Simulation and experimental research on the slicing temperature of the sapphire with diamond wire

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Abstract

Temperature has an important influence on the wafer quality in the sapphire slicing process with fixed abrasive diamond wire saw. Temperature fields on the wafer surface during the slicing of sapphire ingot were studied with simulation and experiment. The effect of coolant on the slicing temperature field was explored. The simulation temperature field without coolant is good consistent with the experimental result. The maximum temperature located at the middle of slicing zone increase with the cutting depth. Coolant had a significant influence on the wafer temperature field. The narrow slicing kerf and wire movement have effect on the coolant supply, which cause the deviation of temperature field between the simulation result and experiment result.

Keywords: Slicing temperature, Wire saw; Sapphire wafer.

Introduction

Sapphire is classified as hard and brittle material and it has superior physical and chemical properties. Therefore, sapphire is often used for the optoelectronics research field [1]. During the manufacturing process of sapphire wafer, slicing is the first step and has important implications in the subsequently processing. The emergence of fixed diamond wire saw has significantly improved the slicing efficiency and wafer quality by generating smaller surface damage [2].

A massive source of heat was generated during the cutting process. A part of heat is carried away by the coolant while the rest is absorbed by the ingot and dispersed on it. Some studies have shown the relationship between temperature and surface quality of the wafers [3]-[4]. The uneven temperature field caused by slicing is severely detrimental to the processing quality. It could further increase the undesirable warping of wafers by the uneven thermal expansion of the sapphire ingot. To explore this issue, it is critical to research the slicing temperature in the cutting process. Therefore, in the past decade, researchers have paid mainly attention to the slicing temperature of brittle material. Sumeet Bhagavat conducted a finite element 2D model to analyze and synthesize temperature variation of silicon wafers during multi-wire saw slicing [5]. Lars Johnsen studied the heat transfer experimentally and computationally solved with the steady state 3D model by the Computational Fluid Dynamics (CFD) software during multi-wire sawing of silicon wafers [3]. Recently, Shinya Moriyama used the infrared camera to measure the temperature distribution of the sapphire during multi-wire sawing and measured the local dynamic temperature of the ingot by using K-type thermocouple [6]. Among the previous reports, simulation has emerged as an essential candidate because of its impressive convenience. Hence, it is no surprise that combination of simulation and experiment have been targeted as the best choice to study the single-wire sawing temperature.

In this paper, the finite element method (FEM) is employed to simulate the temperature field of the sapphire with fixed abrasive diamond wire saw. The sawing tangential force was measured to calculate the sawing heat. The sawing temperature was also measured by infrared thermal imager camera to verify simulation results. The effect of coolant on the wafer temperature field was discussed.

FEM Modeling

FEM model

The commercial finite element package ANSYS® was employed to perform the FEM modeling of the sapphire in slicing process. The sapphire ingot was modeled as a cylinder with a diameter of 50.8 mm. The length of ingot was cut to 15 mm under the premise that the calculation accuracy is guaranteed. In full accordance with the actual experimental situation, the wafer thickness considered in the FEM model is 1 mm and the kerf width is 0.25 mm. The following assumption is made to obtain the simplified model: the wire is assumed to move straight through the slicing kerf with a constant gap distance. Although the wire is flexible and bended due to forces acted upon it in the slicing kerf in practice.

For more realistic results, the properties of the C-plane sapphire were initially introduced in the FEM model in accordance to the literature [7]-[8]. The main constitutive parameters are heat capacity, conductivity, and coefficient of thermal. The values of these parameters, as well as Poisson ratio, density and elasticity modulus of the modeled materials are summarized in Table 1. For simplification purposes, the parameters are equal to their values at normal temperature and under small changes in the surrounding water temperature.

Table 1. Material properties

Material	C-plane sapphire
Density (kg/m^3)	3980
Elasticity modulus (Pa)	$3.3251 \cdot 10^{11}$
Poisson ratio	0.28
Heat capacity (J/kg K)	757.3
Conductivity (W/m K)	49.97
Coefficient of thermal expansion (/K)	$5 \cdot 10^{-6}$

Boundary conditions

In a slicing system, mechanical energy is transformed into thermal energy. The heat quantity in the contact area is generated by the friction forces. The energy dissipated in the form of heat can generate temperature. The temperature of the ingot will change through heat conduction and convection when the heating disperse freely with movement of wire saw, thereby influencing the wafer temperature distribution. The temperature field of the wafer changes with cutting depth and time.

The objective of thermal analysis is to assess the temperature distribution in the wafer surface with different cases. Input parameters used in simulation are material property, heat flux, film coefficient and bulk temperature. Output parameters are the temperature profile of wafer surface.

