Journal of Applied Mechanics and Technical Physics, Vol. 44, No. 1, pp. 135–140, 2003

STRENGTH AND SPECIFIC FRACTURE ENERGY OF METALS SUBJECTED TO A THERMAL SHOCK

A. M. Molitvin

UDC 620.171+539.4.019

Time dependences of spalling strength and critical specific fracture energy of some metals under a thermal shock initiated by x-rays of a nuclear explosion are obtained. Under thermal-shock conditions, the durability of metals decreases exponentially as the amplitude of the fracture stress increases. The critical specific fracture energy of metals subjected to a thermal shock increases with the duration of tensile stresses. Using an example of cones, conical shells, disks, and rods, it is shown that the geometric factor should be taken into account, which can reduce the fracture threshold and increase the degree of fracture of an object subjected to a thermal shock. This is a result of stress cumulation, occurrence of cumulative ejection of the material, and stability loss due to the action of powerful energy fluxes.

Key words: *fracture of metals, thermal shock, experiment, spalling strength.*

In recent years, the properties of materials subjected to short-term pulses of laser, electron, and x-ray radiation, ion beam, etc., have been intensely studied (see, e.g., [1–12]). Upon irradiation, the energy input is so fast that the material has no time to expand, which results in high compressive stresses and a thermal shock. To remove the compressive stresses, the material is expanded in two directions, which is equivalent to propagation of rarefaction waves into the heated material. During merging of the rarefaction waves, tensile stresses arise which can lead to spalling failure.

The character of deformation of a material under thermal-shock conditions differs much from that of the material subjected to shock-wave loading by collision of plates and explosion of a condensed explosive at the surface of a target made of the material studied [6]. Under shock-wave loading, initially the material is compressed and its density increases compared to the initial state, then the material expands in rarefaction waves. In an idealized case of instantaneous and uniform heating of the material, compressive stresses occur and material volume remains unchanged. From this state, the substance expands (in the presence of free surfaces) to a density lower than the initial density. In these loading regimes, the temperatures of the material also differ substantially. For shock loading to tens of gigapascals, the increment in the average temperature of continuous metals is small (100–200 K), whereas in the case of a thermal shock, fracture occurs at a temperature comparable with the melting point of the metals.

In optically thick specimens subjected to a thermal shock, multiple spalls may occur on both the front face (turned to the radiation source) and the rear (back) side of the specimen. An analysis of wave processes in a plate and a compact cylinder absorbing intense electromagnetic radiation [3] shows that the wave processes can lead to cumulation of tensile stresses so that they can exceed the initial compressive stresses severalfold. This factor (stress cumulation) cannot be taken into account in solving similar problems in the one-dimensional formulation.

A characteristic feature of spalling fracture of optically thin flat specimens subjected to a thermal shock (for small energy-release gradients) is that they split into two parts. In this case, the criterion characteristics of fracture threshold of irradiated specimens can be determined with a higher accuracy compared to the case of optically thick specimens.

In the present paper, we study special features of spalling fracture of metals and alloys under a thermal shock initiated by a short-term pulse of x-rays of a nuclear explosion. To this end, we use the kinetic and energy approaches to the problem of spalling fracture of solids.

Institute of Experimental Physics, Sarov 607188. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 44, No. 1, pp. 163–169, January–February, 2003. Original article submitted March 27, 2002.

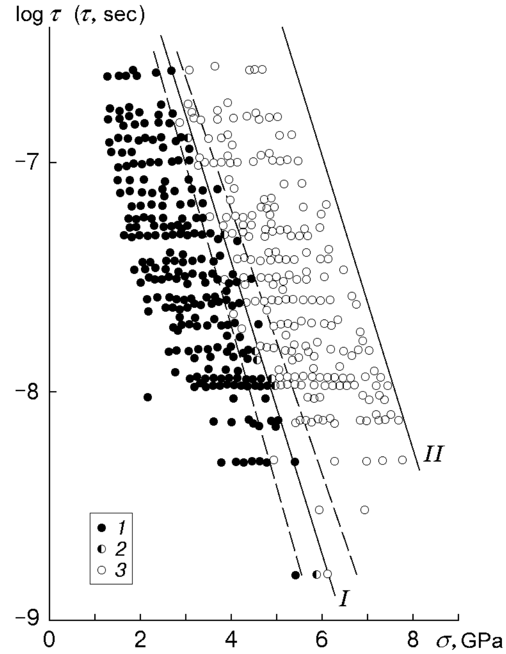

Fig. 1. Time dependences of spalling strength of copper under a thermal shock (curve I) and shock loading (curve II): points 1 refer to the case where no visible failure is observed, points 2 refer to spalling nucleation (onset of visible failure), and points 3 refer to spalling or complete failure of the specimen.

