Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 4, 2000

EFFECT OF ENERGY DISSIPATION ON THE SHAPED-CHARGE FLOW REGIME

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UDC 532.522+536.422.1

Convergence of a viscous shaped-charge liner to the symmetry axis is described. It is shown that energy dissipation has a significant effect on the process considered. Convergence at small angles can lead to a strong phase explosion of the metastable liquid of the inner, strongly heated, layers of the liner, which is comparable to TNT *explosion. An increase in the angle of convergence results in a weak phase "explosion," which leads to different behavior of shaped-charge jets for different types of liner material.*

The main difference in the action of plane shaped charges and charges with axisymmetric liners lies in the fact that during acceleration by an explosion, a wedge-shaped liner does not undergo considerable deformations. An axisymmetric liner compressed by the detonation products of an explosive is subjected to large deformations, under which the layers of the liner slide over each other. In this case, convergence of the liner to the symmetry axis is significantly affected by the energy-dissipation mechanisms. For explosively driven charges with plane liners, energy dissipation is practically absent even in acceleration by a gliding detonation wave because there is no sliding of the layers of the plate. This is suggested by the shape of indicating wires pressed in the plate [1]. After oblique collision of the plates, the shape of the wires is considerably distorted, especially near the collision surface. Hence, for plane charges, dissipation of mechanical energy is possible only at the stage of collision and jet formation.

Considering explosive compression of cylindrical liners, Matyushkin and Trishin [2] showed experimentally and theoretically that convergence of the liner to the symmetry axis is described most adequately by the model of a Newtonian liquid. Hence, because of the action of viscous forces during collapse of axisymmetric liners, the energy-dissipation process should change the characteristics of the shaped-charge jets formed depending on the type of liner material. In addition, it is possible to choose charge and cylindrical-liner parameters such that the initial kinetic energy of the liner is completely converted to thermal energy and the liner stops upon reaching a certain radius R^* [2].

For approximate calculation of a shaped charge with a conical liner, the liner can be divided into a number of rings by sections perpendicular to the axis of the cone and the rings can be assumed to move independently of each other.

For inertial motion of a ring of a viscous incompressible liquid, Matyushkin and Trishin [2] obtained the following equation of motion for the inner surface of a cylindrical liner of radius R:

$$R\dot{R} = (R_0\dot{R}_0 + 4\nu)\frac{\sqrt{\ln (R_{10}/R_0)}}{\sqrt{\ln (R_1/R)}} - 4\nu. \qquad (1)$$

Here R_1 is the outside radius, R_{10} is the inside radius at $t = 0$, R_0 and $\dot{R}_0$ are the radius, respectively, of the inner surface of the liner and its velocity at $t = 0$, and ν is the kinematic-viscosity coefficient.

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TABLE 1

r_0, cm	r, cm	Cu		Fe	
		ΔT_1, K	H, J/g	ΔT_1, K	H, J/g
1.00	[illegible]	1710	650	5550	3550
1.01	[illegible]	1420	540	4600	2940
1.02	0.36	1210	460	3910	2500
1.03	0.39	1050	400	3090	1980
1.05	0.44	830	320	2680	1720
1.07	0.48	680	260	2200	1410
1.09	0.53	550	210	1790	1150
1.10	0.55	510	195	1660	1070

TABLE 2

r_0, cm	r, cm	ΔT, K	H, J/g
1.00	0.10	5700	2180
1.01	0.17	2760	1050
1.02	0.22	1910	730
1.03	0.26	1500	570
1.05	0.33	1060	405
1.07	0.39	820	310
1.09	0.45	640	240
1.10	0.47	590	225

From the condition of incompressibility of the liner it follows that

$$R_1^2 - R^2 = R_{10}^2 - R_0^2 = A^2. \tag{2}$$

The specific power of dissipation forces is

$$N = \frac{dE}{dt} = 4\nu \frac{(R\dot{R})^2}{r^4},$$

where r is an independent variable ($R \leqslant r \leqslant R_1$) and E is the specific energy. From the incompressibility of the liner it follows that $r^2(t) = R^2(t) + r_0^2 - R_0^2$, where r_0 is the initial radius of a particle located in the depth of the liner ($R_0 \leqslant r_0 \leqslant R_{10}$). Hence, in the adiabatic approximation for a particle with radius r_0, we obtain the temperature increment

$$\Delta T = \frac{4\nu}{c} \int\limits_0^t \frac{R^2 \dot{R}^2}{(R^2 + r_0^2 - R_0^2)^2}\, dt. \tag{3}$$

