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STRENGTH AND FRACTURE OF PLUTONIUM AND ITS ALLOY WITH GALLIUM UNDER IMPACT LOADING

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Results are presented from a theoretical analysis of the conditions of cleavage fracture of plutonium and its alloy with 1.6 wt. % *gallium under shock loading. Experimental data obtained earlier are used to determine the critical tensile stresses corresponding to the initial stage of macroscopic cleavage fracture of specimens. The elastoplastic properties of the materials and polymorphic transformations that occur in the alloy at normal and high* (315°C) *temperatures were taken into account in the calculations.*

From both a scientific and a practical standpoint, there is definite interest in questions related to the study of the strength and fracture of key materials in nuclear technology such as plutonium and its δ-stabilized alloy with gallium. Uniaxial tensile tests of specimens have shown that certain factors tend to affect the mechanical properties of these materials. For example, Hecker and Morgan [1] studied the effect of strain rate on mechanical properties over a broad range of rates. The effect of strain rate and initial temperature was examined by Merz [2] and Beitscher [3]. The only investigation that concerned more intensive and shorter impact loading is [4], which reported results of a study of the cleavage fracture of plutonium and its δ-stabilized alloy containing 1.6 wt.% gallium. The specimens were impacted through a protective shield by a fast-moving plate. The series of tests that was performed involved determination of the impact velocities corresponding to the initial and subsequent stages of macroscopic cleavage fracture of the specimens. A difference was observed by the character of cleavage fracture of brittle plutonium and its relatively ductile alloy. In this paper, which is a continuation of the study begun in [4], we report results from metallographic analysis of test specimens and theoretical analysis of the conditions of cleavage fracture of the indicated materials.

Let us first briefly discuss the setup and results of the tests conducted in [4]. The specimens were 4-mm-thick disks whose greater diameter was 40 mm and the sides were beveled at an angle of 45° for ease of fastening. The specimens were fastened to a copper shield 12 mm thick which was the cover of a hermetic container. The shield was impacted by a 4-mm-thick aluminum plate accelerated to the necessary velocity w by damped explosion of a layer of a plastic explosive. The specimens were tested at normal and high temperatures. An electric heater was used to heat each specimen and its container to 315°C. The specimens that retained their macroscopic integrity were cut into pieces, and the extent of their cleavage fracture was examined on polished metallographic specimens of diametral longitudinal sections. The test results are shown in Table 1. For two of the cases in which complete cleavage fracture took place, the table gives the thicknesses h_s of the resulting layers.

To determine the structure of the test materials and the character of their cleavage fracture, we performed a metallographic analysis of the test specimens. Metallographic sections prepared from longitudinal sections of the specimens were subjected to electrolytical etching in a 50% solution of nitric acid in ethyl alcohol and examined under a metallographic microscope. Figure 1 shows the characteristic structure of the materials with incipient microscopic cleavage defects. The magnification is 300. The structure of the tested plutonium is characterized by nonuniform grains of the α-phase. Brittle cleavage fracture is initiated in this

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TABLE 1

Material	T, °C	w, m/sec	Degree of cleavage fracture
Plutonium	40	259	Cleavage fracture
		134	Cleavage fracture, $h_s = 1.9$ mm
		134	Major cleavage crack
		113	Integrity retained
Plutonium alloy with gallium	40	499	Cleavage fracture
		385	Cleavage fracture, $h_s = 1.2$ mm
		262	Major cleavage crack
		257	Initiation of a main cleavage crack
	315	226	Wide-open main cleavage crack
		208	Small cleavage crack
		193	Integrity retained

