

Measuring stress in glass production: a key quality control operation

Since glass is a brittle material, most of its failures occur at minute defects/discontinuities, located in areas where tensile residual stresses introduced in manufacturing are present. Quality control of glass product must eliminate these potential failures, and ensure that annealed glass does not contain residual stresses above a specified level or that a heat-strengthened glass contains a protective layer of compressive stress. The product specifications must also clearly define the desired stress levels.

As an example, ASTM¹ C1048 requires that a heat-strengthened glass must exhibit a surface-compression between 3500 and 10000psi, or an edge compression greater than 5500psi, and a fully tempered glass must exhibit an edge and surface compression that is no less than 10000psi.

The glass-tempering and heat strengthening is a broadly used practice, not only in flat glass products, but also increasingly in the tableware, container and pressed-glass industry.

Whether the product is designed and specified as annealed or tempered,

measuring of the residual stress is a fundamental quality control operation, needed to ensure the product conformance.

Since glass is transparent the measuring of residual stress is not only possible but reasonably straightforward, using photoelasticity techniques.

Measuring stress using the photoelastic principle

The principle of photoelasticity are well-known, and used for measuring residual stresses in all transparent materials. The optical schematic is illustrated in the Figure 1.

Stressed glass becomes birefringent. A polarised light beam propagates at different speed along principal stresses S_1 and S_2 . After crossing a thickness t , the fast and slow beams are separated by a distance R (called retardation) that is related to the difference of principal stresses:

$$S = S_1 - S_2 \text{ by}$$
$$R = S \times t \times C_B$$

Measuring of residual stresses needed to improve quality and eliminate costly breakage. This article discusses ways to improve the reliability of visual inspection processes. Also, PC-based methods are shown and their merits discussed.

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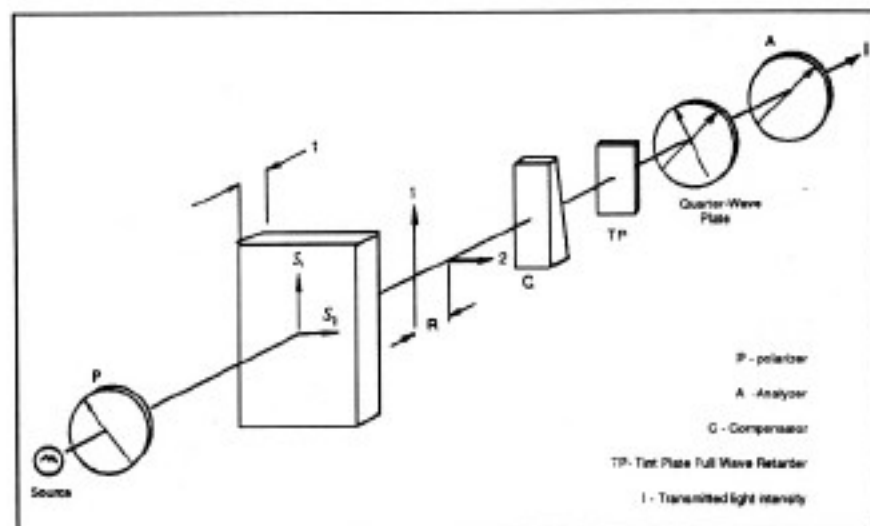


Figure 1. Light propagation in a polarimeter.

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Glass type	Brewster constant C_B $10^{-12} \text{m}^2/\text{N}$	Fringe constant psi-in/fringe
Soda lime	2.55	1270
Zerodur	5	1080
Borosilicate	3.8	850
Aluminosilicate	2.6	1250
60% PbO	2	1600

Table 1. Stressoptic material constants.

Colour observed in dark field polariscope	Retardation R(nm)	Fringe order	Colour observed using a full-wave retarder	
			Fringe order	Retardation R(nm)
Black	0	0	-1	-565
Grey	150			-415
White-yellow	250			-315
Yellow	300	.5	-5	-265
Orange (dark yellow)	450			-115
Red	500			-65
Indigo-violet (1st order fringe)	565	1	0	0
Blue	600			35
Blue-green	650			85
Green-yellow	750			185
Yellow	850	1.5	.5	285
Orange (dark yellow)	950			385
Red	1050			485
Indigo-violet (second order fringe)	1130	2	1	565
Green	1300			735
Green-yellow	1400			835
Pink	1500			935
Violet (third order fringe)	1695	3	2	1130
Green	1750			1185

Table 2. Colour sequence observed versus retardation values.

