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The spalling of long bars as a reliable method of measuring the dynamic tensile strength of ceramics

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Abstract

An analysis of the spall bar test as a reliable method of determining the dynamic tensile strength of brittle materials is presented. The method is based on the propagation and reflection of elastic waves in bars. Failure occurs when compressive waves are reflected into tensile ones on reaching a free end. The study analyses the hypotheses needed to obtain the true tensile strength with this experimental technique, referring to the requirements of the material and of the experimental procedure. The analysis is complemented with numerical simulations of the testing procedure. The correct way to determine the true dynamic tensile strength of ceramic materials is outlined. Finally, the results of tests of some ceramic materials, three different aluminium oxides, an alumina reinforced with zirconia, silicon carbide and boron carbide are presented. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: High strain rate; Dynamic tensile strength; Ceramic materials; Spalling

1. Introduction

New advanced ceramics have begun to replace more traditional materials in applications requiring high specific stiffness and strength and good performance at elevated temperatures. Impact applications have provided a strong stimulus to the development of these materials on account of their ballistic performance and relatively low density. Materials such as aluminium oxide, silicon carbide, boron carbide and aluminium nitride are commonly used in the design of armour prototypes [1]. The main drawback of these materials lies in their extreme brittleness and limited ability to withstand plastic deformation, given their low fracture toughness and the marked difference between their tensile and compressive strengths.

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To design a structural component made of ceramic material, a constitutive equation to relate stress and strain under a general state of loading and a failure criterion to control the material status must be determined. Ceramics are usually considered elastic materials, at least at moderate temperatures or pressures. Most failure criteria are based on the compressive and tensile strengths [2], the latter being commonly one order of magnitude lower than the compressive one, and in most cases the property which controls failure.

In dynamic applications (ballistic impact, collisions, explosions, etc), tensile loads can appear in the component when the initial compression waves generated by impacts are reflected from the solid boundaries [3]. The materials fail or not depending on their tensile strength under working conditions, which in the above mentioned examples are associated with a high strain rate.

Measurement of the tensile strength of ceramics (or other brittle materials such as concrete or glass) is not an easy task from the experimental point of view. Even at low strain rates, direct tensile tests are difficult to perform because of very little misalignments, or stress concentrations along the loading system may produce undesirable fail modes. Numerous specimen geometries have been designed with different loading methods, but the results have not been very successful and the complexity of the specimen geometries proposed increase in the cost of the experiments [4].

To overcome these difficulties, another kind of test was developed based on the idea of using compressive loads to generate tensile stresses in the specimen. The well known three or four point bending tests are the most widely used in static conditions. The result of this type of test is the modulus of rupture, a property related to the tensile strength but with limited usefulness as a property of design. Another well known method is the splitting test of discs or cubes (Brazilian test), originally developed to characterise the tensile strength of concrete [5]. These tests are less complicated to carry out, but the stress state produced in the material is not uniaxial and consequently some doubts remain about the value of the tensile strength provided.

When the tests are performed at low strain rates, the experimental difficulties are solved reasonably well, but when the strain rate is increased, another kind of trouble could condition the results. If techniques such as the Split Hopkinson Pressure Bar are used, the stress equilibrium requirements are hard to attain, especially when using geometries with free ends like the prismatic ones typical of the bending tests. That is the reason why, to the authors' knowledge, no results of dynamic bending tests are available. However, several studies have extended the Brazilian tests to the high strain rate field with acceptable results using the Split Hopkinson Pressure Bar [6,7]. The equilibrium requirements are easily achieved and some experimental problems regarding the failure pattern can be solved if care is taken with the procedure. However, the main question remains on how the biaxial stress state could affect the tensile strength.

All these factors point to the need of a reliable method to determine the dynamic tensile strength of brittle materials. In recent years, some papers have suggested the spalling of long bars as an alternative to the above mentioned tests in the characterisation of ceramics [8,9], glass [10] or concrete [11]. The fundamentals of the test rely on the controlled propagation and reflection of elastic waves along cylindrical bars. A projectile impacts against one of the ends of a cylindrical bar generating a compressive wave, which is reflected as tension at the free end of the specimen.

So far, only the principles of the test and some experimental results have been presented. No detailed study of the validity of the method, checking the hypotheses and analysing the effect of changes in the experimental procedure, has been made. In this paper, the hypotheses of the test are clearly identified, a validation is performed and a procedure for the test is proposed. The experimental work was done on advanced ceramic materials with applications in ballistic armours: aluminium oxides, alumina reinforced with zirconia, silicon carbide and boron carbide.

A testing method is more valuable when it is easy to perform from the experimental point of view and when the data can be analysed following a simple procedure.

Although in this work, a sophisticated experimental system is used, including strain gauges instrumentation of the specimen and high-speed photography, under certain circumstances the use of these techniques can be avoided. On the other hand, the procedure proposed to analyse the raw data is based on the simple one-dimensional theory of elastic waves. It provides the true material tensile strength with the advantage of not including more complicated phenomena, such as three-dimensional effects due to the failure process or the well known dispersion of a pulse travelling along a cylinder. This is just one of the interesting points of this paper.

2. Testing method description

The basis of the test relies on the propagation and controlled reflection of elastic waves along cylindrical bars. If a one-dimensional wave propagation is assumed, the equation of motion can be formulated as $\partial^2 u/\partial t^2 - c^2(\partial^2 u/\partial x^2) = 0$, where u is the displacement, t represents the time, x the longitudinal coordinate and c the longitudinal speed wave propagation. This expression can be integrated, and the solution has the form $u(x,t) = f(x-ct) + g(x+ct)$, where $f(x-ct)$ represents a wave travelling in the positive x-axis direction and $g(x+ct)$ represents other wave travelling in the opposite direction. The strains and particle velocities can be obtained directly by the following expressions:

$$\varepsilon(x,t) = \frac{\partial u(x,t)}{\partial x} = f'(x-ct) + g'(x+ct)$$

and

$$v(x,t) = \frac{\partial u(x,t)}{\partial t} = -cf'(x-ct) + cg'(x+ct).$$

The stresses can be obtained by $\sigma(x,t) = E\varepsilon(x,t) = E[f'(x-ct) + g'(x+ct)]$ if linear elastic behaviour is assumed.

