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SPECIFICATION AND EVOLUTION OF LOCAL (PERIODIC) PERTURBATIONS IN EXPERIMENTAL STUDIES OF THE RAYLEIGH–TAYLOR INSTABILITY IN STRONG MEDIA

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Various techniques for specifying the initial local or periodic perturbations on the boundaries of strong solids are discussed. The evolution of a local perturbation is studied experimentally. It is shown that the "mass inhomogeneity" of the perturbation zone and the geometrical dimensions of an insert play an important role in the perturbation transformation.

Instability of perturbed interfaces and the free surface of a substance that moves with varying acceleration is of considerable interest for researchers in various fields of high energy density physics. Traditionally, studies deal with the Rayleigh–Taylor instability caused by the acceleration applied to an interface of media with different densities whose vector is normal to the interface and directed from a medium of lower density [1], the Richtmyer–Meshkov instability which occurs when a stationary shock wave (SW) propagating perpendicularly to an interface of media with different densities travels through this interface [2], and the Kelvin–Helmholtz instability which occurs if there is a discontinuity in the tangential component of the velocity field [3]. It should be noted that these phenomena have been studied extensively for substances in the liquid and gaseous states. The instability in strong solids is less understood, and the available publications are fragmentary and contradictory. Nevertheless, experimental [4–8] and numerical-theoretical investigations within the framework of the ideal elastic [9] and ideal yielding [10–12] models of the medium have shown that the rheological properties of the medium (strength and viscosity) stabilize the development of the boundary and surface perturbations. Depending on the models of the medium used, the following perturbation parameters are taken as criteria that determine the transition of the perturbed surface from a stable to an unstable region: the critical wavelength [9, 10], the critical initial amplitude [13], and their combination [11].

Various techniques for specifying the initial local (periodic) perturbations are known. Their choice often depends on whether the technique is convenient for numerical calculations. It is therefore reasonable to dwell on the question of specifying the initial local and periodic perturbations on the boundaries (surfaces) of strong solids, the instability of which is studied in experiments.

Apparently, Barnes et al. [4, 5] were the first who obtained experimental instability results for the boundaries in strong media. In their experiments, sinusoidal perturbations were specified in the form of grooves on the surface of steel and aluminum plates accelerated by a high-explosive (HE) charge. It should be noted that because of "mass inhomogeneity," the thinner parts of the plate are bound to acquire higher velocities. By the mass inhomogeneity, we understand the difference between the specific masses in the perturbed and unperturbed regions, normalized to the specific mass in the unperturbed region. Therefore, the process considered can be affected by the increase in the perturbation amplitude because of the mass inhomogeneity: $\Delta t/t \simeq \Delta m/m$. Moreover, Lebedev et al. [8] showed that, for the same technique of

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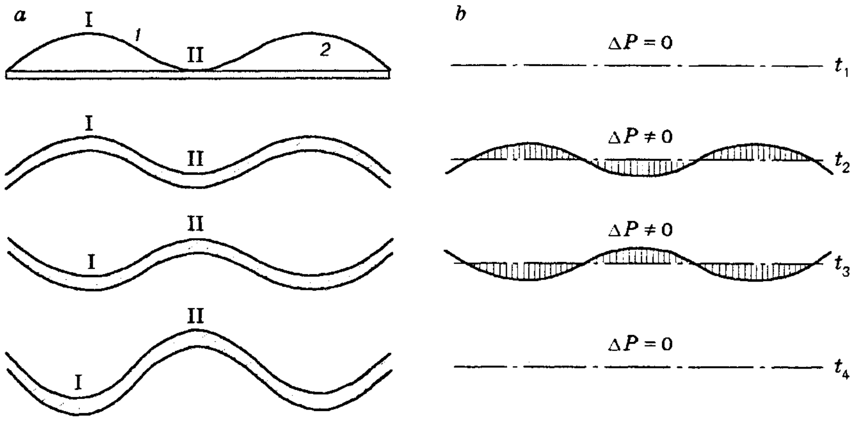


Fig. 1

specifying perturbations on aluminum plates, the plate material tears along the grooves.

