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The significance of impact data for brittle non-metallic materials

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Experimental data for the impact energy of a number of brittle materials are reviewed and their significance discussed in terms of material properties and test conditions. For each material and test method several interpretations need to be considered but it is not always possible to extract meaningful information from the data. At one extreme, for strong, very brittle materials like ceramics, the impact strength may be controlled by the elastic energy in the specimen at the instant of fracture initiation. At the other extreme, for weaker or tougher materials like graphite and fibre reinforced plastics, the impact strength may be controlled by the work of fracture of the specimen. However, in many cases, the situation is less clear and it is emphasized that great care should be taken in the interpretation of test data.

1. Introduction

There is an increasing interest in the use of brittle materials for engineering applications. For high temperature duty the best metallic alloys are limited to working temperatures up to about 1000°C because of inherent chemical and mechanical deficiencies; a number of ceramics are both chemically and mechanically stable to higher temperatures and are thus obvious candidate materials. Carbon fibre composites are attractive for structural aerospace components at lower temperatures because of their high specific strengths and stiffnesses.

A major barrier to the widescale use of such materials as engineering components is their brittleness. The extreme brittleness of ceramics can be overcome to some extent by fibrous reinforcement but it is unlikely that brittle fibre reinforced ceramics or plastics will be produced with toughnesses approaching those of metals. A parallel development in component design philosophy is therefore required.

The key material property in this context is toughness. Although the concept of toughness is perhaps clear at an intuitive level, the measurement and interpretation of toughness presents certain problems. It is the purpose of this note to discuss methods for measuring toughness, their significance, and their relationship to service conditions.

2. Toughness

There is no universally agreed definition of toughness, but toughness must reflect the response of a material, in terms of fracture characteristics, to applied or induced stresses and strains. Tough materials can thus withstand mechanical or thermal shocks without fracturing and without deterioration in mechanical properties. Most toughness parameters relate the energy required to fracture a specimen (U) to the area of material fractured (A) so that toughness is proportional to U/A. Confusion arises because there are several ways of defining and measuring U. Consideration of two main types of test – the work of fracture test and the impact test – will make this clear.

3. Test methods

3.1. Work of fracture

This test [1] is illustrated in Fig. 1a. A notched bar is deformed in three point bending and the force-deflection curve recorded. On the rising part of the curve the specimen and machine store elastic strain energy equal to the area under the curve. At failure the load falls and the specimen-machine system begins to lose its stored energy. Three types of behaviour are possible (Figs. 1b, c and d). When the notch is sufficiently deep a completely controlled fracture is achieved (Fig. 1b) with the rate of crack

