Journal of Applied Mechanics and Technical Physics, Vol. 37, No. 6, 1996

DURABILITY OF COPPER, NICKEL, TITANIUM, BRASS, AND BRONZE UNDER IMPULSIVE IRRADIATION

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UDC 620.171+539.4.019

The time dependences of the spalling strength of copper, nickel, titanium, brass, and bronze under thermal shock initiated by a short-time pulse of x-ray radiation of nuclear explosion are found by calculation and experimentation. The durability of copper, nickel, titanium, brass, and bronze under conditions of thermal shock is shown to reduce exponentially with an increase in the ultimate-stress amplitude (spalling strength) and can be described on the basis of the kinetic concept of strength.

One-dimensional spalling phenomena have been actively studied mainly by the methods of plate collision and by blasting of condensed explosives at the surface of a barrier made of the material to be investigated (see, for example, [1–4]). In recent years, intensive studies of the mechanisms of failure of solid bodies under thermal shocks caused by fast heating of material due to the action of penetrating radiation have been initiated [5–11].

In the theoretical case of instantaneous heating which is uniform in mass, the pressure $P = \Gamma\rho\varepsilon$ (Γ is the Grüneisen coefficient, ρ is the density of the material, and ε is the concentration of the heat energy injected per unit mass) is generated in the material. The one-dimensional tension in a specimen, whose transverse sizes are much larger than its thickness, occurs during the interaction of two counter expansion waves propagating from free surfaces and meeting in the mid-plane of the specimen. In an acoustic approximation, the amplitude of tensile stresses is $|\sigma| = P$, and the time of their action is $t \sim \Delta/c$ (Δ is the thickness of the specimen and c is the sound velocity). Since the time t_0 of material heating is finite, the amplitude of stresses is less than that in the regime of instantaneous heating [11]. For small values of the nondimensional parameter λ ($\lambda = ct_0/\Delta \ll 1$) that characterizes the heating rate, this decrease in the amplitude of stresses is insignificant and can be ignored.

Spalling stresses under fast space heating are comparable with spalling stresses under the usual shock-wave loading (HE blasting, plate collision). However, as noted in [4, 8], the physical processes that cause spalling in fast-heating experiments differ substantially from the processes occurring under shock-wave loading (Fig. 1 shows the methods of deformation of elastoplastic material in the stress σ and strain e coordinates, curve A refers to the instantaneous-heating regime, and curve B to the method of plate collision, curves 1 and 2 are the shock adiabat and isentropic expansion, respectively).

In the case of shock-wave loading, the material in the future region of spalling first contracts, entering into a higher-density state in comparison with the initial one, and then expands in rarefaction waves, going through the initial specific volume. In a theoretical state of instantaneous and uniform heating, compressive stresses are generated in the material, although its volume remains the same. The material then expands from this state (if there are free surfaces) to a state with a density smaller than the initial one (Fig. 1). A considerable variation in material temperatures is another distinction between the loading regimes considered. An increase in the average temperature under shock loading up to tens of gigapascals in continuous metals is small ($\sim$ 100–200 K), whereas for failure in a thermal-shock regime, a temperature is necessary which is comparable with the melting point of a material under normal conditions.

Thus, spalling experiments in the fast-heating regime give qualitatively new information, which is very important for the physics of solid-body failure. These investigations are of practical significance, because the

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Institute of Experimental Physics, Sarov 607200. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 37, No. 6, pp. 116–121, November–December, 1996. Original article submitted March 9, 1995; revision submitted July 31, 1995.

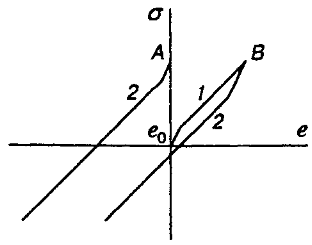

Fig. 1

stresses occurring under thermal shock lead to spalling of the members of modern constructions, such as pulse reactors [12, 13], powerful induction accelerators [14], magneto-cumulative generators [15], etc.

The purpose of the present paper is to determine the mechanisms of thermomechanical spalling of copper, nickel, titanium, bronze, and brass under thermal shock. In the experiments, flat specimens (metallic foils) made of copper (M1, M1T, and M1M), nickel (NP2 and NP2M), titanium (VT1-0), bronze (BrB2 and BrB2M), and brass (L62 and L63) were subjected to fast space heating by a short-time pulse of x-ray radiation of a nuclear explosion. As delivered, the specimens were 0.005–1 mm thick, and their thickness was much smaller than their diameter (~10 mm) to diminish the effect of lateral unloading in the central zone of the specimens and to make free the face (facing the x-ray radiation source) and back (shadow) surfaces of the specimens. This makes it possible to consider spalling processes in a one-dimensional approximation. To observe "pure" spalling, melting and evaporation in the materials were excluded by dosing filters intensely absorbing the soft part of the x-ray radiation spectrum, in accordance with the experimental conditions. The characteristic time of material failure under thermal shock was varied (from $\sim 10^{-9}$ to $\sim 10^{-6}$ sec) by varying the thickness of the specimens (foils) (from 0.005 to 1 mm). Thermomechanical failure of the metallic specimens of various thickness occurred at a temperature close to the melting point. The gradients of the absorbed-energy concentration in most of the metallic foils subjected to thermal shock were small and, therefore, spalling occurred near the central area of the foils.

