



Standard Test Method for Photoelastic Measurements of Birefringence and Residual Strains in Transparent or Translucent Plastic Materials¹

This standard is issued under the fixed designation D 4093; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Light propagates in transparent materials at a speed, v , that is lower than its speed in vacuum, c . In isotropic unstrained materials the index of refraction, $n = c/v$, is independent of the orientation of the plane of vibration of light. Transparent materials, when strained, become optically anisotropic and the index of refraction becomes directional. The change in index of refraction is related to strains. If n_o is the refractive index of unstrained material, the three principal indices of refraction, n_i , become linear functions of strain:

$$n_i - n_o = \sum A_{ij} \epsilon_j$$

Using photoelastic techniques (initially developed to measure stresses in transparent models) strains in plastics can be assessed. In isotropic materials, two material constants, A and B , are sufficient to describe their optomechanical behavior:

$$\begin{aligned} A_{ij} &= A \text{ when } i = j, \text{ and} \\ A_{ij} &= B \text{ when } i \neq j. \end{aligned}$$

When light propagates through a region (where principal strains ϵ_1 and ϵ_2 are contained in the plane perpendicular to the direction of light propagation (see Fig. 1), the incoming vibration splits into two waves vibrating in planes of ϵ_1 and ϵ_2 . The difference between the indexes of refraction $n_1 = c/v_1$ and $n_2 = c/v_2$ (or birefringence) is:

$$n_1 - n_2 = (A - B)(\epsilon_1 - \epsilon_2) = k(\epsilon_1 - \epsilon_2)$$

where k is a material property called the strain-optical constant. As a result of their velocity difference, the waves vibrating along the two principal planes will emerge out of phase, their relative distance, or retardation, δ , given by:

$$\delta = (n_1 - n_2)t = kt(\epsilon_1 - \epsilon_2)$$

where t is the thickness of material crossed by the light. A similar equation, relating δ to the difference of principal stresses, σ_1 and σ_2 , can be written:

$$\delta = (n_1 - n_2)t = C(\sigma_1 - \sigma_2)$$

The objective of photoelastic investigation is to measure: (a) the azimuth, or direction of principal strains, ϵ_1 and ϵ_2 (or stresses σ_1 and σ_2), and (b) the retardation, δ , used to determine the magnitude of strains. A complete theory of photoelastic effect can be found in the abundant literature on the subject (an extensive bibliography is provided in Appendix X2).

1. Scope

1.1 This test method covers measurements of direction of principal strains, ϵ_1 and ϵ_2 , and the photoelastic retardation, δ , using a compensator, for the purpose of analyzing strains in transparent or translucent plastic materials. The test method can be used to determine the difference of principal strains or

normal strains when the principal directions do not change substantially within the light path.

1.2 In addition to the method using a compensator described in this test method, other methods are in use, such as the goniometric method (using rotation of the analyzer) mostly applied for measuring small retardation, and expressing it as a fraction of a wavelength. Nonvisual methods employing photoelectric conversion and eliminating the human judgement factor are also possible.

1.3 Test data obtained by this test method is relevant and

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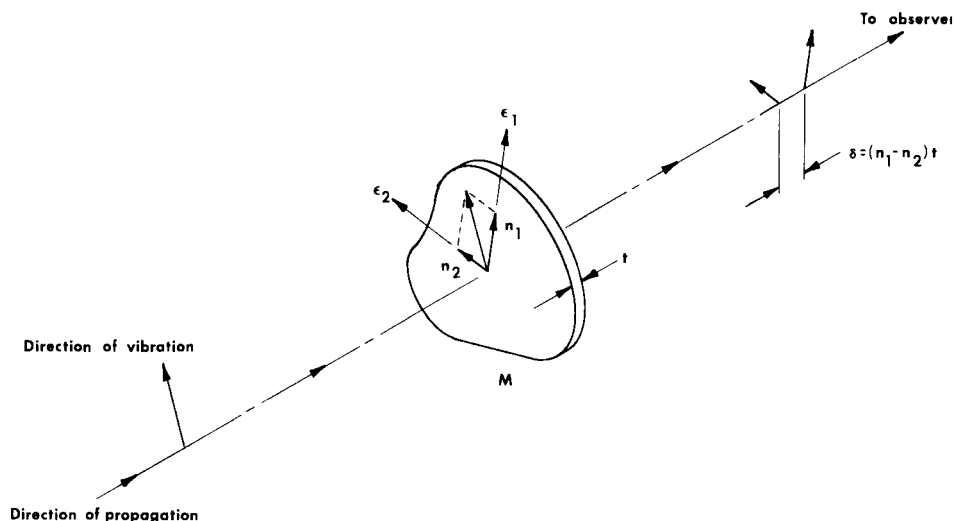


FIG. 1 Propagation of Light to a Strained Transparent Material

appropriate for use in engineering design.

