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The relation of failure under 1D shock to the ballistic performance of brittle materials

N.K. Bourne

AWE, Aldermaston, Reading RG7 4PR, UK

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Abstract

The response of brittle materials to uniaxial compressive shock loading is still not well understood. Describing the physical mechanisms resulting from the more complex triaxial states that result from impact and penetration is thus empirical. The physical interpretation of the yield point of brittle materials in one-dimensional strain (the Hugoniot elastic limit (HEL)), the rate dependence of this threshold, the form of stress histories and the effect of polycrystalline microstructure still remain to be comprehensively explained. However, evidence of failure occurring in glasses and ceramics behind a travelling front that follows a shock front has been accumulated and verified in several laboratories. Such a boundary has been called a failure front. The variations in properties across this front include complete loss of tensile strength, partial loss of shear strength, reduction in acoustic impedance, lowered sound speed and opacity to light. It is the object of this work to collect observations of these phenomena and their relation to failure and the HEL in brittle materials. Further, to relate these uniaxial strain measurements of their failed states to the depth of penetration (DoP) in the widely conducted test.

Keywords: Brittle; Armour; Shock; Penetration; Failure

1. Introduction

The high yield strength and low density of brittle materials have prompted their use as armour materials or in engine turbine blades. However, there is as yet incomplete understanding of their dynamic response and this limits their potential use in engineering design. Early work showed that they exhibited high dynamic compressive strengths [1–4]. New testing methodology and instrumentation allowed investigators to obtain accurate figures for the elastic limit and generated renewed interest in ceramics for use in impact situations [5].

The simplest brittle material is a silicate glass. Yet production of these results in additives remnant within the microstructure and processing flaws such as cracks or voids. Open structure, high-purity silicates like fused quartz and borosilicate glass, exhibit a complex response when subjected to plane shock-wave loading. In particular the initial rise of the stress or particle velocity wave, which traverses the specimen is composed of a nearly linear ramp up to ca. 2.5 GPa followed by a steep rise to the Hugoniot elastic limit (HEL) at a stress level of 7–9 GPa [6,7]. This, behaviour is due to the decreasing elastic moduli of these glasses with pressure up to about 2.5 GPa. On the other hand, other glasses like soda-lime have been considered to exhibit a response which is elastic up to ca. 4 GPa with a second threshold at 6–7 GPa and inelastic response for higher stresses [8–10].

Work by Rasorenov et al. [11] showed that a failure wave propagates behind the elastic wave in glass at velocities in the range 1.5–2.5 km s^{-1}. This was deduced from a small recompression signal on the velocity interferometry (VISAR) record of the free surface velocity of a K19 glass (similar to soda-lime). Later work by Brar et al. [12] confirmed the existence of these waves by using more direct techniques of spall strength and shear strength measurements ahead of and behind the failure wave. It was found that the high spall strength diminishes to zero behind this front and a substantial decrease in shear strength (as evidenced by the lateral stress measurements) results

E-mail address: neil.bourne@mac.com

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when the failure front traverses the specimen. Work by Raiser et al. [13] using VISAR, showed that the failure wave phenomenon does not depend on surface features. Direct imaging of these fronts using high-speed photography confirmed the phenomenon as one of fracture and differing morphology was observed fully filled, soda-lime and borosilicate (pyrex) glasses. Further, it was shown that failed material and intact material had very different impedance leading to apparent differences in the material equation of state [14]. More recent work has compounded information on the transition states at 4.0 and 6.0 GPa in soda-lime glass [15–17].

In order to account for these waves various analyses have been proposed. Clifton proposed a model, in the context of non-linear wave theory, according to which the failure front was a propagating phase boundary, which separated comminuted from intact material with a transformation shock [10]. Grady [18] has also described some of the response using a model that assumes material change in the shock. These models account for some of the observations of failure waves in glasses, but there is no complete description, which captures them all.

