How to Select Photoelastic Coatings

Introduction

The proper selection of photoelastic coating materials is as important to this method of experimental stress analysis as gage and adhesive selection are to the strain gage user. Although the selection of a coating material is largely a matter of common sense, it is helpful to follow a systematic procedure in order to avoid the omission of one or more important considerations. Naturally, the primary desire is to select a coating material that will give maximum reliability and accuracy under a given set of test circumstances, and do so with minimum effort and expense. Since there are numerous factors that affect the performance of a photoelastic coating, and a variety of sometimes conflicting performance requirements, a compromise is often necessary. The terms of the compromise are usually dictated by the ultimate purpose and conditions of the test.

The best practice is to list all the factors important to the particular application and satisfy the more critical requirements first. Following are the principal considerations in the selection of a photoelastic coating for a specified set of test conditions:

1. Method of plastic application to the test surface
2. Sensitivity
3. Contour severity
4. Reinforcing effect
5. Maximum elongation
6. Test temperature

1.0 Method of Plastic Application

Photoelastic coatings are available in two basic forms:

- Solid flat sheets
- Liquids for casting contourable sheets

There are several different types of coating materials available in each of the forms; and these can be classified generally into three categories according to their elastic moduli — that is, high-, medium-, and low-modulus materials. Micro-Measurements Document Number 11222 includes descriptions and properties of all of the materials.

When the surface of the test part to be coated is flat, it is preferable to use flat sheets, since these offer the following advantages:

- Uniform thickness (tolerance, ±0.002 in and ±0.003 in [±0.05 mm and ±0.08 mm], depending upon the material type)
- Uniform physical and photoelastic properties
- Ease of handling
- Availability from stock or within four weeks of order placement

For irregularly shaped structures which cannot be coated with flat sheets, liquid plastic must be selected and applied using the contoured-sheet method. (See Application Note IB-221, "*Instructions for Casting and Contouring PhotoStress® Sheets*".)

2.0 Sensitivity

Perhaps the single most important factor to be considered in the selection of a photoelastic coating is the birefringent sensitivity of the plastic material, since this property is involved in the basic equation used for photoelastic coating analysis:

Table 1

Typical Application	Light Source	Reflection Polariscope Model LF/Z	Sensitivity of Instrument or Method	Average Overall Sensitivity of Measurement	Number of Fringes to be Observed (N)
Laboratory testing room with shades or darkroom; large or small specimens; static testing	White	Null balance compensation	1/50 fringe	1%	1 to 4
Static testing in field or under difficult lab conditions; slowly moving parts	White	Null balance compensation	1/25 fringe	2%	1 to 4
Vibrating or rotating parts	Stroboscopic light	Null balance compensation	1/25 fringe	2%	1 to 4
High fringe order expected; measurement in the plastic range of deformation	White	Black & white photographs using a monochromator	1/2 fringe	4%	5 to 20
Dynamic or static measurements using color photography for recording; interpretation of high-speed motion pictures; visual interpretation	White	Color matching or color estimating	1/5 fringe	≈10%	1 to 4

$$\varepsilon_1 - \varepsilon_2 = \gamma_{MAX} = N \bullet \frac{\lambda}{2t_c K} = N \bullet f$$

where: $\varepsilon_1, \varepsilon_2$ = principal strains, in/in [m/m]

γ_{MAX} = maximum shear strain, in/in [m/m]

N = fringe order, dimensionless

λ = wavelength of light used in polariscope, in [m] — usually taken as 22.7 x 10^{-6} in [0.577 x 10^{-6} m] for white light

t_c = coating thickness, in [m]

K = strain-optic coefficient of the *plastic material*, dimensionless

f = fringe value, or coating sensitivity, accounting for the thickness of the coating, in/in per fringe [m/m per fringe]

As the foregoing equation shows, the overall sensitivity in strain measurement depends primarily upon two elements:

1. The sensitivity of the coating as expressed by the fringe value, f. The fringe value represents the difference in principal strains, or the maximum shear strain, required to produce one fringe. The lower this parameter, the more sensitive the coating.
2. The sensitivity of the polariscope system for examining the photoelastic pattern and determining the fringe order, N.

