work at RFNC – VNIIEF. I do not list the names because no sampling would be sufficiently representative. It can be said that we are discussing the science of RFNC – VNIIEF in broad terms.

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Hydrodynamic instabilities

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1. Introduction

This article presents results of experimental research on exploring hydrodynamic instabilities and turbulent mixing in liquid, gaseous, and strength media. In particular, it is shown that (1) the development of perturbations and turbulent mixing in gases is sensitive to the Mach number of the shock wave; (2) the speed of propagation of a gas front in liquids does not change as the Reynolds number increases from 5×10^5 to 10^7; (3) the stable and unstable regimes in media with strength depend on the wavelength and amplitude of initial perturbations; (4) hydrodynamic instability may serve as an instrument to explore the strength properties of materials.

One of the most ambitious and important scientific and practical problems is that of controlled nuclear fusion (CNF). The realization of the CNF idea turned out to be principally dependent, among other things, on one 'trifle' — the Rayleigh–Taylor [1], Richtmyer–Meshkov [2, 3], and Kelvin–Helmholtz [4] hydrodynamic instabilities. Arbitrarily small initial perturbations at the interface between different media begin to grow, which, with time, leads to a turbulent mixing of substances. As a result, energy losses occur, leading to limitations on the energy density required for ignition that can be accumulated in targets.

Research on the hydrodynamic instability and turbulent mixing has been carried out at the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics (RFNC–VNIIEF) beginning practically from its foundation date. In particular, the main results found by Taylor (1950) (for the so-called gravitational instability) were independently obtained by S Z Belen'kii and E S Fradkin from the Lebedev Physical Institute (FIAN); they took part in work on the atomic problem at that time, and their results were collected in a series of unpublished VNIIEF reports in the late 1940s and early 1950s. This research also proposed the first semi-empiric model for the evolution of the mixing zone [5]. In 1951, through the initiative of A D Sakharov, Yu F Alekseev, I G Proskurin, and N F Zelentsova carried out the first experimental studies on turbulent mixing on an interface between two liquids, the results of which have not been published even to date.

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In the middle of the 1960s, in experiments on a shock tube, E E Meshkov discovered that the interface between two gases is unstable not only when the shock wave (SW) travels from a 'light' gas into a 'heavy' one (according to Richtmyer's results) but also when the SW moves in the opposite direction [3]. Since then, the instability of the interface induced through a SW is referred to as the Richtmyer–Meshkov instability. In the early 1970s, in VNIIEF, V V Nikiforov started developing the first semi-empiric models of turbulence, and the first numerical simulations of turbulent flows saw their implementation at that time (V A Andronov, S M Bakhrakh, A V Pevnitskii, and others).

The first research in the USSR on the Rayleigh–Taylor instability in solids began at VNIIEF in the late 1950s and was associated with the names of A D Sakharov, R M Zaidel', A G Oleinik, and others. The overwhelming majority of their results were not published in the open press, except the series of studies [6].

Over the last decade, hydrodynamic instabilities in different media remained the subject of thorough research, both theoretical, assisted with physical and numerical modeling, and experimental. Experiments, being a source of basic data for verification of physical and numerical models, also serve as the source of information on fundamental laws of process development and properties of substances — their strength, rheology, and phase transitions.

In Sections 2–4, we sketch some directions and results obtained over recent years in classical shock-wave experiments in shock tubes and in explosion gasdynamic systems.

2. Development of turbulent mixing and perturbations at a contact interface between gases

Numerical simulation of flows affected by turbulent mixing requires experimental data to verify and test the models. The information currently available for this purpose (see, e.g., Ref. [7]) is insufficient for the emerging new tasks. To substantiate computational algorithms, in particular, we have carried out a set of experiments in air shock tubes on the evolution of turbulent mixing in three-layer gas systems: air – SF_6 – air, air – He – SF_6, and air – He – air [8]. The contact gas interfaces were arranged perpendicular or at an angle to the direction of the SW, or had breaks. Such location of interfaces resulted in a two-dimensional flow. The gases were initially separated by a thin polymer film (1 μm thick). The Mach number of the SW reached $M \approx 1.3$. The Kelvin–Helmholtz instability, in addition to the Meshkov–Richtmyer instability, was observed at contact interfaces (Fig. 1). A fairly complex flow was formed as a result of the interaction of rarefaction and shock waves with the interfaces, offering ample material to calibrate computational techniques.

