JOURNAL OF APPLIED POLYMER SCIENCE VOL. 11, PP. 1661-1665 (1967)

Relation Between Impact Strength and Dynamic Mechanical Properties of Plastics

YASAKU WADA and TETSUO KASAHARA, *Department of Applied Physics, Faculty of Engineering, University of Tokyo, Bunkyo-ku, Tokyo, Japan*

Synopsis

A simple theory is developed which correlates the Izod impact strength of polymers with $(G'_{100} - G'_{300})^2/G'_{100}$, where G'_{100} and G'_{300} are dynamic shear moduli at 100°K. and 300°K., respectively. The theory assumes the Maxwell element for the material and the fracture time smaller than the relaxation time. The theory is verified by experimental data for numerous polymers. Another approach which correlates the impact strength with the integrated loss factor from 0 to 300°K. is also proved valid.

Introduction

The purpose of an impact test is to measure the toughness or the resistance to breakage of materials under high velocity impact conditions. The impact strength is related to nonlinear mechanical properties of materials but it is useful to analyze it in terms of linear properties for the purpose of understanding its physical nature.

The Izod test (ASTM D256-56) uses a notched cantilever-type specimen which is struck on the free end by the hammer. The hammer has more than enough kinetic energy to fracture the specimen, so the strain rate is almost constant up to fracture. The impact strength is defined by the lost energy of the hammer through breakage of the specimen. This energy is the sum of three quantities: the energy required to fracture the specimen, the energy to throw the broken end of specimen, and the energy dissipated in the device supporting the fixed end of the specimen.

The purpose of this study is to correlate the notched Izod impact strength of various plastics to linear dynamic mechanical properties.

Theory

We assume here the impact strength I is proportional to the fracture energy W. If the specimen is struck by the hammer at $t = 0$ and broken at $t = t_0$,

$$W = K \int_0^{t_0} \sigma(d\epsilon/dt)dt \qquad (1)$$

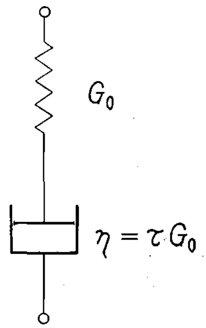

Fig. 1. Maxwell element.

where K is the constant, σ the stress, and ϵ the strain. The Maxwell element in Figure 1 is adopted here to represent the material. Then the stress under the constant rate of strain $d\epsilon/dt = \gamma$ is

$$\sigma(t) = \gamma\eta(1 - e^{-t/\tau}) \tag{2}$$

and therefore we obtain from eq. (1)

$$W = K\gamma^2\tau^2G_0[(t_0/\tau) - (1 - e^{-t_0/\tau})] \tag{3}$$

For small t_0/τ, the first-term approximation of W in the powers of t_0/τ is

$$W \simeq (K/2)\gamma^2\tau^2G_0(t_0/\tau)^2 \tag{4}$$

The linear viscoelasticity of the Maxwell element is expressed in terms of relaxation modulus,

$$G(t) = G_0e^{-t/\tau} \tag{5}$$

The value of $G(t)$ at $t = t_0$ is approximated for small t_0/τ by

$$G(t_0) \simeq G_0[1 - (t_0/\tau)] \tag{6}$$

From eqs. (4) and (6), we obtain

$$W \simeq (K/2)\gamma^2\tau^2[G_0 - G(t_0)]^2/G_0 \tag{7}$$

For the purpose of expressing W by dynamic modulus G', we replace G_0 (instantaneous modulus) by G' at a sufficiently low temperature, at 100°K. for example, where the frequency dependence of G' is not appreciable. Since the impact test is made at room temperature, $G(t_0)$ can be replaced by G' at 300°K. at the angular frequency $\omega = 1/t_0$. Then the final form for impact strength at room temperature is

$$I \simeq K'\tau^2[G'_{100} - G'_{300}(\omega = 1/t_0)]^2/G'_{100} \tag{8}$$

where K' is the constant.

Comparison of Impact Strength with Dynamic Shear Modulus

The fracture time t_0 for the Izod test has been reported as several milliseconds for the common plastic materials.[1] In the present study, we use

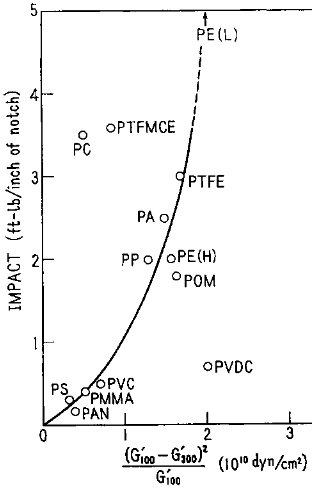

Fig. 2. Relation of Izod impact strength to dynamic mechanical modulus: PE(L), low-density polyethylene; PE(H), high-density polyethylene; PP, isotactic polypropylene; PTFE, polytetrafluoroethylene; PTFMCE, polytrifluoromonochloroethylene; PC, poly(bisphenol-A carbonate); PA, nylon 6; POM, polyoxymethylene; PS, polystyrene; PAN, polyacrylonitrile; PMMA, poly(methyl methacrylate); PVC, poly(vinyl chloride); PVDC, poly(vinylidene chloride).

G' values in the range of 0.1–10 cps because these frequencies do not deviate so much from $1/t_0$ and at the same time the data in this range are available for various polymers.

In Figure 2, the correlation between I and $(G'_{100} - G'_{300})^2/G'_{100}$ is illustrated. The impact values were obtained from conventional tables[2,3] and the recent literature.[4] In the cases where a range of values are presented, the median value was adopted. G' values were taken from the literatures.[5–9] For the cases in which only Young's modulus E' was available, E' was reduced to G' by multiplying by the factor 2/5.

