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The Work of Fracture and its Measurement in Metals, Ceramics and other Materials

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A method of measuring the work of fracture is described and assessed. Typical values for a number of materials are given and various mechanisms for the energy-absorption associated with fracture are considered.

1. Introduction

In using the Griffith equation, it is often difficult to know what value to insert for γ, the effective energy term, which relates the appearance of new fracture face to the disappearance of stored elastic energy. Hasselman has pointed out the relationship that exists between the effective surface energy and a material's thermal shock performance [1]. It is common practice to use the value of the surface free energy, or an estimated value of the surface free energy, but this assumes that the only energy-absorbing process in fracture is the production of new surface, and it does not allow for plastic flow, or any other energy-absorbing process that may be inseparably connected with fracture.

A method, similar to Nakayama's [2], for measuring the energy absorption as a crack grows through a material, is described and assessed in this paper.

1.1. Theory of the Method

The Griffith energy balance criterion for crack growth is

$$-\frac{\partial U}{\partial A} = \gamma$$

where U is the elastic energy stored in the structure, A is the area of the fracture face, and γ is the surface energy. When this criterion is fulfilled, it is energetically possible for the crack to grow, and if it should do so, its subsequent behaviour depends upon how the value of $-\partial U/\partial A$ changes as the crack increases in size, i.e. it depends on the value of $-\partial^2 U/\partial A^2$. If $-\partial^2 U/\partial A^2$ is positive, the crack will accelerate, because the energy being released is more than sufficient to create the new surface area. If it is negative, there may come a point during the propagation of the crack when $-\partial U/\partial A$ becomes less than γ, and external work must be done to keep the crack moving. In such a case, the growth of the crack can be controlled, and it is possible to measure the amount of energy required to make it grow [3].

This situation may be realised in practice by limiting the amount of elastic energy stored in the specimen and machine at the moment of fracture initiation. A reduction in this stored energy can be achieved in two ways: (i) by using a hard testing machine; and (ii) by shaping the specimen so that only a small load is required to initiate crack growth. By paying attention to these factors, it has been possible to grow cracks in a controlled manner in specimens of polycrystalline alumina, magnesia, single crystal alumina, glass, reactor graphite, firebrick, wood, pottery, plastics, and a variety of metals, including copper.

2. Practical Details

2.1. Hardness of the Machine

If a material has either a low work of fracture or a high fracture stress, or both, a very hard machine is required. In the measurements to be reported here, a floor model Instron tensile-testing machine was used with the 500 kg compression load cell on its most sensitive range (i.e. to measure loads up to 10 kg). With this combination, it was possible to cope with such unfavourable materials as magnesia, that had a work of fracture of only 4200 erg/cm^2 but a fracture stress of 2.5×10^9 dyne/cm^2. The 500 kg load cell deflects 9×10^{-5} cm/kg load. A softer

load cell would militate against the success of this type of measurement which is deemed to have failed if the growing crack does not halt in the specimen, for then the two pieces of fractured specimen carry away with them an unknown amount of kinetic energy.

2.2. Shape of Specimen

The stored elastic energy is proportional to the square of the load, so it is particularly advantageous to shape the specimen so that fracture begins at a small load. The specimen shape most commonly used in this series of experiments is shown in fig. 1.

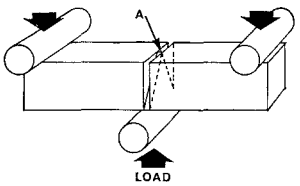

Figure 1 Diagram showing the shape of specimen used to measure the work of fracture, and the method of loading.

It is a square bar containing two cuts, put in by 0.381 mm thick diamond slitting wheel, to reduce the square cross-section to an isosceles triangular cross-section. The load is applied through three rollers, two of which are fixed directly to the table of the load cell, and the third to the underside of the cross-head (see fig. 2). Various sizes of specimen have been used.

When a load is applied, a stress-concentration of sufficient magnitude exists at A, the apex of the triangular cross-section, that a crack initiates from there before sufficient elastic energy is available to break the specimen completely. Further crack-growth takes place in a "controlled" manner, if the potential energy of the system is increased by deflecting the specimen with a movement of the cross-head. A typical load versus deflection curve for an alumina specimen is shown in fig. 3. The time taken for the controlled growth is about 3 min. In principle, any shape of cut that gives sufficient stress-concentration would give rise to controlled crack-growth, but it has been found that the shape shown in fig. 1 allows the more ductile materials to be tested, because a sharp crack grows from A before very much plastic flow takes place.

