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Phenomenology of Impact Resistance and Impact Testing

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Synopsis

The impact resistance of plastics can be described in terms of three contributions; these are the elastic, plastic, and crack propagation phases. By using a recording pendulum impact device it is possible to analyze any material as to the relative importance of the above phenomena. It was found that most plastics which exhibit good impact resistance have large plastic elongations or good resistance to crack propagation or both. A simple analysis of the cantilever beam impact shows that reasonable values of modulus and of maximum fiber stress can be obtained if care is taken to account for shear and compressive contributions to the overall response. It was also noted that plastic samples under impact conditions tend to bounce against the striker head.

Introduction

In 1962, Wolstenholme[1] reported his Autographic impact tester, which for the first time laid bare those features which contribute to impact resistance in plastics. It also facilitated the investigation of associated phenomena such as crack propagation times,[1] notch sensitivity, temperature dependence of maximum stress, etc.[2]

At the time the Autographic tester was introduced, members of our laboratories were working on an independent method of measuring crack propagation times.[3] A comparison of our results with those of Wolstenholme[1] lead us to believe that a transducer system with faster response times would be desirable. Accordingly, a pendulum was built incorporating the improved transducer as well as several other unique features.

Apparatus

Figure 1 depicts the basic pendulum. The arm is 3 ft. long which gives an intrinsically higher speed than the traditional Izod. A load mass near the axle raises this speed still higher so that a top striker speed of 25 ft./sec. is attainable with a 10-lb. mass. (In order to achieve this speed without the load mass a 6-ft. pendulum would be needed.) A counter weight permits continuous control of the arm speed from zero to 21 ft./sec., with a useful low range of about 3 ft./sec.

The clamping arrangement which is used is unique in that it is a mechanically operated constant pressure unit. This clamp has several advantages:

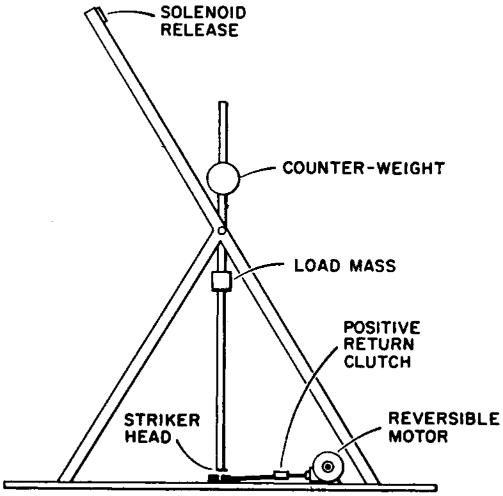

Fig. 1. Variable speed pendulum and sample clamp.

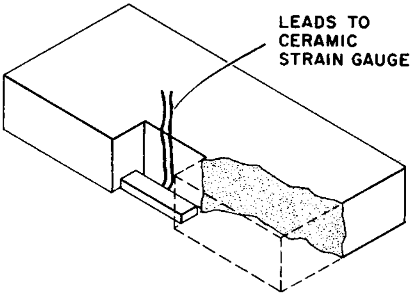

Fig. 2. Striker head assembly.

(*1*) it holds samples with a reproducible force, (*2*) it is faster than using a torque wrench for the same purpose, (*3*) it maintains a positive mechanical position which will not change on impact, (*4*) it can hold samples of any width up to three inches.

The transducer, too, is novel (Fig. 2). Wolstenholme put his transducer in the clamp with the result that it was necessary to correct his readings for the clamping pressure. The transducer used here is the striker head itself with the active element being a ceramic strain gage rather than the conventional resistance gage. This arrangement has several advantages over Wolstenholme's in that the gage is self-generating, instead of being part of a bridge circuit, and has a considerably higher output than most resistance gage units (up to 30 v. has been recorded). The ceramic gage has an extremely rapid response with times of the order of 10 μsec. easily resolvable. Unfortunately the electrical capacity of the gage is quite low and only short time events can be measured accurately. Even using an isolation amplifier of 1000 megohms input impedance to drive our oscilloscope, an elapsed time of only 20 msec. was the upper limit.

Calibration Procedures

Three features of the impact tester need calibrating; (*1*) the arm speed, (*2*) the transducer sensitivity, (*3*) the maximum energy available at each speed.

