EVALUATING STRESSES IN GLASS JOINTS AND SEALS

RESIDUAL STRESS EVALUATION SHOULD BE INCORPORATED INTO QC PROCEDURES TO MINIMIZE FAILURES.

Fused joints between glass components and glass-to-metal seals are routinely designed into many glass products. A broad range of products incorporate glass-to-glass seals, glass-to-metal seals, glass/ ceramic interfaces and decorations, electrical/electronic feed-through wires, support buttons, etc., which combine relatively simple components into complex assemblies. The design of joints is often the result of years of research and experience.

RESIDUAL STRESSES

A three-dimensional state of residual stresses develops in the region surrounding the fused materials. The stress concentration can cause product failures and therefore must be carefully monitored to ensure that the residual stresses do not exceed tolerance limits.

The stress field is highly localized and directly related to differences in the coefficient of thermal expansion (CTE) of the joined parts (α_a- α_b). Materials are considered highly compatible when their CTEs are the same or very similar; otherwise, their response to heating and cooling processes will differ. This difference often results in undesirable residual stresses, which ultimately cause manufacturing problems and product defects. The following material properties will also greatly affect the final state of residual stresses between components:

- Young's Modulus of joined materials,
- Differences in strain points,
- Thermal diffusivity, and
- The pre-existence of residual stresses before the fusion of components.

In industrial processes, fusion heating is supplied in the limited region and temperature gradients contribute to the local thermal stress and temperature as well. Analytical computations of stresses stipulate satisfaction of continuity and equilibrium.

Continuity. Total strains (thermal- and stress-induced) in both joined materials must be the same along the fused interface. A system of residual stresses σ_a and σ_b develops along the interface. Resulting strains ε_a and ε_b in both components (a) and (b) must satisfy the following relationship along the x,y interface:

$$(\alpha_a - \alpha_b)\,\Delta T = (\varepsilon_{x,y})_a - (\varepsilon_{x,y})_b$$

where $\varepsilon_{x,y}$ are in-plane strains in the plane of the fused joint, and ΔT is the difference between the room temperature and strain point.

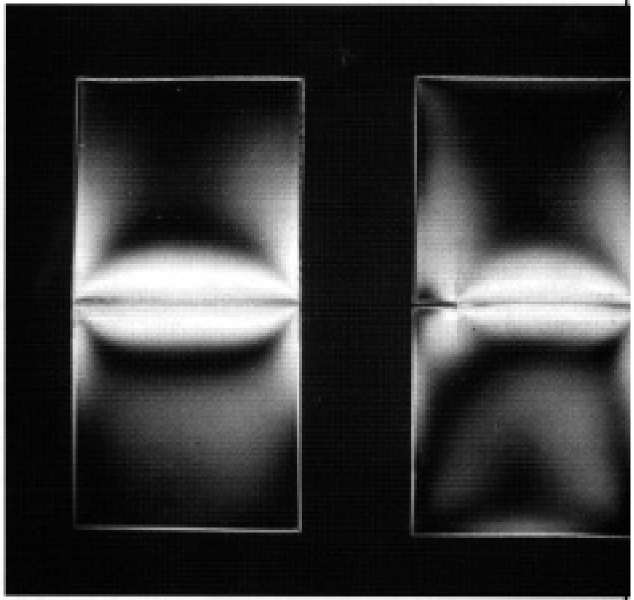

Figure 1. Photoelastic pattern reveals stresses in two glass-to-glass fused joints.

Equilibrium. The state of stress is three-dimensional. In addition to interface strain continuity, the stresses σ_a and σ_b in the fused components must satisfy all equilibrium conditions. In particular, the integrated stress on any cross-section becomes zero.

The stresses along the fused interfaces are not only influenced by the difference in the thermal contraction of the joined materials, α_a and α_b, but also by the geometry of the assembly. The solution of the stress equilibrium equation is only possible for simple

BY ALEX S. REDNER, PRESIDENT & B. HOFFMAN, DIRECTOR OF MARKETING,
STRAINOPTIC TECHNOLOGIES, INC., NORTH WALES, PA.

REPRINTED FROM THE SEPTEMBER 1997 GMT SUPPLEMENT, *CERAMIC INDUSTRY* MAGAZINE

geometries, after making some simplifying assumptions. For any fused configuration, a "shape factor" can be established analytically or experimentally, relating the stresses to the difference in CTE and Young's Modulus E of the fused components.[1,2,3] Examples of "shape factors" are shown in American Society for Testing and Materials (ASTM) test practices, where the measured stresses are related to the difference in their CTE, Young's Modulus, and thickness.

