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DYNAMIC TESTING OF CERAMICS UNDER TENSILE STRESS

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Abstract—Three types of tests are considered: the three-point impact bending test, the Brazilian test and a modified version of the spalling test in which a specimen is loaded under uniaxial stress. The importance of conducting a sufficient number of experiments to interpret the results in terms of Weibull statistics and to achieve a simple state of stress is emphasised. Of the three techniques, the uniaxial spalling test satisfies both requirements and permits measurements at rates of strain of the order of 10^3 s^{-1} and above.

INTRODUCTION

The brittle nature and high stress wave speed of ceramics present an exciting challenge to the experimentalist interested in measuring their mechanical properties at high rates of strain. The split Hopkinson bar apparatus is commonly used for compression tests, where the only difficulties arise from the mismatch between the hardness and impedance of bars and ceramics. Spalling tests in which a state of uniaxial strain prevails are also common in the ballistics field. Dynamic tests in which the ceramic fails under uniform uniaxial tensile stress require elaborate precautions to ensure perfect alignment. Failure under tensile bending stress in three-point loading arrangements is, on the other hand, easier to achieve in a reproducible manner. The Brazilian test is another technique that will be considered in this paper.

THE THREE-POINT IMPACT BENDING TEST

In this test, a beam of rectangular cross-section simply supported at its ends is struck a blow midway between the supports with a heavy pendulum or a bar. A notch may be machined, as in the Charpy configuration, or a crack may be grown prior to the test. The fracture energy can be obtained directly from the pendulum. A not insignificant part of the energy is used as kinetic energy to accelerate the fragments produced when the specimen breaks, the rest is consumed in crack initiation and propagation (Kalthoff *et al.* 1991). With impact velocities within the range 0–6 m s^{-1}, it was found that the actual fracture energy in Al_2O_3 was independent of the impact velocity. Other authors, as reviewed by Ruiz (1989), have come to different conclusions, but some of the results are suspect because the importance of the kinetic energy correction has not always been recognized.

The use of a Hopkinson bar offers certain advantages over the standard instrumented Charpy pendulum (Ruiz and Mines, 1985; Mines and Ruiz, 1985). In particular, the striker delivers a sharper blow that results in a near-rectangular force pulse whose amplitude and duration can be easily controlled by varying the impact velocity and the length of the bar. A strain gauge, fixed near the end of the bar, responds to the incident and to the reflected strain pulses. Using simple one-dimensional wave theory, it is quite straightforward to obtain the variation with time of the force applied to the specimen. The interpretation of the results in terms of fracture toughness of the material, K_{IC}, depends on the validity of two assumptions: (i) the incident stress pulse is non-dispersive; and (ii) the duration of the test is such that quasi-static conditions prevail.

The first assumption is accepted as valid when the striker bar has a small diameter, say less than 10 mm, and has the same impedance along its whole length. In practice, the striking end is wedge-shaped. Bacon (1993) has studied the effect of a tapering end by considering the propagation of a stress pulse in the form of a ramp, rising to a maximum after a time t_r [Fig. 1(a)]. When $t_r = 0$, i.e. for a rectangular pulse, and a square-ended bar ($L = 0$), the strain gauge fixed 50 mm from the end gives a signal proportional to the amplitude of the incident pulse over 0.2 ms, until the reflected pulse cancels it out to satisfy the stress free condition at the end, 0.02 ms corresponds to the time taken for the stress pulse to travel from the strain gauge station to the end and for the reflected pulse to return. In a tapered end with $L = 25$ mm, the reflected pulse causes a sharp drop of the signal, which exhibits a sharp negative spike. The difference between the theoretical rectangular pulse and the calculated signal is most pronounced when $L = 50$ mm. It may be concluded that dispersion will introduce an inadmissible error when the duration of the event of the same order as (L/c), i.e. 0.01 ms in this example where c is the longitudinal wave speed of the material.