(*1*) The arm speed (which is controlled by the counter-balance) was calibrated by gluing two magnets to the end of the arm and clamping a pickup coil in the sample clamp. The output from the coil as the magnets passed over it was displayed on an oscilloscope and the time between passages was measured from the trace.

(*2*) As noted above, a dynamic method was needed to calibrate the transducer. A small steel ball (3.51 g.) was placed on a pedestal in the clamp in such a position that it would be swept off by the striker head. The maximum force generated was then calculated from eq. (1)

$$F = \pi m V_0/t_r \tag{1}$$

where m is the mass of the ball, V_0 is the head speed, t_r is the time of the rebound (zero force to zero force). On this basis forces as high as 500 lb. were generated at a head velocity of 16 ft./sec.

(*3*) At low impact levels it is possible to measure impact energies by integration of the force–time curve directly according to

$$I = V_0 \int_0^t F(t)dt \tag{2}$$

which of course assumes that the head speed remains constant. This approximation becomes a gross error at high impact levels (high with regard to the total amount of energy available). It was determined that a correction was possible if one knows the maximum amount of energy available from the striker. We derive this correction as follows. We have the impulse directly from the oscilloscope trace, i.e., we know

$$E = \int_0^t F(t)dt = \bar{F}(t) \tag{3}$$

Our approximation involved the calculation of a pseudo-work figure as

$$W_p = \bar{F}(t)V_0 \tag{4}$$

whereas the actual work[4] is

$$W_a = \bar{F}(t)^1/_2(V_0 + V) \tag{5}$$

where V is the velocity after impact.

We also know[4]

$$\bar{F}(t) = m(V - V_0) \tag{6}$$

hence

$$W_a = \bar{F}(t)V_0\{1 - [\bar{F}(t)/2\bar{m}V_0]\} \tag{7}$$

where $\bar{m}$ is the effective head mass.

The maximum energy available from the striker head is

$$E_{\max} = {}^1/_2 m V_0^2 \tag{8}$$

thus

$$W_a = \bar{F}(t) V_0 \{1 - [\bar{F}(t) V_0 / 4E_{\max}]\} \tag{9}$$

or

$$W_a = W_p[1 - (W_p/4E_{\max})] \tag{10}$$

Therefore, if we know $E_{\max}$ we can correct the pseudo-work to give actual work and hence actual impact strengths. In order to get $E_{\max}$ the arm was allowed to drop at various speeds against a bar which would withstand the total force. The impulse curves were then integrated to give W_p (total) (care was taken to account only for the energy supplied by the pendulum) and $E_{\max}$ calculated according to:

$$E_{\max} = W_p \text{ (total)}/2 \tag{11}$$

Cantilever Impact Test

The cantilever beam specimen which is the standard for most impact testing is an extremely difficult specimen to analyze due to the complicated nature of its response. If one can assume (and one cannot) that the specimen follows the motion of the striker head through the impact period we are faced with four contributing factors in the elastic response of the specimen. This does not include such important phenomena as cold drawing and the mode of fracture (the latter point is particularly important in the case of Lexan[5] and evidences itself as a variation of impact strength with thickness).

First of the contributing factors is the existence of the notch in most test samples. Notch sensitivity is a particularly difficult value to assess since it varies from material to material and for the same material it can vary with temperature and notch geometry. Therefore, if it is desired to characterize the material under test in any way other than by the Izod impact strength, the notch should be eliminated.

Even working with unnotched samples there are three more contributions which must be considered: (*1*) beam bending, (*2*) shear at the clamp surface, and (*3*) compression at the point of impact. The composite equation for the distance traveled by the striker head is[6]

$$Vt = \frac{2Pl^2(2l + a)}{bd^3E} + \frac{12Pl(1 + \nu)}{5bdE} + \frac{Pk}{bE} \tag{12}$$

where V is the head velocity, t is time, E is Young's modulus, ν is Poisson's ratio; b is the material thickness; k is an undetermined constant, and P, l, a, and d are defined in Figure 3. The three terms on the right-hand side of eq. (12) refer to bending, shear, and compression, respectively. To demonstrate that this equation accounts for a reasonable share of the

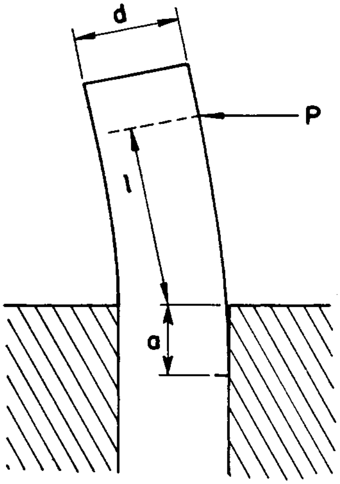

Fig. 3. Distance traveled by striker head.