POLARISCOPIC MEASUREMENTS

Figure 1 illustrates the stress pattern that develops in a simple glass-to-glass seal as result of material differences in CTE, viewed using a polariscope. In this illustration, the joined members have a nearly identical Young's Modulus E and the same geometry, which permits a simple computation of the shape factor. In this example:

$$\sigma_a = -\sigma_b = \frac{(\alpha_a - \alpha_b)\Delta TE}{2}$$

Measuring the stress in a simple test joint establishes the difference of CTE $\alpha_a - \alpha_b$, and demonstrates how well the fused materials will combine.

Using polariscopic measurements, a difference in CTE of 10^{-6}/°C can be measured. In Figure 1, the polariscopic fringe pattern reveals stresses along the length of the joint. In a perfect geometry, the stress σ_z and the shear stress σ_{xz} at the edge of the fused joint (see Figure 2) are larger than the stress parallel to the interface σ_x and opposite in sign. The stress concentration factor is affected by the corner imperfections due to:

- offset between fused faces,
- imperfect fusion, and
- bulged face or cement bulge.

When designing products, this fused sample approach is very effective for evaluating material matches. A difference in CTE as small as 0.1 x 10^{-6}/°F between two materials can introduce a residual stress in excess of 500 psi. An excessive stress will cause the seal to crack or fail.

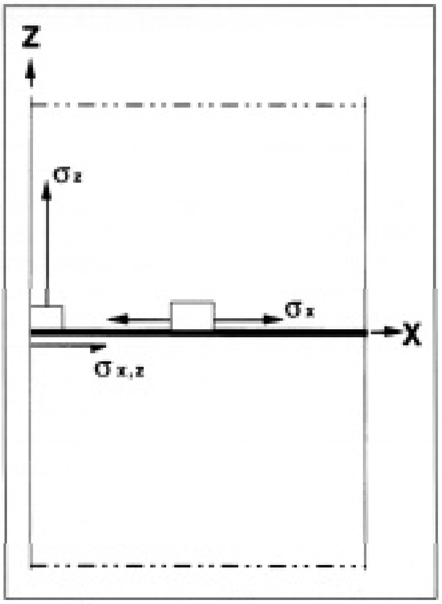

Figure 2. Stresses in a fused joint.

Various materials can be tested to determine the best fusion results, and acceptable material matches should go through extensive experimental verification. In production, ongoing residual stress evaluation should be incorporated into quality control procedures to ensure that stresses remain within prescribed bounds to minimize failures.

STRESS EVALUATION

Maintaining an optimum manufacturing process in a production environment is a never-ending challenge. Several types of instruments and approaches are available to measure residual stresses. Off-line stress evaluation often involves polariscopic observation of a sampling of the production run. Figure 3 illustrates a tubular-joint geometry frequently examined at the fused joint between a television panel and tubular extension, shown using polarized light.

