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Thermal Stress Analysis on Cleaving Sapphire Material by CO_2 Laser

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Abstract: This study investigates thermal-stress behavior during cleaving process of sapphire wafer by CO_2 laser irradiation. Thermal-stress cleaving process is used to separate the sapphire wafer by extending the fracture via thermal stress generated by a laser heat. The process capable to produce an excellent separated surface condition. The finite-element method was used to evaluate a steady-state thermal stress by considering the temperature transient during irradiation process. Fracture initiation has been determined by analysing the stress intensity factor, K_1. The result shows that energy from the CO_2 laser was absorbed mostly on the surface area of the sapphire material. Thermal stress was generated and tensile stress developed at the bottom surface of the sapphire wafer. Fracture starts from the bottom surface of the material, instead of from the pre-prepared micro-groove on the irradiation surface if higher power laser is used. The fracture cannot be controlled and may lead to a poor cleaving surface. Therefore, laser absorption characteristics perform an important factor on fracture initiation in thermal-stress cleaving technique.

Key words: Thermal-stress cleaving, stress intensity factor, CO_2 laser, sapphire wafer, Japan

INTRODUCTION

Sapphire substrates are currently on demand due to its excellent properties of high strength, high rigidity, good electrical insulation, good thermal conductivity and great optical transparency to visible light. The application of sapphire wafer spread to wide-ranging of industries due to its unique features. Sapphire substrates are being used to produce a new generation of LED lighting which offers lower power consumption and longer lifespan. Because of shatterproof and scratch-resistant characteristics, sapphire crystal has being applied for camera lenses and premium-watch covers.

Well-versed selection of processing techniques is compulsory to ensure product quality and process efficiency in order to align with the growth in demand for sapphire substrates. Thermal stress cleaving with a laser beam has been applied in processing sapphire (Lumley, 1969). In this technique, material is divided by extending the fracture via thermal stress generated by a laser beam material separation is similar to crack extension. The process produces an excellent surface finish does not produce machining chips and not require a machining liquid.

Numbers of experimental investigations on thermal-stress cleaving processes using a CO_2 laser have been performed on sapphire wafer (Imai *et al*., 1989; Kurobe *et al*., 1995; Ueda *et al*., 2002, 2011). It has been reported that heat damages can be minimized by establishing appropriate laser irradiation conditions. However, the thermal-stress condition inside the material during laser irradiation is yet to be verified. In this study, the Finite-Element Method (FEM) is used to analyze the thermal-stress conditions during irradiation of a sapphire wafer with a CO_2 laser. Thermal-stress distribution during laser irradiation is varies depend on the absorption characteristics of laser beam and material properties. Due to the nature of the process, pre-process micro-groove position also need to be considered to ensure the fracture can be controlled and results good cleaving surface. This study reports on a computational analysis results of a temperature transient on the laser irradiation on the sapphire wafer. Then, a steady-state thermal-stress analysis is evaluated and discussed.

Finite element analysis: Thermal-stress cleaving behavior during laser irradiation was analyzed using Finite-Element Software (ANSYS) by considering the finite-boundary effect. The finite-element model has been considered as a 3-dimensional problem as the temperature and thermal-stress distribution from the laser spot diverged along the thickness direction of the substrate. In this study, the size of specimen used was 6×6×0.15 mm.

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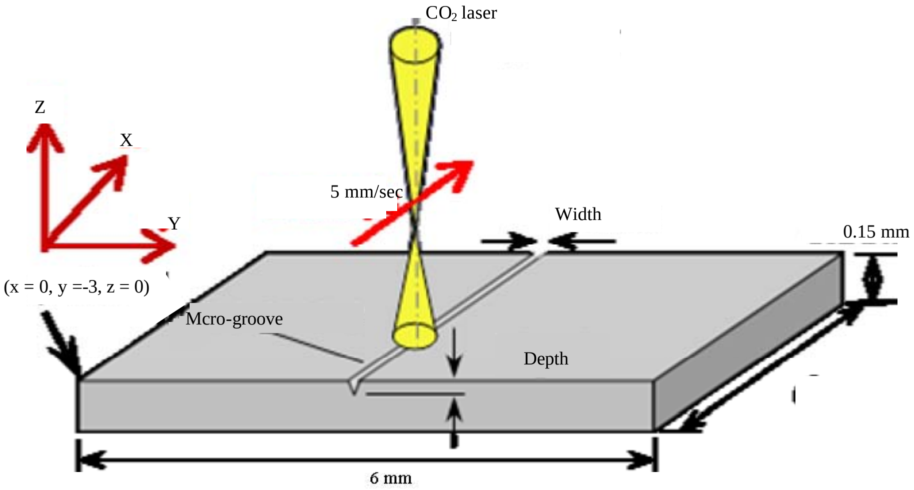

Fig. 1: Specimen and coordinate system

The analysis model was formed as a symmetric model to minimize the analysis element number. The model with a coordinate system is shown in Fig. 1. A groove of 15 μm in depth and 5 μm in width was created along the x-axis.