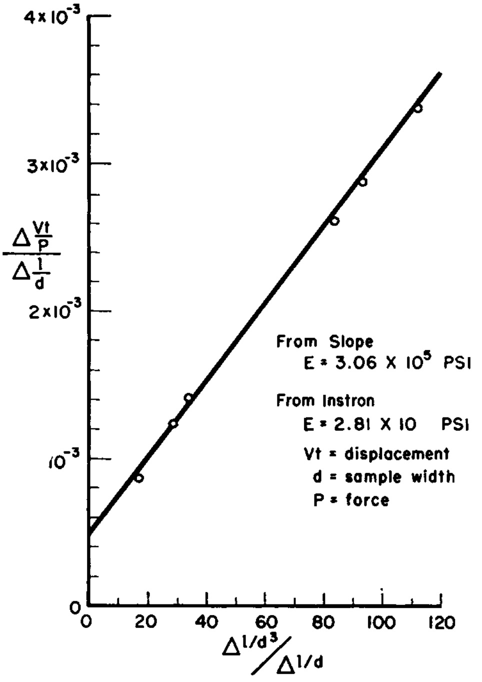

Fig. 4. Modulus plot for Styron 666.

specimen response several samples of Styron 666 (The Dow Chemical Company) of varying widths d were broken. The initial slopes of the stress–time curves were measured and plotted and a value of E determined (3.06 × 10 psi) (Fig. 4). The same material measured in the Instron gave 2.81 × 10 psi, which is remarkable agreement.

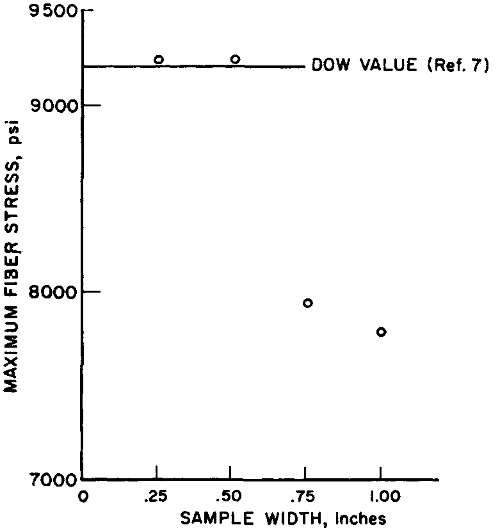

Fig. 5. Maximum fiber stress as a function of sample width for Styron 666.

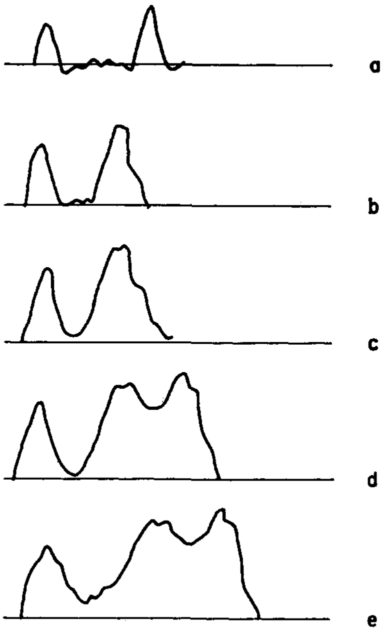

Fig. 6. Evidence for Tyril 767 sample bounce at Izod speed of 11 ft./sec.: (*a*) $^1/_2$-in. sample; (*b*) $^3/_4$-in. sample; (*c*) 1-in. sample; (*d*) $1^1/_4$-in. sample; (*e*) $1^1/_2$-in. sample.

