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A numerical simulation of machining glass by dual CO_2-laser beams

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Abstract

In the flat panel display (FPD) industry, lasers may be used to cut glass plates. In order to reduce the possibility of fracture in the process of cutting glass by lasers, the thermal stress has to be less than the critical rupture strength. In this paper, a dual-laser-beam method is proposed, where 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. The distribution of the thermal stress and the temperature was simulated by using finite element analysis software, Ansys. The thermal stress was studied both when the glass sample was machined by a single CO_2-laser beam and by dual CO_2-laser beams. It was concluded that the thermal stress can be reduced by means of the dual-laser-beam method.

Keywords: CO_2-lasermachining; Thermal stress; Dual-laser-beam method

1. Introduction

With the development of laser technology and flat panel display (FPD) technology, many studies have been carried out to investigate the methods of cutting glass using lasers [1–15]. J.F. Li et al. [3] put forward a mathematical model to explain the heat transfer of glass heated by lasers and to analyze the differences of the effect on the thermal behavior of glass between the application of lasers as a volumetric heating source and that of a surface heating source. C.Y. Wei [4] and W.X. Tian [5] investigated the thermal behavior of glass heated by a CO_2-laser beam numerically, and concluded that the resulting temperature distribution was strongly dependent on the speed of the moving laser beam and the laser parameters, i.e., the size of laser beam and the power of the laser. Chwan-Huei Tsai et al. [6] studied the thermal stress of alumina ceramic substrates irradiated by a moving laser beam. Meanwhile, experiments were carried out to investigate how the crack propagation was influenced by laser power, cutting speed, and specimen geometry. R.M. Lumley [7] used a controlled fracture technique to cut brittle materials such as ceramic and glass for the first time in 1969, and a 7 mm thick alumina substrate was separated successfully under a speed of 50 mm/s. With this controlled fracture technique, a liquid crystal display (LCD) glass substrate was also cut successfully by S.L. Ye et al. [8]. Several patents for glass laser cutting are also available, such as those by W. Hafner [9], Willy Verheyen et al. [10], and Kazuyuli Komagata et al. [11].

When a laser beam irradiates on the glass surface, part of the laser energy is absorbed and conducted into the material, and thermal stress is produced as a result of thermal expansion. If the stress exceeds the critical value, the fracture will be induced undesirably. Lots of work has been done previously to search for a suitable method to reduce the thermal stress and avoid fracture when glass is machined by lasers. Chui [12] preheated glass to the annealing temperature (510–590 °C) in a high furnace before laser cutting. L.Bradley et al. [13] used a flame-assisted method in the laser surface treatment in order to avoid fracture. It has been shown that glass should be machined in a high-temperature condition for desired results. But, the methods mentioned before have proved to be impractical due to the heavy pollution and low efficiency caused.

A dual-laser-beam method has been applied to manufacture brittle materials in recent years, where an off-focused laser beam is used to control thermal stress. In this

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way, the defects of using the high furnace and the flame-assisted method can be eliminated. D. Triantafyllidis et al. [14] used two kinds of laser sources (a CO_2-laser and a diode laser) to control the thermal gradients in the surface modification of alumina ceramics. An active-stressing technique was used by R. Akarapu et al. [15] to cut alumina, and an off-focus laser beam was applied to control (delay) the fractures. Meanwhile, how the fracture propagation is affected by the laser parameters and the relative location of two laser beams was also numerically studied by him. In most of the previous studies on machining brittle materials with the dual-laser-beam method, the focused beam was first applied to the brittle materials, followed by the off-focused beam for reducing the cooling rate and controlling the fracture propagation [7,8,14,15]. In this study, an off-focused CO_2-laser beam was applied ahead of the focused CO_2-laser beam to preheat the glass so that the thermal gradients in the machining process are reduced.

In the present study, glass was machined both with a single CO_2-laser beam and with a dual CO_2-laser beam. Meanwhile, the distribution of the temperature and the thermal stress was simulated using Finete element analysis (FEA) software, Ansys. The calculated results showed that the thermal stress could be reduced with the dual-laser-beam method.