where c is the specific heat of the liner. It is possible to find an approximate solution of Eq. (3), taking into account that at the initial stage of collapse, $\dot{R}$ differs from $\dot{R}_0$ only slightly [3]. Then, relation (3) becomes

$$\Delta T = \Delta T_1 + \Delta T_2 = \frac{4\nu}{c}\dot{R}_0^2 \int\limits_0^{t_*} \frac{R^2}{(R^2 + r_0^2 - R_0^2)^2}\, dt + \frac{4\nu}{c} \int\limits_{t_*}^{t} \frac{(R\dot{R})^2}{(R^2 + r_0^2 - R_0^2)^2}\, dt, \tag{4}$$

where t_* is the time during which $\dot{R}$ differs from $\dot{R}_0$ only slightly.

If we set $R = R_0 - \dot{R}_0 t$, the first integral ΔT_1 is easily evaluated:

$$\Delta T_1 = \frac{2\nu \dot{R}_0}{c} \left[\frac{R_*}{R_*^2 + r_0^2 - R_0^2} - \frac{R_0}{r_0^2} + \frac{1}{\sqrt{r_0^2 - R_0^2}} \arctan \frac{(R_0 - R_*)\sqrt{r_0^2 - R_0^2}}{r_0^2 - R_0^2 + R_0 R_*} \right].$$

To determine ΔT_2 when the inner surface of the ring approaches the axis ($R \to 0$), we expand the denominator of relation (1) in a series and, using (2), we obtain its value $(1/2)\ln(A^2/R^2) = (4/3)(1 - 3\varepsilon)$ with accuracy up to $\varepsilon^2 = (R^2/A^2)^2$. Then, from Eq. (1) we have

$$R^2 = (R_*^2 + b/a)\exp(-a\tau) - b/a. \tag{5}$$

where $a = (2.598/A^2)(R_0\dot{R}_0 + 4\nu)(\ln(R_{10}/R_0))^{1/2}$, $b = 0.667A^2 a - 8\nu$, and $\tau = t - t_*$. From relations (4) and (5) we obtain

$$\Delta T_2 = -\frac{a\nu}{c}\left[\frac{B}{\exp(-a\tau) + B} - \frac{B}{1 + B} + \ln\left(\frac{\exp(-a\tau) + B}{1 + B}\right)\right],$$

where $B = (r_0^2 - R_0^2 - b/a)/(R_*^2 + b/a)$. Results of calculation of the temperature distribution ΔT_1 over the thickness of copper and iron rings with $R_* = 0.3R_0$ are presented in Table 1, and the temperatures ΔT_2 for copper rings at $R = 0.1R_0$ are given in Table 2 ($\Delta T = \Delta T_1 + \Delta T_2$). For both rings, the initial velocity is $\dot{R}_0 = 10^5$ cm/sec and the initial geometrical dimensions $R_0 = 1$ cm and $R_{10} = 1.1$ cm are identical. They differ only in the kinematic-viscosity coefficient ν, which, at an initial strain rate of about 10^5 sec^{-1}, is $(0.7\text{–}1.0) \cdot 10^4$ cm^2/sec for copper [2, 4] and $(3.8\text{–}5.1) \cdot 10^4$ cm^2/sec for iron [5]. For radial convergence of a cylindrical liner, the strain rate is defined by

$$\dot{\varepsilon} = \frac{R_0 \dot{R}_0}{\delta_0}\Big(\frac{1}{R} - \frac{1}{\sqrt{A^2 + R^2}}\Big),$$

where $\delta_0 = R_{10} - R_0$. In the calculations, the specific heats of copper and iron were set equal to 0.382 and 0.64 J/(g · K).

The heating due to viscosity is nonuniform over the thickness of the liner material and increases during convergence of the liner to the center. Maximum increase in temperature is attained on the inner surface of the liner. An increase in temperature changes the properties of the liner material and, in particular, the dynamic-viscosity coefficient.

According to the Frenkel'–Airing theory [5], developed for liquids and used in [6] to describe experiments on shock-wave loading of metals up to the melting point, the dynamic-viscosity coefficient η of a liquid is related to the temperature T and the degree of compression σ by the formula

$$\eta(\sigma, T) = \eta_0 \sigma \exp\,[E_a(\sigma)/T].$$

From physical considerations it follows that for the work related to viscous motion during formation of vacancies, the activation energy E_a has the form $E_a = A + B\sigma^3$. The constants A and B were determined from shock-wave experiments in metals.

