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HIGH SPEED THERMAL STRESS CLEAVING BY MOVING HEAT WITH MIST COOL

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Abstract Two types of different trials were examined experimentally to improve a cleaving velocity in thermal stress cleaving. One is a partial cooling by water mist spray on the propagating crack surface and the other is a pre-formation of a slightly high temperature zone by preheating. It is known that when other cleaving conditions are fixed, the cleaving velocity decreases with increase of width of the target object. This characteristic of thermal stress cleaving is often considered as a shortcoming for practical applications. Therefore, improvement of the cleaving efficiency by increasing a cleaving velocity is one of the important issue in the thermal stress cleaving. It was found experimentally that the maximum attainable cleaving velocity was increased from 38mm/s to 55mm/s when mist cooling was employed in addition to the usual laser beam heating of 10W magnitude for 31mm width specimen. On the other hand, the most effective preheat technique realized more than 400% increase of the cleaving velocity for 62mm width specimen. The background why these two types of different approaches both contribute to improve the cleaving velocity was discussed based on the linear elastic fracture mechanics.

Keywords Fracture Mechanics · Thermal Stress Cleaving · CO₂ Laser · Mist Cooling · Preheating

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1 Introduction

A thermal stresses induced by a localized temperature change in the vicinity of a crack tip often causes crack growth. Taking advantage of this phenomenon, some brittle materials can be cleaved without employing any cutting tools but with an appropriate control of temperature distribution of the body[1–6].

This type of processing technique is often referred as thermal stress cleaving. Recent years, industrial use of glass-like materials has been increased with a spreading needs for high functional devices such as wide-screen TV, LCD (Liquid Crystal Displays), PDP (Plasma Display Panels), and so on. Therefore, it becomes quite important to process brittle materials with high efficiency and high accuracy. The thermal stress cleaving is known as one of the desired processing techniques for such materials[7–10]. Different from normal machining processes such as grinding and polishing, the generated surface by thermal stress cleaving is smooth and almost free from micro-cracking which may decrease the material toughness[11]. At the same time, no cutting margin is required and clean and silent processing can be achieved. Since no machine tool is required, running cost is also low compared with usual machining processes. Improvement of the cleaving velocity is one of the important issues in the thermal stress cleaving. Increase of heating power directly increases the cleaving velocity. On the other hand, increase of heating power also induces a thermal damage of the material. In order to improve the cleaving efficiency without increasing the heating power, two types of different approaches were examined. One is mist cooling during cleaving and the other is pre-formation of a slightly high temperature zone before cleaving. As a test specimen, borosilicate glass plate of 0.4mm thickness was employed and various heating-cooling conditions were examined systematically. It was found from the experiment that the mist cooling method achieved about 45% improvement of the cleaving velocity. On the other hand, the preheat method resulted more than 400% improvement of the cleaving velocity compared with a normal laser beam cleaving by moving heat source.

2 Basic mechanism of thermal stress cleaving

The most fundamental and simplest situation of thermal stress cleaving can be found in the problem of an infinite domain. When an infinite plate of thickness B is heated by a continual point heat source applied at the origin, the temperature rise T at the arbitrary point whose distance from the origin is r , after a heating duration t is given by[12],

$$T(r, t) = \frac{Q}{4\pi\lambda} E_1 \left(\frac{r^2}{4\kappa t} \right) \quad (1)$$

where Q is the magnitude of a point heat source per thickness, λ is the thermal conductivity, κ is the thermal diffusivity and $E_1(x)$ is the integral exponential function. It should be noted that Eq.(1) expresses the mean value of a temperature rise in the thickness and the heat dissipation from

Fig. 1 Thermoelastic field due to a point heat source acting in an infinite plate

the surface is ignored for simplicity. The axisymmetric thermal stress field corresponding to Eq.(1) under plane stress condition is expressed by using Young's modulus E and the coefficient of linear expansion α as,

$$\sigma_r(r, t) = -\frac{\alpha EQ}{8\pi\lambda} \left\{ \frac{1 - e^{-\frac{r^2}{4\kappa t}}}{r^2/4\kappa t} + E_1 \left(\frac{r^2}{4\kappa t} \right) \right\} \quad (2)$$

$$\sigma_\theta(r, t) = \frac{\alpha EQ}{8\pi\lambda} \left\{ \frac{1 - e^{-\frac{r^2}{4\kappa t}}}{r^2/4\kappa t} - E_1 \left(\frac{r^2}{4\kappa t} \right) \right\} \quad (3)$$