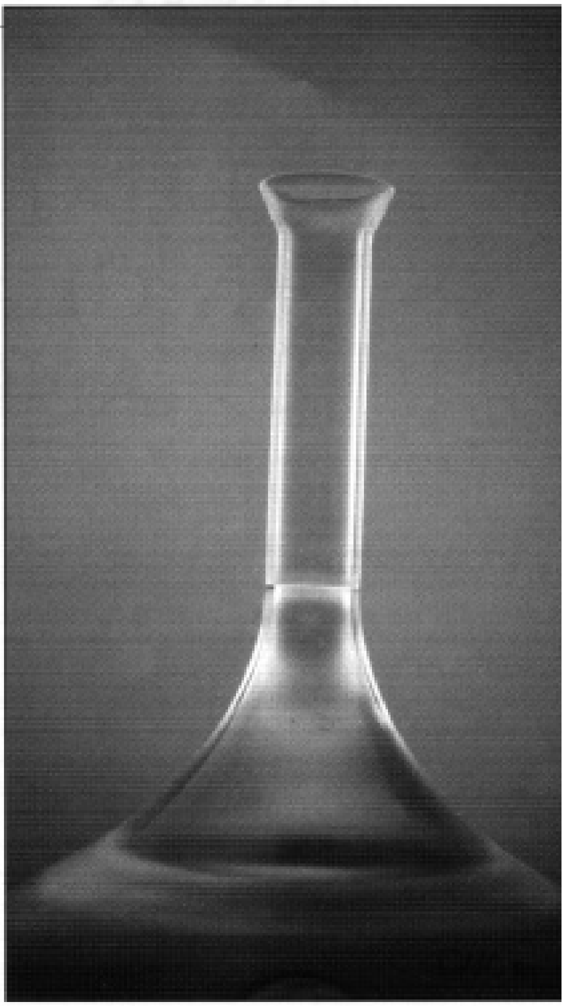

Figure 3. Television glass viewed with polarized light.

Stresses in glass develop birefr
gence, which can be viewed usi
polarized light. This type of evaluati
basically involves the use of transm
ted-light polarimeters to reveal str
patterns. Interpretation of the observ
stress patterns can be challengi
since:

- polariscopic observation requi
  proper alignment of component
- product samples should be prop
  ly positioned to align the directi
  of the stresses relative to t
  polarizer axes; and
- stresses often vary within mate
  als: in complex geometries, t
  direction of stresses is not alwa
  apparent, plus stresses near s
  face layers can be different th
  those found in midlayers.

As a consequence of these issu
training is required to properly set up a
use visual stress measurement devices

When measuring stresses usi
transmitted light, a polarized light pa
A-B (Figure 4) crosses layers of hi

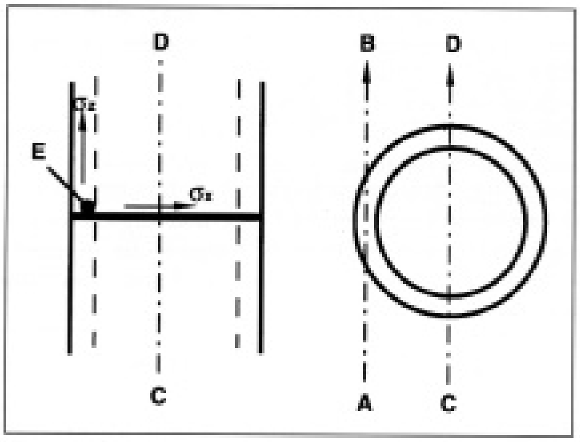

Figure 4. (above) Light path used for inspection of tubular joints. Path A-B: Immersion is required for inspection. Path C-D: No

and low stresses. The net effect yields an average integral retardation (R) that is viewed and measured using a polarimeter. In the case of tempered glass, the integral effect could add up to zero, since compressive (-) surface stress layers and tensile (+) stress midlayers are crossed along a path A-B. This is a misleading result, and consequently stresses in heat-strengthened and tempered glass types are evaluated using edge stress or surface stress measurement devices.[4]

GLASS SEALS

When inspecting glass seals, polariscopes or polarimeters are widely used for stress evaluation. In simple geometries, the approach is relatively straight-forward. In more complex applications, proper selection of the inspection path makes it possible to "see" one layer of stresses at a time. In some applications, the inspected item must be immersed in index-matching fluid for evaluation.

The example in Figure 3 is a very common type of glass-to-glass seal that requires high quality control standards. Poor material matching can have devastating results for manufacturers. Here, frequent stress inspection is required to simultaneously verify the annealing process and the match of materials. When examining this type of a fused joint, two measuring approaches are used:

- Figure 4 shows a schematic of the fused joint. An integral path A-B reveals a stress concentration (point "E" of Figure 4). However, the length of the light path and the direction of the stresses in this region substantially vary, making it impossible to interpret the acquired information in terms of stress. Simple polariscopic evaluation becomes meaningless, and measurement of the σ_z stress is not possible without using immersion liquid and/or very complex integral photoelasticity methods. As a result, this approach is very impractical.
- Evaluation of a simpler center-line path C-D (Figure 4) does not require immersion or complex methods, and can even be applied on-line. Measurement above and below the fused line easily yields the fused-line stresses σ_x. This is the more practical and preferred approach.

Selecting the best inspection procedure is important, and each procedure requires serious consideration and experimentation before a final method is selected and implemented.

