Int J Adv Manuf Technol (2015) 81:329–334
DOI 10.1007/s00170-015-7229-5

ORIGINAL ARTICLE

Slicing parameters optimizing and experiments based on constant wire wear loss model in multi-wire saw

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Received: 12 November 2014 / Accepted: 26 April 2015 / Published online: 7 May 2015

Abstract Multi-wire saw becomes the dominant method in slicing the hard brittle material into wafers. In this process, saw wire is the critical consumable and the dominant component of the wafer's slicing cost. However, unreasonable process parameters lead to the fact that the saw wire was not fully used. This enormously increases the wire cost. For this reason, the constant wire wear loss model is presented by taking the free abrasive wire sawing as an example. This model takes the various cutting conditions into account and ensures the whole wire wear loss to reach the preset reasonable value. Firstly, a hypothesis that there is a mapping relation between the wire wear loss and the wire slicing area during the wire lifetime is built. According to this hypothesis, the wire allowed wear loss can be transformed into wire allowed slicing area. Secondly, the calculation method is deduced based on the model. The function relation is obtained between the wire feedback ratio and the actual slicing conditions under the constraint condition of the preset wire wear allowed loss. This rational feedback ratio of wire is obtained based on the actual process parameters. Thirdly, experiments are carried out. The results indicate that the relation between wire wear loss and wire slicing area is linear under the condition of the experiments and the wire consumption is reduced obviously. Meanwhile, wafers' quality meets the requirements. This method can effectively save saw wire cost, referring to slicing other hard brittle materials by multi-wire saw.

Keywords Multi-wire saw · Hard brittle material · Constant wire wear loss · Wire feedback ratio

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1 Introduction

Multi-wire saw (MWS) is the critical equipment for machining hard brittle materials, such as silicon and sapphire substrate. Moreover, these materials are the foundation of integrated circuit (IC), photovoltaic (PV), and light-emitting diode (LED). MWS can provide high-quality and thinner wafers with high productivity and lower cost [1–3].

In the MWS process, the saw wire is one of the most important consumables [4–7]. This is the important factor for determining the wafer's quality and cost [8, 9]. Goodrich et al. [10] built the cost model to analyze the saw wire cost and wire life for PV wafers in multi-wire saw. Some researchers have been focusing on saw wire studies. Hwang et al. [11] studied the relationship between the wear loss in the MWS process and the mechanical properties of the steel saw wire. Meißner et al. [12] researched the mechanism of wire tension loss. Hsu et al. [13] examined the effects of machining parameters on some machining characteristics, such as material removal rate and machined surface roughness of wafer, steel wire wear, and flatness. These studies are beneficial for understanding the slicing process about wire and help engineers solving the problem in the factories. However, these researches did not focus on how to determine the reasonable slicing parameters according to the varied slicing conditions for the goal of reducing the wire wasting. Hence, the process parameters are being adjusted empirically for the goal of saving. These parameters cannot obtain the uniform wear loss even causing the wire break. Through analyzing the process, the wire wear loss varies with ingot length, wafer thickness, contact length of kerfs, wire feedback ratio, table speed, etc. Many factors affect the wire wear so that conservative process parameters are being adopted to prevent wire breakage. For example, when the ingot length is short or the wafer thickness is thick, the wire wear loss is small if the parameters are not adjusted accordingly. Even if in the same cut, the wire wear loss can be different: there is more wear loss in the middle of the ingot than at the beginning or ending during slicing. Therefore, it is urgent to find a way to optimize the process parameters for avoiding wasting wire and reducing the cost.

In this work, the constant wire wear loss model is initially presented by taking the free abrasive wire sawing as an example. Based on the model, the relation between slicing parameters and wire wear loss is deduced. The experimental results demonstrate the linear relation between the wire wear loss and wire slicing area. Meanwhile, the wafer quality can achieve good performance with less wire consumption in the experiment.

