# *Abrasive Distribution of The Fixed Diamond Wire in Wire Sawing Process*

*Chunhui Chung*

*Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan*

*E-mail: chunhui.chung@mail.ntust.edu.tw*

*Abstract – Fixed diamond wire saw has the advantages such as higher cutting rate and clear operation over the slurry wire saw in wafering. However, the higher cost and poor sliced wafer surface are still the obstacles for the diamond wire saw to totally replace slurry wire saw. In this study, the distribution of diamond grits on the wire was investigated by numerical simulation. The results show that there is a critical value of the abrasive interval to transfer from plastic deformation to brittle indentation cracking for the material removal. The value depends on both the wire tension and bow angle during the operation.*

*Keywords – Diamond wire saw; wafering; silicon wafer*

## *I. INTRODUCTION*

Wire saw has been utilized in the slicing process of prime wafer manufacturing over 20 years [1, 2]. It becomes the exclusive slicing tool because of the advantages such as low kerf loss and high yield. In addition, it can slice almost any sizes of ingot with the adjustment of wire span between wire guides. Therefore, it is expected that the wire saw will still be the major tool to slice 450 mm silicon ingot in the near future [3]. Wire saws can be divided into two types, slurry wire saw and fixed diamond wire saw. Slurry wire saw was introduced into the industry at the beginning. During slicing, the slurry is sprayed on the wire net and brought into the slicing zone. The abrasives are suspended in the film between the wire and the ingot and work as three-body abrasion. However, the used slurry has to be disposed, and this is not benign to the environment.

Fixed diamond wire saw emerges because of the advantages such as higher cutting rate and clearer operating environment than the slurry wire saw. However the higher cost of the diamond wire and the poorer sliced wafer surface are the issues which impede it to substitute for the slurry wire [4]. In order the slicing the ingot to wafers more efficiently, the study of the slicing mechanism becomes essentially. Nevertheless, the wire is not the rigid cutting tool as those in turning or milling. The flexibility of the wire will affect the performance of the slicing process such as the material removal rate.

In this study, the theories of abrasive wear and brittle indentation cracking were considered as the mechanisms of material removal. The forces act on the abrasives are analyzed as the fractions of the wire tension to indent the workpiece and move the abrasives forward. The results show that there is a critical value of the abrasive interval to transfer from plastic deformation to brittle indentation cracking for the material removal. The value depends on both the wire tension and bow angle during the operation.

## *II. MECHANISM OF MATERIAL REMOVAL*

Brittle indentation fracture has been considered as the major material removal mechanism for the wire sawing process to slice silicon ingot. Indentation with a sharp tip will introduce the cracks inside the brittle materials, as shown in Fig. 1. The material above the lateral cracks is the one to be removed. However, there is a critical normal loading which determines whether the cracks initiates or not. The value of the critical normal loading depends on different conditions and varies from 0.003 to 0.03 N [5]. In this study, the critical normal loading is assumed to be 0.003 N.

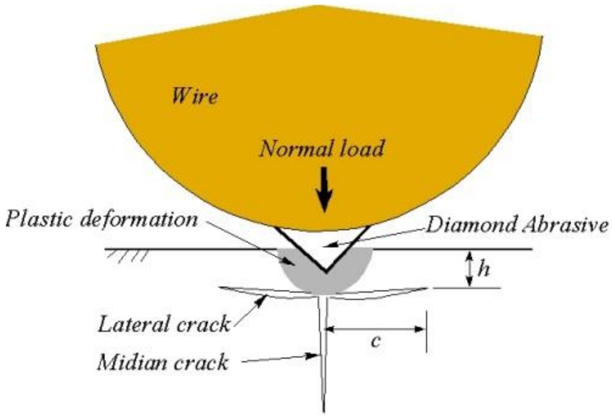



Fig. 1 Mechanism of brittle indentation fracture during fixed abrasive wire sawing.

The penetration of the abrasive into the substrate depends on the geometry of the abrasive, the normal loading, and the hardness of the workpiece, as shown in Fig. 2. Assume that the tip of the abrasive is a cone with tip angle of $2\psi = 90°$. In the model of plowing, the normal force required to penetrate the workpiece is

$$N = A_h \times H = \frac{1}{2}\pi r^2 H \quad (1)$$

where $A_h$ is the horizontal projected area, and $H$ is the hardness of the workpiece. The tangent force required to move the abrasive forward is

$$F = A_v \times P = rhP = \frac{r^2}{\tan\psi}P$$

where $A_v$ is the vertical projected area, and $P$ is the pressure to deform the workpiece plastically. This pressure $P$ is considered as the same as the hardness $H$ [6]. Therefore,

$$F = \frac{r^2}{\tan\psi}H \quad (2)$$

The projected areas are defined in Fig. 2.

