19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

GLASS CERAMIC ARMOUR SYSTEMS FOR LIGHT ARMOUR APPLICATIONS

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This paper describes an experimental evaluation of lithium-zinc-silicate glass ceramics when used as the strike face of an armour system. It is shown that against soft cored 7.62 mm rounds (lead or mild steel cores) glass ceramics offer protection at an areal density which is equal to or better than alumina faced systems. The lithium zinc silicate system has a relatively low hardness (Hv 600) when compared to conventional ceramics such as alumina (typically Hv1300-1500). Consequently the performance of the glass ceramic system against hard cored projectiles is poor.

INTRODUCTION

Glass ceramics are a class of inorganic materials which may be formed from the melt as a glass from which a crystalline phase is then produced by a suitable heat treatment. In the glass state the material is formable and castable allowing complex shapes to be easily manufactured. Upon heat treatment a fully crystalline structure is produced that is generally stronger, tougher and stiffer than the base glass. This provides a relatively cheap method for producing a ceramic tile suitable for armour applications.

In armour applications glass ceramics have been used as the frontal part of a conventional disrupter-absorber system with a composite layer being used as a backing [1]. The primary design driver for this has been the lower density of some glass ceramic compositions compared to more conventional ceramic armour materials. However the ability of glass ceramics to easily form complex shapes and the possibility of varying mechanical properties by heat treatment offer potential gains in armour performance. In this paper ballistic and mechanical properties are determined for a glass ceramic material in various heat treatment conditions. This potentially offers a possibility for isolating the contributions of individual mechanical and physical properties towards ballistic performance without the step change in all properties that is accomplished when comparing, for instance, oxide and carbide materials.

HEAT TREATMENT EFFECTS

The glass ceramic used in this work is based upon the lithium zinc silicate system (LZ1, manufactured by Ceramic Development (UK) Ltd). The glass was initially cast to shape as tiles of approximately 9 mm thickness. It was then subjected to a crystallisation treatment. This consisted of 1hour holds at 450°C and then 500°C followed by a 1 hour ramp up to 800°C, which was held for 2 hours. Samples were prepared from material that had been interrupted at various points through the heat treatment. These were used for mechanical testing, scanning electron microscopy and X-ray diffraction studies. Complete tiles in similar heat treatment states were bonded to 9.5 mm thickness GFRP backing plates (Armadillo Ltd CRA15) and subjected to ballistic testing.

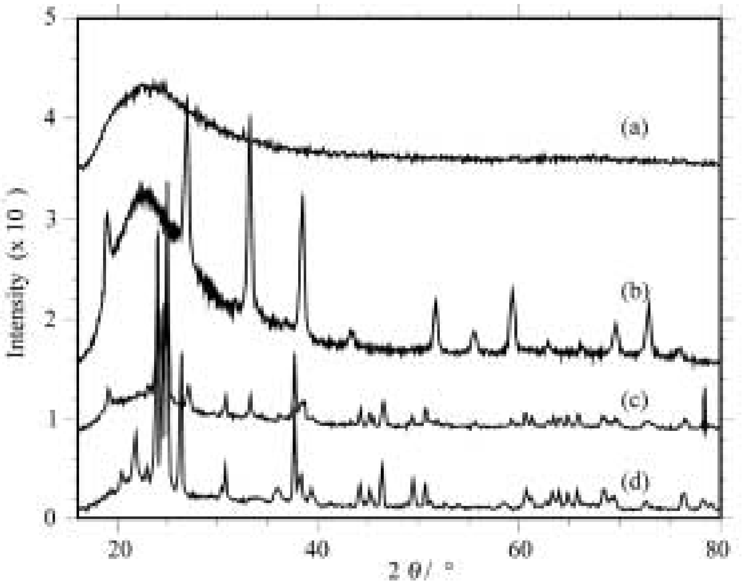

Figure 1: X-ray diffraction spectra of lithium zinc silicate glass ceramic during heat treatment, (a) in the glass state after spinodal decomposition, (b) during initial nucleation phase, (c) after nucleation of main crystalline phase and (d) after full crystallisation.

