Application of Instrumented Impact Test in Polymer Testing

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Synopsis

Advanced methods of conducting and analyzing instrumented Charpy impact tests are described and used in measuring the initiation fracture toughness K_{1c} at a range of impact velocities and temperatures. Improvements developed in the impact testing of metals are discussed and applied in the toughness evaluation of polymers. In lower-speed impact tests where load–displacement records are nearly linear, the maximum recorded load may be used to evaluate K_{1c} by stress analysis K calibration formula. In high-speed impact tests, where the load trace is highly oscillatory, the fracture load to be used in the calculation must be derived indirectly. The indirect derivation of fracture load for this purpose from a "low blow" stiffness measurement and specimen deflection has been studied in detail, and the use of the periodic time of the "low blow" test has been found to offer a reliable method of calculating the system stiffness.

INTRODUCTION

Cyclic and dynamic loading, corrosion, and creep, as well as the effects of environment may lead to unexpected failures of plastic materials. A detailed knowledge of fracture and the other mechanical properties of plastics is therefore necessary for the designer, the materials engineer, and the workshop. In view of their high strain rate sensitivity, the resistance of plastic materials to catastrophic fractures caused by the application of dynamic loads, specially in impact situations, is of particular interest. An evaluation of impact behavior is needed to maintain the quality of established materials and products, in the development of new types of materials, and for the prediction of their performance in engineering applications.

Predictions of the temperature below which a material may behave in a brittle fashion can be obtained from impact tests, a variety of which have been developed over the years. Three-point bend specimens of varying sizes (up to 2 m span or more), as well as compact tension and double cantilever beam specimens, have been investigated in specially built drop weight machines. However, in smaller impact machines the use of three-point bend specimens (Charpy) and, to a smaller extent, cantilever bars (Izod) has been well established. Some new methods used for evaluating the impact behavior of relatively small specimens developed originally for investigating steels and other metals were recently adapted for testing polymers; they are discussed below.

Impact testing has been used for many years as a comparatively simple method of evaluating the resistance of materials to rapidly applied loads. In principle, the impact machine records the total amount of energy necessary to deform and break a rectangular bar at high speeds. Thus, a conventional Charpy test is a common method of determining the amount of energy necessary to fracture a standard notched specimen (provided with a blunt notch of radius 0.25 mm)

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loaded in three-point bend at a constant speed of impact (5 m/sec approximately) and at various temperatures. Although the standard test (see, for example, ref. 1) is very useful, fast, and particularly convenient for a qualitative comparison of materials, the total fracture energy recorded during impact does not provide sufficient information for the prediction of the behavior of a dynamically loaded structure containing stress concentrations in the form of sharp cracks. Linear elastic fracture mechanics (LEFM) facilitates the analysis of these situations and offers methods for evaluating fracture toughness K_{1c}. The fracture toughness, or stress intensity factor, K_{1c}, describes the elastic field in the vicinity of a crack tip by relating the applied stress necessary to cause failure in a structure or a specimen and the size of any defect or a precrack that may be present. Testing methods to obtain K_{1c} values are described in standards[2(b)] and the recommended procedures discussed in reference 2(a) and 2(c). The validity of these tests, developed basically for static loading situations, can be ascertained with the help of ASTM criteria.[2(a)] Their use in dynamically loaded situations deserves further investigation. Although various empirical relations between K_{1c} and the Charpy energy C_v have been proposed and applied under limited circumstances and quasi-static loading conditions, a directly derived dynamic K_{1c} value would be advantageous. The improved instrumentation of an impact machine used here enables detailed interpretation of the impact process as it records all the factors necessary for the fracture toughness evaluation based on the calculation methods for the static tests.

This paper describes some of the procedures used in the development of an instrumented Charpy test, results obtained in an analogue study, and a method for a dynamic toughness evaluation. Results obtained in the impact testing of metals are also included for comparison.

TESTING PROCEDURE

Hints on the construction and installation of a Charpy impact testing machine as well as the recommended dimensions of the specimens and details of the testing procedure are discussed in reference 1, which also contains other relevant information, such as recommended impact speeds, machining tolerances of the test pieces, and testing methods. The machine used in the present program was of a standard design, 30 kgm capacity, with a pendulum head consisting of a large disc, 390 mm in diameter, provided with a removable striking edge. The freely adjustable lifting and releasing mechanism allowed the hammer to swing between 0 and 158¾°. The dimensions and other details of the pendulum are given in the Appendix.

