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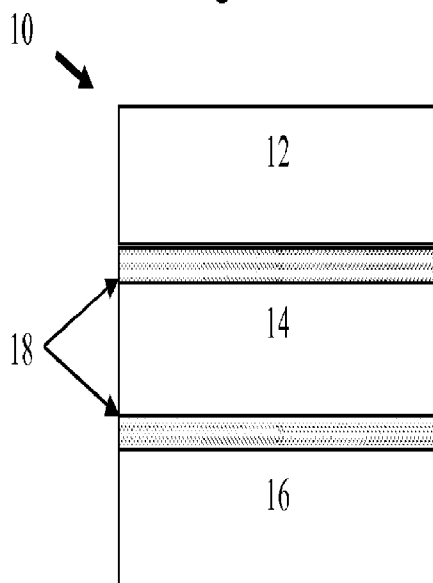
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[Continued on next page]

(54) Title: TRANSPARENT ARMOUR HAVING IMPROVED BALLISTIC PROPERTIES

Figure 1



(57) Abstract: T This disclosure teaches the use of low density, "open"-structure glasses as backing glasses, behind glass-ceramic strike-faces, in transparent armor composite windows. These low density "open-structure" glasses are sometimes referred to as "anomalous" glasses. For transparent armor applications both silica, including fused silica, and borosilicate glasses can be used as backing glass. These backing glasses provide improved ballistics performance over that of standard commercial soda lime backing glass. These glasses should be used either in their as-formed state (e.g. float surfaces) or should be finished using a process designed for minimizing sub-surface damage.



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TRANSPARENT ARMOUR HAVING IMPROVED BALLISTIC PROPERTIES

Priority

[0001] This application claims the priority of United States Provisional Patent Application No. 61/253,280 titled “TRANSPARENT ARMOUR HAVING IMPROVED BALLISTIC PROPERTIES” filed October 20, 2009 in the name of inventors Linda Ruth Pinckney, Robert A Schaut, Steven Allen Tietje and Jian-Zhi Jay Zhang,.

Field

[0002] The disclosure is directed to transparent armor laminates including a glass or glass-ceramic strike-face layer, one or a plurality of glass or glass-ceramic backing layers and spall-catcher layer. In particular, the disclosure is directed to laminates in which the glass backing layers of selected composition are used in the as-formed state or after finishing using a process designed for minimizing sub-surface damage.

Government Rights

[0003] The subject matter of this disclosure was made with United States Government support under Agreement No. HR0011-08-C-0046 awarded by DARPA. The United States Government has certain rights in this invention.

Background

[0004] Transparent armor (“TA”), used mainly for military vehicle windows, but also having applications such as for windows in high security buildings or to protect against debris from severe storms such as tornados, is usually made using a laminate of float glass and impact resistant plastics such as polycarbonate. The glass and polymer materials are usually in the form of thin sheets (layers) that these are laminated together using transparent adhesive sheets of PVB (polyvinyl butyral) or PU (polyurethane) between the glass and polymer material layers followed by a high-temperature and high-pressure bonding process step that is typically carried out in an industrial autoclave system. The composite material or laminate after the autoclave process appears optically monolithic with no visible bubbles or other defects. Depending on the threat level for which the

armor is designed, the laminate can range in thickness from ½ inches to more than 5 inches. Because current military vehicles face increasingly high levels of threat, these glass-only armor systems often need to be as thick as 4-6 inches, and the weight of these thick, glass-only TA systems over-burdens the vehicles. Consequently, there is a strong need to use more advanced materials in order to reduce TA armor weight and thickness by providing less weights laminates that afford the same protection level or improved protection.

[0005] Researchers and engineers have studied different classes of transparent materials with the aim of delivering lighter weight transparent armor. Fully crystalline, transparent materials include sapphire, spinel and ALON (aluminum oxynitride). These ceramic materials can provide very high hardness and fracture resistance but are very expensive. While these materials work very well for armor piercing projectiles, providing >50% weight savings in stopping single shots over glass, they do not perform particularly well against fragment simulating projectiles, thus making armor system-level weight savings less than 50% when the requirements include both AP (anti-personnel) rounds and FSPs (fragmented simulated projectiles). The cost and performance trade-off makes transparent ceramics less than ideal for field use today. The application herein have been studying transparent glass-ceramics, materials in which crystallites are dispersed in a glass matrix, as a strike-face material, and the use of glass-ceramics have demonstrated 30-40% weight savings in single shot ballistics testing against both APs and FSPs. However, further improvements are needed and have been obtained as are disclosed herein.