When a contact interface between gases is accelerated by a strong shock wave (with the Mach number $M > 5$) or a series of waves passing in sequence through the gases, the gases can be compressed by a factor of several dozen. As a consequence, the contact interface between gases may approach the SW front [9]. In this case, the mixing zone or perturbations appearing at the interface may rest against the front of the SW, which affects the flow character.

To explore such a situation, a laboratory technique enabling research in gases at the SW Mach numbers $M \approx 10$ was proposed in 2002. Obtaining Mach numbers that high in a shock tube was made possible by detonating a gaseous

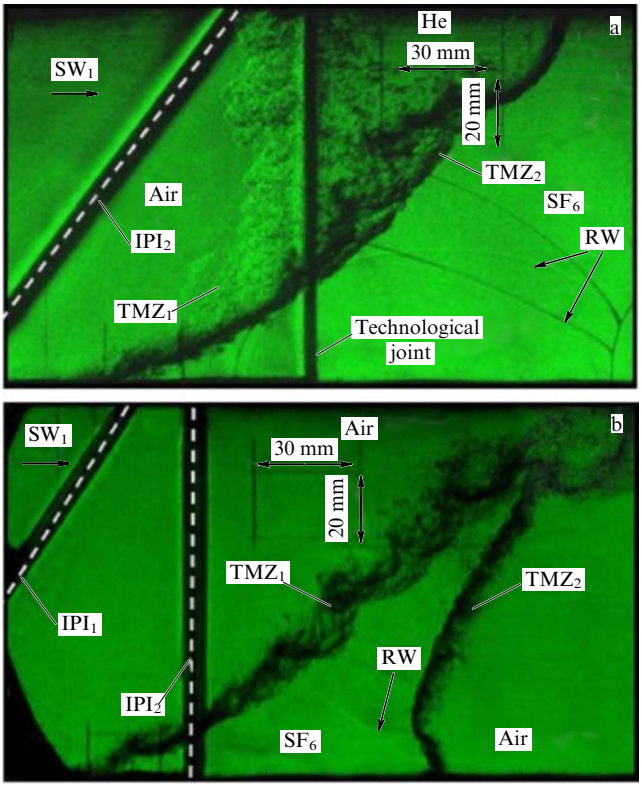

Figure 1. Photos taken in air shock tube experiments exploring the development of turbulent mixing in (a) air–He–SF_6 and (b) air–SF_6–air systems. $IPI_{1(2)}$ is the initial position of the interface, $TMZ_{1(2)}$ is the turbulent mixing zone, and RW is the reflected wave. The size of the reference mesh is 30 × 20 mm.

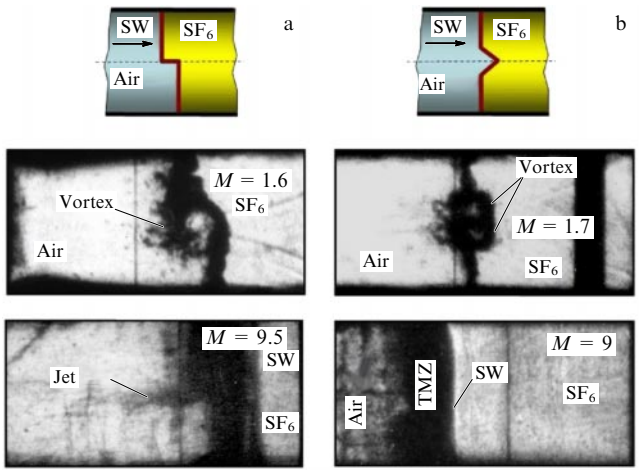

Figure 2. Moving image frames showing the development of two-dimensional local perturbations at the air–SF_6 interface with a contact boundary shaped as a step (a) and a triangular groove (b). M is the Mach number of the SW in SF_6.

explosive mixture ($C_2H_2 + 2.5O_2$) placed into a high-pressure chamber under excessive pressure [9].

Figure 2 displays moving image frames showing the development of two-dimensional localized perturbations at the air–SF_6 interface shaped as a break in the contact boundary (step) and as a triangular groove, which schematically represent possible technological defects of the shell of the nuclear fusion target. Variations in the SW Mach number led to different compression ratios of SF_6.

