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Numerical study on thermal stress cutting of silicon wafer using two-point pulsed laser

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Laser cutting using the controlled fracture technique has great potential to be used for the separation of brittle materials. In this technique, thermal stress is used to induce the crack and the material is separated along the moving direction by extending the crack. In this paper, based on the heat transfer theory, a three-dimensional thermoelastic finite element model which contains a pre-existing crack is established for a two-point pulsed Nd:YAG laser cutting silicon wafer. The mechanism of crack propagation is investigated. Meanwhile the effects of laser power and the distance between the two laser spots on the development of thermal stress are investigated. The numerical results show that the thermal stress is affected by laser power and the distance between the two laser spots, an increase in the laser power for the same distance between the two laser spots or a decrease in the distance between the two laser spots with constant laser power can induce the increase in the cutting speed.

Keywords: brittle materials, thermal stress, laser cutting.

1. Introduction

Most of semiconductor wafers are brittle materials such as silicon, gallium arsenide, indium phosphide and so on. Machining of semiconductor wafers is very difficult due to the hardness and brittleness. The conventional mechanical cutting technique for brittle materials with the help of a metal or diamond saw has been used for decades. Therefore, irregular cut path, chip formation and uncertain fracture of the cut edge are the intractable problems in the conventional mechanical cutting process, especially for thin brittle wafer.

Controlled fracture technique has great potential in brittle materials cutting. This technique uses less laser power and enables high cutting speeds compared to other laser cutting methods, as proposed by LUMLEY [1]. In this technique, the cutting process is based on the fracture mechanism of the brittle material caused by thermal stress. LUMLEY [1] successfully applied CO_2 laser in the cleaving of alumina ceramic substrate and glass. With this controlled fracture technique, a liquid crystal display (LCD) glass substrate was cut successfully by YE *et al.* [2]. TSAI and LIOU [3, 4] proposed an explanation for why the material separation is controllable for the controlled fracture technique by using a single laser. DEKKER *et al.* [5] proposed a method similar to the controlled fracture technique for cutting glass. A small scratch is formed at the start of the cut which helps in initiating the crack and leads to the separation of the glass. In order to improve the cutting quality, JUNKE JIAO and XINBING WANG [6] proposed a dual-laser-beam method to cut glass substrates. An off-focus CO_2-laser beam was used to preheat the glass sample to reduce the thermal gradients and a focused CO_2-laser beam was used to machine the glass. SALMAN NISAR *et al.* [7] examined the cut deviation problem by analyzing the stress fields in the glass during laser cutting process. UEDA *et al.* [8] investigated the cleaving mechanism of a silicon wafer irradiated with pulsed Nd:YAG laser, the results of the experiment showed that the temperature at the area irradiated with the laser is an important factor in the control of the propagation of the crack to achieve high cleaving accuracy and low thermal damage.

In this paper, a two-point pulsed laser cutting method was investigated. Based on the controlled fracture technique, the process of a two-point pulsed Nd:YAG laser cutting silicon wafer was simulated by using the finite element analysis (FEA) software, Ansys. The mechanism of crack propagation was investigated by analyzing the development of the temperature field and the resulting thermal stress field during the pulse duration. The development of stress intensity factor at the crack tip is also discussed. Moreover, the effects of laser power and the distance between the two laser spots on the development of thermal stress are investigated.

2. Numerical simulations

The two-point pulsed laser cutting mode is not like the common pulsed laser cutting mode in which laser scanning is along the cutting line (see Fig. 1). The diagram of two-point pulsed laser cutting process is illustrated in Fig. 1**b**, the scanning paths of