If the first assumption is valid, the Hopkinson bar provides a measure of the force applied to the specimen, F. If the duration of the test is such as to give time for several wave reflections to occur before the specimen breaks, it may be assumed that quasi-static conditions prevail and K_{IC} can be calculated from the static calibration equation,

$$K_I = \frac{3FS\sqrt{a}}{2tW^2} Y\left(\frac{a}{W}\right),$$

where, for $S/W = 4$ (Strawley, 1976),

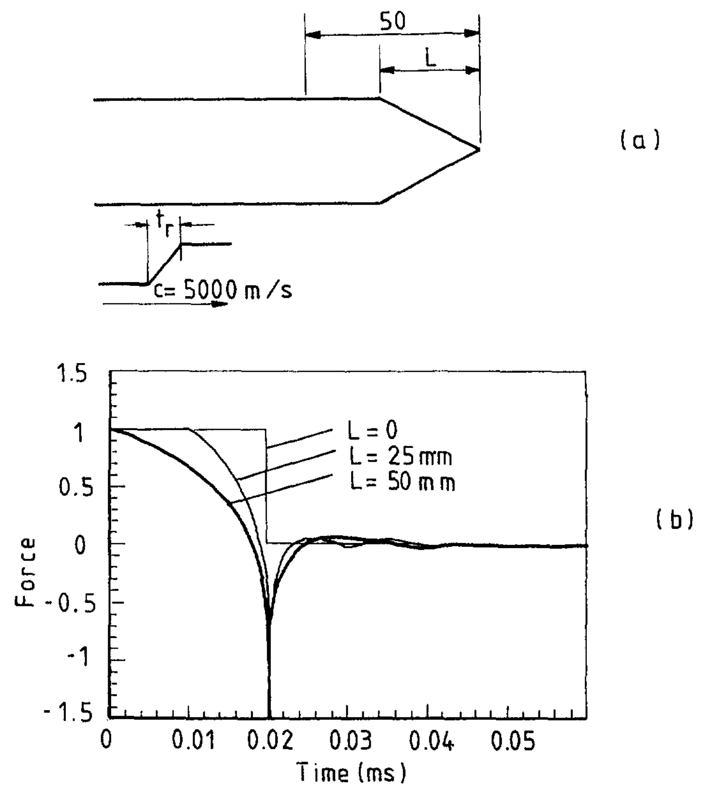

Fig. 1. Transmission of a stress pulse in a bar with a tapered end: (a) stress pulse; (b) comparison between the calculated force and the amplitude of the incident pulse for $t = 0$ [after Bacon (1993)].

$$Y\left(\frac{a}{W}\right) = \frac{1.99 - \frac{a}{W}[1-(a/W)][2.15-3.93(a/W)+2.7(a/W)^2]}{[1+2(a/W)][1-(a/W)]^{3/2}}.$$

A smooth force–time signal is obtained by using the Duhamel integral (Ruiz, 1989; Kishi, 1991),

$$F_D = \omega \int_0^t F(\tau) \sin \omega(t-\tau)\, d\tau,$$

where ω is the first natural frequency of the specimen. To calculate ω, the procedure consists of minimizing the error (Bacon *et al.*, 1991),

$$\xi = \int_0^T (F_D - F)^2\, dt.$$

Bacon (1993), applying this technique, found values of K_{IC} ranging from 1.2 to 2.0 MPa $m^{1/2}$ for glass, the high values corresponding to dynamic tests at $\dot{K}_I = 3 \times 10^4$ MPa $m^{1/2}$ s^{-1}. Using precracked specimens, Kishi (1991) reported a fracture toughness of 6.5 MPa $m^{1/2}$ for Si_3N_4, independent of strain rate up to $\dot{K}_I = 10^6$ MPa $m^{1/2}$ s^{-1}. No strain rate dependence was found for sialon and SiC, but zirconia was strain rate dependent. These conclusions appear to be contradicted by Kalthoff *et al.*'s (1991) test data obtained from notched specimens. The forces recorded in both cases were of the order of several hundred newtons. The duration of the tests, deduced from Kishi's results, was 0.01 ms at the fastest rate, when experimental errors associated with the possible violation of the first assumption may be significant. In Kalthoff's tests, the duration appears to be around 0.1 ms.

To overcome the problems arising from the measurement of the force by an instrumented impactor, Kishi used a strain gauge fixed to the specimen calibrated by static loading. Apart from practical difficulties, the accuracy of the results relies on reaching quasi-static equilibrium conditions by the time of fracture. In tests done with glass and glassy ceramic specimens, Johnstone (1992) measured the impact force and the reactions at the supports of the beams by means of strain gauges. He found that when fracture occurred the two sets of forces were still not in equilibrium. This indicated the importance of the specimen inertia which is ignored in the static calibration.

It will also be noted that when the Hopkinson bar arrangement is used to test specimens in three-point bending what is measured is the fracture toughness at crack initiation. The Charpy pendulum, on the other hand, measures the total fracture energy. In both cases the specimen is accelerated and hence a kinetic energy correction is needed, although the correction is very much smaller in the Hopkinson bar when the specimen remains intact through the test than in the Charpy pendulum when the fragments are ejected.