Experiments show that as the compression of the 'heavy' gas increases with the Mach number being increased, the character of the perturbation evolution changes: the perturbation is retarded by the adjacent shock wave (because of the SW proximity to the contact interface), which leads to its full suppression in the turbulent mixing zone; the mixing zone proper develops more vigorously.

3. Development of turbulent mixing and perturbations at a gas–liquid interface

It is known that for the Rayleigh–Taylor instability at the self-similar stage of turbulent mixing, the penetration depth of a 'heavy' substance into a 'light' one, h_{h-l}, of the light substance into the heavy one, h_{l-h}, and the full mixing zone width H are given by

$$h_{h-l} = \alpha_1 A g t^2, \qquad h_{l-h} = \alpha_2 A g t^2, \qquad H = \alpha A g t^2, \qquad (1)$$

where $A = (\rho_h - \rho_l)/(\rho_h + \rho_l)$ is the Atwood number, ρ_h and ρ_l are the densities of 'heavy' and 'light' substances, g is the acceleration, t is the time, and α_1, α_2, and α are constants characterizing the respective growth rates of h_{h-l}, h_{l-h}, and H. Different sources provide different values of α_1, α_2, and α.

Early experimental study [10] gave $\alpha_2 \approx 0.07$, while calculations in Ref. [11] gave $\alpha_2 \approx 0.05$. Later, Ref. [12] reported $\alpha_2 \approx 0.03$ from computations for ideal liquids, and experiments with mutually soluble liquids gave $\alpha_2 \approx 0.04$ [10]. In experiments on the gas–water interface at $g \approx 10^5 g_0$ (where $g_0 = 9.8$ m s^{-2}), gas temperature $\approx 2000\,^\circ$C, and pressure ≈ 400 atm (i.e., for the supercritical state of the surface liquid layer) and layer displacement $S \leqslant 25$ mm, Ref. [13] reports $\alpha_2 \approx 0.03$. The reasons for scatter in α_2 are still unclear. It was supposed that α_2 decreases with an increase in the Reynolds number of the flow.

To study this question, we constructed a plant enabling flows with Re $\approx 10^7$. In this plant, a liquid layer ≈ 3 kg in mass was accelerated by compressed gas. The acceleration reached $g \approx 10^3 g_0$, the layer displacement was $S = 350$ mm, and the mixing zone width H was equal to 200 mm [14]. The Reynolds number in the experiments was determined as

$$\mathrm{Re} = \frac{H\sqrt{AgH}}{\nu},$$

where $A \approx 1$ and ν is the kinematic viscosity coefficient in water.

It was found in experiments that for Re $\leqslant 10^5$ ($S < 50$ mm), $\alpha_2 \approx 0.11$, and as Re increases to $\approx 5 \times 10^5$ (50 mm $< S <$ 70 mm), α_2 decreases to 0.075. If Re increases further to $\approx 10^7$ ($S > 70$ mm), α_2 does not change. For $S > 70$ mm, the values $\alpha_1 \approx 0.26$ and $\alpha \approx 0.33$ were obtained. The zone asymmetry coefficient is $k = \alpha_1/\alpha_2 \approx 3$.

For the gas–liquid interface (under the conditions of heterogeneous mixing) for $g \approx 10^3 g_0$ and $5 \times 10^5 <$ Re $\leqslant 10^7$, we thus find the value $\alpha_2 \approx 0.07$, which coincides with the results of earlier experiments. Therefore, the reduction in α_2 to 0.03–0.04 cannot be explained solely by an increase in the Reynolds number. The value $\alpha_2 \approx 0.03$ can be related to a special case for particular experiments and computations. Research is needed to find the conditions under which α_2 decreases, because α_2 determines the physical scale of substance mixing.