Specimens used in all the impact tests were of the standard Charpy type. Their dimensions were as recommended in reference 1, i.e., 10 × 10 × 55 mm long. However, in the tests on PVC the specimen thickness was that of the plate supplied, namely, 12.7 mm. In order to avoid the effects of inhomogeneity, all plastic specimens were cut with their longitudinal axis parallel to one edge of the plate. The axis of the metal specimens was along the rolling direction, although another orientation would be acceptable. It should be remembered that the orientation of the fracture plane may influence fracture toughness considerably. All the specimens were provided with notches through the plate thickness. The plastic materials were notched at room temperature by sharpening the root of the notch with a razor blade, while the metal specimens were fatigued in a specially built three-point bend rig. The methods used for sharpening have been well established and are described in detail in the literature [cf., for example, reference 2(a)]; for other impact testing methods, see reference 2(d).

INSTRUMENTATION

The development of the instrumented Charpy machine used here and its application in the impact testing of a wide range of materials (plastics and metals) has been described in detail elsewhere.[3] Basically, this equipment records specimen deflections and applied load during the test. In the deflection measurement a beam of parallel light directed on to a fast-response photocell (Mullard) is cut by the edge of the pendulum and the signal, previously calibrated, displayed on the CRO screen. For the load record, semiconductor strain gauges (Microsystems, U.S.A., Type DCO-6A7-16-350) fixed close to the striker edge provide a strain gauge measuring bridge the output of which is again displayed on the oscilloscope (Tektronix, 565 two-beam). The system is calibrated by applying static load to the pendulum and a dummy specimen via a proving ring, mounted on a support frame. The angle of swing of the hammer can be varied to provide a range of impact speeds, producing marked differences in the type of load/time records obtained in the test. These differences and the methods of analyzing instrumented impact tests are discussed in some detail below.

The solution of two problems is sought: firstly, to obtain a true load value in the full-speed impact test for the evaluation of toughness by the K formula, and secondly, to record a true deflection measurement in all tests evaluated by the energy method. In the former case the well-known expression for the stress intensity factor K in three-point bending[2(a)] may be used:

$$K = 6YMa^{1/2}/BW^2 \tag{1}$$

where Y is a function of a/W, M is a bending moment, a is crack length, B is beam thickness, and W is width of the beam. A convenient polynomial form of the function Y is given in eq. (6) below. In the latter case, load point deflections may be measured either by the photocell recording the velocity of the hammer during the test or by high-speed photography of the specimen at the moment of impact.[4] Because of the local deformations of the specimen at the point of contact with the striking edge and the supports, an appropriate correction factor has to be included in the calculations. Such factors have been established in static tests for various materials.

DISCUSSION

A meaningful load evaluation is of primary importance in the measurement of fracture toughness. At very low striker speeds, generally used in slow bend tests (approximately 10^{-3} mm/sec), the response and the accuracy of standard recording equipment is sufficient for most engineering applications, and the fracture load value can be read off directly from the load/time or load/deflection chart. Examples of such load–time records obtained in the low-speed tests on PVC at different loading rates at 21°C are shown in Figures 1(b) and 1(c). Very

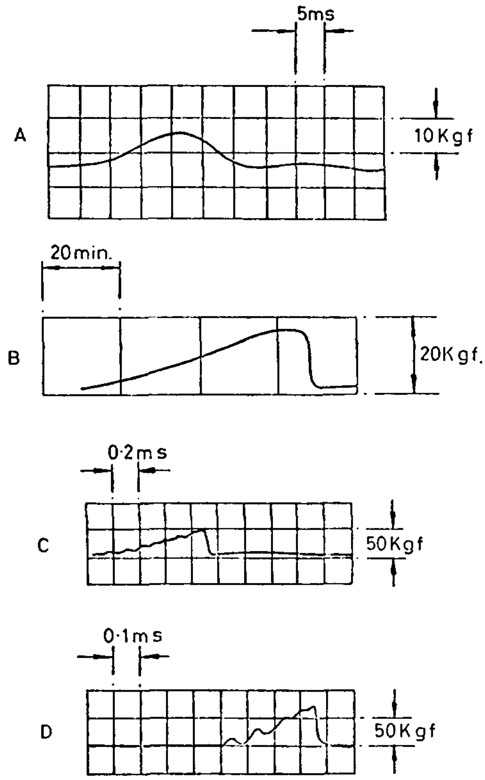

Fig. 1. Load–time records on PVC at 21°C in three-point bend tests: (a) 1° low blow (40 mm/sec); (b) 1×10^{-3} mm/sec; (c) 500 mm/sec; (d) 1500 mm/sec.