THE BRAZILIAN TEST

In the Brazilian test a ceramic disc is crushed between the input and the output bases of a split Hopkinson bar apparatus. Typical strain gauge traces are shown in Fig. 2. The arrival of the incident compression wave at gauge 2 occurs after approximately 0.3 ms. The load applied by the input bar and the reaction on the output bar, detected by gauges 2 and 3, respectively, are seen to be in equilibrium within 0.01 ms of impact, as is to be expected since the time taken for a compressive stress wave to travel across the specimen is only 0.003 ms. Given that the duration of the test until fracture is 0.135 ms, a state of quasi-static equilibrium may be assumed and the stress distribution will be as predicted by the classical theory of elasticity (Timoshenko and Goodies, 1970). According to this, the stress along the diameter AB consists of a tensile component $\sigma_x = 2F/\pi dh$ and a compressive

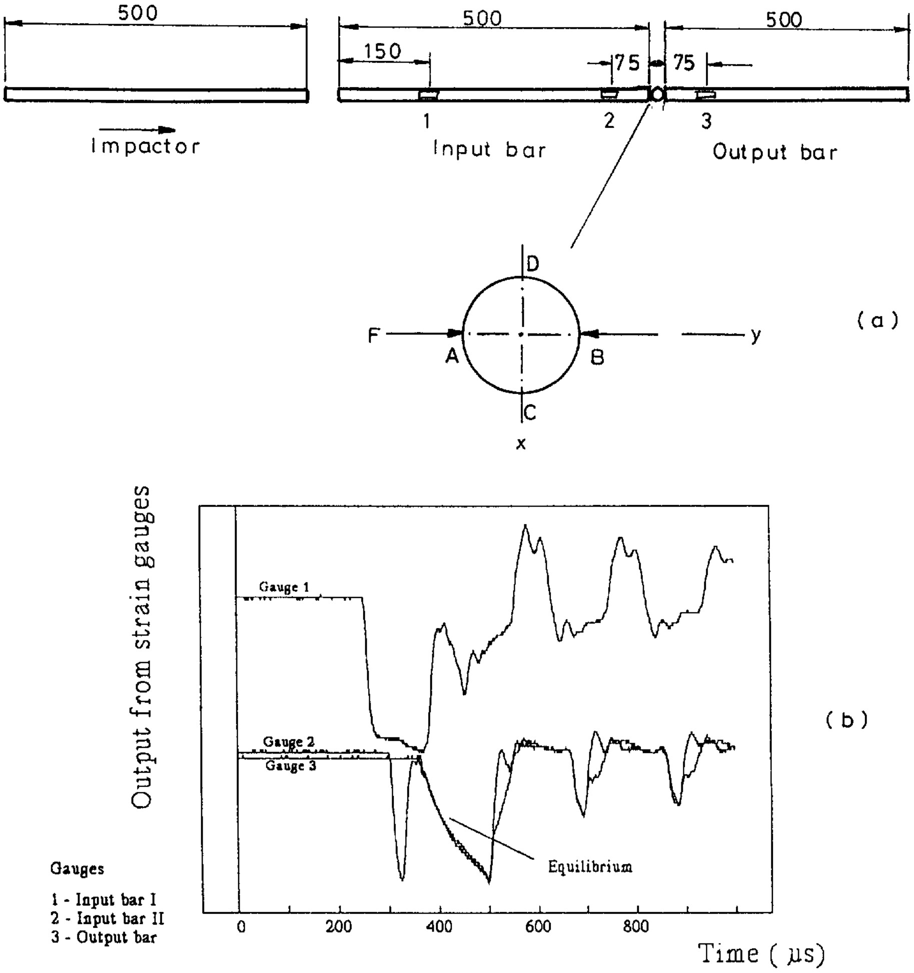

Fig. 2. Split Hopkinson bar arrangement for the Brazilian test (a) and output traces (b).

component σ_y limited by Hertzian contact at A and B and falling to $-3\sigma_x$ at the centre of the disc.

