A STUDY ON IMPACT RESISTANCE OF GLASS FIBRE REINFORCED VINYLESTER COMPOSITES AGAINST BALLISTIC PROJECTILES

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Abstract

Glass fibre reinforced vinylester laminates show very high impact resistance, the charpy impact strength measuring upto 576 kJ/m^2. Void-free laminates prepared from E-glass fibre-reinforcement and vinylester resin matrix combined with resin bonded alumina sheets as facing have been subjected to high velocity impact of 7.62 mm bullets fired from a distance of 10 meters. Glass fibre and Kevlar-29 fibre reinforced vinylester laminates with a thickness less than 10 mm (areal density ~14.24 kg/m^2) have been tested against 1.1g fragment simulated projectiles (FSP) in the form of steel balls and 9 mm carbine fire. The laminates thus tested withstood the bullets without any bulge at the back. The possible mechanism of the hyper velocity impact resistance of the FRP laminates has been discussed.

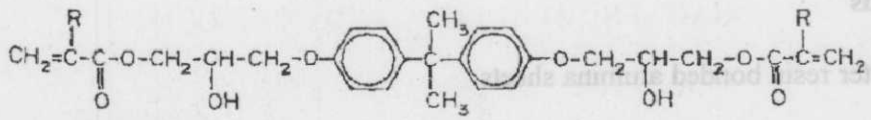
Introduction

Fibre reinforced plastics (FRPs) with ceramic facings are advanced materials being evaluated for their use in body armours against hypervelocity bullets. FRPs have a very high fracture toughness due to synergy in interaction of the constituent materials where the fibre-matrix interface plays an important role in absorbing impact energy. Ceramics exhibit hardness values much higher with Vickers Hardness Number (VHN) ranging from 2000 to 3000 than the conventional armour materials like steel (VHN of the hardest steel being 750) [1] and can offer higher protection levels by breaking the impacting bullets before penetration [2,3]. Another important advantage of these materials is their low density. Thus they can provide improved protection at reduced weights. This paper reports results of ballistic immunization tests of laminates made out of E-glass fibre and vinylester having resin bonded alumina as facing against 7.62 mm rifle fire. In addition, the authors have also evaluated E-glass and Kevlar-29 fibre reinforced vinylester laminates with a thickness less than 10 mm for ballistic immunization against 9 mm carbine fire. These types of laminates are being currently used in body armour to protect against casualties in ground battles [4].

Materials

Vinylesters

The divinylesters of diglycidylether of bisphenol A (VE of DGEBA, Structure I) were prepared by reacting diglycidylether of bisphenol A with acrylic acid or methacrylic acid in 1:2 molar ratio in the presence of benzyltrimethylammonium methoxide as the catalyst. The completion of the reaction was marked by disappearance of 915 cm^{-1} epoxide peak in the IR spectrum of the reaction mixture. It took about 1h at 110°C for acrylate resin and 3 h at 90°C for methacrylate resin for completion of the reaction. A small amount of hydroquinone inhibitor was added to the reaction mixture to prevent polymerization of the unsaturated acid and cross-linking of the vinylester formed. The detailed procedure is reported elsewhere [5].



R = H, Acrylate vinylester

R = CH_3, Methacrylate vinylester

STRUCTURE I, VE of DGEBA

The number average molecular weights of the acrylic and methacrylic acid based resins measured by vapour pressure osmometer (Herbert-Knauer) using 1,4-dioxane as the solvent were 524 and 550 respectively.

The vinylesters have been selected as matrix materials for two reasons. In the first instance, they can provide better structural integrity due to their superior wetting properties accruing from the pendant -OH groups and secondly they are tougher than any other thermoset resin [6,7].

E-glass and Kevlar-29 fibres

E-glass fibre woven rovings with plain weave were obtained from M/s Twiga India Ltd and Kevlar-29 fibre woven rovings (imported) were supplied by DMSRDE, Kanpur. The fibre specifications as supplied by the suppliers are given below.

Specifications of fibres

	E-glass	Kevlar 29
Average wt. (g/m^2)	360	480
End per 10 cm	61	68
Pick per 10 cm	55	66
Count of warp yarn (Tex)	305	330
Count of weft yarn (Tex)	305	330

Alumina

Alumina used was of indigeneous commercial grade obtained from the trade.

Methods

Vinylester resin bonded alumina sheets

Methacrylate vinylester resin was used as the binder for alumina to get a better solid loading in the final product. The resin mix contained 67 parts by weight of the resin dissolved in 33 parts by weight of styrene monomer. To this were added 1.5 ml of cobalt nephthenate accelerator per hundred parts of the resin and 1.5 ml of methylethylketoneperoxide (MEKP) catalyst per hundred parts of the resin with constant stirring to ensure thorough mixing. Alumina powder was then added to this mix slowly till no more solid could be accommodated into the resin. Thus a maximum solid loading of 60% alumina in the resin was obtained.