Experimental data on spalling were obtained under conditions of pulsed irradiation of model assemblies with metal specimens. The experimental data were analyzed with the help of the methods and programs ÉLIZA [13] and UP-OK [14]. The first program was used to determine energy-release profiles and the second program to determine the character of the wave processes and evolution of stresses in different cross sections of specimens subjected to a thermal shock.

Each model assembly comprised several metal foils arranged one behind another normally to the irradiation direction. To avoid the mechanical effect of expansion of neighboring foils, each foil was insulated by optically transparent dampers. The energy flux of x-ray radiation was attenuated by dosing filters, which absorbed the soft part of the x-ray spectrum. Introduction of a plug-damper made of porous foamed plastics into the structure made it possible to obtain information even under conditions of intense fracture of the dosing filter. To observe "pure" spalling, special measures were taken to eliminate evaporation and melting of the foil substance.

We studied foils made of copper (M1, M1T, and M1M), nickel (NP2 and NP2M), titanium (VT1-0), brass (L62 and L63), bronze (BrB2 and BrB2M), molybdenum (MCh-1), tungsten, tantalum (TCh), cadmium, lead, zinc, silver, and nine types of structural steel (St. 8, St. 10, Kh18N10T, 36NKhTYu, 42NKhTYu, 50NKhS, 80NKhS, 65G, and 60S2A) of thickness varied from 0.005 to 1 mm. To exclude the effect of lateral unloading on the central part of foils, their diameter (10–16 mm) was chosen large compared to their thickness. The front and back surfaces were free, which allowed us to study processes of spalling fracture in the one-dimensional approximation.

Under a thermal shock, spalling fracture of metal foils occurred at temperatures close to the corresponding melting points of the substance under normal conditions. For most foils, the energy-release gradients were small. Data on nonuniform heating of foils and steepness of the stress-pulse front can be found in [6].

In calculations by means of the UP-OK program, the two-term equation of state of the substance in the Mie–Grüneisen form was used, and elastoplastic properties of metals and alloys and the duration of the x-rays pulse were taken into account. Depending on thickness, each specimen was divided into a certain number of parts (from 10 to 200), the amplitude of tensile stresses and duration of their action being calculated in each part.

Identifying the total duration of the action of tensile stresses in the spalling cross section in the first transverse rarefaction wave with the durability of the material τ and the amplitude of the fracture stresses with the spalling strength of the material σ, after systematization of calculated and experimental results, we obtain the time dependence of spalling strength of the material subjected to a thermal shock.

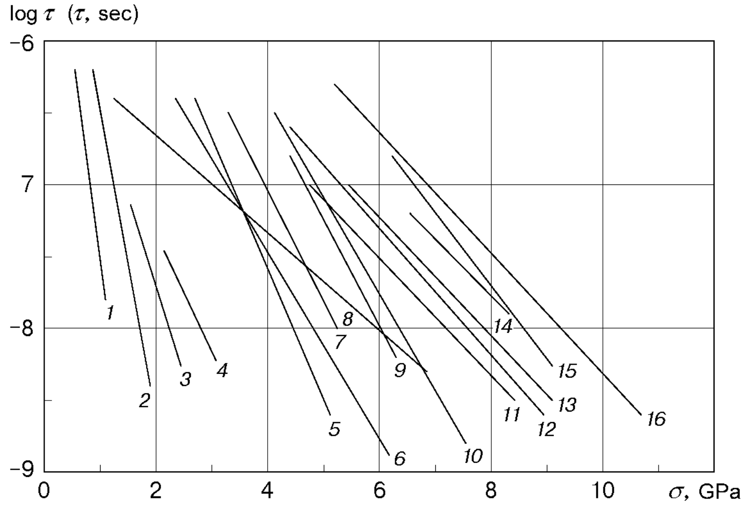

Fig. 2. Time dependences of spalling strength of metals and alloys under a thermal shock: lead (1), cadmium (2), zinc (3), silver (4), brass (5), copper (6), bronze (7), molybdenum (8), titanium (9), St. 10 steel (10), tungsten (11), nickel (12), steel (Kh18N10, 36NKhTYu, 42NKhTYu, 50NKhS, and 80NKhS) (13), steel (65G and 60S2A) (14), St. 8 steel (15), and tantalum (16).