For accelerated plates, Ivanov et al. [6] specified a local near-sinusoidal perturbation by the curved front of a shock or detonation wave (DW) generated in a screen or in an HE layer adjacent to this wave in the loading by a curved striker. For cylindrical shells, Ivanov et al. [7] also specified the initial periodic sinusoidal perturbations by the curved front of a DW generated by the multipoint initiation of an HE charge over its external surface. These techniques of specifying the initial perturbations are more appropriate for practical purposes such as the high-rate throwing and deceleration of metal liners, the problems of inertial thermonuclear fusion, etc. In this case, however, there are certain specific features of the evolution of initial perturbations that are associated with pressure nonuniformity ("dynamic inhomogeneity") behind the curved front of a DW or SW when these interact with the plate (shell) investigated. By the dynamic inhomogeneity, the difference between the pressure-pulse distributions in the profile $P(t)$ in the perturbed and unperturbed regions is meant. Figure 1a and b shows, respectively, the evolution of the plate form and the excess pressure profiles for the case where the curved DW front reaches the plate (1 for the DW and 2 for the plate). In this case, owing to the convergence, the lagging parts of the front (region I) are followed by the high-pressure zones ($\Delta P_+ > 0$), and the leading parts of the front (region II) are followed by the low pressure zones ($\Delta P_- < 0$). The absolute values of ΔP_+ and ΔP_- depend on the curvature of the corresponding parts of the front. Since the ΔP have opposite signs behind the lagging and leading parts, the lagging parts of the plates acquire higher velocities and are ahead of the neighboring parts. At first sight, the perturbations must increase unlimitedly due to the difference between the velocities of regions I and II. However, this is not the case, since the relation between ΔP_+ and ΔP_- and the difference between the velocities do not remain unchanged. The local high- (low-) pressure zones that appear at the initial moment generate spherical compression (extension) waves, and the compression regions are replaced by the extension regions when the oscillation amplitude ΔP decreases monotonically. Indeed, the experiments on thin plates accelerated in air and vacuum [6] showed that the specific feature considered, which is associated with the dynamic inhomogeneity of the curved SW front, causes the phase of the initial perturbation to change and has no effect on its amplitude at subsequent times. This is supported by experimental results on the acceleration of plates upon multipoint initiation of an HE charge [14]. At the same time, it was pointed out in [14] that if the value of ΔP is comparable with the strength of the plate material, the perturbation transformation, for example, doubling of its frequency, can occur owing to the dynamic inhomogeneity.

Below, we give results of an experimental study of another technique for specifying the initial local perturbations to study the Rayleigh–Taylor instability in strong media. The structure composed of two plates of different densities, say, aluminum and steel plates. In one of the plates, there is an insert to specify a perturbation (Fig. 2a refers to $\rho_4 > \rho_2 > \rho_1$, and Fig. 2b to $\rho_4 > \rho_2 > \rho_3 > \rho_1$). This geometry of the structure makes it possible to vary and control the characteristic initial and current parameters of the

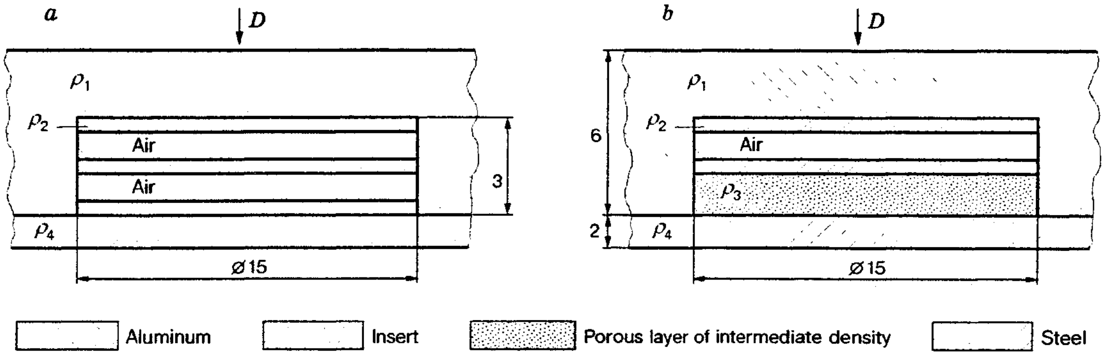


Fig. 2

developing instability:

— one can deform the shock-wave front by the choice of the density ratio and geometrical dimensions of the insert (Fig. 2) with a view to obtaining the required shape and amplitude. Based on the specification conditions of a local perturbation, the SW parameters are readily calculated for one- and two-dimensional geometries;

— the specific mass can be perturbed locally by varying the mass in the perturbation zone and keeping, for example, the SW curvature fixed. This technique allows one to estimate the effect of a certain physical quantity on the instability development (for a specified local perturbation);

— one can create perturbations in the pressure amplitude of the SW and in the pressure distribution behind the SW front, i.e., one can generate a pressure profile of the required shape and duration in the SW. This effect is also produced by fitting the densities and geometrical dimensions of the insert.

