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Force-Displacement Evaluation of Macromolecular Materials in Flexural Impact Tests. I. Apparatus and Data Handling

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Synopsis

The determination of the force-displacement curve during an impact experiment can provide more qualitative and quantitative information on the impact behavior of a material than conventional single-value characterization. To this aim, an Izod-type pendulum was instrumented, so that both the impact force and the displacement of the free end of the specimen can be accurately monitored and recorded. The force-displacement curves produced are analyzed by means of a suitable computer program to obtain different significant characteristics.

INTRODUCTION

The capability of withstanding an impulsive load is one of the most important properties of macromolecular materials, i.e., materials often applied for end items that are qualified as "unbreakable." In spite of its great practical and technological relevance, however, it is still an ill-defined and far from properly characterized mechanical property.[1-3] Stemming from habits inherited from metals technology, the so-called "impact resistance or strength" is currently identified with the total energy absorbed in breaking a test specimen in some standardized fashion. In practice, a number of standard tests are commonly used.[3] In the plastic industry, the most widely used standard test remains the notched Izod version,[4] in spite of many criticisms.[1-3,5]

According to the Izod method, a standard specimen vertically tightened cantilever-fashion in a vice is struck at the free end by a pendulum hammer, at specified speed and energy. The overall energy lost by the pendulum is measured and assumed as energy to break. Actually, the value indicated by the standard instrument sums several terms, corresponding to all the mechanical processes induced by the hammer blow. They may be listed as follows[4]: (1) initiation of the fracture of the specimen; (2) propagation of the fracture across the specimen; (3) bending of the specimen; (4) plastic indenting of the specimen at the line of impact; (5) toss of the free end of the broken specimen; (6) vibration in the pendulum arm and vibration or horizontal movement of the machine frame or base; and (7) overcoming of all the frictions, comprising that of the striking nose against the surface of the bent specimen.

The aim of this work is a more precise and detailed characterization of the impact response of macromolecular materials, using the breaking technique of the standard Izod test, but purging the measured quantity of some of the parasitic terms listed above and deriving other quantities that may provide a more complete information of the material behavior. This can be obtained by instrumenting the impact tester so that the whole development of the force and the displacement in the course of the collision can be followed.

Instrumentation of impact tests has been extensively studied for metals. There, interest is oriented mainly to the Charpy test method that lends itself to an easier analysis of the results through linear fracture mechanics. (A comprehensive review of instrumented Charpy V-notch tests can be found in Turner.[6]) For macromolecular materials, the experimental work with instrumented impact testers has been more limited[7-10] and mainly devoted to the Izod method.

In this paper, we report on our own work of instrumenting an Izod-type pendulum to record directly the force-displacement curve generated during impact, and of the relative data handling to obtain a number of significant parameters.

Attempts to treat impact data by fracture mechanics analysis to obtain intrinsic properties of the material were lately reported in some cases as successful, at least for brittle polymers.[11,12] At this stage, however, we intend first to enlarge our knowledge of the phenomenology of the impact behavior of different types of macromolecular materials.

INSTRUMENTAL

Basic Apparatus

The Izod-type pendulum manufactured by Karl Frank GmbH, Weinheim (Mod 565 K; impact energy, 40 kg cm; impact velocity, 2.9 m/sec) was instrumented as shown in Figure 1.

The force transmitted to the holder by the test specimen and the hammer displacement are transformed into electrical signals by means of appropriate transducers. These signals are fed to an oscilloscope (Tektronix 5103N) and yield a force-displacement curve on its screen. This curve can be photographed by means of a Polaroid camera (Tektronix C-5).

Force Measurement

The test specimen is clamped to a steel bar as shown in Figure 1. Under the blow, the bar is bent and its deformation is sensed by a strain gauge glued on its surface. The resistance variation in the strain gauge is amplified through a conventional Wheatstone bridge.

