SHOCK-WAVE FAILURE OF A WOUND GLASS-FIBER-REINFORCED PLASTIC IN DIFFERENT DIRECTIONS

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Glass-fiber-reinforced plastics are currently the subject of intensive research and development, and the region of application of these materials is expanding significantly [1, 2]. Glass-plastics have a whole range of valuable properties, especially high specific mechanical characteristics. Meanwhile, the possibilities of altering their fibrous structure make it possible to vary the properties of the composite within a fairly broad range. Ivanov et al. [2] and Syrunin et al. [3] showed the promise of using these materials in structures subjected to impulsive (explosive) loads. However, the experimental data on the dynamic strength of glass-plastics under momentary loads (10^{-3}-10^{-7} sec) is clearly inadequate [2-5]. It should also be noted that there is a large number of different types of glass-plastics and that these materials have a wide range of static and dynamic characteristis [1, 2, 6]. In the present investigation, we examine the strength and cleavage of a widely used glass-plastic in different directions. The material is based on high-modulus magnesium—alumosilicate fibers and epoxy binder. It will be studied under shock-wave loading (loading time 10^{-6} sec).

In the anisotropic material, we determined the limiting tensile stresses in directions perpendicular to the reinforcement planes σ_{t_z} and in one direction parallel to these planes σ_{t_x} (Fig. 1).

Both the specimens and the strikers were cut from a cylindrical shell with a radius of 1 m. The shell was formed by the alternate winding of double spiral ($\varphi = 40 \pm 5°$) and annular ($\varphi = 90°$) rovings of a material based on glass fibers. The ratio of the thicknesses of these strips was 1:1. During the winding operation, the shell was impregnated with binder ÉDT-10 and then dried with the application of heat. The resulting glass-plastic specimens (targets) had the form of disks 30 mm in diameter and 10 mm thick. The strikers were made of the same material and had a thickness of 5 mm. The density of the glass-plastic was determined by hydrostatic weighing ($\rho = 1850 \pm 25$ kg/m^3). The orientations of the reinforcement planes in the specimens were parallel (type 1 - Fig. 1a) and perpendicular (type 2 - Fig. 1b) the direction of the tensile stresses, while they were perpendicular in the striker (similar to the type 2 specimens). The plane collision of the striker and the target took place on a pneumatic impact unit with a bore of 76 mm. We used electrocontact transducers to record the velocity of the striker W and its approach to the target.

The velocity of the shock wave in the material was determined for two directions (D_x, D_z) in special experiments conducted with piezoelectric transducers. When the striker collided with the specimen, a shock wave was propagated in the latter* and compressed it. To determine the velocity of the shock wave, two sensors were placed at opposite ends of the specimen and D_x and D_z were calculated from the time shift of the signals for a known sensor spacing.

Failure during shock loading (cleavage phenomena) develops with the attainment of the critical tensile stresses σ_t in the plane of contact of rarefaction waves. There are presently no direct methods of measuring these stresses during cleavage. The simplest approximate method of determining the threshold value of loading pressure, corresponding to the value of σ_t that develops in a material during the collision of two bodies, is the method

*A compression wave is realized at low collision velocities. In the present study, we make no distinction between such waves and shock waves.

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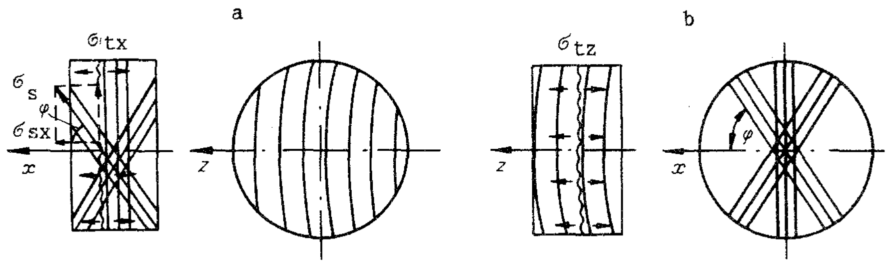

Fig. 1

of acoustic approximation. This method can be used for theoretical estimates only in the case of relatively low collision velocities ($W \ll D$), as is realized in the collision of the two bodies made of glass-plastic. The tensile stresses σ_t in the cleavage plane (plane of fracture of the material) and the total time over which they act were determined from the formulas

$$\sigma_t = \rho D_1 u,\ u = W/(1 + D_1/D_2),\ t_t = 2\delta/D_1,$$

where D_1 and D_2 are the velocities of the shock waves in the specimen; δ is the thickness of the cleaved plate; u is mass velocity. These relations were obtained for the case when the striker and the target are made of materials having the same density.