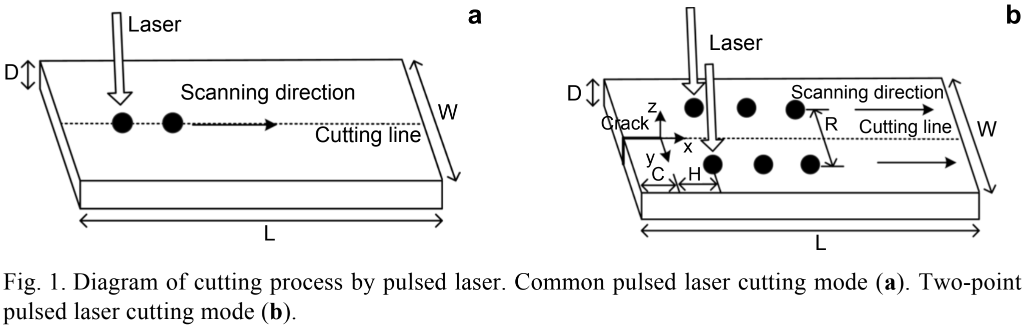

Fig. 1. Diagram of cutting process by pulsed laser. Common pulsed laser cutting mode (**a**). Two-point pulsed laser cutting mode (**b**).

the two pulsed laser beams locate on both sides of the cutting line. In order to obtain the distribution of the temperature field and thermal stress field in the silicon wafer during the cutting process, the finite element model is established using Ansys.

The dimension of a silicon wafer is 11.5 mm×6 mm×0.5 mm. A pre-existing crack of 1.5 mm length is formed in the silicon wafer before cutting which helps in initiating the crack and leads to the separation of the wafer.

Before the mathematical model is established, some assumptions should be made:

1. In the paper, the initial temperature is 300 K, the maximum temperature during the cutting process is lower than 700 K, all the physical parameters of silicon are temperature-independent.
2. On the surface of the silicon wafer where there is no laser heating, the superficial heat irradiation is negligible.
3. The cleaving direction and the crystal plane of the wafer are $\langle 0\bar{1}1\rangle$ and $\langle 100\rangle$, respectively.
4. The specimen was annealed and hence it was free of any residual stresses.
5. The stress-strain relationship of the silicon wafer is perfectly elastic.
6. In this study, the phase change is not taken into consideration.

Based on the above assumption, the mathematical heat transfer model can be established as [9]

$$\rho c \frac{\partial T}{\partial t} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{1}$$

$$T(t) = T_0 \quad \text{at} \quad t = 0 \tag{2}$$

$$-k \frac{\partial T}{\partial z} + h(T_s - T_0) + B\varepsilon\left(T_s^4 - T_0^4\right) = \alpha I(x, y, z, t) \quad \text{at} \quad z = 0 \tag{3}$$

$$-k \frac{\partial T}{\partial n} = h(T_n - T_0) \quad \text{at} \quad z = -D; \quad x = 0, L; \quad y = \pm \frac{W}{2} \tag{4}$$

where k is the thermal conductivity, c and ρ are the heat capacity and the density, respectively, T_0 denotes the initial temperature of silicon, which is the same as the environment temperature, T_s denotes the temperature of the heated zone and T_n denotes the temperature of the area without laser heating, h is the convection heat-transfer coefficient, B is the Stefan–Boltzmann constant, $I(x, y, z, t)$ is the density of the laser power, and n is the direction cosine of the boundary.

The laser beam maintains a constant TEM_{00} mode. The density of the laser power can be described as follows:

$$I(x, y, t) = \frac{p_0 \alpha}{\pi r^2} \exp\left(-\frac{x^2 + y^2}{r^2} \right) \exp(-\alpha z) g(t) \tag{5}$$

here,

$$g(t) = \begin{cases} 1 & 0 < t \le \tau \\ 0 & t > \tau \end{cases}$$

where τ is pulse duration, and $\tau = 1$ ms; p_0, α and r are the laser power, the absorption coefficient and the radius of the laser beam, respectively.

In this study, the stress and strain responses are assumed to be quasi-static at each interval and the thermo-elastic model is used. During the process of the laser cutting, rapid heating or cooling could induce thermal stress. The thermal stress σ_{therm} caused by the temperature difference ΔT, is given by [10]

$$\sigma_{\text{therm}} = \frac{E\beta\Delta T}{1-\theta} \tag{6}$$

where θ is the Poisson ratio, E and β are the Young modulus and the coefficient of linear expansion, respectively.