The number of fringes to be observed and measured depends upon the test conditions and the type of instrumentation employed. Table 1 gives, for a variety of test conditions, the instrumentation needed, the number of observable fringes, and the expected measurement sensitivity. Assuming, with the aid of Table 1, the number of fringes to be observed, and estimating the expected strain level, the desired coating sensitivity, or fringe value, is calculated as follows:

$$f = \frac{\varepsilon_1 - \varepsilon_2}{N} = \frac{\gamma_{MAX}}{N} = \frac{\text{expected strain level}}{\text{max. number fringes desired}}$$

Ideally, the expected strain level will correspond to incipient yielding of the material under stress analysis. In practice, however, a lower strain level is often imposed by specified test and loading conditions. When no better information is available, Table 2 can serve as a guide for estimating the strain level to be expected for several broad classes of test conditions.

Table 2

Typical Test Conditions	Expected Strain Level
Elastic range; freedom to load the part as desired	Yield Strain
Elastic range; load prescribed below the yield strain	1/2 Yield Strain
Elastoplastic range; slight localized yielding	Yield Strain
Plastic range only; eventual rupture	1/2 maximum elongation of the material

How to Select Photoelastic Coatings

Once the fringe value has been established from the expected strain level and number of fringes, the type and thickness of the plastic which will satisfy the sensitivity requirement can be determined with the following relationship:

$$f = \frac{\lambda}{2t_c K}$$

For convenience in plastic selection, this relationship has been plotted parametrically in Figure 1. The figure shows standard coating thicknesses and the ranges of the strain-optic coefficient for which there are available materials. To use the graph, enter along the ordinate at the appropriate value of f and project horizontally until an intersection with a sloped thickness line which falls within one of the cross-hatched zones is found. This intersection defines a value of K, read from the abscissa, and a coating thickness which are consistent with the sensitivity requirement.