Summary

[0006] This disclosure teaches the use of low density “open-structure” glasses as backing glasses, behind glass-ceramic strike-faces, in transparent armor composite windows. These low density, “open-structure” glasses are sometimes referred to as “anomalous” glasses. The definition of anomalous glass regards the occurrence of Hertzian-like cone cracks during Vickers indentation. Such a particular behavior can be related to anelastic densification processes occurring in the highly stressed region beneath the indenter. Conversely, glasses defined as ‘normal’ show mainly a median/radial crack system and plastic deformation is accounted for shear faulting. Borosilicate glasses, together with silica glass, including fused silica glass, are commonly considered as ‘anomalous’ glasses. For the TA application both silica, including fused silica, and borosilicate glasses can be

used as backing glass. These backing glasses provide improved ballistics performance over that of standard commercial soda lime backing glass. Preferably, these glasses should be used either in their as-formed state (e.g. float surfaces) or should be finished using a process specifically designed for minimizing sub-surface damage.

[0007] The disclosure describes the use of borosilicate glass backing glass having a composition consisting essentially of, in weight percent (wt%), of 75-85, 10-15 wt% B_2O_3 , 1-3% Al_2O_3 , and 3-5% Na_2O , and 0.3- 2wt% K_2O . The disclosure also describes a glass composition, in wt%, consisting essentially of 100% SiO_2 glass, neglecting impurities, made by a chemical vapor deposition process. In one embodiment the glass is made by the float process. In an additional embodiment the glass is made by a roll process.

[0008] In one embodiment the disclosure describes a transparent glass-ceramic/glass armor system, said system comprising a glass-ceramic layer having a strike face and a bonding face, said faces having been finished after the glass-ceramic is made from a glass material capable of being cerammed; one or a plurality of anomalous glass backing layers, one of said glass layers being bonded to the bonding face of the glass-ceramic, and, when a plurality of glass backing layers are present, the remainder of the anomalous glass layers being bonded sequentially to one another in a face-to-face manner; and a spall-catcher layer bonded to the glass layer furthest from the glass-ceramic layer; wherein said transparent glass-ceramic/glass armor system has a V50 greater than 2950 ft/sec. In another embodiment of the glass/ceramic/glass armor system the backing glass is a glass sheet having a composition consisting essentially of 75-85 wt% SiO_2 , 10-15 wt% B_2O_3 , 1-3 wt% Al_2O_3 , and 3-5 wt% Na_2O , and 0.3- 2 wt% K_2O . In an additional embodiment the backing glass is a glass sheet having a composition consisting essentially of 100 wt% SiO_2 glass; and in an embodiment the silica glass is fused silica glass. In a further embodiment the 100 wt% SiO_2 backing glass has surface roughness of less than 3 Angstroms Ra (30 nm Ra), preferably less than 2 Angstroms Ra (20 nm Ra). In an additional embodiment the backing glass is a glass sheet having a composition consisting essentially of 100 wt% chemical vapor deposited SiO_2 glass. In a further embodiment the backing glass is a 100 wt% chemical vapor deposited SiO_2 glass having a surface roughness of less than 3 Angstroms Ra (30 nm Ra), preferably less than 2 Angstroms Ra (20 nm Ra), and more preferably in the range of 0.5-2 Angstroms Ra (5-20 nm Ra).

[0009] Brief Description of the Drawings

[0010] Figure 1 illustrates the structure of the laminates that were tested.

[0011] Figure 2 is a bar chart illustrating the effects of composition and surface treatment on V50.

[0012] Figure 3 is a bar chart illustrating V50/AD Figure of Merit for the glass listed in Table 3.

[0013] Detailed Description

[0014] As disclosed in U.S. Patent Application No. 11/974028 (Corning Incorporated) a benefit in transparent armor protection was found by combining a glass-ceramic strike-face with a glass backing layer. This “hybrid” configuration yielded improved ballistic performance over all-glass or all-glass-ceramic configurations. The present disclosure is directed to the role of the backing glass and to determining the most suitable glass(es) for TA applications. This disclosure specifically addresses the different ballistics results obtained with a glass-ceramic strike-front and different types – composition and surface finish - of glass backing layers. The key advantages of the armor configurations disclosed herein stem from their lower weight and lower thickness coupled with:

1. The ability to achieve ballistics performance equivalent to that obtained with conventional soda lime backing glass, but with lower areal density, thereby providing critically-needed lower weight for armor systems.
2. The ability to achieve superior ballistics performance with the same areal density used for current transparent armor.
3. Less optical distortion due to reduction of window thickness, particularly beneficial in a moving vehicle.
4. Other weight saving opportunities due to reduction in window thickness, such as reduction in metal frame weight

Few studies have been carried out on the role of the backing glass for a hard strike-face in armor configurations. Anecdotal evidence has suggested that density and Young's modulus of the glass may play a role, but most of the speculation is based on static material properties of glasses, not their dynamic properties, and it is well known that these properties do not always correlate with each other. Some ballistics studies at Corning Incorporated on ion-exchanged and thermally-tempered backing glasses produced inconclusive results. However, a study which concentrated on the composition and surface preparation of the backing glass produced clear results and trends which are disclosed herein.