It is argued that all the work done, which is represented by the area under the load versus

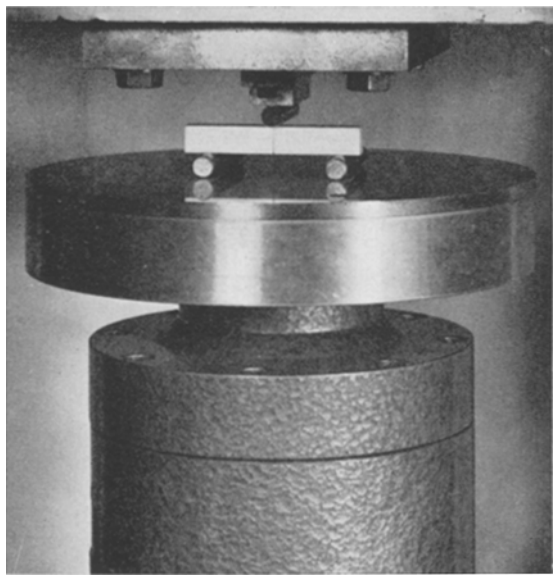

Figure 2 An alumina specimen, 5 cm long, in position on the table of an Instron compression load cell, with the centre loading cylinder attached to the underside of the crosshead.

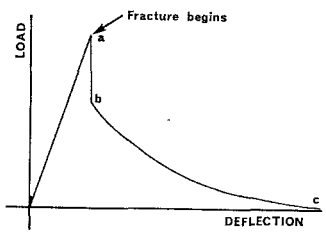

Figure 3 Schematic load-deflection curve obtained from a work of fracture measurement. The load drop, a to b, corresponds to the catastrophic part of the crack growth, whilst the remainder of fracture, b to c, is the controlled part.

deflection curve, is used in the growth of the crack and unavoidable damage directly related with the crack-growth. At the beginning and end of the experiment, the stresses in the structure of the testing machine are zero, and the only damage done, as a consequence of the work expended, is that to the specimen itself. Experimental evidence is presented later, to suggest that negligible energy loss occurs during the catastrophic part of the growth. This being so, all the work done has gone in damaging the specimen. However, the maximum load reached is so small that, if the specimen had contained no notches, no permanent damage would have resulted to it. Thus, no damage would be expected to occur in the arms of the specimen

beam, and so the energy must be consumed very locally, in the region of the moving crack front, by processes that result in fracture or are an unavoidable consequence of it.

The total work done was measured by an Instron integrator connected to the testing machine. This amount of work was divided by the area of the fracture faces to give the values quoted for the work of fracture. No account was taken of fine-scale irregularities on the fracture face, the areas of which were measured with a planimeter from drawings of the outline of the triangular areas, made using a low power projection microscope. Preliminary tests were aimed at determining if there was any dependence of the value obtained upon the specimen size or velocity of crack.

3. The Effect of Changing the Test Parameters

3.1. Effect of Specimen Size

Two alumina bars from Thermal Syndicate (505 recrystallised rod) were used to make a total of eight large specimens, 8 mm square × 5 cm long. After they were fractured, smaller specimens, 3.2 mm square × 2.5 cm long, were cut from the resultant pieces. Table I gives the individual work of fracture values for the large specimens, with the standard deviation to be expected on a single value, as calculated from the four samples cut from each original bar. The mean of the values obtained from the smaller specimens is presented along with the standard deviation to be expected on the mean value. On applying "Student's" t-test to these results, it is found that the difference in the means (a 6% difference) could be exceeded on the basis of pure chance with a probability of 7%, and therefore the difference is thought to be significant.

TABLE I Comparison of results of work of fracture measurements using two sizes of specimen.

Specimen number	Work of fracture values (10^4 erg/cm^2) Large specimen results	Mean of results from the small specimens
A 11/T 174	5.50 ± 0.22	5.12 ± 0.09 5 results
A 11/T 175	5.42 ± 0.22	5.02 ± 0.22 5 results
A 11/T 176	5.13 ± 0.22	5.14 ± 0.12 7 results
A 11/T 177	5.73 ± 0.22	
A 12/T 178	5.29 ± 0.20	4.96 ± 0.25 5 results
A 12/T 179	5.60 ± 0.20	
A 12/T 180	5.10 ± 0.20	4.94 ± 0.16 5 results
A 12/T 181	5.51 ± 0.20	5.09 ± 0.30 5 results

3.2. Effect of Crack Velocity

Two different crack-growth rates were obtained by using two different load cells, the 500 kg and the 100 kg. When the load is sufficient to initiate fracture, more elastic energy is stored in the system if the softer, 100 kg load cell is used and this results in a greater fraction of the fracture process having a catastrophic nature.