2 Constant wire wear loss model

2.1 Slicing process analyzing

Figure 1 illustrates the schematic of the multi-wire saw. A single steel wire is drawn from the supply spool and wound over four grooved cylindrical wire guides to form a wire web. When wire guide is rotating, the wire moves at a given speed. And, the wire moves through the wire web until it enters into the take-up spool. The slurry nozzles eject the slurry on the wire web. The crystalline silicon ingot mounded on the table is fed downward slowly. The moving wire carries the slurry to slice the ingot into wafers. Several hundred wafers are produced simultaneously when finishing the process.

Now supposing a point on the wire, it starts to slice at the front side of the ingot and ends to slice at the rear side of the ingot. This is the lifetime of the wire. During the lifetime, the wire wear loss is increasing steadily. At the same time, the table is fed slowly. The wire slice area during the lifetime varies as table speed, ingot length, diameter of ingot, cutting position, the pitch of wire guide, wire speed, and wire feedback ratio. So, the relation of these parameters is the key to address this issue. Modeling is the important way to analyze the relation.

2.2 Modeling

Before modeling, hypothesis is introduced: wire wear loss is proportional to the slicing area during the wire lifetime. So,

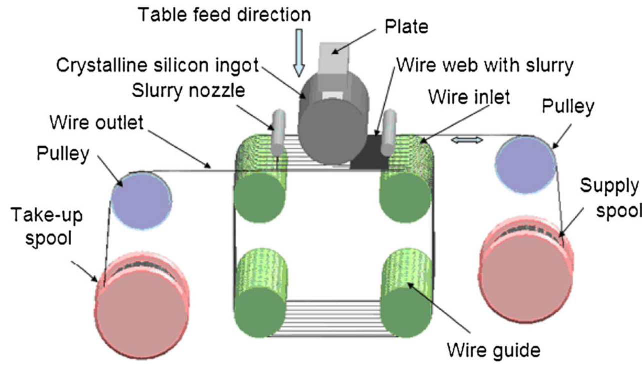

Fig. 1 The schematic diagram of multi-wire saw

assuring the wire wear loss constant means that the wire experiences the corresponding slice area in slicing. Figure 2 is the sectional sketch of the slicing model. The slicing section is perpendicular to the axis of the ingot.

The radius of the ingot is R. The shaded area is the uncut area. The slicing depth is h. With the table feeding, the cut depth becomes $(h+\Delta h)$ through a micro time Δt. So, the small time increment Δt can be expressed as follows:

$$\Delta t = \frac{\Delta h}{V_f} \tag{1}$$

where V_f is the table feed speed. From the section of Fig. 2, the slice area for one wafer kerf during the Δt is described by

$$\Delta s = 2 \cdot \sqrt{R^2 - (R-h)^2} \cdot \Delta h \tag{2}$$

where R is the radius of the ingot and h is the cut depth.

For the whole cut, the total cut area Δs_t is obtained

$$\Delta s_t = 2 \cdot Len \cdot \Delta s \Big/ P \tag{3}$$

where Len is the total length of the ingots and P is the pitch width of the wire guides. From Eqs. (1) and (3), the slicing area speed can be expressed as

$$V_s = \frac{\Delta s_t}{\Delta t} = 4 \frac{Len \cdot \sqrt{R^2 - (R-h)^2} \cdot V_f}{P} \tag{4}$$

where V_s is the slicing area speed which means the accomplished slicing area in unit time. Meanwhile, the wire is worn when it carries the slurry sawing the ingot at high speed. So, the wire diameter gradually becomes smaller and some wires finish the lifetime entering into take-up spool. During the slicing, the wire moves forward for a distance and then periodically reverses direction for another distance. This is regarded as a cycle as shown in Fig. 3. In Fig. 3, x-axis denotes the time, and y-axis denotes the wire speed. V_w represents the wire forward speed. "$-V_w$" represents the wire back speed. The cycle time is divided into six parts: T1 and T4 denote the accelerating time when the wire speed varies from 0 to V_w,