Polycrystalline ceramics are multiphase materials containing crystals of hard material bonded with a matrix, which is glassy. Mesoscale flaws within the microstructure consist of pores or poorly bound interfaces between crystals. Several authors [19–22] have modelled these effects at the mesoscale to illuminate processes observed at the continuum. Grady et al. [23] have presented the most comprehensive continuum description of the failure of a generic brittle material. The model incorporates time-dependent fracture and rate-dependent plasticity and allows yield surfaces for these materials to vary with strain rate of the pulse delivered. The dynamic response of polycrystalline materials is dominated by physical processes that occur at the elastic limit. In particular, it has been shown that fracture can be driven from the surface into the bulk of shock-loaded polycrystalline ceramics [24–27]. This fracture can be suppressed at will by making impact symmetrical or by adding cover plates to targets thus reducing the lateral strain to initiate and propagate intergranular fracture [28].

Recently, a more complete picture of the transition from elastic to inelastic response has become apparent. The insight is brought from a combination of techniques ranging from continuum sensors to one-dimensional recovery, and microstructural investigation, of shocked material [29,30]. Analysis is completed by using continuum failure criteria and numerical mesoscale simulation [20,21,31].

This work divides the response to one-dimensional loading classified into three regimes, elastic, mixed-state and inelastic response. The thresholds between these regimes define features of the observed one-dimensional stress and particle velocity histories seen in a range of polycrystalline materials. The lower threshold, conventionally referred to as the HEL (hereafter, HEL_L), relates to the onset of plasticity in suitably oriented grains. The upper, (HEL_U) relates to the completion of this process across all grains in the sample volume and appears on recorded histories as a transition from a convex to a concave rise. These definitions are defined for D975 alumina considered later (Fig. 4a). However, it is the extra modes of fracture that occur at these thresholds that determine response, triggered as they are, by plasticity in the grains under the applied load. The fracture has two regimes of influence between the grains over all stress levels, and across them, down, for instance, the twinning planes. In the AD995 studied, it is intragranular fracture within the twinned grains, inducing a step change in the volume of flaws within the microstructure that reduces tensile strength and alters failure wave speeds through the composite that remains.

The failure wave is believed to be a limiting case of the fracture that occurs within the bulk, driven down intergranular paths in the elastic regime and then into the partially failed material above HEL_L. Eventually, a high applied load is sufficient to drive the fracture into the shock front. Thus, the failure wave is a transient feature that allows a quantitative measurement of the initial strength of failed material in a controlled geometry.

Over the past years, a matrix of plate impact experiments on several brittle materials including glasses, aluminas, silicon carbides, titanium diboride, aluminium nitride and boron carbide using embedded stress and strain gauges, velocity interferometry and high-speed photography [25,26,32–34]. Specifically, the lateral stress degradation behind the failure front is presented below to contrast the brittle failure behaviour of these materials. It is believed that this presents a means of quantitatively measuring the failed strength of the ceramics thus providing an upper limit on the strength of material encountered by projectiles during penetration. Failure wave speeds are slow in polycrystalline materials and a comparison with other brittle materials has been summarized in an earlier overview [27].

There has been much study of the penetration of semi-infinite and plate targets by projectiles, and comprehensive reviews of the relevant investigations and discussion can be found in the works of Corbett et al. [35], Backman and Goldsmith [36], Zukas et al. [37], and the proceedings of the Ballistics Symposia. The majority of the investigations covered only normal impacts [38–41] with the effects of obliquity receiving less attention [42–46]. Bringing together this work with the ranking of failed strength obtained from plate impact provides a more complete picture of the response of polycrystalline materials to three-dimensional attack. It has been previously suggested by a number of researchers that the ballistic performance of ceramics depends on the strength of the failed material, rather than the intact strength. This includes work by Walker [47], Anderson Jr. [48], Orphal [49], and Johnson and Holmquist [50,51] for example.