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SHOCK ADIABATS AND PROFILES OF WEAK SHOCK WAVES IN METALS

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1. Description of the Parameters of the Medium

The mathematical model of an isotropic medium, suggested in [1-3], supposes that the substance is defined by an internal energy E per unit mass of substance and by a characteristic time τ of relaxation of tangential stresses. The internal energy E is related by the equation of state of the medium

$$E = E(\alpha, \beta, \gamma, S) \tag{1.1}$$

with the density of the entropy S and the quantities α, β, γ. The parameters α, β, and γ are the logarithms of the "elastic" extensions k_1, k_2, and k_3 along the principal axes of elastic deformation

$$\alpha = \ln k_1,\ \beta = \ln k_2,\ \gamma = \ln k_3.$$

The equations of state of the type (1.1) are given in [2] for iron (α-phase), aluminum, copper, nickel, lead, and titanium. The characteristic time τ of relaxation of tangential stresses is determined by the formula for its dependence on the stressed state of the medium

$$\tau = \tau(\sigma, T), \tag{1.2}$$

where T is the temperature; $\sigma = (1/\sqrt{2})\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$ is the intensity of the tangential stresses (σ_1, σ_2, and σ_3 are the principal stresses). The form of this relation is given in [3] for iron, aluminum, copper, and lead.

When calculating shock waves, a relation is used which is a variant of the corresponding formula from [3]:

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TABLE 1

	Fe	Al	Cu	Pb	Ni	Ti
ρ^0, g/cm³	7,84	2,785	8,90	11,34	8,86	4,51
b_0, km/sec	2,866	2,941	2,141	0,812	2,485	2,963
c_0, km/sec	5,726	6,208	4,697	2,214	5,636	5,834
μ, g/mole	55,85	26,98	63,54	207,21	58,71	47,90

$$\begin{gathered}\tau = \tau_0 \left(\frac{\rho^0 b_0^2}{\sigma n_0}\right)^{n(T)-1} \exp\left(\mu \frac{U(T)}{RT}\right),\\ n^{-1}(T) = n_1 \left[\left(\frac{T}{\theta_0 n_2} - \nu\right)^2 + n_3\right],\\ U(T) = c_0^2 \frac{T}{\theta_0 n_4}\left(1 - \frac{T}{\theta_0 n_5}\right) n(T).\end{gathered} \tag{1.3}$$

where μ is the atomic weight; $R = 8.31 \cdot 10^7$ g $\cdot$ cm²/sec² $\cdot$ deg $\cdot$ mole is the universal gas constant; ρ^0 is the density of the substance in the normal state; c_0 and b_0 are the longitudinal and transverse wave velocities in the normal state. The values of ρ^0, b_0, c_0, and μ for iron, aluminum, copper, lead, nickel, and titanium are given in Table 1. The interpolated coefficients τ_0, n_0–n_5 for iron, aluminum, copper, and lead are given in Table 2. For lead, $\nu = 0$; for iron, aluminum, and copper, $\nu = 1$.

The formula in [3] for the dependence of the time of relaxation of the tangential stresses on the stressed state of the medium differs from formula (1.3) in the correction factor of the type $\exp(\Phi(\sigma)/RT)$, where $\Phi(\sigma)$ is some specified function [3]. This correction factor was introduced in [3] in order to describe the function $\tau(\sigma, T)$ over the range of deformation rates $\dot{\varepsilon} \approx 10^7$ sec^{-1}, which corresponds to $\tau \approx 10^{-7}$ sec. Calculations of the plastic adiabats are limited to values of $\tau \geqslant 0.5 \cdot 10^{-6}$ sec, at which, as the calculations showed, the effect of the correction factor is insignificant.

2. Shock Waves

The system of differential equations describing the motion of a viscoelastic medium parallel to a specified x axis in the space (x, y, z) is considered in [4], and which is a one-dimensional variant of the system of equations suggested in [1]. Suppose that $\rho = \rho^0 \exp(-\alpha - \beta - \gamma)$ is the density, and u is the velocity along the x axis. The principal stresses σ_x, σ_y, and σ_z are related to α, β, and γ by the formulas $\sigma_x = \rho E_\alpha$, $\sigma_y = \rho E_\beta$, and $\sigma_z = \rho E_\gamma$.

