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A Relation Between Toughness and the Dynamic Mechanical Properties of Polymer Films

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Synopsis

A relation is shown to exist between toughness and the dynamic mechanical dissipation factor when both are evaluated under the same conditions. In addition to exploring why this relation exists, its limitations are considered.

INTRODUCTION

It is of interest to establish a relationship between the ability of a material to withstand an impact and its dynamic mechnical properties. This is because such a relationship may give insight into how structure influences impact strength, and because it has obvious extensions to impact fatigue and wear resistance and improved behavior under cyclic loading.

Although it is well known that dynamic mechanical measurements are confined to the elastic region while impact strength measurements deal with the plastic region, it is also well documented[1-6] that various correlations do exist between these two measurements: while several deal with the integration of dissipation factors between two arbitrary temperatures[1,3-5] or the presence or absence of a low-temperature loss peak,[2] only one[6] demonstrates that resistance to impact requires a dynamic mechanical energy dissipation mechanism at the temperature and frequency of the impact. This latter study indicates the existence of some relation between resistance to impact and the magnitude of the dynamic mechanical dissipation factor *evaluated at a definite temperature and frequency,* rather than integrated between two arbitrary temperatures. It is the purpose of this note to indicate the existence of such a relation, and to explore its limitations.

Although impact strength is usually derived from procedures such as the Izod or Charpy tests (ASTM D256), such procedures are not applicable to the thin films considered here. Instead, resistance to impact was measured in terms of toughness (the integrated stress–strain curve), it having previously been shown[7] that toughness measured at high strain rates (0.333 in./sec) correlated with impact strength.

EXPERIMENTAL

A wide variety of thin films was chosen to establish the relationship. They include (a) 2.5-mil duPont Fairprene Type UN 0001 polyurethane-impregnated nylon fabric, (b) 1-mil duPont Kapton Type H polyimide film, (c) 2-mil duPont Tedlar Type SG40TR poly(vinyl fluoride) film, (d) 2.5-mil Bayer Makrofol Type KG polycarbonate film, and (e–g) 15-mil samples of Conap Types DPPA 4541, 4546, and 4547 polyurethane elastomer coatings. These coatings were cast on du Pont Teflon sheet, cured according to the manufacturer's directions, and stripped.

Dynamic mechanical properties were determined on a Toyo Rheovibron direct-reading viscoelastometer Model DDV-II, at frequencies of 3.5, 11, 35, and 110 Hz, in the temperature range of −100° to +100°C. Toughness was evaluated from the stress–strain curve obtained on an Instron Model TT-D tensile tester, at a temperature of 25°C and a strain rate of 0.333 in./sec. In each case, three to five samples were run and averaged.

RESULTS AND DISCUSSION

As determined from the rise time of the impact,[8] typical impact frequencies lie in the kHz range. Such a range is accessible only with difficulty for dynamic mechanical measurements, the usual procedures being either to extrapolate or to carry out a transformation[9] capable of shifting the data into this range. The present procedure involves extrapolation, in order to obtain equivalent data in a frequency range more amenable to measurement.

Dissipation factor–temperature plots established the shapes and temperature maxima of the loss peaks. Within the precision of the experiment, these gave linear Arrhenius plots whose slopes indicated the change in loss peak temperature with frequency. These slopes were such that a reasonable 5-kHz impact frequency at 25°C extrapolates back to 0–15°C at 11 Hz, one of the Rheovibron measuring frequencies. The calculated activation energies range from 15 to 40 kcal/mole for the peaks considered.

If the ability to withstand an impact depends on the magnitude of the dissipation factor in the temperature and frequency range of the impact, one should be able to correlate the toughness with this property *or its equivalent extrapolated to a more conveniently measurable range.* Because of the relatively narrow range of activation energies and the ±10% precision of the measurements, it is convenient to assume that all the peaks have the same activation energy; that is, it is convenient to assume that the impact conditions extrapolate to the same temperature at the chosen experimentally accessible frequency, for all the materials considered. Since, as previously noted, the temperature range at 11 Hz was 0–15°C, I have chosen to correlate the toughness with the magnitude of the dissipation factor at an average 10°C at 11 Hz.

The plot in Figure 1 was constructed using the data in Table I. Only the Tedlar falls significantly off the straight line. The stress–strain curve showed the reason for this: the material elongated some 200%, with the toughness at the yield stress accounting for only 1.65% of the total toughness. That is, plastic deformation contributed more than 98% of the toughness. This is shown in Figure 2. Since the plastic contribution for this material far overshadows the elastic contribution and the dissipation factor is measured in the elastic region, correlation between the two is not expected. However, when the total toughness of this material is replaced by the toughness at the yield stress, the (solid) point falls gratifyingly close to the line in Figure 1. The equation for that line is

$$\text{toughness (in. lb/in.}^3) = 1.606\times10^4 \tan\delta - 352. \qquad (1)$$