Figure 2 shows the grid structure of the silicon wafer. Around the crack tip, the size of an element is optimized balancing the demand for simulating precision and computational efficiency, which turns out to be smaller than that in other regions.

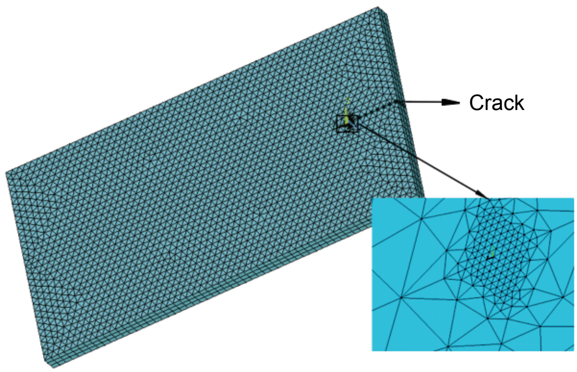

Fig. 2. Mesh model of a silicon wafer.

Given the material parameters and the suitable boundary conditions of the mathematical model, the temperature and thermal stress can be calculated by Ansys. The Nd:YAG pulsed laser with the wavelength of 1.06 μm is used for cutting. The pulse duration and beam radius are 1 ms and 0.5 mm, respectively. The material parameters [11] are shown in the Table.

T a b l e. The physical parameters of silicon wafer.

ρ [kg m^{-3}]	C [J kg^{-1}K^{-1}]	K [Wm^{-1}K^{-1}]	β [K^{-1}]	E [GPa]	σ	α [m]
2340	761	156	2.62×10^{-6}	117.4	0.262	5000

3. Simulation results and discussion

3.1. Analysis of temperature field and thermal stress field

The cutting line and one of the scanning lines are selected to investigate the development of the temperature field and thermal stress field when the silicon wafer is irradiated by the two-point pulsed laser.

The temperature field induced by laser heating at 1 ms with the laser power P = 180 W and the distance between the two laser spots R = 2 mm is shown in Fig. 3, and the temperature history of the central point of laser spot is shown in Fig. 4. The temperature increases rapidly during the laser irradiation and the maximum temperature of the center of laser spot reaches 698.6 K at 1 ms which is the end of irradiation. After the pulse duration, the temperature descends slowly as a result of heat loss by conduction.

Figure 5 shows the normal stress σ_{yy} distribution along the cutting line. The maximum tensile stress is always at the crack tip ($x = 0$) because of the concentration of stress by the crack. The tensile stress at the crack tip keeps increasing during the pulse duration, it reaches 126 MPa at 1 ms. When the tensile stress induced by the laser becomes large enough, the crack will propagate along the cutting line. During the next

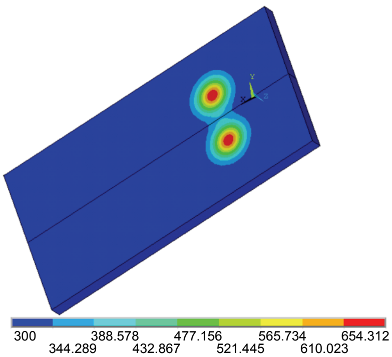

Fig. 3. The distribution of the temperature at 1 ms.

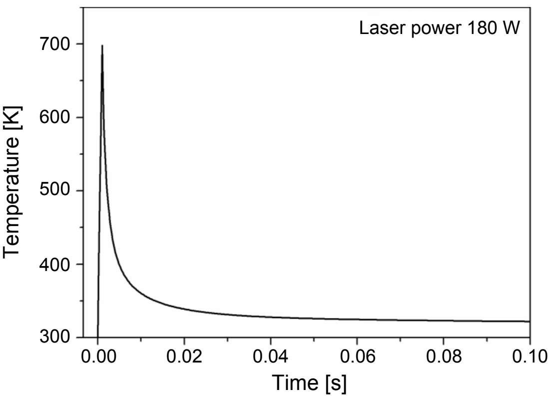

Fig. 4. Temperature history of the central point of laser spot.