In order to make resin bonded alumina sheet a steel mould was prepared. A steel plate of 35 cm x 35 cm x 8 mm as a base plate, a cavity of 30 cm x 30 cm x 16 mm made by using a square frame of 16 mm thick steel rod and a top steel plate of 29.5 cm x 29.5 cm x 12 mm formed the mould. The internal mould surfaces were coated with wax as mould release agent and two layers of resin impregnated woven glass fibre rovings were placed in the mould. The mixture of resin and alumina prepared as described above was transferred to the mould cavity and properly spread. Over this were laid two layers of resin impregnated glass fibre. The upper steel plate was placed over the layout in the mould cavity which served as the mould plunger. The mould was placed on a 60 tonne hydraulic press maintained at 120 ± 1°C with the platens closed on the mould till the resin gelled. A pressure of 182 kg/cm^2 was applied with a temperature of 120 ± 1 °C for 30 minutes and maintained for further two hours after putting off the heaters. The moulded sheet of resin bonded alumina was removed from the mould and post cured at 100°C for about 1h.

E-glass fibre and Kevlar-29 fibre reinforced laminates.

E-glass fibre reinforced vinylester laminates with thickness varying from 4.3 mm to 30.5 mm and Kevlar-29 fibre reinforced vinylester laminates with thickness varying from 8 mm to 10 mm were made by the procedure reported earlier [8]. The method involved impregnating the required size glass or Kevlar fibre woven rovings with the resin system and stacking them to get the required thickness followed by compression at 120 ± 1° C and 100 kg/cm^2 in a hydraulic press.

Mechanical testing of laminates.

The Charpy impact and the interlaminar shear strength (ILSS) tests followed the procedures in BS-2872, Part 3, Method 351A:1977. The flexural strength and flexural modulus measurements were made according to BS-2782, Part 3, Method 335A:1978. Voidlessness of the laminates were tested by X-ray radiography.

Ballistic immunization tests of laminates

The ballistic immunization tests were carried out by firing bullets perpendicularly from a small arm weapon onto the target laminate which was secured firmly by a heavy duty steel clampstand assembly at a distance of 7 m or 10 m depending on whether the projectile is a 9 mm carbine bullet or a 7.62 mm rifle fired bullet respectively. The impact and residual velocities of the bullet (if it penetrates through the laminate) were determined from the measured travel times of the bullet by two electronic counters each connected to a pair of aluminium screen assemblies in front and at the back of the target laminate at known distances respectively.

Results and Discussion

The mechanical properties of the laminates are listed in Table 1.

As is evident from the table, the resin bonded alumina sheets exhibit very poor mechanical strength. Moreover, the GRP skins of the resin bonded alumina must have contributed to the values of parameters reported. The Charpy impact strength is higher for E-glass fibre laminates compared to that for Kevlar-29 fibre laminates. One of the values obtained for the Charpy impact strength of E-glass fibre-acrylate vinylester laminate was 576 kJ/m^2 which is higher than that for similar laminates using any other thermoset resin as matrix material. The lower Charpy impact strength of Kevlar fibre laminates may be due to the bigger diameter (0.011 mm) of the Kevlar fibres compared to that of E-glass fibres (0.0076 mm). Under high momentum impact, the fibre breaks at its weakest point inside the matrix and is pulled out of the matrix for complete failure. The thinner the diameter of the fibre better is the impact resistance due to reversible bending and delamination of the fibre in a composite [9]. Moreover a highly adherent and flexible matrix such as vinylester needs a very high fracture and debonding energy for complete failure of the composite [6]. This explains the outstanding impact strength of E-glass fibre reinforced vinylester laminates.

The results of ballistic immunization tests of the combination of vinylester resin bonded alumina sheet and E-glass fibre reinforced vinylester laminate against 7.62 mm rifle fire are tabulated in Table 2.

Table 3 shows results of similar tests with E-glass fibre reinforced acrylate VE laminate alone as the target. The percent velocity attenuation as the bullet pierced through the laminate has been plotted against their areal densities (weight per unit area) in Fig. 1. For the targets made out of the combination of E-glass fibre reinforced vinylester laminate with and without resin bonded alumina facing the relationship between the percent velocity attentuation and the areal density of the laminates is exponential. Similar relationship was also obtained in previous studies [8]. Fig. 1 also shows that the E-glass fibre reinforced laminate exhibits much superior ballistic resistance at the same areal density than its combination with resin bonded alumina as facing. Moreover the resin bonded alumina sheet alone attenuated the velocity of the bullet from a 7.62 mm rifle by only about 9%. This falls in line with the low Charpy impact and falling weight impact values for these sheets.

Specific energy absorbed (SEA) defined as the energy absorbed by the laminate per unit areal density as the bullet travels through the laminate is a better parameter for comparing ballistic resistance of different targets. In Fig. 2 the specific energy absorbed has been plotted against areal density. From the curves it is clear that at lower areal densities the combination is marginally better than E-glass fibre reinforced vinyl ester laminates. But at areal densities larger than 42 kg/m^2 the glass fibre laminates outweigh the combination in their ability to absorb energy under high velocity impact. One more conclusion that can be drawn from the curves of SEA versus areal densities is that laminates having larger areal densities show two different failure mechanisms under high velocity impact.

