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Cutting glass substrates with dual-laser beams

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ABSTRACT

In order to improve the cutting quality, a dual-laser-beam method was proposed to cut glass substrates in the current study, where a focused CO_2-laser beam was used to scribe a straight line on the substrate, and a defocused CO_2-laser beam was used to irradiate on the scribing line to generate a tensile stress and separate the substrate. The finite-element-method (FEM) software ANSYS was applied to calculate the temperature distribution and the resulting thermal stress filed. Through experimental study, it concluded that the glass substrate can be separated along an expected path with dual-laser beams and the cutting quality can be improved comparing with the cutting using a defocused laser beam alone. The relation between the cutting speed and the defocused laser power was also investigated in cutting glass with this method.

1. Introduction

In the past few years, the science of cutting glass using lasers has attracted a significant amount of attention with many studies done to improve the cutting quality [1–7]. As we know, glass substrates can be separated by a focused laser source along the laser moving path in a controllable situation. However, the glass material always melts and vaporizes with this method and lots of microcracks and burrs are generated on the cutting profile. Recently, a low-power and defocused laser has been applied to separate glass without melting the glass material by Kondratenko [8] and an additional water jet coolant has been applied to produce tensile stress along the cutting path. Besides the water coolant jet, a pre-bending technique was proposed by Tsai and Lin [9] to improve the cutting speed and the quality of the cutting profile.

However, the fracture propagation is difficult to control and the substrate is always separated along an unexpected path when the glass substrate is cut by a defocused laser beam alone. To solve this problem, scribing method has been applied recently. A scoring wheel was employed to generate a microcrack along the cutting path on a glass surface in Verheyen's study [10]. A defocused laser beam followed the movement of the scoring wheel to drive the fracture completely through the glass thickness. A rotation chisel was used to scribe the glass plate surface in Ikeda's research [11], and a CO_2-laser followed behind the chisel to separate the substrate. A diamond tool was applied to scribe a groove on the glass surface before cutting with the fracture method in Tsai's report [12].

Although, scribing a straight line with mechanical methods mentioned above could make the glass separated along the desired path, it has several disadvantages. The glass substrate is always destroyed by the mechanical tools, and the whole cutting process is complicated. Recently, a method of scribing a line on the workpiece with a focused laser beam before laser cutting has been proposed to cut ceramics. Segall [13,14] applied this method to cut ceramic plates, where a leading and low-power beam was used to pre-score a shallow groove while a defocused high-power beam was adopted to drive a crack along the predicted path. Tsai [15] used a focused Nd:YAG laser to scribe a groove on the ceramic substrate and applied another defocused CO_2-laser to induce thermal stress to separate the substrate along the laser moving path under control. However, only the ceramic substrates cutting was discussed in these studies and the scoring laser source was the Nd:YAG laser. In this work, the CO_2-laser source was proposed to scribing a line on the glass substrate, which was more efficiency than Nd:YAG laser in scribing due to its higher absorption efficiency to the glass material.

In this study, a dual-laser-beam method was proposed to cut glass substrates, where a focused CO_2-laser beam was used to scribe a line on the substrate surface. Another defocused CO_2-laser beam was applied to heat the substrate along the scribing line. The temperature and the thermal stress fields were calculated by FEM software ANSYS and the cutting quality was analyzed through experimental study.

2. Numerical analysis

2.1. Assumptions and the mathematical models

A soda-lime glass substrate was selected in this study and the temperature dependent physical properties of this material have

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been mentioned in Ref. [16]. The geometry of the soda-lime glass substrate was $75 \times 25 \times 1\,mm^3$. Before the temperature and the thermal stress field were calculated by ANSYS, some assumptions should be made as follows:

1. The physical properties of the glass material are isotropic and symmetrical.
2. The phase change is negligible in this study.
3. Heat transfer is not affected by thermal expansion. Inertia effects are negligible during stress development.
4. On the surface of the glass where there is no laser heating, the superficial heat irradiation is negligible.
5. The CO_2-laser energy is fully absorbed by soda-lime glass, and the glass sample is treated as the black body.

The laser beam maintains a constant TEM_{00} mode and travels in the X-direction with a constant velocity v (Fig. 1). The density of the laser power can be expressed in Gaussian distribution as Eq. (1). The absorption depth is less than 15 μm, so the CO_2-laser beam is treated as a surface heating source, and the impulse function $\delta(z)$ is applied in Eq. (1).

$$I(x, y, z, t) = \frac{p}{\pi r^2} \exp\left(-\frac{(x - vt)^2 + y^2}{r^2}\right)\delta(z) \tag{1}$$

where $I(x, y, z, t)$ is the density of the laser power. P and r are the power and the radius of the CO_2-laser beam, respectively.

