Optical waveguide effect of thermally tempered sheet and plate glasses — application to surface stress measurements

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Sheet and plate glasses have refractive index inhomogeneity parallel with their surfaces. Refractive index maxima near the surfaces behave as optical waveguides. Light waves can be excited in the guides from outside and can be extracted non-destructively, using the technique popular in optical integrated circuits. Stress birefringence, caused by surface stress in thermally tempered glasses, gives different effective indices for two linearly polarized light beams which vibrate in directions vertical to and in parallel with the surfaces. Effective index observation by two polarized light beams allows non-destructive surface stress determination.

Introduction

Thermally tempered glasses are widely used in the automobile and building industries. Tempered glasses are produced by air blast quenching of plate glasses which are heated to the softening temperature range. Surface compressions, which are built in by the procedure, reinforce the glass plates mechanically. The strength of the tempered glass corresponds to the surface stress. Surface stress measurement is important for quality and process control of tempered glass production. The stress must be measured non destructively, because cutting, chipping and grinding operations inevitably break the glass into small fragments, thus relieving most of the stress.

Kitano[1] reported an apparatus for surface stress measurement of tempered glasses. This paper reports a new method and apparatus based on the optical waveguide effect caused by striation layers in plate and sheet glasses.

Plate and sheet glasses as optical waveguides

Acloque and Guillemet[2] found that 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 with sufficient intensity. They suggested that the light was carried as evanescent waves. Osterberg and Smith[3] repeated the experiment and found that the phenomena were more complex than anticipated; in plate glass with striation layers more energy was carried than in homogeneous glass. Isard, Desai and Mwila[4] observed and analyzed light propagation through striations of a plate glass; light was assumed to travel in the form of TM and TE modes.

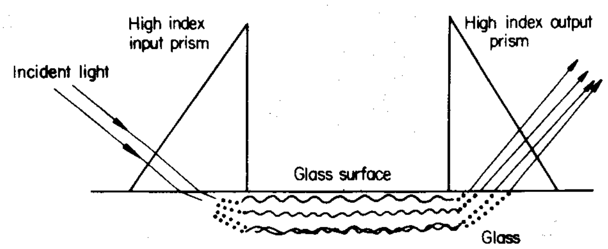

Fig. 1 Optical waveguide effect caused by refractive index maxima. These maxima lie parallel with and near the surface of a sheet or plate glass

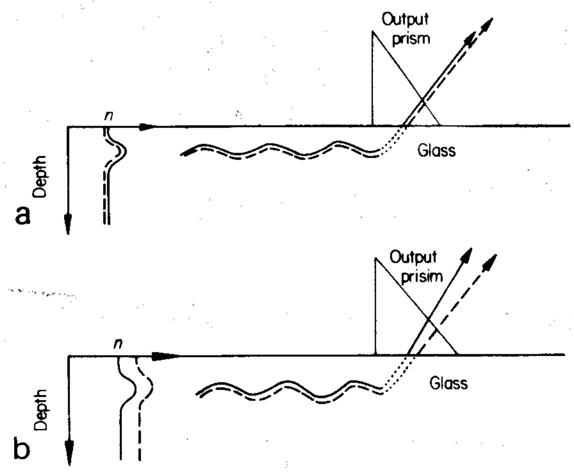

Fig. 2 Surface compression effect onrefractive index distribution and optical waveguide effect: a — without stress; b — with surface compression. n — refractive index; —— — TE wave; ---- TM wave

Theory

Plate and sheet glasses have layer like inhomogeneities which lie approximately parallel with the surfaces. These are often called striation layers. Refractive index distribution, therefore, also has layer like structure. Index maxima behave as optical waveguides which are similar to diffused or graded index light guides. Light can pass in each maximum without escaping. As the guide is thin, light propagates in the form of a mode or modes.