Now, imagine an elastic compressive wave travelling along a semi-infinite bar. In this case, function f is this compressive wave, and function g is zero. When this wave reaches the free end of the bar, the boundary condition is that the stress at the free end should be zero: $\sigma(x_{\text{end}},t) = E \times [f'(x_{\text{end}}-ct) + g'(x_{\text{end}}+ct)] = 0$, this means that at the boundary, it should be $f'(x_{\text{end}}-ct) = -g'(x_{\text{end}}+ct)$, and a reflected wave appears, with the same shape as the incident but with opposite sign, as represented in Fig. 1. That is, the initial compressive wave is being reflected as a tensile pulse. But how exactly the reflection process is essential to understand what is happening. During reflection, the stress in the specimen is the superposition of the initial wave and the reflected one. If the initial compressive wave is lower than the compressive strength but its absolute value exceeds the material dynamic tensile strength, the specimen will fail during reflection process.

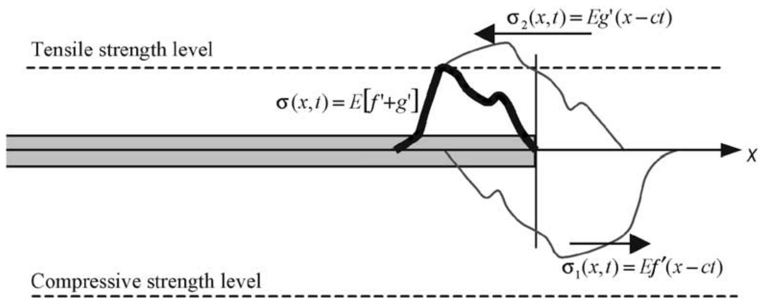

Fig. 1. Reflection of a wave in a free end.

Table 1
Hypotheses of the spall bar test

Hypotheses	
Material	Test
Linear elastic behaviour	Unidimensional wave propagation
Compressive strength much higher than tensile strength	Single initial crack
Initial compressions do not damage the material	

In actual experiments, the tensile stresses produced in the reflection will not emerge abruptly in the specimen. The compressive wave will decrease gradually while the tensile stress is growing up to the material dynamic tensile strength. When this value is reached, the material fails (see Fig. 1). At this moment, the specimen bar can be divided into two parts: a finite bar where a portion of the pulse is trapped and a semi-infinite bar with a new free end produced by the fracture.

Focusing attention on the new semi-infinite bar, the fraction of the tensile wave that has surpassed the failure point will continue travelling along the specimen. The maximum remaining pulse would provide the "apparent" dynamic tensile strength of the material tested (the maximum tensile stress recorded in the specimen strain gauge).

The hypothesis of a semi-infinite bar is not essential. In a bar with a high length/diameter ratio the one-dimensional approach of wave propagation can be assumed and the equations of the motion are fully described in the literature [12,13], and a brief description is given above.

The method assumes several hypotheses regarding the material and the test arrangement, as summarised in Table 1. In addition, the material must behave elastically, with high compressive/tensile strength ratio, and it must not be damaged by the initial compressive loading. On the other hand, the configuration of the test should ensure that the one-dimensional wave propagation theory is valid, and the failure process must begin with a single initial crack in the first reflection of the pulse, although subsequently other secondary cracks may appear along the specimen when later reflections occur.

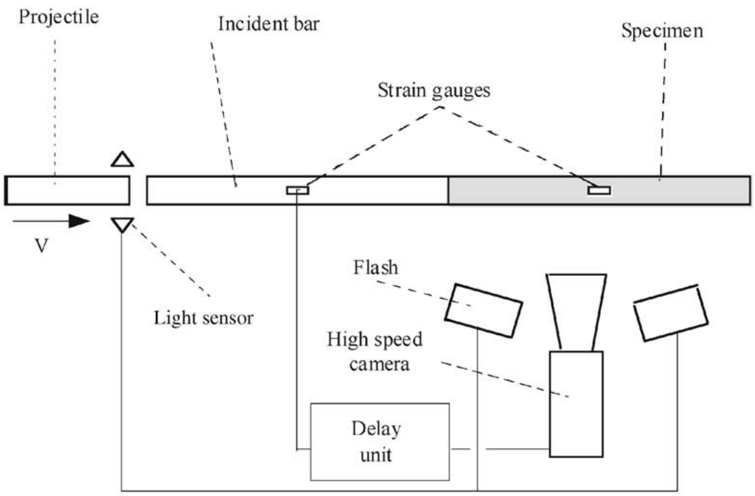

Fig. 2. Scheme of the experimental device.

A scheme of the experimental set-up is shown in Fig. 2. It consists of a projectile propelled against a steel bar in contact with the specimen. As a consequence of the projectile impact, an elastic compressive wave travelling along the bar is generated. This wave is transmitted to the specimen and finally reflected at its free end as a tensile pulse. When the tensile strength of the material is exceeded, the specimen fails. The incident bar is used to avoid the typical irregularities of a direct impact on the specimen. Both the incident bar and the specimen are fitted with strain gauges to measure the strains produced by the stress pulses. The testing device is completed with high-speed cameras. The tensile strength is determined from the strain gauge records and the high-speed images to locate the first crack in the specimen.