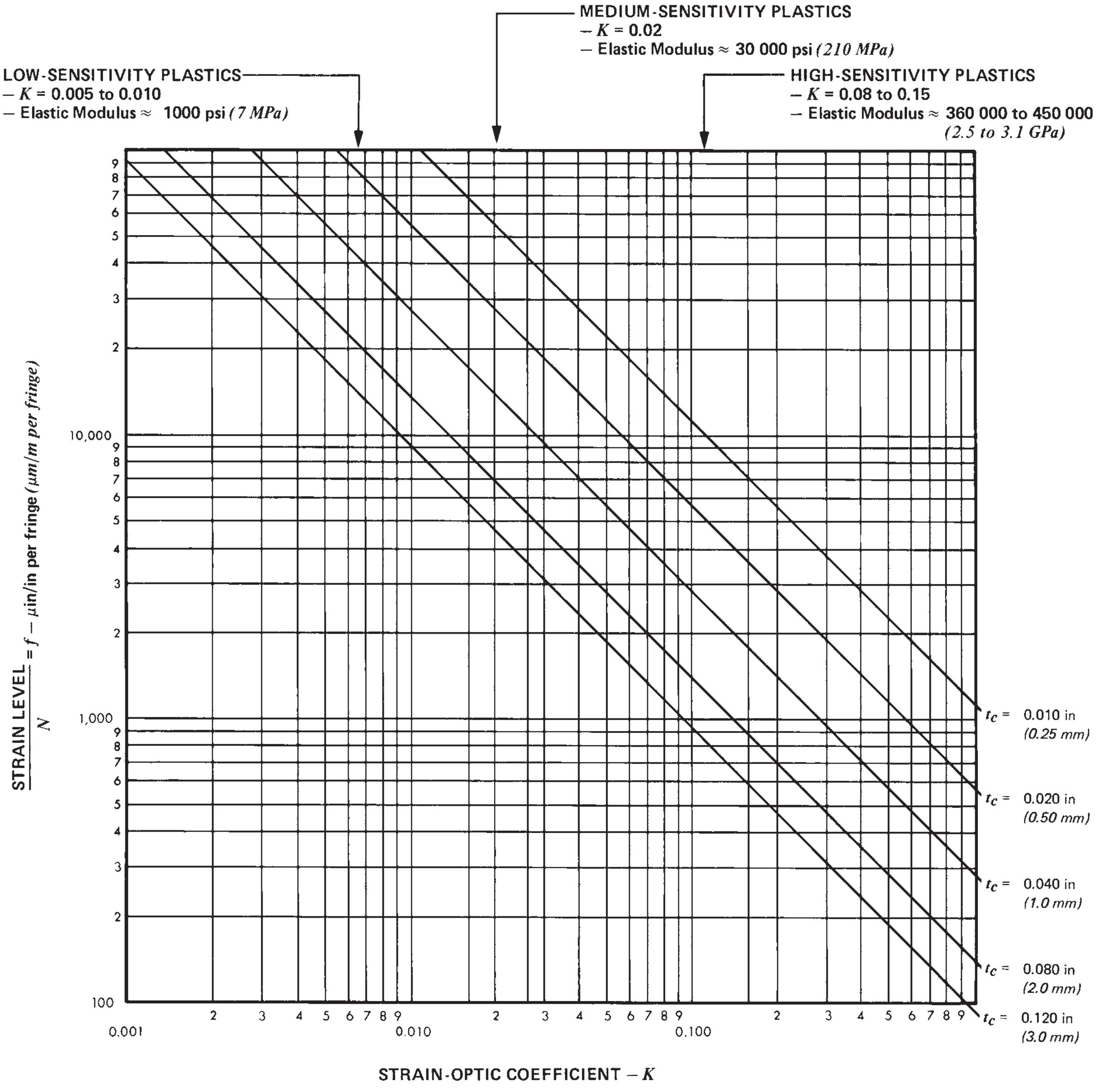

Figure 1

How to Select Photoelastic Coatings

(For use with non-standard coating thicknesses, additional thickness lines between 0.010 in [0.25 mm] and 0.120 in [3 mm] can be plotted on the graph as necessary.) If no such intersection can be found, it will generally be necessary to accept a lower sensitivity and work with fewer fringes. The following exercise will illustrate the procedure.

Numerical Example

Assume that the expected strain level is 3600 μin/in [μm/m]. The maximum observable number of fringes for a coating illuminated with white light is approximately four. Therefore,

$$f = \frac{3600 \times 10^{-6}}{4} = 900 \times 10^{-6}$$

From Figure 1, it is evident that either of two standard thicknesses can be selected. That is, either 0.120 in [3 mm] with a K of approximately 0.10, or 0.080 in [2 mm] with a K of about 0.16. With contourable-sheet coatings, other thicknesses can be selected from the same general area of the graph. In certain instances (discussed in the following section) the plastic may materially reinforce that test member. For such cases the thinnest coating giving adequate sensitivity would be selected.

Assume now that the original estimate of the expected strain level was grossly in error, and the strain is only 1400 μin/in [μm/m]. Recalculating the fringe value,

$$f = \frac{1400 \times 10^{-6}}{4} = 350 \times 10^{-6}$$

Referring to Figure 1, it can be seen that no available combination of sheet thickness and strain-optic coefficient will be sensitive enough to produce four fringes at the applied strain level. However, if the maximum number of desired fringes is reduced to two, f becomes 700, and Figure 1 shows that a coating 0.120 in [3 mm] thick with a K of about 0.13 will be suitable. From Table 1 it can be verified that two fringes will provide an overall sensitivity of approximately one percent when the measurement is made with a null-balance compensator.

3.0 Contour Severity

Another instance when a thinner and less sensitive coating may be required occurs when sheets must be contoured over highly convoluted surfaces. If the surface to be coated has small-radius compound curvatures, it will be necessary to select a coating thickness such that the sheet can be contoured over the projections and into the recesses while maintaining uniform sheet thickness. As a general rule of thumb, the sheet thickness should be less than 20 percent of the radius of curvature of the surface. Somewhat greater thicknesses are satisfactory for simply curved surfaces.

