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The Crack Propagation on Glass in Laser Thermal Cleavage

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***Abstract*—**In the laser cleavage of glass, the laser is mostly adopted as a heat source to generate a thermal stress state on the substrates. The crack propagation of the soda-lime glass in the laser thermal cleavage with the straight-turning paths was investigated in this study experimentally and numerically. The crack propagation was visualized by a high speed camera with the off-line examination on the micro-crack propagation. The temperature and stress distributions induced by the laser heat source were calculated by ANSYS software based on the finite element method (FEM). With the cutting paths in various turning directions, the experimental and numerical results were in comparison and verified. The fracture modes due to the normal and shear stresses were verified at the turning point of the laser cleavage path. It shows a significant variation of the stress profiles along the straight-turning paths and causes a change on the fracture modes.

***Keywords*—**Laser cleavage, glass, fracture, stress analysis.

I. INTRODUCTION

SINCE the laser machining has the flexibility for the rapid change of the product design and manufacturing, it is suitable for the process automation in the modern industry. In comparison with the conventional technologies, laser machining is one of the popular applications of the laser materials processing [1]. According to the extraordinary cutting performance of the brittle materials by the laser beam in the laser cleaving process [2], many attempts have been made for the fracture control on brittle materials such as ceramics and glasses by the laser cutting [3]-[7]. Accordingly, the moving path of the beam spot is a key issue to dominate the heat diffusion, temperature and stress distributions on the cleaving area. Very few studies have been made to investigate the effect of the stress profiles on the crack propagation at the turning point in laser cleavage, and however the micro-cracks of the glass substrate were frequently obtained in laser cutting [8]. Since an urgent need of the precise and clean cut for complex shapes and various dimensions of the glass substrates, it is important to control the thermal stress profiles along the moving path on the substrate, especially at the turning paths. Many above characteristics of the laser processing on glass have not been fully investigated yet, and it is possible to improve the processing quality and product yield based on the study on the crack propagation with complex moving paths of the laser beam. The laser thermal cleavage of the glass at straight-turning cutting paths was investigated in this study, and the modes of the crack generation were visualized by the high speed photography method. The relationships between the cutting path and crack growth will be discussed and compared with the thermal stress fields based on the numerical simulation by FEM.

II. LASER CLEAVAGE EXPERIMENTS

In the laser cleavage of the glass, the experimental arrangement is illustrated in the Fig. 1. A cwTEM$_{00}$ Nd-YAG laser with a wavelength of 1064 nm and power of 2.5 W was focused through a convex lens to irradiate on a soda-lime glass at a beam spot radius of 0.15 mm. The glass substrate was coated with a carbon film on the upper surface to increase the laser absorption to 79% which has been measured by a laser power meter. A high speed camera with an exposure time of 2 ms and filming speed of 10^4 frame /sec was used to capture the crack propagation on the glass substrate. On an x-y table with stepping motor controller, the laser cutting process could be achieved at various cutting directions at a constant speed of 5 mm/s.

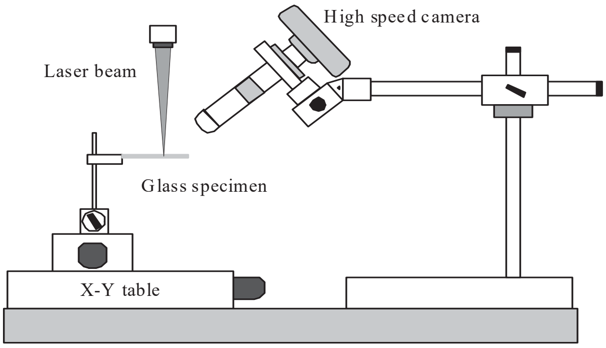

Fig. 1 Experiment set-up

The soda-lime glass specimen with the dimensions of 76 mm x 25 mm x 1 mm was used in the experiment. The physical properties of soda-lime glass were adopted as follows: thermal expansion coefficient of 9.2 x 10^{-6} m/m°C, density of 2500 kg/m^3, average bending fracture strength of 49 MPa [9]. Since the laser beam of 1064 nm wavelength to the soda-lime glass is considered as a high transmittance and approximate 8% will be absorbed [10], therefore the heat affected zone is mainly on the glass surface coated with the carbon film. The path of the laser beam on the specimen could be easily observed due to the carbon film ablated by laser at various cutting paths.