The development of local perturbations in weakly compressible media can differ substantially from the development of perturbations in compressible media. According to Ref. [15], a hemispheric local perturbation (LP) at an unstable

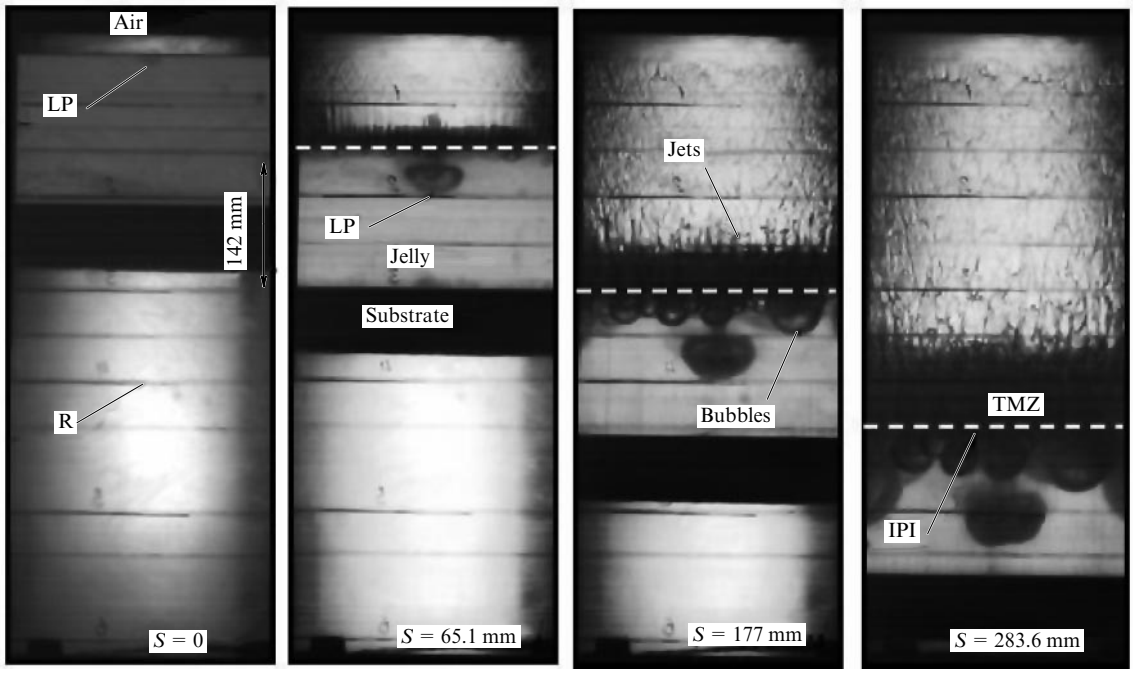

Figure 3. The development of a hemispheric local perturbation (LP) for various displacements of the contact boundary. R is the reference line. A 2.2% (low-strength) jelly of gelatine solution was used as a liquid, similarly to Ref. [16].

interface of an incompressible fluid approaches with time a self-similar regime of evolution. Papers [16, 17] show that as the initial radius of such a perturbation increases from $R \approx 0.5$ mm to $R \approx 3$ mm in the presence of a turbulent mixing zone at a gas–liquid contact interface, the velocity of its penetration in the liquid increases approximately twofold, i.e., self-similarity is absent. Experiments [16] and computations [17] were carried out for fairly small displacements of the contact interface ($S \approx 40$ mm). How does such a perturbation evolve for larger interface displacements? To clarify this question, additional studies were undertaken for layer displacements up to 350 mm.

It was found that a local perturbation initially evolves as in Ref. [16], in the form of a bubble (Fig. 3) ahead of the turbulent mixing front. For the layer displacement $S < 50$ mm, the speed of the perturbation penetrating into the liquid increases as the initial radius of the local perturbation increases, similarly to Refs [16, 17]. For the range of layer displacements $50 \text{ mm} < S < 350$ mm, the rates of perturbation growth become close, i.e., the process of perturbation evolution reaches the self-similar phase. The time it takes the perturbation to reach this mode increases as its initial radius increases. The development of such perturbations in shells of inertial nuclear fusion targets may result in their breakup.

4. Development of perturbations in media with strength

Until some time ago, the presence of strength in solids allowed assuming that they are free of problems with instabilities. But the stabilizing property of strength is lost when stresses exceed it. It is also known that the strength in dynamical nonstationary processes essentially depends on how the material was deformed — on the values of the pressure, temperature, and deformation rate. Additionally, if structural and phase transitions occur in a material under the action of intense dynamical factors, its strength can also change. Hence, it follows that hydrodynamic instabilities, apart from being a subject of research aimed at their eventual suppression, can also serve as a tool for enabling the strength properties and phase state of materials to be explored under extreme conditions.