4.0 Reinforcing Effect

As noted earlier, there are certain cases in which a thick coating may produce a significant reinforcing effect that must be taken into account if accurate results are to be obtained. On structural members such as "I", "H", "U", or box beams and on heavy wall sections, tubular structures, castings and the like, the reinforcement caused by the plastic coating is negligible and can be ignored. The reinforcing effect is usually negligible for plane-stress problems (pressure vessels, plates, and panels with the load applied in the plane of the panel), and for membrane stresses produced with little or no bending.

However, when thin beams or plates are subjected to bending, the plastic coating reinforces the test part noticeably, and the measured strain must be corrected for this effect. Also, in the case of low-modulus materials like plastics, the reinforcing effect for plane stress cannot be ignored, and must be corrected. The factors responsible for the reinforcement error in bending are as follows:

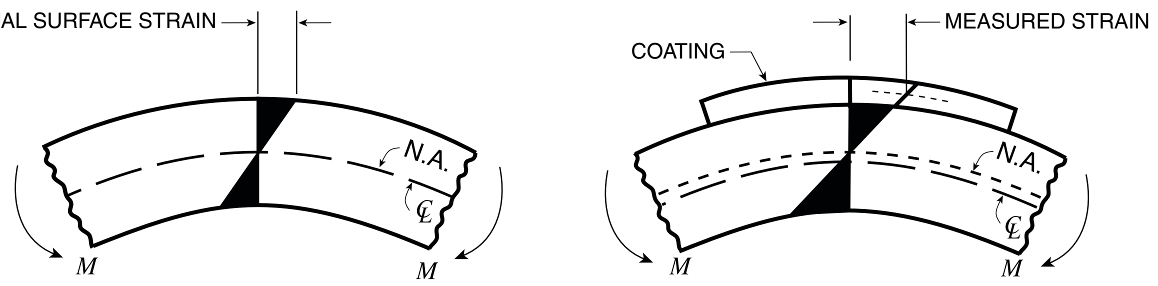

Figure 2

1. The neutral plane shifts toward the coating.
2. The section is stiffened, and thus the curvature produced by a prescribed bending moment is smaller.
3. The photoelastic reading is averaged through the plastic.
4. The average strain in the coating is greater than the strain at the surface of the test specimen.

It will be noticed that the third and fourth factors above are not reinforcement effects as such, but photoelastic and geometric effects, respectively. As shown in Figure 2, however, all four effects act in concert, and it is convenient to lump the errors, thus permitting adjustment of the data with a single correction factor as described in Tech Note TN-706.

5.0 Maximum Elongation

The maximum measurable strain for a particular photoelastic coating depends upon its stress-strain curve and the linearity of photoelastic behavior. Table 3, below, gives the allowable elongations for some typical coatings. The performance required of a coating for measuring fully plastic strains in metals is different from that for the elastic or elastoplastic ranges. With plastic strains, coating sensitivity is less significant because of the high strains present. The most critical consideration is the ability of the coating and adhesive to follow the metal into the plastic region. There are two different approaches to solving this problem:

Table 3

Coating Material	Maximum Elongation	Typical Application
PS-1	5%	Testing on metals, Concrete, glass, and hard plastics in the elastic and elastoplastic ranges.
PS-10	3%	
PL-1	3%	
PL-10	3%	
PS-3	30%	Testing on soft materials such as rubber, plastics, and wood.
PL-2	50%	
PL-3	>50%	
PS-4	>40%	
PS-6	>100%	Testing on soft materials such as rubber, plastics, and wood.

1. A very thin coating of the higher elastic modulus plastics (PS-1, PS-10, PL-1, or PL-10) is selected.
2. A thicker coating of the lower elastic modulus plastics (PS-3, PL-2, PL-3, PS-4, PS-6) is employed.

The choice between the above alternatives depends upon the information being sought on a particular application. For example,

- *Localized plastic deformation (Lueder's lines) —*

  Select a thin coating of the high elastic modulus plastic to minimize the reinforcement effect.
- *Stress distribution in the plastic range —*

  This is an ideal application for a thin coating of PS-1 because of its five percent elongation capability.
- *Crack propagation —*

  For this application, crack propagation in the coating should be slower than in the metal, and the proper selection is a thicker coating of a low elastic modulus plastic.