Glass Compositions

[0015] Six different glasses were included in this study. These include a commercial soda lime float glass; three borosilicate glasses [Corning Codes 7740 (Pyrex) and 7056; Borofloat® borosilicate glass (Schott Glass) which is similar in composition to Corning Code 7740); an alkali aluminosilicate glass (Corning Code 2317); and fused silica glass (Corning Code 7980)]. The compositions and properties of these glasses are compiled in Table 1.

Table 1

Composition (wt%)	Fused silica	Code 7740 and Borofloat	Code 7056 borosilicate	Code 2317 alkali aluminosilicate	Soda lime
SiO ₂	100	81	68	61	72
Al ₂ O ₃	-	2	3	16	1
B ₂ O ₃	-	13	18	<1	-
Li ₂ O	-	-	1	-	-
Na ₂ O	-	4	1	13	12
K ₂ O	-	-	9	4	1
CaO	-	-	-	<1	8
MgO	-	-	-	4	4
Density (g/cm ³)	2.2	2.23	2.29	2.45	2.53
Poisson's ratio	0.17	0.20	0.21	0.21	0.22
CTE (ppm)	0.56	3.25	5.15	9.1	9.5
Young's mod. (GPa)	73	64	64	73	74
Knoop hardness	550	480	n/a	~550	590
Fracture toughness MPa.m ^{1/2}	0.79	0.77	n/a	0.7	0.75

Ballistics testing

[0016] Sample laminates for single-shot ballistics testing were prepared by machining the backup glasses and glass-ceramic layer (the strike-face layer) into 4"x4" or 6"x6" coupons, and then forming them into a laminate configuration of glass-ceramic ("GC") 12, backing glass ("BG") 14, and ½" polycarbonate ("PC") spall shield 16 as illustrated in Figure 1 (in which the elements are not drawn to scale), where numeral 18 is the bonding material for the layers. For most samples, Corning Code 9665 glass-ceramic was used as the strike-face, but all-borosilicate and all-sodalime laminate samples were also tested to provide all-glass systems baselines in order to illustrate the efficacy of the hybrid concept.

The areal density was kept constant at $\sim 18.8 \text{ lb/ft}^2$. The thicknesses of each layer were chosen to adjust to density differences and provide nearly identical areal densities for each sample. The layers were bonded together using either (1) a two-part epoxy material of negligible thickness, or (2) using an autoclave process with thermoplastic polyurethane (PU) adhesive layers. [Both bonding materials (1) and (2) are represented in Figure 1 by numeral 18.] In the case of using the autoclave process, typical adhesive thickness is 15mil (0.381mm) between glass layers, and 25mil (0.635mm) between the glass and polycarbonate layers. Ballistics testing was carried out at HP White Laboratory (Street, Maryland), a government-certified range. Ballistic testing was carried out using 30 caliber APM2 rounds.

[0017] Ballistics Glossary

Areal density (“A.D.”): The normalized weight, usually given in pounds per square foot.

V50: The projectile velocity at which there is a 50% probability of target penetration by the projectile; given here in units of feet per second.

Highest partial velocity (“HPV”): Muzzle velocity of the fastest projectile stopped by the target.

Lowest complete velocity (“LCV”): Muzzle velocity of the slowest projectile which penetrated the target.

Results

[0018] Table 2A lists all the key configuration information for the samples as well as the ballistics data. Figure 1 illustrates how the sample laminates were constructed for ballistic testing. Table 2B summarizes the configurations in order of highest to lowest V50. Note that, in addition to composition, the samples represent a range of surface finishes from as-formed to ground and polished.

Table 2A: Complete data set for ballistics testing.

Sample#	V50	HPV	LCV	Front	HB	A.D.	SB
S1	2486	2458	2513	9665	polished Borofloat	18.83	½ inch PC
S2	2808	2805	2834	9665	polished 7740	18.83	½ inch PC
S3	2950			9665	as-made Borofloat	18.83	½ inch PC
S4	3083	3094	3107	9665	polished fused silica*	18.82	½ inch PC
S5	2590	2507	2583	9665	polished 7056	18.83	½ inch PC
S6	2720	2568	2782	9665	polished 2317	18.83	½ inch PC
S7	2356	2365	2400	9665	polished sodalime	18.83	½ inch PC
S8	2508			9665	as-made sodalime	18.8	½ inch PC
S9	2296	2262	2329	BF	all as-made Borofloat, no GC	19.1	½ inch PC
S10	2018	2017	1992	SL	all as-made sodalime, no GC	18.96	½ inch PC
S11	2977	2947	3007	9665	fire-polished fused silica	18.78	½ inch PC

Areal density (“A.D.”): The normalized weight, usually given in pounds per square foot.
V50: The projectile velocity at which there is a 50% probability of target penetration by the projectile; given here in units of feet per second.
Highest partial velocity (“HPV”): Muzzle velocity of the fastest projectile stopped by the target.
Lowest complete velocity (“LCV”): Muzzle velocity of the slowest projectile which penetrated the target.
Front: The glass-ceramic layer material.
Hard Backing (“HB”): The glass layer material after the front layer.
Soft Backing (“SB”): The spall catcher material.
9665 is a glass-ceramic
BF is Borofloat borosilicate glass
SL is soda lime glass
 k. **polished fused silica*** = polished using any method producing telescope quality optical characteristics.