One-dimensional wave theory is used to interpret the data in terms of force and displacement of the ends A and B (Harding, 1983), and from these it would seem to be a simple matter to deduce the tensile strength of the ceramic provided that the effect of the compressive stress can be ignored. However, the fracture process of the ceramic disc is extremely complicated. Figure 3 shows that the fracture of the ceramic disc specimen crushed dynamically between two Hopkinson bars is extremely complicated. It shows a series of high-speed photographs taken of an 11.8 mm diameter glass–ceramic disc. The framing interval is 10 s between pictures. The predicted crack along the loading axis can be seen clearly; however, this is supplemented by the presence of a comminuted (fractured) zone on the left edge at the point of contact with the output bar, and cracks emanating from the edges of the contact zone between the specimen and the input bar. As the load increases with time, the size of the comminuted zone grows back along the loading axis to form a triangular region of crushed ceramic. Meanwhile, the cracks originating from the edges of the contact points grow very quickly. The initiation and growth of the comminuted zone and the cracks causes an increase in compliance of the specimen, and the specimen begins to take on an oval shape, with the result that cracks appear on the periphery of the specimen due to bending stresses.

It is possible to reduce the compressive Hertzian stresses by loading the disc between curved anvils or fitting a soft washer between the bars and the disc. Reproducibility and

Fig. 3. Glass–ceramic disc under dynamic diametral loading. Framing interval, 0.01 ms.

impedance mismatch do however arise, and cast some doubt on the accuracy of the experimental results.

SPALLING UNDER UNIAXIAL STRESS

A technique commonly used to measure the mechanical properties of materials at high strain rates and uniaxial strain conditions consists of projecting a plate of the material against a rigid flat target. The stress waves originating in impact and reflected on the back surface of the plate combine to produce spalling or scabbing. A modification of this technique consists of using a long cylindrical rod rather than a plate to obtain uniaxial stress rather than uniaxial strain.

Consider a hardened steel impactor of length L, hitting an input bar of the same length at velocity V_i, with the output bar replaced by a ceramic cylindrical rod of length $2L$. The input bar is in contact with the ceramic output bar, and the Lagrange diagram (Harding, 1983) for the three bars is as shown in Fig. 4. After a time $(3L/c)$ both impact and input bar are entirely unloaded and at rest. The centroid of the ceramic rod then moves with a velocity of $V_i/2$, with the rod alternating between states of tension and compression about the centroid. The maximum tensile stress, following the first compression stage, is $\rho c V_i/2$. It is a simple matter to conduct a series of tests at increasing values of the impact velocity until fracture occurs to find the true uniaxial tensile strength. If required, strain gauges may be attached to the input bar to verify the amplitude and shape of the input pulse. The specimen itself may also be strain gauged since the movement of the centroid over the duration of the test will be very small. For example, considering the impact of a 50 mm long steel bar at 10 m s^{-1}, on a ceramic rod of density 2500 kg m^{-3} and wave velocity of 10 km s^{-1}, the duration of the test will be about 0.015 ms, during which time the centroid of the ceramic rod will have moved by only a fraction of a millimetre.

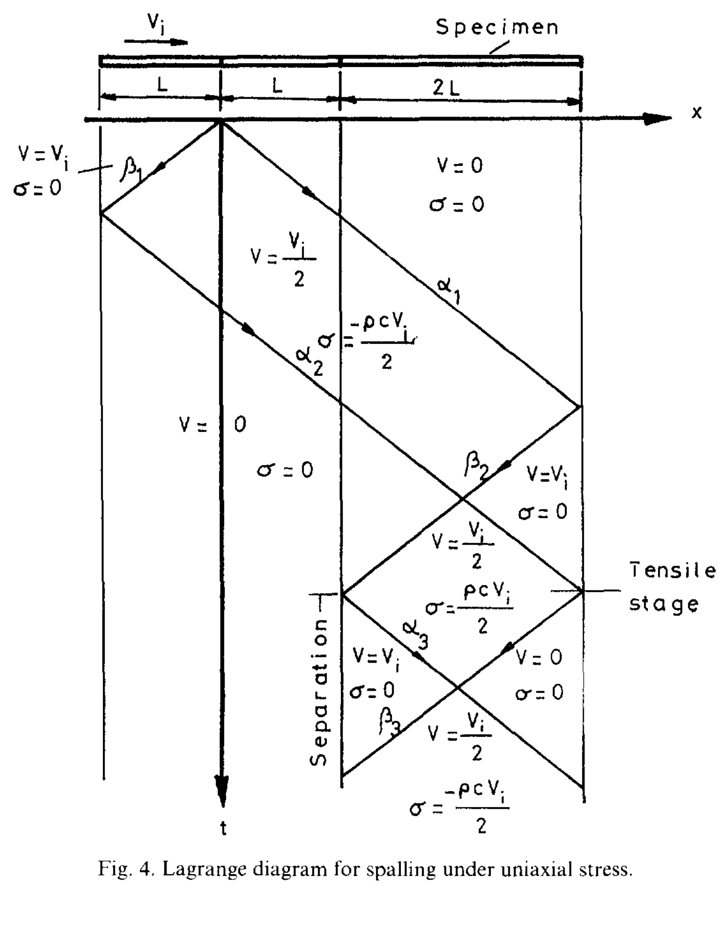

Fig. 4. Lagrange diagram for spalling under uniaxial stress.