PC-BASED INSPECTION

Measuring stresses using a visual polarimeter requires a highly skilled technician. Using compensators and/or an analyzer rotation method, it is possible to measure the retardation (R) within approximately 10 nm. The sensitivity of stress measurements becomes 200 psi (1.5 MPa) in a 3 mm thick wall. In many applications, this is clearly inadequate, particularly when the stress level should not exceed 300 to 600 psi (2 to 4 MPa.)

When high sensitivity is required for evaluating stresses, an automated PC-based stress measurement system should be considered.[5,6] These systems increase measurement speed, reliability, consistency and precision, and they reduce the need for skilled operators.

In a PC-based digital image analysis system, a CCD camera replaces human vision. The stress image is captured using a PC-mounted data-acquisition board in a form of 512 x 512 pixels (or a total of 256,000 points) where the measurements are made. Light intensity is measured at each point by these types of systems, and the measured stresses are automatically extracted from this information using "half-fringe" photoelasticity equations.

ON/OFF-LINE OPERATION

In off-line use, PC-based systems offer a wealth of information on stress that is not available to users of visual polarimeters.[7] The example shown in Figure 5 illustrates detailed quantitative stress distributions of fused joints

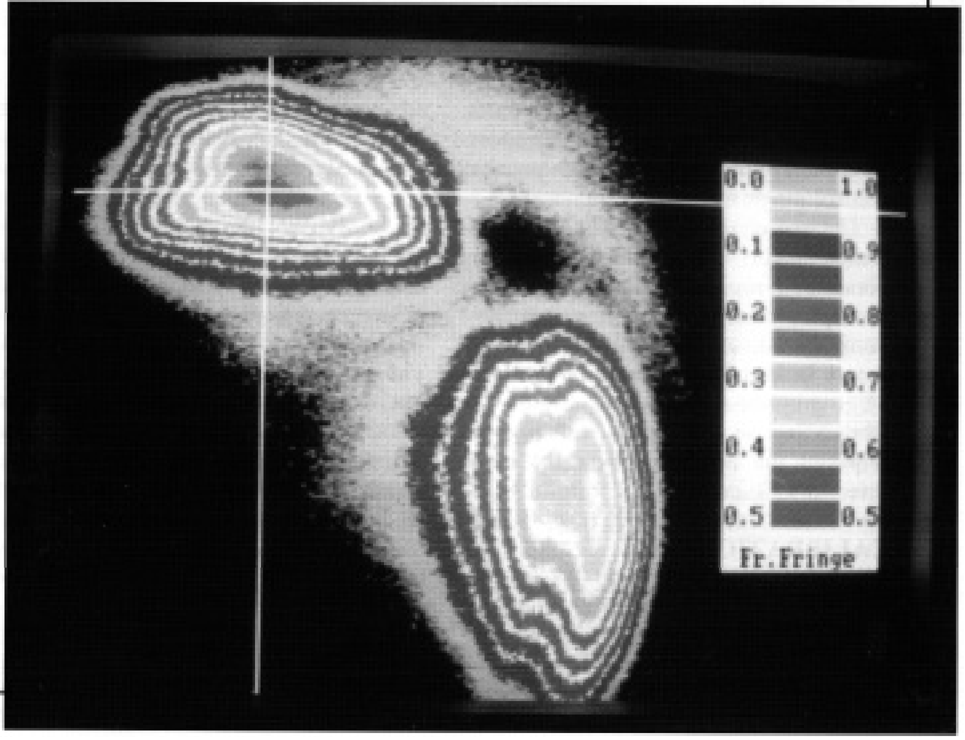

Figure 5. An example of a full-field PC-based stress evaluation.

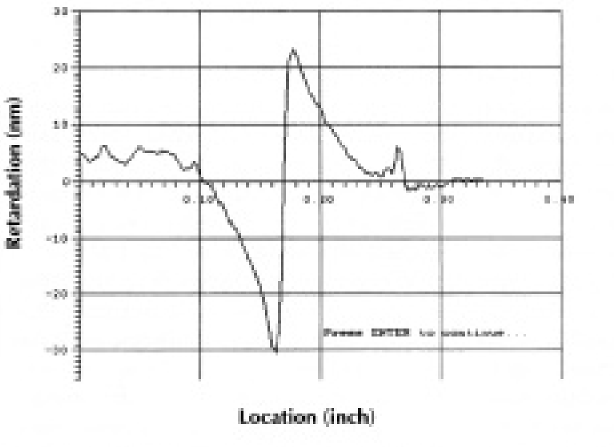

Figure 6. The software allows a line across a fused joint to be analyzed, revealing stress measurements in both fused items in the form of a graph.

between glass components. In this example, results are displayed in the form of a pseudo-color map. Each color correlates to a 5 nm increment of retardation.

