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► To cite this version:

A. Zhuk, G. Kanel, A. Lash. Glass-epoxy composite behaviour under shock loading. Journal de Physique IV Proceedings, 1994, 04 (C8), pp.C8-403-C8-407. 10.1051/jp4:1994862 . jpa-00253422

HAL Id: jpa-00253422

<https://hal.science/jpa-00253422>

Submitted on 1 Jan 1994

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Glass-epoxy composite behaviour under shock loading

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Abstract: Shock compressibility and sound velocity in commercial fibre-glass at pressures up to 22GPa were studied using manganin gauges. Free surface wave profiles were measured by Doppler velocity interferometry at pressures of about 1GPa. Material spall strength and viscosity were evaluated.

1. INTRODUCTION

The dynamic response of composite materials to shock loading has been extensively studied because of the wide application of composites in rocket and space technology. Nevertheless there is a lack of experimental information concerning the spall strength of composite materials and their behaviour at moderate pulse pressures. Shock compressibility of epoxy-based composites with Al and graphite fibre fillers has been explored [1,2]. Experimental Hugoniot were found to be in good agreement with calculations based on the rule of mixtures. Shock front dispersion was detected in Al-epoxy composite [1]. Other authors [3-5] have investigated shock compressibility and spall strength of epoxy-based composites with glass fabric and cloth fillers. Spall strength values of 0.1 to 0.3GPa were close to the spall strength of the pure matrix material. On the other hand, Tohkem and Erlich [6] studied the fragmentation of epoxy-kevlar fibre composite and obtained a spall strength value of about 0.05GPa. In an investigation of epoxy-42 volume per cent. glass microballoons [7], Hugoniot and shock front structure were studied at 0.5 to 4.2GPa and the spall strength was found to be close to zero. Significant dispersion of the shock front was observed. The authors proposed that the dispersion was a result of the collapse of the pores and the crushing of the microballoons. H. Nahme et al. [8] investigated the dynamic behaviour of shock loaded FeO-SiO₂ composite material. The material was found to exhibit a low Hugoniot elastic limit, between 0.01 and 0.03GPa, and a spall strength of less than 0.01GPa. Microscopic and SEM examination of recovered samples showed that even at low impact velocities the material was damaged by local stresses which are caused by the internal structure of the material.

It is possible to conclude that there are at least two features to the behaviour of composite materials under shock loading: i) a significant scattering, from 500GPa to 0.3GPa, of spall strength

values; ii) a complex structure of the shock front. The aim of the present study was to measure the dynamic compressibility, sound velocity and spall strength of a commercial plain-weave glass-epoxy composite and to explore its shock front structure.

2. EXPERIMENTAL

Commercial plain-weave fibre-glass KAST-V (Soviet standard 102-92-74) consisting of epoxy resin VBF-1 matrix and glass fabric filler (Soviet standard 19170-73) was studied. Samples had an initial density of 1.78 to 1.80g/cm³. The loading direction was normal to the plane of the fabric layers.

Shock compressibility and sound speed velocity at pressures of 5 - 22 GPa were measured using manganin gauges [9]. The samples were loaded by the impact of Al plates through an Al base plate. Plates were accelerated by high explosive generators. The first gauge was mounted in the interface between the base plate and the sample and another gauge was installed in the internal cross section of the sample. In order to decrease the influence of the sample roughness, the gauges were separated from the sample by teflon films of a thickness less than 0.09mm. Free surface velocity profiles at pressures of 0.8 - 1.2GPa were measured by means of the Doppler velocity interferometer - VISAR technique [10]. The samples were loaded by the impact of Al plates accelerated by a powder gun. To reflect the VISAR beam, 40 μ m thick Al foil was glued with epoxy adhesive to the free surface of the sample. Samples loaded at pressures from 0.8 to 7.6GPa were recovered. Experimental details are listed in Table I.

TABLE I Details of Experimental Set-Up

(D_i, D_s - impactor and screen thickness, respectively; W - impactor velocity; ℓ - distance between manganin gauges)

D _i (mm)	D _s (mm)	ℓ (mm)	W (km/s)
4	-	-	0.2
6.8	-	-	0.3
4	3.95	4.75	1.5
10	3.95	8.28	2.5
3.9	3.95	4.75	3.8

3. RESULTS

Typical pressure profiles are presented in fig. 1. Elastic precursor and elastic release waves were not observed. Since both profiles exhibit small rises in the pressure plateau, it is believed that the rise is not concerned with a relaxation process in the material but is the result of deformation of the gauges. Free surface velocity profiles were measured for different impactor thicknesses. Shock wave attenuation was observed at small impactor thicknesses. At impactor thicknesses from 2.5 to 6.8mm the free surface velocity did not change under uniform loading conditions. Free surface velocity profiles are shown in fig. 2. A spall pulse is apparently not observed. The shock fronts exhibit an unusually long rise time of about 250ns. Shock wave parameters and sound velocity data are presented in Table II and fig. 3.