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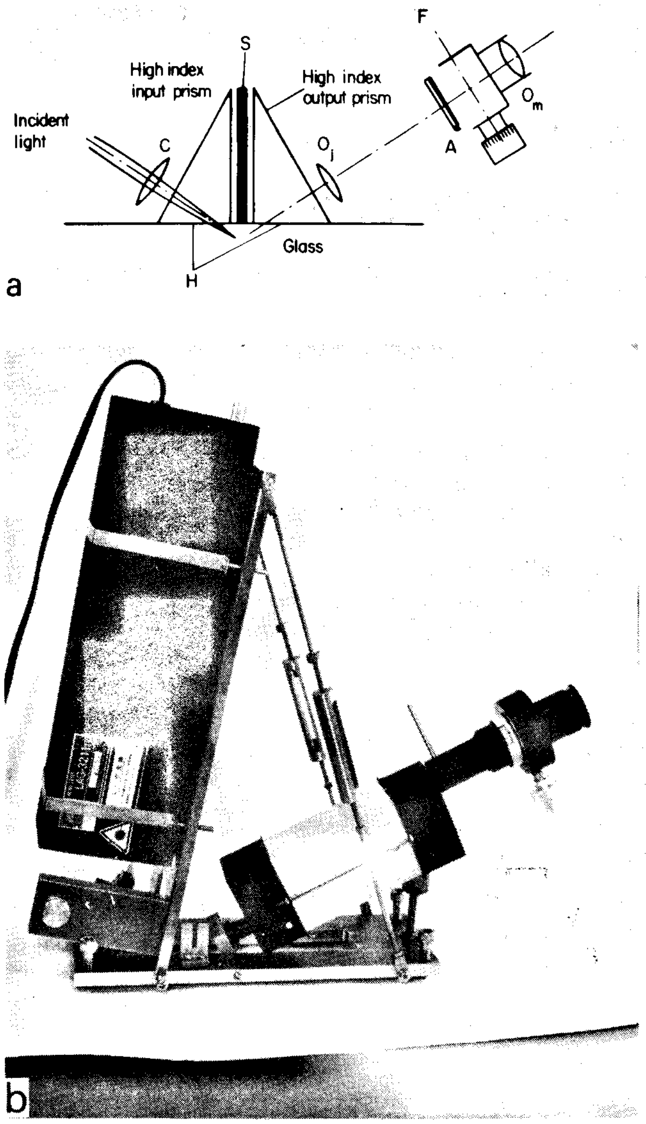

Fig. 3 Experimental equipment and layout: a – diagramtic representation where C – condenser lens (f = 4 cm); S – screen; O_j – telescope objective lens (f = 80 cm); O_m – telescope ocular micrometer (x 10); F – O_j focal plane; A – rotatable analyzer; H – immersion liquid; b – apparatus used in the experiments

When the glass surface-guide distance is less than several micrometers, propagating light mode or modes can be excited and extracted non destructively, using techniques popular in optical integrated circuits (Fig. 1).

Effective indices of the modes depend on the distribution of the refractive index in the guides. Surface stress, caused by thermal tempering, gives rise to a photoelastic birefringence effect in the guides. Effective indices for light waves vibrating normal to (TM wave) and parallel with (TE wave) the surface differ from each other. The difference is proportional to the surface stress, and is reflected in the difference in output angles between TM and TE wave (Fig. 2). Non-destructive stress determination is thus possible.

Tin side surface layers of float glasses have refractive index gradients caused by the diffusion of tin ions during the forming process. The optical waveguide effect in the layers can also be used for tempered glass non destructive surface stress measurement, as described in the previous paper.[5] This paper mainly concentrates on air side surfaces of float glasses and on glasses produced by non-float processes.

Experimental

Tempering

Tempering on a laboratory scale was carried out for glasses cut into 25 x 25 mm samples. They were heated in a horizontal tubular electric furnace for 10 minutes and were then blast-quenched from both surfaces using a two nozzle air injector. Holding temperatures were between 600° and 700°C.

Apparatus

Figure 3a shows a sketch of the apparatus used for the experiment. A 1 mW HeNe gas laser beam was focused with a convex lens (f = 40 mm) and was injected into the surface layer of glass through a high index input prism and excited guided waves propagated through index maxima were taken out by an output prism. The refractive mode angles were determined by the effective mode index and the law of refraction. An objective lens (f = 800 mm) of a telescope formed a pattern with bright fringes on the focal plane. These fringes correspond to the propagating modes. 1 mm between fringes corresponded to 0.00063 in effective index difference Δn_{eff} or to 22 kgmm^{-2} (220 MPa) surface stress. An analyzer allowed fringe observation by TM and TE waves.

Distance between the prisms may be in the range 100 μm – 50 mm. The prisms may be either separate or combined including a screen. The apparatus (Fig. 3b) was 4 kg in weight, including 2 kg for the laser system.

