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# Nondestructive Evaluation Using Polarized Light

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Visual testing (VT) is often more than looking at a specimen. There are a variety of mechanical and optical aids that permit VT to do more than detect missing, broken, or improperly assembled specimens. With the proper aid, you can even see residual stress in a variety of materials. Remember, stress can be essential in some kinds of specimens and detrimental in others. How sweet it is when you can just see it!

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Everyone has seen the beautiful color pattern observed when a molded plastic or tempered glass product is placed between two polarizing filters. But what does this color pattern mean? How does one interpret the information displayed? And how do you use the pattern to obtain valid results?

The fundamentals and principles of the optics involved are relatively simple.

## What Makes Stress Visible?

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

When a polarized light wave is transmitted through a region containing stresses ($\sigma_1$, $\sigma_2$ direction $\beta$), a split into "slow" and "fast" waves will occur (see Figure 1).

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 ($n_1 - n_2 = (\sigma_1 - \sigma_2)F$ and $R = (\sigma_1 - \sigma_2) \cdot t \cdot F$.

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In this relation, $F$ is the material stress constant. This constant is known for most commonly used materials and will vary for different materials (Nickola and Redner, 1984).

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 of order $N$ is observed. Different colors, therefore, represent different stress levels. $R = N \cdot \lambda$.

**The selected method largely depends on the level of accuracy and the processes required by the user.**

The observed color fringes are simply level lines of constant stress with $N = 0,1,2,$ ... etc., along a fringe. The wavelength $\lambda$ in white light observation is 565 to 570 nm (ASTM D4093; ASTM F218).

## Qualitative Evaluation

The simplest tool used for qualitative observation of stress patterns is a handheld viewer that permits the user to place a specimen between two polarizing filters that produce a color pattern (Figure 2). A "retardation versus color" chart is used to interpret the observed pattern (Table 1). (Strainoptic 1985a, 1985b).

Using this method, one can observe the varying stress levels contained in a specimen. An approximate interpretation is possible only when the retardation, $R$, is below 1 wavelength, since otherwise a given color (green, for example) can reveal multiple stress levels. Clearly, this type of multiple stress reading can be very disturbing and, as such, the use of this type of simple inspection instrument should be strictly limited to applications where it is well established in advance that the stresses are very small and the measured retardation is only a fraction of a wavelength. Annealed glass, for example, is a low stress material that can be inspected with the use of this type of simple polariscopic observation.

## Quantitative Measurements

Various methods of quantitative stress measurement are available. The selected method largely depends on the level of accuracy and the processes required by the user.

The concept of quantitative measurements is illustrated in Figure 3. Here, a "compensator" is introduced in series with the specimen, adding its own retardation in the path of light crossing a point, $P$. Compensators are used to quantitatively identify the stress pattern observed. When the retardation of the compensator $R_c$ is equal and the opposite sign of the measured retardation in the specimen $R_s$, the total equals zero.

The interferences are eliminated for all wavelengths and a black fringe is observed at the point of measurement, $P$.

The compensator (also commonly called a wedge) resembles a linear scale and is calibrated, providing a known retardation value at each point of the scale. A typical polarimeter equipped with a measuring wedge is shown as Figure 4.

In a production environment, visual qualitative and quantitative measurements as described above are often considered too slow and rely on the subjective judgment of the user. Truly reliable measurements require reproducibility and accuracy. To accelerate the process and eliminate these subjective factors, modern inspection methods commonly use "machine vision" to acquire quantitative stress measurements. Here, a CCD camera replaces the human eye. The image of the inspected region is acquired through the camera by a computer-based frame-grabber, and the