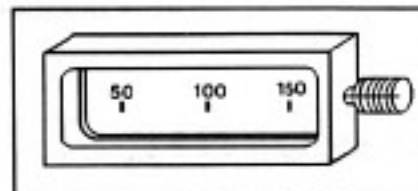
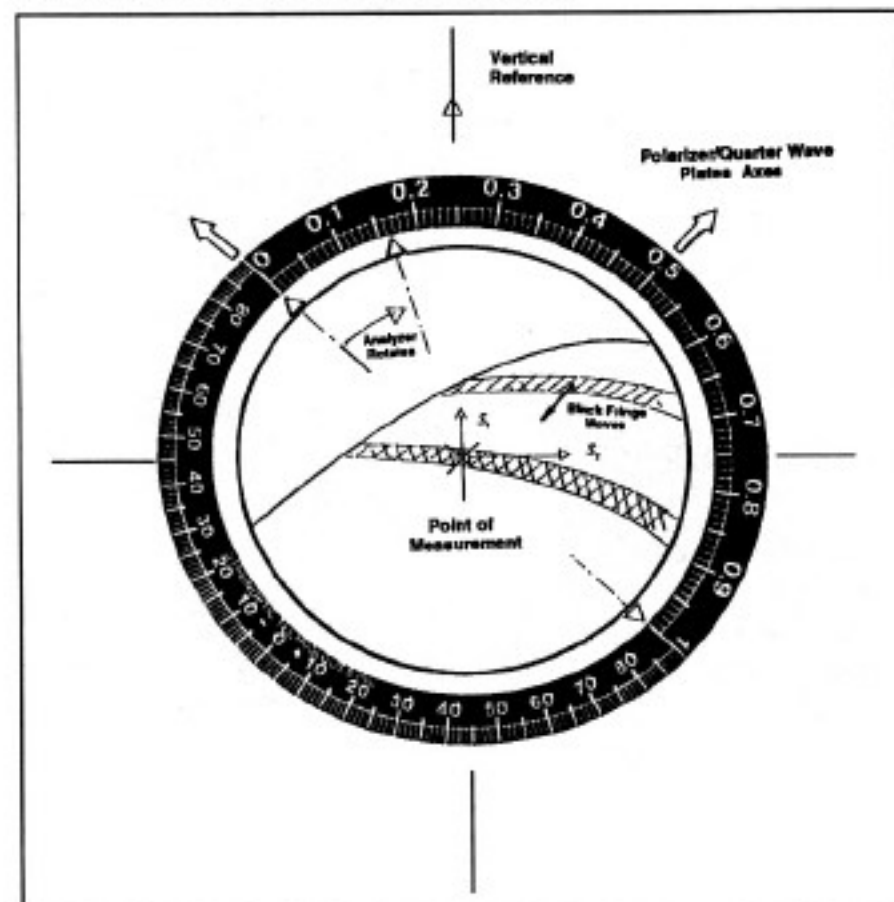


Figure 2. Calibrated reference gauge.

where C_B is a material stress constant (also known as Brewster constant), and t is the thickness of material.

Using visual or automated methods described below, one measures the retardation Rt , and calculates the stress:

$$S = \frac{Rt}{t} C_B$$

Table 1 lists the material constant C_B for some commonly used glass materials.

Measuring stress using visual methods a colour chart

In the simplest approach one visually observes the stress pattern. When a sample exhibiting stress is placed in a polariscope, a pattern of various colours appears. An experienced operator uses a colour chart (Table 2) to evaluate the retardation, from the observed colours.

This chart can be used effectively when:

- The retardation is small (annealed glass)
- At the investigated location, the specimen stress is properly aligned with the axis of the polarimeter
- Only qualitative information is desired, and
- The operator is properly trained and experienced.