small oscillations of the load trace [Fig. 1(c)] are caused by vibrations originating in the loading system and also partly by electrical noise. However, a noticeable increase in the oscillation amplitude may be observed at higher loading rates [Fig. 1(d)], but this record is still perfectly acceptable for evaluating the load using its mean value.

A test performed at a low impact speed (approximately 50 mm/sec), developed for the evaluation of the effective stiffness of the testing system the application of which is discussed later, is usually referred to as a "low blow" test. In this test a specimen is impacted by the Charpy hammer only slightly deflected from its vertical (zero degree) position. Because of the low energy of the hammer, the crack will not propagate, and the deformation in the vicinity of the crack tip is largely elastic. Deflection angles up to 5° have been used in the stiffness evaluation tests on a range of plastics (see Appendix), and a 1° low-blow record of PVC at 21°C is shown in Figure 2(a). For these very low impact angles the shape of the load trace is sinusoidal, but with increasing speeds of the hammer an asymmetry of the trace may be observed. This is caused by the damping capacity of the tested material and is also due to a small amount of plastic deformation at the point of impact. Somewhat higher impact speeds may be applied in testing metals, and typical results obtained on a low-alloy steel A533B are shown in Figure 8(a). Another use of the "low blow" technique has been reported in reference 4(b) for sharpening of the crack starters.

At higher striking velocities (approximately up to 1 m/sec), representing the

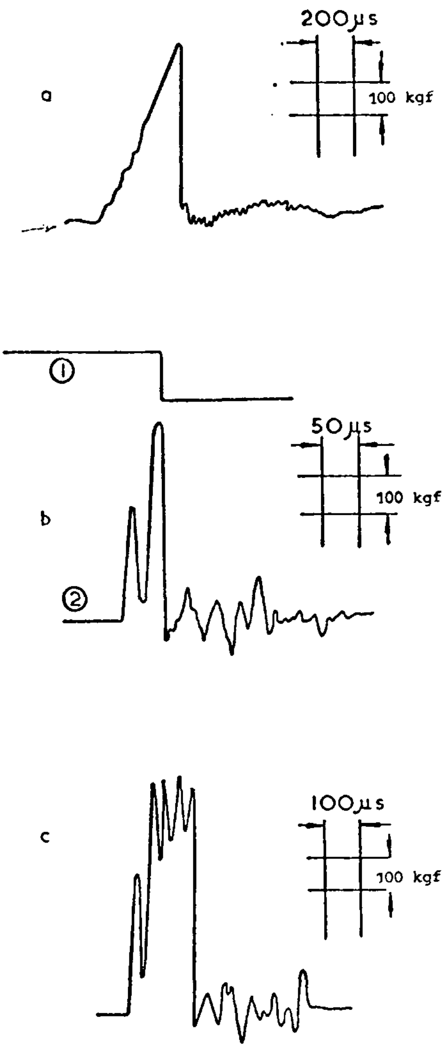

Fig. 2. Oscilloscope records of impact loads in a standard Charpy tester: (a) low-speed impact test on Al alloy at 21°C, 1 m/sec; (b) full-speed impact test on Al alloy at 21°C, 5 m/sec; (c) full-speed impact test on a semiductile material; (d) low-speed, $12\frac{1}{4}°$ swing at −20°C, PVC; P_{max} = 91 kg; (e) full-angle swing at +5°C, PVC; P_{max} = 180 kg, $\omega = \frac{1}{2}\Delta P_{max}$ (fracture during second peak); (f) low-speed $12\frac{1}{4}°$ swing at +21°C, PVC; P_{max} = 120 kg.

lower-speed range of the Charpy impact test, the load values used in the calculation of K_{1c} are the maximum values of the load trace, the latter being reasonably linear and free from large oscillations, Figure 2(a). Small-amplitude oscillations, developed during the initial contact of the striking edge with the specimen, are rapidly damped out; consequently, they do not affect the load values near the point of failure. A sudden fracture is characterized by a steep drop in the load trace.