This is a transient thermal analysis as a function of time with three boundary conditions:

(1) An initial temperature is equal to ambient temperature.
(2) A heat flux entering the contact zone of wire saw and slicing kerf.
(3) A heat transfer by convection applied to all the free surfaces of the ingot. And the heat transfer coefficient depends on experiment conditions because it varies with environment.

The unsteady heat exchange equation is as follows:

$$\frac{\partial t}{\partial \tau} = \frac{1}{C(t)\rho}\left[\frac{\partial}{\partial x}\left(\lambda\frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial t}{\partial z}\right)\right] + \frac{q_n}{C(t)\rho} \quad (1)$$

Where τ is the time, t is the temperature, C is the specific heat capacity, ρ is the density, λ is the thermal conductivity, and q_n is the internal heat source. In this case, $q_n = 0$.

The initial condition was specified by setting the initial temperature to 23℃ unless otherwise mentioned. The initial temperature of the ingot is constant.

$$T(x, y, z, \tau) = 23\ ℃ \quad \text{at time } \tau = 0\ s \quad (2)$$

The determination of the heat transfer coefficients is essential. It is difficult to obtain by exact calculation because these coefficients depend on the location and the construction of the workpiece, the ingredient of coolant fluid, the flow rate of the coolant and, furthermore, air circulation. The convection coefficient of the ingot was determined in this case because the process of heat transfer by radiation is not significant. For the ingot, a convective heat condition simulating cooling was used due to the coolant splashing on it. A heat transfer coefficient for forced cooling by the coolant was applied. The forced convection coefficient for the surrounding of sapphire is h_1 = 1000 W/m^2℃ [9]. Despite the forced cooling, the sapphire ingot was also cooled by the surrounding air at the surface. The boundary condition of the ingot surface is considered free convection heat transfer with outside air. The natural convection coefficient for the front and back of sapphire ingot h_2 = 5 W/m^2℃ [5], the natural convection coefficient for the cutting planes of sapphire is h_3 = 1 W/m^2℃ [5].

Determination of heat flux

Heat flux during any machining can be defined as the power supplied for machining per unit area. Thus, heat flux q entering the kerf can be expressed as:

$$q = \frac{\varepsilon P}{V} \quad (3)$$

Where P is the consumed power for the wire slicing process, ε is the ratio of the power that transform to the heat and is absorbed by the sapphire. ε was defined as 0.667 according to the reference [4]. V is the total material removal rate being machined.

The consumed power P can be expressed as:

$$P = F_c v_c \quad (4)$$

Where F_c is the tangential force during slicing process, v_c is the velocity of the wire during slicing.

The total material removal rate can be expressed as:

$$V = Ldv_w \tag{5}$$

Where d is the width of the sawn kerf, v_w is the feed speed. L is the contact length between the workpiece and wire saw. For this case, the contact length L insists on changing with the increase of cutting depth due to the circular shape for the sapphire wafer. The total material removal rate increases with the increase of L, therefore, the amount of heat entering the workpiece also increases.

Take Eq. 4 and Eq. 5 to the Eq. 3, then the heat flux is described as:

$$q = \varepsilon \frac{F_c V_c}{L d V_w} \tag{6}$$

FEM meshing

With regards to the model meshing, eight-node 3D elements SOLID70 with each node having a single degree of freedom----temperature which used to model conduction heat transfer problems were considered. These elements were chosen because they show a faster convergence than the tetrahedral elements with respect to mesh refinement.

Element size is treated to be the most influencing constituent in the cutting process simulations. The reference [10] confirms that suitable element length should be chosen to achieve a balance between computational accuracy and calculation time.

The sizes of elements were designed. The length and the width of the elements in the wafer surface are both 2 mm, the three kinds of thickness of the wafer element is 0.3 mm, 0.5 mm, 0.7 mm respectively. For a better computational performance, a refined mesh should be employed on the contact area. Therefore, fine meshes were considered for the kerf. The kerf element is 0.05 mm, 0.08 mm and 0.125 mm respectively. The remainder elements were also extruded with 8 different sizes. However, it would be computationally expensive to use this fine mesh for the entire specimen. Hence, spacing ratio of remainder is proposed. This can create elements with gradual increased size to reduce grid number while develop a smooth connection between kerf and remainder. The spacing ratio of remainder that perpendicular to the wafer surface direction (z-direction) is 3 in all cases.