If we denote by w the flow of material through the shock wave, $w = \rho u$ [Mach number, $M = w/\rho_0 c_0$)], then, as shown in [4], the values of the parameters during passage through the shock wave are connected by the relations

$$\begin{gathered}p_1 - p_0 = -w^2\left(\frac{1}{\rho_1} - \frac{1}{\rho_0}\right),\\ u_1 - u_0 = w\left(\frac{1}{\rho_1} - \frac{1}{\rho_0}\right),\\ E_1 - E_0 + \frac{p_1 + p_0}{2}\left(\frac{1}{\rho_1} - \frac{1}{\rho_0}\right) = 0,\\ \alpha_1 = \beta_1 = \gamma_1 = \frac{1}{3}\ln \rho^0/\rho_1,\ \alpha_0 = \beta_0 = \gamma_0 = \frac{1}{3}\ln \rho^0/\rho_0,\\ D = u_1 - w/\rho_1 = u_0 - w/\rho_0,\end{gathered} \tag{2.1}$$

where $p = -\sigma_x$ is the stress along the axis x. The subscripts 0 and 1 denote the values of the quantities in front of the wave and behind the wave, where $\sigma_x = \sigma_y = \sigma_z = -p$. Knowing

TABLE 2

	$\tau_0 \cdot 10^{-5}$, sec	$n_0 \cdot 10^{-4}$	n_1	n_2	n_3	$n_4 \cdot 10^{-3}$	n_5
Fe	14,64	2,6	0,1036	1,545	0,4474	0,14	0,2654
Al	41,15	1,06	0,305	2,57	0,0327	0,0847	2,47
Cu	23,98	1,96	0,0184	0,955	1,902	0,14	7,22
Pb	13,5	0,535	0,00804	1	1,244	0,485	5,464

TABLE 3

	Fe	Al	Cu	Pb	Ni	Ti
p_1	2,512	3,143	2,512	2,867	3,524	5,739
p_2	4,829	8,030	8,120	7,586	13,90	20,35
D_1	1,227	1,530	1,459	1,432	1,812	2,539
p_3	3,545	4,230	3,920	3,994	6,204	4,909
D_2	1,675	2,005	1,887	1,985	2,970	2,208
p^*, kbar	9,406	3,845	7,910	1,859	—	—
η^*	0,9964	0,9965	0,9960	0,9967	—	—
u^*, km/sec	0,02082	0,02185	0,01877	0,007356	—	—
M^*	1,005	1,006	1,010	1,004	—	—
k	3871	7234	1242	2638	—	—
$\Delta t \cdot 10^{-6}$, sec	0,5	0,5	0,5	1,0	—	—
L, cm	0,0165	0,0242	0,0289	0,0485	—	—

the state of the substance ahead of the wave and the mass flow w, by means of Eq. (2.1) the state of the substance behind the wave can be determined. The Hugoniot adiabat in the plane $(p, 1/\rho)$

$$E - E_0 + \frac{p + p_0}{2}\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right) = 0, \ \alpha = \beta = \gamma \tag{2.2}$$

as shown in [4], has only two points of intersection with the Michelson straight line

$$p - p_0 = -w^2\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right), \ \alpha = \beta = \gamma,$$

which correspond to the initial and final state.

On the basis of the calculations carried out, interpolation formulas were constructed for the Hugoniot hydrodynamic adiabat (2.2) for shock waves propagating through a substance existing under normal conditions $\rho = \rho^0$ and $T = 300°K$:

$$\frac{p}{\rho^0 c_v^2} = 1 - \eta + p_1(1-\eta)^2 + p_2(1-\eta)^3,$$
$$\eta = \frac{\rho^0}{\rho}, \ 0{,}85 \leqslant \eta \leqslant 1, \ c_v = \sqrt{c_0^2 - \frac{4}{3} b_0^2}. \tag{2.3}$$

If the velocity of the substance ahead of the shock wave is equal to u_0, then the Hugoniot adiabat (2.2) is represented in the variables p and u by the formula

$$p/(\rho^0 c_v^2) = \zeta \overline{D}, \tag{2.4}$$

where $\zeta = (u - u_0)/c_v$; $\overline{D} = D/c_v$ and $0 \leqslant u - u_0 \leqslant 1$ km/sec. The interpolation formula for the dependence of the wave velocity on the velocity of the substance behind the front has the form

$$D/c_v = 1 + D_1 \zeta, \ 0 \leqslant u - u_0 \leqslant 1 \text{ km/sec}. \tag{2.5}$$

The values of the coefficients p_1, p_2, and D_1 are given in Table 3.

