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Surface stress measurement by the optical waveguide effect in thermally-tempered float glass

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Float glasses have tin-diffused layers on one side. These layers show an optical waveguide effect caused by refractive index gradients in the layer. Surface stress, caused by tempering, gives different refractive index distribution for TM and TE waves via the stress birefringence effect. Non-destructive and rapid stress determination is possible by observing the effective index distributions of propagating modes in TM and TE waves.

Float glasses occupy a major part of plate glass production throughout the world. They are formed into shape on a tin bath from the melt. The glasses have tin-diffused layers on one side (Fig. 1a). These layers show an optical waveguide effect caused by refractive index gradients in the layer.[1] Stresses in the layers, if any, cause photoelastic birefringence and give different refractive index distribution for TM and TE waves. Propagating mode effective index distributions differ from each other for TM and TE waves. This difference allows surface stress determination. This is expected to be true not only for stresses caused by ion-exchange (chemical strengthening)[2] but also by thermal tempering (air-blast quenching) and by elastic deformation.

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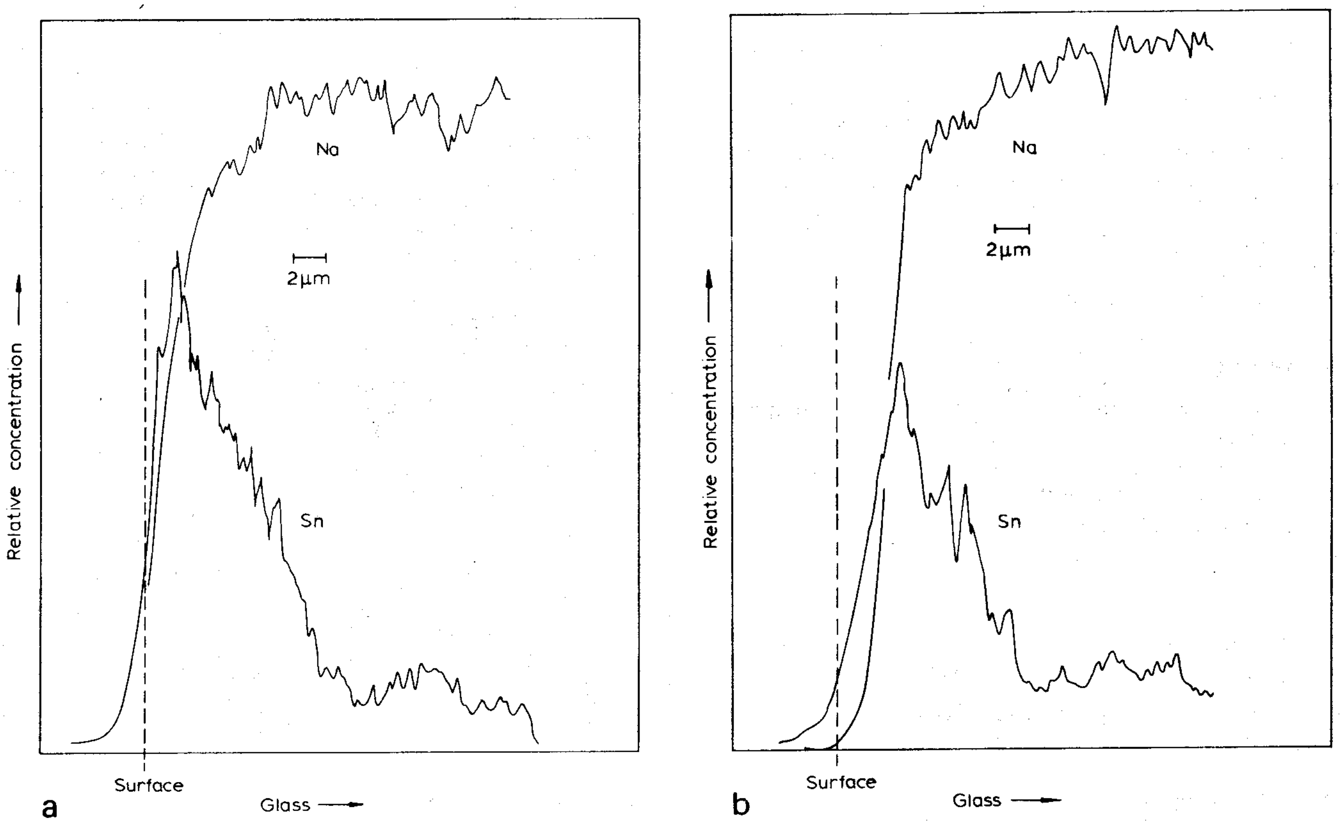

Fig. 1 Tin and sodium concentration profiles in float glasses obtained by electron probe microanalyzer. a — As-received; b — Heat-treated (680°C for 10 minutes)