Specimens of alumina, 4 mm square × 2.5 cm long, and cut from the same rod, were tested using the "hard" cell (9×10^{-5} cm/kg) and the "soft" load cell (45×10^{-5} cm/kg). There was a marked change in the shape of the load versus deflection curves obtained, and typical examples are shown in fig. 4. In table II, the individual results of this series of measurements are given. The average of the hard cell results is greater than that from the soft cell, and "Student's" t-test shows that the difference is significant, because a difference greater than this could occur by chance with a probability of only 3%. However, this difference may be a property of the material rather than a fault in the method of measurement, and as γ for the slow average velocity is actually greater than for the fast average velocity, it is suggested that negligible energy loss occurs during the catastrophic portion of the test when the softer cell is used.

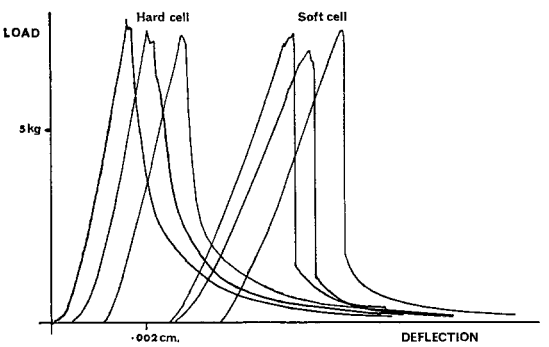

Figure 4 Load-deflection curves for specimens of alumina, showing how the hardness of the testing machine markedly affects the extent of catastrophic fracture.

4. The Results of Fracturing Various Materials

In table III are presented the results of testing specimens of commercial aluminas, made by various manufacturers, and on which an

TABLE II Comparison of results of work of fracture measurements when the hardness of the testing machine is changed.

Rod A4 Work of fracture (10^4 erg/cm^2)		Rod A5 Work of fracture (10^4 erg/cm^2)	
Hard cell	Soft cell	Hard cell	Soft cell
6.42	5.70	7.36	6.03
7.93	6.44	6.68	6.19
8.78	6.94	6.35	6.39
6.63	6.54	6.65	6.09
7.44	7.39	6.53	6.05
7.88		5.77	6.35
		6.47	6.84
		6.69	6.33
			6.15

TABLE III The results of individual measurements of the work of fracture of twenty manufacturers' aluminas. The type numbers correspond with previous work [4, 5].

Type	Work of fracture (10^4 erg/cm^2)							Mean
1	3.72	3.38	3.78	3.71				3.65
2	4.06	3.41	3.24	3.28	3.59	3.13	3.45	3.45
3	4.58	5.31	6.26					5.38
4	5.49	5.20	5.10	5.97				5.44
5	4.22	3.94	3.75	4.04	3.74	4.23		3.99
6	2.26	2.21	3.34	2.94	2.54	3.34		2.77
7								
8	4.78	4.67	4.90	4.85				4.80
9	5.21	5.36	5.25					5.31
10	2.02	2.24	2.13	1.90	2.28			2.11
11	2.93	2.38	3.12	2.58				2.75
12	2.96	1.94						2.45
13	5.46	5.29	5.23	5.19	5.05			5.24
14	4.38	3.45	3.14	3.59				3.63
15								
16								
17	4.24	3.76						4.00
18	3.11	2.90	2.92					2.94
19	5.46	4.85	5.36	5.45				5.28
20	5.01	4.92	4.88	4.68	4.70			4.84

extensive survey of physical property measurements has been made [4, 5]. The different manufacturers are designated by numbers ranging from 1 to 20, which are the same as the numbers given in references 4 and 5. The individual results for each specimen are given, along with the mean values. It is seen that the differences in manufacture have produced very marked changes in the value obtained for the work of fracture, and it would seem to be worthwhile to study the work of fracture as a function of the manufacturing parameters.

In table IV are presented the results of measuring the work of fracture of many materials that have different mechanisms of absorbing energy during the fracture process. The metals listed in this table all gave a clean fracture, with the fracture face appearing crystalline. Aluminium was also tested, but as no proper fracture occurred, only necking, it was considered that this method of testing was inapplicable to this case. The fracture faces of the wood specimens, which were fractured across the grain, were very fibrous, and an important form of energy absorption seems to be that associated with the friction of fibres pulling out from each other. An unavoidable consequence of fracture in polystyrene is the aligning of the molecular chains normal to the fracture face, in a region that extends from the fracture face to a depth of about 2500 Å [6], and this is obviously an energy-absorbing process [7]. The toughened polystyrene, which has a work of fracture four times that of ordinary polystyrene, has small rubber spheres embedded in it, and the action of these must be to provide many centres of weakness in the polystyrene, so that a main crack cannot run without producing a great deal of subsidiary damage in the vicinity of the crack tip. Such subsidiary damage absorbs energy, and provides a mechanism for stress relief around a crack tip. In fully-dense polycrystalline ceramics, the work of fracture has been markedly changed by altering the grain size, preliminary results suggesting that there is a grain size for which the work of fracture is a maximum (table I of reference 5). Nevertheless, theoretically-dense magnesia has not such a high work of

TABLE IV The work of fracture of many types of material.

