On–Line Measurement of Stresses and Optical Distortion for QC of Tempered Glass.

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Keywords

1 = Tempering 2 = Process control 3 = Stresses 4 = Optical Quality

Poster 15

Abstract

Modern tempering furnaces are equipped with controls to adjust temperature and air pressure settings to achieve the desired pre-stress levels. To accomplish this objective, operators use their experience and a trial and error approach. The adjustments are verified using OFF-LINE surface-stress measurements or fragmentation testing, both time consuming and costly.

A newly developed sensor installed at the exit of the tempering furnace yields ON-LINE, real-time measurement of pre-stress levels as each lite emerges from the furnace. The system is based on Spectral Contents Analysis (SCA) technology, broadly used for float line stress scanning. Newly developed hardware and software permits higher data acquisition speed to obtain real-time measurements of pre-stress in tempered glass.

In addition to the new stress measuring system, a new non-contacting sensor measuring optical distortion caused by roll wave was developed for installation and operation in conjunction with the stress sensor. Roll waves are surface waves introduced in the tempering process which introduces optical distortion of reflected images in architectural glass.

This new measuring system is PC-based, non-contacting and can be installed ON- or OFF-LINE. The combination of stress and distortion measurements permits an optimum production control level, eliminating roller wave while maintaining stress levels compatible with specifications.

Introduction – Why ON-LINE Stress Control is a “Must” in Production of Tempered Glass

Tempering of glass is a “VALUE ADDED” business, whereby the tempering furnace operator transforms a low cost float glass into a better, stronger and higher priced tempered glass by adding to it a layer of compressive stresses on surfaces and edges. The profitability is strictly related to the ability of the furnace operator to introduce stresses on these surfaces at a lowest possible cost, assuring at the same time the quality and conformance to standards and specifications.

Until now – the output of the tempering furnace was traditionally controlled OFF-LINE by fragmentation testing in production of “Safety” glass, and by measurements of residual stresses in production of Fully-Tempered and Heat-Strengthened glass.

Both OFF-LINE Quality Control methods are needed to assure the conformance to the specs. Both concepts, however, are expensive in their implementation and do not offer the timely feedback needed in process control.

The fragmentation test is destructive. Not only is it the most expensive procedure, it usually leads to excessively high residual stress, poor optical quality, and a high risk of spontaneous breakage. There is no assurance that tempering is uniform within the width of the furnace, consistent from one batch to the next, or stable with time. The prescribed frequency, typically one test per lot, is extremely costly or simply prohibitive when producing small lots. But the most significant problems appear during set-up, after a change of thickness or temper when several fragmentation tests are needed before a steady stress level is reached. While the fragmentation test at this time is mandatory in the production of Safety Glass, it offers no information or valid test results in the production of Heat-Strengthened glass.

The Non-Destructive Test (NDT) measures the surface compression using GASP® surface polarimeter or edge compression in transmitted light using a GES™ Edge Stress Meter. The ASTM test method C1279 [1] offers an excellent guidance on these procedures. The GASP Grazing-Angle Surface Polarimeter measures the surface compression directly, yielding an accurate quantitative test result. This test must be performed OFF-LINE by a qualified operator. Since a liquid contact between the instrument and the sample is required, this test cannot be implemented ON-LINE.

Measuring of the edge stress is presently handled using visual equipment requiring a laborious extrapolation of data acquired near the edges, resulting in a high labor cost. This method, however, is non-contacting and is adaptable to ON-LINE use. A newly developed, high-speed data acquisition system based on a patented and proven optical technology can easily be used ON-LINE, mounted at the exit from a tempering furnace.

European and US Specifications

The newly introduced CE standards define architectural Tempered and Heat Strengthened glass, [2] specifying a mandatory test shown in the summary Table 1.

The strength requirements are clearly outlined, but the choice of prestress measuring approach and the experimental correlation between the strength and the measured stress is left to the user’s discretion.

The ASTM specification C 1048-97b clearly defines the surface and edge stress level, as shown in the Table 2, but fails to indicate the required frequency, leading to possible problems and litigation.

Table 1.
European Standards prEN 1863 and prEN 12120

Specifications for Heat-Strengthened And Tempered Architectural Glass		
	Heat-Strengthened	Tempered Safety
Definitions	Residual Stress	Residual Stress
	Increased Strength	Increased Strength
	Fragmentation	Fragmentation
Mechanical Prop.	Mandatory	Mandatory
Strength	70 MPa (10,000 psi)	100 MPa (14,500 psi)
Test Method	4-point Bending	4-point Bending
Res. Stress NDT	GASP	GASP
Test Frequency	1 test/batch	1 test/batch
Flatness	0.3 mm/300 mm (130 mdpt)	0.5 mm/300 mm (220 mdpt)

Measuring of edge-stress is only specified for Fully Tempered glass, but reintroduction of the edge stress specification for Heat-Strengthened glass is presently under study.

Considering that the strength in bending is approximately a sum of the strength of annealed glass and temper prestress, the US and CE standard are in reasonably good agreement.