For aluminum and lead, it is established experimentally [6] that with increase in the shock-wave intensity, the viscosity initially increases and then, passing through the maximum at $\sigma \approx 1.4$, decreases. The nontrivial dependence of the viscosity coefficient on the shock-wave intensity can be explained qualitatively by competition of the processes related to compression of the material and thermal processes.

A similar situation is observed during convergence of a cylindrical liner to the axis. The decrease in the viscosity of the inner layers due to their stronger heating is compensated for by the higher degree of compression because on the inner surface of the cylinder and adjacent layers, the pressure increases with decrease in the radius of liner convergence.

For convergence of an incompressible cylindrical liner to the axis, the Navier–Stokes equations have the form

$$\frac{\partial u}{\partial r} + \frac{u}{r} = 0, \qquad \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0. \tag{6}$$

The viscosity does not enter into Eqs. (6). It is given by the expression $\eta(\operatorname{grad}\operatorname{div}\boldsymbol{u} - \operatorname{rot}\operatorname{rot}\boldsymbol{u})$, which is equal to zero in this case since $\operatorname{div}\boldsymbol{u} = 0$ because of the incompressibility of the liquid and $\operatorname{rot}\boldsymbol{u} = 0$ because of the cylindrical symmetry of the flow. The viscosity is included in the boundary conditions. On the inner and outer surfaces of the liner, normal stress is absent ($\sigma_{rr} = 0$). Since $\sigma_{rr} = -p + 2\eta\partial u/\partial r$, we can write

$$p\Big|_{r=R} = 2\eta\Big(\frac{\partial u}{\partial r}\Big)_{r=R}, \qquad p\Big|_{r=R_1} = 2\eta\Big(\frac{\partial u}{\partial r}\Big)_{r=R_1}. \tag{7}$$

From the continuity equation (6), we have

$$u = F(t)/r = R\dot{R}/r. \tag{8}$$

Differentiating relation (5) with respect to time and substituting it into (8), we obtain

$$u = -(1/(2r))(aR^2 + b).$$

Hence, according to (7), the pressure on the inner surface of the cylindrical liner has the form

$$p\Big|_{r=R} = \rho\nu(a + b/R^2). \tag{9}$$

The pressure on the inner surface of the copper ring considered ($\nu = 0.7 \cdot 10^4$ cm^2/sec) is estimated at 245 kbar at $\dot{R}_0 = 10^5$ cm/sec and 720 kbar at $\dot{R}_0 = 1.5 \cdot 10^5$ cm/sec when the inside radius becomes equal to

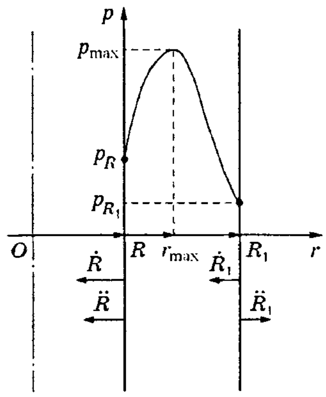

Fig. 1. Diagram of convergence of a viscous cylindrical liner to the symmetry axis. Pressure distribution over the liner thickness.

0.06 cm. It should be noted that the value of the kinematic-viscosity coefficient is chosen from a great body of experimental data on collapse of copper cylinders by layers of 50/50 TNT/RDX of various thicknesses [2]. Precisely for this value of the kinematic viscosity, experimental and calculated curves of $R_1 = R_1(t)$ coincide during the entire collapse of copper liners.

For rough estimation of the degree of compression of the material near the inner surface of the cylinder, we use the following Tait equation of state for metals:

$$p = B[\sigma^n - 1].$$

Here n and B are parameters that describe the liner material (for copper, $B = 2.5 \cdot 10^2$ kbar, and $n = 4$). Hence we find that $\sigma = 1.2$ at $\dot{R}_0 = 10^5$ cm/sec and $\sigma = 1.4$ at $\dot{R}_0 = 1.5 \cdot 10^5$ cm/sec.