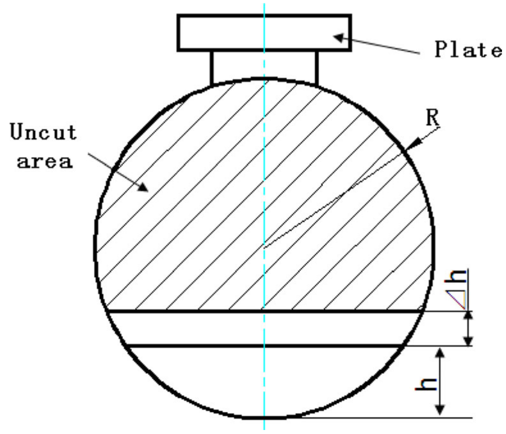

Fig. 2 The schematic of the model

T3 and T6 denote the decelerating time when the wire varies from V_w to 0, and T2 and T5 denote the time when the wire moves at the invariable speed V_w.

The total time T in one cycle can be described as

$$T = T1 + T2 + T3 + T4 + T5 + T6 = \frac{2 \cdot V_w{}^2 + a \cdot f_w \cdot (1+k)}{a \cdot V_w} \quad (5)$$

where a is the acceleration of the wire, k is the wire feedback ratio and f_w is the wire forward length when wire moves forward in this cycle. So, exhausted wire length L in this cycle is expressed as

$$L = (1{-}k) \cdot f_w \quad (6)$$

From Eqs. (5) and (6), the exhausted wire speed V_w is determined by

$$V_w = \frac{L}{T} \quad (7)$$

Equation (4) shows the slicing area in unit time and Eq. (7) shows the exhausted wire length in unit time. The ratio C can be expressed as

$$C = \frac{V_s}{V_w} \quad (8)$$

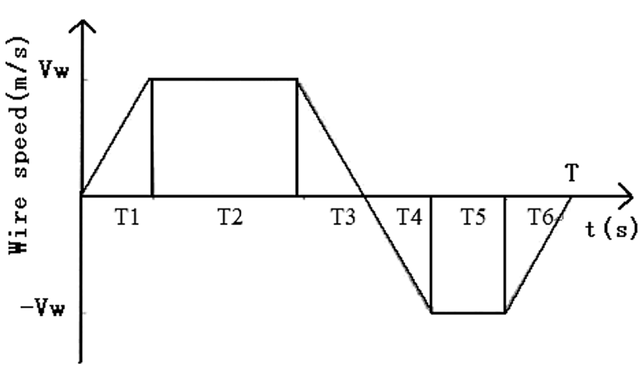

Fig. 3 The cycle of wire back and forth

where C is the slice area in unit used wire length. According to the hypothesis, if the C is constant in the whole sawing process, wire loss will reach the same value. Equation (8) shows the function relation between wire wear loss and slice area. The wire feedback ratio k and slice depth h are variables. The equation can be solved as follow

$$k = 1{-}\frac{4 \cdot C \cdot T \cdot Len \cdot V_f \cdot \sqrt{R^2{-}(R{-}h)^2}}{f_w \cdot P} \quad (9)$$

This formula determines the function between wire feedback ratio k and the cut depth h.

3 Experimental procedure

This constant wire wear loss model is built based on the assumption of the proportional relation between wire wear loss and wire slicing area. So, the reasonable assumption is a prerequisite for the model. In order to verify this mapping relation and benefit the practical application, the experiments are carried out in three steps: the first step: firstly, the slicing parameters were calculated according to the constant wire wear loss model; secondly, starting to slice according to the calculated parameters; and thirdly, the wire web was cut and kept the order after the ending the sawing process. Experiments were carried out on the E400E-12 wire sawing machine. The parameter C was set empirically. The rule was that wire wear loss controlled in a reasonable value of about 10 μm. All conditional process parameters are shown in Table 1.

Equation (9) shows the functional relation between slice depth and the wire feedback ratio. The table feed speed was set as shown in Table 2. So, the wire feedback ratio was calculated by Eq. (9). The detail parameters are shown in Table 2. It can be seen from the table that the wire feedback ratio varies with the slicing position. It is worth to mention that the values of wire feedback ratio are adjusted at the slicing position 0 and 100 %. Their values are modified with 81 and 83 %, respectively, according to their adjacent wire feedback ratio due to the worry about the saw mark which often produces at the entrance and exit of the wafer [14].