In preliminary experiments, we determined the velocities of the compression waves in the glass-plastic: $D_z = (2790 \pm 55)$ m/sec; $D_x = (4230 \pm 105)$ m/sec. The change in $D_x(u)$ and $D_z(u)$ within the investigated range of collision velocities was ignored [4]. With allowance for the characteristics of the fibers and binder [1, 3, 6] the theoretical estimates of sonic velocities c_z, c_x from the elastic constants of the glass-plastic [3, 5] were close to the measured values D_z, D_x and were 2835 and 3870 m/sec, respectively. Table 1 shows the results of tests of the glass-plastic under shock loading and tension in two directions z and x ($t_t = 3.58 \cdot 10^{-6}$ sec).

The limiting tensile stresses, corresponding to microscopic cleavage of the wound glass-plastic along and across the lane of the reinforcing layers, have the values σ_{t_z} = 0.2-0.24 GPa and σ_{t_x} = 1.0-1.14 GPa. This means that the strength of the glass-plastic in the z and x directions differs by a factor of 4.5-5. The mean values of δ (see Table 1) for the specimens with the fiber layers located lengthwise and crosswise differ by a factor of approximately 1.5. This finding is consistent with the observed difference in the velocities D_z and D_x.

Astanin et al. [4] and Golubev et al. [5] studied the analogous parameters for a pressed glass-plastic with a different base. Comparison of our data with the data in [4, 5] shows that the threshold values of loading pressure corresponding to microscopic interlaminar cleavage coincides for different types of glass-plastic. Thus, the interlaminar strength of a glass-plastic under shock loading is determined mainly by the strength of the binder. To approximately compare the interlaminar dynamic and static strengths of the glass-plastic we studied, we will compare the values of σ_{t_z} for cleavage with the strength of the binder in tension σ_t'. The static strength of the epoxy resin is σ_t' = 40-55 MPa [6]. Thus, if we adopt the hypothesis that the strength of the material in this direction is determined by the strength of the binder, the dynamic interlaminar strength of the glass-plastic can be increased to a level 4-6 times greater than the static strength (the increase is by a factor of 1.3-2, if conditions are corrected for the same stress state).

While the interlaminar strength of the glass-plastic is determined mainly by the binder, its longitudinal strength in the x direction is determined to a greater extent by the strength of the fibrous mechanical base. To estimate the stresses in the fiber layers which comprise only about 35% of the area and fracture surface of the specimen but take up most of the loading pressure - we will use empirical values of the critical stresses σ_{t_x}. The rest of the specimen surface is occupied by the polymer binder (~30%), and the layers are oriented to the fracture surface in such a way that their strength in the z direction is commensurate with the interlaminar strength of the glass-plastic. Using the mixture

TABLE 1

Type of specimen	Number of test	W, m/sec	σ_t, MPa	δ, mm	Condition of cleaved clones
2 (z)	1	72,2	0,186	—	Did not separate
	2	76,7	0,198	—	" "
	3	93,8	0,242	5,0	Separated partially
	4	108,4	0,277	3,2	" "
	5	113,5	0,293	4,8	Separated completely
	6	115,0	0,297	4,4	" "
	7	126,2	0,326	5,1	" "
	8	134,1	0,346	5,0	" "
	9	136,9	0,353	5,1	" "
	10	156,5	4,04	5,1	" "
1 (x)	1	179,5	0,558	—	Did not separate
	2	253,4	0,788	—	" "
	3	326,5	1,016	—	" "
	4	366,0	1,138	7,5	Separated partially
	5	370,0	1,151	7,5	" "
	6	387,5	1,205	7,4	Separated completely
	7	405,6	1,262	7,1	" "
	8	410,0	1,275	7,4	" "

rule, we write an expression to calculate these stresses σ_{s_x} in the form $\sigma_{t_x} = 0.35\sigma_{s_x} + 0.6$-$5\sigma_{t_z}$, where $\sigma_{s_x} = 2.8$ GPa.

With the condition that the fibers rupture in the tensile plane without being displaced (the angle φ = const), it follows from Fig. 1a that $\sigma_s = \sigma_{s_x}/\cos^2\varphi = 4.8$ GPa. This corresponds to a limiting fiber strain ~5%. The ultimate strength of the elementary glass fibers in static tension $\sigma_s' = 3$-4.2 GPa [1, 6], i.e., it is ~1.3 times lower than the strength in high-rate tension.