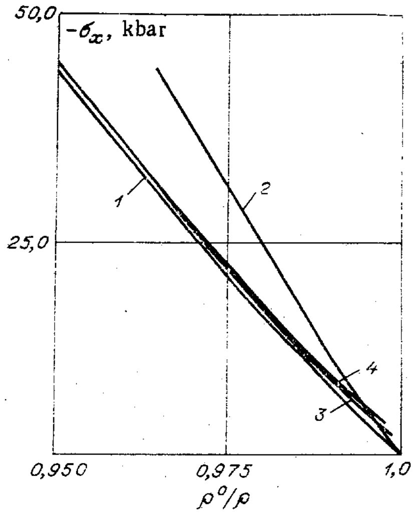

Fig. 1

TABLE 4

M	$\frac{\rho^0}{\rho}$	$-\sigma_x$, kbar	$-\sigma_y$, kbar	T, °K	u, km/sec	$E \cdot 10^2$ km²/sec²	$-\beta \cdot 10^2$
1,17	0,998	3,00	0,85	301	0,0149	0,0251	—0,079
1,02	0,996	4,45	2.33	303	0,0252	0,0458	—0,012
0,970	0,994	6,03	3,94	304	0,0361	0,0793	0,06
0,940	0,992	7.62	5.55	305	0,0470	0,124	0,131
0,924	0.990	8,99	6.94	307	0,0563	0,172	0.193
0,903	0.984	13,7	11,7	310	0.0878	0,400	0.398
0,899	0.970	24,9	23,0	320	0,0160	1,294	0,856
0,910	0,960	35,5	33,7	329	0,226	2,569	1.263
0.920	0,950	46.2	44,5	338	0,290	4,22	1,64
0,932	0,940	56,3	54,6	347	0,349	6,11	1.99
0,950	0,930	67,6	66,1	357	0,413	8,56	2.36
0,960	0.920	79,3	77.8	368	0,478	11,4	2,71
0,980	0,910	92,9	91,5	382	0,550	15,1	3,10
0,990	0,900	106	104	396	0,616	19,0	3.45
1,01	0.890	121	119	414	0,691	23,9	3,83
1,03	0,880	137	136	434	0,768	29,5	4,22
1,05	0.870	154	153	458	0,848	36,0	4,61
1,07	0,860	172	171	485	0.931	43,3	4,99
1,09	0,850	191	190	516	1,02	51,6	5,39
1,11	0,840	212	211	552	1,10	61,0	5,79
1,13	0.830	234	233	594	1,19	71,6	6,18
1,16	0,820	258	257	642	1,29	83,4	6,59

3. Characteristics of the Shock Wave Profile

The shock wave profile, as shown in [4], has two special features. First of all, shock waves moving with supersonic velocity (M > 1) contain a discontinuity on the profile, corresponding to a sudden elastic change of state of the substance from the original state into some intermediate state. When M < 1 (subsonic waves) there is no sudden change.

The interpolation formulas, similar to Eqs. (2.3)-(2.5), for the shock adiabat of an elastic wave propagating through a substance existing under normal conditions have the form

$$\frac{p}{\rho^0 c_0^2} = 1 - \eta + p_3 (1 - \eta)^2, \ 0{,}9 \leqslant \eta \leqslant 1;$$
$$\frac{p}{\rho^0 c_0^2} = \xi D^*, \ \xi = \frac{u - u_0}{c_0}, \ D^* = \frac{D}{c_0}, \ 0 \leqslant u - u_0 \leqslant 0.5 \text{ km/sec}; \tag{3.1}$$
$$D/c_0 = 1 + D_2 \xi, \ 0 \leqslant u - u_0 \leqslant 0.5 \text{ km/sec}.$$

Values of the interpolation coefficients p_3 and D_2 are given in Table 3.