Table 2B: Backing glass in order of V50 Performance

Sample #	V50 (ft/sec)	Strike-face ((Front)	Backing glass (HB)
S12	3477	9665 GC	Low SSD Fused Silica
S4	3083	9665 GC	Polished fused silica
S11	2977	9665 GC	Fire-polished fused silica
S3	2950	9665 GC	Float-surface Borofloat borosilicate
S2	2808	9665 GC	Polished 7740 borosilicate
S6	2720	9665 GC	Polished 2317 alkali aluminosilicate
S5	2590	9665 GC	Polished 7056 borosilicate
S8	2508	9665 GC	Float-surface soda lime
S1	2486	9665 GC	Polished Borofloat borosilicate
S7	2356	9665 GC	Polished soda lime
S9	2296	Borofloat borosilicate	Float-surface Borofloat borosilicate
S10	2018	Soda lime glass	Float-surface soda lime

[0019] Figure 2 is a bar graph of the data in Table 2B with the data grouped by the backing glass. In addition, a data point was added for low subsurface-damaged (SSD) fused silica (FS). Sample number S13, not in Table 2A) where the sample was made using the autoclave process and was 6"x 6", which is the same size as the samples of Tables 1 and 2. The SSD FS sample had an areal density of 15.6 lb/ft² and the V50 was normalized assuming a linear relationship between V50 and areal density. The performance equivalency between 4"x4" epoxy adhesive samples with negligible epoxy thickness and 6"x6" autoclaved samples with 15mil (0.38mm) PU between the glass-ceramic and glass has been established using the "standard" configuration of 10mm GC/22mm Borofloat/12mm PC.

[0020] First, it is clear that the all-glass configurations, with no glass-ceramic strike face, yield inferior ballistics performance relative to a glass-ceramic/glass configuration. This result has been consistently obtained has been shown, for example, in WO 2008.130457 and WO 2009/096930.

[0021] Second, the data presented in Tables 2A and 2B indicate that both composition and surface finish play a role in ballistics performance. These parameters can be considered intrinsic and extrinsic properties of the glass, respectively, and will be further described below.

Intrinsic glass properties: Composition and structure

[0022] A comparison of the six glass compositions with finished (polished) surfaces indicates for these samples V50s that vary by as much as 700 ft/sec given the same strike-face material and areal density. At the low end is sodalime (2356 ft/sec), which is the glass used in current commercial transparent armor. Fused silica, at over 3000 ft/sec, is the “strongest” glass in this data set. Even given some “noise” from minor finishing differences (in the glass and/or glass-ceramic), this 700 ft/sec improvement is quite significant and suggests that the inherent chemical and structural difference between silica and soda lime glasses plays a key role in ballistics performance.

[0023] There are a number of articles in the materials science literature concerning the structure and properties of so-called “normal” and “anomalous” glasses. Normal and anomalous glasses behave differently in many of their thermal and mechanical properties, and a number of studies have been done on static deformation and fracture properties of these glasses (see A. Arora et al., “*Indentation deformation/fracture of normal and anomalous glasses*,” J. Non-Cryst. Sol. 31 (1979), pages 415-428, and Z. Burghard, et al., “*Crack opening profiles of indentation cracks in normal and anomalous glasses*,” Acta Mater. 52 (2004), pages 293-297). Glasses such as soda lime (window glass) glass contain significant amounts of network modifiers, such as alkali and alkaline earth cations, and non-bridging oxygen atoms; these are known as normal glasses. On the other hand, anomalous glasses have few network modifiers or non-bridging oxygen atoms, and their strong tetrahedral networks therefore dominate the structure. Examples of anomalous glasses include silica and germania glass as well as borosilicate glasses, and Corning Code 9665 glass-ceramic, wherein the continuous glassy phase is highly siliceous.

[0024] Two types of plastic deformation – shear flow and densification - are possible in glass (M. Bertoldi and V.M. Sglavo, “*Soda-borosilicate glass: normal or anomalous behavior under Vickers indentation*,” J. Non-Cryst. Sol. 344 (2004), pages 51-59), and normal and anomalous glasses have been shown to react differently in their deformation:

- Shear flow is plastic flow that generates change in body shape but not a volume change. Shear flow occurs via the breaking of bonds, and since bonds to non-bridging oxygen atoms are weaker than Si-O-Si bonds, normal glasses mainly display this kind of deformation.

