EFFECT OF CRITICAL SHEAR STRESSES BEHIND THE FRONT OF A SHOCK WAVE ON THE FORMATION OF FRAGMENTS

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In calculations of the interaction between rarefaction waves leading to breakdown of the material (fragmentation) a hydrodynamic equation of state is generally used. Such calculations are required, for example, with determination of the value of the fragmentation stresses by a calculational–experimental method over the thickness of the forming rear fragment in the sample. At the same time, from experimental work [1-3] it follows that, the region of pressures up to ≈1 Mbar, the behavior of many metals differs considerably from hydrodynamic: The critical shear stresses behind the front of a compression shock wave, determining the amplitude of the elastic unloading wave, can have an appreciable effect on the character of the flow forming (for example, the so-called "nonhydrodynamic" attenuation of shock waves). The value of the critical shear stress σ_* for metals depends on the pressure in the shock wave and reaches a value of ~100 kbar. Therefore, it is of interest to consider the formation of fragments taking account of the effect of shear stresses behind the front of the shock wave.

Let us consider the simplest case of the formation of a fragment with the impact of a plate-striker on a sample (the striker and the sample are made of the same material). The scheme of the interaction between unloading waves is shown in Fig. 1 in the coordinates x–t (path–time) and in Fig. 2 in the coordinates p–u (pressure–mass velocity). The points designated by numbers in Fig. 2 (in p–u coordinates) determine the state of the substance in regions of the flow in the plane x–t (Fig. 1) having the same numerical designation.

With the reflection of compression shock waves from the free surfaces of the striker and the sample, unloading of the substance from the state 1 takes place first in elastic 1–2 and 1–4, and then in plastic 2–3 and 4–5, rarefaction waves [the designation 1–2 corresponds to a wave converting the material from state 1 to state 2 (see Fig. 2), corresponding to regions 1 and 2 (see Fig. 1), etc.].

In the case where the unloading shock wave 1–2 from the side of the striker does not overtake the compression wave in the sample, with intersection of the shock waves 1–2 and 1–4, the material is unloaded in the

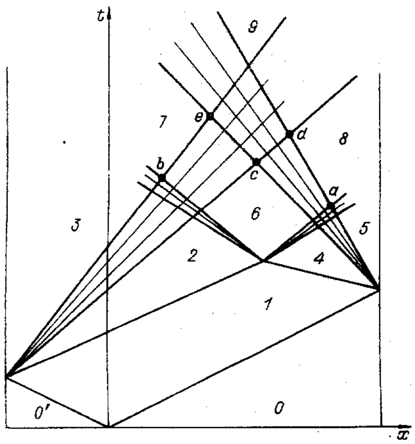

Fig. 1

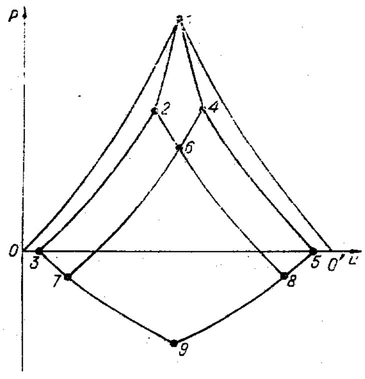

Fig. 2

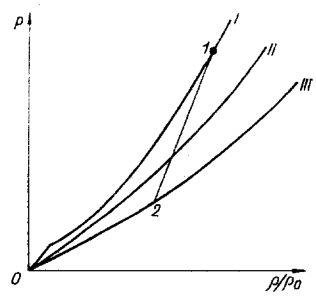

Fig. 3

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TABLE 1

h	t_a	x_a	t_b	x_b	t_c	x_c	t_d	x_d	t_e	x_e	Δt_1	Δt_2
$p = 100$ $\Delta p = -15{,}7$ $p_a = 45{,}6$ $p_{max} = -66{,}7$												
2	0,452	1,450	0,528	0,623	0,484	1,032	0,514	1,179	0,549	0,715	0,124	0,042
4	0,702	3,798	0,931	2,421	0,807	3,096	0,834	3,227	0,939	2,455	0,264	0,014
$p = 200$ $\Delta p = -21{,}3$ $p_a = 112$ $p_{max} = -113{,}5$												
2	0,405	1,509	0,491	0,532	0,414	1,090	0,453	1,304	0,506	0,598	0,096	0,030
3	0,512	2,692	0,683	1,390	0,552	2,180	0,587	2,372	0,693	1,431	0,150	0,020
4	0,619	3,875	0,875	2,247	0,690	3,270	0,720	3,440	0,879	2,264	0,202	0,008
$p = 300$ $\Delta p = -24$ $p_a = 185$ $p_{max} = -149$												
2	0,372	1,552	0,464	0,465	0,370	1,129	0,413	1,379	0,476	0,518	0,082	0,024
3	0,466	2,742	0,649	1,293	0,492	2,257	0,529	2,471	0,656	1,323	0,126	0,014
$p = 400$ $\Delta p = -26$ $p_a = 262$ $p_{max} = -178$												
2	0,344	1,596	0,442	0,411	0,338	1,157	0,383	1,432	0,453	0,458	0,077	0,022
3	0,427	2,797	0,622	1,218	0,451	2,314	0,487	2,540	0,627	1,241	0,120	0,010