In their studies of the Richtmyer–Meshkov instability, the authors of Ref. [18] assumed that as the SW intensity approaches values corresponding to SW metal melting, an abrupt reduction in the strength of the layered system is observed, which leads to the turbulization of the flow and the intense mixing of metals. This effect was indeed observed (Fig. 4) and triggered a series of publications and patents on inventions. However, the observed values of SW amplitudes at which the interface between metals becomes unstable correlate, but do not fully agree with computed parameters for the range of SW melting of the more infusible metal. This is most likely related to thermal strength loss in metals as the range of SW melting is approached from below.

As demonstrated in [19], periodic perturbations at the accelerated interface of an elastoplastic layer can increase up to some final magnitude and then perform periodic oscillations, i.e., the interface motion can be stable. But for a certain combination of parameters, an infinite growth in perturbations is possible, i.e., the Rayleigh–Taylor instability occurs. It was found that the boundary between stable and unstable modes in the amplitude (a_0) – wavelength (λ) coordinates obeys the approximate equation [19]

$$a_0^{\mathrm{c}} = \frac{2Y}{\rho g}\left[1 - \frac{4\sqrt{3}-1}{4\sqrt{3}}\exp\left(-\frac{2\pi h}{\sqrt{3}\,\lambda}\right)\right] \times \left\{\left[1 - \exp\left(-\frac{2\pi h}{\sqrt{3}\,\lambda}\right)\right]^2 - \left(\frac{\lambda}{\lambda_\infty}\right)^2\right\}, \qquad (2)$$

where Y is the yield point, ρ is the density, h is the layer thickness, $\lambda_\infty = 4\pi G/(\rho g)$ is the critical wavelength for elastic half-space, and G is the shear modulus.

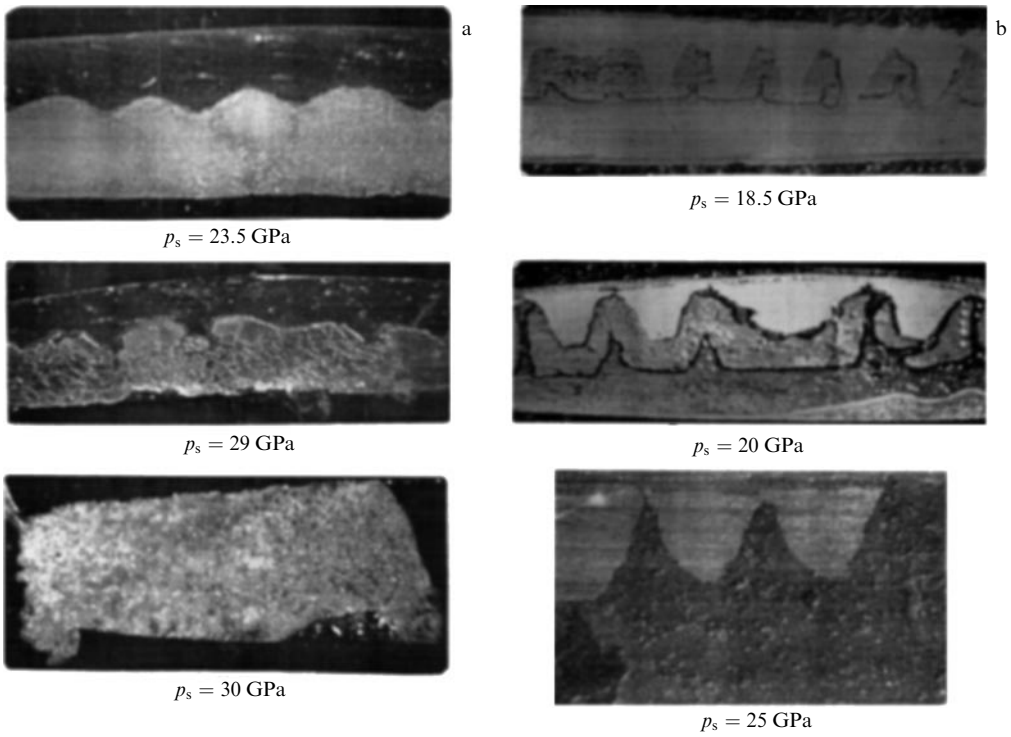

Figure 4. Development of the instability on an Sn–Cd metal interface with $\lambda_0 = 1.1$ mm and $a_0 = 0.2$ mm (a) and Pb–Bi with $\lambda_0 = 1.6$ mm and $a_0 = 0.2$ mm (b) as the SW pressure p_s is increased.

