International Journal of Impact Engineering 76 (2015) 75–82

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Effect of inter-layer toughness in ballistic protection systems on absorption of projectile energy

E.K. Öberg, J. Dean, T.W. Clyne*

Department of Materials Science & Metallurgy, Cambridge University, 27 Charles Babbage Road, Cambridge CB3 0FS, UK

ARTICLE INFO

Article history:
Received 14 May 2014
Received in revised form
28 July 2014
Accepted 16 September 2014
Available online 28 September 2014

Keywords:
Impact
Interfacial toughness
Energy absorption
Layered systems

ABSTRACT

This paper concerns absorption of the kinetic energy of a projectile in multi-layer protection systems, with particular focus on the role of inter-layer bonding. Two-layer samples have been produced, composed of a 2 mm thick alumina front plate and a carbon fibre composite back plate with a thickness of about 0.8 mm. These were manufactured under two sets of conditions. The fracture energy of the inter-layer interface was measured for these two types of sample to be 170 and 620 J m^{-2}. Such samples were subjected to impact by spherical projectiles of hardened steel, with a diameter of 8 mm and an impact speed of about 220 m s^{-1}, corresponding to a kinetic energy of about 50 J. Samples composed of the alumina plate alone and of unbonded alumina and composite layers were also tested. It was found that significantly more projectile energy was absorbed by the strongly bonded samples, and that this difference was greater than could be explained solely in terms of the interfacial debonding energy. This is investigated by estimating the magnitudes of all of the identifiable sources of energy absorption, including that of plastic deformation of the projectile. It is concluded that strong inter-layer bonding can promote greater energy absorption in the composite back-plate.

1. Introduction

There has been extensive work [1–8] on the development of systems offering protection against damage from projectile impact. Most of these are based on multi-layer structures, with a front plate made of a hard material (designed to resist the initial impact of the projectile) and a layer, or layers, behind this, in which the energy of the projectile becomes dissipated. In combination, such systems are designed to impede penetration of the projectile and also to ensure that there is minimal transmission of energy and momentum to the region being protected. Low weight is often desirable and it's become common to use ceramic (often alumina) front plates and tough, polymer-based composite layers in the energy-absorbing role.

Sometimes a layer (usually quite thin and often termed a ***confinement layer***) is incorporated immediately behind the front plate, with a primary function of ensuring that, after impact, the front plate remains in place, even if it becomes fragmented. It is often made of a relatively tough material that is likely to remain intact after impact and there is usually a strong bond with the front plate. The main role of the confinement layer is to confer a good "second strike" resistance [9] on the structure – ie to ensure that the front plate remains sufficiently integral to prevent easy passage of a second projectile that might arrive close to the site of the initial impact.

Attempts are usually made to ensure that the confinement layer is well bonded to the front plate, since this is logical in terms of its primary function. In general, however, it's not very clear whether the overall performance of the system is enhanced by making all interfacial bonding as strong (or tough) as possible. In fact, there is probably an argument to be made along the lines that weak bonding, and hence extensive delamination on impact, could assist in spreading the energy dissipation over a greater area. In practice, while there have been a number of studies [10–15] focussed on energy absorption during ballistic impact of layered structures, there has been only rather limited (experimental or theoretical) examination of this issue [16,17], mainly because there is inevitably a complex interplay between the various phenomena that occur during ballistic impact of a multi-layer protection system, with a substantial number of experimental variables and potential complications. Also, it is relatively uncommon to control and quantify the inter-layer strength (toughness) in a systematic way. The present paper is aimed in this direction, focussing on a simple two-layer system with two (significantly) different levels of inter-layer

* Corresponding author. Tel.: +44 1223 334332.
E-mail address: twc10@cam.ac.uk (T.W. Clyne).

http://dx.doi.org/10.1016/j.ijimpeng.2014.09.006
0734-743X/

bond strength and making an attempt to measure and understand the various contributions to the absorbed energy for the two different cases.

2. Experimental procedures

2.1. Material

The alumina plates, supplied by Hybrid Laser, were 2 mm thick and had a density of 3.84 g cm^{-3} – measured using helium-pycnometry (Micrometrics Accupyc 1330). X-ray diffraction revealed that they were composed mainly (~96%) of α-alumina, with the remainder being a spinel. The surface roughness was measured (using a Dektak 32 stylus profilometer) to have an R_a value of ~1 μm. A fracture surface is shown in Fig.1, where it can be seen that fracture is inter-granular and the grain size varies between about 3 and 10 μm.

A commercial woven fibre composite (Comfil®) was employed as a backing (confinement) layer. It has a 2 × 2 twill weave structure with 0.33 tows mm^{-1}, as shown in Fig. 2. The tows consist of 12 K *Tenax* HTS carbon fibres (6–8 μm diameter) and (low density) polyethylene terephthalate (PET) fibres (~30 μm diameter), intertwined in each of the yarns. The PET fibres soften when heated. At sufficiently high temperatures, and under the action of applied pressure, the PET flows and infiltrates the open spaces, forming a thermoplastic matrix. The consolidated thickness of a single composite ply was ~0.78 mm, with a density of 1.54 g cm^{-3}.