TABLE 2

h	t_a	x_a	t_b	x_b	t_c	x_c	t_d	x_d	t_e	x_e	Δt_1	Δt_2
$p = 100$ $\Delta p = -27$ $p_a = 22$ $p_{max} = -74$												
2	0,664	1,316	0,736	0,708	0,713	0,986	0,738	1,071	0,766	0,805	0,148	0,060
4	1,058	3,541	1,275	2,528	1,188	2,957	1,211	3,037	1,295	2,594	0,306	0,040
6	1,452	5,768	1,813	4,347	1,664	4,929	1,685	5,002	1,824	4,382	0,466	0,022
$p = 200$ $\Delta p = -39$ $p_a = 70$ $p_{max} = -132$												
2	0,610	1,386	0,698	0,635	0,634	1,029	0,674	1,176	0,722	0,714	0,128	0,048
5	1,132	4,793	1,483	3,290	1,268	4,118	1,301	4,241	1,491	3,317	0,238	0,016
$p = 300$ $\Delta p = -43$ $p_a = 138$ $p_{max} = -200$												
2	0,566	1,449	0,666	0,573	0,576	1,065	0,626	1,255	0,687	0,642	0,120	0,042
4	0,876	3,762	1,178	2,304	0,961	3,195	1,001	3,355	1,187	2,333	0,250	0,018

plastic waves 2–6 and 4–6 to some pressure characterized by the point 6 (see Fig. 2). Then, with interaction between the plastic waves 2–6, 2–3 and 4–6, 4–5, there are two regions 7 and 8 with a negative pressure, determined by the amplitude of the unloading shock wave, i.e., by the value of the critical shear stresses. After this, with interaction of the waves 6–7 and 6–8, there arises a region of maximal negative stresses, in which, as is usually assumed, the breakdown of the material takes place.

Thus, up to the start of the action of the maximal elongational stresses, determined by the amplitude of the compression shock waves, in two cross sections of the sample, elongational stresses act for a certain period of time; the value of these stresses is determined by the value of the critical shear stresses with a given pressure in the compression shock wave, i.e., it can be rather large. The characteristic time of the action of the elongational stresses in regions 7 and 8 (see Fig. 1) can be evaluated from the distance from the point a up to the first characteristic curve, departing from the point d($\Delta t = 2(t_d - t_a)$).

Let us evaluate the parameters of an elongational pulse in these cross sections of the sample for copper and aluminum, using known data on the equation of state of these metals [4] and the dependences of the critical shear stresses on the pressure at the front of the shock wave [2].

We assume that at the shock adiabatic

$$p_n = p + (2/3)\sigma_*,$$

where p_n is the pressure of the shock compression, normal to the front of the shock wave; p is the hydrodynamic pressure. The critical shear stress is defined as equal to

$$\sigma_* = |p_n - p_\tau|,$$

where p_τ is the pressure parallel to the front of the shock wave. The value of σ_* is usually calculated under the assumption of the constancy of the Poisson coefficient ν. If it is postulated that the value of σ_* with compression is equal to σ_* with elongation, then, for the case of the propagation of a shock wave, we have

$$\sigma_* = (p_*/2)[(1-2\nu)/(1-\nu)],$$

where p_* is the amplitude of the unloading shock wave.

Figure 3 illustrates the arrangement of the shock adiabatic I, the curve of the hydrodynamic compression II, and the curve of the plastic unloading III. The transition from stage 1 to state 2 takes place along the curve of the elastic unloading.

At the curve of the plastic unloading, the following relationship is satisfied:

$$p_- = p - (2/3)\sigma_*.$$

Knowing the values of σ_* corresponding to the pressure of the shock compression p_n, the curve of the plastic unloading p_- can be constructed.

In the present work, the curve of p_-, plotted from experimental data, was approximated in the region of positive stresses by a function of the form $p_- = [A_0 + A_1(\delta - 1)](\delta - 1)$, and in the region of negative stresses by a function of the form $p_- = A_0(\delta - 1)$, where $\delta = \rho/\rho_0$ is the compression.