The straight-turning cutting path is illustrated in Fig. 2, where the cutting is from the edge of the glass substrate and turn to an angle of θ* at point O$_2$ and the distance between

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O$_1$and O$_2$ is 5.0 mm. The turning angles θ* were selected as 30°, 45°, 60°, and 90° in the present study.

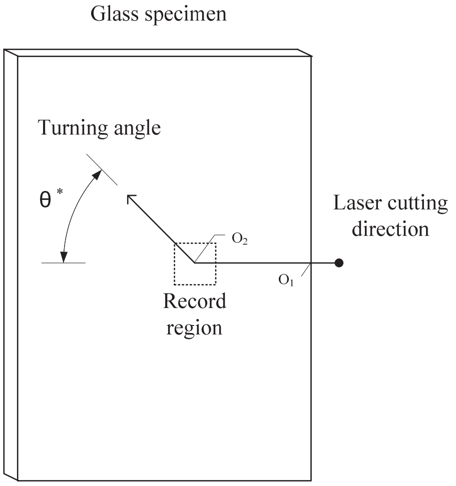
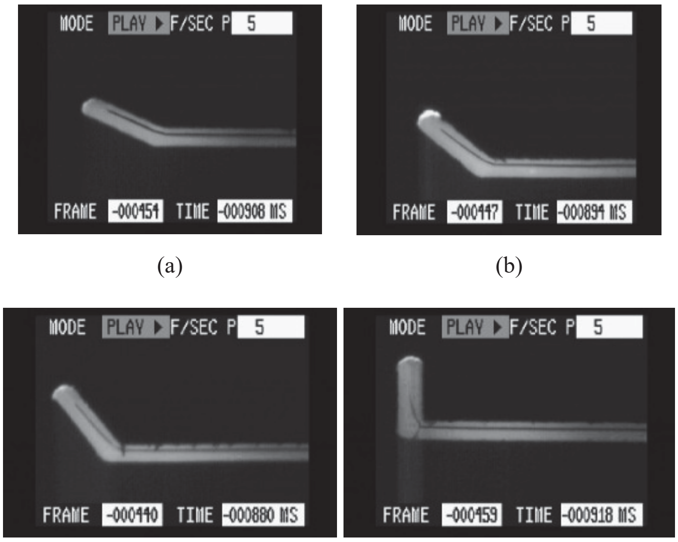


Fig. 2 Illustration of the straight-turning cutting path

Fig. 3 shows the high speed photographs for the laser cutting with various turning angles. It can be found that the thermal cracks do not align with the laser beam near the turning point O$_2$, and the crack is slightly behind the laser beam at the turning point. Similar results have been observed off-line in references [4]. There is clear evidence of the micro-cracks crossing the turning points at large angles such as 60° and 90° as shown in Figs. 3 (c) and (d). It can be found that the growth of the straight crack is at a speed close to the laser beam and slightly behind the laser beam. There is a significant deviation of the straight crack to the laser beam path at the turning point, where the micro-cracks abruptly occurred in the cooling stage after the laser passing the turning point.



(a) (b)

(c) (d)

Fig. 3 Photographs from the high speed camera at various turning angles θ*; (a) 30°, (b) 45°, (c) 60°, (d) 90°

III. Thermal Stress Analysis

The laser beam was applied to the glass cutting as a heat source. The heat was diffused into the glass from laser spot and dissipated into the surroundings. Thus,0 the stress state was generated on the substrate surface to initiate the cracks, and the crack progressively followed with the laser beam [11]. Since the laser cleaving process includes the temperature distribution, stress field and property variation, all of which are significantly inter-related. In order to simplify the analysis, the problem of the laser cleaving on glass sheets herein will be decoupled by two distinct analytical models: the thermal model and the mechanical model in the thermal–elastic numerical analysis. Using the software ANSYS [12], the element Solid 278 was adopted in the thermal analysis. The domain meshes used for the stress analysis are the same, but the element type was replaced by Solid 185 to calculate the stress and displacement. The temperature dependent properties such as the thermal conductivity, specific heat, Poisson's ratio and Young's modulus of soda-lime glass have been considered in the simulation, and the relationships at various temperatures can be found in the reference [10].