When the compressive wave is generated by the impact, it is recorded by the strain gauges of the incident bar. Part of this wave is transmitted to the specimen and part is reflected through the incident bar. The wave transmitted to the specimen can be derived from the incident and reflected waves in the incident bar, but is also recorded by the strain gauges in the specimen. When the material fails, the fraction of the tensile wave that has passed the failure point, continues travelling along the specimen and is recorded again by the strain gauges. The remaining pulse is trapped without producing any effect at the registration point. An actual signal recorded by the specimen strain gauge is shown in Fig. 3. The failure process could be extended to other points along the specimen as is shown in the high-speed photography sequence of an actual test of alumina 99.5% (Fig. 4), where a first initial crack can be identified.

3. Assessment of test reliability

Taking the maximum tensile stress recorded in the strain gauges as the tensile strength of the material without any correction leads to very suspicious values. Previous tests performed by the authors compared to Brazilian tests in the same materials mark these differences [9]. This suggests the need for studying the accomplishment of the assumptions mentioned above, before accepting the results as a true value of the dynamic tensile strength.

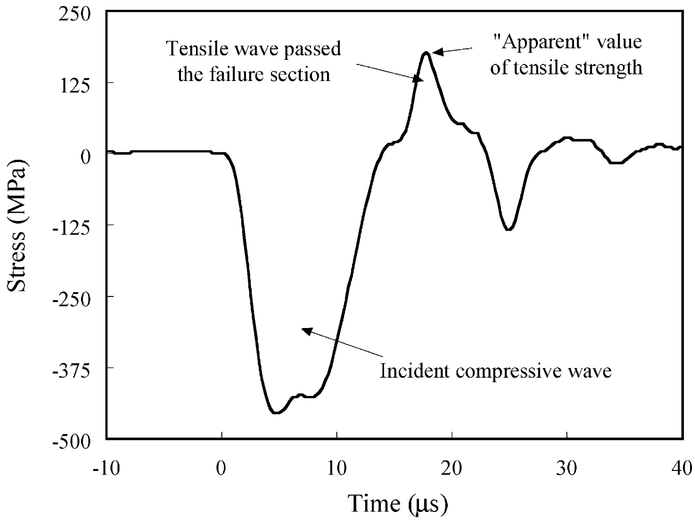

Fig. 3. Signal recorded by the strain gauge bonded to the specimen.

3.1. Material hypotheses verification

The material hypotheses are ensured to a great extent when testing ceramics, because an elastic stress–strain relation up to failure can very well model these materials, and their compressive strength is at least one order of magnitude higher than the tensile strength. In the tests, the compressive stress generated during the first phase of the loading should be maintained at approximately below 25% of the dynamic compressive strength. To ensure the hypothesis of elastic material to a great extent, an easy check can be made. If the materials remain elastic, the incident wave in the steel bar composed with the reflected wave at the steel/ceramic interface should be coincident with the transmitted wave to the ceramic material. The first two waves have been measured in the instrumentation of the incident bar, and the third one in the ceramic specimen. It has been proved that incident and reflected wave are basically the transmitted wave, so the ceramic material remains elastic.

To ensure the elastic behaviour of the materials up to fracture under tensile loads, additional tests were done. It consists in diametral compression tests of discs, where the tensile stresses in the load plane are uniform. When assuming elastic behaviour, this tensile stress can be computed by $\sigma_t = 2P/(\pi LD)$, where P is the load, D the specimen diameter and L the disc thickness. A sample of a test record of alumina 99.5% is shown in Fig. 5, and shows a linear behaviour up to fracture. The conclusion is evident, for these materials, the macroscopic response can be assumed linear elastic up to fracture under tensile loads.

To analyse the possible damage introduced in the specimen during spalling tests, additional work has been done. A set of discs was obtained from a spalling tested specimen as shown in Fig. 6. These new samples were submitted to splitting tests and the results compared with previous splitting tests of the same untested material. The mean values of tensile strength obtained in diametral compression tests were the same in both cases, which shows that the pass of waves in the spalling specimens does not affect the values of the dynamic tensile strength.

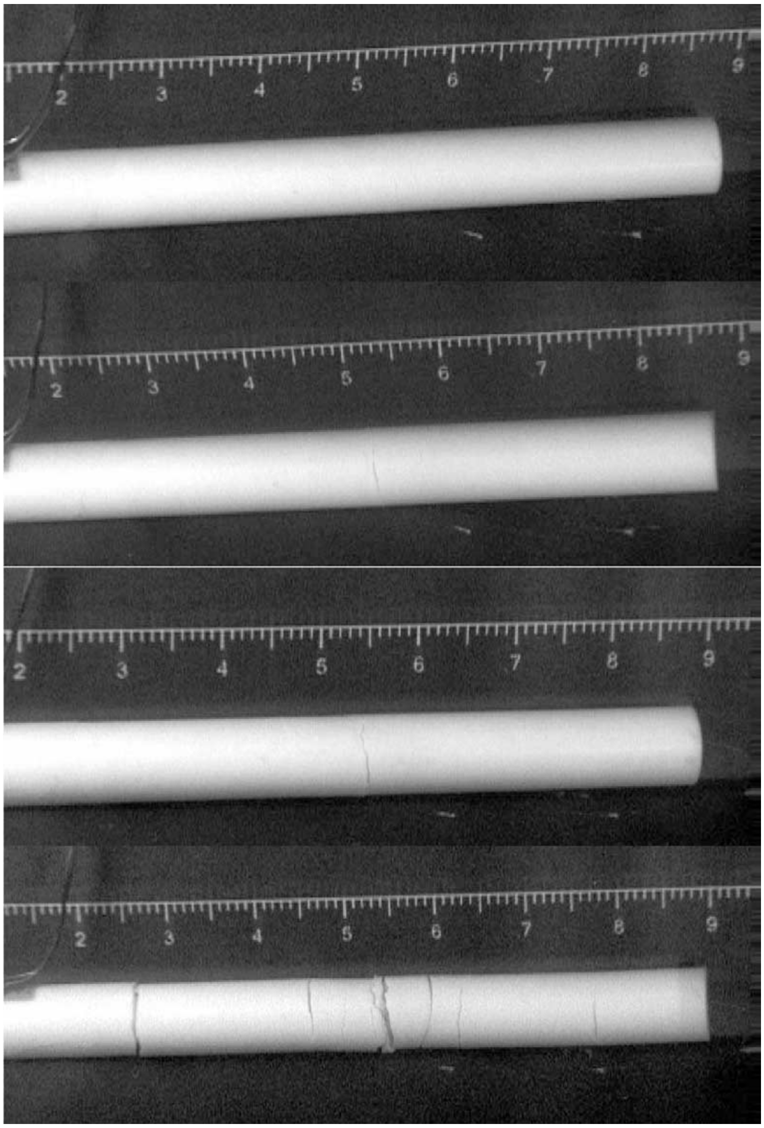

Fig. 4. High speed sequences of a spalling test of an alumina 99.5% bar.