During the initial part of the ramp from 500°C to 800°C the glass undergoes a spinodal decomposition into two glass phases, the X-ray diffraction spectra (Figure 1a) shows no crystalline phases present. Within the first 30 minutes of the ramp to 800°C (corresponding to a temperature of 650°C) a nucleant phase is formed. This shows several ill-defined peaks (Figure 1b) and can be identified as $LiSiO_3$. As the temperature increases rapid changes in crystal phase take place and a major phase of $Li_2Si_2O_5$ is formed whilst the original nucleant phase is consumed (Figure 1c). Holding at the final temperature for 2 hours allows further growth of this main phase at the expense of amorphous material and some transient phases (Figure 1d).

A number of mechanical and physical properties were measured during the progression of the crystallisation process [2]. Hardness was measured using a Vickers pyramid indenter at a load of 5 kg, and fracture toughness was determined by the indentation method [3]. Elastic modulus was deduced from longitudinal wave velocity measured by ultrasonic time of flight. The unconstrained compression strength was measured using square cross section specimens 3 mm x 3 mm with a length of 10 mm which were crushed in an instrumented drop tower at velocities of 1.2 ms^{-1}. Table 1 shows data for the evolution of various mechanical properties during heat treatment and comparative data is given for a 95% alumina using the same test methods. The density of the glass ceramic is a constant 2780 kgm^{-3} throughout the heat treatment stages.

Table 1: Mechanical properties of lithium zinc silicate glass ceramic at various stages of heat treatment compared to a 955 alumina.

Heat Treatments (Cumulative from top)	Hardness (Hv)	Fracture Toughness ($MPam^{3/2}$)	Tensile strength (MPa)	Compressive strength (MPa)	Elastic Modulus (GPa)
None	430	1.86	58	733	63
1hr@450°C	593	3.44	30	660	64
1hr@500°C	825	3.53	129	1080	63
30min into ramp	769		56	1030	65
Top of ramp 800°C	757	3.86	153	1350	80
2hr@800°C	915	3.72	200	1535	77
95% Alumina	1500	3.86	190	1419	340

An initial ballistic trial used 5.56x45 mm SS109 projectiles against tiles 9.5 mm thickness bonded to a 9.5 mm GFRP. However for the tiles heat treated to the later stages it was found that the ballistic limit velocity exceeded the ammunition performance. Therefore a second trial was carried out in which a similar procedure was followed except that a 6.5 mm Kevlar backing with 7.62x51 mm ball and 7.62x51 mm P80 AP projectiles as the threat.

Figure 2 shows the ballistic limit velocities for each of these projectiles as a function of total heat treatment time. It can be seen that for the SS109 threat there is a significant increase in ballistic limit velocity after 2.5 hours corresponding to initial nucleation of crystal phases. A further increase is seen after 3 hours with tests using the 7.62 mm ball ammunition. This corresponds to the formation of the main crystal phase and the armour system exceeds the maximum performance of the SSS109 round from 3 hours onwards. The ballistic performance does not appear to increase for heat treatment beyond 3 hours and shows a significant decline against the 7.62 mm AP threat. However it should be noted that the performance of the glass ceramic against this round is very poor in all heat treatment conditions.

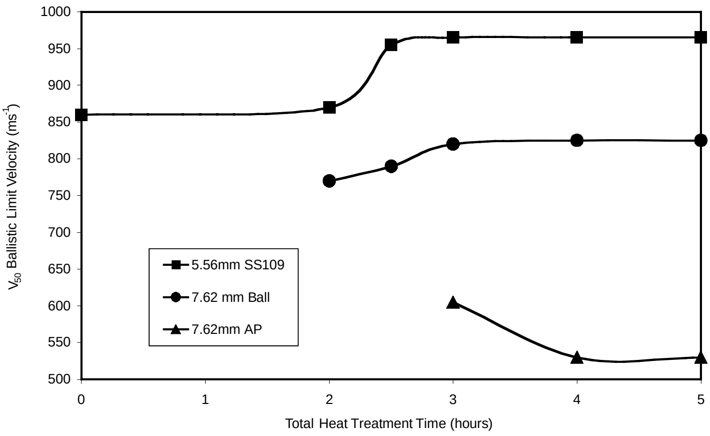

Figure 2: The effect of heat treatment of lithium zinc silicate glass ceramic on ballistic limit velocity.

The appearance of the tiles fractured in impact changed markedly according to heat treatment. In the glass, the impact site was surrounded by closely spaced radial cracks at intervals of only a few degrees. The impact site was completely pulverised and there was extensive circumferential cracking. Fully crystallised tiles show much more limited radial cracking at intervals of 20–30° and no circumferential cracking apart from the conoid failure at the impact point.