TABLE 5

M	$\frac{\rho^{\circ}}{\rho}$	$-\sigma_x$, kbar	$-\sigma_y$, kbar	T, °K	u, km/sec	$E \cdot 10^2$ km²/sec²	$-\beta \cdot 10^2$
1,14	0,998	5,02	1,71	301	0,0105	0,0073	−0,069
1,01	0,996	7,91	4,61	302	0,0188	0.0194	−0,0004
0,96	0,994	10,9	7,61	304	0,0271	0,0386	0,070
0,94	0,992	13,9	10,6	305	0,0355	0,0647	0,140
0,93	0,990	16,6	13,3	306	0,0429	0,0936	0,201
0,91	0,985	24,8	21,5	310	0,0650	0,213	0,386
0,91	0,970	48,4	45,2	320	0,127	0,813	0,894
0,92	0,960	66,1	63,0	328	0,172	1,49	1,25
0,93	0,950	85,5	82,4	337	0,220	2,42	1,62
0,94	0,940	104	101	346	0,264	3,50	1,96
0,96	0,930	125	122	357	0,313	4,90	2,32
0,97	0,920	146	144	369	0,362	6,54	2,67
0,99	0,910	171	168	384	0,416	8,67	3,06
1,00	0,900	195	192	400	0,466	10,9	3,41
1,02	0,890	222	220	420	0,523	13,7	3,80
1 04	0,880	251	249	443	0,582	16,9	4,18
1,05	0,870	282	280	470	0,642	20,6	4,57
1,07	0,860	315	313	501	0,704	24,8	4,96
1,09	0,850	350	348	538	0,768	29,5	5,36
1,11	0,840	387	385	581	0,834	34,8	5,75
1,14	0,830	427	425	630	0,902	40,7	6,15
1,16	0,820	470	467	687	0,973	47,4	6,55

The second special feature is associated with the nonlinear dependence of the relaxation time τ on the parameters of the medium (1.3). For metals these critical dependencies lead to the fact that on the wave profile sections are formed with a rapid change of the quantities representing an individual wave. This section, on waves moving with supersonic velocity, is located after the elastic discontinuity.

In experimental investigations, where a similar structure of the front has been observed repeatedly (see bibliographies in [4, 5]), the elastic wave is called an elastic precursor, and the wave following behind it is called the plastic wave. Following the established terminology, we shall call the section of rapid change of quantities on the profile the plastic wave.

A procedure is described in [4], by means of which the plastic wave can be discriminated in an individual wave. For this, we specify the characteristic duration Δt of the plastic wave and we construct in the plane $(p, 1/\rho)$ a curve, which in accordance with [4] we shall call the plastic adiabat corresponding to $\tau = \Delta t$. The sense of this procedure consists in that the plastic waves of width $\sim\Delta t$ are changed by discontinuities, for which the magnitudes of the discontinuities are calculated by means of the plastic adiabat. Figure 1, together with the hydrodynamic and elastic adiabat (curves 1 and 2), shows the plastic adiabats corresponding to $\Delta t = 10^{-5}$ sec and $\Delta t_1 = 0.5 \cdot 10^{-6}$ sec (curves 3 and 4) for aluminum, which exists in normal conditions in front of the wave. It can be seen from Fig. 1 that the plastic adiabats corresponding to $\Delta t = 10^{-5}$ sec and $\Delta t_1 = 0.5 \cdot 10^{-6}$ sec differ very little despite the magnitude of Δt being changed by a factor of 20.

Calculations carried out have enabled tables to be compiled of plastic adiabats for shock waves propagating through substances existing under normal conditions. Table 4 corresponds to the plastic adiabat of aluminum, Table 5 to copper, Table 6 to iron, and Table 7 to lead. The magnitude of Δt for lead is taken to be equal to 10^{-6} sec, and for the other substances it is equal to $0.5 \cdot 10^{-6}$ sec. Table 3 also gives the values of p^*, η^*, and u^*, specifying the point of intersection of the plastic adiabats of Tables 4-7 with the corresponding elastic adiabats.

In addition to the shock adiabats mentioned, the shock adiabats of a substance already subjected to attack can be considered. Thus, graphs and tables are given in [6-9] of shock adiabats for shock waves propagating through a substance previously compressed by a shock wave up to values of ρ°/ρ equal to 0.95-0.97.

4. Structure of Shock Waves

Following [4], let us consider now the possible structures of the profile of shock waves and the method of discriminating plastic waves.

