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# Thermally tempered glass surface stress measurement by critical ray

T. KISHII

A critical ray was excited along the glass surface by laser beam incidence. Part of the critical ray was refracted during propagation. The angle of refraction depended on the refractive index of the glass surface. When the glass surface was birefringent due to the photoelastic effect, the angles of refraction differed from each other between two linearly polarized beams. This difference allows surface stress determination.

Optical surface waves are useful for non-destructive surface stress measurement for tempered glasses[1]. Three measurement methods are known which use:

1. Evanescent wave[2,3],which is excited by light incident at angles greater than the critical angle of total reflection.
2. Guided wave, which is trapped in striation layers near the surfaces of plate and sheet glasses[1,4,5].
3. Guided wave, which is trapped in high refractive index surface layer formed by ion exchange[6,7,8].

When the glass surface is birefringent due to photoelastic effect, effective indices[1,6,7] or optical paths[3] differ from each other between two linearly polarized beams vibrating in directions vertical to (TM wave) and parallel with (TE wave) the surface. Measurements of these differences allow surface stress evaluation.

This paper proposes a fourth method which uses a critical ray. The method is applicable to glass in which guided wave mechanisms are lacking.

## Theory

Assume that a convergent beam **B** is projected onto a boundary surface S from the high refractive index medium side at a near critical angle $\phi_0$ for total reflection (Fig. 1). Part of the ray, which is incident at $\phi_0$, is refracted and propagates along the surface as a critical ray C.[9] A small part of critical ray r is refracted back to the high index medium side at every point along the critical ray path. The angles of the second refraction are equal to $\phi_0$. Refracted rays r can be collected by a convex lens $L_2$ to form a spot or fringe s on focal plane F for lens $L_2$.

When a low index medium G is birefringent due to the photoelastic effect, and provided that the incident beam contains critical angles for two linearly polarized lights, vibrating in directions parallel with and vertical to the plane of incidence, the spot or fringe splits into two parts.

The author is at the R and D Center, Toshiba Corp., Kawasaki, Japan 210. Paper received 29 October 1979. Revised version 14 January 1980

Spacing between the spots or fringes is proportional to the stress at the surface of the low index medium. Here, the low index medium is a glass sample to be measured. The high index media are optical glass prisms and immersion liquid.

## Experimental

Two kinds of glasses were used; SK-3 optical glass (refractive index $n$ = 1.64) from Ohara Optical Glass Co. and thermally tempered infra-red absorbing glass filter ($n$ = 1.51) by Toshiba Glass Co. Both were obtained commercially. Photoelastic constants were 1.31 and 2.4 $(\mathrm{nmcm}^{-1})/(\mathrm{kgcm}^{-2})$ for SK-3 and infra-red absorbing glasses, respectively.

Optical arrangements are shown in Fig. 1. The apparatus parameters are given in the figure caption. Both incident light beam and telescope were adjusted to have critical angle $\phi_0$ at input prism-sample glass and sample glass-output prism interfaces.

An SK-3 glass block was cut into platelets 5 x 20 x 25 mm in size. The platelets were optically polished on both surfaces. They were heated in an electric furnace at 650° ∿ 670°C for ten minutes and then blast quenched by a two nozzle air injector. Air pressure was varied to obtain samples with a wide range of surface stress.