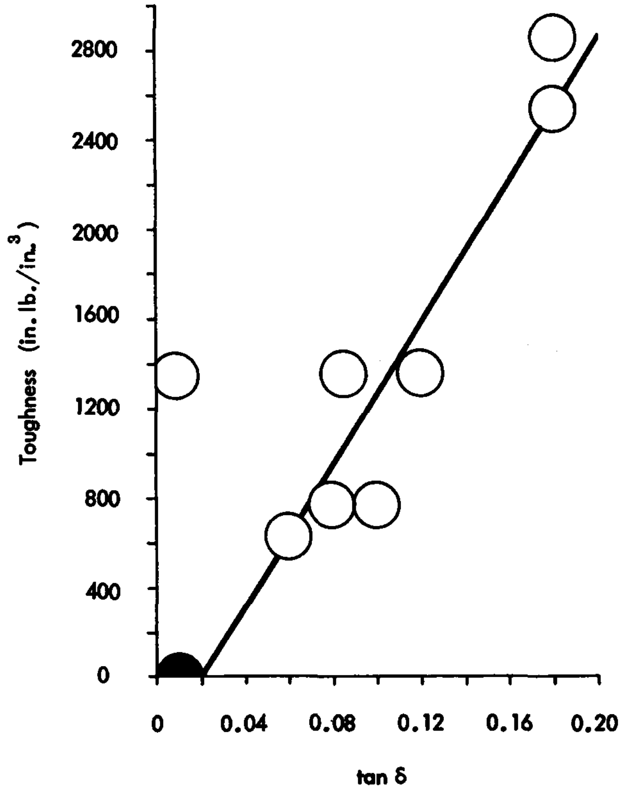

Fig. 1. Plot of toughness vs. dissipation factor. Solid point represents the toughness of Tedlar up to the yield stress.

The Tedlar data indicate that, for eq. (1) to hold, the toughness due to the elastic region must not be an insignificant fraction of the overall toughness. That is, since one may write

$$\text{toughness} = \int_0^{\epsilon_{\text{yield stress}}} \sigma d\epsilon + \int_{\epsilon_{\text{yield stress}}}^{\epsilon_{\max}} \sigma d\epsilon \tag{2}$$

eq. (1) is not expected to apply when

$$\int_0^{\epsilon_{\text{yield stress}}} \sigma d\epsilon \ll \int_{\epsilon_{\text{yield stress}}}^{\epsilon_{\max}} \sigma d\epsilon. \tag{3}$$

If, however, this proves to be the case, the toughness at the yield stress [first term on r.h.s. of eq. (2)] should be used in eq. (1).

The values of the slope and intercept in eq. (1) should not be viewed with significance, due to the arbitrariness of the measurement conditions. For example, the toughness evaluated at another high strain rate, or the dissipation factor determined at the appropriate temperature at another experimentally accessible measuring frequency, leads to different values in eq. (1), although the form is retained. The purpose of the equation is to show that, under appropriately chosen conditions, a linear relation exists between toughness and dynamic mechanical properties. It is surprising that the fit in Figure 1 is so good since, although the limitations of eq. (3) are not exceeded, the second term on the r.h.s. of eq. (2) contributes different amounts to the different materials. Fur-

TABLE I

Toughness and Dissipation Factor Values[a]

Material	Toughness at 0.333 in./sec and 25°C, in. lb/in.^{3}	tan δ at 11 Hz and 10°C[b]
Fairprene UN 0001	1360 ± 378	0.12
Makrofol KG (machine direction)	2860 ± 356	0.18
Makrofol KG (transverse direction)	2536 ± 240	0.18
DPPA 4541	627 ± 202	0.06
DPPA 4546	769 ± 351	0.10
DPPA 4547	769 ± 485	0.08
Kapton 100H	1350 ± 373	0.09
Tedlar 200SG40TR	1350 ± 33 (22.5 ± 4)[c]	0.01

[a] Averages of three to five runs.

[b] Precision: ±0.003 or less.

[c] Toughness contribution taken to the yield stress.

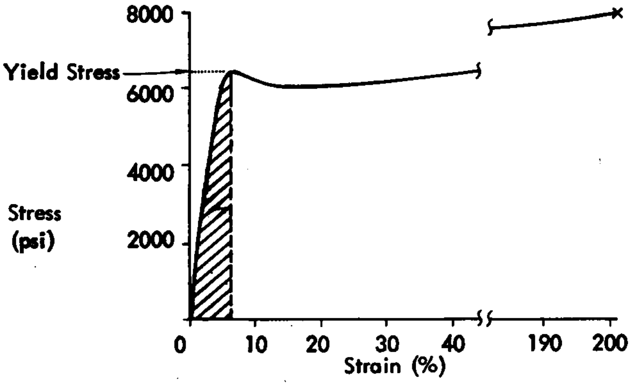

Fig. 2. Typical stress–strain curve for Tedlar. The shaded area, the toughness contribution taken to the yield stress, amounts to 1.65% of the total area to break.

ther, the activation energies were approximated to be the same, as was the impact frequency. All factors probably contribute to the scatter in Figure 1, as well as the nonzero intercept. In spite of this, the approximations appear reasonable.

Equation (1) is taken as confirmation of the previously proposed theory[6] that impact energy is dissipated through a dynamic mechanical mechanism in the temperature and frequency range of the impact. The present study has shown this to be so in the absence of large plastic deformations. The applicability of this correlation is shown by the wide range of materials used: impregnated fabric, glassy and rubbery films, and several structurally different elastomers.

One must not lose sight of the fact that, because a significant contribution to the toughness of Tedlar arises through plastic deformation, the present correlation indicates only that fraction of the toughness arising from the elastic region. Since the impact modification of commercial polymers may also lead to increased plastic deformation,[10–13] the present correlation may be similarly limited in these cases.

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