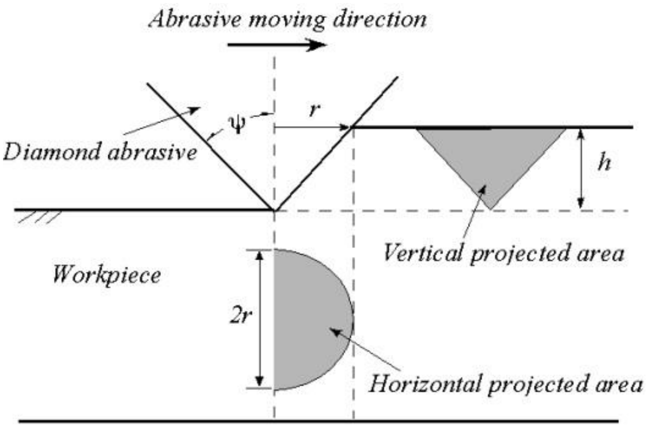



Fig. 2 Mechanism of conical abrasive wear.

Once the normal loading is less than the critical loading, the mechanism of material removal can be assumed as the abrasive plowing process[6]. In this case, the material removal rate for each abrasive can be consider as the vertical projected area, which is that

$$Q = A_v = \frac{r^2}{\tan\psi}\ \ (\mathrm{m^3/m}) \tag{3}$$

where $Q$ is the material removal rate with the unit of the material removal volume per sliding distance. If the normal loading is over the critical value, the material above the lateral cracks will be considered as being removed, and the material removal rate will be

$$Q = 2ch\ \ (\mathrm{m^3/m}) \tag{4}$$

where $c$ is the length of the lateral crack, and $h$ is the depth of the lateral crack, as shown in Fig. 1. They can be obtained by the following equations [7, 8].

$$c = (\cot\psi)^{1/3}\frac{E^{1/2}}{H}N^{1/2}$$

and

$$h = \left(\frac{{\zeta_L}^{1/2}}{M^{1/4}}\right)(\cot\psi)^{5/12}\frac{E^{1/2}}{{K_c}^{1/2}H^{1/2}}N^{5/8}$$

where $\zeta_L = 25\times10^{-3}$ and $M = 3/4$.

## *III. FORCE ANALYSIS*

The wire utilized in the wire saw process is flexible, and the configuration of the wire, as well as the bottom of the slicing groove, is a curve rather than a straight line. In this study, the configuration of the bottom of the slicing groove is assumed as an arc with an arc angle defined by the bow angles of the wire, as shown in Fig. 3.

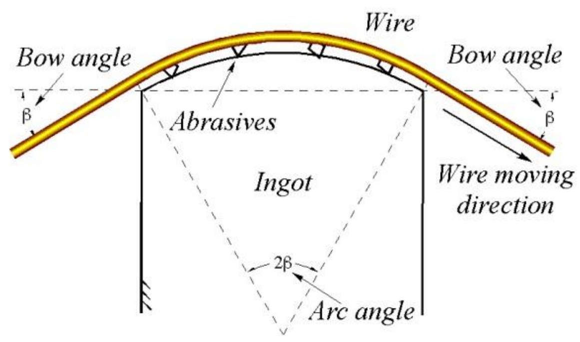



Fig. 3 Configurations of the wire and slicing groove.

The normal load is introduced from the wire into the abrasives to indent on the workpiece. This depends on the average interval of the abrasives and the tension of the wire. In this study, only the abrasives underneath the wire are investigated. Therefore, the number of abrasives can be defined according to the slicing length, $L$, and the average interval of the diamond abrasives, $d$, which is

$$n = \frac{L}{d}$$

when the bow angle is very small.

The wire is assumed to be stretched by the tension on it, and results in normal force and tangent force. The normal force will provide the load for the abrasives to penetrate into the workpiece, and the tangent force is the force required to overcome the strength of the workpiece to move forward. The wire tension and it fraction around an abrasive grit are shown in Fig. 4. The normal force is

$$N_i = T_i\sin\frac{\beta}{n} + T_{i+1}\sin\frac{\beta}{n} \tag{5}$$

The tangent force is

$$F_i = T_{i+1}\cos\frac{\beta}{n} - T_i\cos\frac{\beta}{n} \tag{6}$$

Substitute equations (5) and (6) into equations (1) and (2), and solve the equations to obtain the relationship between $T_i$ and $T_{i+1}$ as follows.

$$T_{i+1} = T_i\frac{\tan\psi\cos\left(\frac{\beta}{n}\right) + \frac{2}{\pi}\sin\left(\frac{\beta}{n}\right)}{\tan\psi\cos\left(\frac{\beta}{n}\right) - \frac{2}{\pi}\sin\left(\frac{\beta}{n}\right)} \tag{7}$$

Therefore, the wire tension should be increased from the left to the right (the entry to the exit) in the range of slicing. The total material removal rate will be the sum of that resulting from each abrasive.