This set of favourable conditions is not necessarily extended to other brittle materials. For example, concrete cannot be properly described through a linear elastic model up to failure, or the most brittle metallic alloys do not satisfy the requirement of a high compressive/tensile strength ratio. This work is only concerned with advanced ceramics, especially those applicable to ballistic design.

If the ceramics tested will verify the requirements to determine the tensile strength from spalling tests, the test configuration should be also studied carefully.

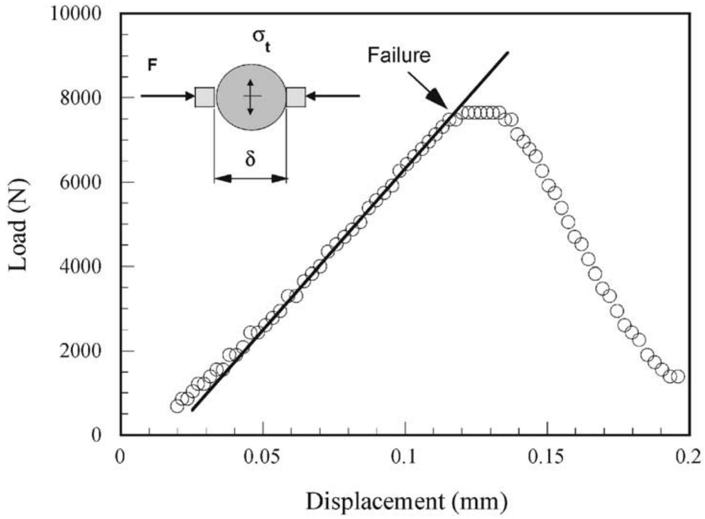

Fig. 5. Splitting test of alumina 99.5%. The load/displacement curve is linear up to failure.

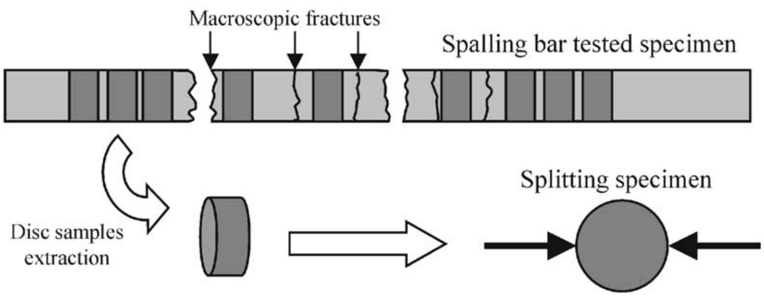

Fig. 6. Extraction of splitting samples from a spalling tested specimen.

3.2. Wave propagation analysis

The comparison between incident, reflected and transmitted waves at the steel/ceramic interface also justifies the hypothesis of one-dimensional wave propagation.

The next aspect to verify is the signal recorded by the strain gauges. The failure point of the specimen cannot be at the location of the strain gauges. When failure occurs, the wave has a maximum tensile stress, and this wave continues propagating along the specimen until the strain gauge measures its value. The following question is immediate: Can the stress measured at the location of the strain gauges attached to the specimen directly extrapolate to the failure point? To answer this question several specimens were instrumented with strain gauges at different locations. The result shows that the stress pulse is weakening during its propagation, as shown in Fig. 7. The reason of this alteration of the simple one-dimensional theory of propagation of elastic waves is not clear, but it is experimentally proved in relation to the failure phenomena. If during an experiment the material does not fail, the stress pulse is not appreciably modified during its

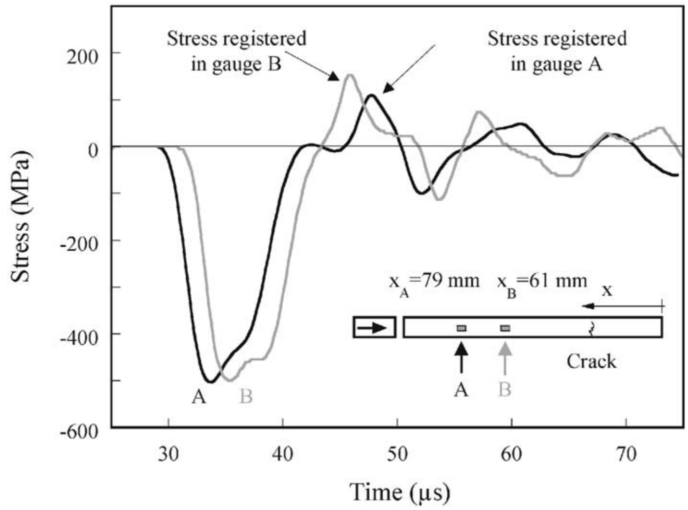

Fig. 7. Signal recorded by two different strain gauges bonded to the specimen.

Table 2
Material properties used in numerical analysis

Ceramic material Al_2O_3 99.5%	
Constitutive equation	Linear elastic
Density	3840 kg/m^3
Elastic modulus	360 Gpa
Shear modulus	150 Gpa
Failure criterion	Maximum principal stress
Maximum tensile stress	220 Mpa

propagation along the specimen, so explanations based on wave superposition or pulse dispersion seem indecisive.