The 'plastic' and 'elastic' instability criteria were respectively proposed in [20, 21]. The Drucker criterion is valid for perturbations with wavelengths much smaller than the critical one ($\lambda \ll \lambda_c$), while the Miles criterion becomes relevant for perturbations with small amplitudes. As follows from Eqn (2), the stability domain in $a_0 - \lambda$ coordinates has a finite area and is realized for fairly small amplitudes and wavelengths. For a wavelength larger than the critical one, $\lambda \geqslant \lambda_c$, the interface is unstable for any perturbation amplitude.

In real SW processes, the layer acceleration has a pulsed character, and the instability domain is smallest at the instant of maximum acceleration. Although a steady boundary of the stability domain does not exist in this case, the growth of the perturbations for a certain combination of the initial amplitude and the wavelength of perturbations appears to be highly sensitive to the initial perturbation size, the value of the occurring stresses, and the real dynamical shear strength of the material.

This is the basis of the method of constructing and testing models of material strength — the dynamic perturbation method. Its essence is as follows. Periodic (or local) perturbations are applied to the surface of a layer of the substance to be explored. The sample is then subjected to pulsed acceleration — in our case, by products of the explosion of a chemical high explosive. The development of the perturbation in the course of liner motion is recorded with the help of the pulsed X-ray or protonographic technique.

A diagram of the method in the case of pulsed liner acceleration by the explosion products is shown in Fig. 5. Shown also are typical protonographic images of the liner obtained in a certain experiment [22].

In choosing a particular model of metal strength, the model parameters are determined by fitting the results of numerical simulations to experimental data on the development of perturbations. The advantage of this method is that by varying the rate and amplitude of the impact and the wavelength and amplitude of perturbations in the case of explosions in planar or cylindrical geometry allows finding the parameters of the constitutive matter equation $Y_d = f(\sigma, T, \varepsilon, \dot{\varepsilon}, \ldots)$ in the pressure range $p \approx 10-300$ GPa, the deformation rate range $\dot{\varepsilon} \approx 10^5 - 10^9$ s^{-1}, and the temperature range from normal to metal melting temperatures.

This method is now used by many laboratories worldwide that deal with extreme states of matter [23, 24] and use not only explosion but also other systems.

One of the principal results obtained with the perturbation method was the discovery of a noticeable excess of the dynamic yield threshold for some metals under quasi-isentropic load ($\dot{\varepsilon} \approx 10^5 - 10^6$ s^{-1}, $p \approx 30-50$ GPa) over that under SW load ($\dot{\varepsilon} \approx 10^8$ s^{-1}). Just behind the SW front, a metal behaves as if it were losing strength over a time interval $\approx 0.1-0.5$ μs and then quickly regained it. The explanation, as currently conceived, consists in the 'instantaneous loss of strength' in narrow ($l \approx 1$ μm) bands of localized shear with the period ≈ 10 μm between them, with a subsequent fast (≈ 1 μs) relaxation of flow. The heterogenous character of the flow behind the SW front is confirmed by independent registration of the metal free surface speed by methods of Doppler diagnostics [25].

Of practical interest is a particular case of the Richtmyer–Meshkov instability when an SW hits a free surface of condensed matter, which is manifested through a microcumulative ejection of the advancing cloud of finely dispersed particles. The main causes of this effect are the initial perturbations of a regular and chaotic character: the roughness of the free surface, structural inhomogeneities of the material, and heterogeneity of the flow behind the SW front mentioned above [26]. Figure 6 presents a moving image frame showing particle ejection from a free surface of a lead

