PROPAGATION OF SHOCK WAVES IN FOAMED POLYSTYRENE

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With the shock compression of polystyrene in the region of pressures less than 1 GPa, it is not possible to adopt the usual scheme of the shock compression of porous substances, assuming that, up to a value of the density corresponding to the density of the solid material (for polystyrene, this density is equal to 1046 kg/m^3), the compression takes place without resistance. A typical diagram of the shock compression of foamed polystyrene [1, 2] corresponds in form to the diagram obtained with quasistatic compression, shown in Fig. 1. The sector of elastic deformation OA is characterized by a linear dependence of the pressure on the deformation; the small sector of a sharp point of inflection of the diagram in the proximity of the point A corresponds to the yield point. The sector AB of a weak dependence of the pressure on the deformation corresponds to plastic deformation with a certain amount of hardening. With further deformation, there is a sharp rise in the pressure with compression up to a density close to the density of the solid material.

Consequently, the shock compression of foamed polystyrene should be accompanied by the propagation of two waves over a sample of the system: a primary shock wave (SW) with a constant pressure for a given density of the sample and a constant velocity, and a following wave of plastic compression, with parameters varying with the time. The velocity of the shock wave is usually assumed equal to the rate of propagation of the longitudinal vibrations, determined by an ultrasonic method [1, 2]. In the literature there are no direct measurements of the pressure in shock waves in foamed polystyrene, and measurements of the yield point with dynamic compression, without taking account of the wavy character of the deformation, give contradictory results. Thus, in [1-3], it is asserted that the dynamic yield point rises by more than 1.5 times in comparison with the static yield point; in [4, 5], the practically complete absence of dynamic hardening is shown. Analogous contradictions can be found also in data for foamed polyurethane, which is close to foamed polystyrene in its mechanical properties.

The present article gives the results of direct investigations of the structure and parameters of a compression shock wave (pressure, wave and mass velocity) with the shock loading of foamed polystyrene.

The investigation was made on samples of PS-1 (FPS) polystyrene. With the aim of reducing the inhomogeneity of the density of the samples, each of them was cut from disks with a diameter of 180 mm and a thickness of 10 mm, differing from the nominal density of the sample by no more than 10 kg/m^3. The nominal density of the investigated samples lay within the range 100...580 kg/m^3.

The sample was mounted on a solid steel base. Shock loading was effected by a steel plate, i.e., a striker, accelerated by the explosion of a charge of explosive. The initial velocity of the striker was varied within the limits 40...90 m/sec. The steel striker and the base were regarded as rigid bodies, since the acoustical rigidity of steel is an order of magnitude greater than the acoustical rigidity of polystyrene.

A piezoquartz pressure pickup with a diameter of 12 mm and a height of 3.2 mm was used to measure the pressure and to note the time of arrival of the shock wave. The error in determination of the value of the pressure does not exceed 15%; the fall of the front of the rectangular pulse does not exceed 1 μsec [6]. The pressure pickups were installed in the sample at different distances from the loaded surface, which made it possible to follow the changes in the parameters of the shock wave with its movement over the sample. A typical oscillogram of the signal of a pressure pickup is shown in Fig. 2. The time of arrival and the pressure in the shock wave were determined in accordance with the scheme of Fig. 3, used,

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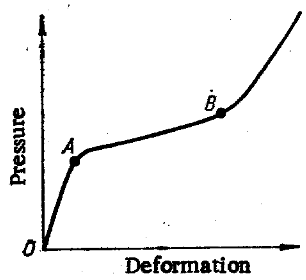

Fig. 1

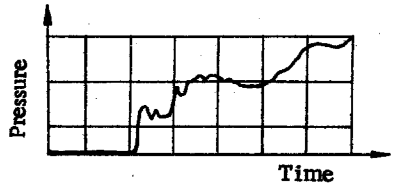

Fig. 2

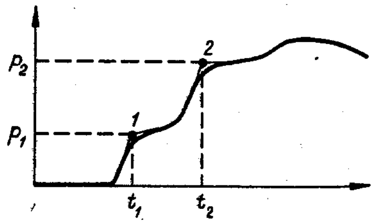

Fig. 3

specifically, in [7]. The subscript 1 in Fig. 3 relates to the primary shock wave; 2, etc., to the second and succeeding compression waves.

The velocity of the free surface of the sample was determined in special experiments by the method of a capacitance pickup [8]. For the conduct of these measurements, the surface of the sample was covered by a thin layer of copper. The mass velocity in the first shock wave was taken equal to half the velocity of the free surface.

A study of the structure of the shock wave showed the presence in FPS of two stationary shock waves, behind which follows a wave of plastic compression (see Fig. 2). With the motion of the shock waves over the sample, their amplitude and wave velocity remain unchanged and depend only on the relative density of the FPS, defined as the ratio of the density of the sample of FPS to the density of polystyrene.

The results of the measurements are given in Table 1, where ρ is the density of FPS; c is the velocity of the propagation of supersonic longitudinal vibrations; U_1, U_2 are the wave numbers of the first and second shock waves, respectively; p_1, p_2 is the pressure in the first and second shock waves, respectively; u_1 is the mass velocity in the first shock wave.

An analysis of the results showed that the dependence of the parameters of the first and second shock waves and the speed of sound in FPS on its relative density is best described by stepwise functions.