COMPARISON WITH ALUMINA

Comparison trials were carried out between the glass ceramic and a 95% alumina using 7.62x51 mm ball and 7.62x51 mm AP P80 projectiles [4]. The Depth of Penetration (DoP) technique as described by Anderson [5] was used to measure the performance of the armour materials. In this method a test projectile is fired into a large block of metal of density ρ_B and the depth of penetration P_B is recorded. A ceramic tile of thickness t_C is then placed against a similar block and the residual depth of penetration P_R of a similar projectile is recorded. From these measurements it is possible to derive number of indices of ceramic performance. The critical ceramic tile thickness (t_{crit}) to just defeat the projectile can be calculated from

$$t_{crit} = \frac{t_C P_B}{(P_B - P_R)} \tag{1}$$

Tiles of the two ceramic materials were attached to 75 mm cubes of aluminium 7018, which was used in an overaged state to give a Vickers hardness of Hv 70. The tiles were attached using a polyurethane elastomeric adhesive (Sikaflex 221), and a single layer of glass cloth was applied over the ceramic tile with an epoxy binder/adhesive. The aluminium cubes were struck with both projectile types with no tile present or with 4, 8, 12, and

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13 mm glass ceramic or 1,3,7 and 10 mm alumina tiles on the front face. After the test, the blocks where sectioned through the centre line of the resulting cavity in order to measure the residual DoP.

Figure 3 shows the effect of tile thickness upon DoP. The data for individual tests is plotted as open symbols with trend lines whilst the mean critical tile thickness according to equation 1 is indicated by the filled symbols on the x-axis. Against the 7.62 AP projectile the glass ceramic tiles have a very poor performance with a 28 mm thickness tile being calculated to just stop the projectile. This compares with only 11 mm thickness of alumina being required against the same threat. However against the 7.62 mm ball threat the glass ceramic tile needs to be 9.8 mm thick compared to 8.7 mm for the alumina.

In a second series of comparison the V_{50} ballistic limit velocity was measured for 95% alumina or glass ceramic tiles when bonded to GFRP backing panels of 9.5 mm thickness [6]. In addition to conventional flat tiles some glass ceramic tiles were produced with ridged faces [7]. The ridges were 5 mm deep with peek and trough angles of 90° so that the faces were inclined to the plane of the armour by 45°. Three types of ridged panels were used: 9.5 mm (maximum) thick with ridges to the front, 12.5 mm (maximum) thick with ridges to the front, and 13 mm (maximum) thick with ridges on both sides. The first type was tested against the SS109 ammunition whilst the latter two types were tested against 7.62 P80 AP ammunition.

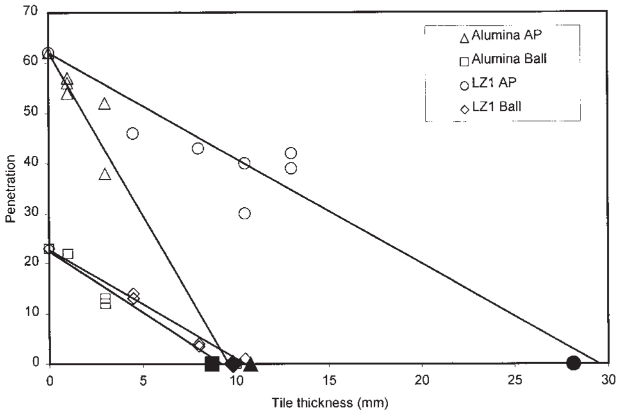

Figure 3: DoP results for 7.62 ball and 7.62 mm AP projectiles against glass ceramic and alumina targets. Filled symbols indicate the mean calculated critical tile thickness.

Figure 4 shows the ballistic limit velocity for all these tile types when tested with 7.62 mm AP and 5.56x45 mm SS109 projectiles. The glass ceramic tiles show little resistance to the 7.62 mm AP projectile with only marginal increase in the ballistic limit velocity with increasing areal density. An increase in areal density from 45 kgm^{-2} to 59 kgm^{-2} (7 mm to 12 mm tile thickness) produced an increase in ballistic limit of only 43 ms-1. In some cases the penetrator was recovered and was found to have no appreciable erosion of its tip. The alumina faced armour had a ballistic limit velocity of 825 ms^{-1} and only small fragments of the penetrator were recovered. However against the SS109 projectile the glass ceramic armour was only marginally poorer than the alumina.