The sizes of grids were varied to conduct 16 groups test was shown in Table 2. FEM mesh-independence in slicing process simulations was certified as shown in Fig.1. From Fig. 1, it can be seen that for the more mesh grids, the deviation between simulated results becomes less and less. It can be concluded that the meshing method should be choose which temperature is insensitive to the element size with least calculation time.

Table 2. Variation of the sizes of grids

size(mm) / numbering	wafer surface	wafer	kerf	remainder	grid number
1	2x2	0.3	0.05	3	16000
2	2x2	0.5	0.08	3	13600
3	2x2	0.7	0.125	3	12000
4	2x2	0.3	0.05	5	12800
5	2x2	0.5	0.08	5	11600
6	2x2	0.7	0.125	5	8800
7	2x2	0.3	0.05	7	12000

8	2x2	0.5	0.08	7	9600
9	2x2	0.7	0.125	7	8000
10	2x2	0.3	0.05	10	10400
11	2x2	0.5	0.08	10	8000
12	2x2	0.7	0.125	10	6400
13	2x2	0.5	0.08	0.3	82400
14	2x2	0.5	0.08	0.5	52000
15	2x2	0.5	0.08	1	28800
16	2x2	0.5	0.08	2	17600

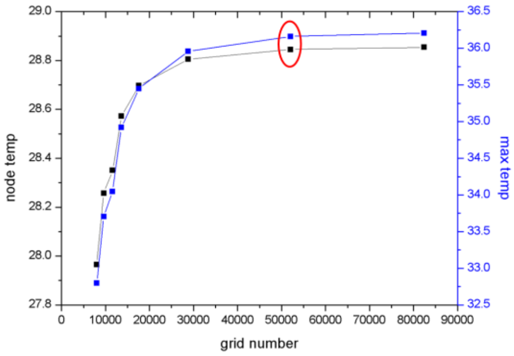


Figure 1. Profile of the grid independence of the model.

By comparison, the suitable result is chosen as shown the red circle in Fig.1. The length and the width of the elements in the wafer surface are both 2 mm, the thickness of the wafer element is 0.5 mm. A column of elements with width equal to a quarter of the thickness of the kerf is constructed for the part of kerf. The size of remainder element is 0.5 mm. Total number of elements and nodes were 25600 and 27456. Thus, it was concluded that the proposed grid resolution was sufficient. A better view of the model and the meshing distribution is presented in Fig. 2.

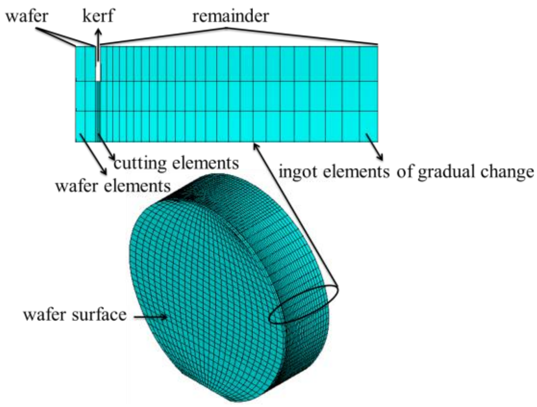
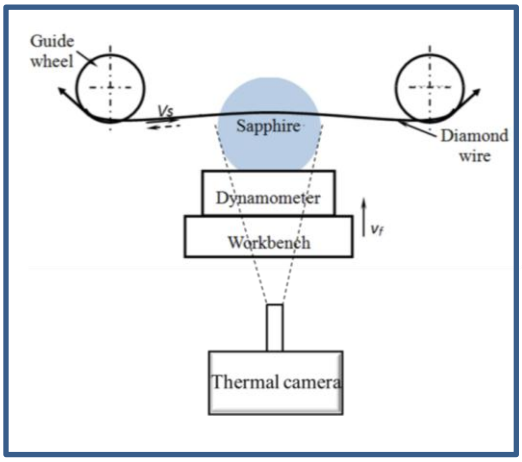


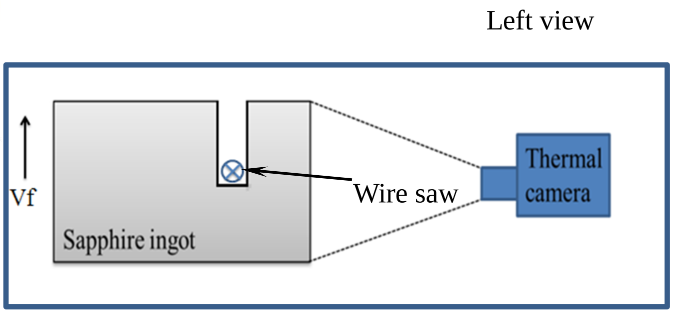
Figure 2. Finite element model with cut elements.