2. Theoretical approaches

The dimension of glass sample is $80\,\text{mm} \times 40\,\text{mm} \times 2\,\text{mm}$ and the sample is irradiated by a moving CO_2-laser beam. The diagram of laser processing is illustrated in Fig. 1. Before the mathematical model is established, some assumptions should be made:

1. Glass is isotropic and all the physical parameters of glass are temperature-independent.
2. The CO_2-laser energy is fully absorbed by soda-lime glass.
3. The glass sample is treated as the black body.
4. In this study, the temperature is lower than the softened value (730 °C) of soda-lime glass. Meanwhile, the tension stress is less than the critical value (70 MPa) of the fracture. Hence, the phase change and the cutting groove are not taken into consideration.

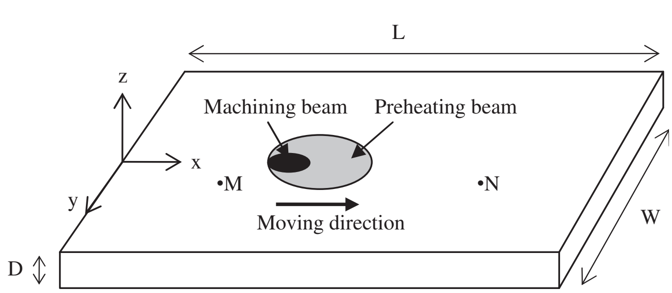

Fig. 1. Diagram of glass irradiated by dual CO_2-laser beams.

5. Heat transfer is not affected by thermal expansion. Inertia effects are negligible during stress development.
6. The CO_2-laser beam is regarded as a surface heating source.
7. On the surface of the glass without laser heating, the superficial heat irradiation is negligible.

Based on the above assumptions, the mathematical heat transfer model can be established as follows [16]

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T, \tag{1}$$

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

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

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

where k is the thermal conductivity, c and ρ are the heat capacity and the density, respectively, T_0 denotes the initial temperature of glass, 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 boundary.

The laser beam focusing on the top surface maintains a constant TEM_{00} mode and travels in the x direction at a constant velocity v (see Fig. 1). The density of the laser power can be described by Gaussian distribution as in Eq. (5). The CO_2-laser beam is treated as a surface heating source, so the impulse function $\delta(z)$ is applied in Eq. (5):

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

where p_0 and r are the power and the radius of the CO_2-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. The entire surfaces of the glass plate are free of stress, and the distribution of the thermal stress can be obtained by solving the heat–elasticity equation mentioned in Ref. [17].

During the process of the laser glass machining, the thermal stress may be established as a result of thermal gradients in glass, frequently caused by rapid heating or cooling. If the outer temperature changes more rapidly than the inner temperature, differential dimensional changes restrain the free expansion or contraction of the adjacent volume elements within glass. Therefore, rapid heating or cooling could induce tensile stress. Here, the thermal stress σ_{therm} caused by a temperature difference

ΔT, is given by [14]

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

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

The distribution of the thermal stress affects the quality of glass machined by lasers. If the thermal stress exceeds the critical value, the fracture will be produced. Eq. (6) indicates that the thermal stress rises with increasing thermal gradients. Therefore, with the purpose of avoiding the fracture in the process of machining, the thermal gradients should be reduced. A reliable method to reduce the thermal gradients is to preheat glass to a proper temperature before machining.

3. Simulation with Ansys

In this study, the FEA method is used to calculate the temperature and the thermal stress with the software Ansys. Since the laser beam travels along the x-axis (see Fig. 1), the symmetry axis of the glass plate, only half of the glass plate is considered in the simulation to save computing time. The grid structure of the glass plate is shown in Fig. 2. On the traveling path of the laser, the size of elements 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 on the traveling path of laser is 1 mm, which is accurate enough for this study.