The reliability of the visual evaluation can be greatly improved, when instead of written description of a colour a calibrated reference standard is used. The reference gauge, shown in Figure 2, is placed in the polariscope alongside with the observed specimen.

The operator no longer needs to judge the observed colour, or rely on his or her colour memory. Now, the operator simply matches the observed pattern to the gauge colour. The reference standard is also a valuable tool and should be used in operators training.

Analyser rotation method (Senarmont)

The method permits quantitative measurement of retardation. The principle is illustrated in Figure 3. A rotation α of the analyser will move the black

Figure 3. Principle of the analyser rotation method.



Figure 4a. Measuring of edge stress in tempered glass using a DW compensator.



Figure 4b. Measuring surface stress using a quartz wedge (GASP).

fringe (zero order) to a new location where the retardation is:

$$R = \% \cdot d$$

The fraction $\%$ is called a fractional fringe order N . The practice of this method¹ requires a careful aligning of all elements, as shown in Figure 5. The direction of the measured stress must be at 45° to the orientation of the polariser/analyser axis P, A .

Only a highly trained operator should attempt to use this method since the black fringe moving to the POI continuously changes its colour. Also the interpretation of a sign based on colour sequence requires extensive experience.

The sensitivity of this method can be greatly enhanced by placing of a tint plate in the field of view. Here again a calibrated reference gauge placed

alongside with the specimen helps the operator training and eliminates judgement errors occurring in deciding whether the fringe effectively crossed a point.

Compensators^{3,4}

The compensator operation is simple, the operator moves the quartz wedge until a black fringe is observed at the point of measuring (Figure 4a and 4b), and reads the position of the wedge on a counter or on a visible scale. Even an inexperienced operator can obtain accurate readings after some minimal training. The compensator must be calibrated using monochromatic light.

PC-based instruments

The reliance on visual observation of colours clearly limits the precision,

speed and reliability of inspection. In the present technological environment, where the emphasis on quality of the product and reliability of inspection procedure is very high, one must look into the more objective and accurate alternatives.

Two PC-based methods are now available:

- Full-field observation, using digital image analysis, and
- Stress-scanners, using spectral analyser.

The digital image analysis systems (DIAS) (shown in Figure 5) uses a CCD camera and a PC-mounted digitising board, capable to acquire the image on an array of 512×512 points. The software, that is customised to the user's need, permits to perform the required quality control operation. The inspected item is placed visually or mechanically in the field of view, and the image is acquired.

The result of the inspection permits typically the following results:

- Maximum stress within the inspection area, and its location
- Stress profile along the selected inspection line
- Full field inspection of stress, displayed in isobars (pseudo colours), and
- Reject warning DIAS method is mostly used for inspection of annealed products. Out in some applications, heat-strengthened glass can also be inspected.

The stress scanners are based on the spectral contents analysis (SCA) approach. These instruments (Figure 6) can measure stress at a point very accurately (resolution is 1mm) and very fast,

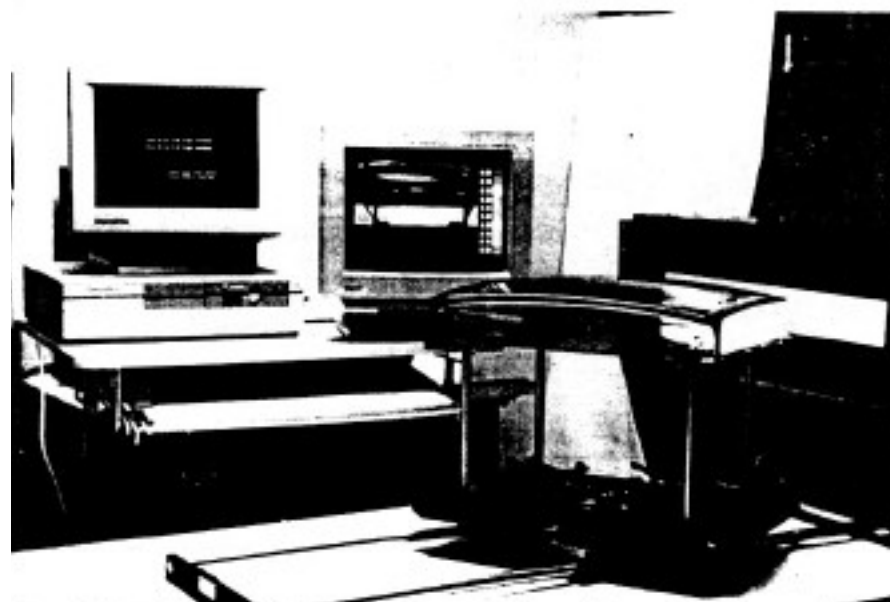


Figure 5. Digital image analysis system for inspection of panels.