1.4 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:

- D 618 Practice for Conditioning Plastics and Electrical Insulating Materials for Testing²
- D 638 Test Method for Tensile Properties of Plastics²
- D 882 Test Methods for Tensile Properties of Thin Plastic Sheeting²
- D 4000 Classification System for Specifying Plastic Materials³
- E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method⁴

3. Terminology

3.1 Definitions:

3.1.1 *compensator*—an optical device used to measure retardation in transparent birefringent materials.

3.1.2 *polarizer*—polarizing element transmitting light vibrating in one plane only.

3.1.3 *quarter-wave plate*—a transparent filter providing a relative retardation of $\frac{1}{4}$ wavelength throughout the transmitting area.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *birefringence*—retardation per unit thickness, δ/t .

3.2.2 *retardation*, δ —distance (nm) between two wave fronts resulting from passage of light through a birefringent material. (Also called “relative retardations.”)

3.2.3 *strain*, ϵ —*strain (or deformation per unit length)*—could be permanent, plastic strain introduced in manufacturing

process, or elastic strain related to the existing state of stress. Both types of strains will produce strain-birefringence in most polymers. Birefringence can also result from optical anisotropy due to crystalline orientation.

3.2.4 *strain-optical constant*, k —material property, relating the strains to changes of index of refraction (dimensionless).

$$k = (n_1 - n_2)/(\epsilon_1 - \epsilon_2) \quad (1)$$

3.2.5 *stress-optical constant*, C —material property relating the stresses to change in index of refraction. C is expressed in m^2/N or Brewsters ($10^{-12} \text{ m}^2/\text{N}$). C is usually temperature-dependent.

$$C = (n_1 - n_2)/(\sigma_1 - \sigma_2) \quad (2)$$

4. Summary of Test Method

4.1 To analyze strains photoelastically, two quantities are measured: (a) the directions of principal strains and (b) the retardation, δ , using light paths crossing the investigated material in normal or angular incidence.

4.2 The investigated specimen or sample is introduced between the polarizers (see Fig. 2 and Fig. 3). A synchronous rotation of polarizers follows until light intensity becomes zero at the observed location. The axes of the polarizers are then parallel to direction of strains, revealing these directions.

4.3 To suppress the directional sensitivity of the apparatus, the setup is changed, introducing additional filters. A calibrated compensator is introduced and its setting adjusted until light intensity becomes zero at the observed location. The retardation in the calibrated compensator is then equal and opposite in sign to the retardation in the investigated specimen (see Fig. 4).

5. Significance and Use

5.1 The observation and measurement of strains in transparent or translucent materials is extensively used in various modeling techniques of experimental stress analysis.

5.2 Internal strains induced in manufacturing processes such as casting, molding, welding, extrusion, and polymer stretching can be assessed and part exhibiting excessive strains identified. Such measurements can lead to elimination of defective parts, process improvement, control of annealing operation, etc.

² Annual Book of ASTM Standards, Vol 08.01.

³ Annual Book of ASTM Standards, Vol 08.02.

⁴ Annual Book of ASTM Standards, Vol 14.02.