Capabilities of digital image analysis systems include:

- full-field color display of stress data,
- click-of-a-mouse stress measurements at any cursor-selected point,
- instant stress graphs along any mouse-selected line (see Figure 6),
- quick identification of maximum stresses in user-defined regions, and
- storage of results for record-keeping and retrieval.

On-line use of automated stress inspection may also be considered without significant added expense. A CCD camera can capture stress images of stationary or moving parts, and stress measurements can be reported locally or remotely for process control purposes.

The software guides the set-up procedure to perform measurements in any prescribed region of the sample. For example, a line across a fused joint can be analyzed, revealing stress measurements in both fused items in the form of a graph (as shown in Figure 6). Depending on the type of information required, the total inspection time takes three to 12 seconds.

CALIBRATION AND STANDARDIZATION

Measuring stress using photoelastic principles requires accurate alignment of polariscopic equipment components and detailed instruction concerning interpretation of the observed stress pattern. When visual measurements are used, the operator must know, understand and properly interpret these instructions. In practice, interpretation of results can be a highly subjective matter.

A PC-based system does not have any difficulty in keeping instructions in its memory, or in consistently using the interpretation program. Even so, system calibration is routinely exercised to ensure users of accurate results and to satisfy quality certification requirements.

Calibration standards have been in existence for many years for most measurement functions, but until recently these tools have been rare and expensive for stress measurement applications. These devices are very useful to verify operator performance, and they also confirm proper alignment of stress measurement instrumentation (such as light sources, polarizers, etc.). For PC-based instruments, calibration standards enable users to check system accuracy. The most practical tool for calibration of both visual and PC-based stress measurements is a calibrated retarder.[8]

For the container industry, calibrated retarders or "strain discs" are produced in the form of 3-inch diameter circular gages, exhibiting a retardation of 0.04 wavelength (22.6 nm) near the outside diameter.[9] To use the discs, the operator stacks one or more discs until a color match is achieved between the discs and the highest stress region of the container bottom. These retarders can be difficult to use, since the operator must often stack several discs to obtain a matching color in accordance with the procedures. It is also difficult to get an exact color match.

A linear Calgage is considerably easier to use since a single gage contains variable retardation, permitting verification for a broad range of applications. When used with polariscopes for visual inspection, these devices can be used for "color matching" and pass/fail QC decisions. The calibration of these retarders is performed using monochromatic light at a standard wavelength of 565 nm and digital image enhancement of fringe-shifts in quartz wedges, yielding a 1-nm precision of calibration.

AUTOMATING STRESS EVALUATION

In both research and production, the use of PC-based methods help simplify stress evaluation. These methods reduce the need for skilled operators and provide far greater speed, accuracy, consistency and precision. Automation also offers a means to record and store measurement files for retrieval and to analyze trends over time. ❑

REFERENCES

[1] ASTM F14, "Standard Practice for Making and Testing Glass-Metal Bead Seal," 1991.

[2] ASTM F140, "Standard Practice for Making Reference Glass-Metal Butt Seals and Testing for Expansion Characteristics by Polarimetric Methods," 1991.

[3] ASTM F144, "Standard Practice for Making Reference Glass-Metal Sandwich Seal and Testing for Expansion Characteristics by Polarimetric Methods," 1980.

[4] ASTM C1279, "Nondestructive Photoelastic Measurement of Edge and Surface Stress in Annealed, Heat-Strengthened and Fully Tempered Glass," 1994.

[5] Adams, B. and Redner, A.S., "Digital Image Analysis-Based Stress Measurements for Quality Control," *Ceramic Transactions*, Vol. 28, 1992.

[6] Redner, A.S., "Precision Measurements of Stress-Birefringence in Glass," XVI International Congress on Glass, Madrid Spain, October 1992.

[7] PC-Based DIASS-1600 System Software Manual, Strainoptic Technologies, Inc., 1996.

[8] Calgage Bulletin, Strainoptic Technologies, Inc., 1996.

[9] ASTM C148, "Standard Test Methods for Pol-ariscopic Examination on Glass Containers," 1992.