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SHEAR INSTABILITY AT THE "EXPLOSION PRODUCT–METAL" INTERFACE FOR SLIDING DETONATION OF AN EXPLOSIVE CHARGE

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Periodic perturbations at the "explosion product–metal" interface were studied experimentally. Experiments were performed for both spherical and plane geometry. Critical conditions of wave formation (detonation velocity of an explosive charge $D \geqslant 6.9$ mm/μsec) are determined, and an explanation of this effect is given. It is found experimentally that a dynamic pulse causes intense plastic strains at the "explosion products–metal" interface, leading to thermal softening of the steel boundary layer. In this layer, Kelvin–Helmholtz instability occurs. Calculation-analytical estimates of the critical boundary unstable wavelength agree satisfactorily with experimental results.

Kelvin–Helmholtz instability (shear instability) is hydrodynamic instability that occurs at the interface between two contacting flows having different tangential velocities [1]. Mathematical description of interface instability is approximate. Phenomena such as molecular diffusion (for gases or liquids capable of mixing), vaporization or condensation, and viscosity are commonly ignored. For simplicity, the Kelvin–Helmholtz instability was first determined for an idealized (incompressible inviscid) fluid. In the simplest form, the instability is described by the boundary conditions [2]

$$U(y) = \begin{cases} U, & y < 0, \\ U', & y > 0, \end{cases} \qquad \rho(y) = \begin{cases} \rho, & y < 0, \\ \rho', & y > 0, \end{cases} \tag{1}$$

where ρ and ρ' are the densities of the fluid layers and U and U' are their velocities, respectively.

Kelvin–Helmholtz instability is dynamic instability of the flow interface $y = 0$ for boundary conditions (1) including the case of $\rho = \rho'$ (homogeneous fluid) and $g = 0$ (g is the acceleration of gravity). Surface tension at the boundary $y = 0$ weakens the instability but does not eliminate it altogether.

From a mathematical viewpoint, the problem of Kelvin–Helmholtz instability in an inviscid fluid is an initial-value problem for an autonomous conservative Lagrange dynamic system with an infinite number of degrees of freedom. Equilibrium flow [under conditions (1)] is the state of equilibrium of a system whose stability can be studied using small-perturbation theory. According to this theory, an arbitrary small perturbation can be represented as a linear superposition of elementary wave solutions. The amplitude $a(t)$ of any kth elementary equation satisfies the ordinary differential equation

$$\frac{d^2a}{dt^2} = S(k)a. \tag{2}$$

The stability condition has the form $S(k) < 0$ for all k. Here $S(k)$ is the so-called perturbation growth factor, which is a function of wavenumber.

In the particular case of a plane interface described by relations (1), the elementary wave solution of the differential equation (2) corresponds to sinusoidal perturbations of the interface with an arbitrary wavelength $\lambda = 2\pi/k$. For a horizontal interface in a vertical gravity field (two fluids of different densities move at different

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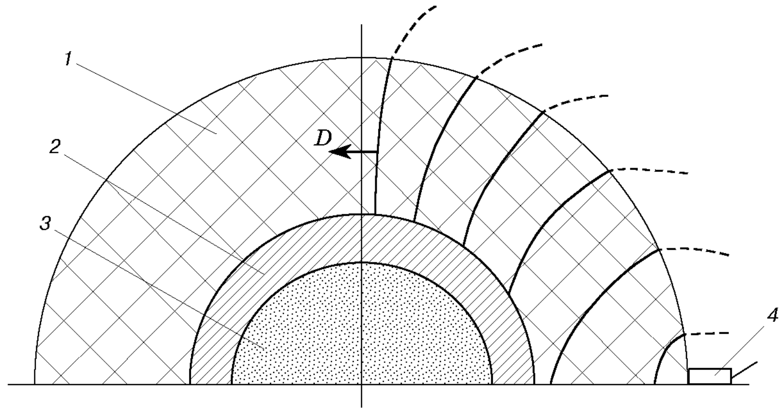

Fig. 1. Loading diagram in the experiment with spherical geometry: 1) spherical layer of the high-explosive (HE); 2) steel capsule; 3) glass powder; and 4) initiating element.

velocities), a sinusoidal perturbation of the interface with wavelength $\lambda = 2\pi/k$ increases as the exponential function $\exp(S(k)t)$ [2], where

$$S(k) = \frac{\rho\rho' k^2}{(\rho+\rho')^2}\,(U-U')^2 - \frac{\rho-\rho'}{\rho+\rho'}\,(g-\ddot{y})k - \frac{\sigma k^3}{\rho+\rho'}. \tag{3}$$

Here $\ddot{y}$ is the acceleration of the light layer, σ is the surface tension at the interface, and $k = 2\pi/\lambda$ is the wavenumber (introduced to symmetrize the plane-wave equation with respect to x and t).