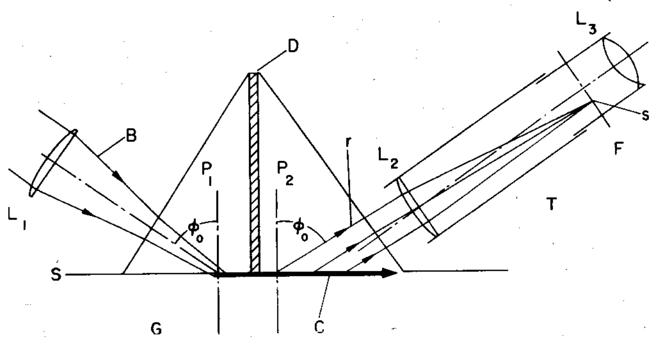


Fig. 1 Principle and apparatus sketch: G – glass sample (low refractive index medium); $P_1$ and $P_2$ – input and output prisms (high refractive index medium, $n$ = 1.75); D – diaphragm; S – glass surface; B – 1 mW HeNe laser beam; $L_1$ – focusing lens, $f_1$ = 80 mm; C – critical ray; r – rays refracted back; $\phi_0$ – total reflection critical angle; $L_2$ – objective lens for telescope T, $f_2$ = 250 mm; F – focal plane of lens $L_2$; s – spot or fringe; T – telescope; $L_3$ – ocular lens of telescope T, X10. Immersion liquid ($CH_2T_2$, $n$ = 1.73) was applied to the G/$P_1$ and G/$P_2$ interfaces, respectively

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When the glass was stress-free, a sharp fringe appeared on the focal plane F (Fig. 2). After thermal tempering of the glass, the fringe split into two fringes (Fig. 3). They were formed by linearly polarized light with vibration direction perpendicular to and parallel with the plane of refraction and were assumed to have originated from TM and TE components of the critical ray, respectively. This indicated that the effective refractive index of the glass surface for the TM wave was higher than that for the TE wave, due to the photoelastic effect.

The apparatus sensitivity was:

1 mm distance between fringes

→ 0.0013 birefringence for $n = 1.64$

and

→ 0.0020 birefringence for $n = 1.55$

Here, $n$ indicates the sample glass refractive index. When surface stress was compressive, the TM wave had a higher effective index than TE wave.

A conventional method[10] was also applied to the surface stress measurement for comparison; Photoelastic retardation in the ray, which propagated along the surface, was assumed to be twice that in the ray which propagated along the central plane (Fig. 4).

## Experimental results

Stresses at the centre of surfaces of thermally tempered SK-3 glass platelets were measured. They are compared in Fig. 5 with stresses measured by the conventional method.

A thermally tempered infra-red absorbing glass filter gave two-fringe patterns (Fig. 6). The stress was estimated to be 14 kg $mm^{-2}$

## Discussion

It should be noted that experiments similar to that reported here have already been carried out. Acloque and Guillemet[3] found that the light incident near the critical angle for total reflection upon a portion of a glass surface could be collected from an adjacent portion of the surface. They suggested that the light propagated as an evanescent wave, and proposed a method for surface stress measurement using an evanescent wave. Their idea has formerly been considered important in the plate glass industry[11].

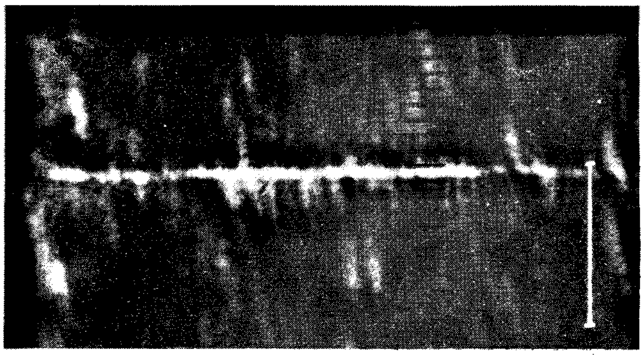

Fig. 2 Fringe obtained on stress-free SK-3 optical glass surface. Bar – 1 mm spacing on focal plane F and 0.0013 in effective index difference