A satisfactory correlation is found in Figure 2, except for a few polymers. The correlation is not linear, however, against the expectation from eq. (8) if τ is assumed constant. Of course, τ should vary from polymer to polymer. Short τ values are expected for materials of low impact strength which have a glass temperature higher than room temperature and hence τ is associated with a low temperature relaxation. Polymers with high impact strength, on the other hand, have a glass temperature near or below room temperature, so τ is associated with the primary relaxation and hence τ should be long. This may be the reason for the nonlinear correlation in Figure 2.

Exceptionally high impact values for polycarbonate and polytrifluoromonochloroethylene may presumably be ascribed to fracture times much longer than the reciprocal frequency at which G' is measured. According to LeGrand,[10] polycarbonate shows brittle fracture in the impact test, and the impact value is very much decreased when this polymer has been an-

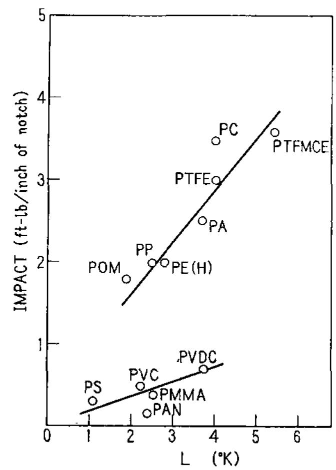

Fig. 3. Relation of Izod impact strength to integrated dynamic mechanical loss. Points identified as in Fig. 2.

nealed at 60°C. The low impact value of poly(vinylidene chloride) may in turn be ascribed to much shorter fracture time. However, measurement of the high-speed stress–strain curve may be necessary to reach a final conclusion.

Comparison of Impact Strength with Dynamic Mechanical Loss

The part of this study is an attempt to correlate the impact strength with the dynamic mechanical loss. Since the loss modulus $G''(\omega)$ is related to $G'(\omega)$ by

$$G'(\infty) - G'(0) = (2/\pi)\int_{-\infty}^{\infty} G''(\omega)d\ln\omega \tag{9}$$

it may be possible to substitute the modulus drop in eq. (7) by the integrated loss. In Figure 3, the impact strength is compared with the integrated loss tangent,

$$L = \int_{0^\circ\text{K.}}^{300^\circ\text{K.}} (G''/G')dT \tag{10}$$

The physical meaning of this correlation is that relaxation mechanisms from sufficiently short times (i.e., sufficiently low temperature) to t_0 should contribute to energy dissipation in the material. Relaxation mechanisms which contribute most to L are the primary relaxation for polymers with glass temperature near or below room temperature and local-mode or side-chain relaxations for polymers with high glass temperatures. In most polymers, values of loss tangent G''/G' are known only above liquid nitrogen temperature. The values are, however, so small below this point that L can be well approximated by the integration above 100°K.

In Figure 3, the plots are divided into two groups. The first group with high impact values includes polymers with low glass temperatures. Polymers with high glass temperatures belong to the second group. Polycarbonate is an exception in this case too.

The authors wish to express their thanks to Dr. K. Nakamura at Konishiroku Photo Industries Co. and Mr. H. Hirose at Dainihon Transparent Paper Co. for their valuable discussion. Thanks are also due to Dr. D. G. LeGrand at General Electric Co. for permission to cite his unpublished results.

References

1. W. E. Wolstenholme, *J. Appl. Polymer Sci.*, **6**, 332 (1962).
2. Plastics Properties Chart, *Modern Plastics Encyclopedia*, 1965.
3. L. E. Nielsen, *Mechanical Properties of Polymers*, Reinhold, New York, 1952, p. 122.
4. J. J. Pellon, N. M. Smyth, R. L. Kugel, K. J. Valan, and W. H. Thomas, *J. Appl. Polymer Sci.*, **10**, 429 (1966).
5. K. Schmieder and K. Wolf, *Kolloid-Z.*, **134**, 149 (1953).
6. J. A. Sauer and A. E. Woodward, *Rev. Mod. Phys.*, **32**, 88 (1960).
7. F. P. Reding, J. A. Faucher, and R. D. Whitman, *J. Polymer Sci.*, **54**, S56 (1961).
8. N. G. McCrum, *J. Polymer Sci.*, **54**, 561 (1961).
9. N. G. McCrum, *J. Polymer Sci.*, **60**, S3 (1962).
10. D. G. LeGrand, private communication.

Résumé

Une théorie simple est développée qui permet de relier la force d'impact Izod des polymères avec $(G'_{100} - G'_{300})^2/G'_{100}$ où G'_{100} et G'_{300} sont les modules de cisaillement dynamiques à 100°K et 300°K respectivement. La théorie suppose un élément Maxwell pour le matériau et un temps de cassure plus petit que le temps de relaxation. La théorie est vérifiée par les résultats expérimentaux pour de nombreux polymères. Une autre approche qui relie force d'impact avec le facteur de perte intégré de 0°K à 300°K a également été trouvée valable.

Zusammenfassung

Eine einfache Theorie zur Korrelierung der Izod-Schlagzähigkeit von Polymeren mit $(G'_{100} - G'_{300})^2/G'_{100}$, wo G'_{100} und G'_{300} die Werte des dynamischen Schubmoduls bei 100°K und 300°K sind, wird entwickelt. Die Theorie nimmt für das Material das Maxwell-Element und eine kleinere Bruchdauer als die Relaxationszeit an. Die Theorie wird durch Versuchsdaten an zahlreichen Polymeren bestätigt. Eine weitere Behandlung, bei welcher die Schlagzähigkeit mit dem von 0°K bis 300°K integrierten Verlustfaktor korreliert wirt, erweist sich ebenfalls als durchführbar.

Received January 10, 1967
Prod. No. 1574