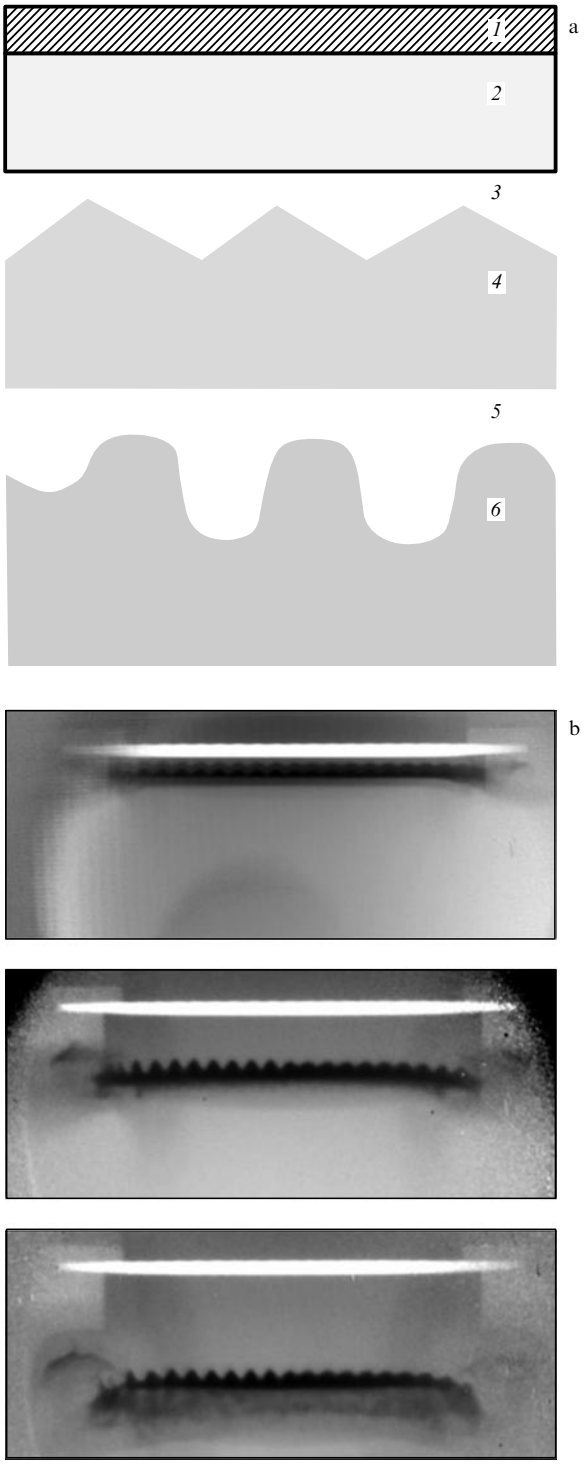

Figure 5. (a) Schematic illustration of the process of pulsed acceleration of a liner: *1* — the generator of a plane detonation wave, *2* — high explosive, *3* — vacuum gap, *4* — the sample in its initial state, *5* — products of explosion, *6* — the sample in motion. (b) Protonographic image of the liner.

sample under the action of an SW with the intensity 15 GPa, obtained by high-speed microscopic electronic-optical recording with pulsed laser illumination [27].

Gravitational instabilities also play a dominant role in the explosive volume expansion, breakup, and dispersion of metals as they melt in an SW and the rarefaction wave that follows [25].

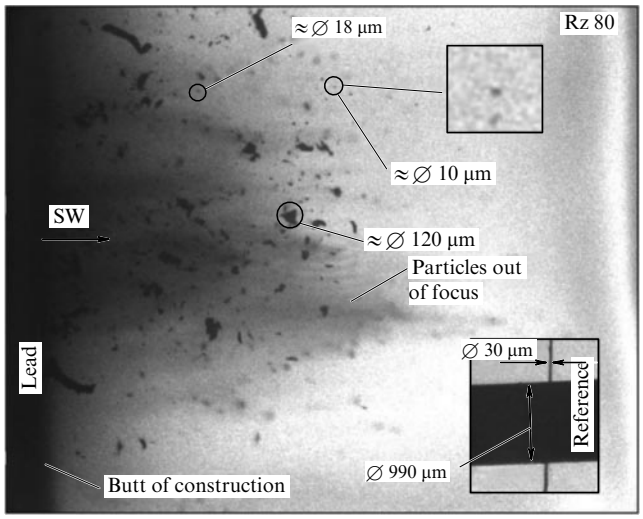

Figure 6. Moving image frame of particle ejection from the free surface of a lead sample under the action of an SW with the intensity 15 GPa. The inset in the right bottom corner shows reference scales that help determine the sizes of ejected particles. Rz 80 is the parameter of surface roughness.