When impact tests are carried out using larger angles of swing than, say 20° (above 1 m/sec), the load record becomes increasingly oscillatory. In the full-speed impact test, the load record consists of large oscillations, Figure 2(b), which

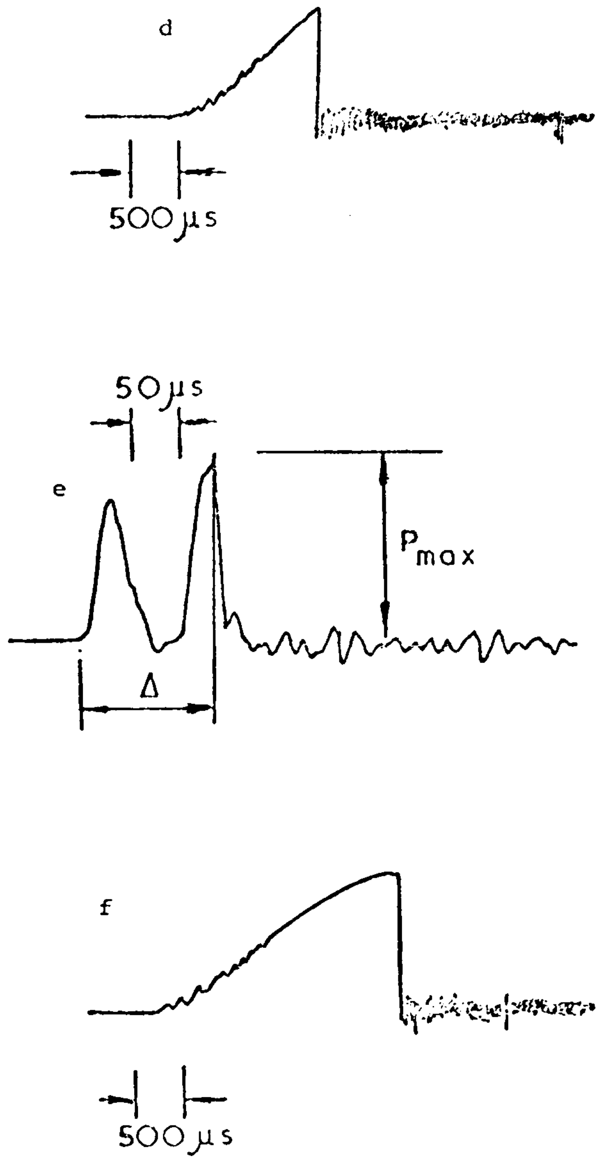

Fig. 2. (Continued from previous page.)

show the variation of the true dynamic load in the striker and also in a localized region of the specimen near the point of contact provided the contact has been maintained. However, this highly oscillatory "contact load" is modified through the specimen by the spring-mass behavior of the latter so that the "effective" or fracture load is much less oscillatory. Kennish[5] considered in detail the problem of the oscillatory load records in instrumented impact tests in an analogue study. In that work the effects were studied of geometric and testing variables upon the load–deflection and bending moment–time diagrams. Particularly the effects of span S, width W, crack depth a, impact velocity V, and "contact stiffness" k_p were examined over the first few oscillations, with the intention of understanding and interpreting the diverse load–deflection diagrams obtained from tests with different values of variables, e.g., different machines and/or specimen sizes.

The analogue record for a particular stiffness value $k_p/k = 4$ (where k is the stiffness of an unnotched beam and is equal to $48EI/S^3$) and for a range of notch ratios a/W in the nondimensional form of load versus time is shown in Figure 3. All load traces are increasing in an oscillatory fashion. While for very short times, load–time records are nearly identical, at longer times they begin to separate. Figure 3 shows that in the tests performed on deeply notched specimens the load falls to zero after the first oscillation and a loss of contact between the specimen and striker occurs. Conducting silver paint applied to the back of the specimen is useful here. The experimental result obtained in a full-angle impact test on PVC at 70°C shows the loss of contact at 100 μsec (Fig. 4).