The size of the bar was determined by searching the best compromise between two relevant factors: the bar natural vibration frequency and the sensitivity of the measurement. The frequency of the natural vibrations of the bar has to be sufficiently high to enable to distinguish their signal from that

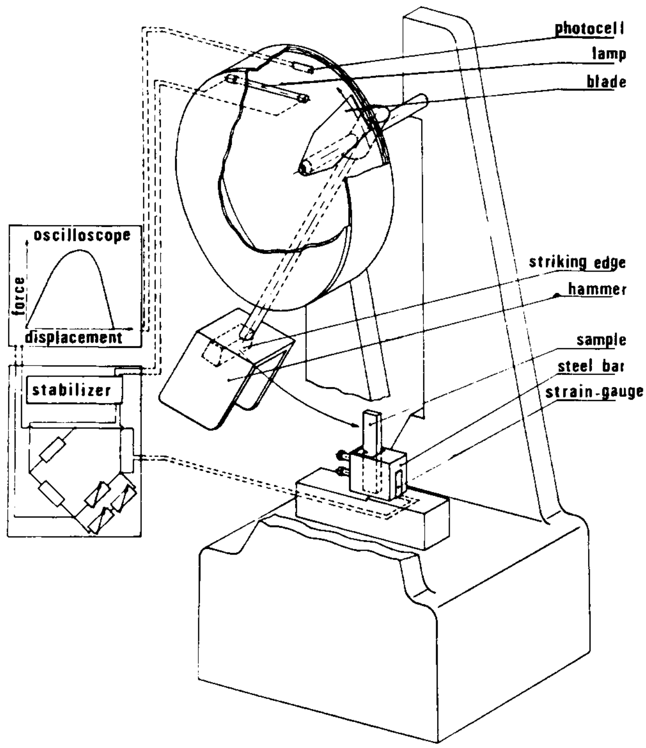


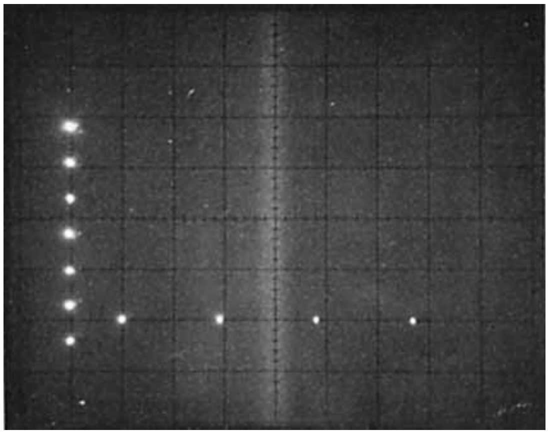
Fig. 1. Instrumented Izod-type pendulum.

of the applied force. This can be achieved by increasing the rigidity of the bar: the dimensions of the bar were chosen so that the period of its natural vibrations (around 0.05 msec) turned out to be sufficiently lower than the time required to break the specimen (around 0.5 msec). On the other hand, as the rigidity of the bar increases, the sensitivity of the measurement drops; to keep this high enough, a very sensitive semiconductor strain gauge had to be used (Philips PR9862). Under these conditions, the bar vibrations appeared as visible small oscillations of the trace giving the force-displacement curve. Some of these oscillations could be cut off by inserting a low-pass filter.

The minimum measurable force was calculated to be around 0.2 kg, that is, of the order of a few per cent of the experimental impact forces.

Displacement Measurement

The displacement of the test specimen at the contact point with the hammer striking edge was measured by continuously recording the position of the pendulum arm in a convenient rotation sector. The pendulum arm position was sensed by means of a semiconductor photocell (Sensor Technology, Type ST-100G; response time, 3–20 μsec) illuminated by a linear filament lamp (Chicago Miniature Lamp Works, Type CM8-1123). A blade fixed to the pendulum arm, rotating between lamp and photocell, varies the illuminated area of the photocell cathode. The photocell output signal has to be calibrated in order to measure the actual displacement of the impact point.



(a) (b)

Fig. 2. (a) Ordinates: force calibration. Points correspond to 0, 5, 10, 15, 20, 25, 30 kg from bottom to top, respectively. Scale factor: 0.5 mV/large div. (b)Abscissas: displacement calibration. Points correspond to 0, 3, 6, 9 mm displacements of the hammer striking edge, from left to right, respectively. Scale factor: 0.2 mV/large div.

EXPERIMENTAL

Calibrations

The force-measuring system was calibrated statically by applying a series of different weights (through a simple pulley arrangement) to a dummy specimen, at its point of contact with the hammer striking edge. The strain gauge output was fed into the oscilloscope, and a series of luminous points was obtained on its screen (Fig. 2a). The force–strain gauge output relationship turned out to be linear, so that a calibration constant was easily determined.