TABLE 6

M	$\frac{\rho^0}{\rho}$	$-\sigma_x$, kbar	$-\sigma_y$, kbar	T, °K	u, km/sec	$E \cdot 10^2$, km²/sec²	$-\beta \cdot 10^2$
1,04	0,997	8,32	3,61	302	0,0178	0,0262	—0,021
0,96	0,995	11,8	7,16	303	0,0275	0,0482	0,048
0,92	0,993	15,4	10,7	304	0,0370	0,0789	0,116
0,90	0,990	20,5	15,9	306	0,0509	0,140	0,215
0,88	0,985	29,5	24,9	308	0,0747	0,290	0,385
0,87	0,980	38,2	33,6	311	0,0976	0,487	0,547
0,87	0,970	55,8	51,2	317	0,143	1,03	0,863
0,88	0,960	76,9	72,5	324	0,196	1,93	1,23
0,88	0,950	99,9	95,6	332	0,252	3,19	1,61
0,89	0,940	123	119	340	0,307	4,73	1,98
0,90	0,930	145	149	349	0,359	6,46	2,32
0,91	0,920	171	167	361	0,416	8,68	2,69
0,92	0,910	196	192	374	0,473	11,2	3,05
0,94	0,900	223	219	388	0,531	14,1	3,41
0,95	0,890	253	250	406	0,595	17,7	3,81
0,96	0,880	285	282	428	0,660	21,8	4,20
0,98	0,870	315	312	450	0,720	25,9	4,56
0,99	0,860	350	347	478	0,788	31,1	4,95
1,00	0,850	386	383	511	0,858	36,8	5,35
1,02	0,840	425	422	549	0,929	43,2	5,75
1,04	0,830	465	463	592	1,00	50,3	6,15
1,05	0,820	508	506	642	1,08	58,1	6,56

TABLE 7

M	$\frac{\rho^0}{\rho}$	$-\sigma_x$, kbar	$-\sigma_y$, kbar	T, °K	u, km/sec	$E \cdot 10^2$, km²/sec²	$-\beta \cdot 10^2$
1,02	0,997	1,72	1,21	303	0,0067	0,0023	—0,0105
0,98	0,995	2,65	2,15	304	0,0108	0,0058	0,0576
0,96	0,993	3,59	3,09	306	0,0149	0,0111	0,126
0,95	0,990	4,89	4,39	308	0,0205	0,0209	0,218
0,95	0,989	5,48	4,97	309	0,0230	0,0264	0,260
0,95	0,979	10,6	10,1	319	0,0446	0,0996	0,614
0,95	0,975	12,6	12,1	322	0,0527	0,139	0,744
0,96	0,970	15,0	14,5	326	0,0624	0,195	0,900
0,96	0,965	17,9	17,4	332	0,0740	0,274	1,08
0,97	0,960	20,7	20,1	336	0,0848	0,360	1,25
0,98	0,955	23,7	23,1	342	0,0966	0,467	1,44
0,98	0,950	26,7	26,1	348	0,108	0,585	1,61
0,99	0,945	29,7	29,2	353	0,120	0,716	1,79
1,00	0,940	32,9	32,2	359	0,131	0,860	1,96
1,00	0,935	36,3	35,7	366	0,144	1,04	2,15
1,01	0,930	39,8	39,3	373	0,157	1,23	2,34
1,02	0,925	43,1	42,5	379	0,168	1,42	2,50
1,03	0,920	46,8	46,2	387	0,181	1,65	2,69
1,04	0,915	50,6	50,0	395	0,195	1,90	2,88
1,04	0,910	54,2	53,5	403	0,207	2,14	3,05

For subsonic shock waves ($M < 1$), the shock wave profile shown in Fig. 2 is characteristic where, for lead ($M = 0.975$), computed graphs of $-\sigma_x$ (curve 1) and $-\sigma_y$ (curve 2) are shown as a function of distance for a fixed instant of time. There is a section (P_1, P_2) on the wave profile with large stress gradients, corresponding to a reduction of magnitude of the relaxation time. Points where $\tau = 10^{-5}$ and 10^{-6} sec are denoted by small circles and crosses, respectively. It can be seen from Fig. 2 that the plastic wave can be distinguished, for example, by the points P_2 (onset of wave) and P_1 (end of wave); in this case, $\tau = \Delta t = 10^{-6}$ sec.

For waves with velocities slightly exceeding the velocity of sound, $1 < M < M^*$ (the quantity M^* is tabulated in Table 3), the structure of the wave profile has the form depicted in Fig. 3 (aluminum, $M = 1.00552$).

On the profile ahead of the plastic wave (P_1, P_2), the nature of which is the same as for subsonic shock waves, there is an elastic discontinuity Q, the magnitude of which is determined by formulas (3.1). Curves 1 and 2 of Fig. 3 depict $-\sigma_x$ and $-\sigma_y$, respectively.