The stability condition for relation (3) is written in the following form [2]:

$$4g(\rho-\rho')\sigma > \rho^2\rho'^2(U-U')^4/(\rho+\rho')^2.$$

Kelvin–Helmholtz instability is well understood for liquids and gases (gas–gas, gas–liquid, and liquid–liquid interfaces were considered) [1–5].

In recent decades, some experimental results on shear instability at the interface between two metals have been published [6–9]. However, the state of the interface between a strong medium (metal) and a strengthless medium (gas or liquid) under conditions of high-velocity relative flow has not yet been studied. The acceleration of plates by explosion products (EP) for sliding detonation of a high explosive (HE) charge is well understood and has been used for a long time (explosive welding, cladding, etc.); however, special features of the "EP–metal" interface after dynamic loading have not been reported. Mindeli et al. [10] found that an analog of a shape-charged jet is formed at the "EP–metal" interface (for sliding detonation of an EC), as suggested by the marks (cavities) produced by the jet on the metal target surface perpendicular to the direction of detonation-wave propagation.

Below, we give experimental results on the development of perturbations at the "EP–metal" interface for sliding detonation of an HE charge. The loading diagram is shown in Fig. 1. A loading device of spherical geometry was used. A spherical capsule made of St. 10 steel (outer radius $R = 87$ mm and thickness $\Delta = 4$ mm) was filled with a porous material (glass powder of bulk density $\rho \approx 1.4$ g/cm^3) and placed in a spherical layer of TNT ($\rho_0 = 1.6$ g/cm^3, $D = 6.9$ mm/μsec, outer radius $r = 127$ mm, and thickness $\delta = 40$ mm). In the experiments, the HE layer was in contact with the metal. After blasting, large periodic wave-like perturbations on the contact surface ("HE–metal" interface) of the steel capsule were observed. Figure 2 shows a macrophotograph of the surface fragment, and Fig. 3 shows a photograph of a microsection of the "EP–metal" contact surface. The perturbations are characterized by wavelength $\lambda \approx 2.5$ mm and amplitude $a \approx 0.22$ mm.

It is likely that Kelvin–Helmholtz instability was developed along the "hot EP–metal" interface. Data on the occurrence of shear instability during high-rate sliding of a gas along a solid surface were obtained for the first time.

It is worth noting that the perturbations develop steadily in the layer above which the angle between the front of the sliding detonation wave and the contact surface of the shell amounts to 90°.

Similar results were obtained in the experiments with plane geometry. The loading diagram is shown in Fig. 4. A plane HE charge (plasticized composition based on HMX of density $\rho = 1.86$ g/cm^3 and detonation-wave velocity $D = 8.75$ mm/μsec) was located on the surface of a steel plate (St. 3 steel). A sliding detonation wave was

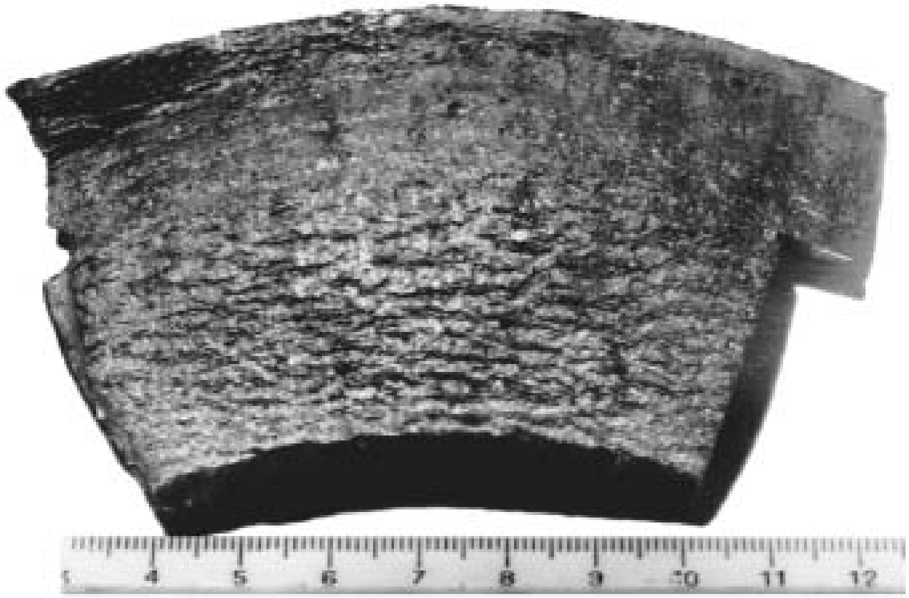

Fig. 2. Macrophotograph of a fragment of the outer surface of the steel capsule.