Material	Work of fracture (erg/cm^2)
Dural	1.4×10^8
Copper	5×10^7
Key steel	5×10^7
Brass	3×10^7
Teak wood	6×10^6
Cast iron	4×10^6
Toughened polystyrene	4×10^6
Deal wood	2×10^6
Cellulose	2×10^6
Polystyrene	10^6
Reactor graphite	10^5
Firebrick	2 to 7×10^4
Alumina	4×10^4
Beryllia	2×10^4
Magnesia	10^4

fracture as a porous magnesia, thus showing that the presence of pores gives rise to an energy-absorbing process.

5. Discussion

Impact tests are often made on metals to get an estimate of their toughness, and, in particular, the Charpy V-notch test is most widely used, because the brittle-ductile transition temperature obtained from it correlates well with the temperature at which metals in service have been observed to fail in a brittle manner [8]. It is well-accepted that a high breaking stress or yield stress is not the only criterion worthy of note when making a choice of a metal for a particular application, because it is often found that a high breaking strength is accompanied by only a small amount of energy-absorption when the metal fractures. This means that the metal is brittle, and its failure is very sensitive to cracks or flaws that develop during service. It is, therefore, interesting to compare the value obtained for the work of fracture of some of the metals listed in table IV with the Charpy values, since they both purport to measure the amount of energy required to break a specimen. For "Naval Brass', of composition 62% Cu, 1% Sn, and 37% Zn, its Charpy value at room temperature is 60.8 ft lb [8]. Since the effective cross-section of a Charpy specimen is 0.8 cm^2, this gives a value of γ which is an order of magnitude greater than that in table IV. Similarly for copper (high conductivity copper), the Charpy value at room temperature of approximately 42 ft lb [8] gives a value of energy expended as 3.58×10^8 erg/cm^2, which is seven times the value in table IV. It is not surprising that the Charpy value is so much greater than the value obtained here for the work of fracture, because, in the Charpy test, energy is expended on vibration, and on giving kinetic energy to the fractured pieces. From the results on alumina, the value of γ for a test that gave partially catastrophic growth was actually less than for a test in which there were no sudden load drops, showing that no energy is lost because of vibration or kinetic energy in the tests here.

Examination of fracture faces and observations of the fracture process in many materials suggest the mechanisms for energy absorption that have been mentioned in the previous section. It is also possible that heat production may account for some loss of energy. In mild steel, it has been found that at least 90% of the mechanical work done during plastic deformation appears as heat and only about 10% as locked-in elastic strain [9]. If the same is true generally, then a small amount of plastic flow associated with fracture may account for a large fraction of the measured work of fracture. For example, Guard and Romo [10] found, by X-ray strain measurement, that the surface layers of the fracture face of polycrystalline alumina had about 1500 erg/cm^2 of stored elastic energy. If this involved the production of heat to the same extent as for mild steel, then the work of fracture would have been at least 15,000 erg/cm^2. In comparison with plastic strains, the thermal effects associated with elastic strains are small and reversible [11], so if the time between loading and unloading is short enough, no significant heat loss will occur, and both the loading and unloading curves will follow the same adiabatic stress-strain path.

Considerations of the work of fracture are of significance only in mechanical loading conditions that give limited strain, as opposed to a constant stress, because in the former case only a limited amount of elastic energy is available for crack-growth. This is in contrast to the condition of constant stress, where, if the body should deform, the undiminished stress would do work that is proportional to the deformation. Examples of limited strain are found in mechanical shock, where one body impacts another to give a maximum strain that is dependent upon the velocities of the bodies and the velocity of the shock waves in the bodies, and also in thermal shock where the amount of strain produced is dependent upon the temperature change. The amount of energy that becomes available to damage the structure of the body when it receives such a shock is dependent also upon the Young's modulus and the fracture stress. Paradoxically, if the fracture stress is low, the body may be damaged to a lesser extent because it becomes impossible to reach a high stress in it, so the available strain all takes place at a low stress. Conversely, if a high stress can be reached before the fracture starts, more elastic energy becomes available for crack-growth, and the probability of complete failure is increased.

However, the relative merits of two materials in a limited strain application that gives rise to equal amounts of energy being available to damage their structures by cracking, are determined by their works of fracture.

6. Conclusions

A method of measuring "work of fracture" has been described and demonstrated on many different types of material. Using polycrystalline alumina, the effects of changing the specimen size, and the crack velocity were studied. Doubling the specimen size caused a 6% increase in the result, whilst using a load cell that was five times softer, to give partly catastrophic crack-growth, caused the result to decrease by 8%. Since no energy is lost due to vibration during catastrophic crack-growth, it is concluded that differences in values obtained for γ reflect the genuine fracture behaviour of the material.

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