Residual Stress Testing for Transparent Polymers

Even parts that are well designed can fail if poor processing conditions produce improper orientation and residual stresses. Manufacturers need reliable, practical stress-testing methods.

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All medical plastics manufacturing processes—including injection molding, extrusion, vacuum forming, and machining—naturally introduce residual stresses. These stresses sometimes have an intentional and highly desirable purpose, as in the case of biaxially oriented films, whose carefully designed orientation enhances mechanical properties. In other products, residual (or “frozen-in”) stresses can be a problem, reducing end-use performance and resulting in increased scrap and rejects. When high levels of stress are present in a part, impact strength is lowered, high-temperature performance is diminished, and environmental stress cracking becomes more prevalent.

Effects of Residual Stress

Distortion from Stress Relaxation. Stress relaxation results in deformation and improper fit during product assembly and is a direct cause of a deterioration in product appearance and of ultimate product failure. Frozen-in stresses become real loads applied to the material upon exposure of the part to slightly elevated temperatures. Medical manufacturers often do not realize that this problem exists until parts are subjected to sterilization or heat-sealing processes.

Cracks. Cracks in a material are the most visible result of excessive residual stress. Cracks are accelerated by the presence of solvents, but can also appear when a molded product is restrained and cannot relax to a shorter, stress-free dimension. Crazing is the appearance of many fine microcracks across a material. This condition may not be evident during production but can be triggered by subsequent exposure to chemicals. For example, styrene parts dipped in kerosene will craze quickly in stressed areas. Proper annealing can minimize these stresses and prevent crazing.

Deterioration of Optical Performance. Clear plastics are used extensively in the production of lenses and optical transparency. Residual stresses introduce birefringence—an asymmetry of the index of refraction—that can make a plastic lens unable to focus properly. Even a small level of birefringence hampers optical properties and product performance.

Changes in Mechanical Properties. Oriented polymers have different mechanical properties than their annealed counterparts. Drawing, forming, and cooling procedures can and do introduce orientation stresses in the part that can lead to property changes.

Figure 1. Medical packaging with excessive residual stresses (top) and the same type of package after annealing has substantially reduced stresses (bottom).
An extruded polymeric tube or sheet has a certain inherent tear strength; maximum elongation inherently creates anisotropy in the material, resulting in a decrease of performance in the unstretched direction. If processed at too low a temperature, the part can shorten in the machine direction and thicken in the cross-machine direction.

**Figure 2. A polarscope will reveal stresses in transparent parts. (Model SV-2000, Strainoptic Technologies Inc.)**

"birefringent." Viewed with polarized light, stresses appear as a series of multicolored bands or fringes. This fringe pattern is rich with information (see box on page 112).

A simple polarscope will allow you to view stresses in transparent parts. Polarscopes essentially consist of a white light source and suitable polarizing elements. The packages illustrated in Figure 1 were evaluated using the polarscope shown in Figure 2. This type of evaluation can be employed to survey stress distribution in a part or to compare stresses in two identical parts.

**MEASURING BIREFRINGENCE FOR QUANTITATIVE RESULTS**

Stress-measurement instrumentation can deliver accurate, quantitative results that cannot be derived using crossed polarizers alone. Quantitative evaluation is preferred over qualitative methods and is far more reliable for quality control. With the right instruments, stress measurement can be easily conducted for transparent parts.

Both on- and off-line instrumentation is available for quantitative measurement of birefringence. Determining the most appropriate tool depends on the application, the level of accuracy or reproducibility required, and the level of operator skill.

A simple test can be accomplished using a polarscope or polarimeter equipped with a compensator—a type of calibrated wedge. The operator adjusts the wedge position until a black fringe appears at the measurement point, as shown in Figure 3. A scale on the compensator supplies a quantitative reading of optical retardation.

The procedure for measuring retardation/birefringence using a compensator is a standard test method described in ASTM D 4093 and is a particularly effective quality control test for clear plastics. The procedure is nondestructive, requiring no chemicals or layer removal. In addition, results are fast, enabling processors to make on-line adjustments as needed.

**ADVANCED TESTING APPROACHES**

Sophisticated computer-based instrumentation is commercially available for applications that require very fast, accurate results, or for those situations in which automated inspection is
WHAT MAKES STRESS VISIBLE?

When a transparent material is subject to stress, it becomes birefringent. That is, light propagates through the material at two different speeds, \( V_1 \) and \( V_2 \), and has two values of index of refraction, \( n_1 \) and \( n_2 \), such that \( n_1 = V_1/C \) and \( n_2 = V_2/C \), where \( C \) is the speed of light in a vacuum.