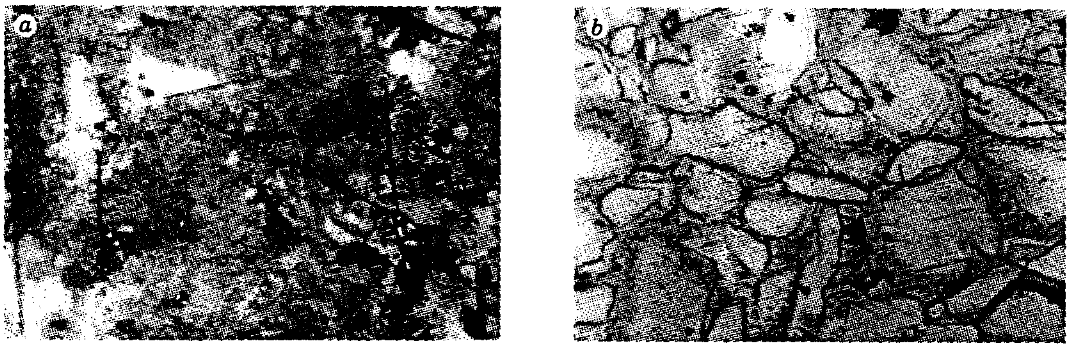

Fig. 1. Structure of materials with incipient microscopic cleavage defects: plutonium (a) and plutonium alloy with gallium (b).

material by formation of cleavage microcracks, and the subsequent propagation of these defects occurs along the grain boundaries. The structure of the alloy with gallium is characterized by equiaxial grains of the δ-phase with dimensions of 30–40 μm. Cleavage fracture is initiated in the alloy in the form of microscopic voids on inclusions in the structure and on the grain boundaries. Fracture develops further as a result of ductile growth and coalescence of the voids.

The conditions of loading and cleavage fracture of the specimens were analyzed using a program that calculates one-dimensional elastoplastic flows. In accordance with the classical scheme, we solved the system of equations

$$\frac{\partial V}{\partial t} - V_0 \frac{\partial u}{\partial x} = 0, \quad \frac{\partial u}{\partial t} - V_0 \frac{\partial \sigma}{\partial x} = 0, \quad \frac{\partial E}{\partial t} = (-P + S) \frac{\partial V}{\partial t}, \tag{1}$$

which in the adiabatic approximation describes the one-dimensional motion of a strong compressible medium in the x direction in a Lagrangian coordinate system. Here V, u, σ, P, and S are the specific volume, velocity, longitudinal stress, and the spherical and deviatoric components of the longitudinal stress, respectively. The spherical component of the stress tensor was expressed in the form

$$P(\delta) = \frac{\rho_0 c_0^2 \delta(\delta - 1)}{[\delta - \lambda(\delta - 1)]^2}, \tag{2}$$

where $\delta = \rho/\rho_0 = V_0/V$. Equation (2) is actually a transformed (using the continuity equation and the equation of conservation of momentum on the shock discontinuity) Hugoniot curve, which represents the

TABLE 2

Material	State	ρ_0, g/cm^3	c_0, km/sec	ν	σ_e, GPa
Plutonium	α-phase	19.6	1.65	0.17	1.4
Plutonium alloy with gallium	δ-phase	15.7	1.37	0.27	0.6
	α-phase	18.9	1.65	0.17	1.2
	β-phase	17.1	1.37	0.27	0.3
Aluminum	—	2.7	5.25	0.34	0.2
Copper	—	8.9	3.95	0.35	0.4

linear relation between the mass and wave rates $D = c_0 + \lambda u$. Use of the transformed equation is completely valid in the given case because the Hugoniot curve coincides with the isothermal compression curve in the low-pressure region being examined. The deviatoric component of the stress tensor was determined in accordance with Hooke's law

$$\frac{\partial S}{\partial t} = -\frac{4}{3}\frac{G}{V}\frac{\partial V}{\partial t}, \tag{3}$$

where G is the shear modulus. When the absolute value of S exceeded $(2/3)Y$, where $Y = (1-2\nu)/(1-\nu)\sigma_e$ is the dynamic yield point in uniaxial tension–compression, we corrected the deviator in accordance with the formula $S = (2/3)Y\operatorname{sgn}(S)$. The finite difference method was used to solve system (1)–(3) subject to initial and boundary conditions.