Figure 2 shows the degree of heating nonuniformity of the metallic foils and the steepness of the stress-pulse front. It also shows the typical stress distributions in copper foils of various thickness Δ (curves 1–5 correspond to $\Delta = 0.026$, 0.041, 0.134, 0.37, and 0.48 mm) at time t_0 (time at which the pulse of x-ray radiation ends).

Donskoi and Ivanova et al. have proposed the procedures and the ELISA [16] and UP-OK [17] programs which we used to process the experimental data. ELISA is intended to determine the energy-release profiles, and UP-OK serves as a basis to determine the character of wave processes (with allowance for the elastoplastic properties of the materials) and the evolution of stresses in different cross sections of the specimens subjected to thermal shock. In the calculations, a two-term equation of state in the Mie–Grüneisen form was used, and the heating time of the specimens is taken into account. Each specimen subjected to thermal shock broke into a definite number of parts (from 10 to 200), depending on its thickness. In each of these parts, the amplitudes of tensile stresses and the time of their action were calculated.

Knowing the location of the spalling cross section in a specimen subjected to thermal shock and identifying the total time τ of the action of tensile stresses in the spalling cross section in the first unloading wave, which is transverse to the specimen, with the durability of the material, and the amplitude of the ultimate stresses σ with the spalling strength of the material, we obtain, after processing of the computational and experimental data, the time dependence of the spalling strength of the material under thermal shock initiated by a short-time pulse of x-ray radiation of a nuclear explosion.

Figures 3–7 show graphically, in the coordinate system $\sigma - \log \tau$, the results of processing of the experimental data on spalling of copper (M1, M1T, and M1M), nickel (NP2 and NP2M), titanium (VT1-0), bronze (BrB2 and BrB2M), and brass (L62 and L63), respectively, which were obtained in the regime of fast space heating. Here points 1 refer to the absence of visible failure, points 2 to the initiation of spalling (onset of visible failure), and points 3 to spalling or complete failure of the specimen.

