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SOME GEOMETRICAL EFFECTS IN THERMOMECHANICAL FAILURE OF METALLIC SPECIMENS UNDER PULSED RADIATION

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Without considering the possible geometrical effects resulting in stress cumulation, cumulative ejection of materials, and loss of stability, the prediction of stability of elements and units of pulsed power and radiation plants to the destructive effect of penetrating radiation due to the rapid energy release in the interaction of penetrating radiation with the materials of structure members can be insufficiently correct and lead to erroneous conclusions. These effects can occur, for example, under the pulsed action of strong fluxes of penetrating radiation on objects of complicated geometry: cones, conical shells, discs, and rods.

The possibility of cumulation of tensile stresses is due to wave processes occurring under thermal shock. In a hydrodynamic formulation the effect of cumulation of stress waves under thermal shock was first studied by N. N. Kholin [1]. The magnitude and place of stress cumulation depend on the object geometry, the heating region, and the spatial distribution of heat sources. Generally speaking, the stress-cumulation effect occurs always, even under complete and uniform heating of a plate. This is the main factor that points to the insufficiently correct solution of such problems in a one-dimensional formulation.

Aptukov and Pozdeev [1, 2] studied wave processes under thermal shock in a two-dimensional axisymmetric formulation and showed that in instantaneous complete uniform heating of an aluminum plate to 430°C (diameter-to-length ratio $D/h = 6$ and $h = 1$ cm) stress waves are cumulated on the periphery, whereas in the case of a compact cylinder ($D = h = 1$ cm) the tensile stresses on the axis exceed the initial compressing stresses by a factor of 3.4. In the region of stress-wave cumulation, the material starts to fracture intensely.

Investigation of the evolution of macrocracks under thermal shock in a plate and a compact cylinder [1, 2] within the framework of a damaged thermoelastoviscoplastic continuum model [3] showed that the position of the macrodamage zone due to stress cumulation depends on the geometry of the heated zone. In a compact cylinder the macrodamage zone is located along its axis, whereas in a uniformly heated plate the macrodamage zone occurs at the center of the peripheral part of the plate.

The goal of this work is to formulate the problem and register experimentally the geometrical effects resulting in stress cumulation, cumulative ejections of material, and the loss of stability under the action of powerful pulsed x-ray radiation fluxes of nuclear explosion on cones, conical shells, discs, and rods.

The geometrical effects were registered on rods with suspended discs, conical shells with angles of the cone 90 and 45° (with base diameter 25 mm), and solid cones with base diameter 12 mm and cone angles of 62 to 5°. The specimens were made of D16T aluminum alloy and St. 3 steel.

The tested specimens were located so that their axes were parallel to the direction of irradiation. In the experiments materials were heated by the x-ray radiation of a nuclear explosion almost instantaneously and nonuniformly over the thickness of the structure (in essence, subsurface heating), and this gave rise to a strong pressure pulse. The following data demonstrate the degree of nonuniformity of heating of aluminum specimens by thermal shock. At depth $\Delta Z_1 \approx 0.055$ mm from the surface (facing the x-ray radiation source) of

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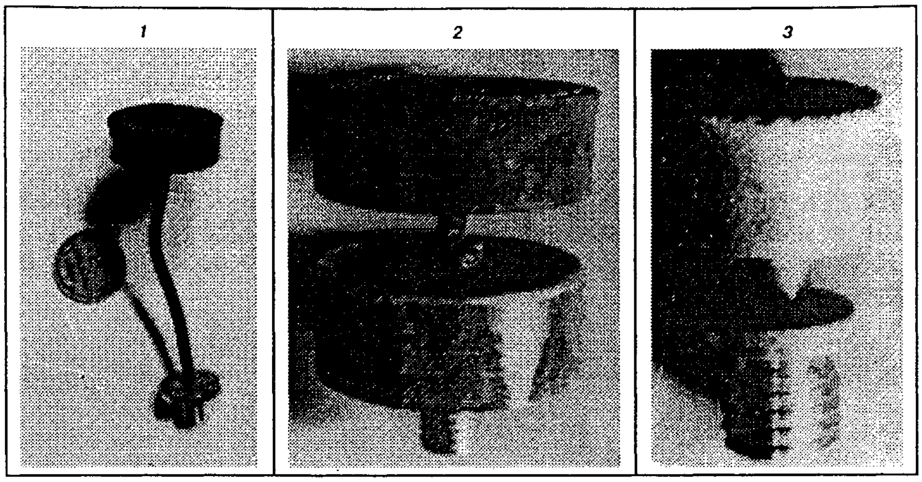

