Photoelastic Stress Analysis of Polycarbonate Medical Parts

For nearly 50 years, Makrolon® polycarbonate has been chosen for medical applications because of its excellent combination of properties including transparency, outstanding toughness, dimensional stability, moldability, low shrink rate, sterilizability and compatibility with many adhesives and welding techniques. Another property, particularly important in medical applications, is the ability to have molding and applied stresses measured via several techniques including solvent stress testing and photoelastic stress analysis. This ability provides another measure of quality control for critical medical parts. Excessive molded-in stress or applied stress during assembly and use can reduce the mechanical performance of the material, even one as tough as polycarbonate, so it is important to monitor the molding and assembly parameters that affect stress levels in the plastic. This article focuses on the photoelastic stress analysis technique.

Theory

The speed of light through polycarbonate (PC) varies as a function of the direction and magnitude of applied or residual stresses. Polarized light passing through stressed PC splits into two wave fronts traveling at different velocities, each parallel to a direction of principal stress but perpendicular to each other. This leads to the stressed material having two different indices of refraction, a property known as birefringence.

The Stress-Optic or Brewster's Law establishes that birefringence is directly proportional to the difference in principal stresses, which is equal to the difference between the two indices of refraction exhibited by the stressed material. Knowing the difference in the indices of refraction at a location and the stress optical or Brewster's constant, you can calculate the difference in principal stresses. The difference in indices of refraction can be determined by dividing the retardation value, a measure of the phase difference between the fast and slow moving light vectors, by the material thickness. The stress equation is then

$$\sigma_{MPa} = \delta_{nm}/(t_{mm} \cdot C_B)$$

where

σ_{MPa} = stress (MPa)
δ_{nm} = retardation value (nm)
t_{mm} = thickness (mm)
C_B = Brewster's constant ≈ 84 for PC

When a stressed sample is viewed between polarizing filters, the components of the light waves passing through the sample interfere with each other to produce a color spectrum. From these color bands or fringes, we can determine the retardation value and complete the stress calculation. When the part and polarizing films are oriented correctly, the areas of lowest orientation and stress appear black, followed by gray and white. As retardation and stress go up, the colors cycle through a more or less repeating pattern as shown in the table below and the intensity of the colors decreases.

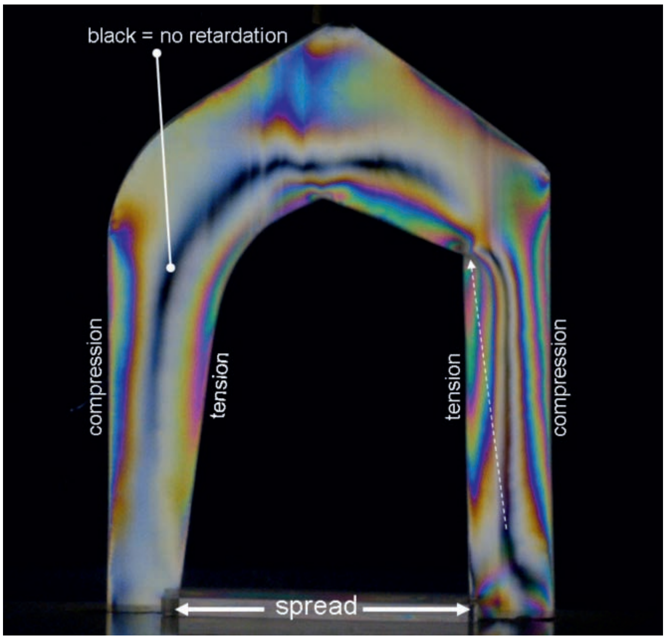
Color Pattern Observation

Color	Retardation	Retardation Wavelengths
Black (zero order fringe)	*0*	*0.00*
Gray	150	0.28
White-yellow	250	0.45
Yellow	300	0.60
Orange (dark yellow)	450	0.79
Red	500	0.90
Violet (1st order fringe)	*570*	*1.00*
Blue	600	1.05
Blue-green	650	1.14
Green-yellow	750	1.32
Yellow	850	1.50
Orange (dark yellow)	950	1.67
Red	1050	1.84
Violet (2nd order fringe)	*1140*	*2.00*
Green-yellow	1350	2.17

Because the colors repeat at different levels of retardation and stress, you have to carefully track the color band sequence from the black or white regions to the point of interest to see how many times the colors have repeated. This can be done using simple polarizing filters, but the results can be quite subjective and allow for only a rough estimate of retardation and stress. Instruments equipped with a calibrated scale to quantify the retardation value, polarimeters, take away much of the subjectivity and facilitate more accurate stress calculations.