The highest pressure is reached in the inner layers of the cylindrical liner. Integrating the second of Eqs. (6) with respect to the radius and taking into account (8), we obtain

$$p(r,t) = p_R + \rho\Big[\frac{(R\dot{R})^2}{2}\Big(\frac{1}{R^2} - \frac{1}{r^2}\Big) - (\dot{R}^2 + R\ddot{R})\ln\frac{r}{R}\Big],$$

where p_R is defined by relation (9) and ρ is the density. The pressure reaches a maximum value at $r_{max}^2 = (R\dot{R})^2/(\dot{R}^2 + R\ddot{R})$, which follows from the condition $\partial p/\partial r\Big|_{r=r_{max}} \equiv 0$. Finally, the pressure distribution over the liner thickness with time has the form (Fig. 1)

$$p(r,t) = \rho\nu\Big(a + \frac{b}{R^2}\Big) + \frac{\rho a^2}{2}\Big(R^2 + \frac{b}{a}\Big)\Big[\frac{1}{4}\Big(R^2 + \frac{b}{a}\Big)\Big(\frac{1}{R^2} - \frac{1}{r^2}\Big) - \ln\frac{r}{R}\Big], \tag{10}$$

and the radius for which the pressure is maximal is given by

$$r_{max} = \sqrt{(R^2 + b/a)/2}. \tag{11}$$

Expression (10) includes time via the dependence $R(t)$ defined by relation (6). In particular, from Eqs. (10) and (11) it follows that at a distance $R = 0.06$ cm from the symmetry axis for a copper ring moving at a velocity $\dot{R}_0 = 10^5$ cm/sec, the maximum pressure $p_{max} = 260$ kbar, and at $\dot{R}_0 = 1.5$ km/sec, we have $p_{max} = 1070$ kbar. These examples show that in the inner layers of the cylindrical liner, the effect of the pressure on the dynamic-viscosity coefficient amounts to the fact that the value of this coefficient can remain unchanged ($\eta = \eta_0$) or even increase in spite of the temperature increase in the layers adjacent to the inner surface of the cylinder.

From the calculations (see Tables 1 and 2) it follows that for liner particles located at a distance $r_0 = 1.01$ cm the rates of increase in temperature for copper and iron liners are $3 \cdot 10^8$ and 10^9 K/sec, respectively.

Martynyuk [7] showed that at heating times of 0.1–10.0 μsec, overheating of the metal liquid can proceed up to the limiting stable states determined by the spinodal. Under real conditions, overheating of the liquid is hindered because the liquid already contains centers (for example, gas inclusions). However, when the energy input is high, the fraction of the material evaporated through the free surface and the surface of nuclei is insignificant. In this case, there is a possibility for overheating of the liquid and close approach to the spinodal, which is the boundary of thermodynamic stability of the metastable liquid that corresponds to the liquid–vapor transition. Estimates show that nearly limiting overheating of the metastable liquid is possible at $\dot{T} \geqslant 10^8$ K/sec [7].

As the metastable liquid approaches the spinodal, fluctuations increase sharply. With intersection of the spinodal, the liquid phase loses thermodynamic stability and, as a result of explosion, enters a two-phase state. The liquid–vapor transition is determined primarily by the kinetics of homogeneous formation of vapor nuclei and not by the kinetics of evaporation through the interface. Formation of such nuclei is possible owing to the fluctuations in the liquid.

At the same time, the metastable liquid at $T/T_c = 0.88$ (T_c is the critical temperature) has considerable stability against fluctuations, which increase sharply only with approach to the spinodal. At $T/T_c < 0.88$, the transition of the metastable liquid to the two-phase state is determined by the mechanism of heterogeneous formation and growth of vapor nuclei.

At the specified pressure, the overheated liquid has excess enthalpy. For a point on the spinodal, we have

$$H_s - H_0 = \int_{T_0}^{T_s} C_p \, dt,$$

where H_0 is the enthalpy at the boiling point T_0 and C_p is the heat capacity of the liquid in the metastable region. In the explosive transition, this enthalpy is expended in partial evaporation of the liquid, as a result of which the temperature of the system decreases. The fraction of the liquid converted to vapor is $\beta_s = (H_s - H_0)/\lambda_0$ (λ_0 is the heat of evaporation at $T = T_0$). Thus, the phase explosion is characterized by the heat effect $H_s - H_0$ and the release of vapor β_s.