The Kevin–Helmholtz instability in metals in its pure form (free slip) is described in Ref. [28], but much more frequently it is detected in regimes of explosive welding — for the oblique impact of plates with the phase speed of the contact point $U_c < c_0$, where c_0 is the speed of sound in the bulk of the metals to be welded.

The dependence of the amplitude of perturbations of a shear nature, generated under similar conditions of explosive welding, on the Mach number, $a = f(M)$, was obtained for certain metals. It reaches a maximum in the vicinity of $M \approx 1.3-1.5$, at which a flow mode with detached shock waves is overtaken by that with waves attached to the impact point.

The most impressive results of this research are the unexpectedly high and dynamic plasticity of beryllium, fragile under static conditions, and the capability of thin (≈ 10 μm) galvanic coatings to suppress the development of shear instabilities [29].

The authors are indebted to all their colleagues at the Institute of Experimental Gas Dynamics and Physics of Explosions (IPE) at RFNC–VNIIEF, whose efforts and collaboration made the results presented here possible.

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Extreme states of metals: investigation using shock wave techniques

R F Trunin

1. Introduction

The beginning of the research reviewed here dates back to 1947, when the gasdynamics scientists of KB-11 [presently the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics (RFNC–VNIIEF)] were given the task of investigating the shock wave properties of the substances used in the design of the atomic bomb developed in the USSR. These properties were required to select its design on the basis of calculations, because the properties-based equation of state, i.e., the relation between pressure, density, and energy, closed the system of equations of motion and thereby allowed estimating the parameters of compression of the active and other substances.

Our pioneers of experimental investigations in this area were L V Al'tshuler, K K Krupnikov, V A Tsukerman, B N Ledenev, V I Zhuchikhin, S B Kormer, and their collaborators. Scientists of the theoretical divisions, Ya B Zel'dovich, E I Zababakhin, G M Gandel'man, N A Dmitriev, V P Kopyshev, and others, actively participated in the development of research methods and the interpretation of the data obtained. The contribution of Yu B Khariton was inestimable as regards the scientific organizational aspects.

The techniques proposed for determining the parameters of shock-compressed substances enabled making the first measurements of their characteristics already in 1947.

The first substance whose properties had to be known to ensure the success of a bomb test was the explosive that was part of the bomb. Many are familiar with the epic work to obtain the detonation parameters of this explosive (see, e.g., Ref. [1]), and I do not therefore enlarge on this issue. I merely mention that only owing to Zel'dovich was it possible to eliminate the existing discrepancies between detonation parameters and thereby resolve the burning problem of the bomb test.

Uranium became the first metal investigated in 1947; its compression was studied at pressures up to 500 kbar.

The measurements were initially made using the spall technique; owing to its low precision, it soon gave way to the absolute method of 'deceleration' [2] and the method of 'reflection' [3] based on its principles.

The majority of measurements whose results are partially outlined in Sections 3–5 were carried out using the last two techniques. According to them, two kinematic parameters are determined from experiments: the shock velocity D in a sample and the velocity of motion of the substance behind the front, the so-called particle velocity U.

The shock velocity is easily determined in both techniques: all that has to be done is, in the path of wave propagation, to place sensors of an arbitrary type that react to the high pressures of the front and to record the time of wave passage between them.

Special methods were introduced for determining the particle velocity, permitting indirect determination of this parameter. The reader can become familiarized with them using source materials [2, 3]. Here, I only recall that according to the deceleration method proposed by Al'tshuler, the velocity W of a striker (liner) approaching a target is precisely equal to the doubled value of the particle velocity U in the target (when the liner and the target consist of the same material). Applications of the reflection method (Al'tshuler, Krupnikov, and Gandel'man) require the knowledge of the equation of state of the material of the screen that covers the samples on the side of the approaching shock wave and the parameters of this wave in the screen. The particle velocity U in the substance under investigation is found by considering the decay of an arbitrary discontinuity in the pressure–particle velocity diagram.

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