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On non-destructive residual stress measurement in glass panels*

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Abstract. A portable scattered light polariscope SCALP has been developed, which permits measurement of the residual stress profile through the thickness of glass panels. At a glass factory strength assessment of glass panels of different thermal treatment was carried out using both residual stress measurement with SCALP and the traditional four-point bending tests. Linear correlation between the residual surface stress and the bending strength was observed. At another glass factory residual stress in glass panels was measured before performing the traditional fragmentation test. The results of the fragmentation test were extremely scattered and had almost no correlation with the values of the residual stress. It is concluded that sufficiently reliable assessment of the strength of glass panels is obtained by measuring the residual stress at the surface.

Key words: glass, residual stress, photoelastic measurements, quality control.

1. INTRODUCTION

According to the European Standard EN 12150-2:2004, to establish if a product conforms to the definition of thermally toughened soda lime silicate safety glass, initial type testing shall consist of a) mechanical strength measurement and b) fragmentation test, in accordance with EN 12150-1:2000. Thus European standards prescribe application of the four-point bending test and the

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fragmentation test. Both of these tests are destructive, time-consuming and expensive.

At the same time, during recent years photoelastic residual stress measurement methods have been considerably developed and applied. In [1] data is described about testing of 360 glass panels by first measuring the residual surface stress with the surface polariscope GASP* [2]. Paper [1] shows that a good correlation exists between surface compressive stress data and mechanical strength according to EN 1288-3 (Fig. 1). Similar results have been obtained by several other authors [3–5].

In a somewhat simplified form the relationship between the bending strength σ_{bs} and surface stress σ_{sf} can be expressed as

$$\sigma_{\mathrm{bs}} = \sigma_{\mathrm{a}} + k\sigma_{\mathrm{sf}}, \tag{1}$$

where σ_{a} is the strength of the annealed float glass and k is an empirical coefficient ($k \cong 1$). Since σ_{a} is known, measurement of the surface residual stress determines the bending strength of the glass.

At the same time, when GASP permits measurement of the surface stress at the tin side of glass panels [2], the scattered light polariscope SCALP permits measurement of the stress profile through the panel thickness. The value of the tensile residual stress in the midsurface of the panel determines the character of the breaking of the panel.

This paper gives a brief description of the portable polariscope SCALP and some measurement results, which are compared with the four-point bending test and fragmentation test. Together with the long-time experience of surface stress measurement with GASP these results lead to the proposal to accept residual stress measurement in glass panels as the basic non-destructive method for the assessment of their strength.

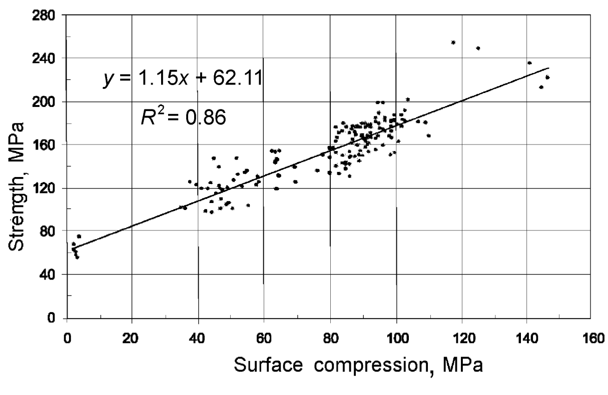

Fig. 1. Relationship between the surface compression and strength of clear float glass specimens (from [1], courtesy of GPD 2005); $y = f(x)$ is the regression equation.

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* GASP is a registered trademark of Strainoptics Technologies, Inc.

2. SCATTERED LIGHT POLARISCOPE SCALP

Scattered light polariscopes for residual stress measurement in glass have been developed by several authors [6,7]. However, these polariscopes are complicated devices, which can be used only in laboratory conditions and can not be used in factory conditions near the production line.

For industrial applications a portable scattered light polariscope SCALP* has been developed at GlasStress Ltd. [8]. Optical measurement schema and photo of the polariscope SCALP is shown in Fig. 2. A laser beam is passed through the panel under an angle about 45°. Stress birefringence changes the polarisation of the laser beam. These changes are recorded by measuring with a CCD camera the variation of the intensity of the scattered light along the laser beam. From this measurement data stress profile through the panel thickness is determined.

The polariscope SCALP is calibrated with the four-point bending test. Since it has no moving parts, no additional calibration is needed. The polariscope is automatic, stress profile measurement time is about 10 s.