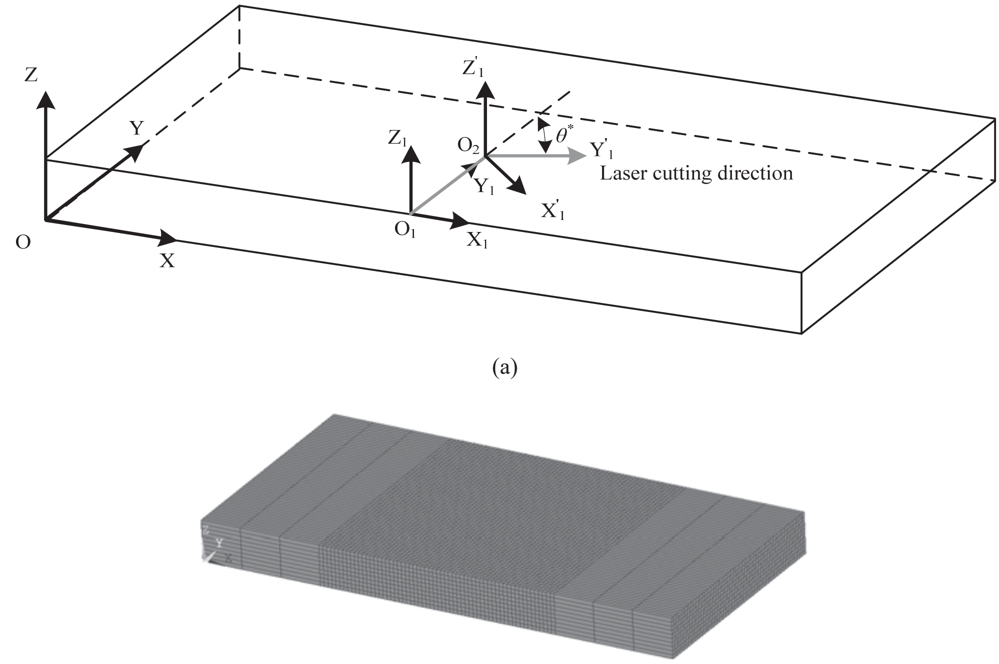
The physical domain of the soda-lime glass specimen is selected with the dimensions of 12 mm x 6 mm x 1 mm in the simulation and illustrated in Fig. 4. Due to the asymmetric cutting path, a fine meshing as illustrated in Fig. 4 (b) around the laser beam was applied to simulate the steep temperature gradients around the heating zone and the number of the meshed elements is 39600. In order to compare the numerical results for various cutting paths, the coordinate system (x_1, y_1, z_1) is for the straight cutting from the point O$_1$ at the edge of the substrate to the turning point O$_2$ and the coordinate system (x_1', y_1', z_1') is the cutting path with a turning angle θ* to the point O$_2$ as illustrated in Fig. 4 (a). Accordingly, the following assumptions are selected in the numerical simulation:

1) The glass properties are homogenous, isotropic and temperature dependent.
2) The laser intensity distribution is Gaussian mode.
3) The thermal boundaries with free convection in the surrounding air are considered.
4) There is no phase change during laser heating.
5) The specimen is annealed before laser cleaving, and its initial condition is free of stress.
6) The stress–strain relationship of the glass substrate is perfectly elastic.
7) Body force has been ignored

There are numerous factors that affect the boundary conditions. The initial temperature of the specimen is assumed to be the ambient temperature of 25 °C. The heat convection has been considered from the surface of the glass substrate and the coefficient of the heat convection is quoted as 21 W/m^2°C [13] on the surfaces including the lower surface of the substrate. The substrate was clamped except for the cutting edge, which was assumed to be free of stress in the analysis. A circular Nd-YAG laser beam with the Gaussian mode intensity is selected and expressed in;

$$I_p\left(x,y\right)=\frac{\left(1-R\right)\times P}{\pi r_0^{\ 2}}\times \exp^{\left[\frac{-2\times\left(x^2+y^2\right)}{r_0^{\ 2}}\right]} \qquad (1)$$

where, $\boldsymbol{I_p}$ is the laser intensity (W/m^2), $\boldsymbol{R}$ is the reflectivity, $\boldsymbol{P}$ is the laser power (W), $\boldsymbol{r_0}$ is the radius of the laser beam spot (m).