The preceding analysis is valid only when all three bars have the same mechanical impedance, i.e. when the ratio AE/c is equal for all bars, where A is the cross-sectional area of the bar, E is the Young's modulus and c is the longitudinal wave velocity. The impedance mismatch between the steel input bar and the ceramic output bar will not affect the mechanics of the test, provided that the length of the input bar is sufficiently long to ensure that the release wave arrives at the steel–ceramic interface and separates the input and output bars before the arrival of the reflected wave created at the steel–ceramic interface. Consequently, the wave transmitted to the ceramic output bar will not have the same amplitude as the wave in the input bar, and therefore it is necessary to strain gauge the ceramic specimen. To account for the difference in wave velocity between the steel bars (impactor and input) and the ceramic output bar, the length of the ceramic rod is adjusted accordingly from $2L$ to $2Lc_{\text{ceramic}}/c_{\text{steel}}$ to ensure that tension initiates at the centre of the rod.

Although the tensile wave initiates at the centre of the ceramic bar, fracture will not necessarily always occur at this point. The position of fracture will depend on the population and size of defects within the ceramic specimen, as these will initiate cracks. Below a critical level, no fracture will occur, and the ceramic bar will simply oscillate between compression and tension with a period of $2L/c_{\text{steel}}$. However, at marginal stress levels, microcracks may be produced as the ceramic undergoes tension. The amplitude and duration of the stress wave may not be sufficient for fracture to occur during the passage of the first tensile wave. However, subsequent tensile waves may result in the production of additional microcracks, which may then coalesce and fracture the specimen. This introduces the concept of cumulative damage in the form of ultra low-cycle fatigue. By subjecting the specimen to stress pulses of increasing amplitude, the production of microcracks at the marginal stress levels has to be considered. In the tests reported here, no attempt was made to determine the sub-critical damage that may be caused at these marginal levels since the small number available necessitated that each specimen had to be subjected to a series of impacts until failure occurred.

The preferred testing method would be to begin testing at a sufficiently high impact velocity so that the specimen will always fracture. Each specimen would be impacted once only, and by gradually reducing the impact velocity for each of the subsequent specimens tested, the impact velocity at which the specimen survives can be obtained. By repeating this procedure a number of times, a value for the true tensile strength at which the specimen fractures, or to be more precise survives, can be determined.

Rods of materials LZI/A glass–ceramic (manufactured by Ceramic Developments Midlands), float glass (Pilkington) and 96% pure alumina, all of 10 mm diameter, were subjected to axial impact tests. The lengths of the LZ1/A and the alumina specimens were 70 and 100 mm, respectively. For the glass, specimens of nominal lengths 80, 60 and 40 mm were produced, to investigate the effect, if any, of varying the duration of the stress pulse. By shortening the length of the projectile, the duration of the stress is reduced. Therefore, to ensure that the ratio of projectile length to specimen length remained constant, so that tension initiates in the centre of the specimen, the length of the glass specimens was adjusted accordingly. The mechanical properties of the three materials tested are given in Table 1.

Spalling tests on strain gauged specimens were performed and the results are presented in Table 2. Figure 5 shows a typical trace obtained from the strain gauges. Note the initial

Table 1. Static mechanical properties of LZ1/A glass–ceramic, float glass and 96% pure alumina

Material	Young's modulus (GPa)	Longitudinal wave velocity ($m\ s^{-1}$)	Flexural strength (MPa)	Weibull modulus (m)
LZ1/A	92.5	6207	339.4	11.6
Glass	69.3	5269	127.2	15.7
Alumina	285.9	9225	200.7	20.0

Table 2. Results of the spalling test

Material	Spall strength (MPa)	Weibull modulus (m)	Predicted strength (MPa)
LZ1/A	92.5	9.3	186–256
Glass	66.5	9.1	70–101
Alumina	175.8	15.5	142–160

compressive pulse, followed by the tensile pulse. After the tensile peak, the wave is distorted as release waves emanating from new fracture surfaces interact.