Calculations show that for the copper ring (see Table 1) even the inner layer is not heated to the spinodal temperature T_s. According to the Furt spinodal equation, the spinodal temperature is determined from the expression $P/P_c = 10(T/T_c) - 9$, and at $P_s = 0$ it is equal to $T_s = 0.9T_c = 4900$ K. Only when the radius $R = 0.1R_0$ is close to the radius of the copper cylinder $R^* = 0.05R_0$ [2] does the temperature of the inner surface and the adjacent neighborhood exceed the spinodal temperature 5700 K (see Table 2). In this case, explosive evaporation of the inner layer with a heat effect $H - H_0 = 1.1$ kJ/g (see Table 2) and gas release $\beta = 0.166$ is possible. For the iron cylinder, even at the stage of motion with constant speed $\dot{R} = 10^5$ cm/sec (see Table 1), the temperature of a layer with thickness 1 cm $\leqslant r_0 \leqslant 1.02$ cm is higher than the spinodal temperature ($T_s = 5700$ K). For the inner layer of the iron cylinder, the explosion parameters are as follows: $H - H_0 = 3.4$ kJ/g and $\beta = 0.54$. The heat effect of the explosion is comparable to that of an explosion of a TNT charge equal to 4.2 kJ/g.

Thus, for cylindrical or conical (with a small cone angle) convergence of the liner material to the axis, phase explosion is possible. Figure 2 shows an x-ray photograph of compression of a copper tube ($R_{10} = 1$ cm, $R_0 = 0.9$ cm, $\dot{R}_0 \approx 1$ km/sec) by a 50/50 TNT/RDX layer in the gliding detonation regime. The measured angle of convergence of the liner to the symmetry axis is about 15°. Inside the tube there are distinct separate liquid fragments of the inner layers of the liner that formed after explosion of these layers. In Figs. 2–4, time reading begins from the moment of initiation of the charge.

Figure 3 shows x-ray photographs of compression of a copper tube ($R_{10} = 1.43$ cm and $R_0 = 1.3$ cm) 60 mm high by a conical charge of 50/50 TNT/RDX with a cone angle $\beta = 30°$ in the regime of gliding detonation propagating from the base to the apex of the cone. In the region where the explosive layer is rather thick, the cylindrical liner converges to the axis at a small angle. Therefore, in the upper part of the liner, a phase explosion of the inner layers of the liner occurs, which ultimately leads to collapse of the upper part of the liner. In the liner regions located below along the pathway of the detonation wave, the convergence

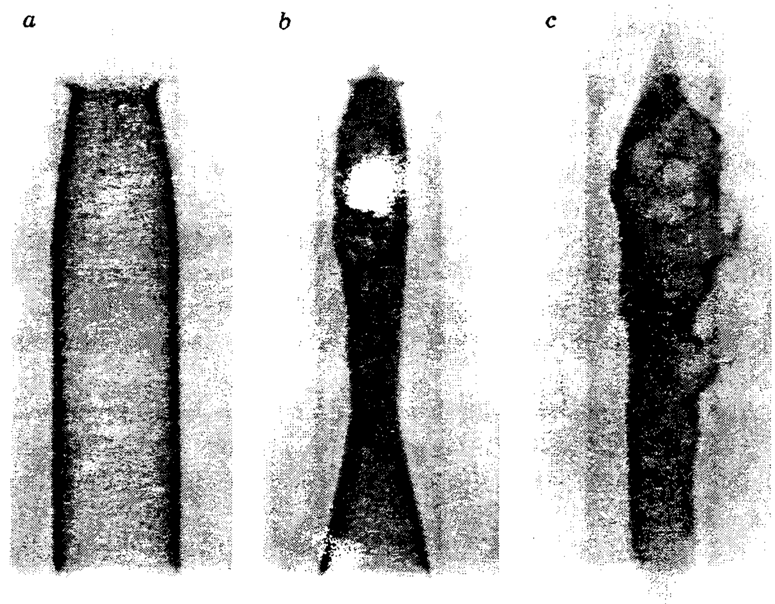

Fig. 2. X-ray photographs of compression of a copper cylindrical liner by a gliding detonation wave propagating along a coaxial charge (from top to bottom) at $t = 9.7$ (a), 17.4 (b), and 22.4 μsec (c).

angle increases progressively because the velocity of the annular elements of the liner located ahead is higher than the velocity of the elements that follow them since the explosive layer decreases progressively during detonation. Indeed, in the upper part of the copper tube, the thickness of the explosive layer reaches 19 mm, and in the lower part, it is 2.7 mm. Then, from the Gurney formula, the acceleration velocity is [8]

$$u = \sqrt{3/(k^2 - 1)}D\mu/(2+\mu) = \sqrt{3/8}\,D\mu/(2+\mu),$$

where μ is the ratio of masses of the explosive and the projectile per unit area. As $\mu \to \infty$, we have $u_1 = \sqrt{3/8}\,D$, and, hence, in the upper part of the tube, where the value of μ is large ($\mu = 2.7$), the acceleration velocity remains almost unchanged and collapse proceeds at constant velocity u_1. In the lower parts, where μ is small ($\mu = 0.385$ in the lower section of the tube), the acceleration velocity $u_2 = \sqrt{3/8}\,D\mu/2$ decreases during detonation in proportion to μ with simultaneous increase in the angle of collapse.