During the analysis the following assumptions for thermo-mechanical conditions were considered. The material properties such as the heat-transfer properties and mechanical properties were assumed to be constant as the temperature range was low. The stress-strain relationship of the sapphire wafer was assumed to be perfectly elastic. Convection conditions were assumed to exist on all boundaries while the surface of the x-z plane (y = 0) was considered to be in adiabatic condition. The laser energy absorption characteristic is represented by the Beer-Lambert Equation (Eq. 1) (Kurobe *et al*., 1995). Based on the equation the laser energy absorption relative to the thickness of the material can be estimated. The variation of laser energy absorption along the thickness direction of sapphire is shown in Fig. 2. The CO_2 laser energy is absorbed mainly on the surface of the sapphire material:

$$\beta = \frac{-\ln T}{x} \qquad (1)$$

Where:

T = The spectral transmittance
β = The absorption coefficient
x = The thickness of the wafer

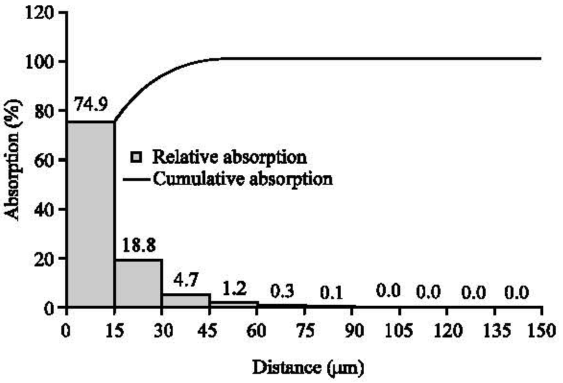

Fig. 2: Variation of laser energy absorption along the thickness direction; Laser type: CO_2 laser; wavelength: 10.64 μm

Table 1: Analysis condition of sapphire wafers

Analysis condition	Unit
Work piece size	6×6××0.15 mm
Laser beam diameter	0.3 mm
Heat transfer cofficient	8 $W/m^2/K$
Initial temperature	20°C
Laser beam scan speed	5 mm/sec
Laser power	3.6 W

Table 2: Properties of sapphire wafers

Properties	Unit
Thermal conductivity	142 W/mK
Special heat	75 J/kgm^3
Density	3980 kg/m^3
Thermal expansion coefficient	5.3×10^{-6}/K
Young modulus	470 GPa
Poission ratio	0.3

During the laser irradiation, a laser beam irradiates the material along the x-axis with a scan speed of 5 mm/sec. At t = 0 sec the laser beam was at the leading edge of the wafer (i.e., x = y = z = 0). The initial temperature and surrounding temperature were both set to 20°C. Transient temperature analysis was performed during laser beam movement. Then, the steady-state stress analysis was performed using the temperature distribution results at a specific point in time. Table 1 and

2 summarized the analysis conditions and the thermal physical properties of sapphire wafer, respectively. The laser-beam spot diameter used in the analysis was 0.3 mm. The heat transfer coefficient used was 8 W/m^2/K and the initial temperature was set to 20°C. During laser irradiation process, occurrence of laser energy reflection was assumed not occur. The boundary condition during the steady-state stress analysis was set as traction-force-free on all surfaces except the x-z surface this surface was set as a fixed plane indicating that the displacement in the y-direction was zero.

MATERIALS AND METHODS

Temperature distribution: The transient temperature was calculated from the edge of the specimen at t = 0 sec. The temperature distributions on the x-z plane at t = 0.02 sec and t = 0.09 sec for sapphire is shown in Fig. 3. It can be seen that higher temperature range is concentrated in the area close to the surface of the specimen. This is because the energy of the CO_2 laser was fully absorbed in the area close to the surface of the material as shows in Fig. 2. The temperature history of the laser spot on the sapphire is shown in Fig. 4. The values refer to the simulated temperature on the surface of the material along the x-axis. The temperature was increased rapidly at the beginning of the laser-beam irradiation on the sapphire wafer until it reached maximum temperature of about 350° and 680°C for laser power of 3 and 6 W, respectively. Then, the temperature was decreased gradually until it reached constant temperature.