The principal conclusion of reference 5 was that although recorded load could vary in a highly oscillatory manner, nevertheless, for certain conditions $[(k_p/k) < 5]$ the effective central bending moment producing fracture varied almost linearly with time after a very short initial stabilizing time. Charpy tests in most materials conform to these conditions (e.g., $k_p/k \simeq 3.5$) and, through the combination of scale factors, so also do some very large-size specimens. Some other conclusions were that for a given k_p/k ratio the first peak was higher and occurred at longer time for shallow notches, while for a given a/W ratio the first peak was higher and occurred at a shorter time for a larger k_p/k ratio. Thus a highly oscillatory record in which the first trough reached zero (and loss of contact between striker and specimen occurred) was obtained with high values of a/W and k_p/k (e.g., $a/W > 0.5$ for $k_p/k = 4$, or $a/W = 0.2$ for $k_p/k > 8$). For a given value of a/W a critical value of k_p/k exists above which the effective central bending moment becomes increasingly oscillatory and random.

The major record differences with machine or specimen size depend on ratios a/w, L/w, and k_p/k, where L is the specimen length. However, in order to produce diagrams of similar form it is necessary, in addition to holding the above factors constant, to perform the tests at constant loading or strain rates and also

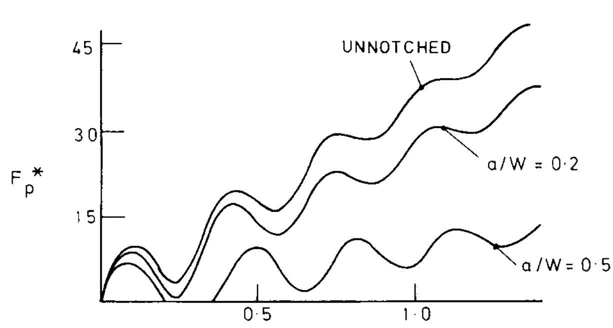

Fig. 3. Analogue model of pendulum load F_p vs time for $k_p/k = 4$.

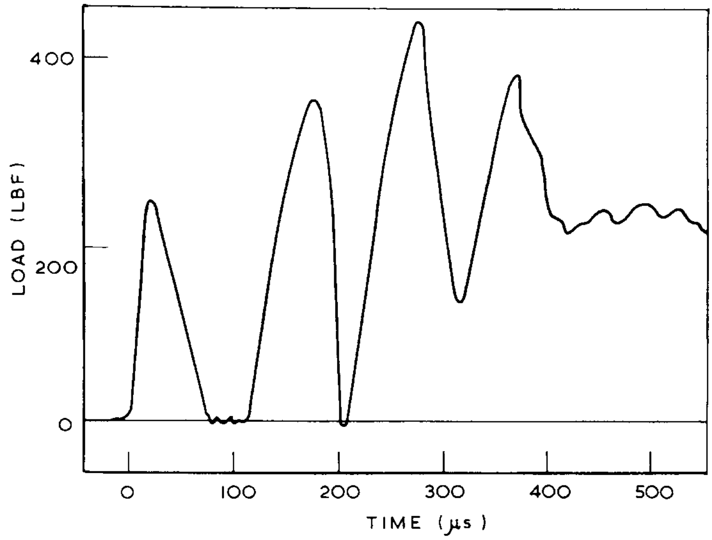

Fig. 4. PVC Charpy impact test at +70°C; a/W = 0.2; full speed (5 m/sec).

to adjust the time scale. The modification of the strain rates in the impact tests on specimens provided with fatigue sharpened cracks is not easy, but the dependence of the toughness on the loading rate can be investigated by varying the impact speed. In the instrumented tests performed on specimens with sharpened cracks at standard impact speed of 5m/sec the recorded value of dK/dt (equal to $\dot{K}$) was found to be of the order of 10^6 ksi$\sqrt{\text{in.}}$/sec.

Further comments on the load oscillations may be included here. As mentioned, it is observed that the amplitude of the successive contact load oscillations progressively decreases in tests where several oscillations occur before fracture. For example, in low-speed impact tests performed on a range of polymers and metals, Figures 2(a) and 2(d), the oscillations are damped out before fracture occurs, and hence fracture load is the maximum recorded load. Also, for tests carried out in the brittle–ductile transition region where the time to fracture t_f is sufficiently long so that several oscillations precede fracture, the value of the contact load approaches that of the true fracture load and may be used to estimate K_{1c}. The conditions for this may be quoted as $t_f > 75$ μsec or $t_f >$ three times the time interval to the first oscillation peak, whichever is the greater. Many instrumented impact tests are brittle tests having $t_f < 75$ μsec, and then the oscillatory contact load is not used.