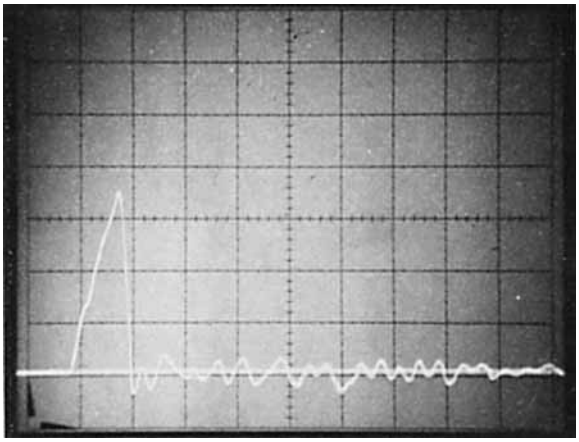
The displacement measuring system was also calibrated statically by placing a series of steel bars of different thickness in the instrument vice, and bringing the hammer striking edge into contact with the surface of each bar. A corresponding series of luminous points was obtained on the oscilloscope screen (Fig. 2b), giving a linear relationship between the photocell output and the position of the hammer striking edge in the range of practical interest. A second calibration constant was so determined.

Because of the strong temperature dependence of the characteristics of the semiconductor transducers used, both calibrations had to be repeated at each test temperature.

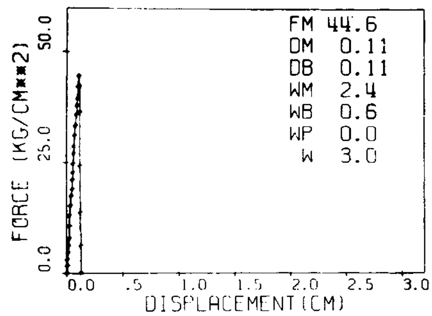
Elaboration of the Photographed Curves

Though the instrumented apparatus gives directly photographs of the sought force-displacement curves, we were induced to search for an analytical description of these curves for two reasons.

First, the photographs obtained cannot in general be directly compared be-



(a)



(b)

Fig. 3. (a) Example of oscilloscope record of force-displacement curve obtained with an ABS sample showing brittle fracture. Scales: abscissas, 0.110 cm/large div.; ordinates, 7.50 kg/large div. (b) Computer-drawn graph corresponding to photograph in Fig. 3a.

tween themselves. In fact, the scale factors of the force and the displacement are usually different for different photographs, as it is necessary to adjust the amplification in the two channels of the oscilloscope for each test in order to contain the complete force-displacement curve within the oscilloscope screen. Moreover, as already mentioned, the force and the displacement calibration factors change with temperature. Some elaboration of the experimental photographs is therefore needed.

Second, for the analysis of the impact behavior, it is desirable to calculate the numerical values of some significant quantities, such as the total and partial energies represented by the areas under the whole force-displacement curve or part of it, respectively. An evaluation of these areas by means of graphic methods or mechanical devices would be time consuming or somewhat inaccurate.

To obtain an analytical description of the experimental force-displacement curve, we have resorted to the method of splines.[13] Accordingly, the photographed curve is approximated by a series of cubics fitting a set of points read on it, with the condition that the resulting curve has continuous first and second derivatives.