If the residual stress state is isotropic $(\sigma_1 = \sigma_2)$ then measurements in one position of the device is sufficient. If $\sigma_1 \neq \sigma_2$, measurements in two perpendicular to each other positions of the device, parallel to the principal stress directions, are needed. Figure 3 shows an example of principal stress profiles through the thickness of a tempered glass panel. In the general case measurements in three directions (0°, +45°, –45°) permit measurement of the principal stress directions and their profiles through the panel thickness.

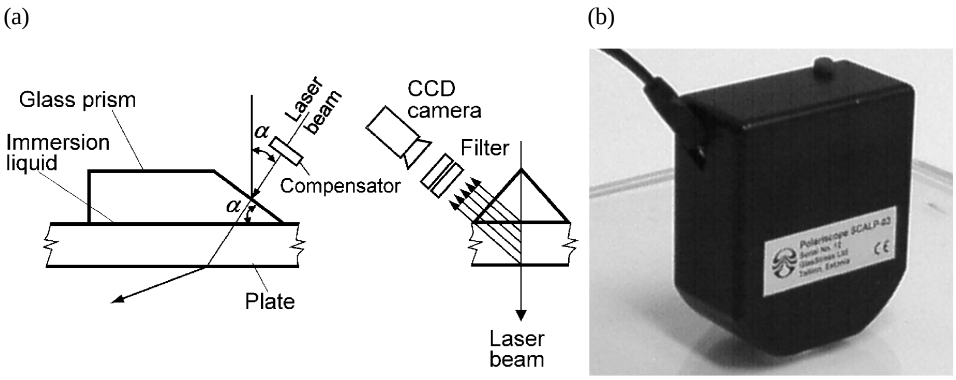

Fig. 2. Optical measurement schema (a) and photo (b) of the portable scattered light polariscope SCALP-04.

* SCALP is a registered trademark of GlasStress Ltd.

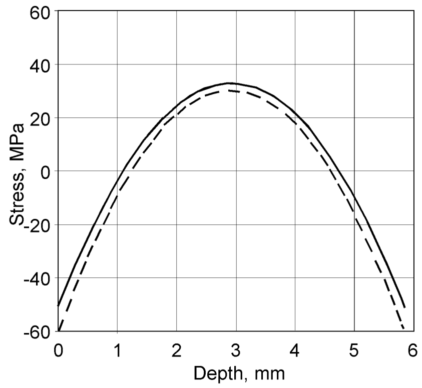

Fig. 3. Principal stress profiles through the panel thickness at a point on the symmetry axis of a tempered glass panel: (—) σ_1, (– – –) σ_2.

3. FOUR-POINT BENDING TESTS

At a glass factory, 16 glass panels were tested by four-point bending according to EN 1288-3:2000. The thickness of the panels was 6 mm and dimensions 360×110 mm. One panel was of annealed glass, 5 were heat-strengthened, 5 were fully tempered and 5 were of safety glass (Table 1).

Before the bending test, residual stress at the surface on the tin side was measured with SCALP. The results are shown in Table 1 and in Fig. 4.

Table 1. Results of the four-point bending stress

No. of the panel	Thermal treatment	Surface stress σ_{sf}, MPa	Bending strength σ_{bs}, MPa
	Annealed		
1		−7.0	52.9
	Heat-strengthened		
2		−61.3	116.3
3		−61.3	108.2
4		−60.7	118.2
5		−64.0	137.3
6		−61.8	121.4
	Fully tempered		
7		−119.7	184.9
8		−120.3	184.7
9		−121.7	186.6
10		−120.6	176.9
11		−121.0	182.3
	Safety glass		
12		−157.1	221.0
13		−157.9	192.3
14		−158.0	218.5
15		−157.2	228.6
16		−157.1	200.7

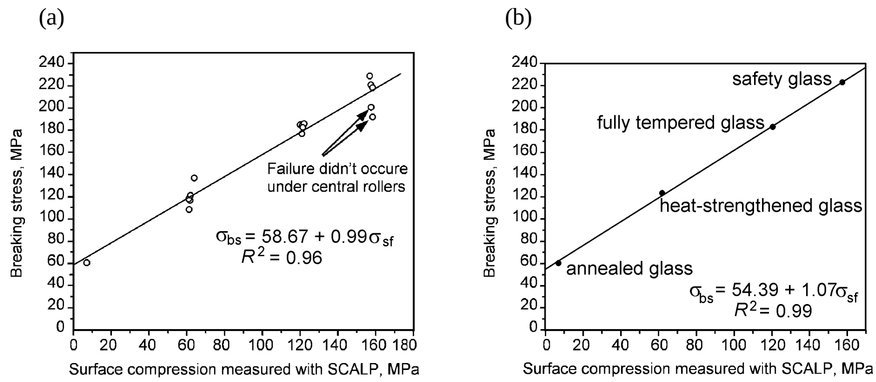

Fig. 4. Bending strength (breaking stress) *vs* residual surface stress in glass panels: (a) all data points, (b) averaged for each kind of thermal treatment.