The thermoelastic fields of Eqs(1~3) are illustrated in Fig.1. Contrast to the distributions T and σ_r , which do not change their sign, σ_θ varies from negative to some positive value depending on $r^2/4\kappa t$. This positive σ_θ around the heating point can be used for a driving force of crack growth. That is, if the crack exists along a radial direction of the heating point, the singular stress field of mode I type would be produced in the vicinity of the crack tip. Once the crack tip approaches to the heating point, however, the negative σ_θ in the vicinity of the heat center may arrest the crack. Therefore, in order to continue to cleave the material, the heating point should be moved in an appropriate velocity to precede a crack growth.

Fig.2 shows a variation of stress intensity factor (SIF) at a tip of an edge crack as a function of crack length when thermal stress cleaving is examined for a finite width plate. In this figure, the point heat source is assumed to move in a constant velocity v along the center line of the plate and the crack is assumed to follow it. In the numerical analysis, the thermoelastic properties of borosilicate glass of 0.4mm thick were used. It should be noted that the fracture toughness of the borosilicate glass for relatively slow crack growth range is about $0.75\text{MPa}\sqrt{m}$ [13]. It should be noted that the fracture toughness of the borosilicate glass is supposed at constant $0.75\text{MPa}\sqrt{m}$, irrespectively of the temperature throughout in this article. Therefore, the $K_{Ic} = 0.75\text{MPa}\sqrt{m}$ level is also indicated in Fig.2.

Fig. 2 Mode I stress intensity factor (SIF) at the tip of an edge crack laying on the center line of the plate under thermal stress induced by moving heat source of magnitude 10W, when moving heat source just arrived at a central location of the plate (borosilicate glass plate of 0.4mm thickness was assumed)

The SIF variation for 31mm width plate is illustrated in Fig.2(a) and that of for 62mm width plate is shown in Fig.2(b). In the present paper, a versatile program for two-dimensional elastic problems based on body force method[14,15] was employed to calculate a SIF at a crack tip under arbitrary heating conditions. This house-made software provides highly accurate solutions of SIF by inputting appropriate calculation data which assign for example the geometry of problem, heating conditions, thermoelastic properties, shape and location of a crack and so on. The degree of boundary division for

Fig. 3 Experimental setup for thermal stress cleaving by CO₂ laser heating combined with mist cooling

the body force method analysis was pre-examined and set so that the typical numerical error of the SIF analysis is less than 0.5%.

In the present study, the uncoupled thermoelastic analysis was examined. That is, the temperature analysis was carried out first then the SIF for various crack tip locations were calculated under the identical temperature distribution. Though the uncoupled analysis might cause considerable error when crack propagates in a much higher velocity comparable to the elastic wave of the material, the uncoupled analysis could be valid for the present situation since the cleaving velocity remains in a order of $v \approx 10^2 \text{ mm/s}$.

From Fig.2, it is recognized that the increase of cleaving velocity v significantly decreases the crack tip SIF. It is also understood from these figures that the SIF decreases with increase of plate width. This fact is also verified in a cleaving experiment. In fact, the measured maximum cleaving velocity in an experiment for 31mm width plate was 38mm/s and it for 62mm width plate was 22mm/s. From practical point of view, however, much larger cleaving velocity is desired for an industrial use. In order to improve the cleaving velocity, two types of different approaches were examined. One is a cleaving method combined with mist cooling and the other is pre-formation of slightly high temperature zone.

3 Improvement of a cleaving velocity by mist cooling

3.1 Experimental setup and result of cleaving experiment

Fig.3 shows the illustration of thermal stress cleaving of finite width plate by using a combination of CO₂ laser heating and mist cooling. The heating power was set at approximately 10W but it had $\pm 0.5\text{W}$ fluctuation to the maximum. The cooling performance can be controlled manually by adjusting a flow rate at a mouth of atomizing nozzle. In order to avoid the interference between laser exciter and the atomizing nozzle, these two devices were placed to the opposite sides of specimen so as to sandwich it from the top and bottom sides. A movable stage that holds the specimen was installed to cool the

Fig. 4 Detail of heating and cooling areas in Fig.3

specimen from the bottom. For the sake of controlling the cooling position, an adjustable table for an atomizing nozzle was also introduced. HDD video camera and thermal camera were used to record the experiment.