- Densification, on the other hand, is based on the compaction of a structure and resultant volume reduction. In general, no breakage of bonds is involved; rather, the bond

angles between silica tetrahedra change and the tetrahedra rotate, causing compaction/densification in the structure. Anomalous glasses undergo chiefly densification deformation. [High pressure (>10 GPa) experiments with silica glass have demonstrated a semi-permanent density increase of 20%. Modeling simulations suggest that some of the densification under high pressure may involve broken bonds, whereby Si coordination increases from 4 to 6. See R.G. Della Valle and E. Venuti, *High-pressure densification of silica glass: A molecular-dynamics simulation*. Phys. Rev. B 54 (1996) 3809-3816.]

[0025] While most of these studies describe deformation under quasi-static conditions, Chaudhri and Kurkjian (*Impact of small steel spheres on the surfaces of "normal" and "anomalous" glasses*. J. Amer. Ceram. Soc. 69 (1986), pages 404-410), used high-speed photography to follow the formation and growth of damage in various glasses impacted by 1-mm diameter steel balls at velocities of ~150 m/sec. They showed that, as in quasi-static experiments, the modes of cracking differ between normal and anomalous glasses, as does the amount of debris generated (with the least amount generated during impact of silica glass). This study involved very small projectiles and low velocities compared to actual ballistics studies. Nevertheless, their results support the thesis of different structure glasses reacting differently in their impact behavior. (It is of interest to note that Sehgal and Ito ("*Brittleness of glass*," J. Non-Cryst. Sol. 253 (1999) 126-132.) noted that fused silica is also the most "brittle" glass, where brittleness is defined as the ratio of hardness to toughness. Of the types of glasses tested in this disclosure, silica is the most brittle glass, followed by borosilicate and then soda lime. Brittleness values correlate well (inversely) with glass density.) Thus, while many static property and low-impact velocity studies do not correlate with the results of actual ballistics experiments, the data summarized above indicate that the ability to undergo densification appears to be a key reason for the improved ballistics resistance of high silica glasses over soda lime.

Extrinsic glass properties: Surface finish

[0026] Subsurface damage is an inherent consequence of a mechanical finishing process. Subsurface damage (SSD) is deliberately induced during the grinding and lapping steps in order to remove material at a cost-effective rate, while the subsequent polishing step is aimed at removing the damage. The amount of remaining SSD can affect the resultant properties of the glass. For example, the amount of SSD in ground and polished ULE

glass was studied by a micro-indentation technique by Yang (*"Effect of subsurface damage on indentation behavior of ground ULE glass,"* J. Non-Cryst. Sol. 351 (2005), pages 3861-3865). Yang determined that the maximum and residual indentation depths in the ground glasses increase with SSD – i.e. the propagation of SSD caused surface degradation.

[0027] Examination of the data in Tables 2A and 2B reveals significantly different ballistics performance in the same material given different surface preparations, as exemplified by polished Corning 7740 (S2, Pyrex) and as-formed Borofloat (S3). While these two glasses have near-identical composition and thermal and mechanical properties, the nature of their tested surfaces was quite different. The surface of 7740 was ground and polished, while that of Borofloat was tested in the as-formed (as-floated) state. Polished Code 7740 under-performed Borofloat by ~150 ft/sec.

[0028] We then decided to polish Borofloat (S1) to emulate 7740's surface conditions and discovered that the V50 of polished Borofloat dropped by ~450 ft/sec from that of its as-floated state (S1). To confirm such effects, we also did a comparison between as-floated sodalime glass (S8) and its polished counterpart (S7), and saw a V50 differential of 150 ft/sec. The less dramatic difference in V50 obtained with sodalime might be attributable to sodalime's tendency to develop surface defects just by exposure to the environment, whereas Borofloat is known to be a durable glass with better resistance to environmental contaminants.

[0029] Using the above findings about the SSD-related "weakening" effects and the improved performance of open-structure anomalous glass, the natural question arose "Wouldn't fused silica in an as-formed state be the ultimate strong backing glass?" Unfortunately, while fused silica cannot be easily formed into a flat sheet without the aid of some form of finishing, it is possible to design a finishing process that does not generate bad sub-surface damage. Test specimens of fused silica that had been polished using a low SSD finishing recipe that was originally developed for the space shuttle windows. Methods that produce telescope quality polish can also be used, for example, polishing using a series of diamond grits (6 μm , 3 μm , 1 μm , 0.25 μm and 0.1 μm) and commercially available polishing machines. The following data summarize a comparison between as-formed Borofloat (S3), fused silica that was processed with "commercial polish", and fused silica that was finished to low SSD. Corning 9665 glass-ceramic was

used as a strike-face, and $\frac{1}{2}$ " (~1.27mm) PC was used as a soft backing. Due to the fact that different areal densities were used in the samples, we normalized V50 by the areal density and used the ratio as a new figure of merit (FOM) that is shown in Figure . It should be noted that this set of data was for 6"x6" laminates that were made using an autoclave process, whereas the previous data discussed earlier in this report were for 4"x4" samples glued together using an epoxy. Both sample size and fabrication method can change the V50, so a comparison should not be made across the two groups. Figure 3 is a bar chart illustrating V50/AD Figure of Merit for the glass listed in Table 3.