Scattering of the breaking test values in Fig. 4a is normal for such kind of test. At the same time, Fig. 4b shows that surface compression gives reliable value for the average breaking stress.

4. FRAGMENTATION TESTS

At another glass factory, 7 panels of different kind of glasses but of the same thermal treatment were investigated, first measuring the surface stress and after that making the fragmentation test according to EN 12150-1:2000. The results are shown in Table 2. They confirm that almost no correlation exists between the residual stress and the number of fragments. This fact is still more convincingly demonstrated in Fig. 5, where data of other fragmentation tests are shown for glass panels of different thickness but of the same thermal treatment.

From Table 2 it follows that while the number of fragments of panels of the same thermal treatment varies more than twice (from 58 to 126), the surface residual stress varies only for 6 percent (from 106 to 121 MPa).

Table 2. Results of the fragmentation tests

No.	Glass	Surface stress, MPa	Number of fragments	Longest fragment, mm
1	Sunergy Clear	−106	58	28
2	Grey	−108	71	28
3	Bronze	−105	76	26
4	Clear	−121	83	19
5	Stopsol Supersilver Clear	−115	96	17
6	Stopsol Supersilver Gray	−115	104	
7	Normal	−112	126	13

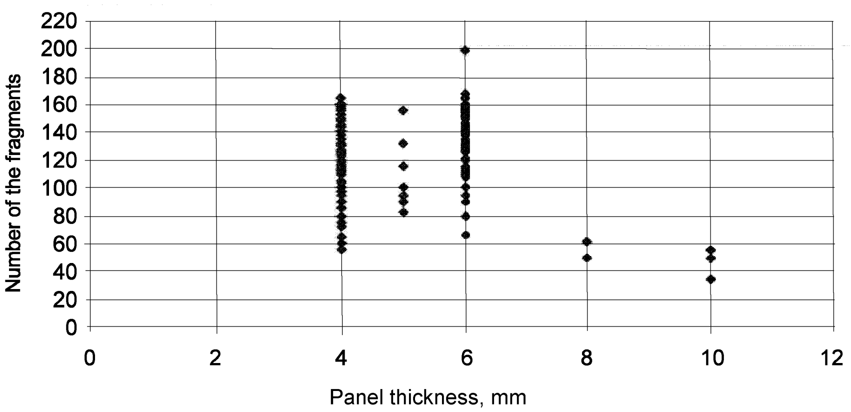

Fig. 5. Results of fragmentation tests with panels of similar thermal treatment and different thickness.

Thus the fragmentation test results can be used only as a rough indicator of the fact that the glass panel has been thermally treated. It does not allow to make any conclusions about the value of the tempering stresses in the panel.

5. CONCLUSIONS

1. Several companies manufacture photoelastic devices either for surface stress or complete stress measurement in tempered glass panels.
2. By several authors linear relationship between the residual stress and bending strength of glass panels has been established.
3. If further investigations confirm the established relationship between the value of the residual stress and the bending strength, it may be possible to reconsider the existing glass quality assessment standards and to replace destructive four-point bending test and fragmentation test by non-destructive residual stress measurement in glass panels. Already publications [1–5,9] speak in favour of this proposal.
4. Although only testing of architectural glass panels has been considered in this paper, the conclusions apply also to automotive glazing.

ACKNOWLEDGEMENT

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Jääkpingete mittepurustav määramine klaaspaneelides

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On välja töötatud portatiivne hajunud valguse meetodi polariskoop SCALP jääkpingete profiili mõõtmiseks klaaspaneelides. Erineva termilise töötlusega klaaspaneelide tugevuse hindamiseks mõõdeti ühes klaasitehases klaaspaneelide jääkpinged, mille järel määrati paneelide tugevus nelja punkti paindekatsel. Seos jääkpingete ja tugevuse vahel osutus lineaarseks. Ühes teises klaasitehases võrreldi eelnevalt mõõdetud jääkpingeid klaaspaneelides fragmenteerimiskatse tulemustega, mis olid väga hajuvad ja jääkpingetest praktiliselt sõltumatud. Tööst järeldub, et kõige usaldusväärsem on hinnata klaaspaneelide tugevust klaasi pinnal mõõdetud jääkpingete põhjal.