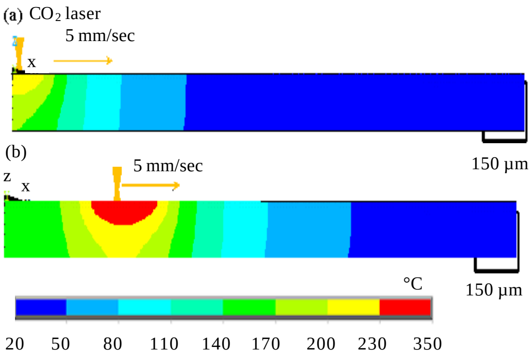

Fig. 3: Temperature distribution of sapphire wafer n x-z plane, P = 3 W : a) t = 0.02 sec and b) t = 0.09 sec

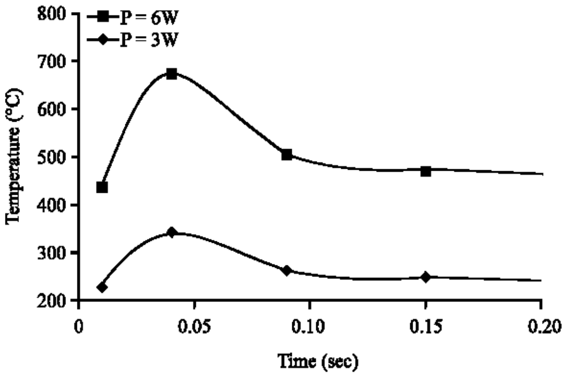

Fig. 4: Temperature histories of the laser spot; Laser: CO_2; scan speed: 5 mm/sec; material: sapphire wafer

RESULTS AND DISCUSSION

Thermal stress distribution: The thermal-stress (σ_{yy}) distributions on the x-z plane for sapphire at t = 0.02 sec and t = 0.09 sec are shown in Fig. 5. Compressive stress was found to be concentrated in the area close to the positions of the laser spot and the magnitude was larger in the area closest to the irradiating surface. This phenomenon occurred due to the laser absorption characteristics of the sapphire.

As the laser beam moved forward in the x-axis direction the maximum tensile stress accumulated at the groove tip (x = 0, z = -0.015 mm) of the specimen. Figure 6

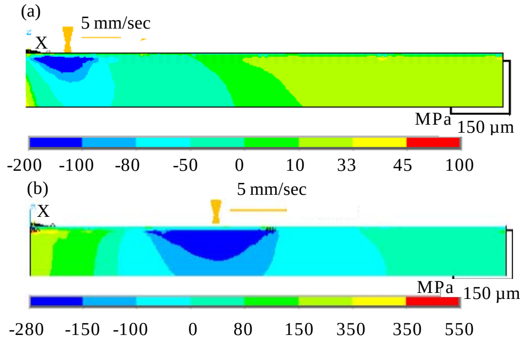

Fig. 5: Thermal-stress distribution for sapphire wafer on x-z plane: a) t = 0.02 sec and b) t = 0.09 sec

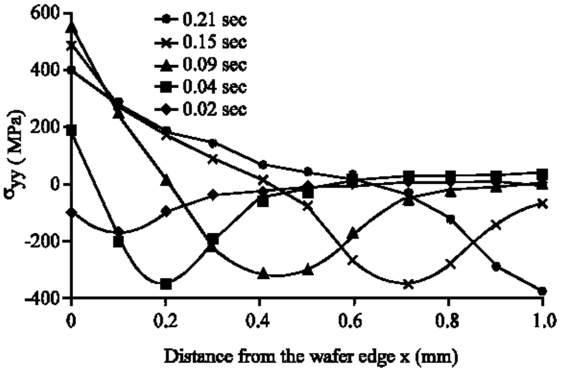

Fig. 6: Thermal-stress (σ_{yy}) distribution of sapphire at various times (z = -0.015 mm); Materia: sapphire; Laser type: CO_2: laser power, P = 3 W; Scan speed: 5 mm/sec