The wafer slicing is a continuous process, a method to express material removal in sawing was proposed by Toshiro [4]. The elements in sliced zone were named “cutting elements”. While the cutting elements were sliced, heat was transfer to them. After the cutting elements had been sliced completely, all of stiffness, heat conductivity and thermal capacity of them become zero. With the operation, the cutting elements were made exception from solution.

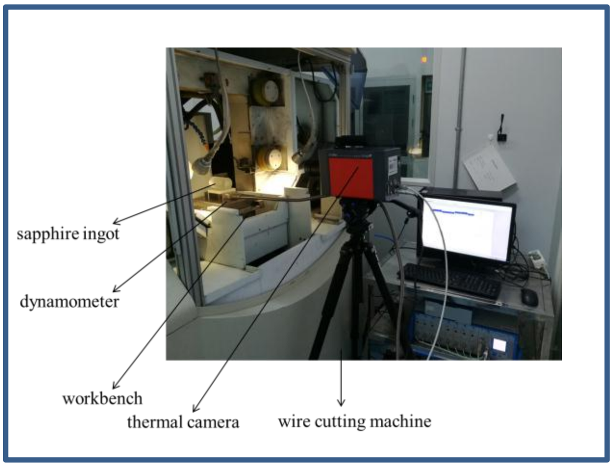
Experimental Conditions

Sawing experiments were conducted on JXQ-1201 single wire reciprocating wire cutting machine. The diamond wire saw produced by Asahi Company was 0.25 mm in diameter with 30 to 40 um diamond grits run reciprocally between the two rollers on the machine. Wire tension was 30 N. During this experiment, the wire speed was 5.83 m/s and the feed rate was 0.3 mm/min. Fig. 3 presents images of the apparatus. The specimen material was C-plane sapphire. The ingot was 50.8 mm in diameter and 100 mm in length.





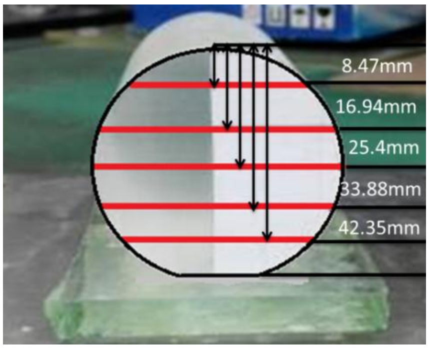
(a) Illustration of the wire slicing setup. **(b) Left view of wire slicing setup**



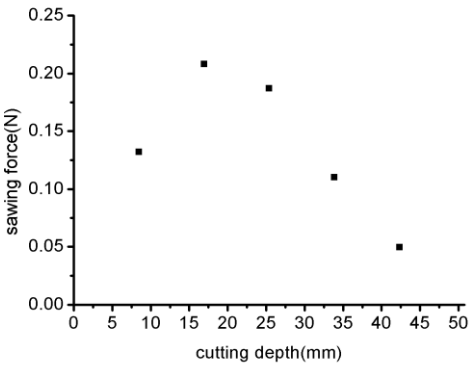
(c) Picture of wire slicing setup.

Figure 3. The wire slicing setup.

A piezoelectric dynamometer Kistler 9119AA2 was equipped to measure the sawing forces. The horizontal force measured by the dynamometer was acted as the tangential force due to the small wire deflection during slicing process. Five different cutting depths divided the wafer equally were selected to measure the sawing force signals. The cutting depths and the corresponding cutting lengths were shown in Fig. 4(a). Two sawing force signals at least at each position were recorded and the average value was taken as the final sawing force for this position. The sawing forces varied with the cutting depth of C-plane sapphire were shown in Fig. 4(b). With the increase of the cutting depth, the tangential force of the material was increase firstly and then decrease.



(a) Measuring Position marked with red line and crystal ingot outline indicated by black line.



(b) Sawing forces with different cutting depths.

Figure 4. Variation of the sawing forces with respect to the cutting depth of C-plane sapphire.

An Image IR 5325 thermal camera was used to determine the temperature distribution on the wafer surface at the same time of the force measurement. The thermal camera was mounted on the camera holder. The distance between the camera and the sapphire ingot was kept at 20 cm during the whole slicing process. The temperature distribution was measured at five cutting depths with and without fluid. In the experimental process, water-based cutting fluid was used, and the flow rate of cutting fluid was 2 L/min. Based on the literature [7], the emissivity of sapphire varies in the interval $0.53<\varepsilon<0.55$ for $273\ K<T<313\ K$. In the present work, an emissivity of sapphire was set as 0.54. The wavelength of the thermal camera is $3.7\mu m<\lambda<4.8\mu m$. According to the preliminary experiment results, the measurement temperature ranged from -10℃ to 40℃ was used as thermal camera setting.