When a polarized light wave is transmitted through a region containing stresses (\( \sigma_1, \sigma_2, \) direction \( \beta \)), the light will split into "slow" and "fast" waves. As a result of their difference in speed or birefringence (\( n_1 - n_2 \)), these waves will separate. Their relative distance (or "retardation," \( R \)) is related to the principal stresses or strains and the thickness \( t \):

\[
(n_1 - n_2) = (\sigma_1 - \sigma_2)F \quad \text{and} \quad R = (\sigma_1 - \sigma_2) \times t \times F.
\]

In this relation, \( F \) is the material stress constant, which characterizes the stress-related properties of the material and will vary for different materials. This constant is known for most commonly used materials.

Another polarizing filter called an analyzer causes the two emerging waves to interfere. The observed color pattern is the result of their constructive or destructive interference. Each time the relative retardation equals a multiple integer of wavelength, a destructive interference will occur, and an isochromatic (or equal color) fringe order \( N \) is observed. Different colors, therefore, represent different stress levels, in which retardation \( R = \) fringe order \( N \times \) wavelength \( \lambda \).

The observed color fringes are simply level lines of constant stress, with \( N = 0, 1, 2, \) etc., along a fringe. The wavelength \( \lambda \) for white-light observation is 570 nm. At the point where two fringes appear, retardation is \( 2 \times 570 \) or 1140 nm.

Measuring the retardation \( R \) allows the measurement of the birefringence at any desired location. Birefringence is thus retardation per unit thickness, such that

\[
\text{Birefringence} = \frac{\text{Retardation (R)}}{\text{Thickness (t)}}
\]

preferred. These systems replace the human observer with computerized vision systems. PC-based instruments can provide information about retardation, birefringence, and residual stress in transparent films or discrete parts.

One type of PC-based instrument offers a high level of accuracy through spectrophotometric analysis. Using a method known as spectral contents analysis or SCA, such a system can quickly and automatically report quantitative retardation, birefringence, or stress for any selected point as well as generating a graph of stress versus position for any scanned line.

While not limited to film applications, this advanced method is particularly effective for evaluating both uniaxially and biaxially oriented films. Figure 4 shows a system used for laboratory evaluation of biaxially oriented film. A 50-mm-wide (2-in.-wide) strip of film of any length is placed on the unit's specimen holder. Motor force feeds the ribbon while the measurements are obtained at a preset number of menu-selected points, typically in 20-mm increments. Upon completion of the scan, the results are printed in the form of a graph, and a data file is saved. This compact, self-contained instrument can be used in the laboratory or on the factory floor.

Similar instrumentation is available for in-line inspection, with the optical scanning heads bolted to a carriage to scan the film during the production process. The SCA method can be easily adapted to perform process monitoring for real-time process control.

Another method, digital image analysis, employs a digital camera to replace the human observer. This technique is ideal for inspection of optical elements or other annealed parts that exhibit very low birefringence. In addition to supplying measurements for any point or along any scanned line, a digital image analysis system can display a full-field stress map, as shown in Figure 5. Using this feature, inspectors can readily identify maximum stress regions in samples, specify retardation/birefringence thresholds, and automatically select or reject parts for quality control.

Both the SCA and digital image analysis methods are free from operator-to-operator variations and provide quick, accurate, highly repeatable information about residual stresses in transparent parts.

CALIBRATION AND CERTIFICATION

Calibration standards have been in
existence for years for most measurement functions, but until
recently these tools have been rare and expensive for stress-
measurement applications. Such standards are useful to ver-
ify both human and PC-based measurements and to ensure
proper alignment of polarimeters and other stress-measure-
ment instruments.

The most practical tool for calibrating both visual and PC-
based stress measurements is a calibrated retarder, which can
exhibit uniform retardation (e.g., 100 nm). The retarder is trace-
able to the National Institute of Standards and Technology and
can be supplied with certification documents to satisfy ISO
requirements.

CONCLUSION

A commitment on the part of medical manufacturers to
evaluating residual stresses in their parts
can contribute greatly to improved produc-
t quality and consistency. Stress-free parts are more likely to maintain their
strength, optical clarity, stability, and
resistance to environmental stress fac-
tors. For transparent parts, the test meth-
ods described here can be performed
using inexpensive, nondestructive pro-
cedures that can be used either on- or
off-line without slowing down pro-
duction. The benefits can be significant,
since these simple tests can help pro-
cessors monitor and identify problems
before parts fail.

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If you think stress measurement means looking at your product through crossed polarizers, then

THINK AGAIN

Remove the
guesswork from stress inspection.
Quantify your results and improve your quality control.

You can improve your QC procedures and cut costs today
by integrating a smarter stress measurement system. Our
instruments deliver accurate, quantitative results that can’t
be obtained using crossed polarizers alone. You'll gain
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