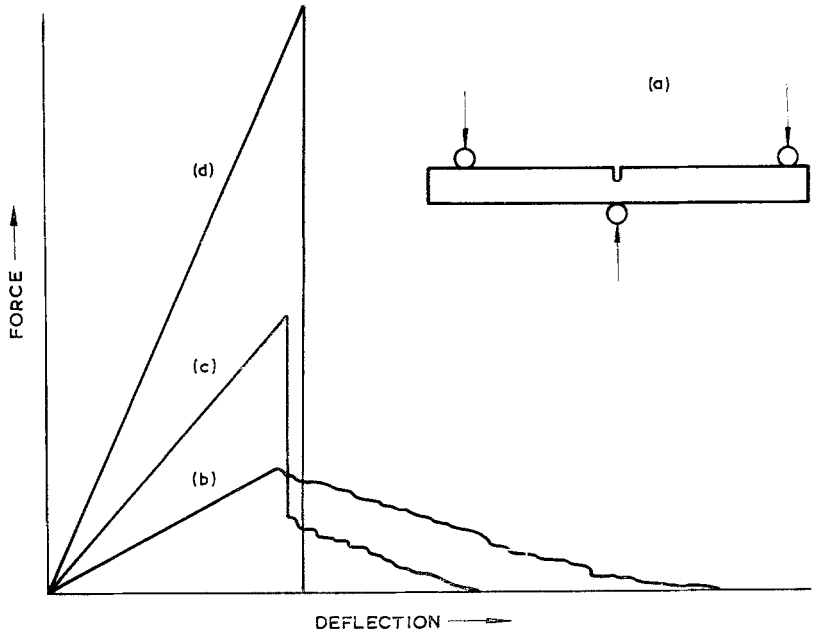

Figure 1 The work of fracture test. (a) Specimen geometry. Force-deflection curves for (b) controlled fracture, (c) semi-controlled fracture and (d) catastrophic fracture.

growth determined by the strain-rate of the testing machine. For any material there is always a theoretically attainable minimum value of U required to create unit area of fracture surface under given conditions of temperature, environment, mode of failure and crack propagation speed. This minimum value is determined uniquely by the physical processes that occur within the material during fracture and is called the fracture surface energy γ. The significance of Fig. 1b is that, under these conditions of testing, the rate of release of stored elastic energy at failure is less than γ and additional work must be done by the testing machine to break the specimen. In cases where the notch is shallower, a semi-controlled fracture occurs (Fig. 1c). Initially the rate of release of strain energy is greater than that required to generate the new fracture surfaces and there is a rapid crack extension as the specimen and machine lose their stored elastic energy. However, there is insufficient stored elastic energy in the specimen-machine system to totally fracture the specimen and there is a final stage of controlled growth. During a controlled or semi-controlled failure, the energy represented by the area under the force-deflection curve divided by the area of fracture surface is called the work of fracture, γ_f. In Fig. 1b all the elastic energy stored in the specimen-machine system is converted to fracture surface energy and $\gamma_f = \gamma$. For semi-controlled failure it is found experimentally [2] that γ_f is typically ~ 1.5 times γ. This is because, during the uncontrolled stage of fracture, energy may be lost from the specimen-machine system by subsidiary processes, such as vibration in the machine, which bear no relation to the physical processes occurring within the material during fracture. Finally, with a very shallow, or no notch, failure is completely catastrophic (Fig. 1d). The stored elastic energy at the instant of fracture initiation is more than sufficient to fracture the specimen and no estimate of the work of fracture is possible.

The conditions for which of these three types of failure occur are determined by the geometry of the specimen, its fracture surface energy, strength and elastic modulus, and the testing machine method. The precise form of the curves indicated in Fig. 1 will thus vary considerably from material to material. Those in Fig. 1 are typical of strong ceramics like alumina. For weaker materials (e.g. graphite) or tougher materials (e.g. composites) the force-deflection curve may be controlled or semi-controlled even in the absence of a notch, with the degree of control increasing with increasing notch depth.

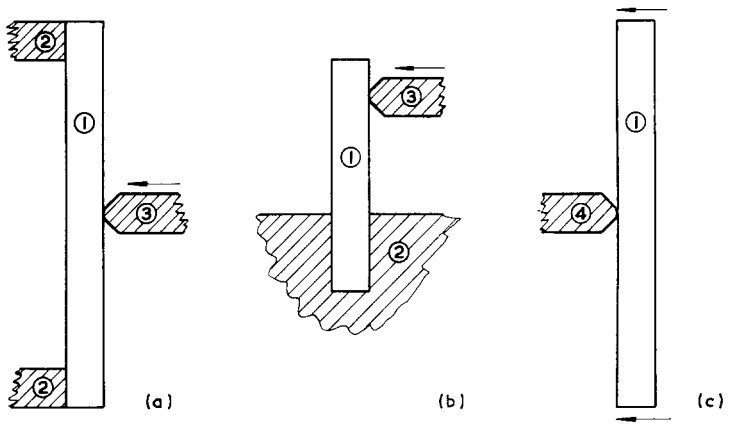

Figure 2 Impact tests. (a) Charpy test. (b) Izod test. (c) Modified Charpy test using the specimen as pendulum. 1: Specimen; 2 and 4: Specimen supports; 3: Swinging pendulum.