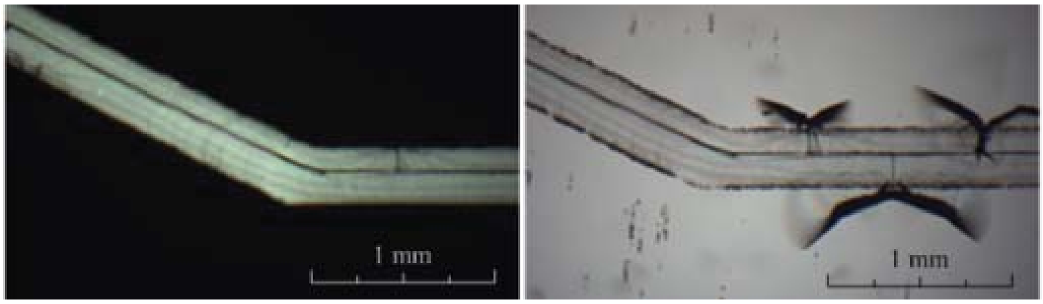
(a)

(b)

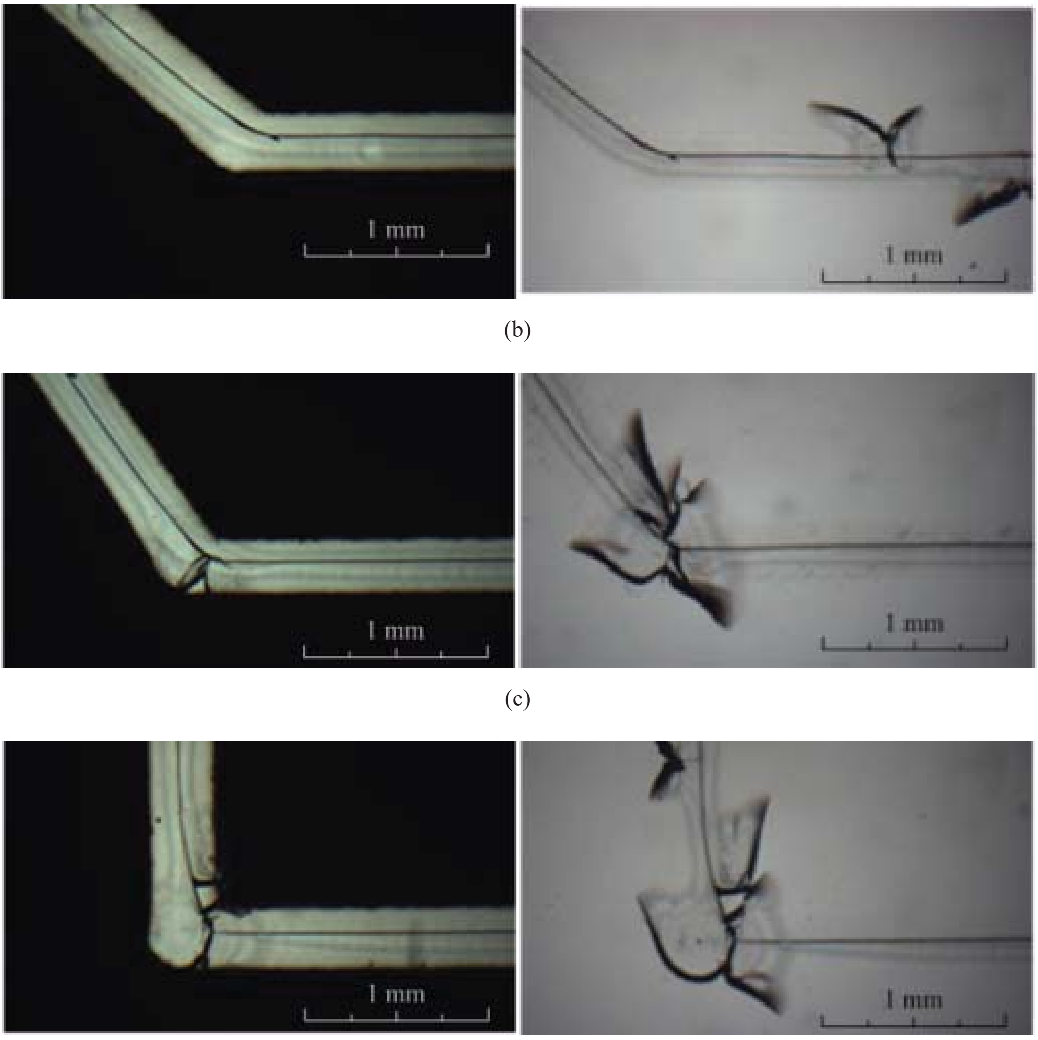
Fig. 4 Physical domain in the numerical simulation; (a) coordinate systems, and (b) meshed grids