4 Experimental results and discussion

4.1 Wire wear loss

In establishing the constant wire wear loss model, the reliable assumption is the critical condition. In order to verify this hypothesis, the wire web was cut orderly after ending the process and the wire diameters were measured in accordance with 17-wire-spaced sampling. So, the changes of the wire

Table 1 Cutting process parameters

Content	Parameter
crystallographic orientation	<111>
Ingot size (inch)	5
Ingot length *Len* (mm)	536
Acceleration a (m/s^2)	3
Wire speed V_w (m/s)	10
Wire diameter (mm)	0.12
Wire tension (N)	23
Pitch P (mm)	0.725
Wire forward length f_w (m)	172
Cut area in unit wire length C (mm^2/m)	774

diameters reflect the wire wear loss. From the front to the end of the ingot, the wire slicing area increases continuously. Meanwhile, the wire wear loss increases steadily. So, the slice area for each sampled wire is calculated averagely. Even though the value is not very precise, the trend can give useful references. The relation between wire wear loss and slicing area is built as Fig. 4.

From Fig. 4, the rough proportional relation between them is obvious. The fitting line is conducted from the scattered data points based on the least square method. R^2 is a linear fitting evaluation index which is 0.9124. This means that relationship can be described as a linear relationship for processing. The equation is shown as

$$y = 0.0076x + 0.7023 \tag{10}$$

where x is the slicing area and y is the wire wear loss. Therefore, the assumption is reasonable in the experimental conditions.

Table 2 The table speed and wire feedback ratio in different cutting position (%)

Slicing position (%)	Table speed V_f (mm/min)	Wire feedback ratio k (%)
0	0.5	81
5	0.5	81
15	0.45	73
25	0.4	71
35	0.35	72
45	0.32	73
55	0.32	73
65	0.35	72
75	0.385	72
85	0.42	75
95	0.42	83
100	0.42	83

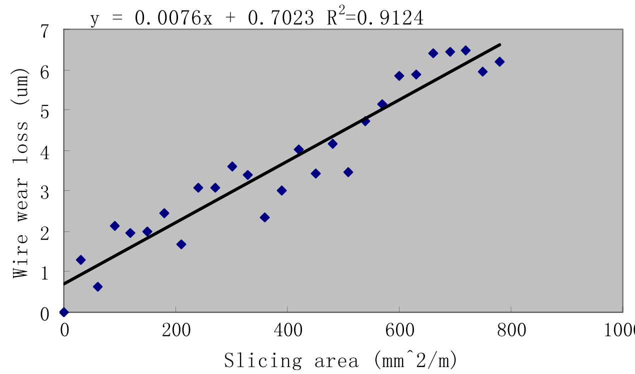

Fig. 4 The relation between wire wear loss and slicing area

4.2 Wire consumption

This method can obtain the optimized process parameters according to the cutting conditions. So, it can reduce the wire consumption. If the conventional process is adopted, the wire consumption is 29.8 km while the actual wire consumption is 23.4 km in this cut. So, the wire consumption is reduced about 6.4 km and 24.8 % in this experiment. This obviously verified that this method can reduce wire consumption and costs of production. But, the example cannot fully show the optimized effect in MWS. In practice, the process parameters vary according to the actual slicing conditions. This is the key factor which makes the process difficult to control and lead to the instability of the wafer performances. Therefore, the constant wire wear loss model takes the varied parameters into account. The following examples will examine the effects of the optimization. In order to show the effect, only one typical process parameter is changed based on the experiment parameter (see Table 1). In practice, the cut length is often different due to the changed ingots [15]. So, the cut length becomes from 536 to 800 mm (see Table 1). Other changed parameters are the table feed speed and ingot size. For the table feed speed, the parameter value becomes a constant value 0.45 mm/min from the varied value (see Table 2). This method is benefit to examine the effects on the feedback ratio. In the experiment, the ingot size is 5 in. Now, we suppose it is 8 in. The results deduced from the constant wire wear loss model are shown in Fig. 5.