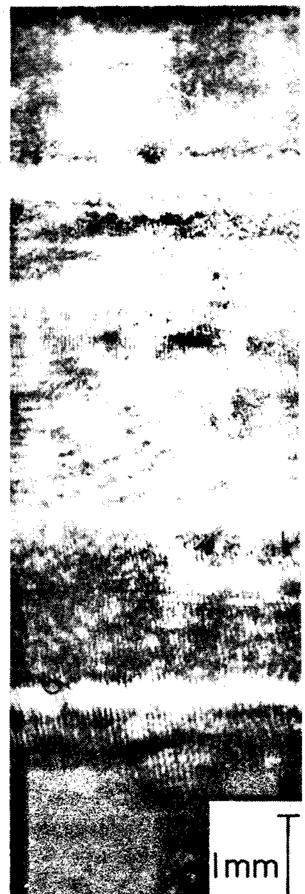

Fig. 4 Optical waveguide effect observed in float glass tin side surface. Bar indicates 1 mm on the focal plane

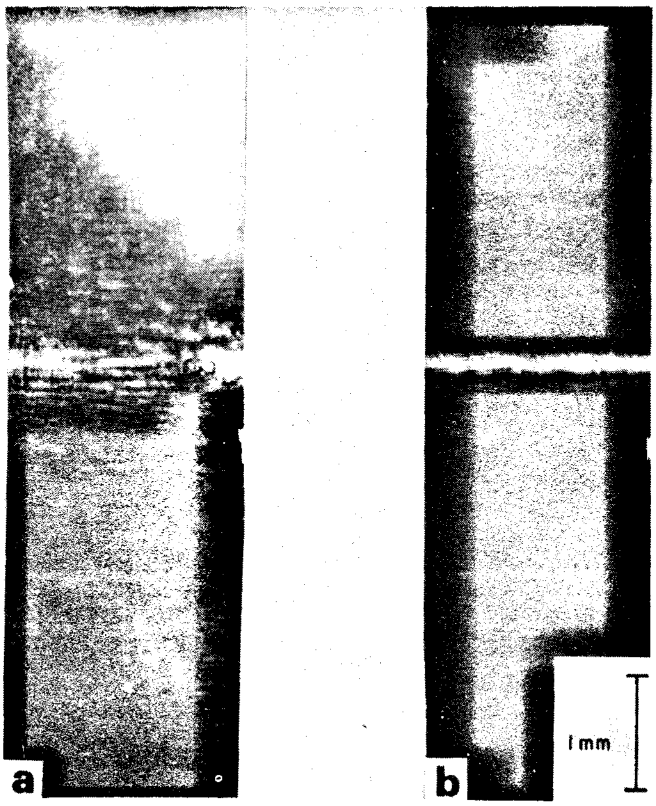

Fig. 5 Observed optical waveguide effect: a – in air side surface, 3 mm thick float glass; b – in air side surface, 6 mm thick float glass. Bar indicates 1 mm on the focal plane