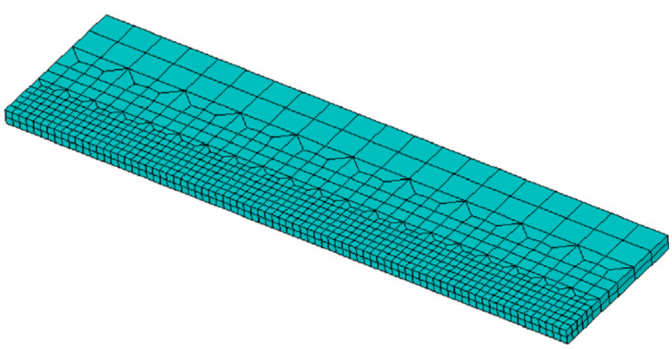

Fig. 2. Mesh of the glass sample.

Given the physical parameters of soda-lime glass and the suitable boundary conditions of the mathematical model, the temperature and the thermal stress can be calculated by Ansys. The physical parameters of soda-lime glass are shown in Table 1 [18]. The initial temperature T_0 is 20 °C and the convection heat-transfer coefficient h is $10\,\mathrm{W\,m^{-2}\,K^{-1}}$.

Fig. 3 shows the distribution of the temperature and the thermal stress when the CO_2-laser beam is traveling along the x-axis on the soda-lime glass top surface.

Table 1
The physical parameters of soda-lime glass

ρ/(kg m^{-3})	C/(J kg^{-1} K^{-1})	k/(W m^{-1} K^{-1})	β/(k^{-1})	E/(GPa)	σ
2520	800	1.03	8.7×10^{-6}	71.6	0.23

4. Results and discussion

An off-focus CO_2-laser beam is used to preheat glass before a focused beam is applied to machine the glass. The machining process is briefly illustrated in Fig. 1. On the laser-traveling path, the preheating laser beam travels ahead of the machining laser beam, and the distance in between remains constant. The parameters of CO_2-laser beams used in this work are shown in Table 2. The distance between the center of the preheating beam and the machining beam is 1 mm.

Table 2
The parameters of the dual CO_2-laser beams

Parameters	Non-preheated	Preheated	
		Preheating laser beam	Machining laser beam
P (W)	40	50	30
r (mm)	2	5	2
v (mm s^{-1})	15	15	15

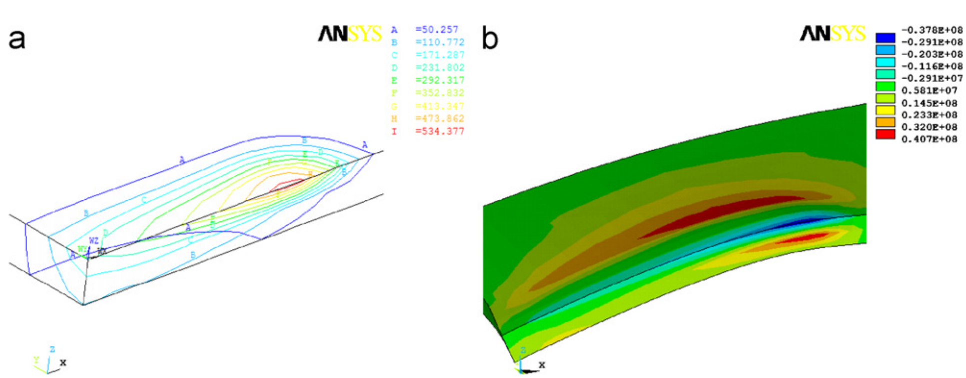

Fig. 3. The distribution of the temperature (a) and the thermal stress (b).