3.2. Impact tests

Various types of impact tests are recommended by Standards committees. The ASTM for example [3] recommends two types of test for plastics and electrical insulating materials as shown in Fig. 2. The Charpy test (Fig. 2a) is geometrically similar to the work of fracture test and the specimen is impacted opposite a notch while supported at its ends. The Izod test (Fig. 2b) is more complex; the specimen is rigidly clamped and impacted near one end. In both these impact tests energy is imparted to the specimen via a swinging pendulum. The impact strength is defined as the difference between the energy in the pendulum blow (which is kept constant) and the energy remaining in the pendulum after breaking the specimen. Additionally, energy is needed to throw the free end(s) of the broken specimen – the "toss factor". The ASTM specifications define a procedure for estimating the toss factor in the Izod test and this correction is considered very important for brittle materials. Procedures also exist for estimating the toss energy in Charpy tests.

The two tests are often used with unnotched specimens, and another variation on these tests is to increase incrementally the impacting force until there is just sufficient energy to fracture the specimen. This serves to minimize possible energy losses. One complicating feature of the Charpy and Izod tests is that the specimen is restrained at the moment of fracture by either the supports or the clamp. A simpler arrangement, that has been used for ceramics [4], is to use the specimen as an unrestrained pendulum which then makes contact with a fixed anvil as shown in Fig. 2c. This is also used in an increasing incremental loading manner.

3.3. Comparison and significance of the tests

To effect a direct comparison between work of fracture and impact tests, experimental results will all be expressed in terms of energy per unit area ($J\,m^{-2}$). The energy term is defined as described above, and will be related to twice the nominal area of specimen fractured.

The Charpy impact test is clearly similar to the slow bend work of fracture test and it is useful to compare and contrast data from these tests. In general, the impact energy may be regarded as being made up of several different contributions: energy equivalent to the area under the force deflection curve; toss energy; and energy lost in the machine. The last term corresponds to energy lost in the slow bend test, and a well designed impact machine will minimize this. By analogy with the slow bend test, it might be argued that the three different types of behaviour shown in Fig. 1 could occur during impact fracture, and this has been demonstrated [5] by oscilloscope traces of instrumented impact machines. Thus, it is proposed that two extremes of behaviour could occur. One extreme corresponds to that of Fig. 1b in which the energy absorbed by the specimen corresponds to the fracture surface energy. The other corresponds to Fig. 1d where the specimen obtains from the pendulum, energy equal to its stored elastic energy at failure. On the basis of this simple picture, it is thus expected that, if corrections are made for toss energy and energy lost in the machine, the resulting Charpy energy will be related to the

elastic stored energy at fracture or to $2A\gamma$, whichever is the larger. However, the picture is rather more complicated in that under rapid fracture conditions, there may be insufficient time for the stored elastic energy to be given up to the fracture surface and thus higher impact energies may be recorded.

We shall now consider data for alumina and other ceramics, graphite and carbon fibre composites – materials that possess very different mechanical properties.

4. Experimental data

4.1. Ceramics

There are extensive data available for the work of fracture of alumina [6, 7]. Values between 21 and 54 J m^{-2} were found for a range of twenty commercially available materials. This is over an order of magnitude greater than the value expected from fundamental thermodynamic reasoning ($\sim$ 1 J m^{-2}) to simply break the atomic bonds in a single crystal. This difference has been rationalized in terms of the increased fracture surface roughness for polycrystals and the narrow zone of plastically deformed material adjacent to the fracture faces [2]. A quantitative assessment of the various contributions to the surface energy of polycrystalline magnesia supports this analysis [8]. A more detailed study [2] of a particular 95% alumina indicated work of fracture values from 38 J m^{-2} for controlled fracture (Fig. 1b) to 66 J m^{-2} for a mainly catastrophic fracture (Fig. 1c).