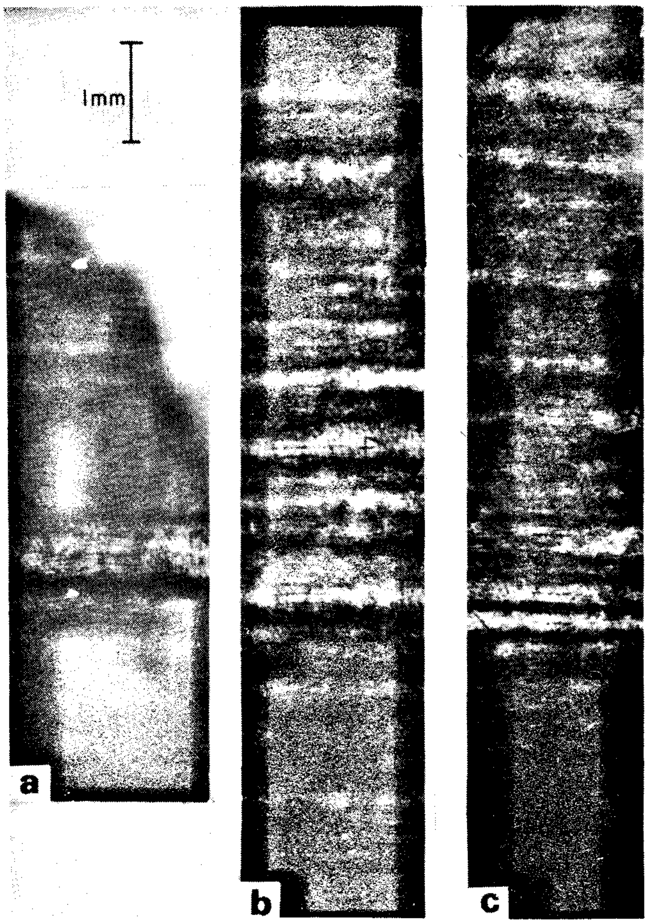

Fig. 7 Optical waveguide observed in sheet and plate glasses produced by non float processes a – 1.5 m thick; b – 2 mm thick; c – 2 mm thick. Bar indicates 1 mm on the focal plane

Experimental results

Float glasses as received

Float glasses were easily identified by distinct optical waveguide effects in tin side surfaces (Fig. 4).

Although air side surfaces of most float glasses showed single fringe patterns (Fig. 5), a few did not show any fringe pattern. Surface dilute hydrofluoric acid etching, however, gave rise to fringe patterns, indicating that optical waveguides existed only at a depth of more than a few micrometers (Fig. 6).

Fringe patterns were the same for TM and TE waves.

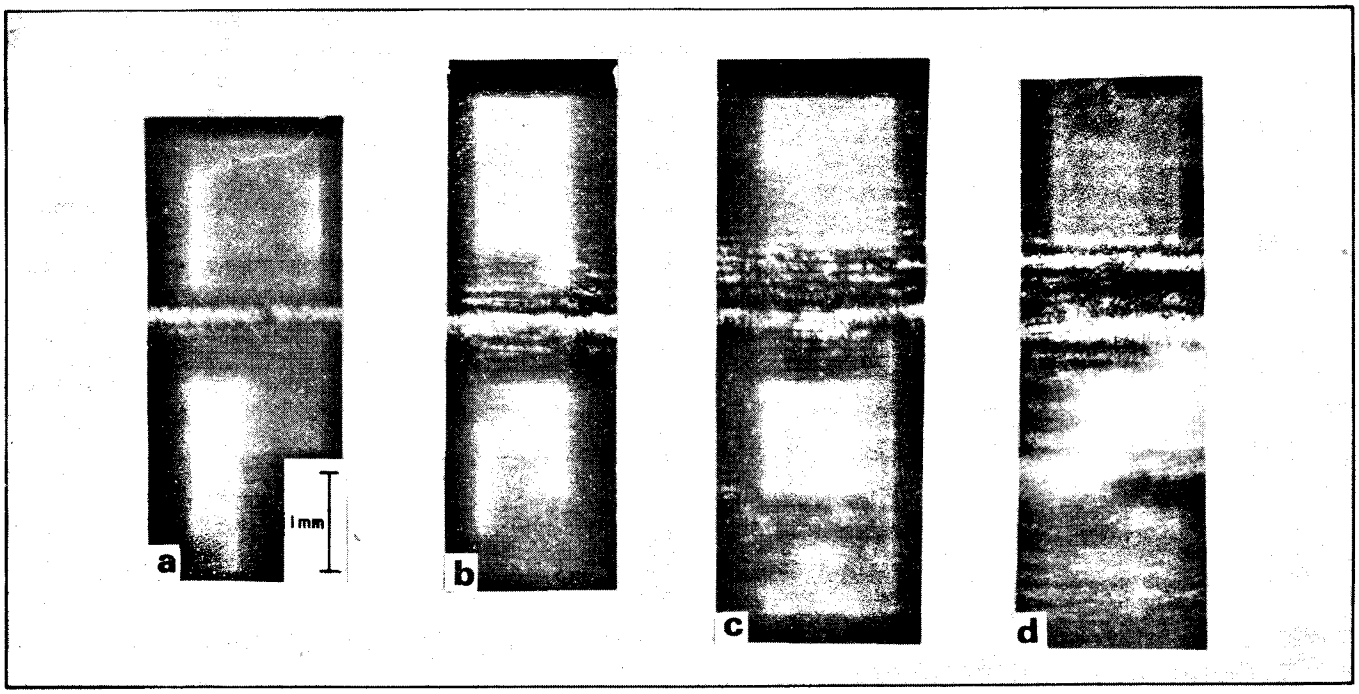

Fig. 6 Dilute hydrofluoric acid etching effect on optical waveguide effect in float glass air side surface. Before etching, the fringe was very weak. Etching time: a – 8; b – 15 s; c – 30 s; d – 120 s. Bar indicates 1 mm on the focal plane