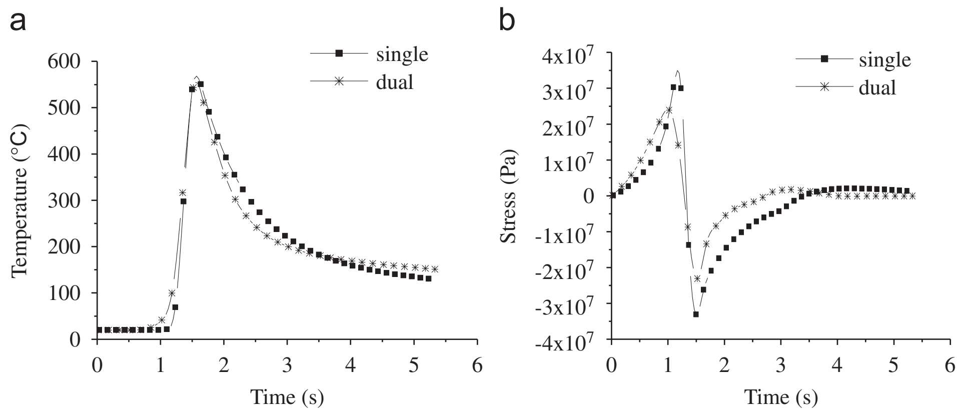

Fig. 4. The time history of the temperature (a) and the thermal stress (b).

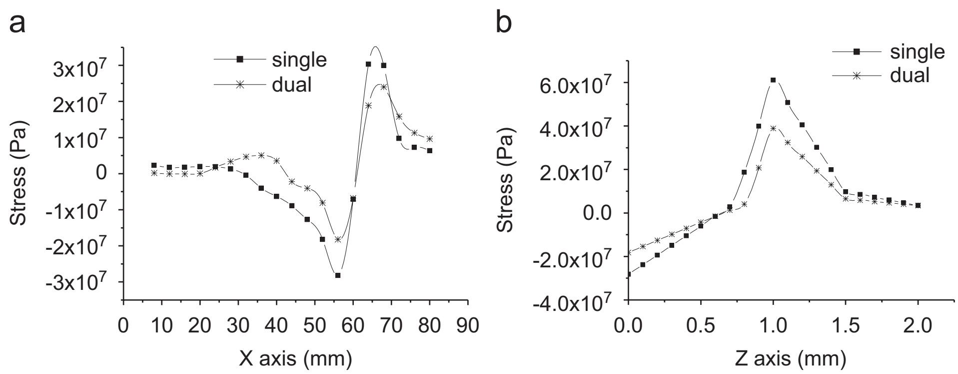

Fig. 5. The distribution of the thermal stress on the glass surface (a) and along the thickness direction (b).

As shown in Fig. 4, a specific point M ($x = 20$ mm) on the laser-traveling path is selected to study the time history of the temperature and the thermal stress when the glass sample is irradiated by CO_2-laser beams.

In Fig. 4a, before the machining laser beam reaches the point M ($t \leqslant 1$ s), the temperature of glass at this point remains at a constant value. When this beam is irradiating this point, the temperature rises rapidly due to a high density of the laser power. After the laser beam moves away from this point, the temperature descends slowly as a result of heat loss by conduction, irradiation, and convection. It is also shown that the temperature changes more rapidly when the glass is machined by a single CO_2-laser beam.

The time history of the thermal stress of the point M is shown in Fig. 4b. The glass material at this point first experiences tensile stress, followed by compressive stress, and finally little tensile stress. In the process of the laser beam approaching this point, tensile stress is produced as a result of material expansion. When the laser beam is irradiating point M, the material under the beam is constrained by the surrounding expanded material, and compressive stress is produced. After the laser beam moves away from the point, the constrained material is cooled down by conduction and convection, and the compressive stress slowly changes into tensile stress. The same phenomenon can also be observed in Fig. 5a. Although the machining temperatures for the glass sample machined by a single CO_2-laser beam and dual CO_2-laser beams, are both 565 °C, the thermal stress induced by the dual beams (23.6 MPa) is less than that induced by a single beam (34.7 MPa).

When $t = 4$ s and $x = 60$ mm, i.e. the machining laser beam is traveling to point N, the variation in thermal stress along the x-axis on the top surface was studied (see Fig. 5a). The compressive stress and the tensile stress are produced in the heated zone and on the right-hand side of the laser spot, respectively. On the left-hand side of the laser spot, the compressive stress relaxes into low tensile stress. It is also shown that the tensile stress in glass machined with a single CO_2-laser beam is a little higher than that induced by the dual CO_2-laser beams after the laser beams move away.