The distance between centers of heating and cooling areas can be adjusted in the range of 0mm to 25mm as seen in Fig.4. The diameter of CO₂ laser beam heater was 3mm and cooling diameter was about 10mm. Both the shapes of heating and cooling areas can be approximated by a circle. The shape of the specimen was a rectangle of 31mm for width, 250mm for length and 0.4mm for thickness. In order to make crack to initiate easily, artificial scratch was introduced at the end of the specimen. The specimen was placed on the movable stage that moves between the laser heater and mist cooler. The flow rate of mist was fixed at about 100ml/s. The mist was a mixture of water and air of room temperature. The attainable cleaving velocity was investigated by changing the distance between the centers of heating and cooling. The experimental result is shown graphically in Fig.5.

It was observed that the maximum attainable cleaving velocity varied with the distance between the centers of heating and cooling. When heating power was 10W, the observed maximum cleaving velocity was 38mm/s for heating only, but it was increased up to 55mm/s when mist cooling was introduced. When the highest cleaving velocity (55mm/s) was realized, distance between centers of heating and cooling was 21mm. During the crack growth, the crack tip was positioned between the centers of heating and cooling. Once the crack growth delayed and the crack tip moves behind the cooling area, the crack was suddenly arrested and the cleaving was not completed. The location of mist cooling at the beginning of crack growth was also important. If the cooling location is advanced from the crack tip, no crack growth was observed.

Fig.6 shows a comparison of a temperature measured during a thermal stress cleaving without (Fig.6(a)) and with (Fig.6(b)) mist cooling for a 31mm width specimen. The ordinate is a temperature rise at the surface of a specimen when traverse velocity of the laser spot was 38mm/s and the total heating power was 10W. The heating diameter was 3mm and the cooling diameter was about 10mm and distance between centers of heating and cooling was set at 10mm. The maximum temperature was appeared inside of a heating circle and is a little bit backward of the center of heating circle. The measured maximum temperature was almost identical at about 200°

Fig. 5 Measured maximum cleaving velocity as a function of distance between centers of laser heating and mist cooling (see Fig.4)

irrespective to the existence of a mist cooling. When mist cooling was employed, however, the temperature rise behind the heating area was suppressed considerably.

3.2 Mechanics of crack growth assisted by mist cooling

It is difficult considerably to evaluate the amount of energy taken away by mist cooling from the surface of the specimen. In order to estimate the removed energy by mist cooling, the temperature analysis was carried out and the result was compared with measurement (Fig.6(a),(b)). It was roughly found from temperature analysis that the removed energy by mist cooling for 38mm/s traverse velocity of 10W laser heating is about 2~5W. The analyzed SIF at a crack tip is shown in Fig.7 in which the assumption that the mist cooling can be replaced to be a 5W negative circular heat source of 10mm diameter is applied. The SIF is plotted against a location of the crack tip c when the center of heat source arrived at 90mm position. In this figure, 6 curves are plotted at the same time. Thick curve shows a SIF variation without mist cooling and the other narrow curves show that of with mist cooling for a different distances between centers of heating and cooling " D ". The traverse velocity of the heat source is set 40mm/s and the center of cooling is assumed to follow it in an identical velocity. It can be seen as the crack tip SIF exceeds $0.75\text{MPa}\sqrt{m}$, the thermal stress cleaving would be realized if the distance between centers of heating and cooling is located appropriately. That is, the thermal stress cleaving would be realized if the distance between centers of heating and cooling is in the range of 15mm~25mm. This inclination well accords with the experimental observation shown in Fig.5.

Although the cooling method is effective to increase a cleaving velocity, there exist a limitation of the removed energy from the surface of specimen by mist cooling. As the attained maximum cleaving velocity in the experiment was 55mm/s for 10W heat source as seen in Fig.5, the further improvement

Fig. 6 Measured temperature distribution of borosilicate glass plate of 0.4mm thick and 31mm width (heating power: 10W, moving velocity: 38mm/s, diameter of heating circle: 3mm, diameter of cooling circle: about 10mm)

of the cleaving velocity is highly desired. In the next section, the preheat method is discussed.