The data obtained on testing of E-glass fibre and Kevlar-29 fibre reinforced vinylester laminates against 9 mm carbine fire with impact velocity of 420 + 5 m/s indicated that the Kevlar laminates are superior to the glass fibre laminates in their ballistic resistance. Kevlar-29 fibre reinforced vinylester laminate with areal density of 12.28 kg/m^2 (9.71 mm thick) embedded all the bullets fired at it.

Conclusion

Improvement in the ballistic resistance against 7.62 mm rifle bullets of E-glass fibre reinforced vinylester laminate by incorporating resin bonded alumina facing could not be achieved. This may be due to low alumina percentage in the resin bonded sheet. Probably by use of sintered alumina or alumina fibre-aluminium-lithium composite facings the ballistic resistance of the system may be increased. However, all the laminates tested are good protective materials against 9 mm carbine fire.

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Table 1
Mechanical Properties of Laminates

Sl. No.	Laminate	Charpy impact kJ/m²*	Flexural Strength MPa	Flexural modulus GPa	Interlaminar shear strength MPa	Falling wt. impact Joules**
1	E-glass fibre + Acrylate VE	465.647	236.39	26.08	22.10	23.47
2	E-glass fibre +(Acrylate VE 50% + Methacrylate VE, 50%)	494.699	238.25	24.20	22.61	28.56
3	K-29 fibre + Acrylate VE	320.00	196.32	15.57	18.93	—
4	Methacrylate VE resin bonded alumina with GRP skins	174.81	37.76	5.57	4.54	15.34

* *Charpy impact velocity : 2.5 m/s, Striking energy : 85 Joules*

** *Total energy absorbed by the sample - Drop impact velocity : 2.06 m/s, Striking energy : 165 Joules*

Table 2
Results of ballistic immunization tests against 7.62mm rifle bullets
Target : Methacrylate VE alumina sheet (facing) + E-glass fibre reinforced acrylate VE laminate (backing)

Sl. No.	Thickness mm	Areal density kg/m²	Impact velocity m/s	Remaining velocity m/s	Velocity attenuation %	SEA J-m²/kg
1	21.5	35.975	843.5	754.2	10.59	18.75
2	23.0	49.083	839.8	712.0	15.22	19.09
3	33.0	63.014	832.6	656.6	21.14	19.66
4	37.0	74.400	853.1	549.0	35.65	27.08
5	42.5	94.480	837.7	172.0	79.42	33.62

Table 3
Results of ballistic immunization tests against 7.62mm rifle bullets
Target: E-glass fibre reinforced acrylate VE laminate

Sl. No.	Thickness mm	Areal density kg/m²	Impact velocity m/s	Remaining velocity m/s	Velocity attenuation %	SEA J-m²/kg
1	9.5	15.040	767.63	754.16	1.75	6.44
2	12.0	21.198	764.19	712.00	6.83	16.39
3	21.0	39.337	757.69	656.60	13.34	17.17
4	25.0	50.767	776.32	549.00	29.28	28.04
5	30.5	62.561	762.34	172.00	77.44	41.65

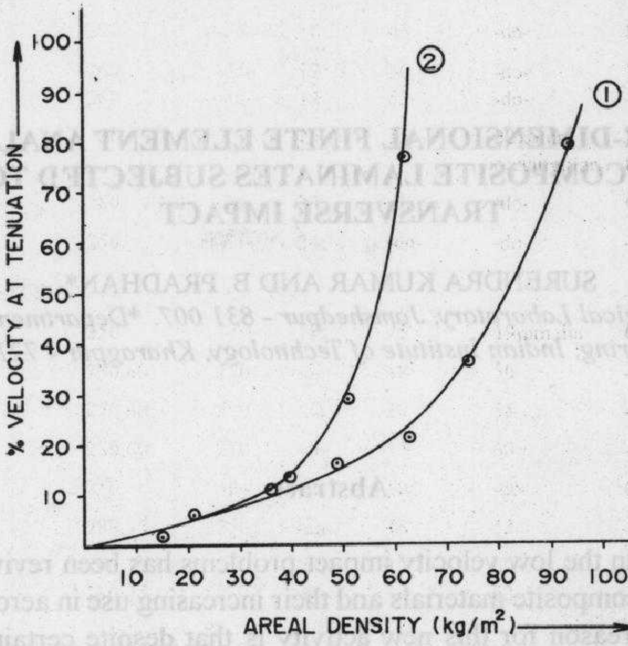

Fig. 1 - Percent velocity attenuation as a function of areal density of target laminates. 1) E-glass fibre-acrylate vinylester laminate with methacrylate vinylester bonded alumina sheet as facing. (2) E-glass fibre-acrylate vinylester laminate.

Fig. 2 -Specified energy absorebed (SEA) as a function of areal density of target laminates.1) E-glass fibre-acrylate vinylester laminate with methacrylate vinylester bonded alumina sheet as facing. (2) E-glass fibre-acrylate vinylester laminate.