The structure is accelerated by the explosion products after the HE charge detonates. In the process, the acceleration is directed from a light (aluminum) to a heavy (steel) layer, and the conditions are created for the Rayleigh–Taylor instability. As in [6, 15], in our experiments the behavior of the surface of a steel plate in the neighborhood of an insert was investigated by a photochronographic method with the use of an optical receiver with a cut-off, located at different distances l from the plate surface. Experimental results are listed in Table 1, where Δt is the "time inhomogeneity" of the part of the steel plate in the neighborhood of the insert (by the time inhomogeneity, we mean that the different parts of the plate intersect the plane of the optical receiver asynchronously), $\Delta m = (m_{\rm p} - m)/m$ is the mass defect introduced by the insert material, the minus or plus sign of the Δm shows that the region with the insert is lighter or heavier than the unperturbed region, respectively, and $m_{\rm p}$ and m are the masses of the perturbed and unperturbed regions, respectively.

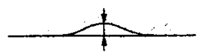
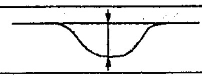
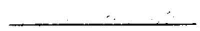
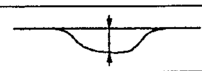
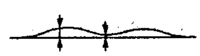
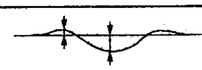
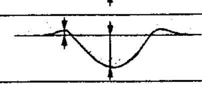
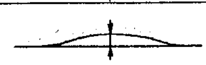
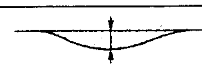
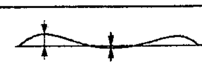
From Table 1 follow the same specific features associated with the perturbation evolution as those in the above cases of a curved SW or DW front. Immediately under the insert, an SW emerges with a certain lag Δt determined by the difference in the SW velocities.

During the flight of the plate, the perturbation of the plate free surface in the region under the insert changes sign: the lag transforms into advance independently of the mass inhomogeneity, the value of which varied within the limits $-8\% < \Delta m < 8\%$. For $\Delta m = -8\,\%$ and $\Delta m = 0$, the perturbation changes sign at the initial stage of plate motion ($l \leqslant 5$ mm), and, for $\Delta m = 8\%$, the perturbation changes sign at subsequent stages.

For the same gauge length, the change in the mass of the local perturbation toward positive Δm leads to a decrease in the advance perturbation. The lag occurs under the edges of the local perturbation, but the region that corresponds to the perturbation center remains ahead. As noted above, the lag under the local perturbation is determined by the difference between the SW velocities in the plate and the perturbation zone.

The unloading waves that form on the boundaries of the zones moving at different velocities decelerate

TABLE 1

Local perturbation scheme	Free-surface profile of steel plate	l, mm	Δm, %	Δt, μsec
$\rho_4 > \rho_2 > \rho_1$		0	−7.4	0.31
		2	−7.1	~0
		5	−7.0	+0.32
		10	−7.1	+0.69
		0	~0	−0.29
		2	~0	~0
		5	~0	+0.14
		10	~0	+0.20
		20	~0	+0.47
		2	+7.9	−0.19
		5	+8.1	−0.22
		10	+7.9	−0.28
		20	+7.9	+0.39
		30	+7.9	+0.62
$\rho_4 > \rho_2 > \rho_3 > \rho_1$		0	~0	−0.15
		20	~0	+0.28
		20	+8.5	+0.26
		20	+10.7	+0.22

the flight of the unperturbed region in the plate. As a result, the lag zone (dent) moves at higher velocity, and an advance perturbation (convexity) forms. Charging the perturbation zone ($\Delta m > 0$) smooths out the effect of the rarefaction wave.

In summary, it is noteworthy that in the large-diameter perturbation tests performed (the insert diameter is 30 mm), with other things being equal, the character of evolution of the local perturbation as a whole remains the same, and the replacement of a steel layer by a lead layer results in an increase in the perturbation amplitude. Thus, the above technique for specifying local perturbations makes it possible to vary and control the initial and current perturbation parameters in studying the instability in strong media.

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