The effect of casting a ridged surface into only the front surface of the tile is marginal. However using a corrugated tile with ridges on both faces produces a significant increase in ballistic performance. This configuration of the glass ceramic tile started to approach the performance of a plain alumina tile in tests with the 7.62 AP projectile. It was also noted that projectiles penetrating the ridged tiles often showed very large deflections in flight path upon exit.

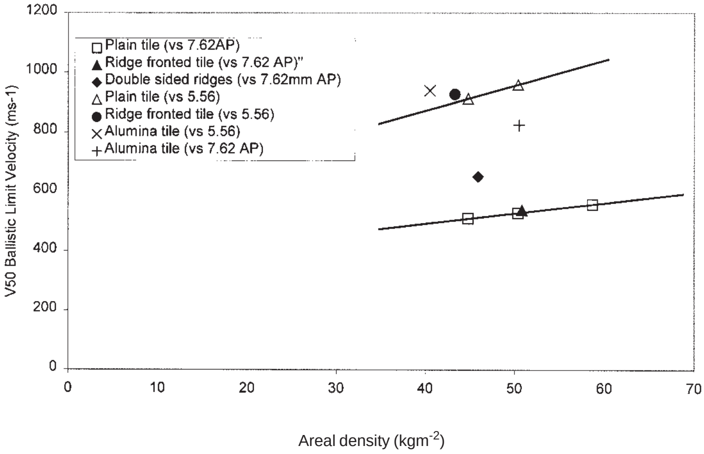

Figure 4: Ballistic limit velocity data for glass ceramic (open symbols) and alumina faced (filled symbols) systems tested with 7.62 mm AP and 5.56 mm SS109 projectiles.

SUMMARY

During heat treatment from the base glass to the fully crystallised condition the ballistic limit velocity of the glass ceramic is increased by approximately 100 ms^{-1}. Most of the change occurs during the early part of the crystallisation sequence. The geometry of fracture also changes from one of extensive circumferential and radial cracking, typical of a glass, to a more widely spaced radial failure in the crystalline material, typical of a conventional sintered ceramic. The decrease in cracking and increase in ballistic performance suggests that a transparent glass ceramic would have superior performance to glass in armour glazing applications with increased post impact transparency.

The dynamic compressive strength shows a steady increase through the heat treatment sequence from 600 MPa to 1500 MPa. This test simulates the conditions experienced by the ceramic immediately under the impact site, and as such should give some indication of the resistance to penetration of the ceramic. This test used relatively slender specimens (l/d = 3.3) offering little constraint. Consequently the peak stress may be controlled by surface flaw propagation and therefore the increase in compressive strength is probably due to a combination of the increase in hardness and toughness.

It has been suggested [7] that resistance of the ceramic to shear failure is an important property. This has been quantified [8] as the energy dissipated by frictional loses during shear failure under compression. The magnitude of the energy dissipated in shear failure is then a function of the friction coefficient between fracture surfaces which has been shown to be equal to the ratio of compressive strength to fracture toughness. This ratio is equal to 0.50 for the untreated glass and 0.73 for the fully heat treated ceramic. It is not clear whether this would be expected, the glass tends under normal loading rates to produce smoother fracture surfaces than the crystalline material. However the intense crack branching seen in the fractured glass under ballistic loading indicated severe crack instability which would give rise to rough fracture surfaces.

The relatively low hardness of even the fully heat treated glass ceramic indicates that its main use is likely to be in systems designed to stop soft cored rounds. Against the 7.62 mm AP threat the performance of the glass ceramic is quite poor although the use of a corrugated tile significantly improved this performance. Against soft cored rounds the performance of the glass ceramic is better than alumina with DoP tests indicating a requirement for 9.8 mm of glass ceramic (areal density 29.2 kgm^{-2}) compared to 8.7 mm for the alumina (areal density 33 kgm^{-2}). Therefore against soft cored high velocity projectiles the lithium zinc silicate glass ceramic has a better mass efficiency than alumina, and this can be further improved by the use of corrugated tiles.

ACKNOWLEDGEMENTS

The author would like to acknowledge the help and support of Dr R Jones of Cera Dynamics Ltd (formerly Ceramic Developments (UK) Ltd).

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