Application

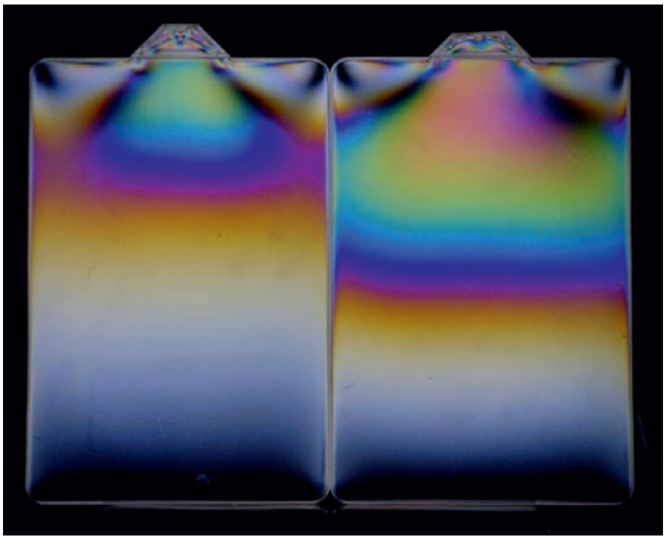
Photoelastic stress analysis can be used qualitatively or quantitatively, and on applied or molded-in stresses. The photo below shows a shape cut out of extruded PC sheet. A spacer was inserted to spread the two vertical legs, and the resulting fringe pattern was viewed between a pair of polarizing filters. Before the stresses were applied, no fringe pattern appeared on the sample. The fringe pattern, due entirely to the applied deformation, provides a wealth of information about the stress distribution.



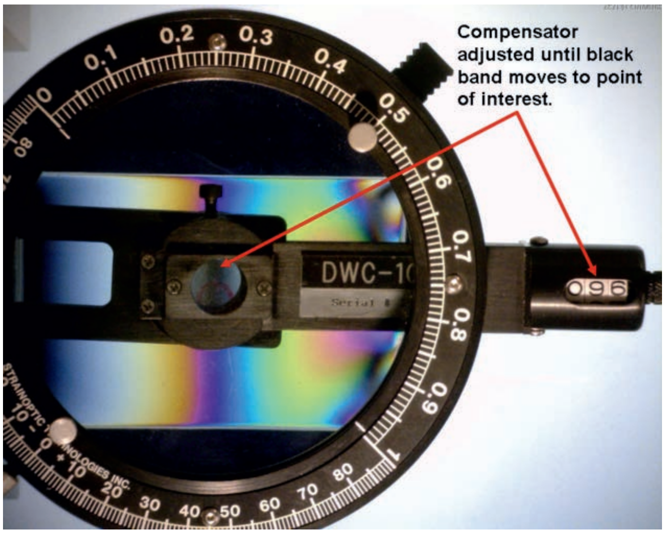
The fringes near the inner edge of the sample represent tensile stresses. Those near the outside edge reflect the compressive stresses. The orientation of the stresses is obvious in this example based on how the sample is deformed. When it is not so apparent, there are methods to determine if a fringe represents a tensile or compressive stress. The tensile and compressive stresses cross over at the black fringe at the center of each leg. By tracking the fringe sequence from the black band to the highest fringe near the part edge or corner, we can estimate the retardation and calculate the stress level.

This sample was created specifically to show the benefit of rounding inside corners and tapering the thickness or width of features that will flex in use. Deflecting the right leg outwards concentrates the stresses near the inside corner at the top of the leg. This is reflected in the many fringes that appear along the dashed white arrow. The rounded, tapered left leg does a much better job of distributing the stresses.

Qualitative evaluation of molding stresses can be performed in a similar way. The photo below shows identical test plaques molded at different processing conditions. Tracking the fringes from the black band at the bottom to the highest fringe near the gate at the top, we count fewer fringes and see a lower overall fringe level in the part on the left. From this, we can infer lower residual molding stresses in the left plaque.



If the difference in fringe patterns can be correlated to a difference in a key part performance parameter, then this simple, non-destructive test can be used as a quality control at the molding press. Pictures of acceptable and unacceptable fringe patterns can be displayed at the press. After the parts fully cool, they can be viewed between polarizing films for a quick evaluation of molding stresses.