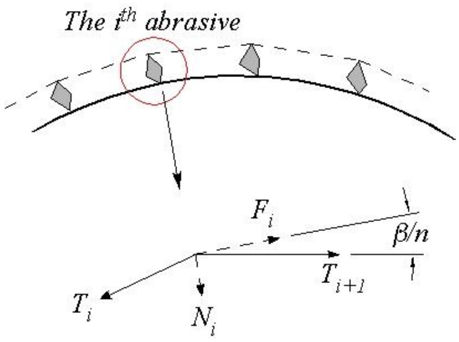



Fig. 4 Analysis of wire tension around an abrasive grit

## IV. SIMULATION RESULTS

In the simulation, the mechanical properties of the silicon are listed in Table 1. The simulation compares the average abrasive interval and the total material removal rate. In addition, the wire tension at exit is also investigated. However, the results show that the abrasive interval does not affect the wire tension at exit. Figure 5 shows an example with the initial wire tension of 20 N and the wire bow angle of 5°.

TABLE I
Mechanical properties of the silicon in the simulation [9, 10]

| Young's Modulus | Hardness | Fracture Toughness |
|---|---|---|
| $E$ = 127 GPa | $H$ = 10 GPa | $K_c$ = 0.7 MPa |

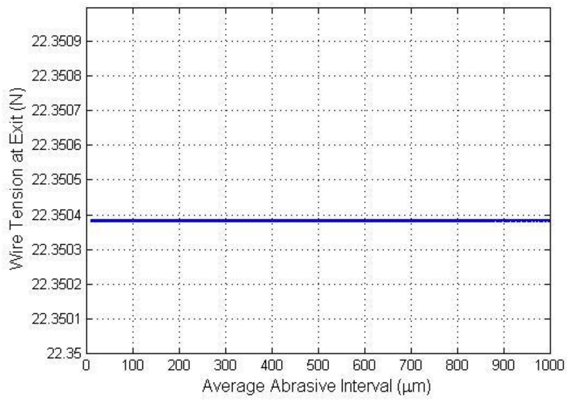



Fig. 5 Wire tension at the exit versus the variation of abrasive interval. The wire tension at the entry is 20 N, and the bow angle is 5°.

In Fig. 6, the material removal rate is compared with different bow angles. The results show that with larger bow angle, the material removal rate is higher. In addition, there is a transition of material removal rate at certain abrasive interval. The material removal rate increases dramatically when the average abrasive interval is larger than a critical value. However, this value depends on the slicing parameters such as bow angle and wire tension. This transition also presents the mechanism of material removal is from plastic deformation to brittle indentation cracking. Although the plastic deformation can eliminate the subsurface damage resulting from the cracking, the material removal rate with plastic deformation is much lower than that with brittle indentation cracking. For example, the material removal rate with abrasive interval of 57 μm is $2.350 \times 10^{-10}$ $(m^3/m)$ in Fig. 6(b). However, it is $1.865 \times 10^{-7}$ $(m^3/m)$ with abrasive interval of 67 μm. Figure 7 shows the simulation results of material removal rate with different wire tensions at the entry.