IV. RESULTS AND DISCUSSIONS

According to the experimental results as shown in Fig. 5, a mix mode consisted of the opening and in-plane shear fractures on the side cracking has been considered [4]. Fig. 5 shows that the thermal cracks generate slightly different patterns at various turning angles, but the trends are in a good agreement. There is a round curve near the turning point, and the average radius of the cracking curve is increased with the turning angle. The side crack occurs near the turning point and it is significantly affected by the turning angle of the laser beam. The micro-crack will accumulate at the turning point at large angles. The micro-crack might extend backwards to the cutting direction beyond the turning point with an angle larger than 45^o in the present study. In the cases of the turning angles of 60^o and 90^o, it can be found that the crack is irregular and do not follow the cutting path as shown in Figs. 5 (c) and (d). There is no over-cut along the initial direction of the straight-line cutting, the lag between the laser beam and crack is similar to the straight-line cutting after the turning point.



(a)

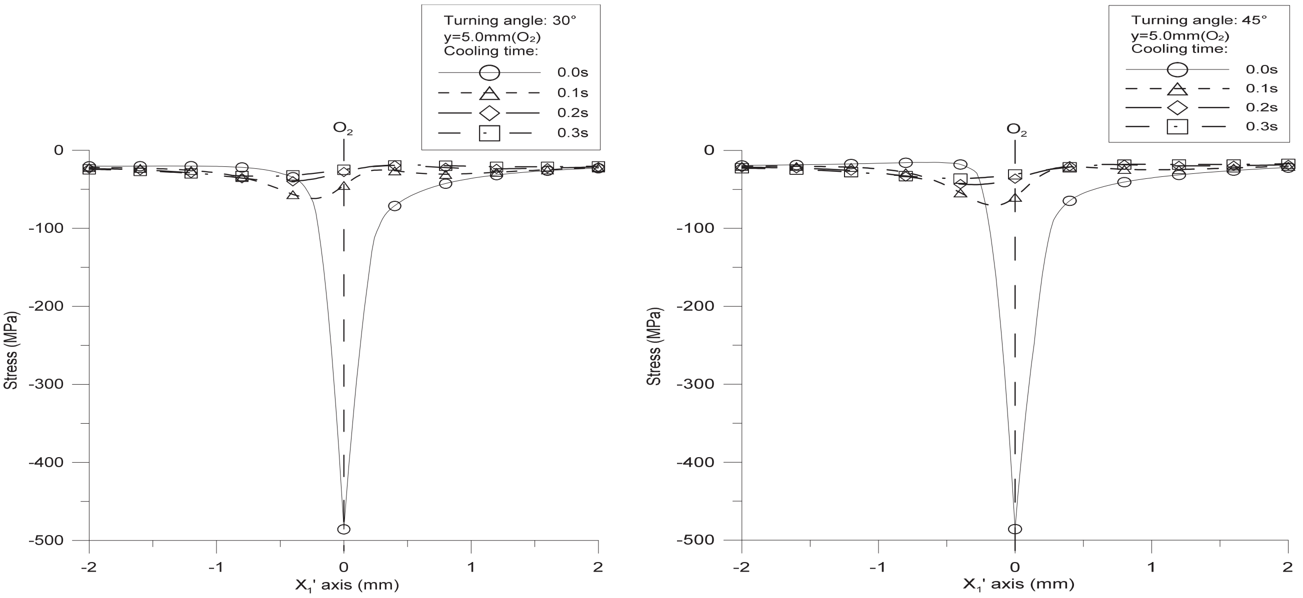


(b)

(c)

(d)

Fig. 5 Photographs of the cutting paths and side cracks at various turning anglesθ^*; (a) 30^o, (b) 45^o, (c) 60^o, (d) 90^o



(a)