The experimental correlation between the fragmentation parameters surface and edge stress was established by several investigators. In particular, S. W. Joehlin [4] demonstrated that the break-pattern cannot be correlated to surface compression or to the strength for Heat-Strengthened glass, but for Safety glass, the particle size in fragmentation testing can be reliably predicted from the measured residual stress. The figure 1 below originally developed by Jacobs [3] shows the prestress levels needed to assure the desired break pattern.

In the presence of defects or inclusions, "spontaneous" fragmentation could occur whenever the combined effect of mid-plane tension, defect size, and externally induced stress reaches a critical level. For this reason, inclusion and an upper limit for the temper is highly desirable.

Development of the SCA Edge-Stress Measuring Method and Software

The operating principle of the Spectral Contents Analysis based SCA-1500 system [5] is based on measuring light intensity at several wavelengths. The transmitted light acquires a retardation δ, related to the stress S at the point of measurement.

$$\delta = t \times C \times S \qquad \text{[eq. 1]}$$

In eq. 1, t is the thickness and C is the material Stress Constant.

$$I = I_0 \sin \pi\delta / \lambda \qquad \text{[eq. 2]}$$

The light transmittance I/I_0 becomes a function of stress and of the wavelength λ.

Using a spectrophotometer, the light intensity I_i is measured at several wavelengths λ_i providing a set of simultaneous equations sufficient to retrieve the retardation R and compute stress. The basic principles and applications of this method are extensively documented in several publications. The system schematic Figure 2 illustrates the light path and information flow.

The design of the spectrophotometer and selection of the spectral range, determines the speed of data-acquisition, resolution and maximum range of measured stress. At the edge of tempered glass 10 mm thick and prestressed to 100 MPa, the measured retardation becomes 2,500 nm (in excess of 4 fringe orders). The SCA based system is capable of measuring retardation in excess of 8,000 nm.

The resolution of retardation measurement is 1 nm, needed for measuring low stress in annealed and HS glass. A typical edge stress scan obtained along a line perpendicular to the edge is shown in Figure 3.

Table 2.
ASTM C1048-97b

	Surface Compression	Edge Compression (3)	Optical (5) Distortion
Annealed (4)	< 400 psi	300 – 900	N/A
H-S (1)	3500 - 7500	3500 – 7500	N/A
F-T (1)	> 10,000	> 9600	< 85 mdpt
Safety (2)	15,000 – 22,000	15,000 – 22,000	< 85 mdpt

(1) ASTM C1048-97b. (2) Safety glass is defined by ANSI 2.91.1 and automotive industry standards specifying fracturing in small fragments with a max. particle weight or size. (3) The edge compression levels indicated are measured in accordance with ASTM C1279. (4) ASTM C158-95. (5) GANA Roll Wave Specification approvals.

Figure 1
Surface compression and fragment size

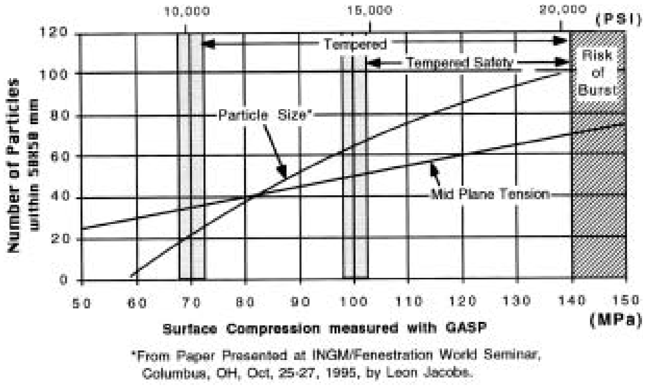


Figure 2.
Schematic of the SCA Measuring System

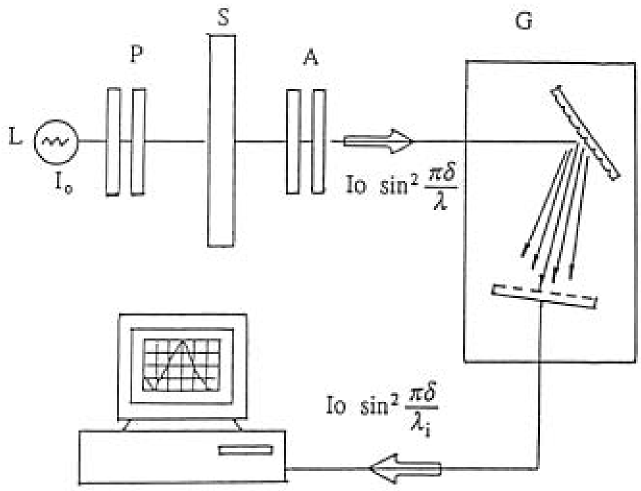
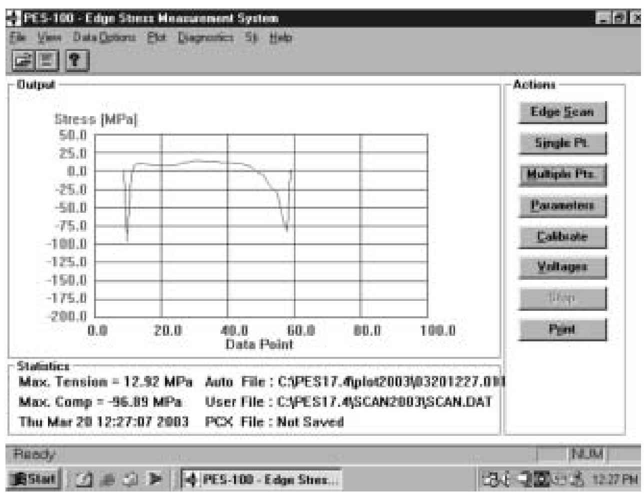