2.2. Production of layered specimens by hot pressing

Layered specimens were manufactured by hot pressing, using an applied pressure of 30 bar. Two hot pressing temperatures were employed – 200 °C and 230 °C. Prior to hot pressing, the alumina was cleaned with detergent and ethanol, before being submerged in an ultrasonic bath for 20 min.

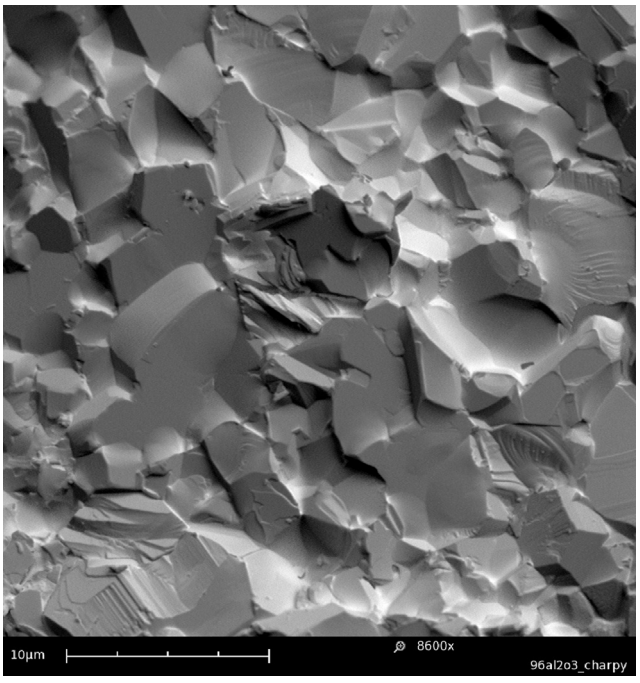

Fig. 1. SEM micrograph of a fracture surface from an alumina plate.

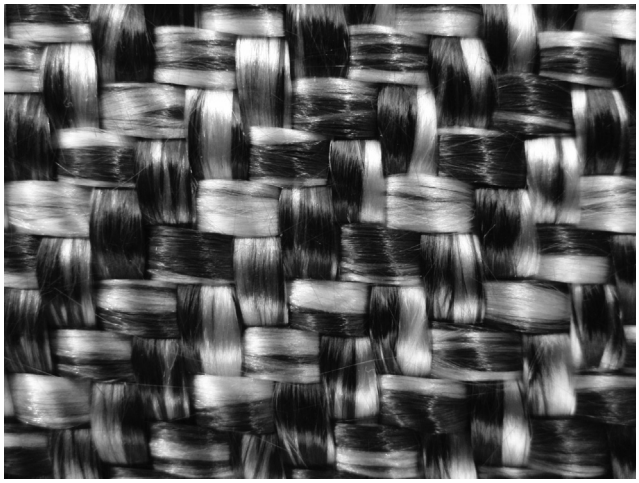

Fig. 2. Optical micrograph of the free surface of C-PET twill woven ply, before consolidation.

2.3. Alumina fracture energy measurement

The fracture energy of the alumina plates was measured using the Charpy impact test. The specimen sizes were 15 × 5 × 50 mm. The samples were pre-notched, with a notch depth of 1.5 mm. To calibrate the apparatus, the pendulum was allowed to swing without the sample present, and the energy loss due to friction alone was measured at 0.01 J. Compared to typical measured values of the fracture energy, this was found to be negligible and could be ignored. Cases in which fracture did not take place from the notch were excluded.

2.4. Inter-layer fracture energy measurement by 4-point bend delamination

To measure the inter-layer fracture energy (between the alumina and the C-PET layer) the 4-point bend delamination test, as developed by Charalmbides et al. [18] and Howard and Clyne [19], was employed. This test tends to produce strongly "mixed mode" fracture conditions. The stiffness of the C-PET layer was enhanced by the addition of a Ti–6Al–4V layer, with a thickness of 1 mm. (Without this, the energy released by inter-layer debonding would have been insufficient to drive an inter-layer crack, particularly with a relatively tough interface: the effect of the stiffening element is incorporated in the analysis.) The titanium alloy sheets were sand-blasted, in order to create rough surfaces that allowed the bond between the titanium and the C-PET to be tough enough to ensure that delamination occurred (only) between the alumina layer and the C-PET layer. The measured R_a value for the sand-blasted titanium alloy was ~3.6 μm, which is ~3.5 times greater than that obtained for the alumina. The yield stress of the titanium alloy sheet (~1 GPa) is high enough to ensure that it did not undergo any plastic deformation during the testing.

Any excess polymer, visible around the edges of the specimens after hot pressing, was removed prior to testing, in order to prevent residual polymer ligaments from forming across the de-bonding interfaces. A pre-crack along the interface between the alumina and the C-PET ply was introduced by adding thin kapton sheets (7 mm in length on either side of the notch in the alumina) before hot pressing. In all cases, it was found that the inter-layer crack did indeed propagate between the alumina and C-PET layers, and the Ti alloy sheets remained bonded to the C-PET layers throughout.