The elastoplastic properties of the materials of the impactor, the shield, and the specimen were taken into account in the calculations. For the alloy with gallium, we also took into account the polymorphic δ–α and δ–β transformations that take place at normal and high temperatures. Table 2 shows the material characteristics used in the calculations, such as density ρ_0, volumetric speed of sound c_0, Poisson's ratio ν, and Hugoniot elastic limit σ_e. These values were taken from [5–7]. A value of 1.5 for the coefficient λ was used for all of the test materials except aluminum, for which $\lambda = 1.4$. A value of 0.3 GPa was used for the σ_e of the δ-phase at 315°C. In accordance with the data of [8], for the pressures corresponding to the reversible polymorphic transformations, we took values of 0.7 GPa (δ–α transformation) and 0.4 GPa (δ–β transformation). Theoretical analysis was performed using several simplifying assumptions, which were inevitable because of insufficient experimental data. We assumed that the material of the specimens was not damaged in the tension region, i.e., we did not consider tensile stress relaxation that corresponds to damage accumulation. The reversible polymorphic transformations in the alloy with gallium were assumed to be noninertial, i.e., we did not consider the kinetic laws governing their actual occurrence. Each polymorphic transformation was accounted for in the computational scheme by changing the parameters of Eq. (2) when the limiting value of P for the given phase or the corresponding value of δ was reached.

The most interesting aspect of the investigation from a practical standpoint was the establishment of a criterion for the macroscopic cleavage failure of plutonium and its alloy with gallium under impact loading. As this criterion, we can use the experimentally determined impact velocities of 134 m/sec for plutonium at room temperature, 257 m/sec for the alloy at room temperature, and 208 m/sec for the alloy at elevated temperature (test Nos. 1–3, respectively). Figure 2 shows the change in the impulse of the longitudinal stress for these cases. Time is reckoned from the moment the impactor comes into contact with the shield. The impulses entering the specimen from the shield are shown on the left of Fig. 2, and the right side of the figure shows the impulses transformed after travelling a distance equal to the thickness of the specimens, i.e., 4 mm. The differences in the character of the change in the impulses are due to mainly the differences in the values of σ_e for the different phase states of plutonium.

Figure 3 shows graphs of the tensile stresses on the plutonium and alloy specimens at normal and high temperatures. The results of these calculations make it possible to determine probable thicknesses of

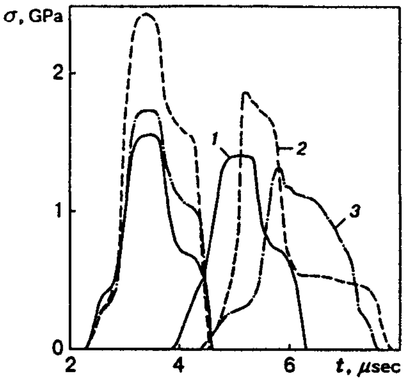

Fig. 2. Change in the impulse of the longitudinal stress during its passage through the specimen: curves 1–3 corresponds to test Nos. 1–3, respectively.

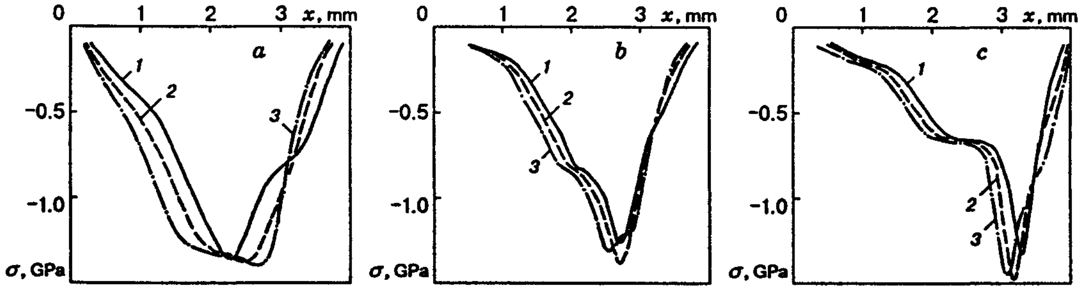

Fig. 3. Tensile stresses in the specimens: a–c) test Nos. 1–3; curves 1–3 correspond to the following times reckoned from the moment of contact of the impactor with the shield: 5.6, 5.7, and 5.8 μsec (a), 6.7, 6.8, and 6.9 μsec (b), and 6.9, 7.0, and 7.1 μsec, respectively (c).

the cleavage layers and the maximum tensile stresses formed in the specimens at the given thicknesses. The calculated thickness of the cleavage layer that was formed was 1.8 mm for plutonium, and the maximum value of tensile stress was 1.4 GPa (Fig. 3a). For the alloy, these values were 1.3 mm and 1.4 GPa at room temperature (Fig. 3b) and 0.9 mm and 1.5 GPa at elevated temperature (Fig. 3c).