Figure 3.
Edge scan result



The speed of data acquisition was the key software design parameter. Considering the steep stress gradient near the edge, it appears necessary to secure a spatial resolution better than 0.25 mm. Since the glass emerging from the furnace travels at velocities ranging between 100 and 500 mm/sec, a measuring speed of 2000 points/sec is required.

The location of the edge stress measuring had to be refined. In the ASTM test method C1279 edge stress can be measured whenever the depth of the ground edge finish is less than 0.25 mm. When the edge finish depth exceeds 0.25 mm, a linear extrapolation is specified. The software developed for the ON-LINE system automatically detects the depth of the finish and the limits of data validity. The software implements the ASTM linear extrapolation and offers users choice of extrapolation region. In addition, an additive correction algorithm, used in some industries, is incorporated.

The appearance of the information ON SCREEN is shown in figure 4. As the batch emerges from the furnace, the leading and trailing edge-stress for each lite is measured and reported. The operator can see in real time if every item falls between the specification limits, and follows up throughout the production. The system calibration using a built-in traceable retardation standard can be performed with one click of the mouse. Whenever a questionable result is obtained, the complete data file is called, and a detailed graph showing the stress vs. distance from the edge is shown (figure 3). In automated ON-LINE controls, each emerging lite is inspected, generating a data file and numerical output.

Optical Distortion and ON-LINE Measuring of Roll Wave Distortion

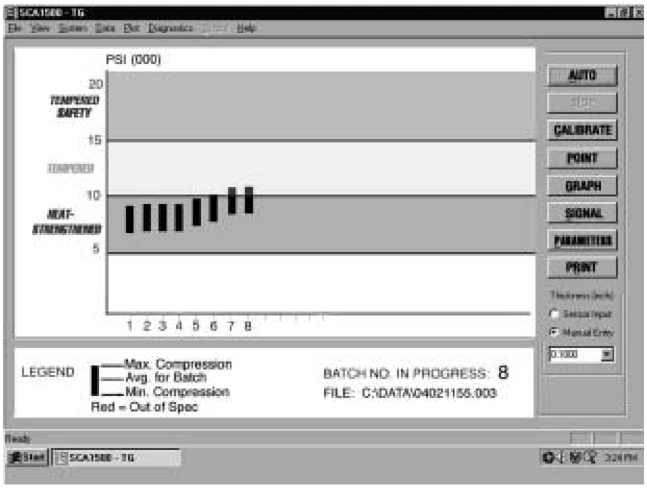
Roll Wave was measured for years using portable depth gages, permitting peak-to-valley measurements of depth W. Newly developed GANA requirements specifies a limitation of Roll Wave created optical distortion, expressed as

$$D = \frac{4\pi^2 W}{L^2} \qquad \text{[eq. 3]}$$

When W is the depth of the wave and L is the wavelength. Strainoptic has developed a non-contacting optical sensor, yielding directly the optical distortion D, that can be installed ON-LINE and provides instantaneous response. The sensor can be installed OFF-LINE or ON-LINE. The PC-based readout, common with the SCA stress measuring system can log the Temper and Roll Wave simultaneously.

Figure 4.

On-Line edge stress control



Summary

A new, stress and optical distortion measuring system for ON-LINE control in production of tempered and Heat-Strengthened glass was developed. The system can be installed at the exit of new or existing tempering furnaces, yielding in real time Edge Compression and Roll-Wave for each emerging lite. Measurements are automated and no presence or attention of the furnace operator is required. The system greatly simplifies furnace control, permits operation at optimum stress level, and thus eliminates the optical distortions due to excessively high temper. The benefits include not only the elimination of rejects and re-tempering resulting from missed targets, but also a substantial reduction in set-up costs.

References

[1] ASTM C1279, "Standard Test Method for Non-Destructive Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened and Fully Tempered Flat Glass," Conshohocken PA, 1994.

[2] European Standards prEN1863 (part 1 and part 2) and prEN 12120 (part 1 and part 2) draft, 9-2000, CEN, rue de Stassart 36, B-1050 Brussels, 2000.

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[5] Redner, A.S., "Photoelastic Measurements by Means of Computer-Assisted Spectral Contents Analysis," Experimental Mechanics 25(2), pp 148-153, June 1985.