Fig. 1

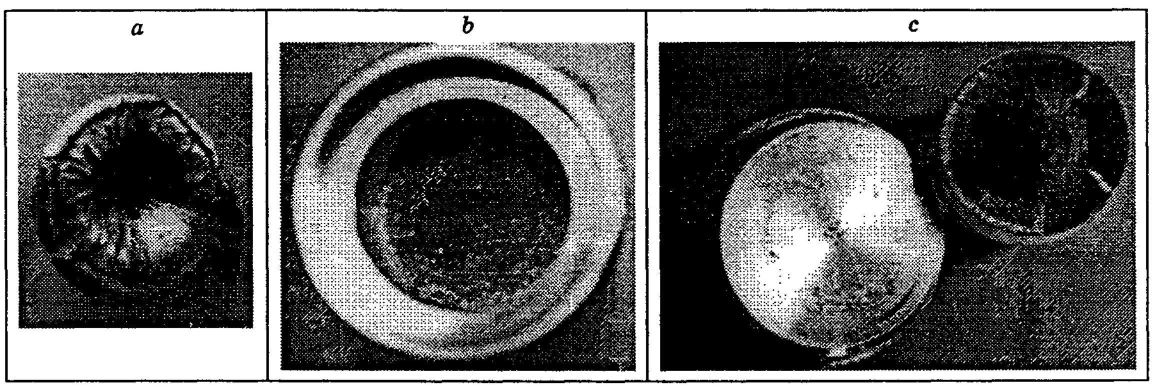

Fig. 2

the aluminum disc the concentration of absorbed energy was 50% of the concentration of the energy absorbed by the face surface of the aluminum disc, 20% at $\Delta Z_2 \approx 0.25$ mm, 10% at $\Delta Z_3 \approx 0.5$ mm, 5% at $\Delta Z_4 \approx 1$ mm, and 0.27% at $\Delta Z_5 \approx 10$ mm. The concentration of the absorbed energy decreased by a factor of 10 at depth $\Delta d_1 \approx 0.3$ mm of the subsurface layer in a conical aluminum specimen with a cone angle of 62° and at $\Delta d_2 \approx 0.03$ mm in a conical aluminum specimen with an angle of 7°. The failure pattern of the specimens subjected to thermal shock depended on the x-ray radiation intensity, on the geometry of the specimens, and also on the physicochemical properties of the materials of the specimens.

The effects of thermal shock on rods with suspended discs, conical shells, and solid cones of D16T aluminum alloy subjected to identical radiation conditions are shown in Figs. 1–5. Five cones were irradiated by an x-ray radiation fluence greater by a factor of 3.5. The view of the cones from above (a) and from the side (b) after exposure is demonstrated in Figs. 6a and 6b. Figure 7 shows magnified images of the cones. It should be noted that the maximum energy release on the face (facing the radiation source) side of the objects is 10.7 kJ/g and 37.45 kJ/g in the first and second cases, respectively.

The wave processes of compression–unloading in relatively compact discs of D16T aluminum alloy subjected to thermal shock (ratios of the diameters of discs 1–3 in Fig. 1 to their thicknesses are $D_1/h_1 = D_2/h_2 = 2.5$ and $D_3/h_3 = 1.2$, with $h_1 = h_2 = h_3 = 10$ mm) led to cumulation of tensile stresses, which resulted in a marked separation of the peripheral zone from the central part of the discs (see Fig. 1). Traces of