Another bit of information which can be gleaned from the stress–time curves is the maximum fiber stress which the material can withstand. This is not the same as the tensile strength but should be allied with it. Figure 5 shows the results obtained on the polystyrene Styron 666 as a function of sample width, *d* (not thickness, *b*). For narrow samples the results are in excellent agreement with reported values,[7] while the value drops for wider pieces, indicating a probable error in evaluating the fiber strain. This error could be due to a shear contribution to the total strain at the point of incipient failure. In any case it is fairly obvious that modulus and maximum fiber stress should be attainable at high speed.

All of the above analyses assume that the cantilever specimen follows the striker head motion, which is not true. Figure 6 shows the actual response for a series of Tyril 767 (The Dow Chemical Company) samples. The existence of multiple peaks strongly suggests that something is rebounding. From the change in peak spacing with increasing width it was concluded that the sample was bouncing rather than the striker head. For some materials, particularly the very brittle ones, this bouncing was somewhat of a problem in evaluating their impact strengths, but for the higher impact materials the period of bouncing was only a small fraction of the test time and did not interfere with the analysis.

Impact Resistance

In Figure 7 are shown idealized stress–strain curves for various types of responses. A material with the "brittle" curve can exhibit impact resistance if its tensile strength is high enough, although for most plastics the condition of very high tensile strength at low elongations is not found. The second case of high elongation is found in a number of plastic materials all of which are considered to have high impact resistance. Often the condition of slow crack propagation coincides with high elongation, but not always. Moreover, it is possible to move from one type of failure curve to another by the simple expedient of changing the test temperature.

Figure 8 is an example of the change in impact response curves which can occur. The curves shown here are for a polybutadiene-modified polystyrene, beginning with the brittle response at −170°C., passing on to high

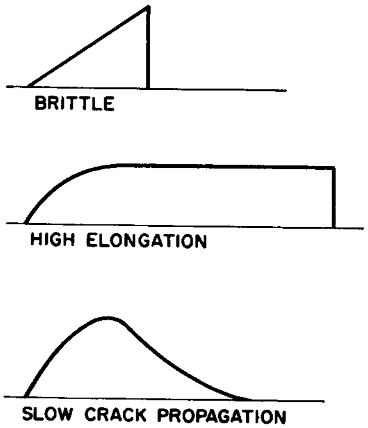

Fig. 7. Idealized impact response curves.

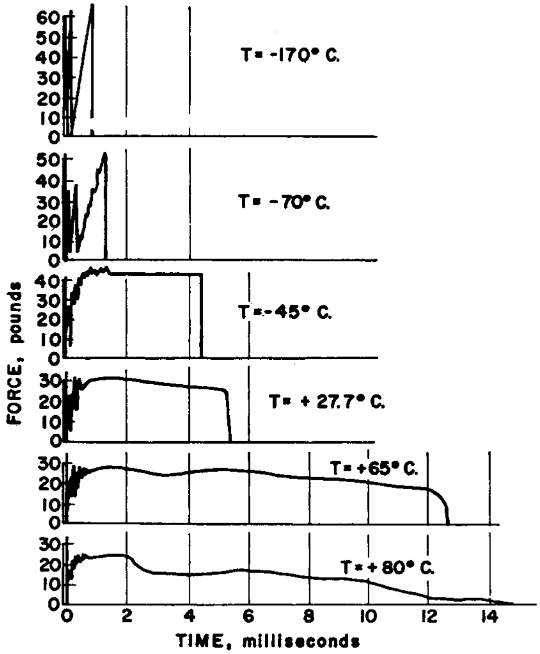

Fig. 8. Impact response of polybutadiene-modified polystyrene at various temperatures.

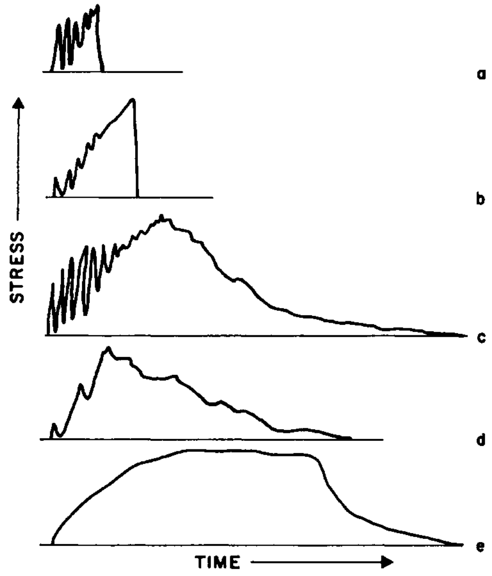

Fig. 9. Stress–time curves for various materials: (*a*) Styron 666; (*b*) SBR-modified polystyrene (compression-molded); (*c*) SBR-modified polystyrene (injection-molded); (*d*) glass-reinforced phenolic; (*e*) Teflon.