Table 3

Sample	M/AD	V50	V50/AD	FM	Th.	Den	AD
A	17.5	2970	169.71429	9665	0.394	2.75	5.631664
B	15.56	2878	184.96144	9665	0.394	2.75	5.631664
C	17.5	2789	159.37143	9665	0.394	2.75	5.631664

Table 3 (continued)

Sample	HB	Th.	Dens.	AD	SB	Th.	Dens.	AD
A	FS	0.775	2.201	8.87748	PC	0.545	1.2	3.399269
B	LSSD-FS	0.62	2.201	7.09283	PC	0.53	1.2	3.305711
C	BF	0.748	2.23	8.67027	PC	0.54	1.2	3.368083
AD = Areal Density M/AD = Measured AD V50 = the projectile velocity at which there is a 50% probability of target penetration by the projectile. V50/AD - ratio of V50 ÷ AD FM = Front (Strike-face) Material Th. = Thickness, inches; 0.394 in = ~10 mm 0.775 in = ~20 mm 0.62 in = ~17 mm 0.53 in = ~13 mm				Dens. = Density, g/cm ³ HB = Hard Backing SB = Soft Backing FS = fused silica LSSD-FS = Low Sub-Surface Defect Fused Silica BF - Borofloat PC = polycarbonate				

[0030] The results indicate that with the strike-face and soft backing kept constant, the performance differential can only be attributed to the backing glass. The results also indicate that fused silica with a “commercial polish” out-performs as-formed Borofloat, and a fused silica with a low SSD polish should be expected to deliver further performance improvements.

[0031] In summary, two major factors that impact backing glass performance have been identified: glass composition/structure and surface condition. The optimal backing glass would have a low-density, “open” structure (anomalous glass) and low/shallow surface flaw populations. The surface condition should be such that there is low subsurface damage; for example without limitation, scratches or surface cracks.

[0032] The glass and glass-ceramic layers of the armor system can be bonded together using adhesives of a bonding polymer interface material in sheet form. Adhesives in gel, paste or other fluid or semi-fluid form may be cured and bonding achieved by application

of heat or radiation, with or without pressure being applied. When the bonding material is a polymer interface material in sheet form the bonding is typically carried out using a combination of heat and pressure. The bonding materials, adhesive or polymer material, should match the refractive index of the other materials as closely as possible so as not to lessen optical performance. In one embodiment the adhesive and polymeric materials should be transparent to infrared radiation.

[0033] The backing layer, also known as the “spall catcher,” comprises a spall-resistant material such as a polymeric material. Suitable polymeric materials include polyacrylates, polycarbonates, polyethylenes, polyesters, polysulfones and other polymeric materials as used in currently available transparent armor. As with the glass-ceramic materials and the glasses used in the armor laminates of the invention, the spall-resistant material must meet the criteria of transmissivity and low distortion as described elsewhere herein.

[0034] Thus in one aspect the disclosure is directed to a transparent glass-ceramic/glass armor system, said system comprising a glass-ceramic layer having a strike face and a bonding face, said faces having been finished after the glass-ceramic is made from a glass material capable of being cerammed; one or a plurality of anomalous backing glass layers, one of said glass layers being bonded to the bonding face of the glass-ceramic layer, and, when a plurality of glass backing layers are present, the remainder of the backing glass layers being bonded sequentially to the layer bonded to the backing glass layer bonded to the glass-ceramic; and a spall-catcher layer bonded to the glass layer furthest from the glass-ceramic layer. The transparent glass-ceramic/glass armor system has a V50 greater than 2950 ft/sec and a surface roughness of less than 3 Angstroms Ra. In one embodiment the backing glass can be a glass sheet having a composition consisting essentially of 75-85 wt% SiO₂, 10-15 wt% B₂O₃, 1-3 wt% Al₂O₃, and 3-5 wt% Na₂O, and 0.3- 2 wt% K₂O. In another embodiment the backing glass is an as-formed float glass composition consisting essentially of 75-85 wt% SiO₂, 10-15 wt% B₂O₃, 1-3 wt% Al₂O₃, and 3-5 wt% Na₂O, and 0.3- 2 wt% K₂O. In a further embodiment the backing glass has a surface roughness in the range of 0.5- 2 Angstroms Ra. In an additional embodiment the backing glass consists essentially of 100 wt% SiO₂ glass having a surface roughness in the range of 0.5- 2 Angstroms Ra. In some embodiments the backing glass consists essentially of 100 wt% chemical vapor deposited SiO₂ glass having low sub-surface damage, said glass having a surface roughness of less than 2 Angstroms Ra. In other embodiments the transparent

glass-ceramic/glass armor system has a V50/AD Figure of Merit of at least 150. In further embodiments the V50/AD Figure of Merit is at least 160. In additional embodiments the V50/AD Figure of Merit is at least 180.