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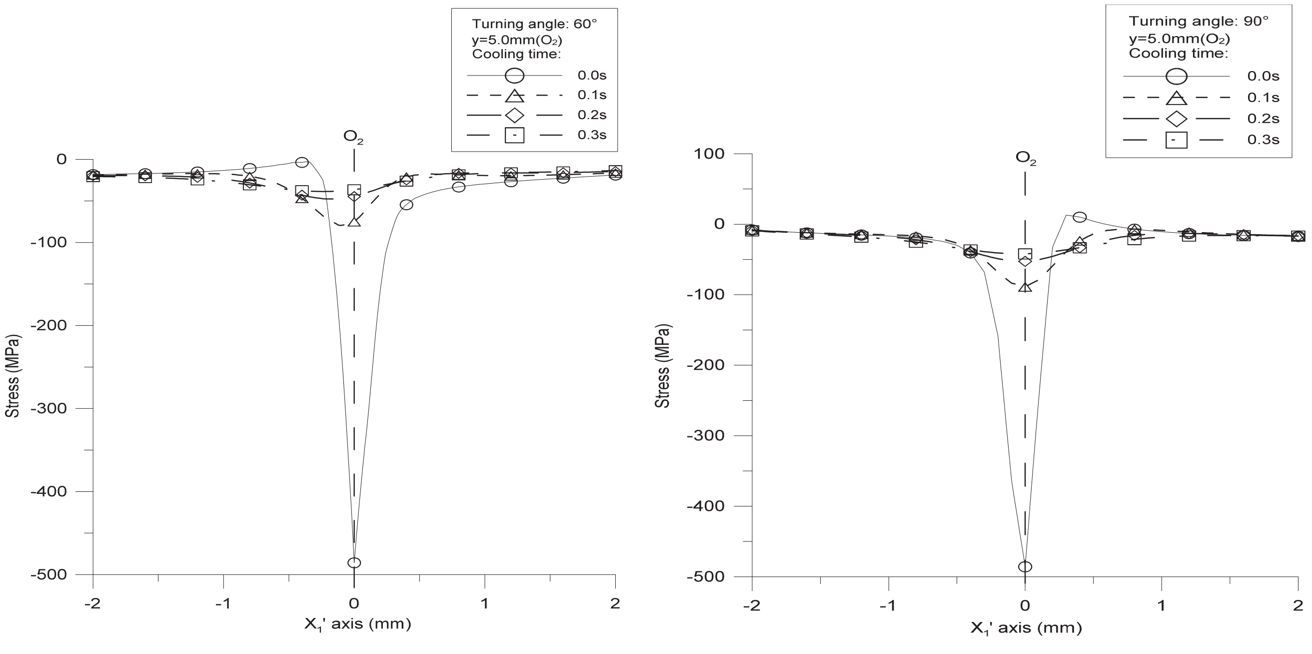
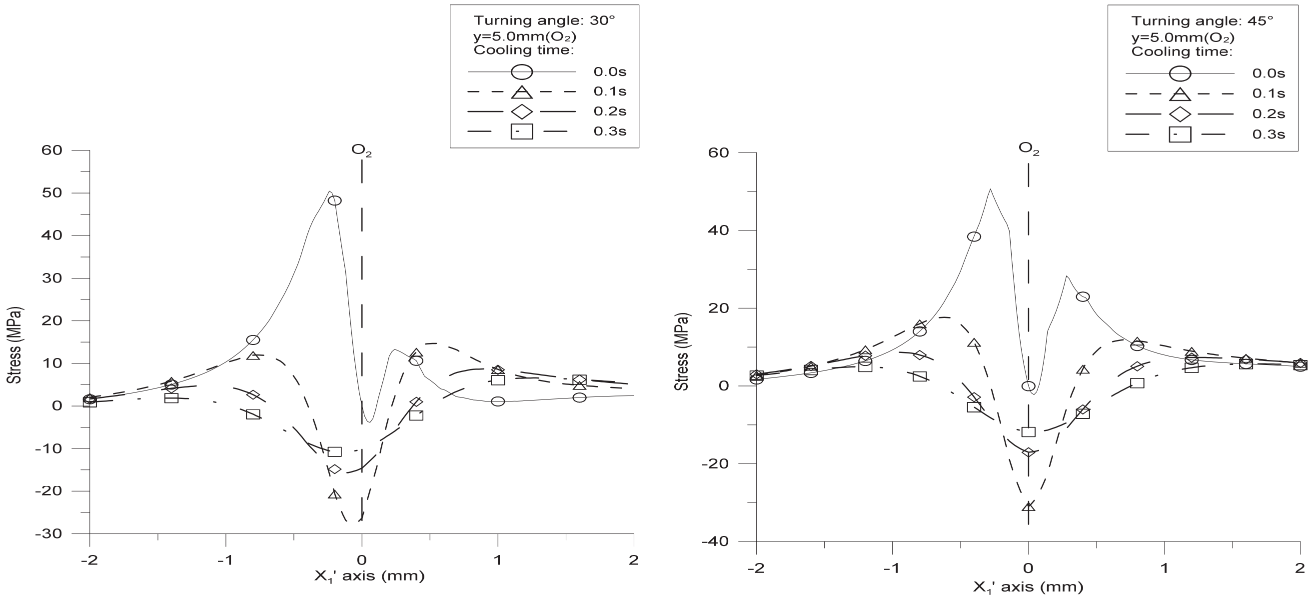