This means that the strength characteristics of the anisotropic material depend not only on the strength and structure of the reinforcement, but also on the loading conditions [3]. The values of σ_{t_z} and σ_{t_x} found above for the glass-plastic make it possible to determine the unit (per unit surface) work of rupture of the material λ in two directions (x, z) in accordance with the expression [7, 8]

$$\lambda = \sigma_t^2\delta/(2\beta\rho c^2), \qquad (1)$$

where $\beta = 1$ is for a square wave realized in the collision of two plates.

The critical breaking stresses of the glass-plastic in the z and x directions $\bar{\sigma}_{t_z} = 0.22$ GPa, $\bar{\sigma}_{t_x} = 1.12$ GPa, while the corresponding thicknesses of the cleaved layers $\delta_z = 5\cdot10^{-3}$ m, $\delta_x = 7.5\cdot10^{-3}$ m. At $\rho = 1850$ kg/m^3 and $c_{x,z} = D_{x,z}$, we find that $\lambda_z = 8.5\cdot10^3$ J/m^2 and $\lambda_x = 142\cdot10^3$ J/m^2, i.e., there is a difference of more than 15-fold. The value of λ_z is close to the values for plexiglas [9], while λ_x is comparable to λ for a number of metals (such as quenched steel [8]). The value found for unit work $\lambda_x = 142\cdot10^3$ J/m^2 for the glass-plastic nearly coincides with the analogous literature value 2γ [7]. The quantity $\gamma = 60.5\cdot10^3$ J/m^2 is the surface fracture energy for a unidirectional glass-plastic with a crack perpendicular to the fibers [10].

Strictly speaking, the value found for λ should be regarded as an effective value. In fact, Eq. (1) was obtained for a homogeneous material under the assumption that its length in the direction perpendicular to the shock front is infinite. This condition is not met in the case of the x direction. The decisive role is played by the glass fibers, with no manifestation of a scale effect when they rupture (σ_t is independent of δ) [2]. As was shown above, ruptures of the glass fibers begin at σ_{t_x} corresponding to $\varepsilon_t = 5$%, while the value of λ for the glass is only 92 J/m^2 [11]. With allowance for this, $\lambda_x = 5.56\cdot10^3$ J/m^2. The latter value is even less than λ_z.

It is also very interesting and of practical importance to study the so-called "precleavage" stage in glass-plastics. The first microcracks begin to appear during this stage [4, 5]. We compared macrostructural representations of sections from specimens subjected to different levels of loading. Figure 2a and b (W = 72.2 and 93.8 m/sec) and Fig. 3 (W = 366 m/sec) show the form of longitudinal sections of specimens (magnified by 50x) loaded by impact at high velocities. It can be seen from Fig. 2a that the fracture centers are defects present in the structure of the material. The preferred direction of the cracks is perpendicular to the impact direction. However, these small cracks do not yet coalesce, so that the specimen does not yet undergo macroscopic fracture (separation into parts). The loading (stress) level which nucleates cracks can be considered the critical stress for the

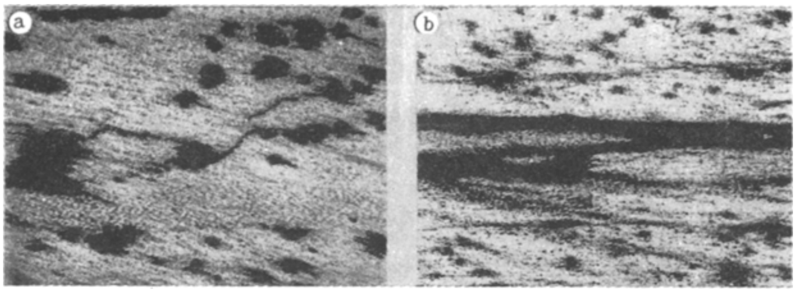

Fig. 2

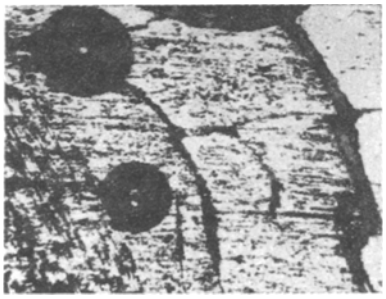

Fig. 3

material. With an increase in load, the cracks grow and coalesce into a main crack (Fig. 2b and Fig. 3). Macroscopic fracture of the specimen takes place, i.e., cleavage occurs.

The experimental results presented here are of interest in the design of structures made of glass-fiber-reinforced plastics that are subjected in service to intensive and instantaneous (impact) loads.

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