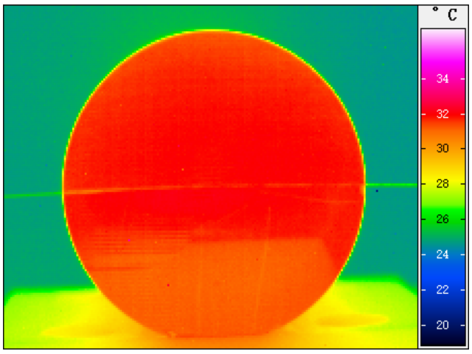
In order to stabilize environmental temperature, room temperature was maintained at 23℃. Tangential force, wire speed, feed speed and the corresponding cutting length were recorded to calculate heat generated by slicing process.

Results and Discussion

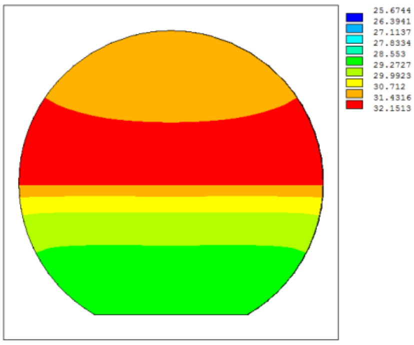
Experimental and simulation result of slicing temperature without coolants

Fig. 5 shows the experimental and simulation result of slicing temperature without coolant when the cutting depth is 25 mm. The temperature field distribution from experiment is shown in Fig. 5(a). While cutting the ingot without coolant, the temperature field of sapphire wafer is more than 30℃, which is obviously higher than the ambient temperature. The ambient temperature reaches at about 25℃, 2℃ higher than the initial temperature because the more heat was transfer to the surrounding air. The temperature of wire saw is lower than that on wafer surface which may due to the good thermal conductivity properties of metal wire. For the sapphire wafer, the temperature field below the wire saw is slightly less than that of other regions as shown in Fig. 5(a).

Simulation result is shown in Fig. 5(b). The high temperature area is concentrate on the region over the wire saw. In the wire saw cutting zone, the temperature remains constant. The temperature decrease slightly with the distance from the wire saw. The temperature below the wire saw is lower than that of other region, which is similar with the experimental results.



(a) Temperature field from measurement without coolant.

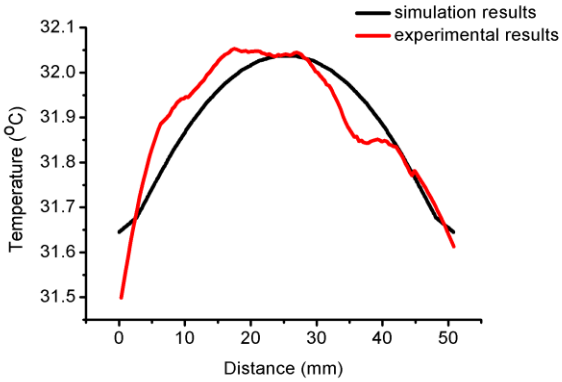


(b) Temperature field from simulation without coolant.

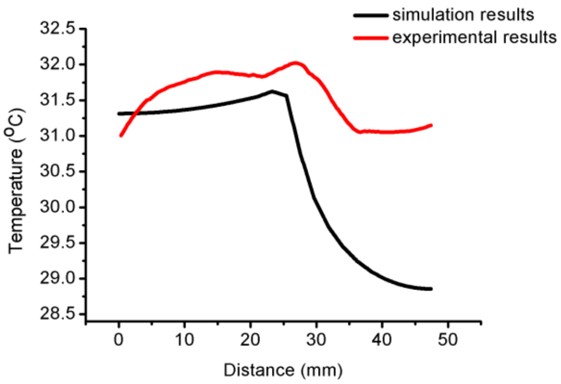
Figure 5. Results from simulations and measurements without coolant when the wire is half way through the ingot of dry cutting.

The temperature along the horizontal direction at the position of 25 mm cutting depth is shown in Fig. 6(a). The simulation temperature curve is similar with the experimental temperature curve. It is shown that the maximum temperature is about 32 ℃ as shown in Fig. 6(a). The simulation temperature profile is fairly axisymmetric, as shown the black curve in Fig 6(a). However, the experimental temperature profile (red curve) is a slightly different. The temperature peak is deviate slightly between measured temperature and calculated temperature. It is indicated that the temperature near the exit region is higher than that near the enter region..