(c)

(d)

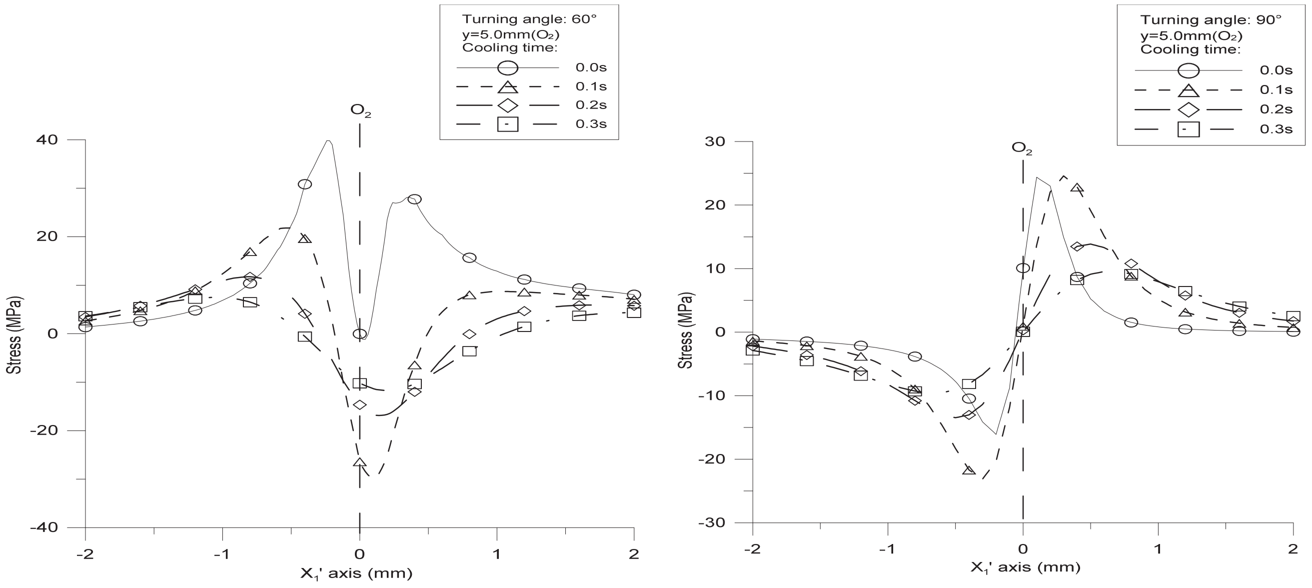
Fig. 6 Distributions of the normal stress σ_{xx} at various turning angles and cooling times

In the cutting with various turning angles, the stress states are shown in Figs. 6 and 7 at the turning point O_2. There is a tremendous change of the shear stress near the turning point as the laser passing in the cooling stage. However, the normal stresses σ_{xx} is almost in the compressive state at the turning point O_2. Fig. 7 shows a tremendous shift on the shear stress profiles at the turning point in the numerical simulation. Accordingly, the stress contours of the crack formation indicate that the shear stress σ_{xy} with a corresponding compressive normal stress σ_{xx} dominates the fracture mode as the laser beam passing the turning point O_2. The side crack could be formed at a large turning angle and cause a failure in the laser cleaving on a glass substrate. Therefore, it is possible to avoid a sharp turning angle and achieve a curvature of the crack in a sequence of cut to prevent the increase of the shear stress.