The four different curves have the same trend: the wire feedback ratio in the middle of curves is lower than that at both ends of the curves. This phenomenon reflects that wire wear loss is less at the both ends of the ingot due to the shorter contact length (see Fig. 2). So, the higher wire feedback ratio increases the wire work time for the goal of the constant wire wear loss. Comparing with original parameters, the changed cut length and ingot size reduce the wire feedback ratio due to the increasing slicing area. This means that the wire consumption increases with the slicing area. Seen from Eq. (9), the same conclusion is also easy to obtain. The curve with constant table feed speed is closed to the original parameters'

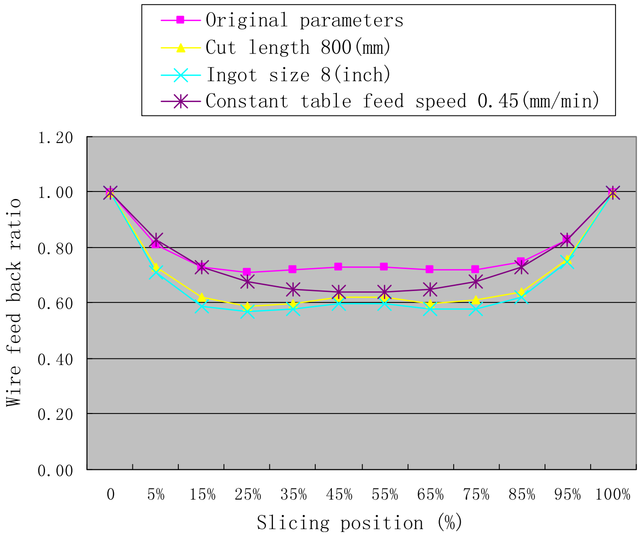

Fig. 5 The comparison of wire feedback ratio to different process parameters

curve. The difference lies in the middle of the curves. For the original curve, the table speed is about 0.32 mm/min while the constant table feed is 0.45 mm/min. The comparison indicates that the faster table feed increases the slicing area in unit time (see Eq. (4)). So, the wire feedback ratio is lower. These examples show that the optimized method based on the constant wire wear loss model can effectively adapt to the varied process parameters in MWS. However, it is difficult to determine the parameter C in Eq. (8) due to the unknown maximum reasonable wire loss. In current practice, it is given by engineers based on their experiences. So, the parameter C is feasible but not optimal. This is an important issue for further study.

4.3 Wafer quality

In actual production, the first rule is to ensure the quality of silicon wafer [16]. So, wafer quality is an important factor which affects the method applying into the factory. The tight warp and total thickness variation (TTV) specifications are the critical inspection contents [17]. Therefore, 15 pieces of wafers are uniformly sampled and measured for warp and TTV. The results are shown in Table 3. For TTV, the maximum value is 7.81 μm, the minimum value is 5.88 μm, and the mean value is 6.47 μm. For warp, the maximum value is 15.5 μm. Considering the permitted values are 15 and 25 μm for TTV and warp, respectively, these wafers meet the requirements. Currently, the constant wire wear loss processes have been successfully applied in practice.

Table 3 Inspection results

Inspect content	Minimum	Maximum	Average
TTV (μm)	5.88	7.81	6.47
Warp (μm)	6.18	15.5	9.87

5 Conclusions

The constant wire wear loss model is established. This model reveals the relation between wire feedback ratio and related process parameters based on the hypothesis which expressed as “wire wear loss is proportional to the cutting area during the wire lifetime.” Those actual process conditions such as the length of ingot, wire speed, table feed speed, wire forward length, and radius of ingot are the foundation of calculating the process parameter based on the model. Therefore this model makes the process more reasonable and efficient for constant wire wear loss. The hypothesis is verified by the experiment. Meanwhile, this method can reduce wire consumption by 24.8 % compared with conventional method for the experimental conditions and obtain the good wafer quality which meets the tight requirements. Furthermore, the effects of varied parameters on the wire feedback ratio are examined. This optimized method can obviously reduce wire cost and provide references for slicing other hard brittle materials by multi-wire saw.

Acknowledgments The authors would like to acknowledge the Zhejiang QL Electronics Science and Technology Co., Ltd, and the excellent operators who provided the selfless help for the experiments.

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