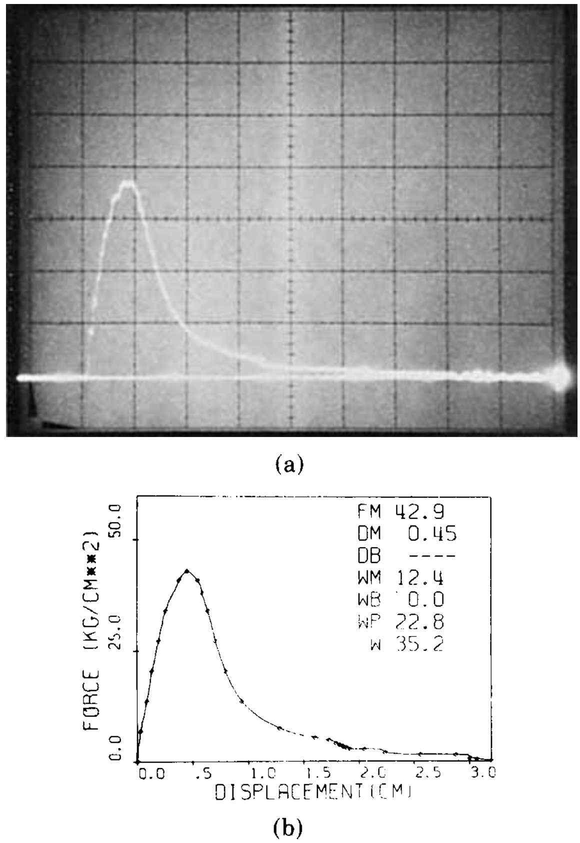


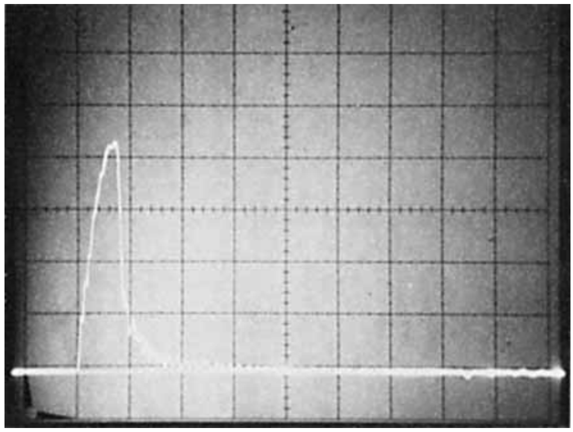
Fig. 4. (a) Example of oscilloscope record of force-displacement curve obtained with an ABS sample showing ductile fracture. Scales: abscissas, 0.550 cm/large div.; ordinates, 7.50 kg/large div. (b) Computer-drawn graph corresponding to photograph in Fig. 4a.

A computer program was written to perform all the calculations. The Cartesian coordinates of a set of points read on a photographed force-displacement curve, together with the scale and the calibration factors, are fed as input into the computer, which provides for the drawing of the transformed force-displacement curve and for the calculation of the wanted parameters.

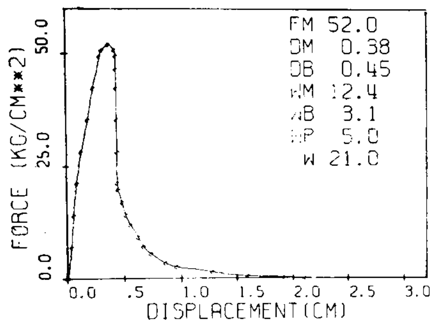
The number of points required for a sufficiently accurate representation of a photographed force-displacement curve was usually not over thirty.

RESULTS AND COMMENTS

Three photographs and the corresponding transformed drawings of the force-displacement curves obtained by the method described above, on three samples of ABS resins with different rubber content, are shown, respectively, in Figures 3a, 4a, and 5a, and in Figures 3b, 4b, and 5b. As can be seen, the direct comparison of different materials on the photographs is difficult, while it can be done easily on the computer-drawn graphs.



(a)



(b)

Fig. 5. (a) Example of oscilloscope record of force-displacement curve obtained with an ABS sample showing an intermediate fracture behavior. Scales: as in Fig. 4a. (b) Computer-drawn graph corresponding to photograph in Fig. 5a.

In Figure 3b, the force increases almost linearly up to a maximum, after which it drops abruptly to zero, indicating brittle fracture. In Figure 4b, the force drops slowly to zero after the maximum has been reached, indicating ductile fracture. In Figure 5b, an intermediate behavior can be observed.

The oscillations which may be seen on the photographs were not reproduced on the graphs because they were regarded as disturbances coming from the measuring system.

In Figure 6, the total energy computed from the force-displacement graphs of a series of measurements is plotted against the energy indicated on the instrument dial. The experimental points lie significantly below the one-to-one correspondence line.