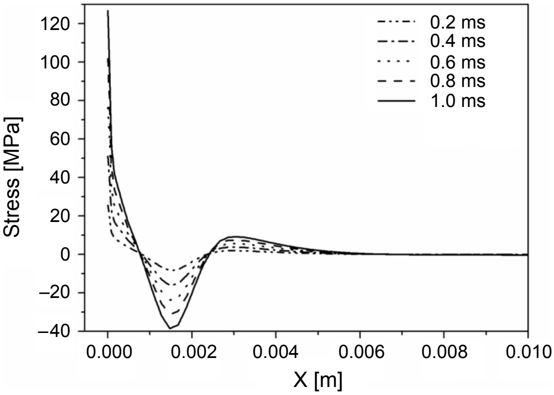

Fig. 5. The stress σ_{yy} distribution along the cutting line.

pulse, the maximum tensile stress is also at the new crack tip because of the concentration of stress, and the crack will go on propagate.

3.2. The effects of laser power on the development of thermal stress

When the distance between the two laser spots is 2 mm, 120 W, 150 W and 180 W are selected for laser power.

Figure 6 shows the temperature distribution along the scanning line and the normal stress σ_{yy} distribution along the cutting line at 1 ms (the end of the pulse duration). The maximum temperature is in the center of laser spot, and the maximum temperature increases with laser power. The maximum tensile stress is at the crack tip ($x = 0$) because of the concentration of stress by the crack. With the increase in laser power, the maximum tensile stress becomes larger. During the pulse duration, if the tensile stress exceeds the critical value, the crack will propagate. So if the higher laser power is used in the cutting process, the tensile stress induced at the crack tip becomes larger, and the propagation of the crack will be easier.

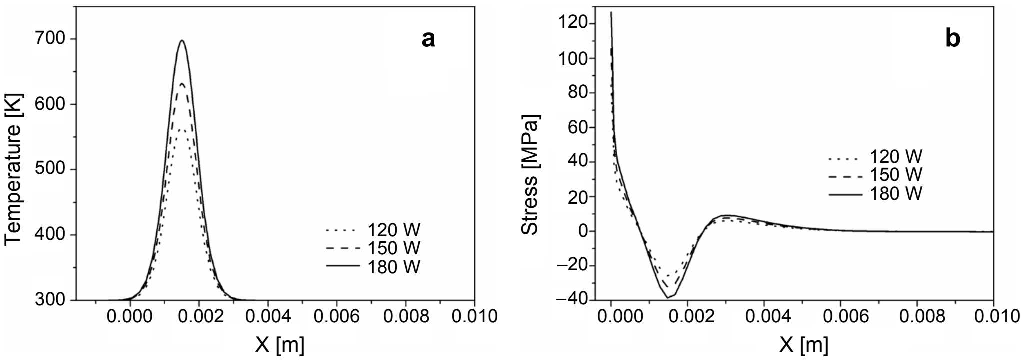

Fig. 6. Temperature distribution along the scanning line (**a**) and the normal stress σ_{yy} distribution along the cutting line (**b**).

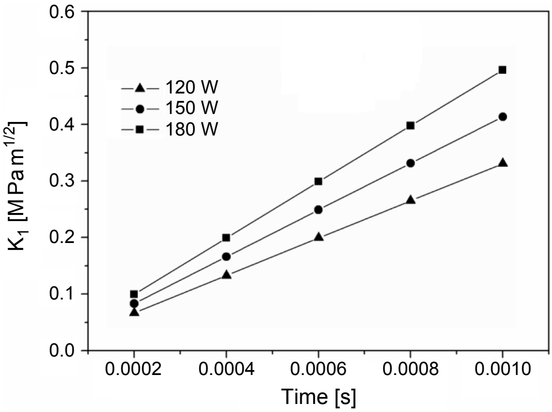

Fig. 7. The time history of the stress intensity K_1 during the pulse duration.