The temperature along the vertical direction is shown in Fig. 6(b). It is found that the simulation temperature varies greatly with the vertical position. The temperature is increase slightly along the vertical direction and the highest temperatures are reached at the wafer center that is the position of wire saw. The maximum temperature is 31.5 ℃ then it decreases to 28.7℃ rapidly over distance. The measurement temperature curve variation along the vertical direction is similar with the simulation results. The temperature is increase slightly firstly and then decrease sharply, as shown the red curve in Fig. 6(b). However, the variation range of temperature value for the experiment is smaller than the case for the simulation, as shown in Fig. 6(b).



(a) Temperature along the saw wire from the wire entrance to the wire exit.



(b) Temperature on wafer surface perpendicular to the saw wire.

Figure 6. Results from simulations and measurements without coolant when the wire is half way through the ingot of dry cutting.

The maximum temperatures obtained by simulation and measurement for each measured depth is shown in Fig. 7. It is found that the experimental results are very consistent with the simulation results. The maximum temperature increases linearly from 26℃ to 35℃ with the cutting depth from 8.47mm to 42.35 mm. Heat accumulation is the main cause of the temperature increase. At position of cutting depth 42.35 mm, the simulation temperature is slightly small than the experiment results, which may due to the effect of fixture of sapphire ingot.

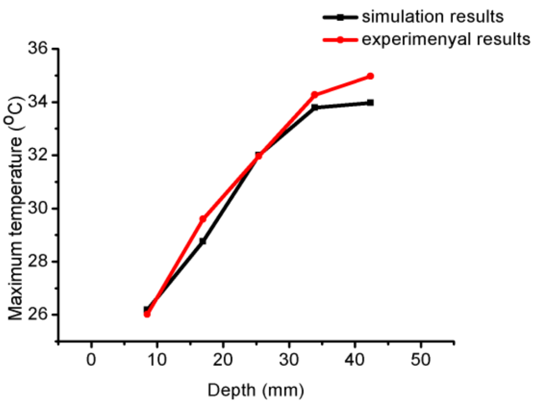
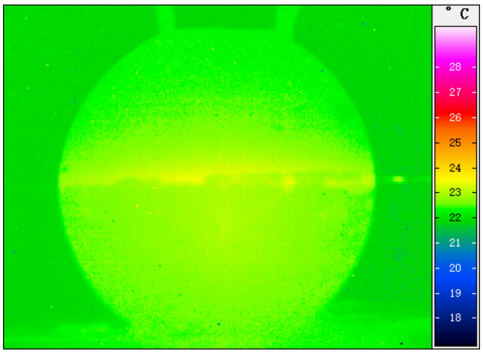


Figure 7. Results from simulation and measurement of temperatures when the wire is through the five cutting depth that divide the ingot equally.

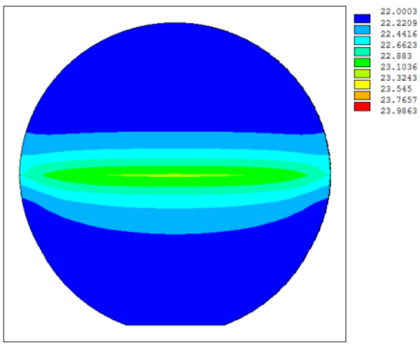
Experimental and simulation result of slicing temperature with coolants

Fig. 8 shows the experimental result and simulation result of slicing temperature with coolant when the cutting depth is 25 mm. The experimental temperature field of sapphire wafer and ambient has little variation as shown in Fig. 8(a). The experimental temperature of sapphire wafer ranged from 22℃ to 23℃ for the wire slicing with coolant, which is much lower than the case without coolant. Ambient temperature remains at 22℃ as shown in Fig. 8(a), which indicates that the more heat was taken by the coolant. The wire saw is the bright yellow line in the picture; it indicates the zone in which heat is generated more than other region. However, the temperature of wire saw is only about 24℃.

Simulation temperature of sapphire wafer is shown in Fig. 8(b). The high temperature zone is concentrate on the position of wire saw, which is similar with the experimental result. The temperature in the middle zone is higher than that in the two sides as shown in Fig. 8(b). The temperature upper and below the wire saw position is almost equal to the initial temperature. The whole temperature field of simulation result is almost consistent with the case of experimental result.



(a) Temperature field from measurement with coolant.