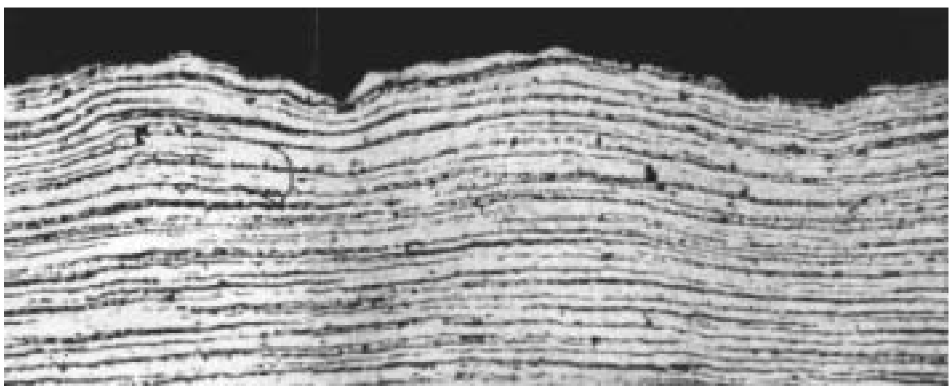

Fig. 3. Photograph (×25) of a microsection of the contact surface of St. 10 steel ($a \approx 0.22$ mm; $\lambda \approx 2.5$ mm).

initiated in the HE charge along the contact line. At a distance from the initiation point $L \geqslant 200$ mm, where the detonation-wave front is almost perpendicular to the plate surface, periodic wave-like perturbations were formed at the "EP–metal" interface (0.08 mm $\leqslant a \leqslant$ 0.1 mm and 1.8 mm $\leqslant \lambda \leqslant$ 2.0 mm), which were seen at the surface of the plate after the explosion (Fig. 5).

Apparently, the perturbations are formed due to Kelvin–Helmholtz instability at the "EP–metal" interface. Heated to a temperature of approximately 2000°C, the EP slide with a high velocity ($U = D/4 \leqslant 2.2$ mm/μsec) over the surface of the steel plate. Under these conditions, both tangential and normal velocities of the metal-layer material can be ignored. As a result of short-term dynamic action, intense plastic strains occur at the "EP–metal" interface. This leads to heating and thermal softening of a thin boundary layer of the metal. The metal is subjected to the dynamic action for time $t_1 \approx 8$ μsec (until the rarefaction wave from the external boundary of the HE layer arrives at the contact boundary).

For the experiment with spherical geometry, the thickness of the heated soft steel layer can be estimated from the relation

$$l \approx (\tau æ)^{1/2}. \quad (4)$$

Here l is the length of the heated layer, τ the time of temperature action, and æ is the thermal diffusivity.

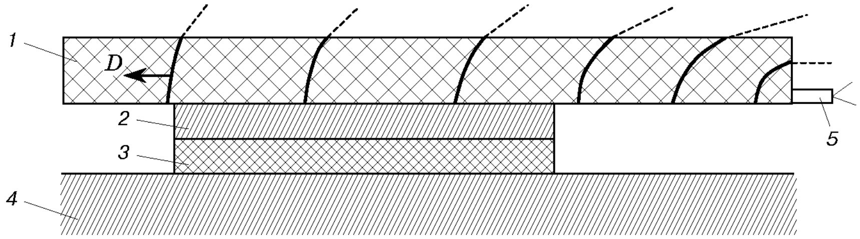

Fig. 4. Loading diagram in the experiment with plane geometry: 1) plane HE charge; 2) steel plate; 3) foamed plastics plate; 4) support; 5) initiating element.