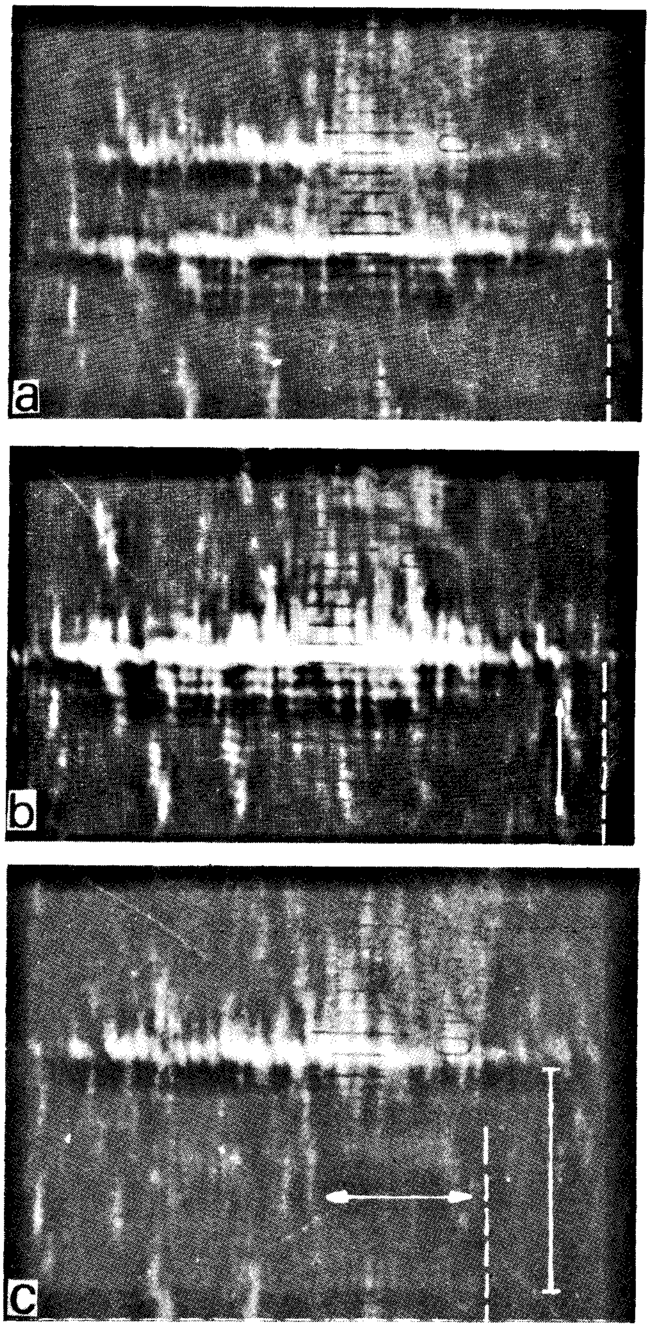


Fig. 3 Fringes obtained on thermally tempered SK-3 glass surface. a – ordinary light, b and c – linearly polarized light. Bar – same as in Fig. 2. Arrows – vibration direction of linearly polarized lights; dotted lines – planes of refraction

Later, Osterberg and Smith[8] repeated the experiment and found that the phenomena were more complex; in plate glass with striation layers, more energy was carried than in homogeneous glass.

Recently, guided waves in striation layers have been experimentally observed[4,5] and analyzed, and a method has been proposed for surface stress measurement of plate and sheet glasses by the waves.[1] The author of the present paper insists that the evanescent wave, if any, plays a minor role in the present experiment. The reasoning is as follows: An evanescent wave is excited by light incident at angle $\phi$ beyond $\phi_0$. The intensity of the wave as a function of $\phi$ shows broad extrema at $\phi_0^2$. On the contrary experiments have shown that rays refracted back, r, are observable only when the incident beam B includes $\phi_0$. This is compatible