Figure 1 shows the experimental results on spalling fracture of copper under a thermal shock initiated by x-ray radiation of a nuclear explosion. The solid curve I shows the most probable boundary of spalling fracture of copper, identified with the dynamic branch of copper durability under a thermal shock initiated by x-rays. It separates the region of thermal-shock fracture of copper from the region where no visible fracture of copper is yet observed. The dashed curves bound the region in which the boundary of spalling fracture of copper can be located because of an error in determining stresses. Curve II refers to the dynamic branch of copper durability, obtained by the plate-collision method in [15]. The difference between curves I and II is explained by the fact that the spalling strength of copper decreases with an increase in temperature and also by the above-mentioned special features of copper deformation under a thermal shock, compared to the plate-collision regime. Under plate-collision loading, copper is initially compressed by a pressure wave, and then it is extended after a rarefaction wave arrives. Under a thermal shock, there is no compression phase, and pressure is produced only by x-ray heating of copper. As a result, equal tensile stresses occur in copper for different degrees of its deformation.

Figure 2 shows the time dependences of spalling strength of metals and alloys subjected to a short-time pulse of x-radiation of a nuclear explosion, which were borrowed from [6–11]. These results show that, within the time interval of 10^{-6}–10^{-9} sec, the durability of metals and alloys under the action of a thermal shock decreases exponentially as the amplitude of fracture stresses increases. This agrees with the kinetic concept of spalling fracture.

To analyze experimental data on spalling fracture of metals and alloys under a thermal shock initiated by x-ray radiation of a nuclear explosion, one can use the kinetic model of spalling fracture [7, 15], in which the amplitude of fracture stresses σ is related to the duration of their action τ by the formula

$$\sigma = (U_0 - AkT\ln(\tau/\tau_0))/(\gamma\Omega).$$

Here Ω is the atomic volume, U_0 is the sublimation energy of the lattice atoms, T is the effective temperature, k is the Boltzmann constant, and A, γ, and τ_0 are the parameters of the model, given in [6–10].

Along with the kinetic approach to the problem of spalling fracture of solids, in which spalling is considered as a time-dependent process, the energy approach based on comparing the energy stored in a specimen with the fracture work is intensely developed [8–11, 16, 17].

We write the necessary condition for integrity of a structure in the simplest form

$$\int_V \xi\,dV < \int_S \lambda\,dS,$$

where ξ is the elastic energy of a unit volume, λ is the specific (per unit area) work of the fracture-crack propagation, V is the volume of the object, and S is the area of the fracture surface.

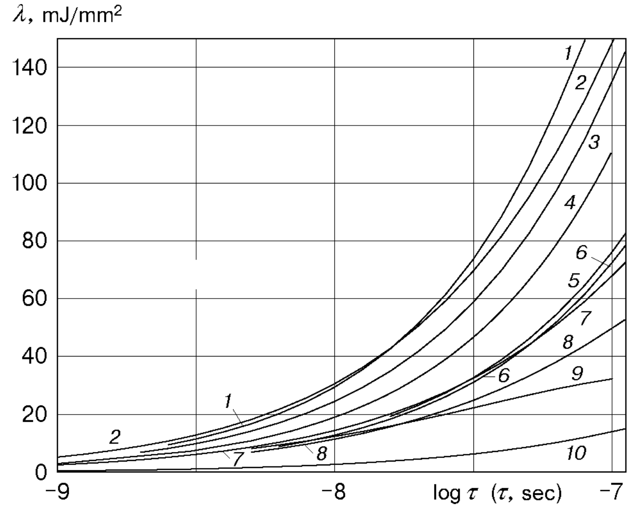

Fig. 3

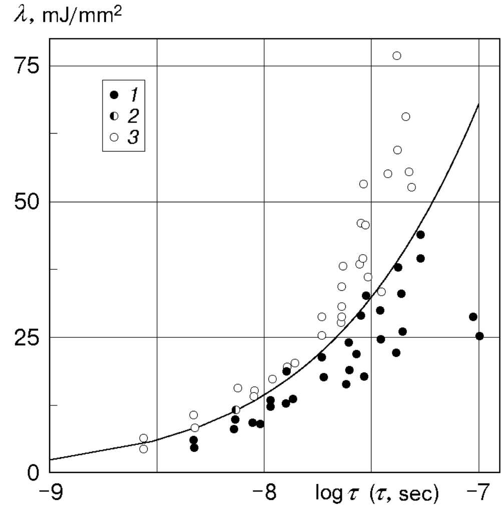

Fig. 4

Fig. 3. Time dependences of the critical specific fracture energy of metals and alloys subjected to a thermal shock: titanium (1), nickel (2), tantalum (3), St. 10 steel (4), bronze (5), brass (6), copper (7), tungsten (8), molybdenum (9), and cadmium (10).