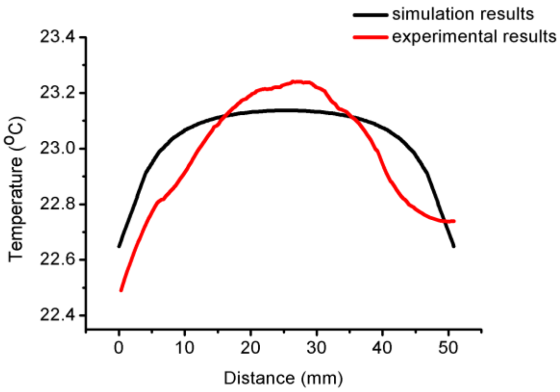


(b) Temperature field from simulation with coolant.

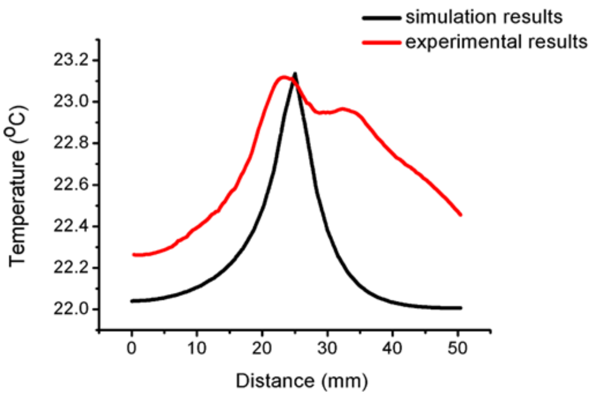
Figure 8. Temperature field from simulation and experiment with coolant when the wire is half way through the ingot.

Fig. 9(a) is the temperature curves along the horizontal direction at the position of 25 mm cutting depth. Both simulation temperature curve and experimental temperature curve show that the temperature in the middle position is higher than that in the two sides position. The experimental temperature is higher than the simulation temperature in the middle position, and is lower than simulation result in two sides. The simulation temperature profile is fairly axisymmetric, as shown the black curve in Fig 9(a). The maximum temperature located in the middle of the temperature curve is about 23.1℃ for simulation and 23.25℃ for experiment respectively. It is similar with the experimental results presented by Shinya [Shinya (2015)], which carried out the sapphire slicing with CeO_2 abrasive in water.

Fig. 9(b) shows the temperature curves of sapphire wafer perpendicular to the wire saw. The maximal temperatures are in the central area of the wafer and the values are similar. Unlike the temperature curve without coolant, the temperature increases sharply to the highest value along the vertical direction, and then decreases sharply as shown in Fig. 9(b). The profile of simulation result is more steeply than that of experimental result. The measured temperature profile has two peaks, as shown the red line in the Fig. ((b), which may due to the influence of the grits insert surface around the cutting zone.



(a) Temperature along the saw wire from the wire entrance to the wire exit.



(b) Temperature on wafer surface perpendicular to the saw wire.

Figure 9. Temperature profile results of simulation and experiment with coolant when the wire is half way through the ingot.

The maximum temperature with coolant obtained by simulation and measurement for each measured depth is shown in Fig. 10. It is found that the experimental temperature increases from 23.1℃ with the slicing depth until to 23.24℃ at the middle position and decreases slightly to 23.19℃ as shown the red line in the Fig. 10. However, the simulation temperature is keep at 23.1℃ except 24.1℃ at the position of slicing depth 16.94 mm.

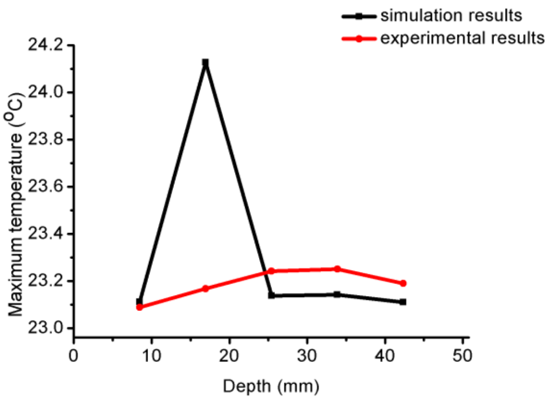


Figure 10. Results from simulation and measurement of temperatures when the wire is through the five cutting depth that divide the ingot equally.