[0035] The disclosure is also directed to a transparent glass-ceramic/glass armor system, said system comprising a glass-ceramic (“GC”) layer having a strike face and a bonding face, an anomalous glass backing layer bonded to the GC layer and a spall-catcher layer bonded to the glass layer furthest from the glass-ceramic layer; wherein the backing glass consists essentially of 75-85 wt% SiO₂, 10-15 wt% B₂O₃, 1-3 wt% Al₂O₃, and 3-5 wt% Na₂O, and 0.3- 2 wt% K₂O, and the transparent glass-ceramic/glass armor system has a V50 greater than 2950 ft/sec, and the backing glass layer has a surface with a roughness of less than 3 Angstroms Ra. In one embodiment the armor system has a V50/AD Figure of Merit of at least 150. In another embodiment the transparent glass-ceramic/glass armor system has a V50/AD Figure of Merit of at least 160.

[0036] The disclosure is also directed to a transparent glass-ceramic/glass armor system, said system comprising a glass-ceramic (“GC”) layer having a strike face and a bonding face, an anomalous glass backing layer bonded to the GC layer and a spall-catcher layer bonded to the glass layer furthest from the glass-ceramic layer; wherein the backing glass consists essentially of a 100 wt% fused silica glass, and wherein said transparent glass-ceramic/glass armor system has a V50 greater than 2950 ft/sec, and said backing glass layer has a surface with a roughness of roughness of less than 3 Angstroms Ra. In one embodiment the armor system has a V50/AD Figure of Merit of at least 160. In another embodiment the armor system has a V50/AD Figure of Merit of at least 180.

[0037] It will be apparent to those skilled in the art that various modifications and variations can be made to the present disclosure without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this disclosure provided they come within the scope of the appended claims and their equivalents.

We claim:

1. A transparent glass-ceramic/glass armor system, said system comprising:
 - a glass-ceramic layer having a strike face and a bonding face, said faces having been finished after the glass-ceramic is made from a glass material capable of being cerammed, and;
 - one or a plurality of anomalous backing glass layers, one of said glass layers being bonded to the bonding face of the glass-ceramic layer, and, when a plurality of glass backing layers are present, the remainder of the backing glass layers being bonded sequentially to the layer bonded to the backing glass layer bonded to the glass-ceramic and
 - a spall-catcher layer bonded to the glass layer furthest from the glass-ceramic layer;
 - wherein said transparent glass-ceramic/glass armor system has a V50 greater than 2950 ft/sec, and said backing glass layer has a surface with a roughness of less than 3 Angstroms Ra.
2. The transparent glass-ceramic/glass armor system according to claim 1, wherein the backing glass is a glass sheet having a composition consisting essentially of 75-85 wt% SiO₂, 10-15 wt% B₂O₃, 1-3 wt% Al₂O₃, and 3-5 wt% Na₂O, and 0.3- 2 wt% K₂O.
3. The transparent glass-ceramic/glass armor system according to claim 1, wherein the backing glass is an as-formed float glass composition consisting essentially of 75-85 wt% SiO₂, 10-15 wt% B₂O₃, 1-3 wt% Al₂O₃, and 3-5 wt% Na₂O, and 0.3- 2 wt% K₂O.
4. The transparent glass-ceramic/glass armor system according to claim 2, wherein the backing glass has a surface roughness in the range of 0.5- 2 Angstroms Ra.
5. The transparent glass-ceramic/glass armor system according to claim 1, wherein the backing glass consists essentially of 100 wt% SiO₂ glass
6. The transparent glass-ceramic/glass armor system according to claim 5, wherein the backing glass has a surface roughness in the range of 0.5- 2 Angstroms Ra.

7. The transparent glass-ceramic/glass armor system according to claim 1, wherein the backing glass consists essentially of 100 wt% chemical vapor deposited SiO₂ glass having low sub-surface damage, said glass having a surface roughness of less than 2 Angstroms Ra.
8. The transparent glass-ceramic/glass armor system according to claim 1, wherein said armor system has V50/AD Figure of Merit of at least 150.
9. The transparent glass-ceramic/glass armor system according to claim 1, wherein said armor system has V50/AD Figure of Merit of at least 160.
10. The transparent glass-ceramic/glass armor system according to claim 1, wherein said armor system has V50/AD Figure of Merit of at least 180.
11. A transparent glass-ceramic/glass armor system, said system comprising:
 - a glass-ceramic ("GC") layer having a strike face and a bonding face, an anomalous glass backing layer bonded to the GC layer and a spall-catcher layer bonded to the glass layer furthest from the glass-ceramic layer;
 - wherein the backing glass consists essentially of 75-85 wt% SiO₂, 10-15 wt% B₂O₃, 1-3 wt% Al₂O₃, and 3-5 wt% Na₂O, and 0.3- 2 wt% K₂O, and
 - said transparent glass-ceramic/glass armor system has a V50 greater than 2950 ft/sec, and
 - said backing glass layer has a surface with a roughness of less than 3 Angstroms Ra.
12. The transparent glass-ceramic/glass armor system according to claim 11, wherein the armor system has a V50/AD Figure of Merit of at least 150.
13. The transparent glass-ceramic/glass armor system according to claim 11, wherein the armor system has a V50/AD Figure of Merit of at least 160.

