Stress Whitening of Polymer Blends as a Tool for Experimental Stress Analysis

Observations outlined in this technical note indicate that, although the initial experimental results are of low accuracy, the method has some merits

by R. H. Shoulberg and E. R. Lang

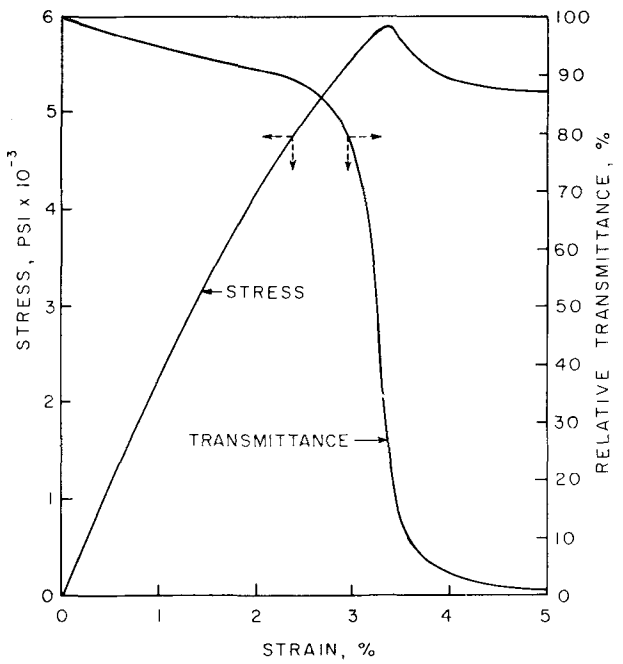


Fig. 1—Stress and relative light transmittance as functions of strain for experimental material "A"

Introduction

The increase in opacity, known as blanching or "stress whitening," of blends* of certain polymeric materials under tensile stress is a well known phenomenon to those engaged in the manufacture or use of such polymers. However, most—if not all—of these materials have, until recently, been opaque or barely translucent (in sheets, say, $^1/_4$ in. thick). A number of experimental polymers made during the past few years in these laboratories are almost transparent in a stress-free state, but become quite opaque over a narrow range of tensile stress almost coincident with the maximum load-carrying capacity of the material. Observations of the behavior of these polymers suggested that one might determine stress-concentration factors by visual examination of specimens under measured loads. Although the initial experimental work showed results of low accuracy, the method appears to be unique and has some merits. The experimental results and a discussion of the technique are presented in the following sections.

R. H. Shoulberg and E. R. Lang are associated with Research Laboratories, Rohm & Haas Co., Bristol, Pa.

Materials

Three materials were selected for initial testing: two cast materials of a high degree of transparency and an injection-molding material which, although not as transparent as the cast materials, shows the same well-defined stress whitening.

Figure 1 shows the relative total white-light transmittance and the tensile stress for cast experimental material "A" as functions of strain for a $^1/_4$-in. thick specimen of uniform cross section, strained at a constant rate of about 0.007 in./in./min at 23° C. The transmittance was measured using a standard automobile light bulb and a Weston Model 594 photronic cell. The total white-light transmittance measured using an integrating sphere is 86 percent at 23° C. (The transmittance is a function of temperature because of different temperature coefficients of the refractive indices of the two phases which are present in these materials, as is explained below.) The curves of Fig. 1 are quite reproducible for different samples of the same material under a given set of testing conditions; in particular, the stress at maximum load shows standard deviations of a few percent if a large number of specimens are tested. However, the stress at maximum load will show a slow linear increase with the logarithm of the straining rate. The stress at maximum load is 5900 psi at 1 percent strain/min; at 10 percent strain/min it is about 6300 psi; and at 100 percent strain/min, about 6700 psi. The important points to be noted in

* *Blends are defined as polymers made in such a fashion that at least two distinct phases are present in the material. The milling together of two polymers, for example, can result in a blend.*

TABLE 1—PHYSICAL PROPERTIES OF TEST MATERIALS

Material	Stress at max. load, 1% strain/min at 23° C, psi	Total white-light transmittance, 1/4 in. sheet, %	Parallel-light transmittance, 1/4 in. sheet, %
A (cast)	5900	86	65
B (cast)	4300	84	35
C (injection molded)	4900	52	25

Fig. 1 are: (1) the rapid decrease in light transmittance over a small stress range; (2) the fact that the relative transmittance starts its precipitous fall slightly before the maximum stress is reached and is equal to only about 30 percent at maximum stress; and (3) the unfortunate fact that the stress–strain curve is nonlinear both before and during the rapid transmittance change. Materials "B" and "C" show similar features, although their properties differ, as shown in Table 1.