Along the thickness direction, the compressive stress is produced on the surface and the tensile stress is produced in the center of the glass. The maximum tensile stresses induced in the glass sample machined by a single CO_2-laser beam and by the dual CO_2-laser beams are 61.2 and 38.9 MPa, respectively.

5. Conclusions

Based on the assumptions, given the physical parameters of soda-lime glass and the boundary conditions of the mathematical model, the temperature and the thermal stress were calculated using FEA software Ansys, when the glass sample was irradiated by a moving laser beam. The dual-laser-beam method was described in the present study, where an off-focused CO_2-laser beam is used to preheat glass and a focused CO_2-laser beam is applied to machine glass. At the same machining temperature of 565 °C, the maximum tensile stress was 61.2 MPa when the glass sample was irradiated by a single CO_2-laser beam, and 38.9 MPa when machined by the dual CO_2-laser beam. These data showed that the thermal stress can be reduced when the glass sample is machined by the dual-laser-beam method. If the parameters of CO_2-laser beams and the distance between the off-focused beam and the focused beam are chosen properly, more tensile stress will be reduced, which needs further investigation.

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References

[1] Kang S, Hong SK, Oh SC, Choi JH, Song MG. A study of cutting glass by laser. SPIE 2002;4426:367–70.
[2] Hermanns C. Laser cutting of glass. SPIE 2000;4102:219–26.
[3] Li JF, Li L, Stott FH. Comparison of volumetric and surface heating sources in the modeling of laser melting of ceramic materials. Int J Heat and Mass Transfer 2004;47:1159–74.
[4] Wei CY, He HB, Deng Z, Shao JD, Fan ZX. Study of thermal behaviors in CO_2 laser irradiated glass. Opt Eng 2005;44(4). 044202–1–4.
[5] Tian W, Chiu WKS. Temperature prediction for CO2 laser heating of moving glass rods. Opt Laser Technol 2004;36:131–7.
[6] Tsai CH, Liou CS. Fracture mechanism of laser cutting with controlled fracture. J Manuf Sci Eng 2003;125:519–28.
[7] Lumley M. Controlled separation of brittle materials using a laser. Ceram Bull 1969;48:850–4.
[8] Ye SL, Ma JS, Huang X, Wang YL, Zhang W, Tang W. Finite element simulation of thermal stress field in cutting LCD glass substrate by laser. Appl Laser 2006;26:267–71.
[9] Hafner W. Method of working glass with absorbent by a laser beam. US Patent No. 3453097, July 1965.
[10] Verheyen W, Mol, Belgium. Glass cutting. US Patent No. 3932726, Jan. 1976.
[11] Komagata K, Iseda T. Method and apparatus for breaking and cutting glass ribbon. US Patent No. 5871134, Feb. 1999.
[12] Chui GK. Laser cutting of hot glass. Ceram Bull 1975;54:514–8.
[13] Bradley L, Li L, Stott FH. Flame-assisted laser surface treatment of refractory materials for crack-free densification. Mater Sci Eng 2000;A278:204–12.
[14] Triantafyllidis D, Bernstein JR, Li L, Stott FH. Dual laser beam modification of high alumina ceramics. J Laser Appl 2003; 15:49–54.
[15] Akarapu R, Segall AE. Numerical simulation of an active-stressing technique for delaying fracture during cutting of alumina. J Manuf Sci Eng 2006;128:921–7.
[16] Shen ZH, Zhang SY, Lu J, Ni XW. Mathematical modeling of laser induced heating and melting in solid. Opt Laser Technol 2001; 33:533–7.
[17] Li WT, Huang BH, Bi ZB. Analysis and application of thermal-stress theory. Beijing: Public Press of Chinese Electric Power; 2004.
[18] Tao WM, Bi GL, Zhang HQ, Yoshiharu M. Finite element simulation of laser-controlled thermal stress separation of soda-lime glass plate. J Zhejiang Univ (Eng Sci) 2005;39:1423–6.