elongation at −45°C. through room temperature to high elongation with stress relaxation and slow crack propagation at +80°C. The technique for measuring these materials was to precondition the sample at the desired temperature, the sample being held between brass plates which acted as heat sinks, and perform the impact test quickly at room temperature. Experience with samples containing thermocouples showed that the temperature would not change by more than 5°C. in 10 sec. With the power-driven clamp we were able to test samples in 7 sec. from bath to fracture.

Conclusions

Figure 9 shows traces of typical response curves for a number of different materials and composites. Note that those materials which have reasonable impact resistance have high elongations, slow crack propagation, or both. Of particular interest is the crack propagation characteristics of the composite materials. For example, SBR-modified polystyrene can have rapid or slow crack propagation, depending upon its method of molding. Where a compression-molded sample derives a negligible amount of impact resistance from its crack propagation tendencies, an injection-molded sample can gain a factor of two or better from just this feature. In addition, the glass-reinforced phenolic appears to derive nearly all its impact resistance from the ability of the glass fibers to retard crack propagation.

References

1. Wolstenholme, W. E., *J. Appl. Polymer Sci.*, **6**, 332 (1962).
2. Wolstenholme, W. E., S. E. Pregun, and C. F. Stark, *J. Appl. Polymer Sci.*, **8**, 119 (1964).
3. Anderson, R. W., E. T. Dumitru, and C. B. Arends, *Soc. Photo. Inst. Eng. J.*, **5**, 180 (1964).
4. Condon, E. O., and W. Odishaw, *Handbook of Physics*, McGraw-Hill, New York, 1958.
5. Christopher, W. F., and D. W. Fox, *Polycarbonates*, Reinhold, New York, 1962.
6. Roark, R. J., *Formulas for Stress and Strain*, McGraw-Hill, New York, 1943.
7. *Strength and Stiffness*, Dow Chemical Company, Bulletin 153-5288-61, 1961.

Résumé

On peut relier la résistance à l'impact des matières plastiques à trois contributions qui sont les phases de propagation élastique, plastique, et brisante. En utilisant un dispositif enrégistreur de pendule à impact, il est possible d'analyser chaque substance en regard de l'importance de phénomènes sus-mentionnés. Il a été montre que la plupart des plastiques qui présentent une bonne résistance a l'impact ont de grandes élongations plastiques ou de tension une bonne résistance à la brisure, soit les deux simultanément. Une analyse simple de l'impact par la méthode du bras "cantilever" montre que l'on peut obtenir des valeurs acceptables du module et du maximum des fibres si l'on prend soin de tenir compte des contributions dues au cisaillement et à la compression dans la mesure globale. Il a également été observé que les échantillons plastiques tendent dans des conditions d'impact à rebondir contre la tête du marteau.

Zusammenfassung

Die Stossfestigkeit von Kunststoffen kann als Wirkung von drei Beiträgen beschrieben werden; diese sind die elastische, die plastische, und die Rissfortpflanzungsphase. Mit einem Recorder-Pendel-Stossgerät kann jedes beliebige Material auf die relative Bedeutung der angeführten Phänomene analysiert werden. Es wurde gefunden, dass die meisten Kunststoffe mit guter Stossfestigkeit eine grosse plastische Elongation oder gute Rissfortpflanzungsbeständigkeit oder beies aufweisen. Eine einfache Analyse des Auslegerstosses zeigt, dass man brauchbare Werte für den Modul und die maximale Faserspannung erhalten kann, wenn dem Scherungs- und Kompressionsbeitrag zum Bruttoverhalten Rechnung getragen wird. Es wurde festgestellt, dass Kunststoffproben unter gewissen Bedingungen eine Tendenz zum heftigen Aufprallen gegen den Schlagkopf zeigen.

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