6.0 Test Temperature

If the test is to be performed at other than room temperature, consideration must be given to the effects of temperature on the behavior of the coating. All of the technical information supplied on the coating label refers to room-temperature properties of the material. If the temperature changes during a test, several of these properties will be affected.

Consider, for example, the strain-optic coefficient, *K*. Figure 3 illustrates the general manner in which the strain-optic coefficient varies with temperature for typical coating materials. The coatings (except PS-1) normally exhibit two temperature ranges over which it varies rapidly with temperature. While the plastics can be used in either constant-*K* range, it is important to select a material for which *K* remains constant throughout the entire temperature range of the test.

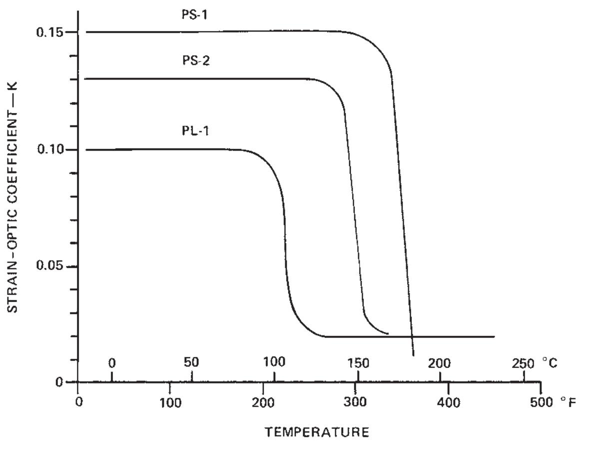

Figure 3

How to Select Photoelastic Coatings

There are additional thermal effects which must also be considered whenever tests are conducted at other than room temperature. For a detailed analysis of these effects and a list of recommended practices for specific situations, the user is referred to: *"Photoelastic-Coating Analysis in Thermal Fields"*, by F. Zandman, S. Redner, and D. Post.

Summary

The information given here on coating selection is based on many years of practical experience with photoelastic coatings. These recommendations can be reduced, in essence, to answering two fundamental questions involved in all instrumentation: (1) Precisely what is to be measured? (2) What degree of accuracy is required? The answers to these questions, along with the physical nature of the part to be stress analyzed, determine the optimum selection of plastic material, coating thickness, and method of application to yield the desired results.

Particular care should be taken not to set unrealistic test requirements which may only complicate the test and add to the time and expense without generating data which are necessary to the purpose of the test. At the same time, an attempt should not be made to read information into the test results which cannot be obtained practically and easily with the selected materials and available instruments.

Whenever questions or problems arise in the selection of a photoelastic coating for a particular job, users should contact the Micro-Measurements Applications Engineering Department at (919) 365-3800 or mm@vpgsensors.com.

Technical References

Document 11222, "Coating Materials and Adhesives"

Tech Note TN-701, "Calibration of Photoelastic Coatings"

Tech Note TN-702, "Introduction to Stress Analysis by the PhotoStress® Method"

Tech Note TN-706, "Corrections to Photoelastic Coating Fringe-Order Measurements"

Tech Note TN-708, "Principal Stress Separation in PhotoStress® Measurements"

Application Note IB-221, "Instructions for Casting and Contouring PhotoStress® Sheets"

Application Note IB-223, "Instructions for Bonding Flat and Contoured PhotoStress® Sheets to Test-Part Surfaces"

Additional References

Post, D. and F. Zandman. "Accuracy of Birefringent-coating Method for Coatings of Arbitrary Thickness." *Experimental Mechanics* **1**: 21-32 (January 1961)

Redner, S. "Photoelastic Coatings." *Experimental Mechanics* **20**: 403-408 (November 1980).

Zandman, F., S. Redner and J. W. Dally. Photoelastic Coatings. Ames, Iowa: Iowa State University Press, 1977.

Zandman, F., S. Redner and D. Post. "Photoelastic-coating Analysis in Thermal Fields." *Experimental Mechanics* **3**: 215-221 (September 1963).

Zandman, F., S. Redner and E. I. Riegner. "Reinforcing Effect of Birefringent Coatings." *Experimental Mechanics* **2**: 55-64 (February 1962).