For large angles of convergence, the flow pattern changes, a shaped-charge jet and a pestle are formed, the picture of cylindrical liner collapse becomes two-dimensional, and the compression-velocity vector is not directed along the normal to the symmetry axis of the cylindrical liner. From results of the experiment it follows that the heating is much lower for parts of the liner that converge at large angles to the axis. In this case, a phase explosion of the inner layers of the liner does not occur. It is suggested that for conical liners, the inner layers must be heated more intensely for steel liners than for copper liners, and, hence, steel jets are heated more intensely than copper jets (for shaped charges with identical parameters). They can undergo a smooth transition to the two-phase state as a result of heterogeneous formation of vapor nuclei and their subsequent growth. Under slight overheating, phase transition of the metastable liquid occurs mainly as a result of growth of heterogeneous nuclei of vapor that arise at the available centers. Since the number of these centers is small and the rate of motion of the interface is about several meters per second [7], the time of phase explosion is rather large (weak phase "explosion.")

To clarify the effect of the physicomechanical properties of the liner material on the characteristics of the jets formed, we performed a series of experiments using flash radiography. In the experiments, we used a 50/50 TNT/RDX charge, whose lower part contained a liner of various metals. In the experiments, the cone

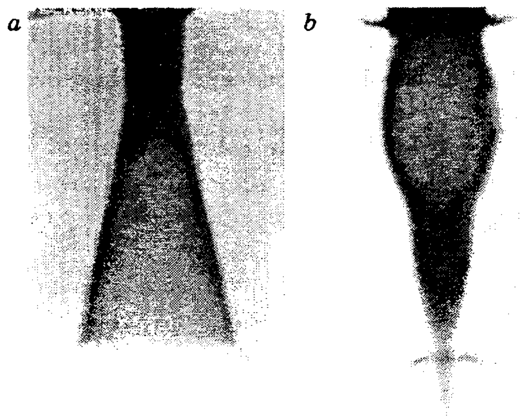

Fig. 3

Fig. 4

Fig. 3. X-ray photographs of compression of a copper cylindrical liner by a gliding detonation wave propagating along a coaxial charge from the base to apex of the cone (from top to bottom) at $t = 16.5$ (a) and 31.7 μsec (b).

Fig. 4. X-ray photographs of steel (a) and copper (b) shaped charge jets from a shapedcharge with a conical liner at time $t = 37$ μsec.

angle was varied ($2\alpha = 30, 45$, and $60°$) and the liner materials were various grades of steel (St. 3, St. 20, and 30KhGSA) and M-1 copper. The densities of these metals are approximately identical, and, hence, the kinematic characteristics of the shaped charges remained unchanged for various liner materials. In flash radiography at the same times, almost complete coincidence of the patterns of liner deformation and free motion of shaped-charge jets is observed (with superimposition of negatives on each other). Simultaneously, we determined the depth of jet penetration into a steel target.

The experiments show that steel jets break into separate fragments while copper jets continue to stretch at the same times without visible rupture. The elongation and breakup of a steel jet is accompanied by its softening (Fig. 4) and not by the "line formation" typical of copper jets at large elongation. Therefore, the depth of penetration into targets is always smaller for steel jets than for copper jets. for example, for charges with a conical liner ($2\alpha = 60°$) at a distance of 150 mm from a steel plate, the penetration depth is 195 mm for a copper jet and 110 mm for a steel jet (Fig. 4). We note that the breakup of a steel jet begins within 20–25 μsec after arrival of the detonation wave at the conical liner apex and does not depend on the cone angle in the examined range of angles $2\alpha = 30$–$60°$.

Thus, during operation of shaped charges with axisymmetric liners, overheating of the liner material is possible. This can initiate a strong phase detonation of the inner layers even at the stage of liner compression by the explosive detonation products or a weak phase "explosion," which leads to softening of the material at the stage of formation and motion of the shaped-charge jet.

The work was supported by the Russian Foundation for Fundamental Research (Grant No. 97-01-00826).

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