85| 3.87 |
| Maximum speed    | 4.03| 4.03 | 4.03| 4.05 | 3.97| 3.99 |
| Minimum speed    | 3.75| 3.70 | 3.65| 3.73 | 3.52| 3.60 |
| Standard deviation | 0.092| 0.097| 0.11 |
| No.1-4 exit average speed | 3.88| 3.87 | 3.87| 3.89 | 3.85| 3.86 |
| No.5-8 exit average speed | 4.00| 4.01 | 4.01| 4.00 | 3.95| 3.96 |
| No.9-12 exit average speed | 3.88| 3.90 | 3.84| 3.89 | 3.76| 3.80 |
| Relative change of exit velocity between No.1-4 and No.5-8 | 3.15%| 3.38%| 3.48%| 2.95%| 2.55%| 2.62% |
| Relative change of exit velocity between No.9-12 and No.5-8 | 3.17%| 2.73%| 4.15%| 2.96%| 4.74%| 4.00% |

3.3. Effect of sandblasting mouth diameter on the flow in tube

From the above analysis, it can be seen that the fluid velocity of each sandblasting port is not the same. In order to achieve uniform sandblasting, each sandblasting port of the agitating pipe should meet the requirement of uniform spraying. Therefore, combined with the quality and velocity of the jet fluid, the diameter of the sandblasting port at different positions is changed, and the momentum change of each sandblasting port under different diameters is analysed.

In this paper, the uniform diameter distribution of the 24 outlets of the agitating pipe is changed, and the fluid flow in the tube with three sandblasting mouth diameters is analysed when the sandblasting mouth angle is 45°.

The first structure A: 24 sandblasting holes with a diameter of 7 mm.

The second structure B: The outlet diameters of the I1-3 and II1-3 are 8 mm, the outlet diameters of I4-9 and II4-9 are 7 mm, the outlet diameters of I10-12 and II10-12 are 8 mm.

The third structure C: The outlet diameter of the I1-3 and II1-3 is 7.5 mm, that of I4-9 and II4-9 is 7 mm, and that of I10-12 and II10-12 is 7.5 mm.

As shown in table 3, the momentum of sandblasting mouth of three kinds of structures is shown. It is found that the average momentum of sandblasting mouth under the three structures is basically the same, while under structure B, the dispersion degree of sandblasting mouth fluid of agitating pipe increases, and the standard deviation is 0.063, which reduces the uniformity of momentum at each outlet of agitating pipe. By increasing the diameter of the sandblasting mouth near the inlet and the sandblasting mouth near the bottom, the momentum of the sandblasting mouth at both ends of the agitating pipe increases significantly, showing a trend of two ends being large and the middle small. It is found that when the diameter of each sandblasting port is 7 mm, the maximum difference of momentum at the front, middle and rear of the agitating pipe is 8.02% and the minimum is 5.80%. When the outlet diameters of I1-3, II1-3, I10-12 and II10-12 are 8 mm, the difference of momentum between the front, middle and rear parts of the agitating pipe increases, the minimum is -21.91%, and the maximum is -13.93%. When the outlet diameters of I1-3, II1-3, I10-12 and II10-12 are 7.5 mm, the difference of momentum at the front, middle and rear of the agitating pipe does not increase obviously, the minimum absolute value is 0.84%, and the maximum absolute value is 6.09%. Comparing the structural characteristics of three kinds of agitating pipes, the best outlet diameter of I1-3, II1-3, I10-12 and II10-12 is 7.5 mm, followed by the uniform diameter of sandblasting mouth of 7 mm, and the outlet diameter of I1-3, II1-3, I10-12 and II10-12 is the worst. The momentum distribution of the sandblasting mouth of the c-structure agitating pipe is large at both ends and small in the middle. The spray characteristics of this fluid will enhance the fluid mixing between the two walls of the sand sweeping pool, and enhance the mixing degree of the sand sweeping pool.
Table 3. Comparison of fluid momentum at sandblasting port

| Analysis object | Position of sandblasting mouth |
|-----------------|-------------------------------|
|                 | AI | AI | BI | BI | CI | CI |
| Mean momentum   | 0.58 | 0.59 | 0.57 | 0.57 | 0.56 | 0.57 |
| Maximum momentum| 0.62 | 0.63 | 0.66 | 0.68 | 0.61 | 0.62 |
| Minimum momentum| 0.51 | 0.53 | 0.49 | 0.48 | 0.50 | 0.52 |
| Standard deviation | 0.029 | 0.063 | 0.029 |
| No.1-4 outlet average momentum | 0.57 | 0.58 | 0.60 | 0.59 | 0.58 | 0.59 |
| No.5-8 outlet average momentum | 0.61 | 0.61 | 0.52 | 0.51 | 0.55 | 0.56 |
| No.9-12 outlet average momentum | 0.57 | 0.58 | 0.59 | 0.62 | 0.54 | 0.57 |
| Relative change of momentum at exit of No.1-4 and No.5-8 | 6.84% | 5.81% | -16.01% | -14.53% | -6.09% | -5.45% |

4. Conclusion
The structure of the agitating pipe plays an important role in improving the uniformity of sand loading in the upper sand tank. The influence of the angle and diameter of the sand blasting mouth on the fluid flow in the tube was analysed by using the fluid dynamics software. The relevant conclusions are as follows:

1. The spray fluid of the central water inlet agitating pipe forms the fluid distribution with the middle velocity larger than that of the two sides, which is smaller than that of the one end. The water type structure and the middle inlet type agitating pipe are more conducive to the formation of uniform fluid distribution in the upper sand trough.

2. The results show that the angle of sandblasting mouth has obvious influence on the fluid flow in the tube, and the performance of agitating pipe is in the order of 30°, 45° and 60°.

3. When the diameter of sandblasting mouth is 7.5 mm in front and 7 mm in the middle, the momentum uniformity of each sandblasting port is higher, which can significantly enhance the mixing degree of fluid in the upper sand tank.

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