Considering the analogue work it can be seen that in principle K is calculable as a function of time from oscillatory load records, but this is impracticable and it is, in general, necessary to determine the effective fracture load by an indirect method. The method used here utilizes a "low blow" stiffness measurement together with a time-to-fracture measurement obtained during the full-speed fracture test either by the conductive grid method[6] discussed later or by the strain gauge response,[7] which is more appropriate for larger than Charpy size specimens. However, with experience it is sometimes possible to identify the point of fracture on the oscillatory load record and hence obtain t_f directly. This can only be achieved in tests that are not so brittle that fracture occurs during the first oscillation or in a region of "loss of contact." In the tests performed at a range of temperatures, all the load records were nearly identical in shape and number of peaks (but not in the absolute values of load and time). Substantial differences were observed only after fracture. Figure 5 shows the load trace of a full-speed Charpy test on PVC at 70°C. Some shorter fracture times corresponding to the tests performed at lower temperatures are superimposed on the main load trace. Similar results were obtained on a series of tests on PMMA. Recent tests on steels[8] provide further evidence (Fig. 6). Inspection of load records may offer a convenient method for establishing times to fracture at a range of temperatures without additional instrumentation of the specimen.

It may be noted that when fracture occurs on the second or subsequent oscillation (i.e., increasingly ductile fractures) and t_f can be inferred, the load value at the fracture point still remains unreliable and the effective fracture load must be derived indirectly. This load P may be calculated from the effective stiffness k_e of the system and the deflection of the specimen, so that

$$P = k_e \Delta \tag{2}$$

The deflection of the specimen Δ is influenced by the deformations of the striker

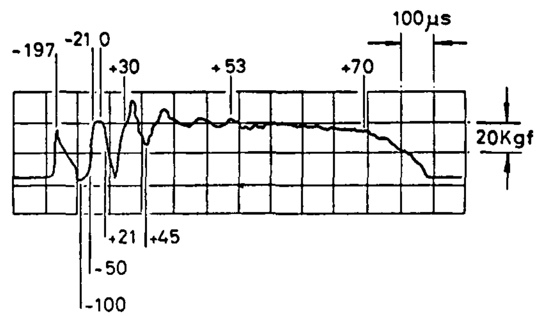

Fig. 5. PVC instrumented Charpy test at +70°C with superimposed points of fracture at a range of temperatures (°C). Full-angle tests.

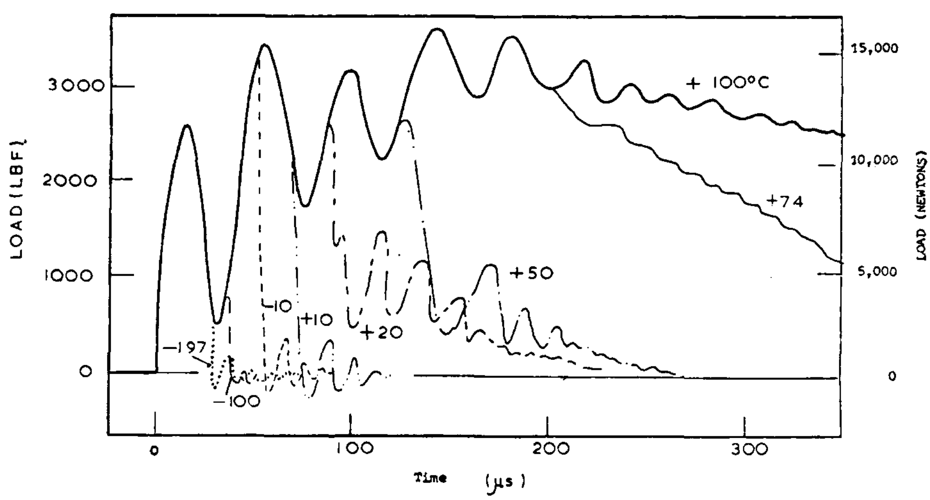

Fig. 6. Full-speed impact fracture of A533B steel Charpy specimens (a/W = 0.25) at various temperatures.

tip, of the supports, and of the specimen; these may be substantial. It is therefore advantageous to express the deflections as a product of the striker velocity and time to fracture. Striker velocity V is measured immediately before impact with a photocell firmly fixed to the frame of the machine as described above. It should be mentioned that this velocity was substantially constant in all tests reported.