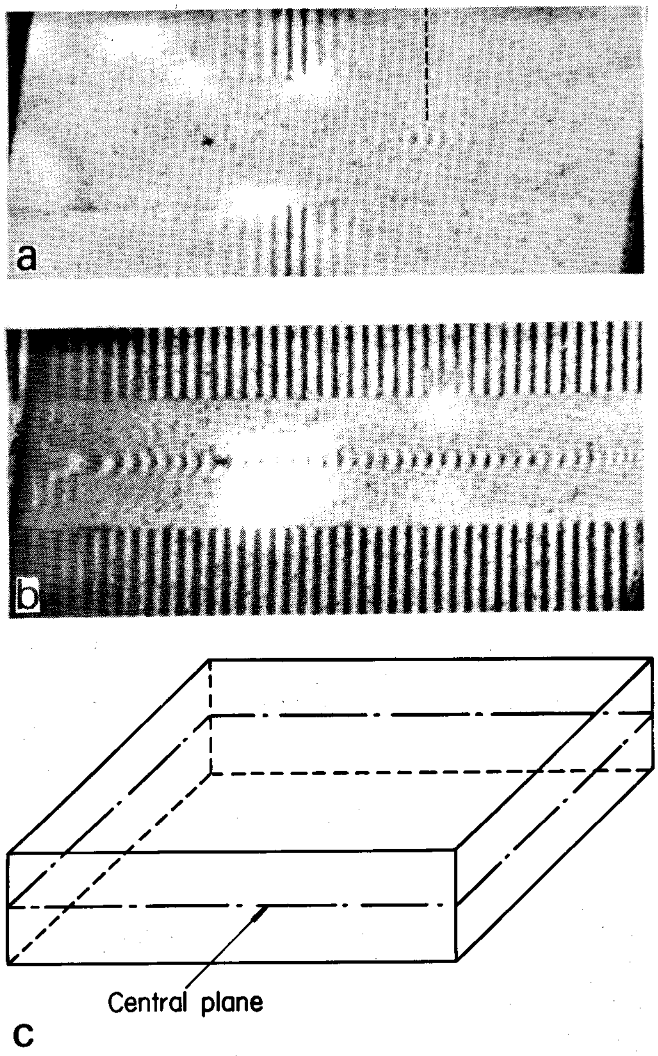


Fig. 4 Photoelastic observation on a platelet using light which propagated parallel with the central plane. Fringes were formed by a quartz wedge. a — white light and b — Na D line were used; c — glass platelet sketch. The arrow shows fringe shift which corresponds to photoelastic retardation between two linearly polarized lights along the central plane. One fringe shift corresponds to 590 nm retardation. Fringe shift at the surface is assumed to be twice that at the central plane in absolute value and to be reversed in sign.

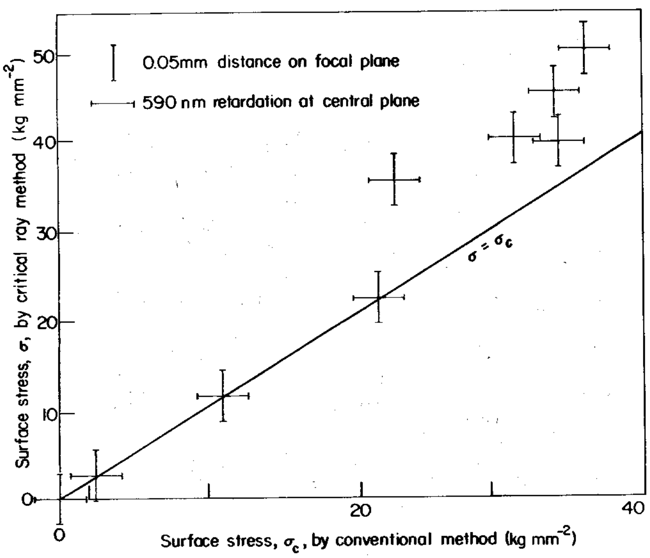


Fig. 5 Surface stresses measured by the conventional method (horizontal axis) and by the present method (vertical axis)