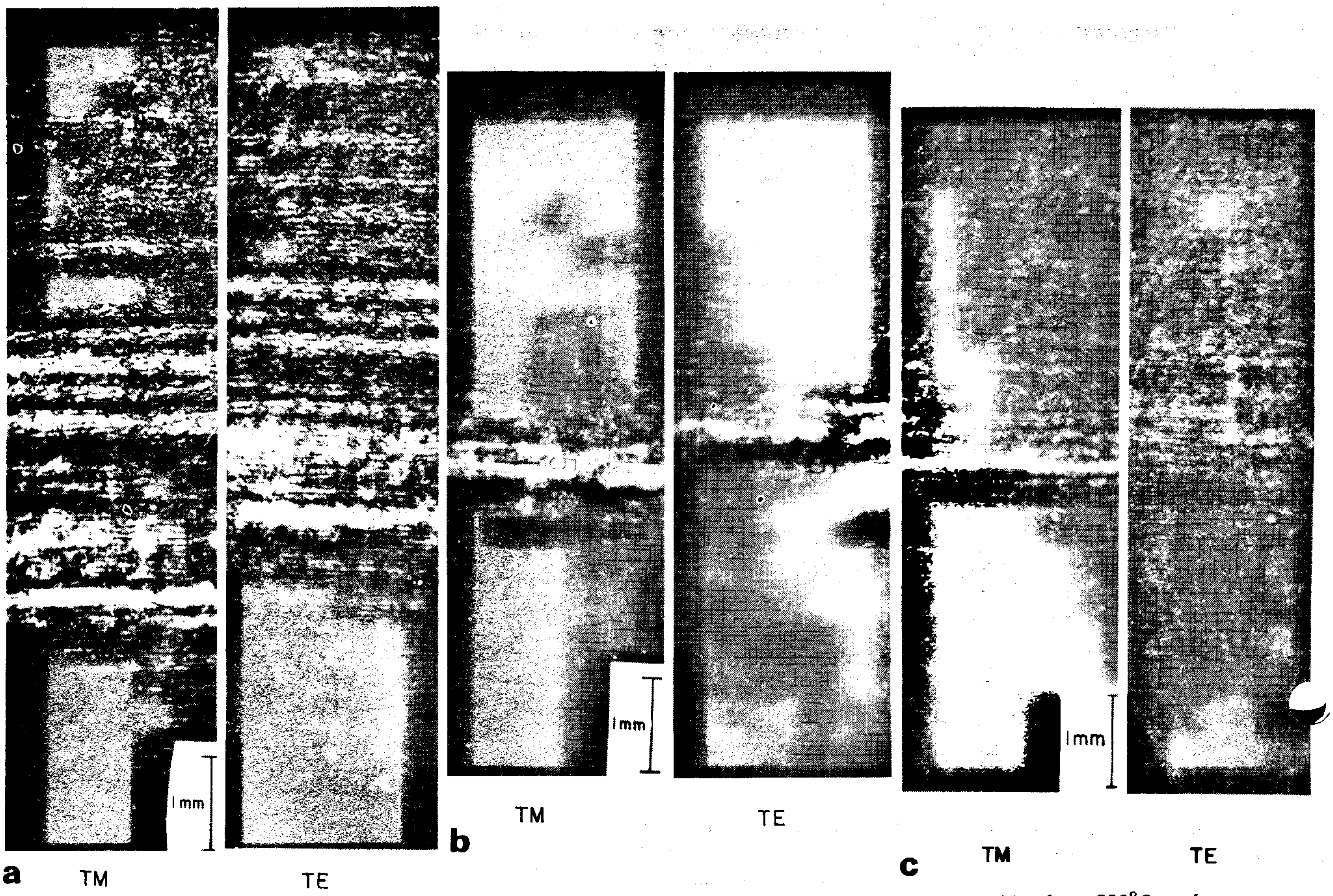

Fig. 8 Optical waveguide effect in thermally tempered plate glass: a – 5 mm thick plate glass after blast quenching from 660°C, surface stress = 20 kg mm^{-2}; b – 2 mm thick sheet glass after blast quenching from 640°C, surface stress = 9 kg mm^{-2}; c – 3 mm thick float glass air side surface after blast quenching from 640°C, surface stress = 7 kg mm^{-2} Bars indicate 1 mm on the focal plane

Glasses produced by non float processes

All glasses tested so far, which were ascertained to be produced by non float processes, gave fringe patterns in both sides. Figure 7 shows some examples. The patterns were the same for TM and TE waves.