During the cutting process, the crack propagates when the stress intensity factor K_1 at the crack tip becomes larger than the fracture toughness of the material [12]. Figure 7 shows the time history of the stress intensity K_1 at the crack tip during the pulse duration. It can be seen that when the laser power 120 W was used, the increase of K_1 is slower than the other two laser sources. The increase of K_1 becomes faster with the increase in laser power. The crack propagation will occur in a shorter time after the laser began to irradiate the silicon wafer if a higher laser power source is used. It means that cutting speed will increase with an increase in the laser power for the same distance between the two laser spots.

3.3. The effects of the distance between the two laser spots on the development of thermal stress

When the laser power is 180 W, 1.2 mm, 1.6 mm and 2 mm are selected as the distance between the two laser spots.

Figure 8 shows the normal stress σ_{yy} distribution along the cutting line at 1 ms (the end of the pulse duration). It can be seen that with the decrease in the distance,

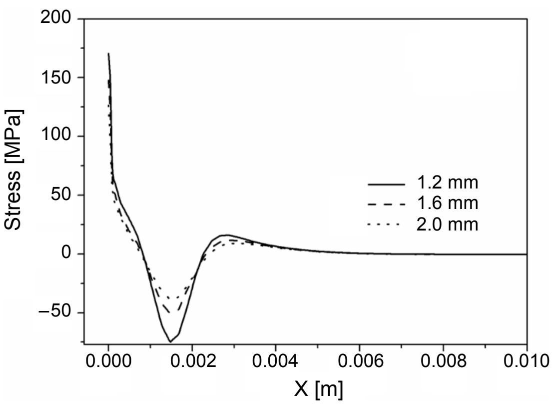

Fig. 8. The normal stress σ_{yy} distribution along the cutting line at 1 ms.

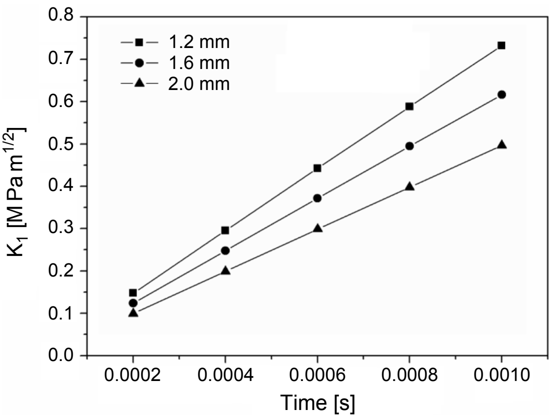

Fig. 9. The time history of the stress intensity K_1.

the maximum tensile stress becomes larger. The thermal stress at the crack tip is 126 MPa when the distance is 2.0 mm. When the distance is 1.2 mm, the thermal stress reaches 170 MPa. If the distance is decreased, the maximum tensile stress will be larger, and the probability of crack propagation will increase.

Figure 9 shows the time history of the stress intensity K_1 during the pulse duration. When the distance between the two laser spots is 1.2 mm, the increase of the K_1 is the fastest. The decrease in the distance can make the crack propagate in a shorter time after the laser began to irradiate the silicon wafer. It means that a decrease in the distance between the two laser spots with constant laser power can induce the increase in the cutting speed.

4. Conclusions

In this study, based on the assumptions that given are the parameters of silicon wafer and the boundary conditions, a three-dimensional mathematical thermoelastic calculational model, which contains a pre-existing crack, was established for a two-point pulsed Nd:YAG laser cleaving silicon wafer. During the pulse duration, the temperature and the thermal stress were calculated using the finite element analysis (FEA) software, Ansys. Through the analysis of the distribution of thermal stress, the conclusion was obtained that the silicon wafer was separated by the tensile stress induced at the crack tip, and the cutting speed was affected by laser power and the distance between the two laser spots. The increase in the laser power and the decrease in the distance between the two laser spots can induce the increase in the cutting speed.

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