Time to fracture, t_f, is defined as a time period between the beginning of load application and the first detectable movement of the crack tip.[9] A method considered adequately accurate for the present purpose consists of a circuit incorporating a conductive silver grid deposited on the specimen at the tip of the crack. A sudden change of the voltage, caused by the crack moving across the grid, is shown in Figure 2(b), trace 1. The assumption that the crack front was square and moved evenly across the ligament width during the fracture can be verified by fractographic examination on the completion of the test. Specimens showing uneven or otherwise distorted crack starters should not be included in the analysis of results. The effective stiffness k_e of the specimen–striker system is measured in a preliminary very low-speed impact test carried out on the specimen using an angle of swing of less than 5°, so that crack propagation does not occur. However, should this impact load result in further extension of the crack, only the final crack length should be used in the analysis as the new arrest mark may be distinguished with ease (Fig. 7); alternatively, the test must be repeated at a lower speed. This "low blow" test may be carried out on the specimen at 21°C or at the actual temperature of the fracture test. When k_e values are measured at 21°C, these must be corrected for the temperature variation of k_e by a ratio obtained in a series of low blow tests conducted at 21°C and at all other test temperatures on a similar (but now conveniently unnotched) specimen.

The low blow test produces an approximately sinusoidal load oscillation [Fig.

Fig. 7. PVC fracture surface, notch, low blow, and fast crack, ×25.

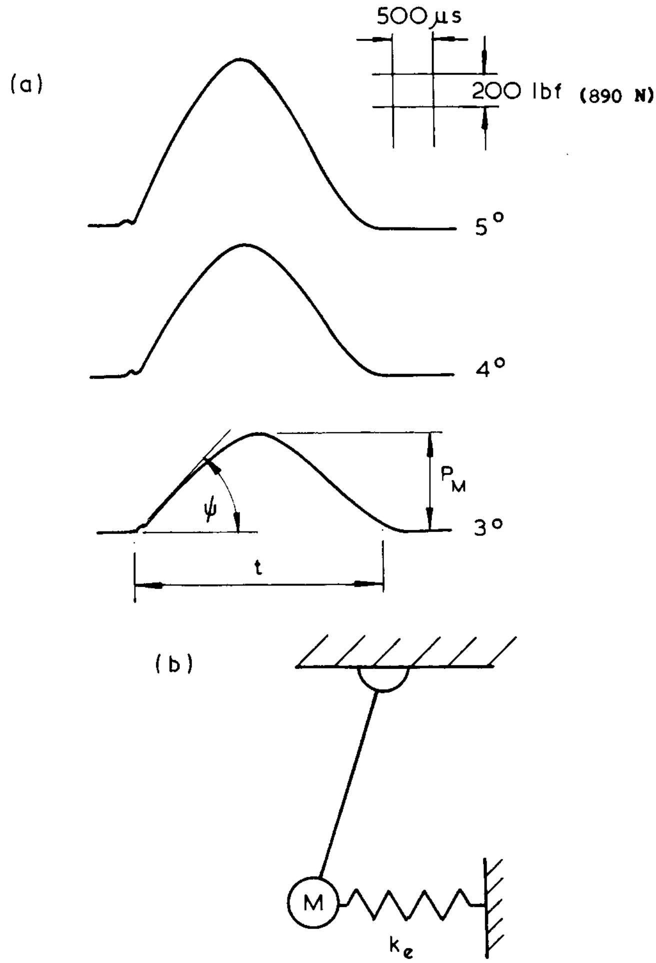

Fig. 8. (a) "Low blow" tests on A533B steel for periodic time measurements. (b) Model of striker–specimen system.