The impact toughness by both Charpy and Izod methods has also been determined [9, 10] in detail for alumina and data is presented in Table I. Two points are obvious. Firstly, for a given material, there is a considerable variation by factors of five and eight in the impact toughness values obtained. Secondly, the impact toughness values are approximately two orders of magnitude greater than those found by the work of fracture method.

Ignoring, for the moment, the variation between the impact toughness obtained by the various methods, the high values of the impact toughness can be rationalized. In the Charpy test the specimen is deformed in three point bending and presumably fractures when the tensile stress on the face of the specimen opposite the pendulum reaches the fracture stress under impact conditions (σ_f). The elastic energy, U_e, in a small volume of material dV under a stress σ with Young's modulus E is $\sigma^2\, dV/2E$. Integration over the specimen volume between the outer supports, V, shows that, for a square section bar, $U_e = \sigma_f^2 V/18E$. Using the following approximate data typical of aluminas: $\sigma_f = 300$ MN m^{-2}, $E = 300$ GN m^{-2}, $V = 100 \times 12 \times 12$ mm^3, gives $U_e = 0.24$ J for the square bars. Relating this to twice the specimen cross-section gives an impact toughness of 0.8 kJ m^{-2}. Additional energy may be lost in the pendulum and the specimen supports. However, the agreement between the above calculated energy and the impact toughness values in Table I for the incremental Charpy test supports strongly the contention that the elastic energy in the specimen is the controlling parameter in a careful impact test. The higher impact toughness values in the other tests are thus artefacts of the test method and bear little relationship to any material property.

A similar analysis can be conducted for impact tests of the type shown in Fig. 2c. The energy losses due to specimen constraint in this test should be less than in the Izod and Charpy tests. Dinsdale *et al* [4] measured the impact energy (the potential energy of a swinging ceramic bar)

TABLE I Impact data for alumina [9, 10].

Material	Specimen dimensions (mm)	Test method	Impact toughness (kJ m^{-2})
92% alumina	64 × 12 diameter	Izod (conventional)	5.0
		Izod (incremental)	3.1
	127 × 12 diameter	Charpy (conventional)	2.3
		Charpy (incremental)	1.1
99.5% alumina	64 × 12 × 12	Izod (conventional)	8.7
		Izod (incremental)	8.2
	127 × 12 × 12	Charpy (conventional)	2.7
		Charpy (incremental)	1.3
	127 × 12 diameter	Charpy (conventional)	2.4
		Charpy (incremental)	1.1

for a wide range of ceramic materials in rod form 77 mm long and ~8 mm diameter. Other material properties were obtained including the three point bend strength σ_b in a static test. They showed that during the impact deformation the stress fell off approximately linearly with distance along the bar from the plane of impact. At fracture therefore the elastic bending energy in the bar is similar to that in a conventional three point bend test. Ignoring strain-rate effects on strength, the elastic bending energy at fracture for round bars is $\sigma_b^2/24E$ per unit volume. Fig. 3 compares the measured "impact strength" with the elastic bending energy, both per unit volume. The impact strengths are ~ 50% greater than the calculated bending energies. This difference can readily be accounted for by the energy absorbed locally around the point of contact with the anvil, plus the fact that the strength under impact conditions will be slightly larger than the statically measured values used in the calculations. Fig. 3 also includes equivalent fracture toughness values for comparison purposes. The two points in the top right corner refer to 85 and 95%