The strain rates achieved in the spalling test are of the order of $10^3\ s^{-1}$. A comparison between the tensile strength, measured in the spalling test, and the three-point bending strength or modulus of rupture (MoR), demands a consideration of the state of stress of the specimen and Weibull statistics (Derby *et al.*, 1993). For the same specimen size, the relationship between the tensile strength and the MoR is given by the expression

$$\frac{\sigma_u}{\mathrm{MoR}} = \left[\frac{1}{2(m+1)^2}\right]^{1/m},$$

where m is the Weibull modulus. Tables 1 and 2 show that m depends on the type of test and therefore an exact value of the ratio cannot be obtained, although the expression can still be used for comparison. As m increases, the ratio tends towards unity, being equal to 0.55 when $m = 9$ and 0.71 when $m = 20$. The values of σ_u predicted from the three-point bending test are those shown in the fourth column of Table 2. The glass–ceramic LZ1/A exhibits a drop in strength with strain rate and so does glass, although much less relatively. In alumina, on the other hand, an increase in strain rate brings a slight increase in strength. The reason for this difference in behaviour could well be the coexistence of two phases with different elastic properties in the glass–ceramic (Ruiz, 1989).

CONCLUSIONS

The tests described above are used to characterize properties of ceramics at high rates of strain. The three-point bending test, using a Charpy pendulum, is only capable of reaching moderate strain rates, higher rates being possible with the Hopkinson bar apparatus, which has the added advantage of delivering a cleaner and more controllable impulse. In either case, data are interpreted on the assumption that a stationary equilibrium has been reached

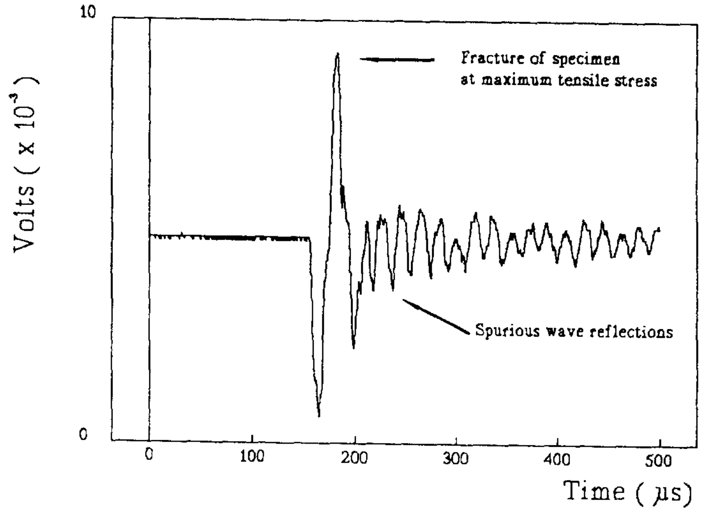

Fig. 5. Strain gauge traces from spalling test.

when fracture occurs. If fracture takes place during the initial transient, the test becomes invalid. Of course, it is always possible to interpret the experimental data using a dynamic rather than a static calibration function, but this presents serious practical problems.

The main objection to the Brazilian test is that the state of stress is far from uniform. This would not be so bad were it not for the biaxiality of the stress at the critical points along the loading axis and in particular near the points of application of the load. A small hole, drilled through the centre of the specimen, would increase the tensile stress component and create a uniaxial state of stress, but this would be at the expense of introducing a steep stress gradient. As the central hole increases in diameter, the specimen becomes a ring, which is more predictable than the disc and under stresses approaching a uniaxial system, but slow to respond to the impulsive loading by reason of its greater compliance than the disc. As such, it offers no advantages over the beam in three-point bending.

The spalling test provides a unique measure of the uniaxial strength of brittle materials, through the axial impact of a steel bar onto a brittle specimen bar. The introduction and subsequent interaction of the stress wave in the specimen bar is well understood, and can be validated both analytically and experimentally. By measuring the amplitude of the stress waves propagating within the specimens, the maximum value of (tensile) stress at which the specimen bars fracture can be determined. However, the possible presence of sub-critical damage caused by impacts at lower velocities should not be discounted.

It is generally accepted when determining the mechanical properties of ceramics that a statistical analysis, usually following a Weibull distribution, is essential. This practice has become accepted when dealing with static properties but not in the case of high strain rate tests where a single or, at most, two or three measurements are very often quoted. Given that the determination of the Weibull modulus is required to compare the results of different tests, it is obvious that it should always accompany the mechanical property to which it refers.

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