Stress whitening is believed to have two causes; the relative contributions from each cause are not easy to assess, but both relate to the polymer structure. The blends are composed of two phases: a hard glassy matrix and a particulate phase of rubbery material. These phases are, on a microscopic scale, well defined, and it is believed that opacity results in part from the scattering of light from interfacial voids which arise under stress. Cavities in the glassy matrix undergo an increase in volume under a tensile stress while the rubbery particles filling these cavities, because of differences in their elastic properties, have a greater resistance to dilatation. When the tensile strength of interfacial bonds is exceeded, parting occurs and a void forms. Whitening will also occur in pure shear, but it is important to note that, whereas whitening occurs in uniaxial tension at 4300 psi for material B, it occurs in pure shear at about 5300 psi, while in uniaxial compression only hazing was noted at 10,400 psi, after which the specimens tested failed by buckling. Thus, the whitening occurring in uniaxial tension does not result from the action of shearing stresses. A beam in pure bending will whiten on the tensile side of the neutral axis, but will usually fail before any whitening is seen on the compressive side. Whitening can also result from scattering of light from cracks in the hard matrix and, in a material with a compressive strength significantly higher than its tensile strength, all of the above observations can be explained by postulating the growth of a network of fine cracks about the rubbery particles as the stress level increases. It is felt at present that both causes of whitening are present: void formation predominating in the early stages of whitening, and matrix cracking predominating near the point where the maximum load is reached.

TABLE 2—STRESS-CONCENTRATION FACTORS

Material	Width of testpiece, in.	Hole diameter, in.	Calculated stress-concentration factor	Stress-concentration factor from photoelastic measurements*
A	2	1/2	2.07	2.36
A	2	1/2	2.20	2.36
A	2	1/8	2.18	2.73
A	2	1/8	2.08	2.73
B	1/2	1/4	1.77	2.15
B	1/2	1/4	1.85	2.15
B	1 1/2	1/8	2.67	2.68
C	1/2	1/8	1.71	2.36
C	1/2	1/8	1.86	2.36
C	1/2	1/4	1.69	2.15
C	1/2	1/4	1.70	2.15

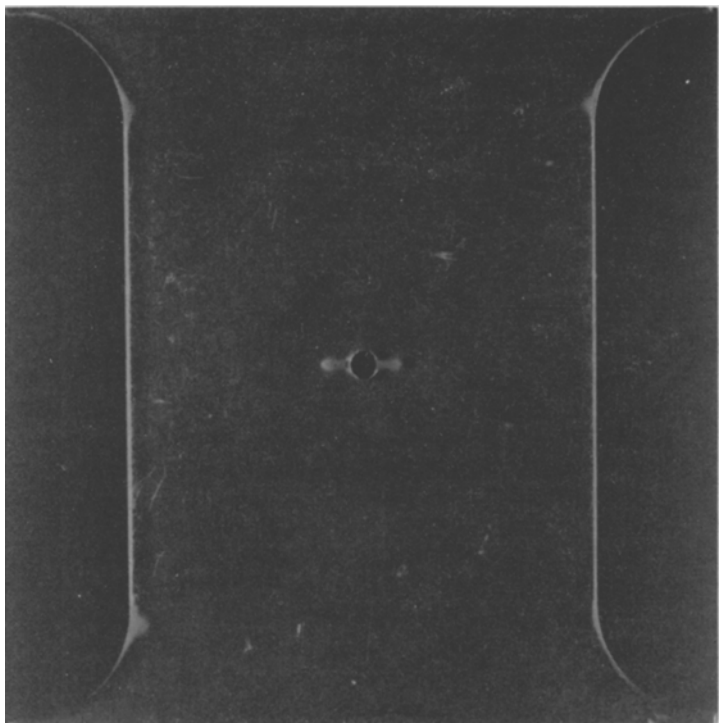
* M. M. Frocht, Jour. Appl. Mech., **2**, 67 (1935).

Measurements of Stress-concentration Factors

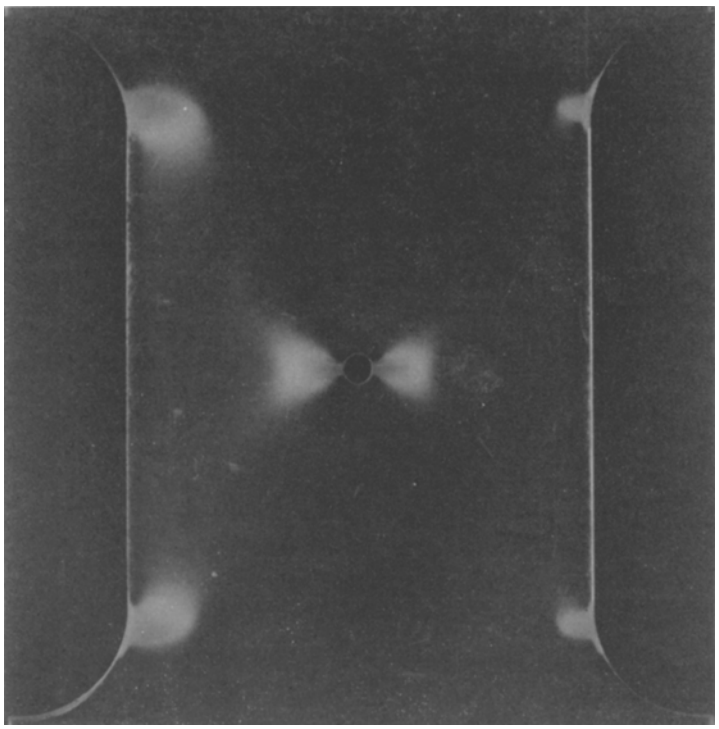
Test samples were made by drilling holes of various diameters in necked tensile specimens of various widths, all having a thickness of 1/4 in. The bars were pulled at a constant crosshead rate, corresponding to a strain rate of about 1 percent/min, on an Instron machine, and the load at which the edge of the hole (at points on the diameter transverse to the direction of pull) rather suddenly whitened was noted. The average stress in the net cross section of the specimen was calculated, and the ratio of the stress at maximum load from Table 1 (chosen because whitening essentially corresponds with reaching maximum load) to this average stress was computed; this ratio is listed in Table 2 as the stress-concentration factor.