To confirm that this effect is not a consequence of the incorrect working of the experimental equipment, a numerical simulation of the test was carried out using the finite difference code AUTODYN 2D [14]. The geometry modelled was the same as that of the experiments, and as boundary condition the actual compressive stress profile was applied to the first end of the specimen. The material behaviour was defined as linear elastic with a failure criterion determined by the maximum principal stress. The specific properties used in the numerical model are those of an aluminium oxide specimen and are included in Table 2.

In the numerical simulations, the stress histories at different locations along the specimen were calculated, including those at the point where the strain gauges were attached. Fig. 8 gives the tensile stress profile at different times, and shows how the maximum increases up to the dynamic tensile strength, at this time the specimen fails, and subsequently the pulse slowly decreases during the propagation along the specimen.

The explanation of this ‘‘softening’’ is not easy. The first aspect to consider is that wave decreasing happens only when failure appears, even in numerical simulations when using elastic

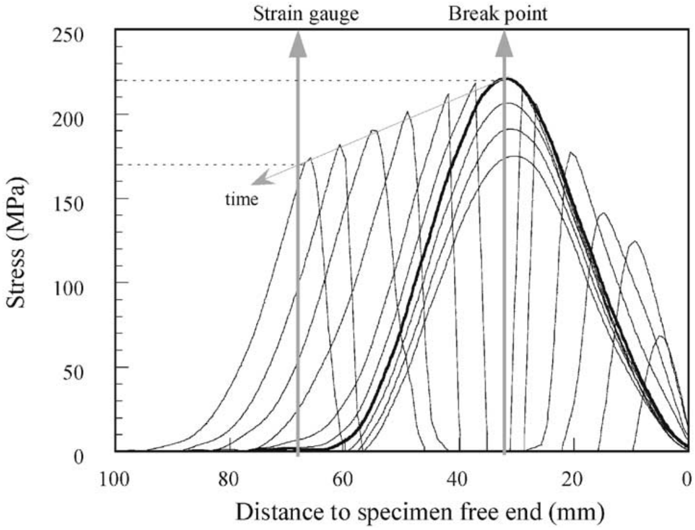

Fig. 8. Numerical simulation results. Tensile stresses during reflection, breaking and post-breaking of specimen.

material behaviour. In the numerical analysis as well as in actual previous tests, the absence of appreciable dispersion of waves has been checked when the specimen does not fail. However, when fracture occurs, the pulse of the tensile wave that has passed the break point decreases. At failure time, a new free surface is created, splitting the specimen into two different parts. This new surface is a new boundary condition and makes the wave propagation more complex. When the crack propagates in the specimen, energy is released, and stress waves of different wavelengths may emanate from the new fracture surface. The one-dimensional theory near the fracture location cannot be assumed. The results of the simulation show that the stresses normal to the specimen axis direction takes values up to 20% of the longitudinal stresses, making the one-dimensional wave propagation theory inapplicable. After fracture, the stress state in the vicinity of the crack location is three-dimensional, and the analytical approach is more complex. This phenomenon leads into a decreasing wave propagating from the specimen failure location that is not easily modelled analytically. At this time, no satisfactory relationship between the distance to the failure point and the reduction of the wave has been obtained. The analyses also show that there is no wave superposition when reflecting at the free surfaces (including the crack) that could explain this phenomenon. Therefore, the tensile strength cannot be derived from the signal recorded at the strain gauges; another method of deriving the dynamic tensile strength should be used.

Additionally, the results of the numerical simulations compared to the corresponding actual test reveal that the break location is perfectly reproduced as well as the time when it occurs.

3.3. Study of breaking modes

The hypotheses of a sole initial crack should also be analysed. The first set of experiments shows an important difference between the tests performed with aluminium oxide specimens and those with carbides. The alumina specimens failed according to the hypothesis, while the silicon and

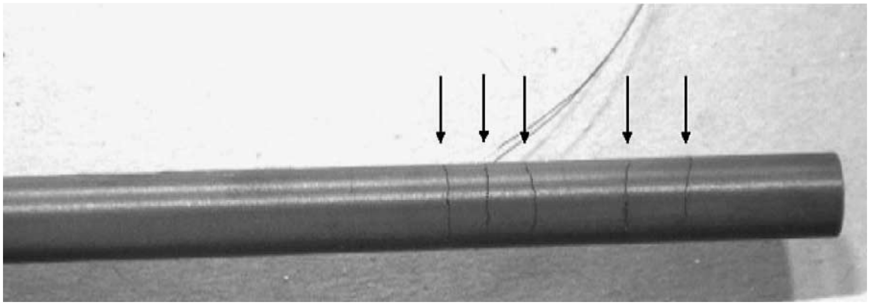

Fig. 9. Simultaneous cracks in a boron carbide specimen.

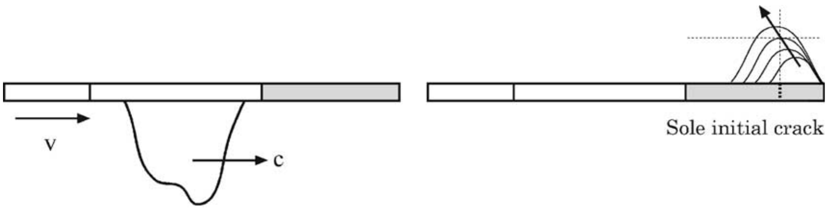

Fig. 10. Reflection of the wave at a free end of an actual test of alumina specimen.

boron carbide specimens presented a cracking process with several cracks appearing simultaneously at different locations, as shown in the high-speed photograph in Fig. 9.