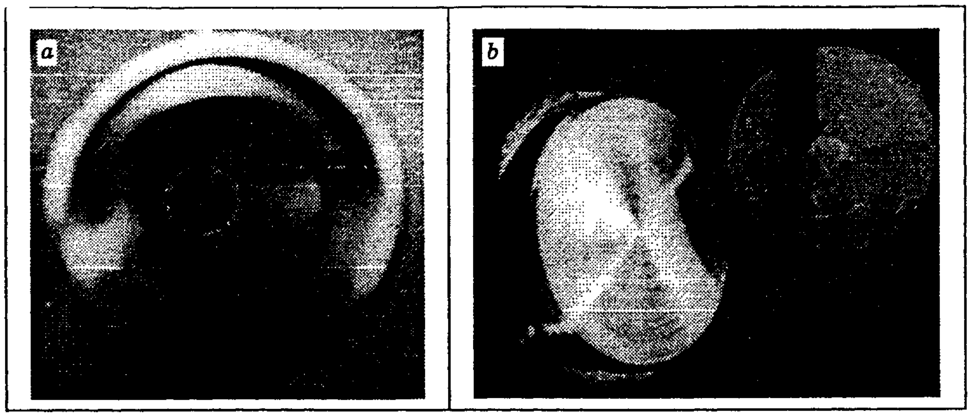

Рис. 3

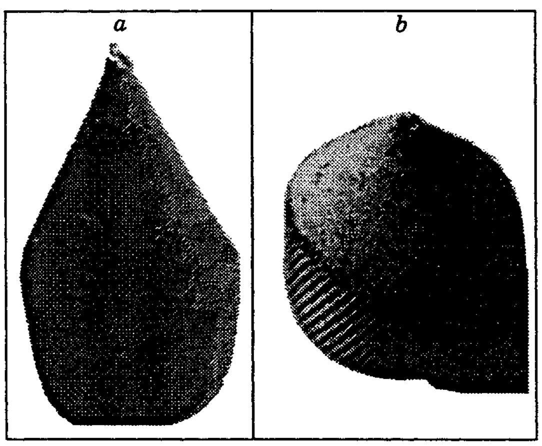

Fig. 4

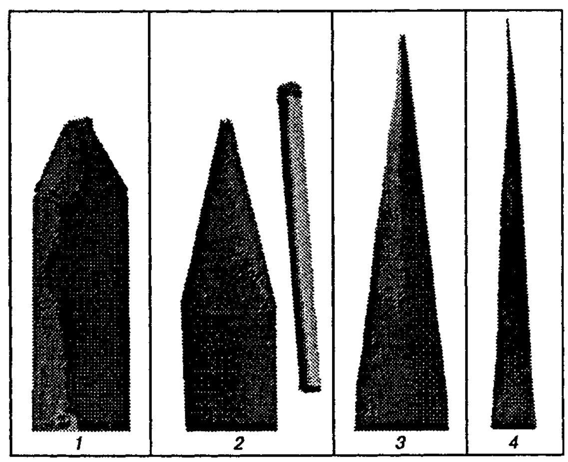

Fig. 5

evaporation, melting, and grinding of the material are evident on the face surface of the irradiated discs. The total ablation of the material due to these effects is $\delta \sim 0.6$ mm. Upon fast strong impact of the suspended disc, the rod loses stability, bends along a sharp multi-peaked curve and, under appropriate loading, breaks up into several parts. Slowly increasing loading would break the rod into two almost equal parts.

With conical specimens the cumulative effects were qualitatively similar to those observed in the experiments on explosive loading [4, 5].

Cumulative ejection from the back part of the cone apex, which resulted in the formation of a small crater in the target (see Fig. 2), was registered on a conical shell of D16T aluminum alloy with a cone angle of 90°. Also, back spalling of the cone shell occurred. Figure 2a shows the spalled backside of the conical shell, Fig. 2b the backside of the conical shell, and Fig. 2c the target and the spalled backside of the conical shell.

A 0.9-mm-diameter ball was ejected from the backside of a conical shell of D16T aluminum alloy with a cone angle of 45°. The target remained intact (see Fig. 3). The figure also shows incomplete back spalling [backside of the conical shell (a); the target (at the left) and a 0.9-mm-diameter ball mm is ejected from the apex of the conical shell (b) (shown by an arrow)].

These effects were not observed for conical shells of steel St. 3 with the same dimensions, since stress cumulation in the steel specimens under thermal shock were insignificant as compared with stress cumulation in D16T aluminum-alloy specimens.