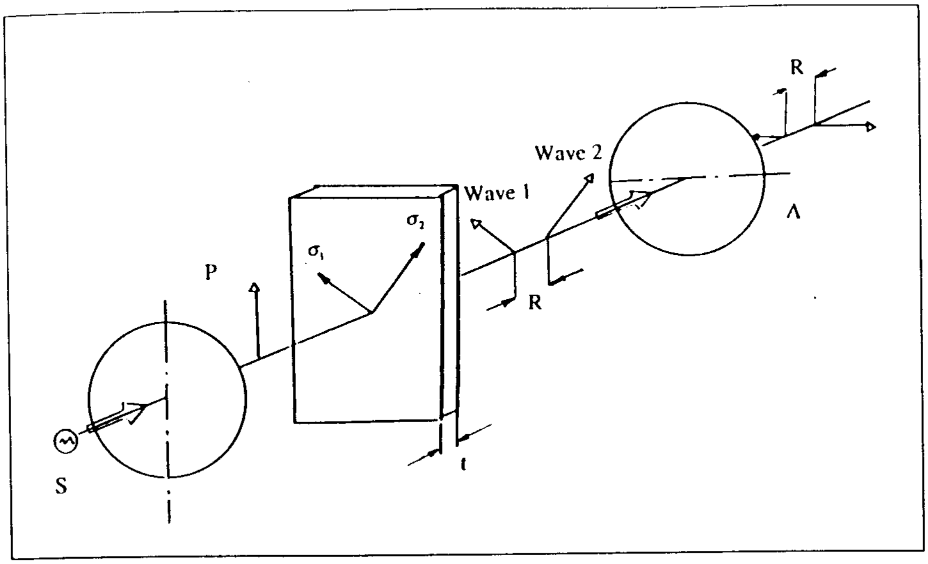


Figure 1 — *Schematic of the principle of light transmission, birefringence, and interference.* S = *light source,* P = *polarizer (allows only one orientation of vibration),* s1, s2 = *principal stresses in the observed specimen,* R= *distance between the slow (1) and fast (2) waves, and* A = *analyzer (retrieves only one component of waves 1 and 2 allowing interference of those waves).*

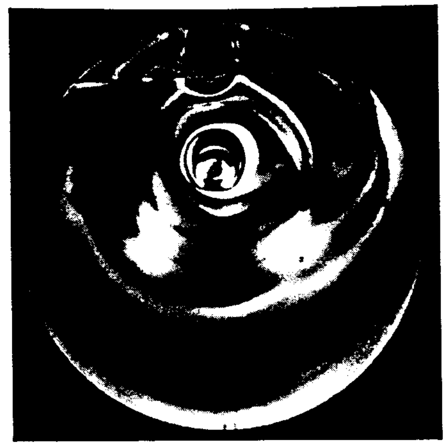

*Figure 2 — A visual display of colors is visible when a cast or molded item is observed between two polarizers.*

light intensity is measured on an array of 512 x 512 points (or pixels). This information is then digested and interpreted using digital image analysis software methods, yielding quantitative stress measurement results for a full field of observation (Figure 5). The user can prescribe the limits of inspection, or threshold of acceptance, for each part that is examined.

The PC-based inspection method not only offers quantitative measurement capabilities, but also permits the most systematic inspection procedure by logging the data for numerous points of inspection, compiling the production trends, and providing suitable warnings of impeding stress problems (Adams and Redner, 1991).

## Why Is the Stress Birefringence Measured?

The inspection of transparent materials using polarized light can provide valuable information about product performance. For the following types of products, inspection is required to identify compliance with product specifications. These specifications are often expressed in retardation units (nm) per unit thickness or in units of stress.

*Optical elements.* Optical elements such as lenses, prisms, optical windows, and compact disks are designed to perform well defined optical functions. Birefringence due to residual stresses introduced in the production process will hamper their optical properties and product performance.

*Molded and cast polymers.* Many polymers develop environmental surface crazing resulting in appearance degradation, loss of transparency, and sometimes cracking when excessive stresses are cast in during their production or machining.

*Oriented polymer films.* A high level of residual stress is not necessarily a defect for these products. In many products, just the opposite is the case. Many polymer films (PTE, OPS, and several other materials) will improve their mechanical properties such as tensile strength, tear strength, or formability when stretched to a carefully controlled level at proper temperatures.

*Tempered glass.* Glass tempering is another example of a process in which residual stresses are intentionally introduced to enhance product performance. Properly tempered glass not only has a two to three times higher strength than annealed glass, but is also capable of fracturing in small particles when broken, helping avoid cuts

**Table 1** Retardation vs. color

| Color | *R* (nm) |
|---|---|
| Black | — |
| Gray | 150 |
| White-yellow | 250 |
| Yellow | 300 |
| Orange (dark yellow) | 450 |
| Red | 500 |
| Indigo-violet (1st order fringe) | 565 |
| Blue | 600 |
| Blue-green | 650 |
| Green-yellow | 750 |
| Yellow | 850 |
| Orange (dark yellow) | 950 |
| Red | 1050 |
| Indigo-violet (2nd order fringe) | 1130 |
| Green | 1300 |
| Green-yellow | 1400 |
| Pink | 1500 |
| Violet (3rd order fringe) | 1695 |
| Green | 1750 |