To understand the origin of these multiple cracks, it is necessary to compare the reflection of the initial stress pulse in both cases. Fig. 10 shows a scheme of the actual reflection of the experimental stress pulse generated in the alumina specimens. The tensile stress profile grows gradually, presenting a clearly identified maximum with a moving location. At every instant, only one section of the specimen is subjected to the maximum stress. Note that the point where the maximum tensile stress is located at each instant moves along the specimen until dynamic tensile strength is reached. At this time, the specimen fails at the point where this maximum exceeds the material tensile strength. Hence, a direct relation between tensile strength and fracture location can be derived.

Fig. 11 shows the same reflection process, but now with the signal corresponding to the actual tests of some carbide specimens. The elastic waves propagate at a substantially higher velocity in silicon and boron carbides than in aluminium oxide. To avoid the overlapping of the incident and reflected waves, the projectile length was reduced from 26 to 20 mm when testing carbides. The stress pulse generated with this shorter projectile change from the approximately trapezoidal shape (shown in Fig. 10) to a triangular one (Fig. 11), being reflected in a quite different way. Note that this pulse introduced in the specimen is triangular, with rising and falling slopes almost equal. Now, the tensile stress appearing during reflection does not present a sole maximum, but a constant value along a considerable zone. When the level of the stress exceeds the tensile strength, the material may fail at any point inside this stress constant zone, with the possible creation of several simultaneous cracks.

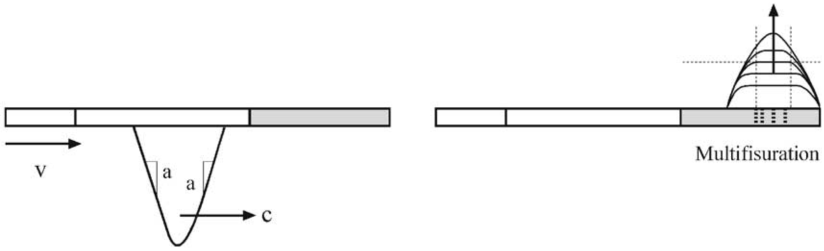

Fig. 11. Reflection of the wave at a free end of an actual tests of a boron carbide specimen. Test not suitable to measure the tensile strength.

To overcome the problems of multiple cracking associated with the use of projectiles of different length, some modifications can be made to get an appropriate reflection process. It is clear that this phenomenon depends on the shape of the compressive wave. To achieve a single initial crack in the carbides, the initial wave should be modified in order to produce a similar reflection to that in aluminium oxides as shown in Fig. 10. To introduce the modifications in this pulse, it is necessary to understand how the shape is produced during impact.

When impact occurs, two stress wave fronts are created at the interface of the projectile with the incident bar. The first wave front moves along the incident bar and the other moves through the projectile in the opposite direction. When the front wave moving in the projectile reaches its free end, it is reflected as a tensile wave, leaving a null stress state behind it. When this front reaches again the interface projectile/bar, we have introduced a pulse to the incident bar with a length that depends on the projectile length. If an ideal perfect contact between projectile and bar is assumed, and both bodies are made of the same material, the stress pulse introduced in the incident bar should be rectangular and double the length of the projectile. But a perfect contact is a theoretical approximation and could not be attained. Due to irregularities in the projectile and bar contact surfaces (rough surfaces, and misalignments) the rising slope of the pulse generated takes some time. This explains the rising time of the compressive wave introduced in the incident bar. The decreasing slope of the pulse is explained by the reflection of the wave on the back face of the projectile. If the projectile is a perfect bar, the rising and failing times of the wave should be the same. This is what happens when shorter projectiles are used in carbides, leading to a triangular pulse, with both slopes almost equal, as it is shown in Fig. 11.

The way to avoid the reflection shown in Fig. 11 is to change one of the slopes of the pulse. Achieving this modification and obtaining a triangular pulse with different rising or falling slopes, the reflection will be produced as in Fig. 10, with a well defined maximum of the tensile stress values displacing along the specimen, as shown in Fig. 12. To obtain this kind of pulse, some modifications in the test procedure are needed. It is clear that any modifications performed in the impact procedure, as a result of quality contacts, will be reflected in both slopes of the pulse. The best way to change the stress wave pulse is to work after the initial rising slope is formed, and acting over the falling one, modifying the rear free end surface of the projectile.

To apply this solution during actual tests, a projectile with a modified rear face was used, consisting of two diagonal cuts on this surface. When the pulse wave generated during the impact reflects on the tail of this altered projectile, a more gradual slope is produced. With this kind of projectile, shown in Fig. 13, the stress compressive wave introduced in the bar and consequently

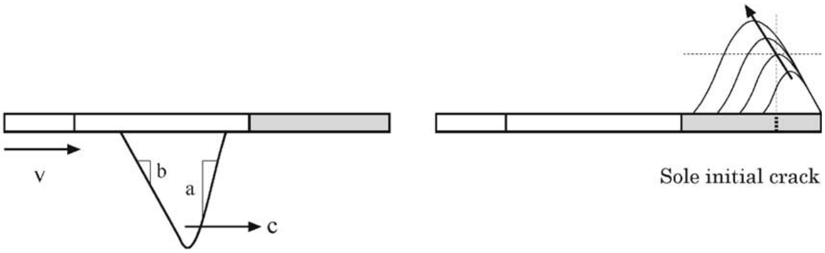

Fig. 12. Reflection of the wave in a free end of an actual test of a carbide specimen with modified projectiles. Valid test to measure the tensile strength.

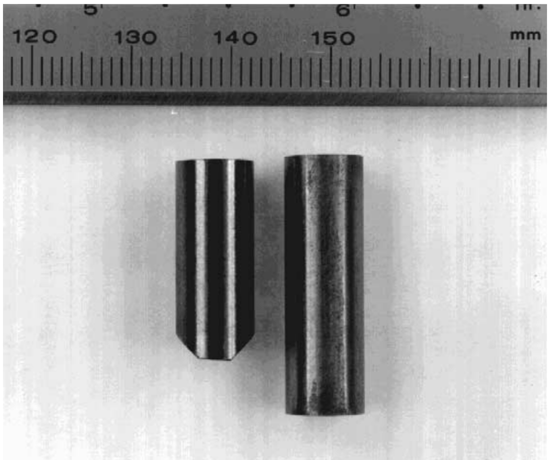

Fig. 13. Modified projectile used to test carbides compared to the one used with aluminas.

into the specimen, has the shape represented in Fig. 12, and the reflection on the specimen free end is reproduced in the same way.