If we define the distance Δl from the elastic precursor to the plastic wave (P_1, P_2) as the distance from the elastic precursor Q to the point on the wave profile nearest to it at which $\tau = \Delta t$ (point P_2), then in the range of Mach numbers $1 < M < M^*$, Δl varies within the limits $\infty > \Delta l > 0$.

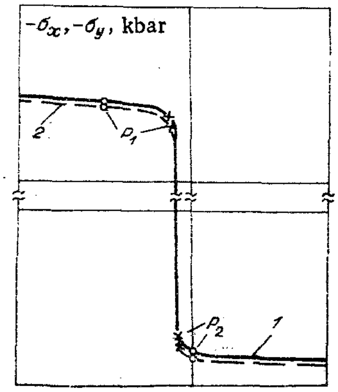

Fig. 2

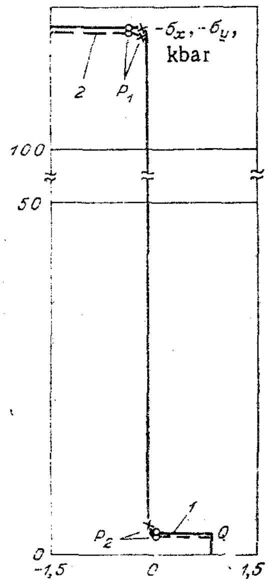

Fig. 3

Figure 4 (curve 1) shows the graph of the function $\Delta l(M)$ for aluminum in the range $1.005 < M < 1.006$. The quantity Δt was assumed in the calculations to be equal to $0.5 \cdot 10^{-6}$ sec. For comparison, Fig. 4 (curve 2) shows also the magnitude of the distance between points on the profile corresponding to $\tau = \Delta t = 0.5 \cdot 10^{-6}$ sec (points P_1 and P_2), which define the width of the plastic wave.

For the materials considered and with the corresponding values of Δt, the function $\Delta l(M)$ can be represented in the form

$$\Delta l = Le^{k(M^* - M)}. \tag{4.1}$$

Values of the coefficients L and K and the corresponding values of Δt are given in Table 3. The form of formula (4.1), determined by the nature of the relation (1.2), (1.3) for the time of relaxation, shows that the stationary two-wave configuration observed experimentally in metals presents difficulties. For other materials, in which this relation may be not so sharp a similar investigation is possible. Papers [10, 11] are devoted to these experimental investigations in Plexiglas.

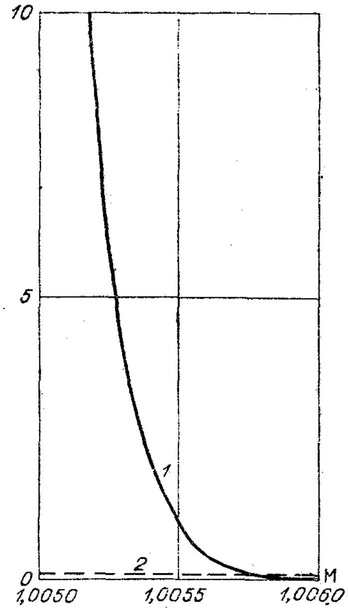

Fig. 4

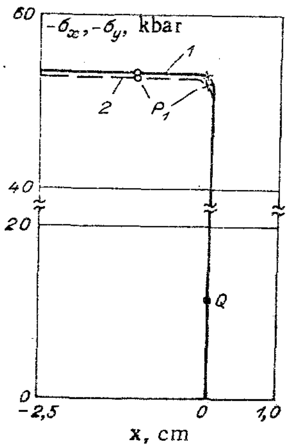

Fig. 5

Finally, for shock waves propagating with velocities corresponding to Mach numbers $M > M^*$, the profile of the shock waves has the structure depicted in Fig. 5. In Fig. 5, curves 1 and 2 depict $-\sigma_x$ and $-\sigma_y$, respectively, for lead ($M = 1.179$). The point Q shows the magnitude of the elastic discontinuity.

As the magnitude of τ between the points P_1 and Q is less than Δt, then according to [4] the section (P_1, Q) cannot be distinguished and the section (P_1, 0) may be regarded as of a single wave.

When the velocity of the wave is increased, as the graphs of the plastic and hydrodynamic adiabats show (see Fig. 1), the difference between the values behind the wave, calculated by the ratios in the plastic wave and by the ratios in the wave in hydrodynamic approximation, becomes insignificant. This serves as evidence that hydrodynamic approximation can be used for strong shock waves.

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