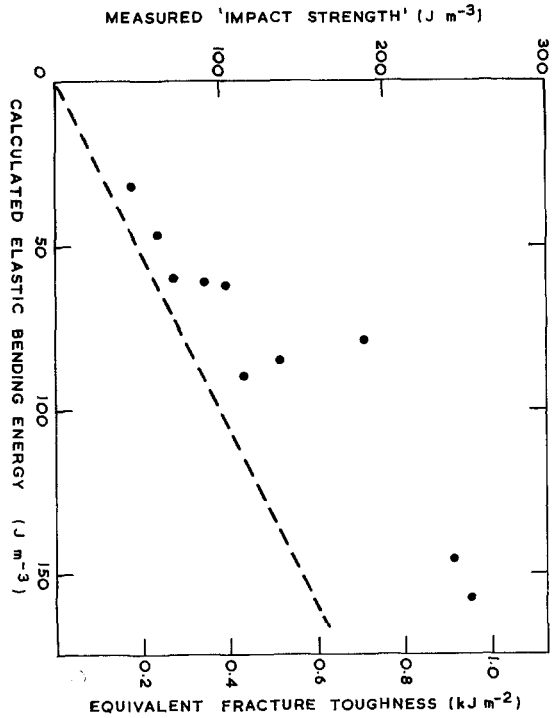

Figure 3 Impact data for various ceramic materials from a modified Charpy test using the specimen as pendulum (4). ●: experimental points; dotted line indicates equivalence between the measured impact strength and the calculated elastic bending energy.

alumina bodies and thus the impact toughness values are somewhat less than values from Izod or Charpy tests. The conclusion from this work is again that in a carefully controlled impact test the property being measured is related to material properties in terms of the elastic energy in the specimen at the moment of fracture.

4.2. Graphite

A very careful series of measurements of the Charpy impact energies of a variety of graphites has been carried out by Mason [11]. Specimens were 50 mm span circular rods of 8 mm diameter and with 3 mm notches. Mason observed that as the energy of the pendulum was decreased, the measured impact energy also decreased – an observation similar to that of the aluminas under incrementally increased impact conditions. Further, Mason was able to show theoretically that up to approximately 70% of his measured Charpy energies were due to the toss energy. However, when this correction was applied to Mason's data, the energy absorbed by his specimens was still found to decrease with decreasing pendulum energy, indicating that there were still unaccounted energy losses in the testing system.

Mason's results which are of particular interest were obtained from two different types of graphite, PGA and HX10. Mason [11] measured the bend strengths, Young's moduli and impact strengths of the two materials, and the works of fracture of a similar PGA and identical HX10 materials have been measured by Davidge and Tappin [2] and Davidge [12]. Table II shows the data for these two different materials, the impact strength quoted being that obtained under the lowest impacting pendulum energy of test and corrected to subtract the calculated toss energy. For the notched bars used as the Charpy specimens, the elastic energy at the point of fracture initiation is about one order of magnitude less than the recorded impact energy. On the other hand the impact energies are slightly in excess of the work-of-fracture values. Thus, allowing for unidentified energy losses, these results indicate that the impact energy is controlled predominantly by the fracture surface energy.

4.3. Carbon fibre composites

Composites of aligned carbon fibres in resin matrices may be made with a range of properties by varying the bond strength between fibres and matrix. Harris *et al* [5] have published the results

TABLE II Experimental data for graphite [11, 12].

Graphite	Bend strength ($MN\ m^{-2}$)	Young's modulus ($GN\ m^{-2}$)	Work of fracture ($J\ m^{-2}$)	Charpy impact energy ($J\ m^{-2}$)
PGA	22.4	10.2	227 (no notch) 132 (half notch)	309
HX10	28.5	14.6	113 (no notch) 64 (half notch)	113

of Charpy impact tests on two different types of carbon fibre-polyester composite. Each contained 40 vol % of high modulus carbon fibres but in one of the materials the fibres were surface treated to produce a high strength fibre-matrix bond, and the other was untreated, resulting in a low strength bond. The toughness of carbon fibre composites is very much affected by the strength of the fibre-matrix interface, and untreated high modulus carbon fibre composites are tougher than composites containing the same volume and type of surface-treated carbon fibre [5]. In flexure the former tend to fail in a more controlled manner, than the latter. Table III shows typical strength, modulus, slow bend works of fracture, and Charpy energies for the two types of material. The Charpy specimens were circular section rods of 50 mm span, 5.7 mm diameter and varied notch size.