Fig. 7 SIF at a crack tip in the thermal stress cleaving by moving point heat source of 10W combined with mist cooling of -5W (moving velocity of the center of heat is 40mm/s)

Fig. 8 Detail of thermal stress cleaving with preheat

4 Improvement of a cleaving velocity by preheat

4.1 Experimental setup and result of experiment of crack growth assisted by preheat

Fig.8 shows a detail of thermal stress cleaving with pre-formation of temperature distribution by preheat. In this experiment, a gentle temperature rise was formed beforehand of thermal stress cleaving by making a specimen contact to a line heater of different width. The pre-formed temperature had a so-called campanulate distribution with maximum temperature rise was about 30°.

The width of specimen used for the preheat experiment was 62mm. Two types of different preheat width, the narrower one is about 1mm and the wider one is about 30mm, were examined. The result of cleaving experiment is shown in Fig.9. The ordinate of this figure is an observed maximum cleaving velocity and the abscissa is a distance between a crack tip and a heat

Fig. 9 Influence of a preheating on measured maximum cleaving velocity

Fig. 10 Numerical model for preheating method (pre-formed temperature is assumed as a cubic function of coordinate variable; $T(y) = T_0\{1 - 3(y/a)^2 + 2|y/a|^3\}$)

center of 10W magnitude. When preheat is absent, the upper limit of the maximum cleaving velocity is 22mm/s for 62mm width specimen. When narrower preheat is used, the attained maximum cleaving velocity was about 100mm/s and the measured distance between a crack tip and a center of moving heat source was about 22mm. When wider preheat is used, the distance between a crack tip and a center of heat decreases with increase of the cleaving velocity. When cleaving velocity exceeded 100mm/s, the crack tip occasionally preceded beyond the center of moving heat source and therefore the crack growth became unstable.

4.2 Mechanics of crack growth assisted by preheat

Fig.10 shows the calculation model for preheating and Fig.11 shows the resulted SIF at a crack tip due to a preheating alone. The maximum temperature rise T_0 in Fig.10 was set at 30° which is identical to the actual experiment and the temperature distribution was assumed as a cubic function of a coordinate variable as $T(y) = T_0\{1 - 3(y/a)^2 + 2|y/a|^3\}$ where a is a positive parameter expressing the extent of temperature rise in preheating. It is found that mere a 30° temperature rise at the highest in $a/W = 0.833$

Fig. 11 SIF at a crack tip due to preheating

situation results a more than $0.65\text{MPa}\sqrt{m}$ in SIF for a wide range of crack length. That is, an appropriate preheating brings more than 85% SIF required for crack propagation. It would be readily understood that if the SIF due to a moving heat source (Fig.2(b)) is superposed on the result of preheat (Fig.11), a thermal stress cleaving that exceeds 100mm/s cleaving velocity can be easily realized.

5 Conclusion

An improvement of the cleaving velocity is important issues in the thermal stress cleaving. Two types of different approaches were examined to improve the cleaving velocity. One is a mist cooling method in which the water mist is sprayed on the crack face in addition to the usual CO_2 laser heating. The other is a preheat method in which the specimen is preheated along its length in addition to the usual CO_2 laser heating. As a specimen, borosilicate glass plate of finite width, was employed and the heating power of CO_2 laser exciter was fixed at 10W for both experiment and analysis.

The obtained results are listed as follows.

1. The maximum cleaving velocity decreases with increase of the width of specimen. For example, the maximum cleaving velocity was 38mm/s for 31mm width specimen and it was 22mm/s for 62mm width specimen, when normal thermal stress cleaving was applied.
2. The realized maximum cleaving velocity by laser heating with mist cooling was 55mm/s, which is 45% improvement of the one experienced when heating only.

3. The realized maximum cleaving velocity by laser heating with preheating was more than 100mm/s, which is 400% improvement of the one experienced when heating only.
4. In the preheating method, mere a 30° increase of temperature at the maximum may bring a more than 85% of required SIF for thermal stress cleaving, when the temperature rise is formed in an appropriate extent.

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