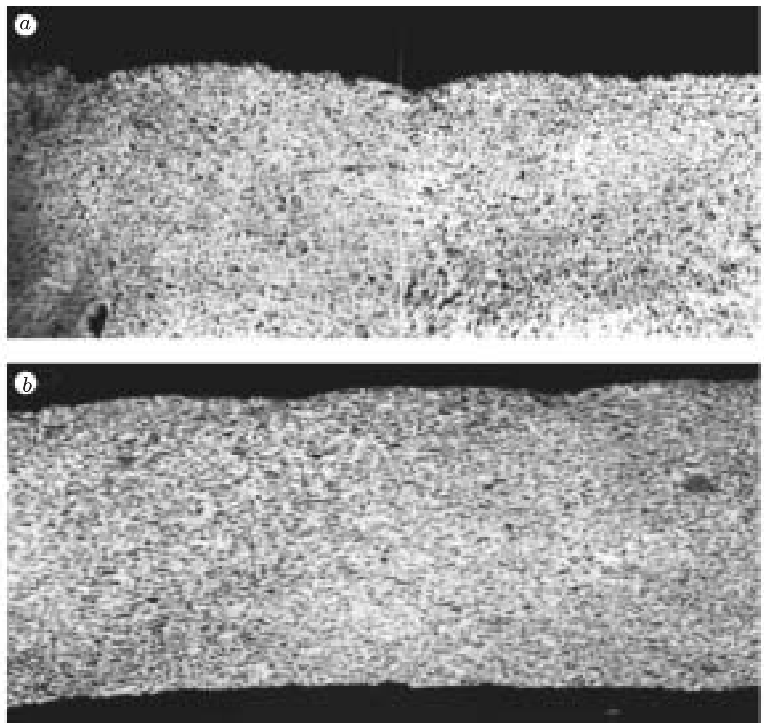

Fig. 5. Photographs ($\times 25$) of microsections of contact boundaries of steel (St. 3 steel): (a) $a \approx 0.1$ mm and $\lambda \approx 2$ mm; (b) $a \approx 0.08$ mm and $\lambda \approx 1.8$ mm.

From (4) it follows that $l \approx 130$ μm. In this layer, Kelvin–Helmholtz instability is caused by the action of the large rotational component of the tangential velocity. In the process, the metal layers adjacent to this layer are also involved in the perturbations. Therefore, the amplitude of the resulting perturbations ($a \approx 220$ μm) exceeds the thickness of the heated soft layer. Generally, the thickness of the unstable layer x is linked to the perturbation wavelength λ by the relation $a \approx \cos(kx) \exp(-2\pi x/\lambda)$. The maximum thickness of this layer is $x \approx \lambda/(2\pi)$. In the case considered above, $x \approx 400$ μm, which is the same order of magnitude as the perturbation amplitude a determined experimentally.

The initial perturbation ($a_0 \approx 10$ μm), determined by the initial surface roughness, increases by an exponential law until the perturbation amplitude equals the thickness of the soft layer. Further perturbation growth is limited by the strength properties of the metal.

Drennov et al. [11] considered the problem of evolution of small perturbations that occur when an ideal fluid slides over the surface of a strong material. This formulation of the problem corresponds to the case where one material slides over another material, whose layer adjacent to the contact surface lost strength.

In the elastoplastic approximation, the following critical condition for stability of the layer was obtained:

$$a_0/\lambda \leqslant (a_0/\lambda)_{\rm cr} \approx (\sigma_{\rm yield}/G)[(\mathrm{M_{cr}}/\mathrm{M})^2 - 1]/(4\pi\sqrt{3}). \tag{5}$$

Here σ_{yield} is the yield point of the layer, $\mathrm{M} = U/c$ is the Mach number, c is the velocity of the shear wave in the elastic layer, U is the velocity of the ideal-fluid layer, M_{cr} is the critical Mach number, which depends on wavelength, and G is the shear modulus of the layer material.

For wavelengths much smaller than the layer thickness, we have $\mathrm{M}_{\text{cr}} \approx 1.8$. In this case, relation (5) takes the form

$$(a_0/\lambda)_{\text{cr}} \approx (\sigma_{\text{yield}}/G)[(1.8/\mathrm{M})^2 - 1]/(4\pi\sqrt{3}) \approx (\sigma_{\text{yield}}/\rho)[(1.8/U)^2 - (1/c)^2]/(4\pi\sqrt{3}).$$

For many metals subjected to moderately strong shock waves ($\rho/\rho_0 < 0.05$), the estimate $(\sigma_{\text{yield}}/G)/(4\pi\sqrt{3}) \approx 10^{-3}$ is valid. For velocity of the explosion products $U \approx 2.2$ mm/μsec and velocity of shear waves in steel $c = 2.8$ mm/μsec, we obtain

$$(a_0/\lambda)_{\text{cr}} \approx 10^{-3}[(1.8 \cdot 2.8/2.2)^2 - 1] \approx 4.25 \cdot 10^3.$$

For standard roughness $a_0 \approx 10^{-2}$ mm, the critical wavelength is $\lambda_{\text{cr}} \approx 2.4$ mm. Perturbations with a larger wavelength do not grow. In the experiments with spherical geometry (the action on the material is most intense), the growth of perturbations with a wavelength $\lambda \approx 2.5$ mm was observed, which agrees with the estimate given above. In the experiments with plane geometry, perturbations with smaller wavelength grow.

In summary, the experimentally observed growth of perturbations at the "EP–metal" interface can be explained by Kelvin–Helmholtz instability, which is responsible for the short-term thermal softening of the near-boundary layer of the metal. The critical perturbation wavelength λ_{cr} was estimated. Perturbations with a larger wavelength do not grow.

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