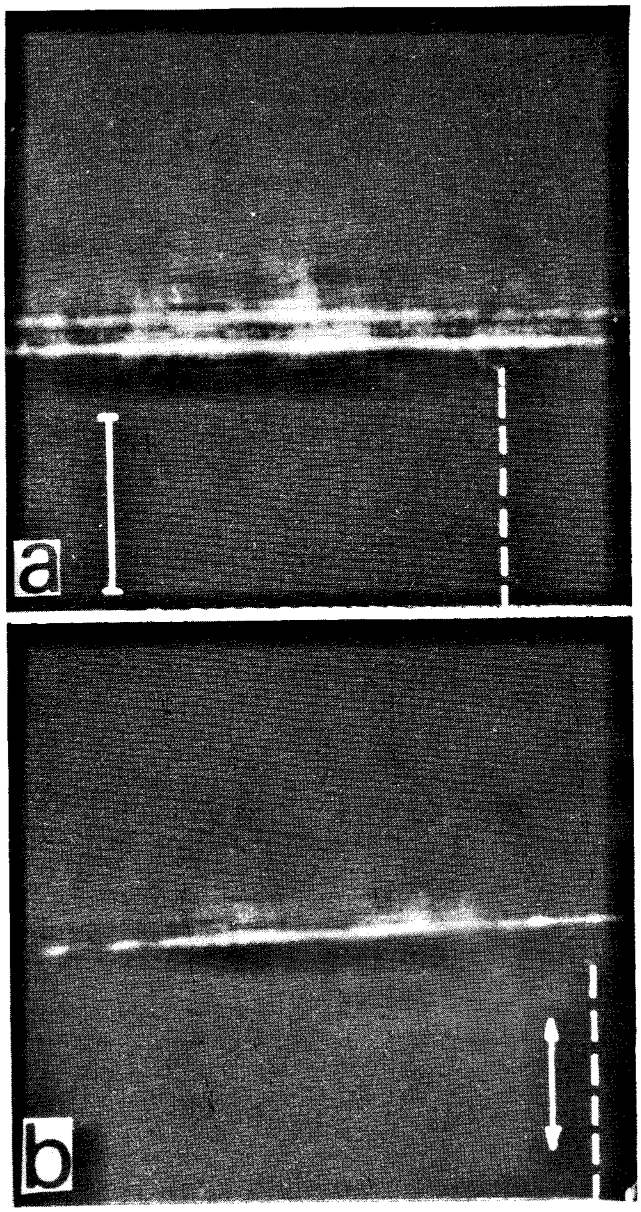


Fig. 6 Fringes formed by the critical ray on thermally tempered infra-red absorbing filter glass. a — ordinary light, b — linearly polarized light Bar, arrows and dotted lines — as in Fig. 3

with the assumption that the rays are refracted back from the critical ray, not from the evanescent wave, provided that critical ray, not from the evanescent wave, provided that the intensity, of the refracted ray, r, is proportional to the intensity of the critical ray or of the evanescent wave.

In Fig. 5, the present method gave values identical with or slightly higher than those obtained by a conventional method. This seemed reasonable, because the present and conventional method gave local and average stress values, respectively.

The sharp single fringe shown in Fig. 2 indicated that the glass was homogeneous and the surface supported no guided wave. The present method is useful for glasses which lack guided-wave mechanisms.

## Concluding remarks

Surface stress measurement by critical angle determination using totally reflected light is a well established technique in the plate glass industry[12,13].

Although the method, in principle, gives identical results with those obtained using the present method, the latter is superior in that:

1. Stress value in a very small area of less than 1 x 5 mm can be obtained.
2. Slight deformation or curvature in the glass surface causes no essential difficulty in measurement.

On the other hand, the drawback of the present method is that simultaneous angular collimation for both incident beam and telescope are very critical and time consuming.

Both methods have a common drawback, in that they are not applicable to glasses in which refractive indices near surfaces increase monotonically with increasing depth, an example is the air side surface of some float glasses.[1]

The author hopes the present method will enable non-destructive surface stress measurement of glasses, enamels, glass linings and synthetic resins in the future.

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