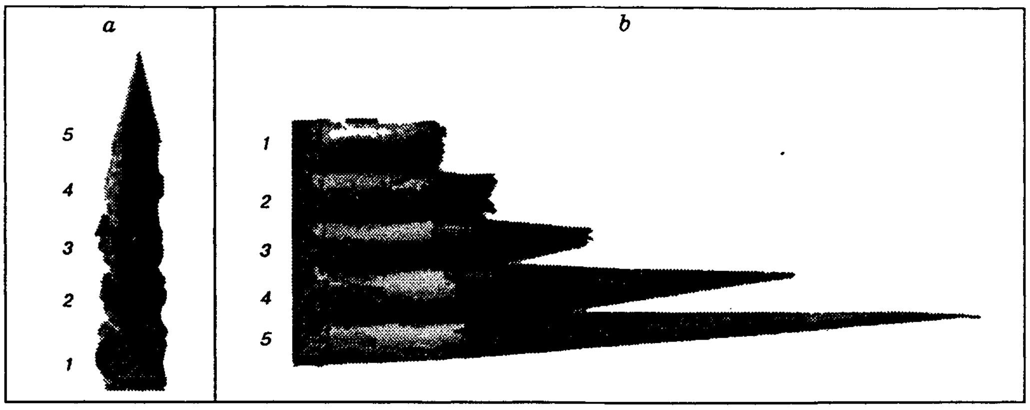

Fig. 6

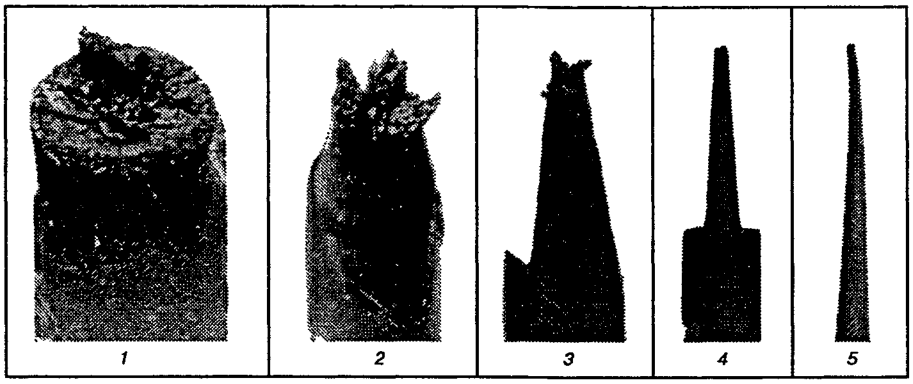

Fig. 7

Note that the geometry of these specimens was such that the thicknesses of the conical shells in the direction normal to the surface of the cone were approximately equal for both types of shell ($\Delta d \approx 4$ mm), while the thicknesses of the shells Δr in the direction normal to the cone axis and ΔZ in the direction of radiation differed significantly: $\Delta r \approx \Delta Z \approx 5.7$ mm for a conical shell with a cone angle of 90° and $\Delta r \approx 4.34$ mm and $\Delta Z \approx 10.5$ mm for a conical shell with a cone angle of 45°.

Stress cumulation in conical shells can cause not only cumulative ejection from the back apex of the shell but also volume failure due to which the apex of the cone acquires a scalloped shape [see Fig. 4 which shows the effect of thermal shock on D16T aluminum-alloy conical shells with a cone angle of 45° and 90° (a and b)].

This effect is most pronounced in solid cones 1–5 of D16T aluminum alloy with cone angles 62, 27, 14, 7, and 5°, respectively, as is shown in Figs. 5–7, where the axes of the cones coincide with the direction of radiation.

Thermal shock results in bending and partial failure of the end of a pointed conical needle 13.74 cm high (cone 5 in Figs. 6 and 7), practically complete failure of a cone about 1 cm high (cone 1 in Figs. 6 and 7), severe damage with splitting of the upper part of a cone about 2.5 cm high (cone 2 in Figs. 6 and 7), and much weaker damage to cones 3 and 4 in Figs. 6 and 7. Similar cones subjected to an x-ray radiation energy fluence smaller by a factor of 3.5 (Fig. 5) were less damaged. Thus, as the cone angle decreases from 62 to 5°, the effect of stress cumulation and the degree of damage to the cones subjected to thermal shock diminish, while an increase in the energy fluence of incident x-ray radiation leads to a more pronounced effect of stress cumulation and, as a consequence, to an increase in the degree of damage to the conical specimens under thermal shock.

The foregoing follows the conclusion that the geometrical effects decrease the damage threshold and increase the degree of damage to the irradiated object because of stress cumulation, cumulative ejections of the materials, and the loss of stability under the pulsed action of strong penetrating-radiation fluxes on cones, conical shells, discs, and rods.

The geometrical effects should be the subject of further studies, because they should be taken into account in determining the stability of structures to the destructive effect of thermal shock due to the rapid heating of structure materials by penetrating radiation. Quantitative estimates for describing the registered phenomena can be obtained from two-dimensional calculations, which are difficult to perform at the present stage of research because of the small volumes of intensely heated regions (fractions of a millimeter).

Subsequent studies using calculation-theoretical failure models will make it possible to develop methods for predicting and increasing the strength of members, units, and structures of various geometry operating under high-speed energy input.

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