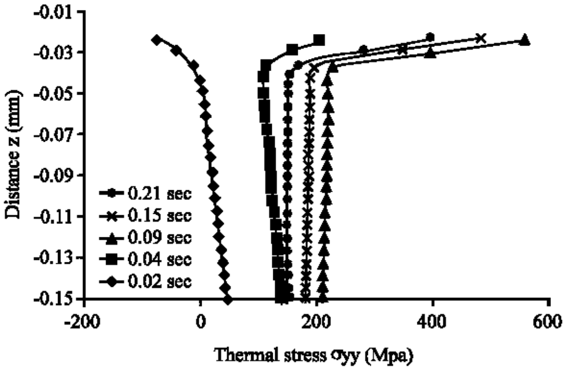

Fig. 7: Thermal stress along z-axis (x = 0); Materia: sapphire; Laser type: CO_2: Laser power, P = 3 W; Scan speed: 5 mm/sec

shows the relationships between thermal stress (σ_{yy}) and time. Thermal-stress profile was measured at the groove tip (z = -0.015 mm), along the x-axis. At the beginning of laser irradiation the thermal stress (σ_{yy}) at the specimen starting edge (x = 0) was a compressive stress. The thermal stress then changed to tension in a short time when the laser beam moved in the x-axis direction. As the laser beam moved further, large tensile stress was accumulated at the groove tip (x = 0, z = -0.015 mm). This significant tensile stress (σ_{yy}) may induce a fracture when the stress reaches the fracture strength of the material. The fracture could be induced along the thickness direction (z-axis) and extended throughout the material.

Figure 7 shows the thermal stress (σ_{yy}) measured along the *z*-axis at the edge of the specimen (x = 0 mm). At the beginning of laser irradiation, t = 0.02 sec the thermal stress (σ_{yy}) on the groove tip (z = -0.015 mm) was compressive and tensile stress resulted on the bottom surface of the specimen (z = -0.15 mm).

The relationship between maximum thermal stress (σ_{yy}) and laser irradiation time for sapphire wafer is shown in Fig. 8. The results indicate that at the beginning of irradiation, compressive stress was produced at the positions z = -0.015 and z = -0.15 mm. Greater magnitude of compressive stress was effected at the groove tip (z = -0.015 mm) because the heat from the laser beam was concentrated on the surface area of the specimen. As the time increases the thermal stress at both positions changed from compressive to tensile stress. The stress level was increased rapidly at the groove tip (z = -0.015 mm) compared to the stress on the bottom surface of the specimen. For laser power of P = 6 W the phenomenon of stress conditions was repeated but with noticeable σ_{yy} value as shown in Fig. 8.

Stress intensity factor: To estimate the stress condition at the positions z = -0.015 and z = -0.15 mm (x = 0), stress intensity factor, K_I has been calculated. A fracture may occur when K_I reaches the critical value (fracture toughness). Irwin found that the stress field σ (r, θ) in the vicinity of a groove tip could be described mathematically as in Eq. 2. Stress intensity factor can be determined by using Eq. 3 by considering that initial fracture occurs according to opening mode I and θ = 0° the σ_{yy} is defined as the magnitude of local stress at a distance r from the groove tip. In this study, K_I was calculated by considering σ_{yy} at a constant distance, r = 0.15 μm:

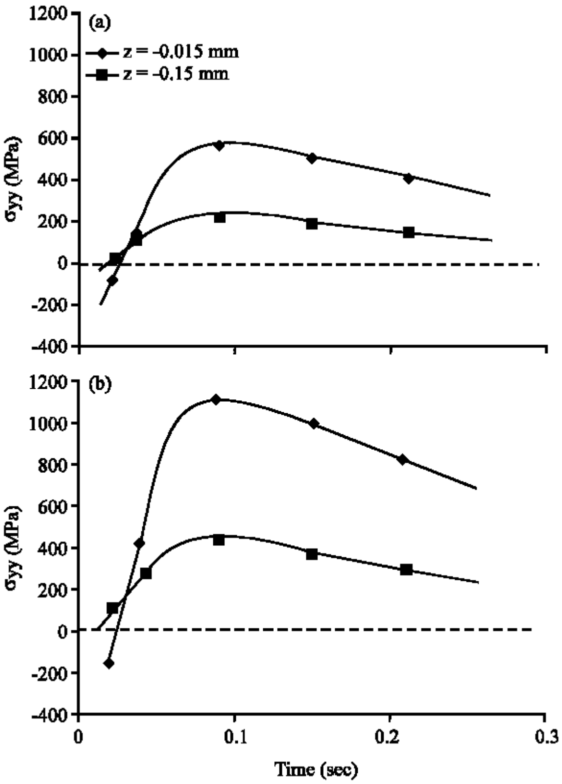

Fig. 8: Maximum thermal stress (x = 0); Laser: CO_2; scan speed: 5 mm/sec: a) P = 3W and b) P = 6W

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1\text{-}\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \tag{2}$$

$$K_I = \sigma_{yy}\sqrt{2\pi r} \tag{3}$$

As the laser beam moves along the cutting path on the pre-prepared groove, tensile stress was accumulated on the edge of the wafer (x = 0). The critical positions were at the groove tip (z = -0.015 mm) and on the bottom surface (z = -0.15 mm). If the magnitude of the tensile stress is high enough the fracture will initiate.