Similar calculations were performed for all of the tests described in Table 1. For example, the maximum tensile stresses were 1.3 and 1.8 GPa in loading of plutonium specimens at impact velocities of 113 and 259 m/sec, and in loading of the alloy specimen at an impact velocity of 385 m/sec, the maximum tensile stress was 2.0 GPa. In the calculations, we also varied the Hugoniot elastic limit within the range 0.1–0.3 GPa for aluminum, 0.2–0.5 GPa for copper, and 1.4–1.8 GPa for plutonium. The pressures corresponding to the polymorphic δ–α transformation for the alloy with gallium were varied within the range 0.7–1.2 GPa. It was observed that varying these characteristics does not significantly affect the critical tensile stresses for the given materials and loading conditions. In all three cases, these stresses were roughly the same and were close to 1.4 GPa.

The values calculated here for the thicknesses of the cleavage layers formed in the specimens agree quite well with the experimental results. This serves as validation of the method used for a simplified theoretical analysis of empirical data. It should be pointed out that the fracture loads obtained for plutonium and its alloy do not correlate exactly with the strength values of the same materials in uniaxial tension. For example, according to [1], as the strain rate changes from 10^{-5} to 10^{2} sec^{-1}, the strength increases from 0.40 to 0.65 GPa for plutonium and from 0.11 to 0.15 GPa for the alloy with 1 wt.% gallium. According to [3], at a strain rate of 10^{-4} sec^{-1}, heating a plutonium alloy with 1.3 wt.% gallium from room temperature to 300°C results in a fourfold reduction in its strength. The impact loading method used in [4] subjects specimens to one-dimensional deformation at strain rates considerably greater than those indicated above. Use of the same method on the materials studied led to smoothing of the above-mentioned effects of both δ-stabilization by alloying with gallium and heating to 315°C on the strength, which are clearly observed in uniaxial tension. Similar tendencies, which are manifested to varying degrees in studies of other metals and alloys under impact loading, have not yet been satisfactorily explained. This can be attributed largely to the insufficient accuracy and information content of available experimental data.

REFERENCES

1. S. S. Hecker and J. R. Morgan, "Effect of strain rate on the tensile properties of α- and δ-stabilized plutonium," in: *Plutonium 1975 and Other Actinides*, North-Holland Publ. Comp., Amsterdam (1976), pp. 697–708.
2. M. D. Merz, "Strength differential effect in α-Pu," *Metall. Trans.*, **4**, No. 4, 1186–1188 (1973).
3. S. Beitscher, "The tensile behavior of Pu/1 wt.% Ga at −60, 30, and 77°C," *J. Nucl. Mater.*, **24**, No. 1, 113–117 (1967).
4. Yu. V. Bat'kov, V. K. Golubev, S. A. Novikov, et al., "Fracture of plutonium and its alloy with 1.6 wt.% gallium under impact loading," *Vopr. Atom. Nauki Tekh., Ser. Fiz. Yadernykh Reaktorov*, **1**, 40–42 (1991).
5. M. D. Merz, J. H. Hammer, and H. E. Kjarmo, "Sound velocity and elastic moduli in α-plutonium at pressures to 50 kbar," in: *Plutonium 1975 and Other Actinides*, North-Holland Publ. Comp., Amsterdam (1976), pp. 567–571.
6. R. L. Moment, "Single-crystal elastic constants of a plutonium–gallium alloy," *ibid.*, 687–695.
7. C. A. Calder, E. C. Draney, and W. W. Wilcox, "Noncontact measurements of the elastic constants of plutonium at elevated temperatures," *J. Nucl. Mater.*, **97**, Nos. 1 and 2, 126–136 (1981).
8. C. Roux, P. Roux, and M. Rapin, "Influence de la pression sur le diagramme de phases Pu–Ga," *J. Nucl. Mater.*, **40**, No. 3, 305–310 (1971).