Discussions

In the sapphire slicing process, the heat is generated in the slicing zone and transfers to the workpiece, wire saw and surrounding medium such as surrounding air, coolant flow. The final temperature field of sapphire wafer is the result of the heat transferred to sapphire ingot and the coolant condition. A good coincidence between the simulation result and experimental result without coolant shown that heat source model used in the FEM model is consistent with experimental practice. The coolant has significant effect on the temperature field of sapphire wafer, The coolant drastically reduce the slicing maximum temperature from 32℃ to 23.1℃ which is proved not only the experimental results but also the simulation result, as compared with Fig. 5 and Fig. 8. Taking into account Eq. 6, ε is represents the fraction of the power that is transforms to the heat and absorbed by the sapphire. This dimensionless parameter is significantly influenced by the cooling condition. The effect of coolant should be discussed in detail because there are mismatch between the simulation results and experimental results. In the FEM model, the heat transfer coefficient for forced cooling by the coolant was uniformly acted on the workpiece. However, it is not coincide with the actual conditions.

A narrow kerf was formed through the wire slicing process. The narrow slicing kerf has significant effect on the coolant supply. The coolant was supplied to the machining zone by the cooling tube mounted two side of workpiece. The enough coolant was provided to kerf and transferred the machining heat in initial stage of slicing. With the increase of the slicing depth, the length of slicing arc increases as shown in Fig. 4(a). It is difficult for the enough coolant to enter the whole slicing zone, especially in the middle of slicing zone. Therefore, the temperature in the middle region is higher than that in the two sides as shown in Fig. 9(a). With the increase of slicing zone, the coolant provided to the middle region reduces and the slicing temperature elevates. When the slicing depth is more than half of wafer diameter, the slicing zone reduce with the increase of slicing depth. The coolant condition is improved; therefore, the slicing temperature remains stable, as shown in Fig. 10.

Wire movement also has effect on the coolant supply. The wire saw is covered by a thin layer of coolant when it enters into the slicing zone, which pushes coolant into the slicing kerf. It can be found the profiles of numerical results are symmetric, but it was found that the temperature peak is deviate slightly between measured temperature and simulated temperature. The temperature near the exit is higher than that far away from the exit in the actual slicing process in the horizontal direction, as shown in Fig. 9(a). More cold air was taken into the slicing zone by the wire movement, so temperature peak deviation was also observed in Fig. 6(a).

According to the above discussion, it is found that numerical simulation and experimental measurement on the sapphire slicing process with different cooling conditions were conducted, the simulated results are found to be acceptable. The uneven coolant condition should be taken into account to improve the simulation accuracy.

Conclusions

A FEM model was successfully established to simulate the temperature field of sapphire wafer in the slicing process. The simulation result is good consistent with the experimental result in the condition without coolant. However, the maximum temperature with coolant obtained by simulation is lower than that obtained by experiment due to the coolant supply method. No matter with or without coolant, the maximum temperature located in the middle of slicing zone. The maximum temperature without coolant increases linearly from 26℃ to 35℃ with the cutting depth. Coolant significantly reduces the temperature field of sapphire wafer. The maximum temperature with coolant increases with the cutting depth with coolant due to the effect of narrow slicing kerf on the coolant supply.

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References

[1] MS Akselrod, FJ Bruni. (2012). Modern trends in crystal growth and new applications of sapphire. Journal of Crystal Growth, **360(1)**:134–135.

[2] C. H. Chung, G. D. Tsay, M. H. Tsai. (2014). Distribution of diamond grains infixed abrasive wire sawing process. International Journal of Advanced Manufacturing Technology, 73(9-12):1485–1494.

[3] Johnsen, L., Olsen, J. E., Bergstrom, T. et al. (2012). Heat Transfer During Multiwire Sawing of Silicon Wafers. Journal of Thermal Science and Engineering Applications, 1–3.

[4] Toshiro, Yamada. (2004). Warpage Analysis of Silicon Wafer in Ingot Slicing by Wire-Saw Machine. Materials Processing and Design: Modeling, Simulation and Applications, 1459–1463.

[5] Sumeet, Bhagavat. and Imin, Kao. (2008). A finite element analysis of temperature variation in silicon wafers during wiresaw slicing. Machine Tools ＆ Manufacture , **48**: 95–106.

[6] Shinya, M. (2015). Study on the slicing of sapphire using a wire tool. Advanced Materials Research, 333–337.

[7] Wakaki, M., Kudo, K. and Shibuya, T. (2007). Physical Properties and Data of Optical Materials. Optical Science and engineering, 383–384.

[8] Dobrovinskaya, E. R., Lytvynov, L. A. and Pishchik, V. (2008). Sapphire：Material, Manufacturing, Applications. Springer Science and Business Media, 12–54.

[9] Incropera, F. P., and Dewitt, D. P. (1996). Fundamentals of Heat and Mass Transfer. Wiley & Sons, Hoboken, NJ.

[10] Ravindra, Ambati. and Yuan, Huang. (2011). FEM mesh-dependence in cutting process simulations. The International Journal of Advanced Manufacturing Technology, 313–323.