Accurate quantitative stress measurements require a polarimeter. The photo above shows a test sample in a polarimeter equipped with both a rotation analyzer, the apparatus with the circular scale, and a compensator mounted horizontally with the counter on the right and the small viewing window centered on the point of interest on the sample. Without the compensator, the rotation analyzer can be rotated to determine the fractional fringe order for calculation of the retardation.

When the compensator is used, the rotation analyzer is aligned to the correct starting position and settings, and the small window of the compensator is positioned over the point of interest. The knob on the counter is then rotated until the black fringe moves to the point of interest in the compensator window, in this example the region between the red and violet fringe. The counter number (96) is then multiplied by the calibration constant for the compensator (5.7 nm/ct) to compute the retardation value of 547 nm. Solving the stress equation,

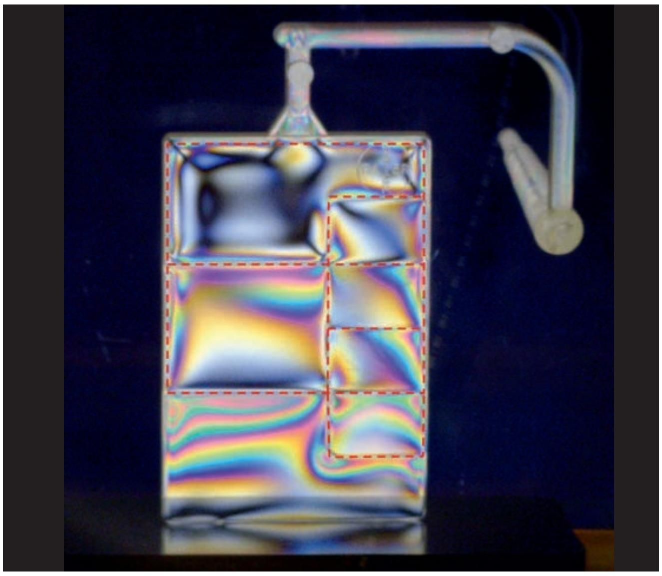
$$\sigma_{MPa} = \delta_{nm}/(t_{mm} \cdot C_B)$$

where

δ_{nm} = 547 (nm) retardation value
t_{mm} = 1.5 (mm) thickness
C_B = Brewster's constant ≈ 84 for PC

yields a calculated stress of 4.3 MPa.

The dashed outlines in the photo below represent regions of different thickness. Thickness appears in the denominator of the stress equation, so the fringes in different thickness regions correspond to different levels of stress. The stresses in each region must be evaluated separately.



Limitations

There are several limitations to the photoelastic stress analysis technique. For it to work, the polarized light can pass through only one part wall. This effectively rules out the technique for many small cylindrical or closed part features. Larger parts or part features can be cut to expose one wall as long as the act of cutting does not alter the stresses at the point of interest. Areas of thickness transition, such along the corner radius at the base of a boss or rib, will also be difficult to analyze.

Conventional photoelastic analysis shows the sum of the tensile and compressive stresses through the part thickness. High tensile stresses on the part surface can be offset by compressive stresses below the surface. The fringe pattern would then not reflect the true stress level on the part surface. When surface stresses are of primary importance, as when optimizing the part for chemical resistance, it is better to use a solvent stress test. Solvent stress testing acts on the part surface and gives stress results for just the part surface.

Summary

Photoelastic testing provides a quick, nondestructive method for evaluating molded-in or applied stresses in transparent, polycarbonate medical parts. Viewing samples between simple, inexpensive polarizing filters can provide a wealth of information about the orientation and magnitude of stresses. If the difference in fringe patterns can be correlated to a difference in a key part performance parameter, then the test method can be used as a quality control at the molding press.

Upgrading to a polarimeter, a device equipped with a calibrated scale to quantify the retardation value, takes away much of the subjectivity and facilitates more accurate stress calculations. Polarized light must only pass through one wall thickness. This can limit the technique in parts with small cylindrical or closed features. The standard photoelastic test method gives the sum of the stresses through the part thickness, and not the stress level on the surface. Solvent stress testing is preferred when surface stresses are the primary concern.

covestro

Covestro Deutschland AG
Business Unit Polycarbonates
D-51365 Leverkusen

plastics@covestro.com
www.plastics.covestro.com