4. DISCUSSION

To calculate specific volume and loading-unloading trajectories for fibre-glass we used the pressure-

Fig. 1 Pressure vs. time profiles at 13.5GPa

Fig. 2 Free surface velocity profiles at different impact velocities

(solid line - 320m/s;

dashed line - 220m/s, impactor thickness, 4mm;

asterisks - 220m/s, impactor thickness, 1.3mm)

TABLE II Shock Wave Parameters

(U_s - shock wave velocity; U_p - particle velocity; P - pressure; V - specific volume; C - Eulerian sound velocity)

W (km/s)	P (GPa)	U _s (km/s)	U _p (km/s)	C (km/s)	V (cm ³ /g)
0.2	0.9	3.07	0.16	-	0.532
0.3	1.3	3.22	0.23	-	0.522
1.5	7.6	4.00	1.06	4.65	0.411
2.5	13.5	4.57	1.66	5.73	0.357
3.9	21.6	5.67	2.13	6.96	0.349

time profiles and the simple wave approximation:

$$dV = -dP/(R_0)^2 a^2$$

where dV and dP are volume and pressure increments, R_0 is the initial material density and a is the Lagrangian phase velocity of perturbation. The release adiabat lies below the Hugoniot. It is the evidence that significant deviatoric stresses exist in the material during the loading-unloading cycle.

If the rise time of the shock front and the Hugoniot for the material are known one may evaluate the shear viscosity, $\eta = T/\dot{\epsilon}$, where T , the shear stress in a steady shock wave, is determined from the deviation between the straight line connecting the initial and final states of the material and the Hugoniot and $\dot{\epsilon}$, the deformation rate, was determined from the equation, $\dot{\epsilon} = [\ln(V/V_0)]/t$, where

Fig. 3 Shock wave velocity (squares) and sound velocity (triangles) vs. particle velocity

t is the rise time and $V_0 = 1/R_0$. We take the shock compressibility data as an approximation to the Hugoniot for fibre-glass. The viscosity appeared to be about $100\text{Pa}\cdot\text{s}$ at a deformation rate of about $0.24 \times 10^6 \text{s}^{-1}$. The fibre-glass shear viscosity is higher than that for metals but lower than the usual viscosity of polymers [11].

Examination of recovered samples showed that fragmentation mainly occurs in matrix layers. Samples recovered after shock loading at pressures less than 1.5GPa consisted of undamaged glass layers separated by strongly damaged epoxy layers. Since a spall pulse was apparently not observed we suggest that the spall strength of fibre-glass KAST-V is less than the measurement resolution. Nevertheless it is possible to evaluate the upper limit of the dynamic tensile strength of the material. The velocity measurement resolution was about $7 - 10\text{m/s}$. We used the known relation for spall strength, S , and free surface velocity change, (dW) ,

$$S = \frac{1}{2}C_0R_0(dW)$$

and assume that the upper limit on the magnitude of the spall pulse corresponds to the resolution of the velocity measurement, i.e. we take $(dW) = 10\text{m/s}$. The spall strength evaluated in this way appeared to be 0.02GPa . The spall strength value for fibre-glass KAST-V is in good agreement with other data [6,8] and with results of static tests [12], but is significantly lower than the spall strength determined in [5]. The final state of the recovered samples in [5] was examined and it is clear that the formation of the macrocracks observed in these samples demands a higher tensile stress and more time than are required for the initiation of failure.

We propose that the low spall strength of fibre-glass, as well as the strong shock front dispersion, is a result of wave reflection between components with different shock impedances and of matrix destruction during compression. Destruction is initiated by shear stresses arising at the uneven contact surface between the epoxy matrix and the coarse-weave glass fabric [8]. In spite of the planar structure of KAST-V, it behaves as a composite with a random distribution of filler particles [7] and does not exhibit the multi-step structure observed in the case of model planar composites [13].

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