To solve the problem of the impact of a plate-striker on a sample, the method of characteristics is applied to the equations of motion of a continuous medium, written in Lagrangian coordinates.

The principal results of the calculations are given in Tables 1 and 2, where p is the pressure in the compression shock wave; Δp is the pressure in regions 7 and 8 in Fig. 1; p_a is the pressure in region 6 in Fig. 1; p_{max} is the maximal elongational stress (pressure everywhere in kilobars); h is the thickness of the sample, referred to the thickness of the plate-striker; t, x are the coordintes of the points denoted by letters in Fig. 1 (the letters with them correspond to the notation in Fig. 1; if the thickness of the plate-striker is 1 mm, then x is measured in millimeters and t, in microseconds; for other thicknesses of the plate-striker, the spatial coordinate and the time vary proportionally); Δt_1 is the characteristic time of the action of the elongational stresses in region 8 near the free surface of the sample; Δt_2 is the characteristic time of the action of the elongational stresses in region 7.

Table 1 gives the results of calculations for aluminum, and Table 2 for copper; it can be seen that the negative stresses in regions 7 and 8 before the action of the maximal elongational stresses are comparable to the value of the splitting strength of the material [2].

One of the special characteristics of the flows under discussion is the fact that the characteristic time of the action of the negative stresses in the region located inside the forming rear fragment is appreciably greater than the time of the action, equal in value, of the elongational stress in the remaining part of the sample (near the impact surface). Since the value of these stresses is on the order of magnitude of the fragmentation strength of the metal under these conditions, then, in accordance with existing concepts with respect to the dependence of the breaking stresses on the time of their action, in both regions a certain pulverizing of the metal is to be expected (the appearance of microcracks, not forming a failure surface). Here the degree of pulverizing (the number of microcracks per unit of surface) in the splitting part of the sample should be greater than in the remaining part.

Experiments were made in which a copper sample with a diameter of 90 mm and a thickness of 10 mm was loaded by the impact of a copper plate 2.5 mm thick, accelerated to a velocity of 500 m/sec. Under these circumstances, the pressure at the front of the shock wave was 100 kbar. In the experiments, the rear fracture was recorded. On the microphotos of a section of the samples at some distance from the impact surface, i.e., approximately in region 7 (see Fig. 1), there can be seen a series of individual microcracks, which can point to the fact of the existence of short-term negative stresses in this section. The network of microcracks over the thickness of the forming rear fragment is considerably denser, which is also in agreement with the results of an analysis of the flows.

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STUDY OF MAXIMUM STRESS FIELD ALONGSIDE CRACKS EMERGING FROM CONTOURS OF OPENINGS IN A PERFORATED PLATE

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UDC 539.375

A considerable number of papers have appeared in recent years (see the reviews [1, 2]) in which the stress state alongside cracks emerging from the contour of a single opening was investigated. The analogous problem of the stretching of a plate with a single opening was the subject of [3].

§1. Let there be a doubly periodic array of circular openings having a radius λ ($\lambda < 1$) and centers at the points

$$P_{mn} = m\omega_1 + n\omega_2 \ (m,\ n = 0,\ \pm 1,\ \pm 2, \ldots),\ \omega_1 = 2,\ \omega_2 = 2le^{i\alpha},\ \ l > 0,\ \operatorname{Im}\omega_2 > 0.$$

Symmetric linear slits originate from the contours of the openings (Fig. 1). The contours of the circular openings and the edges of the slits are free of loads. We consider the problem of the stretching of such a perforated plate by constant forces $\sigma_2 = \sigma_y^\infty$ in a direction perpendicular to the line of the slits. Because of the symmetry of the boundary conditions and the geometry of the region D occupied by the plate material, the stresses are doubly periodic functions with fundamental periods ω_1 and ω_2.

To solve the problem in reasonable fashion, we combine the method developed for the solution of a doubly periodic elastic problem [4] with the method for plotting [5, 6] in explicit form the Kolosov–Muskhelishvili potentials corresponding to unknown normal displacements along the slits.

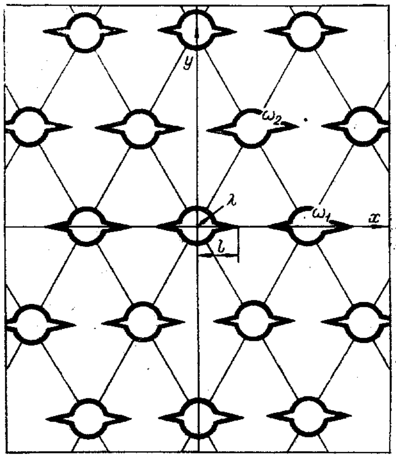

Fig. 1

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