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Electrical monitoring of crack propagation during quasi-static loading and ballistic impact of alumina plates

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Abstract

An electrical methodology has been developed to monitor crack advance during ballistic impact. Velocities of radial cracks can be measured and information about development of the crack pattern can be obtained. This is done via a grid of thin gold tracks, printed onto the front or back surfaces of the sample. These elements were incorporated into an electrical circuit and high speed data acquisition was carried out during impact. The fracture behaviour of two grades of alumina has been examined. Hard spherical projectiles were used, with a range of impact velocities. An increase in radial crack velocity was detected with increasing impact velocity, within this range. Differences in crack velocities were also noted between the two types of alumina. Crack speed values are in good agreement with data reported previously for similar systems, obtained using high speed photography. The methodology proposed here looks to be reliable, convenient and economically attractive.

Keywords: Crack velocities; Impact loading; Printed electrical circuits

1. Introduction

Layered structures (incorporating a ceramic plate on the impact side) have been employed as lightweight ballistic protection systems for several decades.[1] The ceramic primarily acts to break up and decelerate the projectile. Backing layers, often made of a relatively tough material such as a polymer composite, absorb the kinetic energy and keep the ceramic fragments in place. Commonly, a core of highly fragmented material is formed in the front plate beneath the point of impact, from which radial and secondary cracks emanate. Limiting these radial cracks is of interest, since this is the damage that travels furthest from the point of impact and in general it is desirable to limit the damaged area – partly to maintain protection against further projectile impacts. The ceramic thus needs to be hard enough to erode the projectile and to decrease its velocity, but radial crack propagation after impact should ideally not be extensive. It is often difficult to achieve both of these objectives, since high hardness is commonly associated with poor resistance to crack propagation. There is therefore interest in obtaining improved understanding of the deformation and fracture mechanisms in ballistic impact. However, these are not straightforward. In particular, the factors dictating radial cracking characteristics (velocity, spatial distribution, length, etc.) are not well understood. It should also be noted that other characteristics of the impact event, such as the transmitted acceleration and momentum, are often of practical significance.

Various methods have been used to monitor (high speed) crack propagation characteristics, during both static and dynamic loading, many based on high speed photography,[2–4] with[5,6] or without[7] photoelastic or X-ray image acquisition. Ultrasonic waves can also be used to explore crack propagation.[8] Other experimental methods include use of a Cranz-Shardin camera, which is based on multiple light beams and can give information about shock waves.[9–11]

Electrical methods of crack advance monitoring have also been extensively used. Some of these are based on induced changes in the electrical conductance of the sample, or of some kind of sheet or grid attached to it.[12–15] Using a grid allows inferences to be made about the rupture of individual connections, and hence about crack growth geometry. Such methodology has been commonly applied under conditions such that sub-critical

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Table 1
Published values of crack velocity, obtained using different techniques, with well-defined single cracks. The shear velocities are listed for reference (calculated from elastic properties).

Material	Method	U (m s^{-1})	U_S (m s^{-1})	Ref.
Glass	Electrical resistivity, conducting tracks	1580	3500	12
Sapphire	Electrical resistivity, conducting tracks	4500	6400	12
PMMA (weak interface)	Interferometric optical	936	1100	28
PMMA	Electrical resistivity, conducting sheets	332	1100	29
Si single crystal	Electrical resistivity, conducting sheets	3825	5200	19

(i.e. slow) crack growth is taking place, but there have also been studies[16,17] involving the monitoring of rapid connection rupture in certain types of electrical circuit and there has been (limited) application[18] of similar methodologies to ballistic impact conditions. The resolution in such studies is usually limited by the dimensions of the conductive tracks. These techniques are frequently employed for single crack monitoring, with a dominant and straight crack path. For example, there have been detailed studies[19,20] of fast single crack propagation in silicon single crystals. Under ballistic loading, complex fracture patterns often develop, making interpretation of electrical information more difficult. A review of the methods employed has been published by Stalder et al.[14]

The maximum achievable crack velocities are expected to be related to the speed of sound in the material, and hence to its elastic constants. The exact nature of the constraint on crack velocity, and the type of elastic wave velocity to which it relates, are still open to question. Field[21] proposed that the maximum dynamic crack speed is equal to the velocity of Rayleigh (surface shear) waves, although the precise mechanistic link is unclear (since crack velocity is evidently linked to phenomena occurring at the crack tip). Some attention has been devoted to amorphous (glassy) materials. For example, Ravi-Chandar[22] highlighted that the path of such cracks can become more irregular as the velocity increases (leading to “hackle” on glass fracture surfaces). Buehler and Gao[23] proposed that this instability arises from a change in crack growth mechanism, with hyperelastic stiffening in front of the crack being induced above a critical velocity. Among other analytical approaches to this transition is that of Yavari and Khezrzadeh,[24] who used a fractal-based method to predict that the maximum velocity is around 60% of the Rayleigh velocity. There are also some indications[25,26] that, for a given elastic wave velocity, crack speeds are lower in amorphous materials.

In any event, most experimentally measured crack velocities have not exceeded shear wave values. Nevertheless, some measurements made during ballistic impact have suggested that the crack speed rises as the impact velocity is increased. Strassburger et al.[9] reported values approaching the longitudinal sound wave velocity and Petersan reported cracks travelling at speeds higher than the shear wave velocity.[27] A summary of measured crack speed values[9,11,12,19,28–32], and the methods used to obtain them, is presented in Tables 1 and 2, for a range of materials. Table 1 contains information about single (dominant) crack measurements, while Table 2 relates to ballistic impact, with multiple cracking. Unsurprisingly, there is more scatter in the reported values for ballistic impact.

The velocities of longitudinal and shear waves in bulk, isotropic solids are given respectively by the following equations:

$$U_{L:} = \left[\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}\right]^{1/2} \tag{1}$$

$$U_S = \left[\frac{E}{2\rho(1+\nu)}\right]^{1/2} \tag{2}$$

where E is the Young’s modulus, ρ is the density and ν is the Poisson ratio. In ceramics, typical shear velocities are of the order of 5 km s^{-1}, while those of longitudinal waves are about twice this. Expressions for the velocity of Rayleigh (surface shear) waves are relatively complex,[33] but in general the value is approximately 90% of the speed of shear waves.

Alumina is in general the most widely used material for the front plate, offering an attractive combination of performance, ease of manufacture and cost. Steinhauser et al.[11] obtained radial crack speed values of about 4.7–5.4 km s^{-1} for 98% alumina impacted at 140 m s^{-1}, rising to about 6 km s^{-1} for impact velocities of 200 m s^{-1}. Anderson et al.[34] monitored fracture patterns and crater depths in alumina (of varying grain size, with a purity of 99.5%) when impacted by spherical tungsten carbide projectiles at velocities up to 70 m s^{-1}. They reported on the length and density of radial cracks, showing that radial crack

Table 2
Published values of crack velocity, obtained using different techniques, under ballistic impact conditions (with multiple cracking). The shear velocities are listed for reference (calculated from elastic properties).

Material	Method	U (m s^{-1})	U_S (m s^{-1})	Fracture	Ref.
$MgAl_2O_4$	High speed photography	1500	5500	Fracture front	30
Al_2O_3	Cranz-Shardin photography	4700 –5400	6200	Radial cracks	11
Al_2O_3 (98%)	Cranz-Shardin photography	3000 –10,000	6150	Fracture front	12
Borosilicate glass	High speed photography	1800	3700	Cone cracks	31
Borosilicate glass	Multiple strain gauges	2000–3000	3700	Failure wave	32