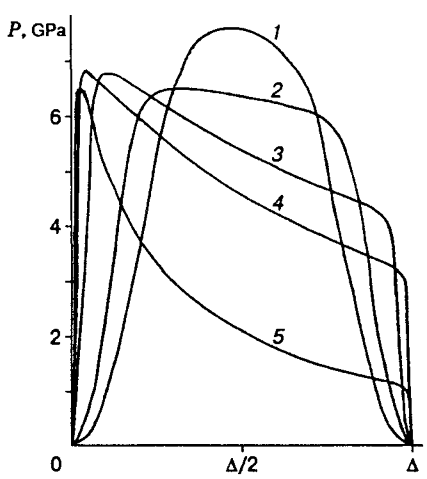

Fig. 2

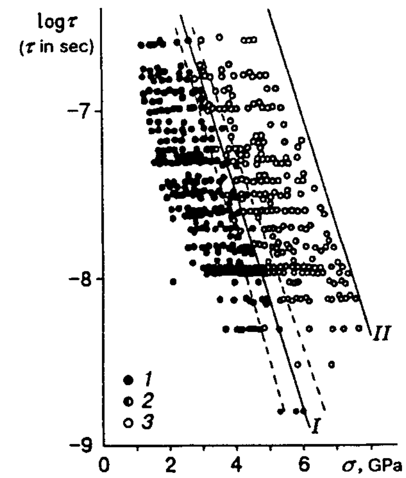

Fig. 3

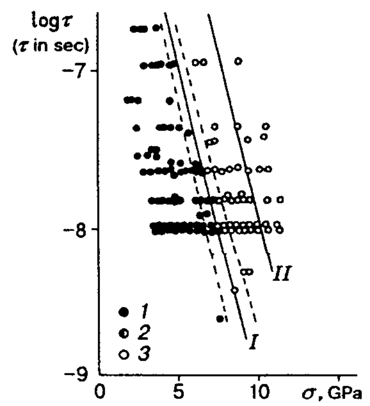

Fig. 4

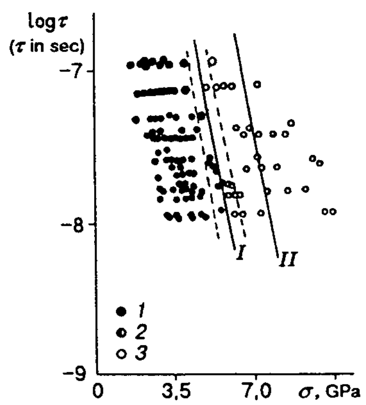

Fig. 5

In these figures, the most probable boundaries of spalling, which we identify with the dynamic branches of the durability of copper, nickel, titanium, bronze, and brass under thermal shock, are shown by solid curves *I*. They separate the failure region during fast space heating from the region in which the material remains visually intact. The error in stress determination was 10–15% (the dashed curves), and the error of estimation of the time of their action did not exceed 10%. In a range of from approximately 10^{-6} to 10^{-9} sec, the durability τ of copper, nickel, titanium, bronze, and brass decreases exponentially with an increase in the amplitude of ultimate stresses σ. This indicates that the kinetic concept of strength is valid.

Curves II in Figs. 3–5 show the dynamic branches of the durability of copper, nickel, and titanium, respectively, obtained by S. A. Novikov and his co-workers [18] by the method of plate collision. The difference in the positions of curves I and II is due to both a decrease in the spalling strength of copper, nickel, and titanium with temperature elevation and the effect of the above-mentioned characteristic properties of the deformation processes occurring in copper, nickel, and titanium under thermal shock in comparison with the plate-collision regime.

To describe the experimental data on thermomechanical spalling of copper, nickel, titanium, bronze, and brass under thermal shock, the kinetic spalling model [18] which relates the amplitude of ultimate stresses σ

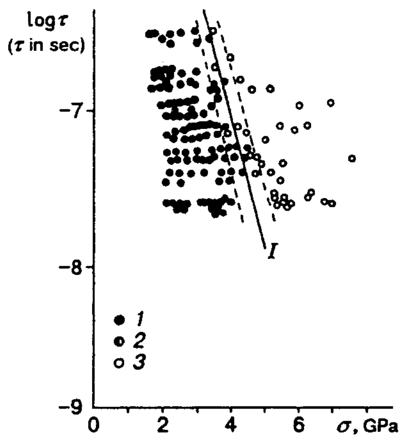

Fig. 6

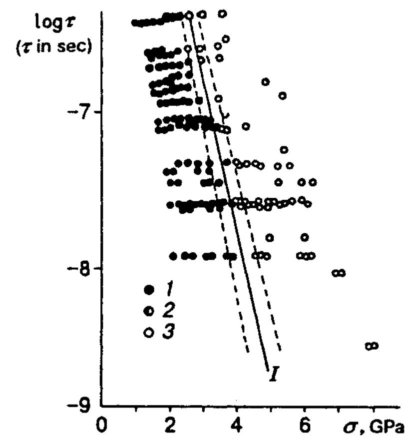

Fig. 7

TABLE 1

Material	T_{mel}, K	U_0, eV/atom	Ω^{-1}, 10^{28} m^{-3}	$\tau_0 = 10^{-12}$ sec		$\tau_0 = 10^{-13}$ sec		A/γ
				A	γ	A	γ	
Copper	1356	3.50	8.45	1.81	4.4	1.59	3.86	0.412
Bronze	1228	3.50	8.45	1.79	4.53	1.59	4.03	0.395
Brass	1178	3.50	8.45	1.86	5.35	1.66	4.75	0.348
Nickel	1726	4.435	9.14	1.77	3.86	1.56	3.4	0.458
Titanium	1941	4.855	5.66	1.48	3.88	1.32	3.47	0.381

to the time of their action τ by the formula

$$\sigma = \frac{1}{\gamma\Omega}\left(U_0 - AkT \ln \frac{\tau}{\tau_0}\right) \tag{1.1}$$

can be used. Here Ω is the atomic volume; U_0 is the sublimation energy of atoms in the lattice; T is the effective temperature; k is the Boltzmann constant; A, γ, and τ_0 are the fitting parameters. The effective temperature T under conditions of thermomechanical failure under thermal shock is close to the melting point.

Relation (1.1) can be written in the form

$$\sigma = \frac{1.6\,B}{\gamma}\left(U_0 - 1.985\,AT \log \frac{\tau}{\tau_0}\right),$$

which is more convenient for calculations (T, 10^4 K; U_0, eV/atom; σ, GPa; and $B = \Omega^{-1}$, 10^{28} m^{-3}).

The computational and experimental data on spalling of copper, nickel, titanium, brass, and bronze under thermal shock are described satisfactorily for the values of the parameters A, γ, and τ_0 given in the Table 1.

The data obtained have shown that the modified kinetic concept of solid-body failure allows one to describe the durability of copper, nickel, titanium, bronze, and brass under conditions of thermal shock initiated by a short-time pulse of x-ray radiation of a nuclear explosion. The results of the present work can be used to design and develop members and units of new pulsed energy-producing and irradiating units, to develop methods for experimentation on simulating devices, and can also be used in further investigations of the strength of solid bodies.

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