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Photoelastic observation of stress distributions in laser cleaving of glass substrates

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ABSTRACT

Photoelastic observations of thermal stress were conducted during the separation of glass substrates by thermal stress cleaving with a laser. A polariscope system was built in the laser cleaving system for observation during laser cleaving, and isochromatic and isoclinic fringe patterns were studied to analyze the thermal stress induced by laser irradiation. The proposed method allows for the visualization of stress asymmetry that decreases the process accuracy, and for the detection of crack stagnation which decreases the process reliability.

1. Introduction

In the production of electronic devices, many electronic circuits are produced on a single substrate wafer to increase the production rate, and then these are diced into pieces before being molded in each package of device [1]. The substrate material is usually brittle, so the dicing process is conducted with a low processing rate using abrasive blades to avoid large-scale brittle fracture formation and edge chipping. Unfortunately, kerf loss of material and sludge contamination are inevitable in the dicing using abrasive blades. An alternative dicing approach includes cleaving the brittle substrates, which does not result in material removal but yields separation into small pieces, with low amounts of waste material and no post-cleaning. This approach may provide a new dicing method with a rapid processing rate, because material cleaving is essentially crack propagation during which crack travels at the speed of sound within the material.

Laser cleaving, which is also termed ‘cutting by controlled fracture’, uses a laser beam as a heat source to generate a steep temperature gradient [2]. Crack propagation is caused by thermal stress in the vicinity of laser spot on the surface of the substrate to be diced [3]. Laser irradiation increases the temperature and results in a compressive stress at the center of the spot, because thermal expansion is restricted by the surrounding cold region. A temperature gradient generates a circumferential tensional stress around the spot, which propagates the crack toward the center of the spot. Therefore, by moving the spot at an appropriate speed, the pre-existing crack can be propagated with a certain gap behind the spot that moves on the designed path along which the substrate must be divided. This method has received attention as a novel sludge-free dicing method that could replace conventional mechanical dicing using abrasive blades, because it can divide or dice substrates along curved lines [4].

Since Lumley proposed laser cleaving, many feasibility studies have been carried out to investigate the practical embodiment of this technology. For example, Kurobe et al. demonstrated that using absorbent increases the temperature gradient and improves the cleaved edge linearity for soda-lime glass substrates [3]. Imai et al. calculated the stress intensity factor of a semi-infinite crack in soda-lime glass substrates that were heated using a stationary carbon dioxide laser spot [5]. Authors have examined the acoustic emissions and temperature at a laser spot using a two-color pyrometer during the cleavage of Si wafers by pulsed laser, and have studied the mechanism of sub-cracking on the edge [6,7]. Finite element analysis (FEM) has been used to clarify the criteria for crack propagation [8]. It has been demonstrated that many types of brittle substrates can be diced using this process [9] and a refrigerating

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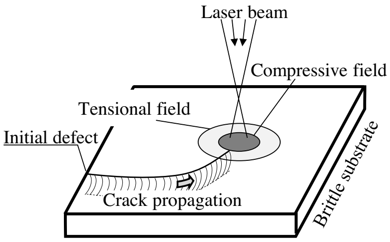

Fig. 1. Principle of thermal stress cleaving of brittle substrate with laser.

chuck has been developed to reduce thermal damage caused during laser cleaving [10,11].

Tsai et al. conducted FEM analysis of temperature and stress distributions to investigate the mechanism of this process. They discussed deviations in crack trajectories in the laser cleaving process for several kinds of cutting paths and proposed an iterative path revision to reduce the deviation [12,13]. Nisar et al. focused on crack-trajectory deviation at the leading and trailing edges of glass sheets, and also conducted thermal stress analysis by FEM [14].

Theoretical analyses of stresses, such as by using FEM [8,12,14–17] and a body-force method [18,19], are effective means to clarify the mechanism of crack propagation and to reveal optimal conditions in the laser cleaving process. However, they have high computational costs and require a significant time to yield the precise results, and it is often difficult to optimize the process. Therefore, the authors recently proposed photoelastic observation to reveal stress distributions and detect errors during the laser cleaving [20]. Experimental observations have some advantages compared with theoretical investigations. For example, the experimental technique is easily applicable at production sites and observations can be obtained in a relatively short time, which enables feedback of the results observed to conditions in the process.

In this paper, we describe the basic idea and experimental procedures for the proposed observation, and show results from feasibility tests of this technique to understand stress distributions during the steady cleaving of substrates by CW laser irradiation.