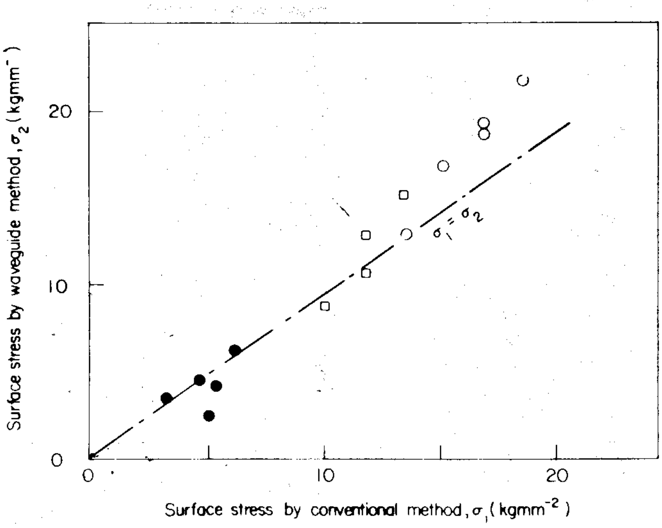

Fig. 9 Comparison between stress values, obtained by conventional and waveguide methods, on glasses tempered in laboratory scale: □ – air side surfaces, 3 mm thick float glasses; ● – 2 mm thick glasses, produced by non float process; ○ – 5 mm thick glasses, produced by non float process

Glasses tempered on a laboratory scale

In blast-quenched glasses, fringe patterns by TE waves were almost the same as those by TM waves. The effective indices by TE waves, however, were smaller than those by TM waves (Fig. 8). Stress values were calculated from the index difference. Stress values by conventional and waveguide methods are compared in Fig. 9. Agreement is satisfactory, considering that the conventional and waveguide methods give average and local values respectively.

Table 1 Possibility of surface stress measurement using optical waveguide effect

Cause of optical waveguide effect \ Cause of stress	Ion exchange $Na^+ \leftrightarrow K^+$	Thermal tempering	Mechanical strain
Ion exchange $Na^+ \leftrightarrow K^+$	Yes[6]	[Yes]	[Yes]
Ion exchange $Na^+ \rightarrow Sn^{2+,4+}$	Yes	Yes[5]	Yes
Refractive index inhomogeneity	[Yes]	Yes This paper	Yes

[ ] : Industrially not important.