(a)

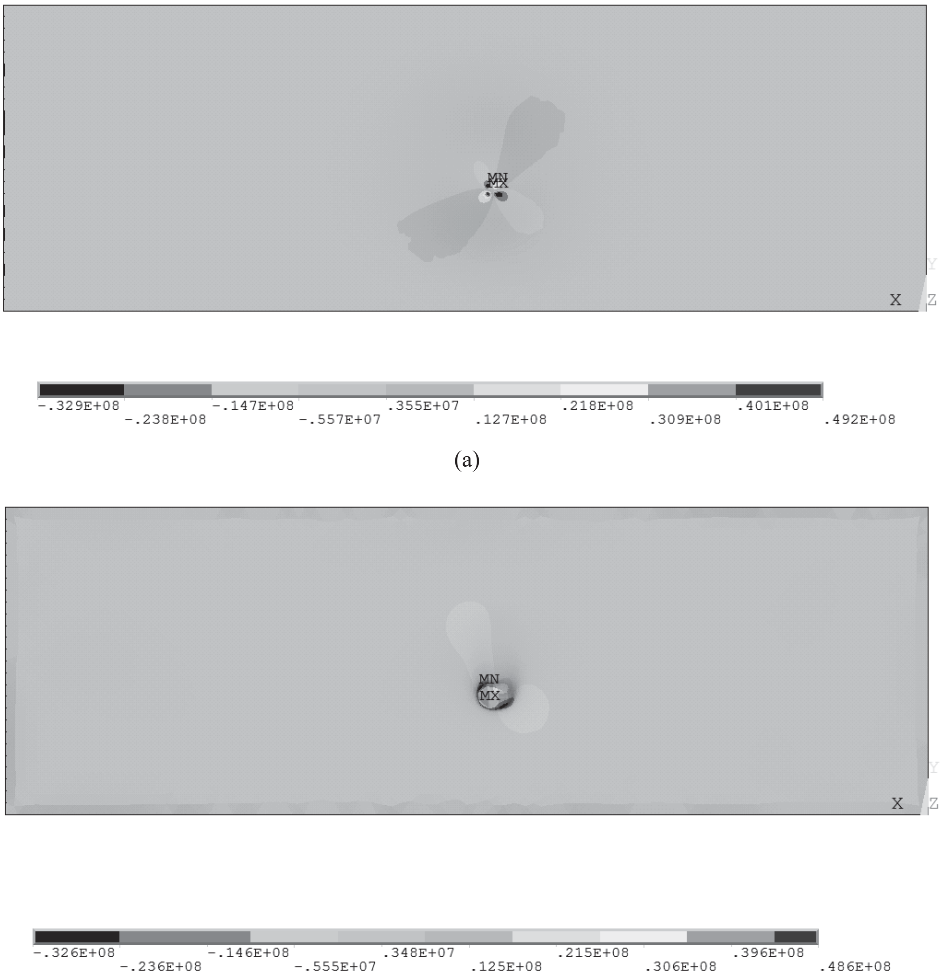
(b)



(c)

(d)

Fig. 7 Distributions of the shear stress σ_{xy} at various turning angles and cooling times



(a)

(b)

Fig. 8 Shear stress distribution of the laser beam; (a) at the turning point O_2; (b) after the turning point for 0.1 s at θ*= 60°

Since the shear stress distributions are mainly caused by the geometrical constrains and cutting path around the laser heating zone, Fig. 8 shows the typical profiles of the shear stress σ_{xy} near the turning point O_2 at the turning angles of 60^o and 90^o, the distorted cracks might form due to the uneven distribution of shear stress at the turning point. Therefore, the crossing crack may randomly appear after the laser passing the turning point O_2.

V.CONCLUSIONS

Under the inspection with high speed photography, the cutting results show that the crack propagation varies with the turning angles. In the laser cleavage of glass, the crack growth does not completely follow the laser beam path; on the cleavage path with various turning angles, the crack will generate a mix fracture mode at the turning point. The stress state may transform to shear stress state and the fracture mode is from opening to in-plane shear mode at a large turning angle. Therefore, the micro-cracks may occur and affect the cutting quality mainly at the turning point in the laser cleavage of glass. A comparison between the numerical and experimental results shows that the control of the crack formation mainly depends on the stress states. The stress distribution would be affected by the turning angles. Therefore, when cutting glasses by laser, there are many parameters that may affect the cutting quality, and the prediction of the stress distribution would be an acceptable method to evaluate the cutting quality and improve the cutting performance.

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