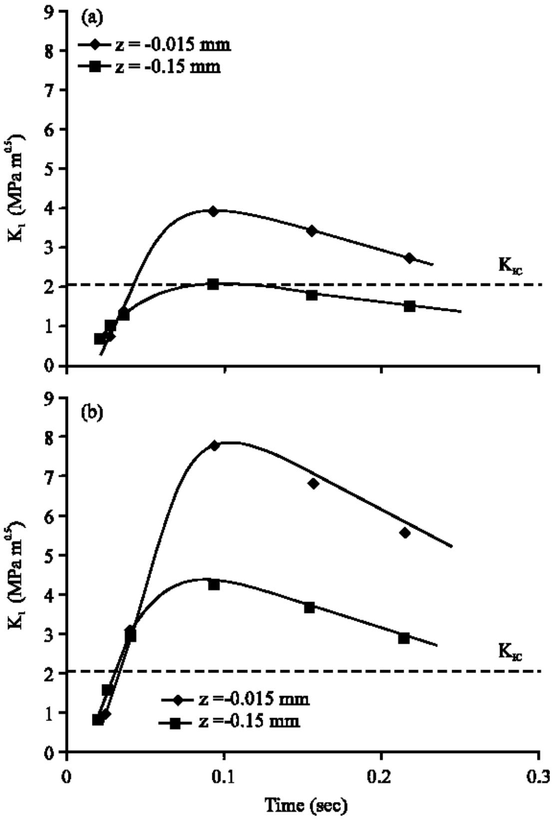

Fig. 9: Stress intensity factor, K_I for sapphire wafer (x = 0) Laser: CO_2; scan speed: 5 mm/sec: a) P = 3W and b) P = 6W

Figure 9 illustrates the relationship between the stress intensity factor, K_I and laser irradiation time at the two positions z = -0.015 mm and z = -0.15 mm for the sapphire wafer at laser power of 3 and 6 W, respectively. For the laser power of 3 W, K_I at the positions of z = -0.15 mm is high at the beginning and increases relatively with time. K_I at the groove tip position (x = 0, z = -0.015 mm) increases rapidly and reaches the critical stress intensity, K_{IC} (fracture toughness), first. However, when the higher laser power of p = 6 W was used, K_I at the positionof z = -0.15 mm achieved fracture toughness, K_{IC}, earlier. This indicates that fracture was initiated from a bottom-surface position when higher laser power is used. However, when this phenomenon happen it may lead to a poor separating surface condition as the fracture cannot be controlled.

Based on the analysis results, it is understood that laser energy-absorption characteristic has a significant effect to fracture initiation in laser cleaving process. Higher values of absorption coefficient, β causes high absorption of laser energy at the surface of the material. When the laser energy is absorbed on the material surface, fracture may start from the bottom surface (x = 0, z = -0.15 mm).

Therefore, the laser energy-absorption characteristic should be considered as a significant factor in deciding groove arrangement on the specimen. For cleaving the sapphire with the CO_2 laser, the groove position should be placed opposite the irradiation surface so that the advantages of thermal-stress distribution can be benefited.

CONCLUSION

Finite Element Method (FEM) has been applied to investigate the thermal stress condition during laser-beam irradiation on sapphire wafer. The heat-source configuration was assigned in FEM analysis by evaluating the laser energy absorption of sapphire wafer. The temperature distribution was analyzed by thermal transient analysis and steady-state thermal stress analysis was executed by using the temperature distribution results at a particular point in time.

Based on the analysis results it is shown that energy from the CO_2 laser was absorbed mostly on the surface area of the sapphire material. Consequently, the heat was accumulated on the surface of the material during laser-beam irradiation. A huge temperature gradient was created in the direction of the material's thickness. Thermal stress was generated and tensile stress developed on the bottom surface of the sapphire wafer.

From the stress-intensity-factor analysis the results clarify that a fracture can start from the bottom surface of the material, instead of from the pre-prepared micro-groove on the irradiation surface. The fracture cannot be controlled and may lead to a poor cleaving surface. Hence, the orientation of micro-groove on the specimen should be considered based on the laser absorption characteristics of the material, so that the advantages of the thermal-stress cleaving technique can be benefited.

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