While other authors report agreement between computed and observed total energies,[7b,10,14] consistently lower computed energies have been found, too.[7b,15] In particular, Wolstenholme[7b] observed very good agreement in the case of catastrophic breaks and consistently lower values in the case of plastic-type breaks. In contrast to the latter result, we have obtained no evidence of such a distinction. In our opinion, the difference between the two

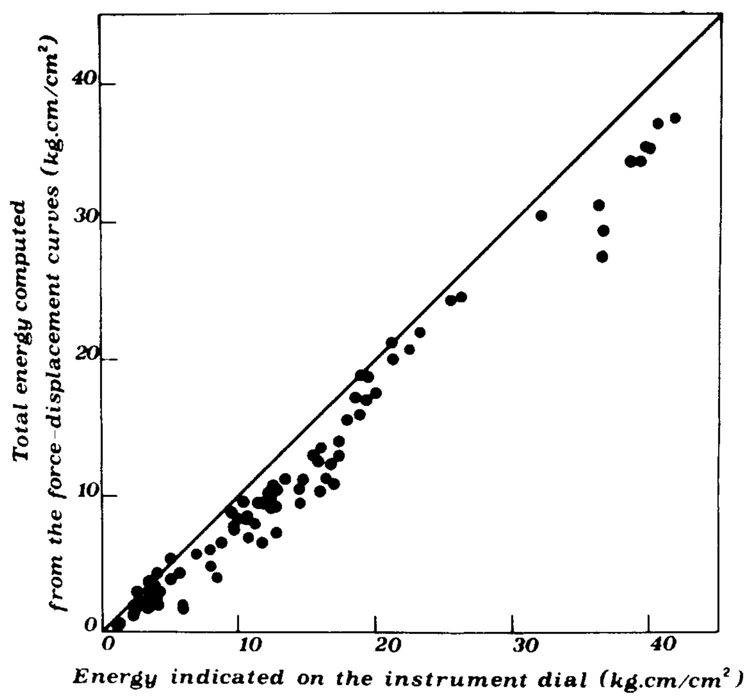


Fig. 6. Total energy computed from the force-displacement graphs vs. total energy indicated on the instrument dial, obtained in series of experiments on different materials.

energies should represent the sum of the energy terms listed under (5), (6), and (7) in the Introduction.

To characterize the impact behavior of a material, the whole force-displacement curve should be considered. In practice, it is more convenient to derive from this curve some characteristic parameters so that different materials—tested under the same conditions—can be compared numerically, avoiding descriptive, nonquantitative terms. Generalizing the force-displacement curve of typical macromolecular materials as schematically drawn in Figure 7, we have found it meaningful to select the following parameters:

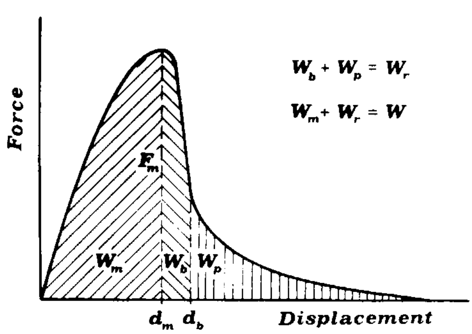


Fig. 7. Schematic representation of a force-displacement curve, showing significant characteristics.

F_m = maximum force developed*; d_m = displacement corresponding to F_m; d_b = displacement corresponding to arrest of brittle fracture; W_m = energy absorbed up to d_m*; W_b = energy absorbed from d_m to d_b*; W_p = energy absorbed after d_b*; $W_r = W_b + W_p$ = energy absorbed after d_m*; and $W = W_m + W_r$ = total energy absorbed during the whole test.*

From the initial slope of the curves the (flexural) modulus of elasticity could also be estimated.

All these quantities, as a whole, constitute the quantitative information set that can be obtained by the technique illustrated here. Each of them, individually, does represent a particular aspect of such information. For example, the value of the maximum force F_m, i.e., the highest load that the test piece can sustain in *this* test, gives a measure of the capability of the material of bearing impulsive loads, very much like the flexural strength in a slow-speed cantilever beam test. As such, F_m could be assumed a better index of *impact resistance or strength*[16] than the conventional total breaking energy W, which is the only value measured in a normal uninstrumented test. In fact, it seems reasonable to think of this peak as a threshold beyond which the material fails, either by yielding or by brittle fracture.

W_m would then represent the energy to failure or *toughness*,[16] while W_b and W_p could be tentatively taken as measures of the energy absorbed by yielding and/or crack propagation and of energy associated with plastic drawing or tearing, respectively.

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* Conventionally, the force and the energies may be referred to unit initial cross section of the specimen at notch.

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