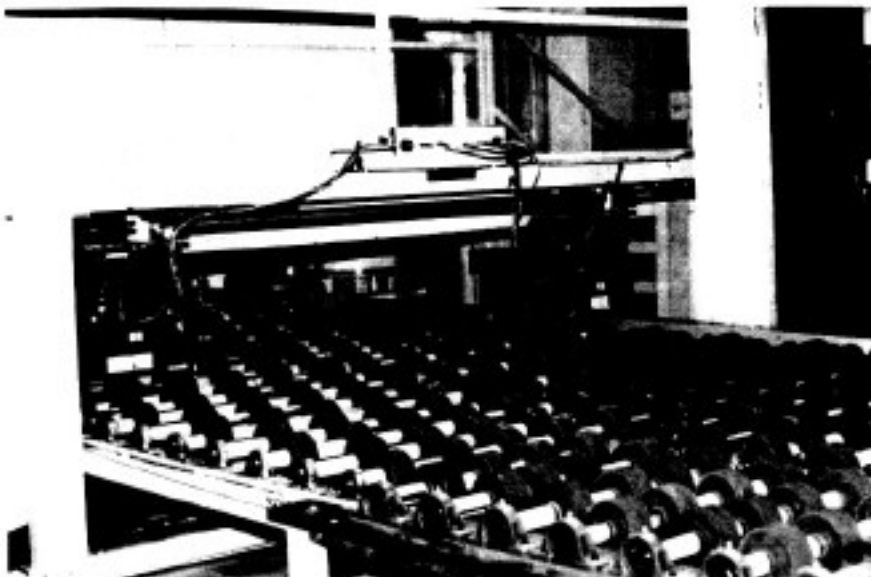


Figure 6. SCA stress-scanner for "on line" inspection of tempered glass.

at a rate exceeding a 1000 points a minute.

In some installations, while the product moves, the data is acquired, and the results are displayed as a numerical data

(maximum stress) or as a graph.

Application of stress scanners include production of float-glass, tempered and heat-strengthened glass, inspection of optical glass and optical glass products,

where the sensitivity of visual inspection is insufficient.

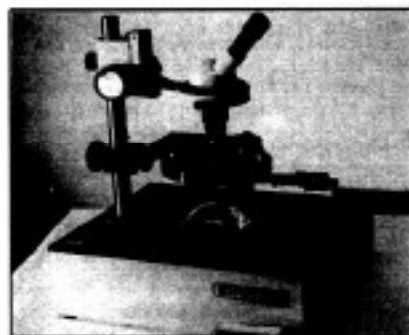
Conclusions

The measuring approaches discussed in this article are extensively used in the industry. Clearly, the instruments using visual methods are least expensive, but require the highest skill level, and operator's training.

The high labour cost of the inspection can be only reduced by extensive use of a PC-based system, that offers the advantage of on-line control, objectivity and reliability. □

References

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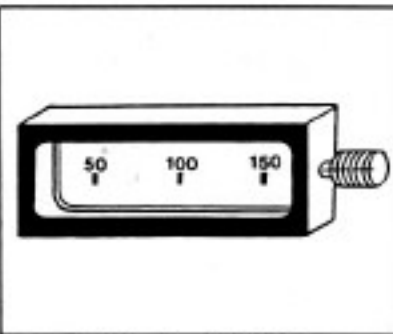
STRESS MEASURING INSTRUMENTS FOR THE GLASS INDUSTRY



On-line Stress Scanners SCA 1-500



Surface & Edges Stress Meters GASP & GES 100



Calibration/Training Standards