14. A transparent glass-ceramic/glass armor system, said system comprising:
 - a glass-ceramic ("GC") layer having a strike face and a bonding face, an anomalous glass backing layer bonded to the GC layer and a spall-catcher layer bonded to the glass layer furthest from the glass-ceramic layer;
 - wherein the backing glass consists essentially of a 100 wt% fused silica glass, and
 - wherein said transparent glass-ceramic/glass armor system has a V50 greater than 2950 ft/sec, and said backing glass layer has a surface with a roughness of roughness of less than 3 Angstroms Ra.
15. The transparent glass-ceramic/glass armor system according to claim 14, wherein the armor system has a V50/AD Figure of Merit of at least 160.
16. The transparent glass-ceramic/glass armor system according to claim 14, wherein the armor system has a V50/AD Figure of Merit of at least 180.

Figure 1

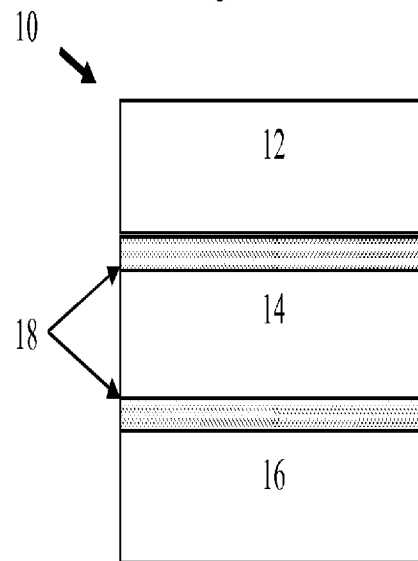


Figure 3

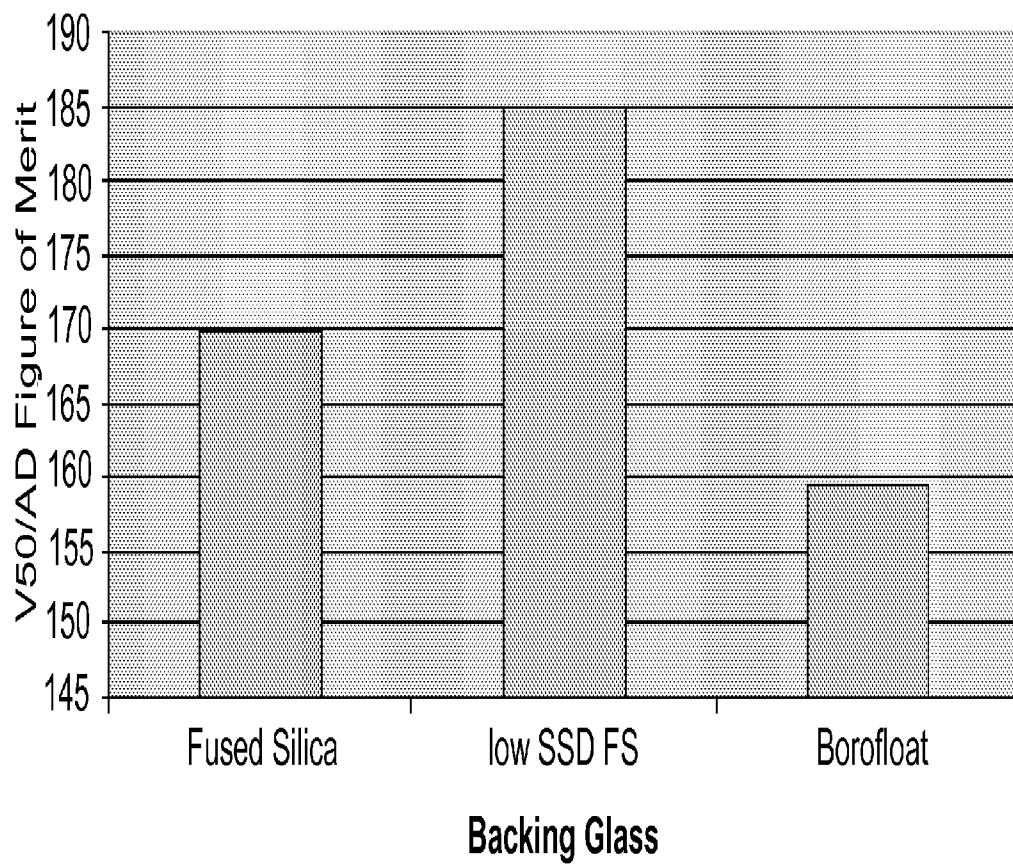


Figure 2