At this point, the procedure to obtain a sole crack is clear. The stress pulse has a well defined maximum, which is displacing along the specimen as a tensile wave growth to reach the dynamic tensile strength of the material. Now, for this kind of test, all the hypotheses are assumed, and the way to obtain the true dynamic tensile strength is completed.

4. Dynamic tensile strength measurement

It has been demonstrated that the tensile stress values calculated from the strain gauge signals are not suitable to get the true tensile strength. It has also been explained how it is possible to establish a direct relation between the location of the first crack and the tensile level that causes the failure if the correct compressive pulse is used. Consequently, by measuring the position of this first fracture, the tensile stresses along the specimen at this time are determined, and so the tensile strength of the material can be obtained.

The procedure is as follows: assuming no fracture, a simple elastic calculation of one-dimensional wave propagation is performed to reproduce the reflection of the experimental compressive wave at the free end of the specimen. As a result of this calculation, the tensile stress distribution along the specimen is obtained as a function of time. This family of curves gives the maximum tensile stress at any instant along the specimen and at which point it is being applied. Finally, if it is possible to identify the fracture location, the tensile growth path calculated by the aforementioned method can provide the corresponding maximum tensile stress. This value is considered the material dynamic tensile strength.

The method is illustrated in Fig. 14 where assuming no fracture; the evolution of the tensile stresses in an actual test of alumina is shown. This calculation belongs to a test when impacting with a 26 mm length and 8 mm diameter projectile rod at 22 m/s, using a 200 mm length and 8 mm diameter steel incident bar and a 100 mm length and 8 mm diameter alumina specimen. The reflection is analytically calculated by wave superposition introducing the incident pulse an initial condition (the compressive part of Fig. 3). Tensile loads are shown in Fig. 12 at 0.25 μs intervals, and the fracture location is obtained by high-speed photography. The stress profile that presents a maximum in the fracture location is identified, and its maximum is labelled as the tensile strength. As shown, this value is significantly higher than the tensile stress measured by the strain gauge. (see also Fig. 3).

This procedure can be done with an easy computer program by analytical methods based on one-dimensional wave propagation. The required data is the initial compressive wave profile introduced in the specimen. The final result is the tensile strength of the material and the failure instant. The fracture location has to be measured independently by high-speed photography or another technique.

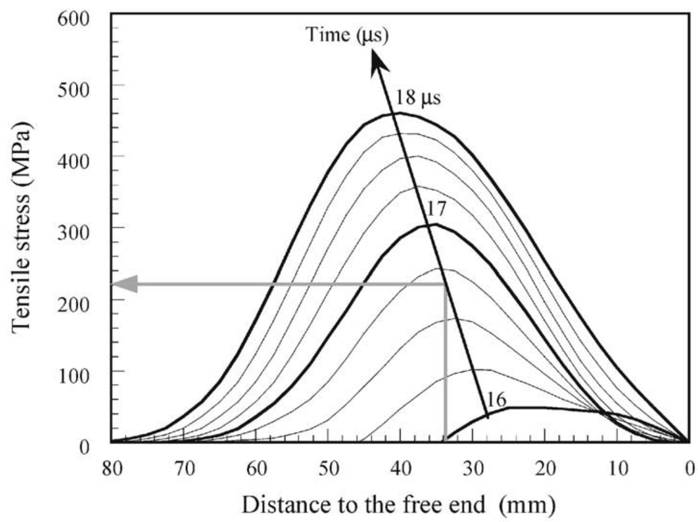

Fig. 14. Tensile growth path in an alumina specimen used to obtain the tensile strength.

5. Test results

The spalling testing technique of long bars has been used to obtain the tensile strength of different materials. The specimen geometry was of long bars of 8 mm diameter and 100 mm length. The materials selected were three different aluminas of three levels of purity, 94%, 98% and 99%, an alumina reinforced with zirconia, and two different carbides silicon carbide and boron carbide. The tests of the alumina based materials were made with 24 and 26 mm length cylindrical projectiles, while the 20 mm length modified projectile mentioned earlier was used to test the carbides.

The results of the tests are shown in Fig. 15. The picture shows the tensile strength obtained in each test performed. The number of tests, the mean value of the dynamic tensile strength for each material and its standard deviation are presented in Table 3. The strain rate has been obtained from the evolution of the stresses in the location of the crack applying the following

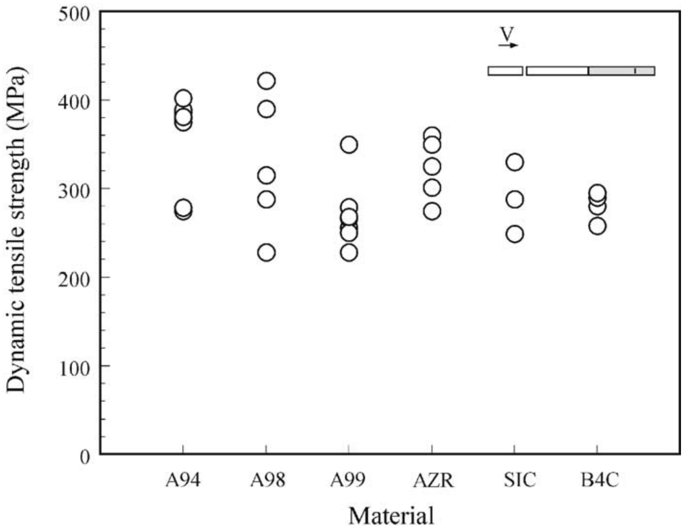

Fig. 15. Results of spalling tests of the different materials tested.