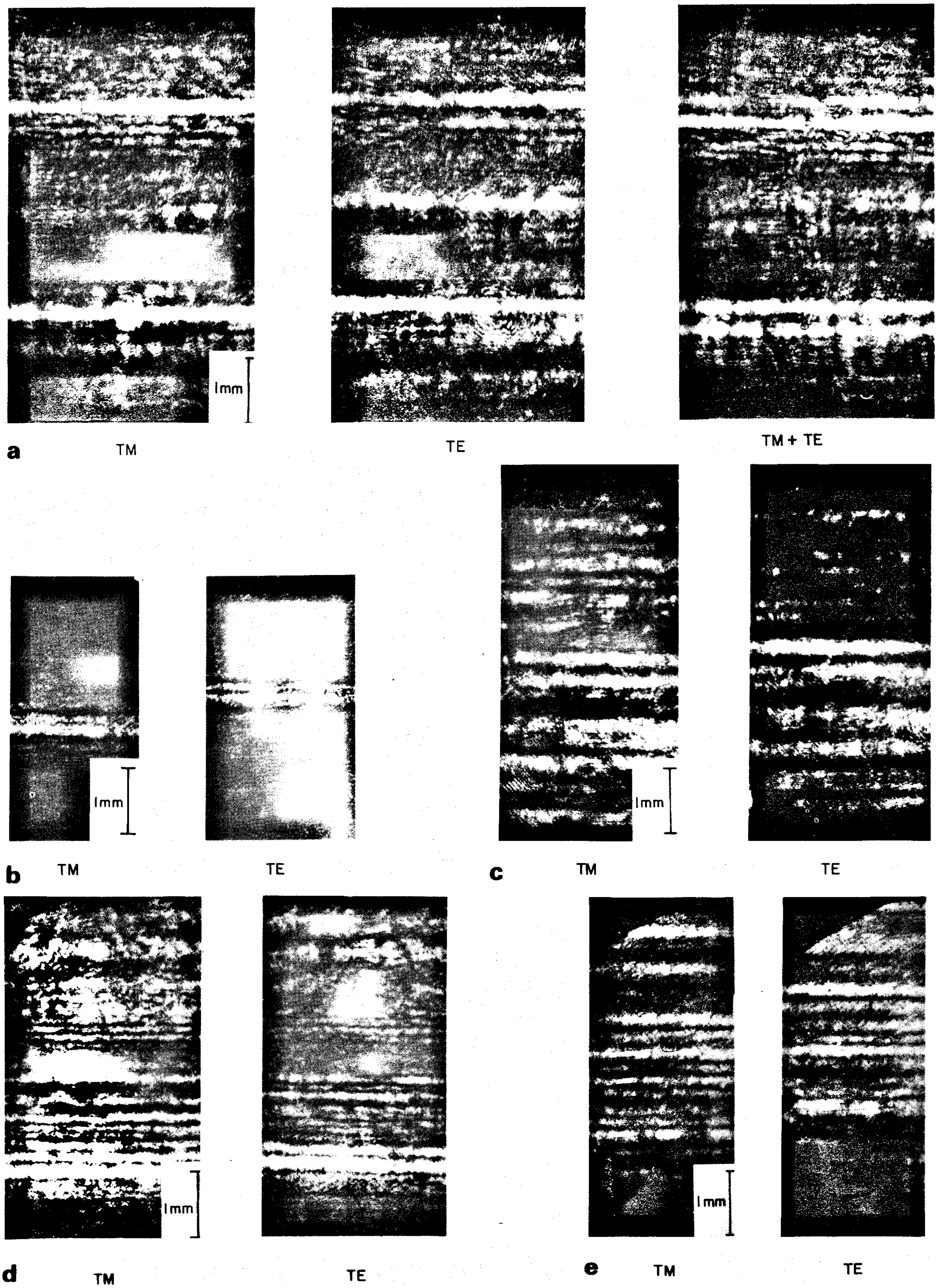

Fig. 10 Optical waveguide effect in commercial tempered glasses: a — tin side surface for 4 mm thick plate glass, surface stress = 9 kg mm^{-2}; b — Air side surface for plate glass identified to be float glass, surface stress = 11 kg mm^{-2}; c — e — surfaces of 4 mm thick glasses identified as produced by non float processes, surface stress = (c) 11 kg mm^{-2}, (d) 7 kg mm^{-2}, (e) 7 kg mm^{-2}. Bars indicate 1 mm on the focal plane

Tempered glasses produced on a factory scale

Figure 10 shows the results on tempered glass samples 4 x 150 x 300 mm in size. They were obtained commercially from a Japanese glass manufacturer.

Concluding remarks

The optical waveguide method described in this paper is a useful means for rapid and non destructive surface stress measurement. Although only flat glasses are dealt with here, a slight modification[7] is expected to enable stress measurement on curved surfaces. It is hoped that this method will contribute to industrial tempered glass production.

The waveguide method has wide areas of application to non destructive surface stress measurement (Table 1).

References

1 **Kitano, I.** *Yogyo-Kyokai-Shi (J Ceram Soc Japan)* **80** (1972) 173

2 **Acloque, P., Guillemet, C.** *Compt Rend* **250** (1960) 4328 Compte rendu du colloque sur la nature des surface vitreuses polies, Union Scientifique Continentale du Verre, Charleroi, Belgium (1959) 121, US Pat 3 286 581 (1966)

3 **Osterberg, H., Smith, W.** *J Opt Soc Amer* **54** (1964) 1073, 1078

4 **Isard, J.O., Desai, S.J., Mwila, K.** *J Phys D: Appl Phys* **11** (1978) 433

5 **Kishii, T.** *Opt laser tech* (to be published)

6 **Kishii, T.** *Yogyo-Kyokai-Shi* **87** (1979) 119

7 **Kishii, T.** *Yogyo-Kyokai-Shi* **86** (1978) 336