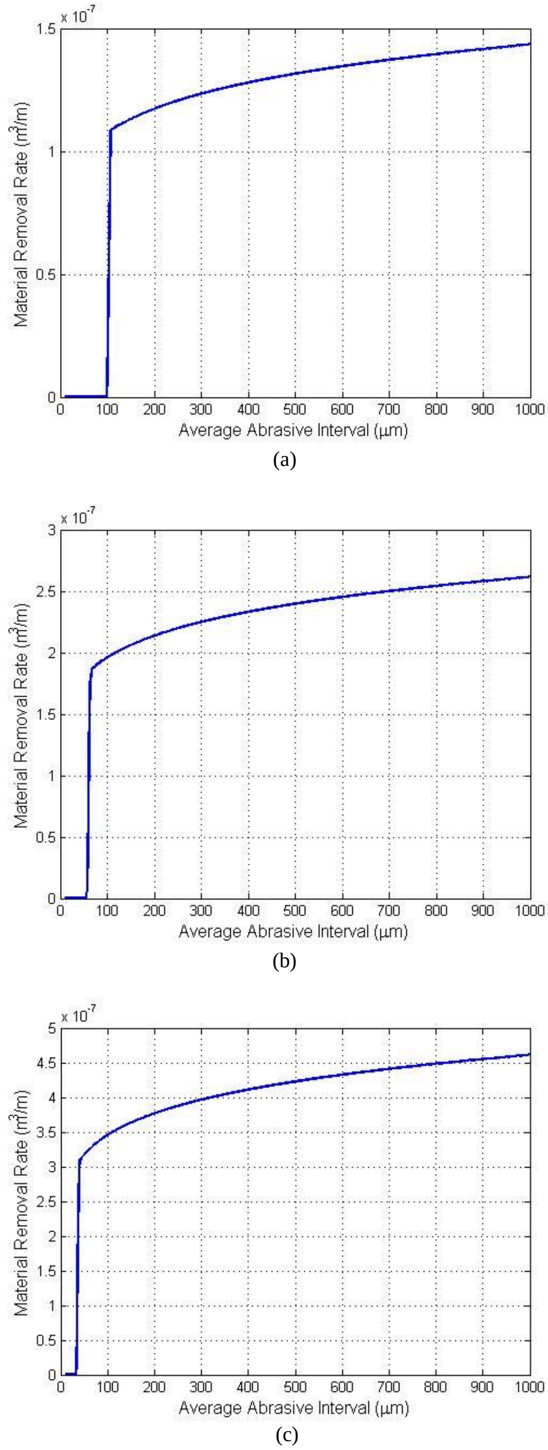
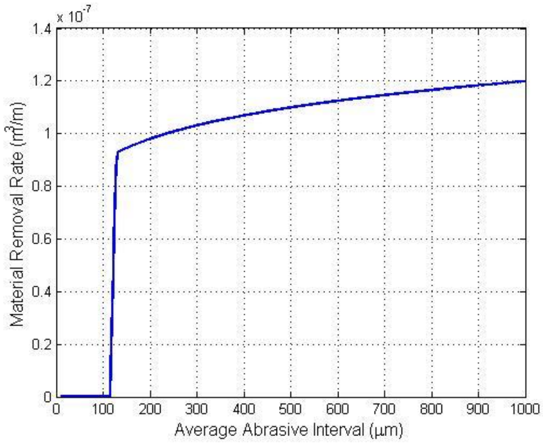
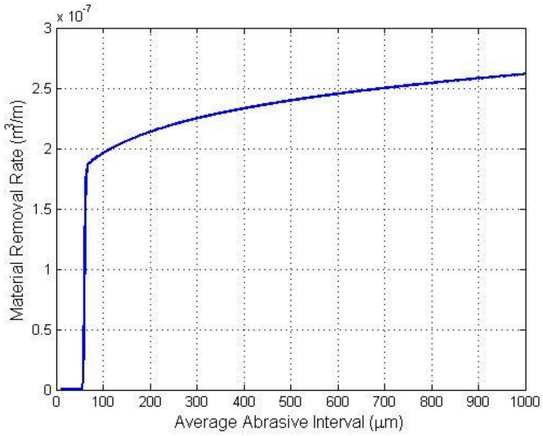


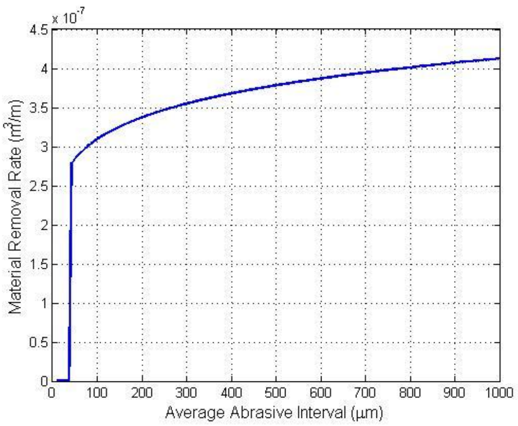

Fig. 6 Material removal rate with wire bow angles (a) b = 3°, (b) b = 5°, and (c) b = 8°. The wire tension at the entry of slicing zone is 20 N.




(a)




(b)




(c)

Fig. 7 Material removal rate with wire tensions (a) P = 10 N, (b) = 20 N, and (c) P = 30 N at the entry of slicing zone. The wire bow angle is b=5°.

## *V. CONCLUSIONS*

In this study, the distribution of the diamond abrasives on the wire for wire sawing process was investigated. The results show that the larger abrasive interval will result in higher material removal rate. In addition, the interval must be larger than a critical value to introduce the brittle indention crack to remove material more efficiently. However, the loading on each abrasive particle will also increase with the increase of the abrasive interval. The higher wire tension or bow angle can also increase the material removal rate, and the critical value of the abrasive interval to initiate brittle indentation cracking will become smaller.

## *ACKNOWLEDGMENT*

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