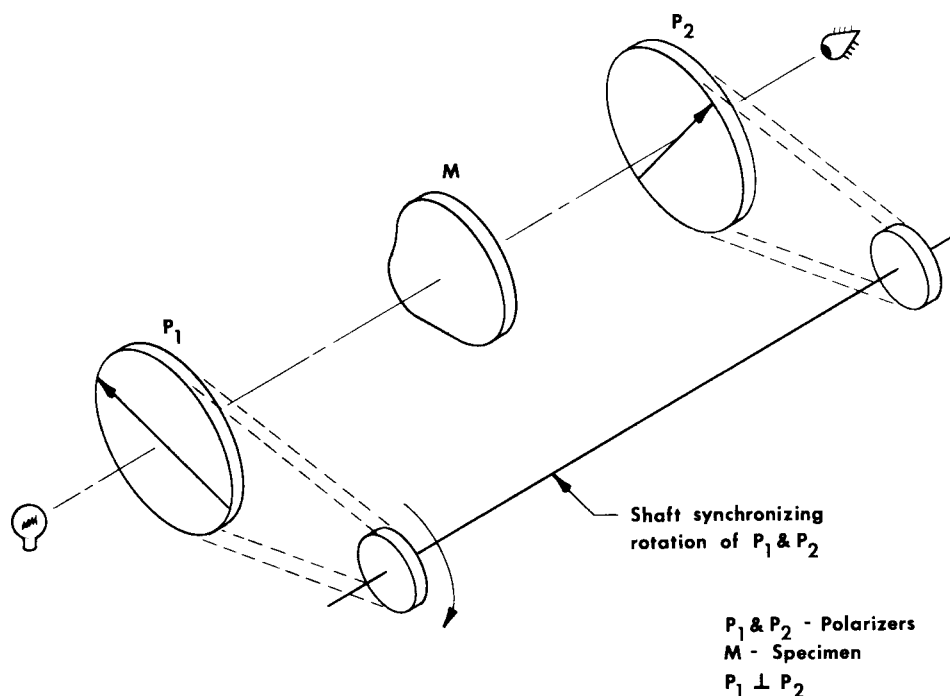


FIG. 2 Transmission Set-up of Polariscope

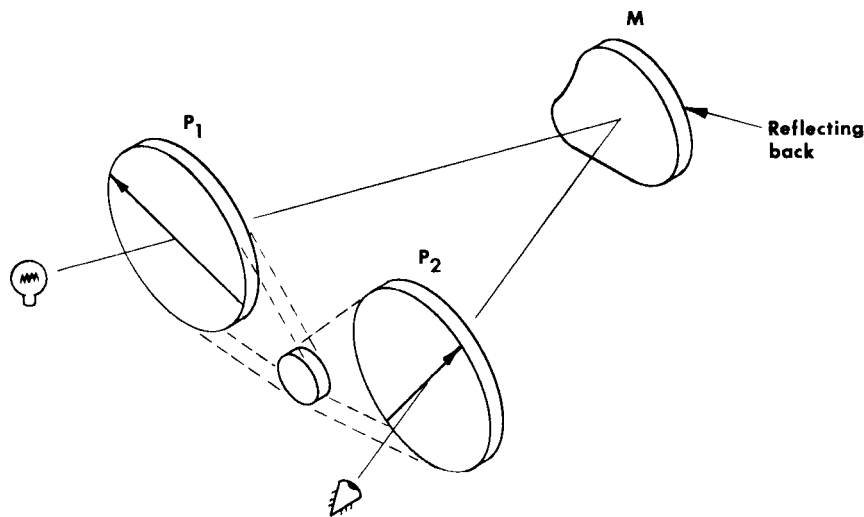


FIG. 3 Reflection Set-up of Polariscope

5.3 When testing for physical properties, polariscopic examination of specimens is required, to eliminate those specimens exhibiting abnormal internal strain level (or defects). For example: Test Methods D 638 (Note 8) and D 882 (Note 11) recommend a polariscopic examination.

5.4 The birefringence of oriented polymers can be related to orientation, shrinkage, etc. The measurements of birefringence aid in characterization of these polymers.

5.5 For many materials, there may be a specification that requires the use of this test method, but with some procedural modifications that take precedence when adhering to the specification. Therefore, it is advisable to refer to that material specification before using this test method. Table 1 of Classification System D 4000 lists the ASTM materials standards that currently exist.

6. Apparatus

6.1 The apparatus used to measure strains is shown schematically in Fig. 4. It consists of the following items:

6.1.1 Light Source:

6.1.1.1 *Transmitted-Light Set-Up*—An incandescent lamp or properly spaced fluorescent tubes covered with a diffuser should provide a uniformly diffused light. To ensure adequate brightness, minimum illumination required is 0.3 W/in.² (0.0465 W/cm²). Maximum light source power is limited to ensure that the specimen temperature will not change more than 2°C during the test. The incandescent lamp must be selected to provide a color temperature no lower than 3150 K. There should be no visible nonuniformity, dark or bright spots