Table 3
Results of the spall bar tests for the different materials

Material	Number of tests	Mean strain rate (s^{-1})	Tensile strength (MPa)	
			Mean	Standard deviation
Alumina 94%	8	850	358	51
Alumina 98%	5	800	329	78
Alumina 99.5%	7	780	271	38
Alumina + zirconia	5	800	322	35
Silicon carbide	3	365	289	40
Boron carbide	4	370	281	16

Table 4
Results of the splitting (Brazilian) tests in Hopkinson bar for the different materials

Material	Number of tests	Mean strain rate (s^{-1})	Tensile strength (MPa)	
			Mean	Standard deviation
Alumina 94%	9	89	278	28
Alumina 98%	6	77	285	31
Alumina 99.5%	8	76	243	43
Alumina + zirconia	6	85	288	30
Silicon carbide	9	66	248	58
Boron carbide	9	65	261	50

expression:

$$\dot{\varepsilon}_{\text{spalling}} = \frac{1}{E}\left(\frac{\partial \sigma_{\text{t}}}{\partial t}\right)_{\text{crack location}}.$$

The comparison of the results of these tests with other methods is not easy because of the differences in the stress state. Nevertheless, results on the same materials of splitting tests in Hopkinson bar are presented in Table 4. The number of tests performed is lower than the usual recommendations of Weibull statistics, so this approach has not been considered. Note that this paper is focused on the method itself, not in the materials.

6. Discussion and conclusions

The procedure proposed is based on the idea that the crack occur at the point where the stress is maximum. Although it is true that brittle materials like ceramics are influenced by the internal defects population, the fact that the failure point is coincident in each test and its correspondent numerical modelling, indicates that the maximum stress level is the key factor of the breaking process.

This method is a reliable technique to determine the true tensile strength of ceramic materials in uniaxial conditions. Spalling tests of long bars have clear advantages over other tests, such as splitting or bending tests. It is evident that the material is subjected to uniaxial stresses, so the maximum tensile stress that appears in the specimen is the true dynamic tensile strength of the material.

To summarise, it is essential to achieve the correct compressive pulse able to produce a reflection with a well-defined maximum tensile level. It should move along the specimen when growing. This aspect avoids simultaneous multifissuration and leads to a tensile growth path suitable to obtain the tensile strength of the material.

Spalling tests of long bars have disadvantages. First, the tests can only be performed at high strain rates. Second, the material is subjected to high compressive loads before tensile failure occurs, but it has been demonstrated that no damage is introduced in the material. This technique requires a sophisticated data acquisition system, a high-speed camera system, and a relatively long time to prepare the tests. However, the testing procedure can be simplified.

In the tests performed, the compressive wave introduced in the specimens was obtained from strain gauges in the specimen, but this wave can be derived from the composition of the incident and reflected waves on the incident bar, avoiding the need to instrument the specimens.

Before performing the tests, the compressive pulse can be known. If the tests are done without a specimen, the records of the strain gauges in the incident bar can provide the compressive pulse. At this moment, the reflection analysis can be done, and the instant of failure can be predicted to synchronise the cameras.

Depending on the materials to be tested and the shape of the initial pulse, the absence of secondary cracks could be achieved. If this were possible, use of a high-speed photography system could be avoided, resulting in a less sophisticated and cheaper testing technique, but this has not yet been achieved.

Finally, some aspects require more research. The weakening of the tensile pulse after the failure appears is not well explained yet, although in this work an alternative method is proposed to overcome this problem and determine the dynamic tensile strength from spalling results.

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References

[1] Viechnicki DJ, Slavin MJ, Kliman MI. Development and current status of armour ceramics. Ceram Bull 1991;70(6):1035–9.
[2] Paul B. Fracture. An advanced treatise. In: Liebowitz H, editor. Mathematical fundamentals, vol. 2. New York: Academic Press, 1971. p. 313–496.
[3] Zukas JA. High velocity impact dynamics. New York: Wiley, 1990.
[4] Engineered materials handbook, ceramic and glasses. vol. 4, ASM International, 1991.
[5] Rocco PC. Influencia del tamaño y mecanismos de rotura del ensayo de compresión diametral, Tesis Doctoral, Departamento de Ciencia de Materiales, Universidad Politécnica de Madrid, 1996.
[6] Rodríguez J, Navarro C, Sánchez-Gálvez, V. Splitting tests: an alternative to determine the dynamic tensile strength of ceramic materials. J Phys IV, Colloque C8 Supplément au Journal de Physique III, No. 4, 1994; 101–6.
[7] Nojima T. Ogawa K. Impact strength of ceramics. In: Harding J, editor, Proceedings of the Fourth Conference on Mechanical Properties of Materials at High Rates of Strain. Oxford: John Harding, 1989.
[8] Najar J. Dynamic tensile fracture phenomena at wave propagation in ceramic bars. J Phys IV, Colloque C8 Supplément au Journal de Physique III, No. 4, 1994; 647–52.
[9] Gálvez Díaz-Rubio F., Rodríguez J., Sánchez-Gálvez, V. Tensile strength measurements of ceramic materials at high rates of strain. J Phys IV, Colloque C3 Supplément au Journal de Physique III, No. 7, d'Août, 1997; 151–6.
[10] Johnstone C, Ruiz C. Dynamic testing of ceramics under tensile stress. Int J Solids Struct 1995;32(17/18):2647–56.
[11] Diamaruya M, Kobayashi H, Nonaka T. Impact tensile strength and fracture of concrete. J Phys IV, Colloque C3 Supplément au Journal de Physique III, No. 7, d'Août, 1997; 253–8.
[12] Kolsky H. Stress waves in solids. New York: Dover Publications Inc., 1963.
[13] Johnson W. Impact strength of materials. London: Arnold, 1972.
[14] Autodyn user manual. Century Dynamics Ltd., 1998.