2. Principle of laser cleaving and photoelastic observation

Fig. 1 shows the basic mechanism of the laser cleaving process. A laser beam is focused on the substrate surface to generate a temperature distribution over a small area around the laser spot that moves at a constant feed rate, *F*. The temperature at the center of spot is lower than the material melting point, but a large temperature gradient generates a compressive stress at the spot and a tensile stress outside the spot, because the thermal expansion of material in the small spot is constrained by the surrounding cold part. If a crack exists in the tensile stress field, it is opened by a circumferential tensile stress and is propagated toward the center of the spot. Therefore, by scanning the spot over an initial defect that is introduced at edge of a substrate, a crack can be propagated from the edge, and the crack follows the spot that moves along the desired path. Thus, the substrate is separated by crack propagation.

Benefits from the process include [6,14]:

- The method is a non-contact material separation process that does not require the removal of material and coolant, so substrates are uncontaminated and post-cleaning is not required.
- The method is economically competitive, because it uses less laser power and enables higher cutting speeds compared with other laser cutting methods.
- The crack trajectory does not depend on the tool shape but is controlled by the laser scanning path, so that cleaving along various path shapes is possible.

Tsai [12] and Imai et al. [18,19] noted that asymmetrical scanning paths result in an asymmetrical stress distribution near the crack tip, and then the crack trajectory veers in an unintended direction. This deviation in crack trajectory was repeated for the same scanning path, so that a prediction of the deviation and a path revision were possible; optimal scanning was determined by trial and error [13]. However, a deviation in trajectory often occurs even for symmetrical paths. This result is because of various disturbances such as defects in the substrates, smears on the surface and preexisting micro cracks that cannot be identified, and whose presence cannot be predicted. In this study, the stress distribution is discussed, instead of the causes of disturbance being detected.

A photoelastic technique [21–23] was used to evaluate the stress asymmetry. This technique is based on the property of birefringence by strain within certain transparent materials. Consider an observation by a circular polariscope. The circular polarized light is transmitted through the photoelastic material with a two-dimensional stress distribution, then the normalized light intensity, I_C, observed using a circular polariscope is:

$$I_C = \sin^2 \frac{\delta}{2} \tag{1}$$

where δ is a relative retardation forming pattern, which is given by the stress-optic law:

$$\delta = \frac{2\pi d}{\lambda} \cdot C \cdot (\sigma_1 - \sigma_2) \tag{2}$$

and *d* is the material thickness, λ is a wavelength of light, *C* is a stress optic coefficient and σ_1 and σ_2 are principal stresses. This fringe pattern described by Eqs. (1) and (2) is an isochromatic pattern related to the distribution of differences in principal stresses $(\sigma_1 - \sigma_2)$. In the observation by a linear polariscope, the normalized intensity of light, I_L, observed using a linear polariscope is

$$I_L = \sin^2 \frac{\delta}{2} \cdot \sin^2 2\phi = I_C \sin^2 2\phi \tag{3}$$

where ϕ is the angle that the principal stress plane makes with the polarization direction. Eq. (3) indicates the focus at which $\phi = 0$ forms a black curve, which is termed an isoclinic fringe. By using white light, this intensity distribution is unaffected by the relative retardation δ and the fringe is an isoclinic pattern related to the distribution of principal stress directions.

Consequently, the isochromatic pattern may be distorted by the temperature distribution because of the temperature dependency of the stress optic coefficient *C*, but the isoclinic pattern is unaffected by temperature distribution.

Fig. 2 shows the arrangement of the circular polariscope required to obtain an isochromatic fringe pattern in the laser cleaving process. The circular polariscope consists of aligned optical elements: a light source, a polarizer, an analyzer and a pair of quarter-wave plates. A band pass filter (@546 nm) was used to capture a clear image with a camera and white-light illumination. However, quarter-wave plates and the filter were not used in the isoclinic fringe observation. A 1.1-mm-thick borosilicate glass substrate was used as the workpiece between the quarter-wave plates, and it was moved linearly at a constant feed rate *F* in the (-*x*)-direction. A CW carbon dioxide laser beam was used as a heat source generating local temperature distribution in the workpiece, the diameter of the laser spot had been investigated before the laser cleaving experiments and was adjusted to the conditions shown in Table 1. The optical axis of the beam is not normal to the workpiece surface but is slanted slightly to prevent the reflected beam from

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