With the above-mentioned assumptions and the mathematical models for heat transfer and mechanical properties mentioned in Refs. [17,18], a coupled-field analysis was performed to determine the temperature distribution and the resulting thermal stress in the workpiece by using FEA software ANSYS. The coupling between the thermal and structural fields was accomplished by direct coupling. A three-dimensional coupled-filed solid element SOLID5 was used in the current work. This element has eight nodes with up to six degrees-of-freedom at each node. The grid structure of the glass substrate is shown in Fig. 1. In the laser heating zone, the size of element is optimized balancing the demand for simulating precision and computational efficiency, which turns out to be smaller than that in other regions. The size of elements in the heating zone is 0.5 mm, which is accurate enough for this study.

2.2. Numerical results

As we all know, the softening point of the soda-lime glass is low, which is about 750 °C. If a small diameter focuses on a narrow spot, the laser energy would concentrate in a local area and a high-temperature filed would be produced. This may lead to the melting of the glass material. Therefore, for a constant output laser power, the laser spot size must be large enough to prevent the melting of the glass material. In the current simulation, a defocused laser beam with 20 W laser power and 3 mm beam diameter was selected to cut the glass substrate, and the cutting speed was 20 mm/s.

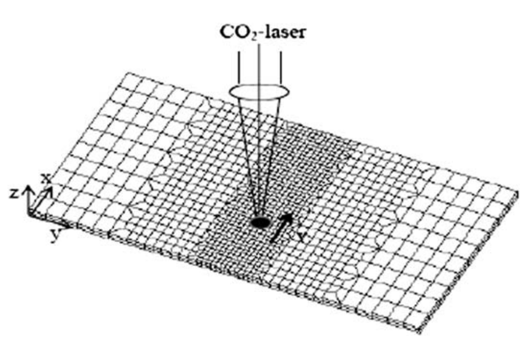

Fig. 1. The diagram of the glass laser cutting and the grid structure of the glass substrate.

As the defocused laser beam moves along a straight line in X-direction on the glass surface, the temperature distribution is shown in Fig. 2(a) and (c), and the resulting thermal stress σ_{yy} is shown in Fig. 2(b) and (d) at the time step $t = 0.75$ s.

As shown in Fig. 2(c), the temperature increases rapidly during the heating period and descends slowly after the laser beam moves away in the laser heating area. This phenomenon is caused by the high density of the laser power and the low efficiency of the convection between the substrate and the air surrounding, respectively. At the bottom surface ($z = 0$ mm) and at the center ($z = 0.5$ mm) of the substrate, the temperature changes slowly due to the low thermal conductivity of the glass material.

Because of the thermal expansion of the glass material, a compressive stress state is produced in the laser heating area. This compressive stress changes into the tensile stress state during the cooling stage (Fig. 2(d)). The maximum tensile stress appears at the edge of the substrate, and it is higher than the critical value of the glass material (75 MPa). This stress would lead to the fracture, starting from this point and propagating along the laser moving path, which separates the glass substrate into two parts. Compressive stress fields are generated both on the top surface and on the bottom surface of the glass substrate. However, a tensile stress field is generated at the center of the substrate ($z = 0.5$ mm), which means that the thermal stress increases from the top surface ($z = 1$ mm) to the center ($z = 0.5$ mm) of the substrate, and descends from the center ($z = 0.5$ mm) to the bottom surface of the substrate ($z = 0$ mm) along the thickness direction.

The time history of the thermal stress on the surface is shown in Fig. 3. As the laser beam travels along a straight line on the substrate surface, the location of the maximum compressive stress varies with time steps, but the maximum tensile stress states at the edge of the glass substrate during each time step. It is this tensile stress that makes the fracture propagating along the laser moving path.

3. Experimental results

The experimental arrangement of glass laser cutting is illustrated in Fig. 4. A focused CO_2-laser was used to scribe a line on the glass substrate and another defocused CO_2-laser followed behind to generate thermal stress and separate the glass substrate. The glass substrate was located on a XY moving table. The moving direction and the velocity were controlled by the computer. The appearances of the cutting surface were examined by an optical microscope.

3.1. Cutting glass substrate without scribing

As a defocused CO_2-laser beam with low-power density irradiates on the glass surface, the material does not melt or vaporize, but a steep thermal stress is generated in the cooling step. If this thermal stress is larger than the critical value, a fracture would be generated around the laser moving path to separate the substrate. As shown in Fig. 5, the defocused laser beam irradiates the glass substrate and travels with a constant speed on the surface. Because of the resulting thermal stress induced after the laser beam passed away, the fracture followed behind the laser spot with a short distance. A higher cutting speed, a longer distance between the crack tip and the laser spot will be generated [19]. Due to the mixed mode stress