The rate of propagation of longitudinal ultrasonic vibrations c is described by the relationship

$$c = Ad^k,$$

where d is the relative density ($d = \rho/\rho_0$); $A = 1850 \pm 40$ m/sec; $k = 0.20 \pm 0.02$. Here and in what follows the parameters of the dependence are evaluated by the method of least squares, and the value of the error is evaluated by the standard deviation. The limiting value of $c = A$ with $d = 1$ is in good agreement with value of the rate of propagation of longitudinal vibrations in a rod of polyatyrene, 1880 m/sec [9]. How an interpretation of the function d^k as a rise in the path of the propagation of the ultrasonic vibrations as a result of an increase in the porosity of the sample must be approached with caution, since an appreciable effect on the rate of propagation of sound (as well as on many other mechanical parameters) can be exerted by the well-known phenomenon of the plasticizing of polystyrene by the products of the decomposition of the pore-forming agent [10].

The dependence for the rate of propagation of the first shock wave has the form

$$U_1 = Bd^l,$$

where $B = 1170 \pm 50$ m/sec; $l = 0.34 \pm 0.02$.

TABLE 1

ρ, kg/m^3	c, m/sec	U_1, m/sec	p_1, MPa	u_1, m/sec	U_2, m/sec	p_2, MPa
100	1030					
100		460—610				
110	1240—1250					
130		560	1,3		180	2,7
130		600	1,6		190	2,7
140		610	1,9			
140		620				
150		570	2,3			
160		620	2,9		280	3,3
200	1240					
210		650				
280	1430—1470					
290		710				
300				32—35		
310	1380					
340		820	8,8		370	12,7
340		840	9,0			
340		830	8,6			
350		820	8,4		400	15,7
380	1525—1540					
390	1410					
400				32—41		
550		1020	22,0			
550		860	20,4		630	32,4
560		1020	21,4			
560		870	22,8		660	35,3
580		900	21,2			
580	1640—1670					

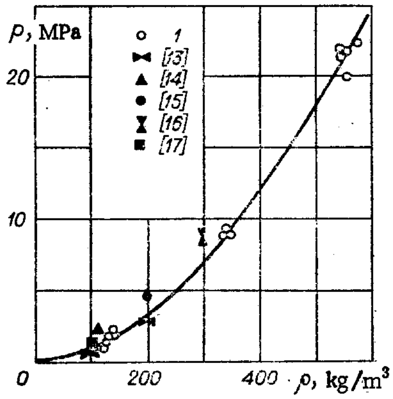

Fig. 4

The limiting value $U_1 = B$ with $d = 1$ is in good agreement with the value of the rate of propagation of ultrasonic shear vibrations in polystyrene 1143 ± 11 m/sec [11], and it can be postulated that, in the first shock wave, the deformaton of the walls of the cells in FPS has a bending character. A similar character of the deformation is observed with an investigation of FPS with a content of the polymer of $\leq 20\%$, using a static method [12].

As can be seen from the relation presented, with a change of the relative density of FPS in the range 0.11...0.56, the velocity of the first shock wave is 1.5-2 times less than the rate of propagation of longitudinal ultrasonic vibrations.

The pressure in the first shock wave is described by the relationship

$$p_1 = Ed^m,$$

where $E = 69.0 \pm 2.6$ MPa; $m = 1.82 \pm 0.03$.

Here it must also be taken into consideration that the function d^m describes not only the change in the effective cross section of the polymer with a change in the density, but also the decrease in the strength of the polymer due to the plasticizing action of the products of the decomposition of the pore-forming agent.

The pressure in the first shock wave is in good agreement with the results of measurement of the quasistatic yield point of FPS [13-17] by the standard method [10] (Fig. 4, points 1).

It can be noted that the rise in the dynamic yield point, observed in [1, 2], is completely explained by the fact that the authors of the cited communications as the velocity of the first shock wave used the velocities of the longitudinal ultrasonic vibrations.

The values of the mass velocity, obtained from the velocity of the free surface, are in excellent agreement with values evaluated from the parameters of a shock wave $u_1 = p_1/\rho U_1$ and c given in [2], obtained by a magnetoelectric method.

The presence of a second stationary shock wave in FPS with large velocities of the striker was unexpected. The velocity of the second shock wave depends on the relative density of FPS in accordance with a linear law, and approaches the value of the velocity of the transverse vibrations with $d \to 1$. The pressure in the second shock wave depends on d according to a parabolic law and practically coincides with the dependence, obtained by the authors, of the quasistatic yield point of FPS p_{20} with a relative deformation described by the relationship

$$p_{20} = Fd^n,$$

where $F = 116.1 \pm 3.3$ MPa; $n = 1.98 \pm 0.03$.

The presence of two stationary shock waves means the simultaneous existence of two yield points in FPS, known earlier from different compression conditions, with a complex deformation state and with one-dimensional deformation.

An analogous complex structure of a shock wave with two stationary waves and a wave of plastic compression in sintered copper was observed in [18], an analysis of whose results shows that the velocity of the second shock wave in sintered copper, as in FPS, is described by a linear function of the relative density and, with $d \to 1$, the velocity of the second shock wave tends toward the velocity of the propagation of shear vibrations in copper.

The above-indicated character of the dependence of the pressure and the wave velocity in the second shock wave, determined from the relationship $u_2 = p_2/\rho U_2$, is found to be independent of the relative density and is equal to approximately 90 m/sec.

It must be noted that reliable recording of the second shock wave in FPS is possible only with large thicknesses of the samples and comparatively small (of the order of 90 m/sec) velocities of the striker. Under the experimental conditions of [2], with velocities of the shock of 150-800 m/sec and thicknesses of the samples of 0.6-1.2 cm, the resolution of the second shock wave and the succeeding compression wave is practically impossible.

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