Discussion and Conclusions

It is clear from the results shown in Table 2 that the stress-concentration factors based upon the stress-whitening phenomenon are significantly smaller than those measured by more accurate methods; the exceptional case where agreement is good is probably accidental. The principal reason for the discrepancy is almost certainly the nonlinearity of the stress–strain curve before whitening occurs; it is also possible that residual stresses affect the results, but these are probably of much less importance. As a tool for quantitative evaluation, the method cannot be recommended for its accuracy. However, in spite of its severe shortcomings, the method has three merits: (1) it is extremely simple, requiring only a measurement of load in order to obtain semiquantitative results (this would seem to recommend it for educational purposes). (2) It would appear to be useful in three-dimensional problems where, in many cases, even an approximate result can be obtained by other techniques only with considerable effort. (3) It differs from photoelastic techniques in that areas of high tensile stresses may be approximately defined and in some cases, at least, immediately distinguished from areas of high shear stress, thus eliminating the need for determining the tensile stress from a knowledge of the dif-



a



b

Fig. 2—Growth of whitened area around a hole in a tension member (experimental material "A")

ferences between principal stresses. To illustrate this latter point, Fig. 2 shows a photograph of two stages in the growth of the whitened area around a $^1/_8$-in. round hole in a 2-in. wide tensile bar. The whitened area in Fig. 2a results from the action of tensile stresses. As the stress level increases, the

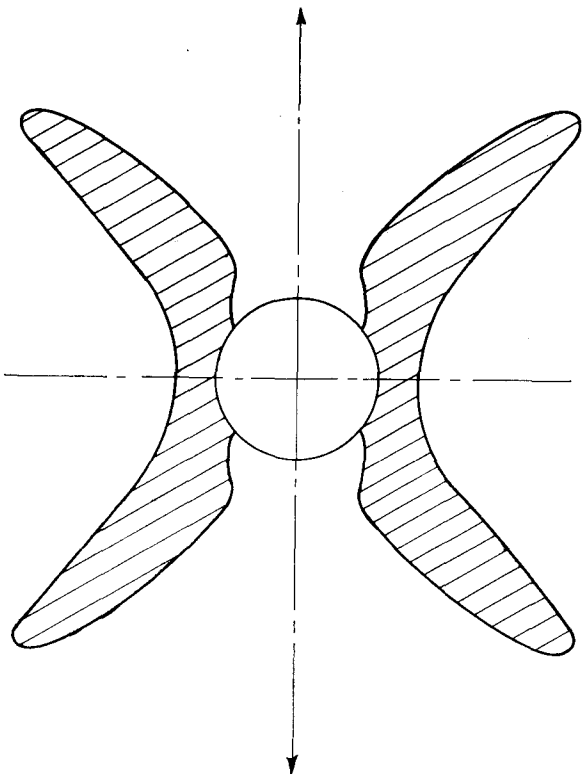


Fig. 3—Spreading of plastic zone in a tension member (after Nadai)

whitened area increases and begins to show whitening resulting from shear stresses. It is interesting to compare Fig. 2b with Fig. 3, a sketch of the spreading of the plastic region from a hole in a tension member after Nadai.* The contour in the latter figure is one of maximum shear stress and, if whitening occurred only as a result of shear, one would expect the edge of the whitened zone in Fig. 2b to correspond to the contour of Fig. 3, which it clearly does not.

Finally, some mention should be made of the fact that brittle models, made of, say, plaster of Paris, in many cases also give stress-concentration factors lower than those found by theoretical or photoelastic methods.† The question arises as to whether the plaster models have some feature in common with the polymer blends which leads to low stress-concentration factors. It has already been mentioned that the stress-whitening results are believed to be inaccurate because of the nonlinearity of the stress–strain relationship. Moreover, the polymer models are not strained to complete failure, while the plaster models reportedly show Hookean behavior to the failure point. It appears, therefore, that the inaccuracies of these two methods do not have a common cause.

* *A. Nadai, Theory of Flow and Fracture of Solids, McGraw-Hill, 1950, page 291. (The authors are indebted to Charles H. Parr of the Redstone Arsenal Research Division of the Rohm & Haas Co. for mentioning this work.)*

† *M. Hetenyi, Handbook of Experimental Stress Analysis, Wiley, New York, 1950, Chap. 14.*