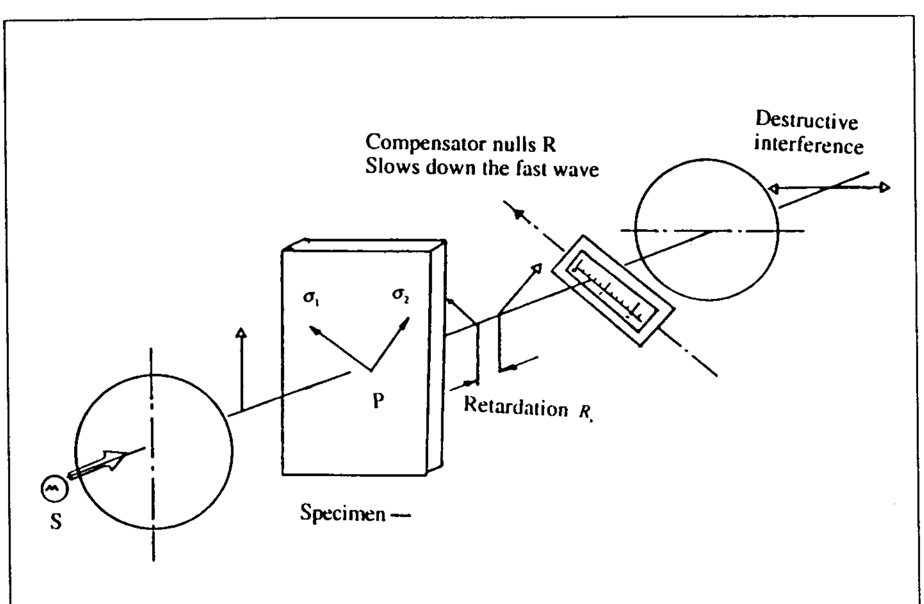


*Figure 3 — Schematic demonstrating the use of a compensator wedge to null the total retardation of light waves.*

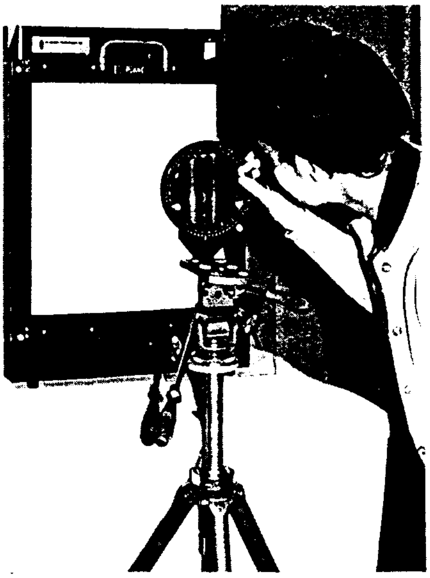

*Figure 4 — Polarimeter for measuring retardation using a compensator.*

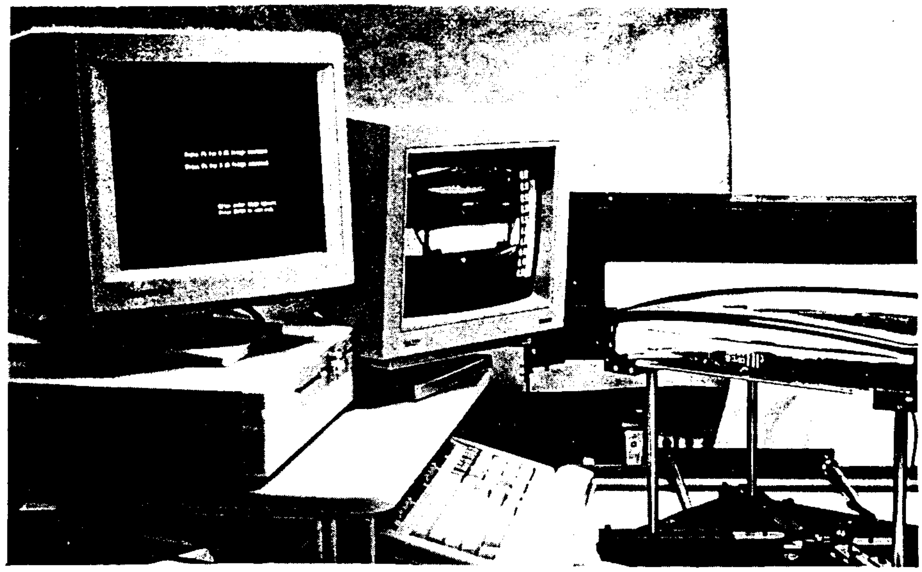

*Figure 5 — Verification of residual stresses in a TV panel production using digital image analysis of stress pattern.*

that large fragments can cause. Stress measurement of tempered glass (ASTM C 1279) helps identify whether or not an adequate amount of compressive stress has been added to the glass product, providing a desired protection layer on the surface.

*Annealed glass.* Glass being a relatively brittle material, it can easily fail when a minor surface crack or scratch occurs at a point where a tensile stress is present. Inspection of annealed glass is performed by hundreds of companies, ranging from one-man art glass operations to the largest glass manufacturers, to identify such stress points to prevent product failure.

## Conclusions

In order to ensure that required properties are achieved in production, stress measurement testing is required, and measurement of stress birefringence will reveal if the product lives up to its required specifications using this simple nondestructive test.

## Want to Know More?

The use of polarized light is a broadly used optical inspection method for stress measurement. However, it need not be a "mysterious" curiosity to engineers and technicians. The following references and general bibliography should help anyone locate additional sources of information on this topic and offers a planned approach to optical inspection for birefringence or residual strains.

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