As in the case of graphite, these materials exhibit impact energies similar to or slightly greater than their works of fracture. The stored elastic energies at fracture are respectively about one or two orders of magnitude less than the Charpy values, for the two composites.

5. Discussion

There are two necessary requirements to fracture a brittle specimen. Firstly, fracture surface energy must be provided for the new fracture faces. Secondly, the specimen must be stressed locally to its fracture stress. The first requirement can be measured by a work of fracture test and there is evidence that the work of fracture γ_f, is a measureable and reproducible material property. The second requirement can be expressed in elastic energy terms, U_e. U_e is equal to $k\sigma_f^2/2E$ where k depends strongly on specimen dimensions (including a notch if present) and the mode of stressing. U_e thus depends partly on material properties and partly on the test method.

For much published impact test data it is not clear which of the two requirements is in fact limiting and there is a tendency to compare data that are not truly comparable. The results discussed above show that for most ceramics, which are normally strong but not tough, the impact data are related to the elastic stored energy at the initiation of fracture. Unless therefore the impact test closely parallels the conditions expected during service, impact test data are of very limited value. At best this is predictable from other material properties. At worst there are unknown contributions to the impact energy imposed by the test method. For other brittle materials such as graphite, or plastic composites, that are tougher than ceramics, the above data shows that the fracture surface energy is the more important parameter in a carefully controlled test. But again a detailed analysis of the data is required before meaningful information can be extracted.

The discussions above have been restricted to the case where failure occurs by the propagation of a crack from the tensile face of a specimen. For composites, fracture can be more complicated. Hancox [13] has shown that the failure of carbon fibre composites under Izod impact conditions initiates from a compressive failure, and that the failure of composites in general can involve several modes of failure such as tension, compression or shear. Such tests, which measure the impact energy resulting from a number of

TABLE III Experimental data for carbon fibre reinforced polyester [5].

Composite	Bend strength ($MN\ m^{-2}$)	Young's modulus ($GN\ m^{-2}$)	Work of fracture ($kJ\ m^{-2}$)	Impact energy ($kJ\ m^{-2}$)
Untreated	640	140	34.0	33.3
Treated	640	140	~ 4	8.8

simultaneous processes, and which cannot be readily analysed to determine the contribution from each process are thus of rather limited value.

It is recommended therefore that extreme care be taken when conducting and interpreting impact tests. Wherever possible impact data should be correlated with other material properties including fracture surface energy, strength and elastic properties.

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References

1. H. G. TATTERSALL and G. TAPPIN, *J. Mater. Sci.* **1** (1966) 296.
2. R. W. DAVIDGE and G. TAPPIN, *ibid* **3** (1968) 165.
3. American National Standards Institute, C59.11-1955 (R1969) Standard Methods of Test for Impact Resistance of Plastics and Electrical Insulating Materials. Designation D256-56. p. 152.
4. A. DINSDALE, A. J. MOULSON, and W. T. WILKINSON, *Trans. Brit. Ceram. Soc.* **61** (1962) 259.
5. B. HARRIS, P. W. R. BEAUMONT, and E. MONCUNILL DE FERRAN, *J. Mater. Sci.* **6** (1971) 238.
6. R. W. DAVIDGE and G. TAPPIN, *Trans. Brit. Ceram. Soc.* **66** (1967) 405.
7. F. J. P. CLARKE, H. G. TATTERSALL, and G. TAPPIN, *Proc. Brit. Ceram. Soc.* **6** (1966) 163.
8. A. G. EVANS, *Phil. Mag.* **22** (1970) 841.
9. A. J. MONACK, *Mater. Res. Stand.* **10** (1970) 26.
10. A. J. MONACK, *ibid* **11** (1971) 24.
11. I. B. MASON, AERE Harwell, unpublished data.
12. R. W. DAVIDGE, unpublished data.
13. N. L. HANCOX, AERE-R6669 (1971).

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