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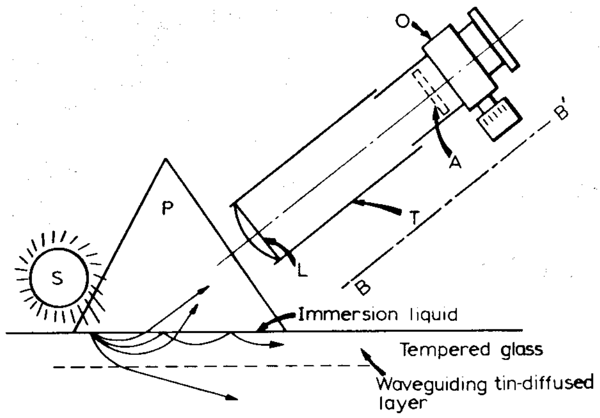

Fig. 2 Experimental arrangement where P — high-index glass prism; S — Na-discharge lamp; T — telescope; L — objective lens (f = 40 cm) of telescope T; O — ocular micrometer (×10); A — rotatable analyzer (when necessary)

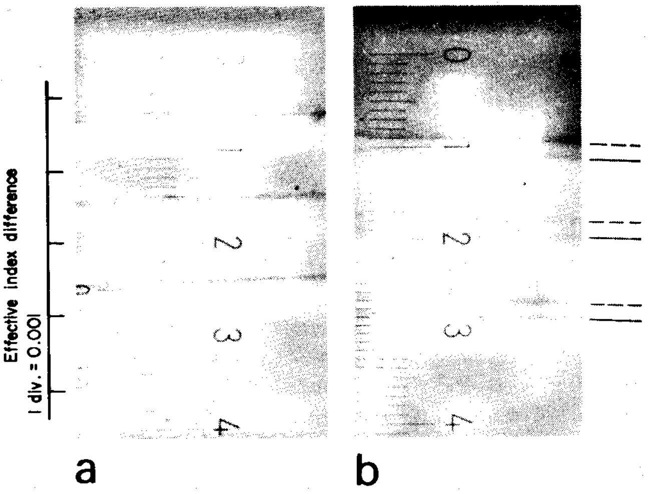

Fig. 3 Patterns obtained by ordinary light. a — as-received glass; b — blast-quenched float glass.
——: TM modes, -----: TE modes

Thermally-tempered glasses are widely used in automobile and building industries. Surface stress directly influences mechanical strength of the tempered glass. Non-destructive and rapid determination of surface stress is important for tempered glass quality and process controls. The waveguide effect is an excellent means of determining this.

Apparatus

The prism shown in Fig. 2 behaves as both an input and an output prism. Optical contacts are realized by liquid between the prism and tempered glass. Some of the monochromatic light injected in the tin-diffused layer forms propagation modes and flows along the layer. Other parts go along mirage paths and come back out of the layer. A telescope forms a pattern with dark fringes in the view field, which correspond to the flow-away modes. A rotatable analyzer may be used, if necessary, to allow pattern observation by TM and TE waves.

When the telescope is placed along BB′ axis (Fig. 2), a bright fringe pattern by 'flown-away and arrived' modes can be observed (see Appendix). The pattern is an exact inversion of the dark fringe pattern.

The author believes that the phenomenon should be understood based on the Maxwell electromagnetic wave equations with given boundary conditions. However the rough explanation described above is still reasonable and useful for practical application.

Experimental results

A float glass plate gave the pattern shown in Fig. 3a. Fringes by TM and TE modes coincided with each other, because surface stress was very low.[3] After air-blast quenching on a laboratory scale at 610°C, each fringe split into two fringes by TM and TE modes (Fig. 3b). Surface stress was estimated[2] to be 11 kg mm^{-2} (108 MPa).

Heating at higher temperature did not affect the tin distribution (Fig. 1b). Surface deformation, however, often