8(a)] which corresponds to a single degree of freedom vibrating system [Fig. 8(b)]. The low blow test can be analyzed in the following three ways: (1) from a measurement of the periodic time T (= $2t$) in the low blow test, and considering the simple harmonic motion (SHM) of the system, k_e may be calculated

$$k_e = \frac{4.79}{T^2}\ \text{lb/in.} = \frac{840}{T^2}\ \text{N/m} \tag{3}$$

(The values of the constants are for the machine used in the present work, details of which are given in the Appendix.) (2) The maximum load P_M of the low blow diagram may be used together with the angle θ of swing of the pendulum to calculate the strain energy and potential energy changes, from which k_e may be derived:

$$k_e = \frac{0.0003708 \times P_M^2}{(1 - \cos\theta)} \tag{4}$$

(3) The initial slope $\tan\psi$ of the low blow diagram and the velocity V of the pendulum at that point may be used to determine k_e:

$$k_e = \frac{\tan\psi}{V} \tag{5a}$$

or

$$k_e = \frac{0.006 \tan \psi}{(1 - \cos \theta)^{-1}} \tag{5b}$$

For metals, k_e calculated from the SHM method has been found to agree well with values calculated by methods 2 and 3. It is, moreover, easier to use and more accurate since the periodic time is independent of angle of swing, and hence load, up to an angle of approximately 5° (except for some softer polymers where hysteresis effects have been observed). It may be noted that methods 2 and 3 involve the measurement of at least two variables such as small angles and maximum load.

A basic assumption of the above method of deriving fracture load is that the bending moment increases linearly with time even in the high-speed brittle tests where contact load is oscillatory. However, some materials are very brittle and fracture at, for instance, 10–20 μsec, i.e., before the bending moment curve has become approximately linear. In these circumstances the above method may still be applied, but the results are less reliable.

It may be noted that stiffness values derived in the low blow test and subsequently used to evaluate high-speed impact tests produce uncertainties in respect of the strain rate dependence of the modulus (and hence derived k_e). The effect is not large for metals, and corrections were produced from measurements carried out over a range of rates and extrapolated to the effective strain rate of the impact test. Some other considerations of the method which apply to polymers (and particularly to soft polymers) are necessary. The total stiffness of the testing system depends partly on the machine and specimen stiffness and partly on the (elastic and plastic) deformation of the contact surfaces. Low stiffness values would lead to an error in K_{1c} evaluation. Similarly low elastic modulus values would result. These differences may be particularly noticeable in the relaxation regions and were discussed in the investigation of the β-peak in PVC.[9]

Fracture load, obtained either directly or indirectly as above, may be used in the K calibration formula to calculate fracture toughness K_{1c}:

$$K_{1c} = \frac{6Ma^{1/2}}{BW^2(1-\nu^2)^{1/2}}\left[1.93 - 3.07\left(\frac{a}{W}\right) + 14.53\left(\frac{a}{W}\right)^2 - 25.11\left(\frac{a}{W}\right)^3 + 25.80\left(\frac{a}{W}\right)^4\right] \tag{6}$$

where M = PS/4 (bending moment), P = fracture load, S = span of specimen, ν = Poisson's ratio, and K_{1c} = critical value of stress intensity factor (i.e., fracture toughness in plane strain and opening mode).

CONCLUSIONS

(1) Methods of measuring specimen deflection and fracture load during an impact test are described. The results are interpreted with the help of a model developed on an analogue computer.

(2) It is shown that a "low blow" stiffness test can be used for the evaluation of high-speed impact tests.

(3) A simplified fracture toughness test suitable to evaluate impact properties of plastics is presented.

Appendix

Charpy Pendulum Details

Weight = 49.5 lb (22.46 kg); distance of C of G from pivot = 2.269 ft (691.5 mm); distance of point of contact from pivot, r = 2.456 ft (748.5 mm); periodic time of swing = 1.757 sec; moment of inertia I about pivot = 281 lb-ft^2 (F.P.S. absolute units).

Notes on Stiffness Measurement in "Low Blow" Test

The linear restoring force due to the stiffness of the system (specimen and machine) is placed equal to the mass acceleration (inertia force) of the system. The force trace originates in strain gauges set in the striker nose and indicates that nose and specimen are in contact throughout the half-period of the oscillation. In these circumstances the mass of the specimen is negligible compared to the mass of the striker, and the periodic time of the specimen–pendulum system during low blow is

$$T = 2\pi\sqrt{\frac{I}{k_e r^2}}$$

and

$$k_e = \frac{4\pi^2 I}{r^2 T^2} \simeq \frac{4.79}{T^2}$$

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