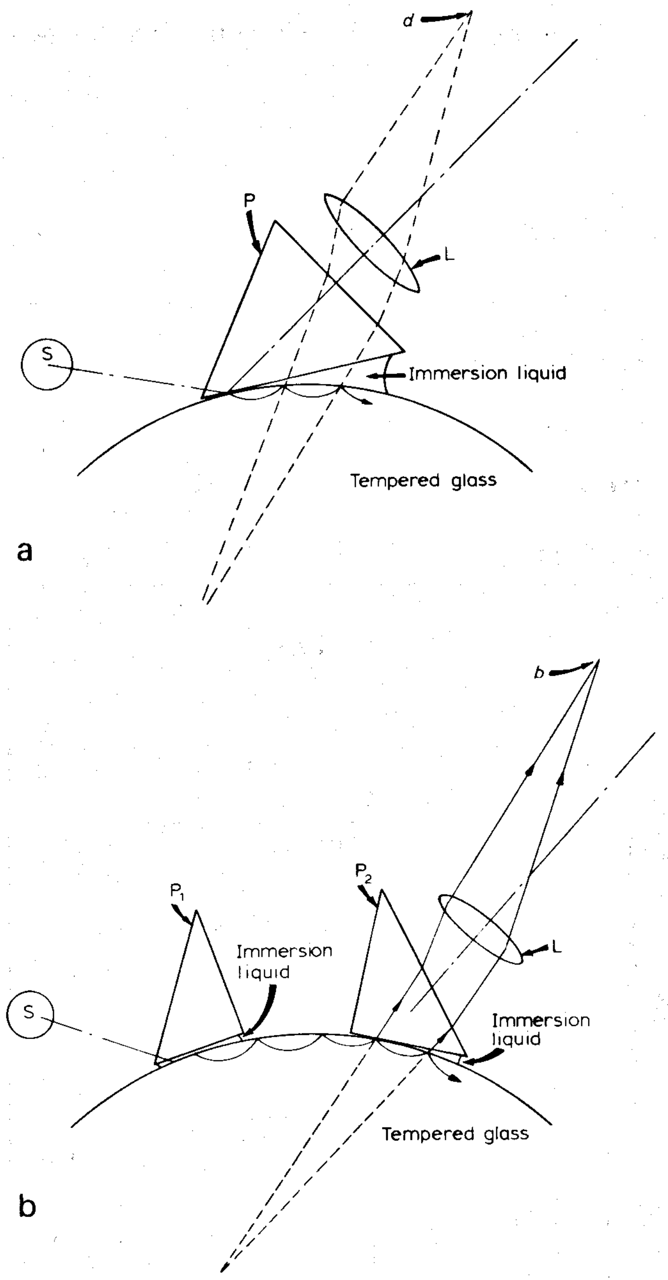

Fig. 4 Optical arrangements for observing a — dark and b — bright fringe patterns formed by curved glass surface. Focal length of the objective lens is selected depending on the radius of curvature of the surface.
P_1 — input prism; P_2 — output prism; d — dark fringe; b — bright fringe, (other letters as in Fig. 2)

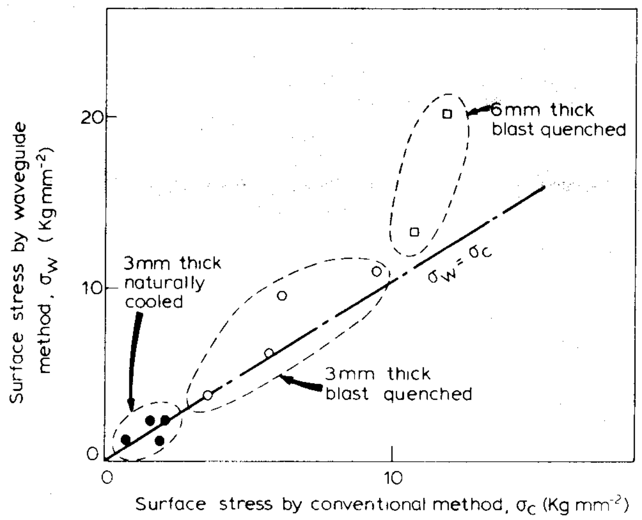

Fig. 5 Comparison between surface stress values determined by the conventional (horizontal axis) and the waveguide (vertical axis) methods

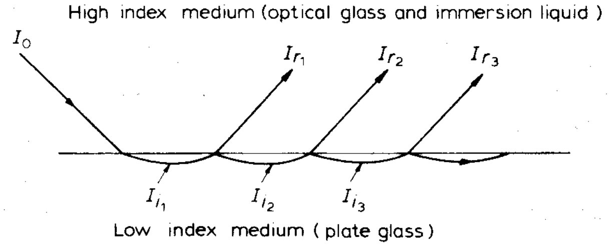

Fig. 6 Model demonstrating the 'flow-away' mode

made fringe patterns obscure. Using the special optical arrangement[4] shown in Fig. 4, stress evaluation of curved surfaces was still possible.

The float glass was cut into pieces 25 x 25 mm in size. These were blast-quenched after heating in a temperature range between 600-700°C. For such small pieces, surface stress determination by conventional methods[5] was possible – surface stress was estimated by measuring the photoelastic retardation of light which passed through the central layers of the pieces.

Surface stresses obtained by conventional and waveguide methods were compared in Fig. 5. The waveguide method gave values similar to or slightly higher than values obtained by the conventional method. The difference seemed reasonable, because the conventional method gives an average stress value while the waveguide methods gives a local stress value.

Conclusion

The optical waveguide effect of float glass is an excellent monitor for surface stress determination of thermally-tempered glass. Non-destructive and rapid determination is possible, using a simple apparatus. The apparatus is applicable to both thermally-tempered and chemically-tempered[2] glasses, and to both flat and curved[4] glasses. The apparatus is now used in all of the Japanese plate glass manufacturers. facturers.

Acknowledgements

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Appendix

The 'flow away' mode can be explained as follows (Fig. 6) injection of light from high index ($n = 1.75$) medium to low index ($n = 1.55$) medium is possible; $1 > I_{i_1}/I_0 \gg 0$. After injection, light can propagate in spite of the attenuation caused by refraction;
$1 > I_{i_2}/I_{i_1} = I_{i_3}/I_{i_2} = \ldots\ldots > 0$.

Refracted light $I_{r_1}, I_{r_2}, \ldots\ldots$ can form a bright fringe in a telescope, which is an exact inversion of the dark fringe pattern shown in Fig. 3.