Fig. 4. Time dependence of the critical specific fracture energy of copper subjected to a thermal shock: points 1 refer to the case where no visible failure is observed, points 2 refer to the spalling nucleation (onset of visible failure), points 3 refer to spalling and entire failure of a specimen, and the curve refers to calculation by formula (2).

Assuming that the fracture work is done only due to the stored elastic energy of extension of a spalling plate, Ivanov and Mineev [16] write the spalling condition in the form

$$\int_0^h \sigma^2\,dx = \frac{2\lambda E(1-\nu)}{(1+\nu)(1-2\nu)}, \tag{1}$$

where h is the length of the loading pulse, E is Young's modulus, ν is Poisson's ratio, and λ is the specific (per unit surface) work of material detachment.

According to [16], spalling occurs if the stored elastic energy in a tensile wave is equal to the work of material detachment. The coordinate of spalling nucleation, i.e., the thickness of the spalling layer is determined by the cross section in which condition (1) is satisfied earlier than in all others.

The use of the energy approach [16] based on comparing the stored energy in a specimen and the fracture work and also the methods and programs UP-OK allowed us to estimate the critical specific fracture energy of a material required for the detachment work to be done (partition of a flat metal specimen under a thermal shock). In calculations, the parameter λ in Eq. (1) was varied to study its effect on the integrity of specimens made of copper, nickel, titanium, brass, bronze, St. 10 steel, tungsten, tantalum, molybdenum, and cadmium of thickness varied from 0.005 to 1 mm, which were subjected to a thermal shock. The calculation results were compared with experimental data on spalling. It was of special interest to study the dependence of the critical specific fracture energy λ_* on the duration of action of tensile stresses in the spalling cross section τ.

Correspondence between experimental data on spalling fracture of metal foils subjected to a thermal shock and calculation results obtained by the program UP-OK with the use of the energy fracture criterion (1) was reached by taking into account the dependence of the specific fracture energy on the duration of action of tensile stresses in the spalling cross section. The time dependence of the critical specific fracture energy of copper, nickel, titanium, brass, bronze, St. 10 steel, tungsten, tantalum, molybdenum, and cadmium under a thermal shock initiated by x-ray radiation of a nuclear explosion can be written as

$$\lambda_* = \alpha\tau(\beta + \log\Theta)^2. \tag{2}$$

Here Θ is a dimensionless quantity equal to τ and α and β are the material parameters given in [8–11].

Fig. 5. Result of the action of a thermal shock on continuous cones from the D16T aluminum alloy with different cone-apex angles: 62° (cone 1), 27° (cone 2), 14° (cone 3), 7° (cone 4), and 5° (cone 5).

Figure 3 shows the time dependences of the critical specific fracture energy of some metals, which were obtained in [8–11]. Figure 4 shows the calculated critical specific fracture energy of copper required for the detachment work.

The results obtained show that the critical specific fracture energy of a metal, required for the detachment work (partition of a flat metal specimen), is not a constant of this material. The critical specific fracture energy of copper, nickel, titanium, brass, bronze, St. 10 steel, tungsten, tantalum, molybdenum, and cadmium depends on loading conditions and increases with increasing duration of the action of tensile stresses in the spalling cross section, which agrees with the data of [16, 17].

For reliable prediction of the resistance of elements and units of pulsed energy and radiation equipment to fracture caused by intense energy fluxes of penetrating radiation under thermal-shock conditions, it is necessary to take into consideration the geometrical factor. Using an example of cones, conical shells, disks, and rods under a pulsed action of energy fluxes of x-rays, Molitvin et al. [12] showed that taking into account the geometrical factor reduces the fracture threshold and increases the degree of fracture of an object as a result of stress cumulation, cumulative ejection of a material, and stability loss of the object. For example, stress cumulation in a conical shell can lead not only to cumulative ejection from the back (internal) apex of the conical shell but also to its volume fracture with the result that the cone apex has stepped appearance. Figure 5 shows initially continuous cones subjected to a thermal shock (cone axes coincide with the irradiation direction). The thermal shock causes bending and partial fracture of the end of a sharp conical spike 5 of height 13.74 cm, entire fracture of cone 1 of height 1 cm, and severe fracture accompanied by partition of the upper part of cone 2 of height 2.5 cm. The fracture of cones 3 and 4 is pronounced only slightly. The stress-cumulation effect and the degree of fracture of cones is reduced as the cone-apex angle decreases. An increase in the x-ray energy fluence enhances the effect of stress cumulation, which results in a higher degree of fracture of conical specimens.

The revealed special features of fracture of metals and alloys subjected to a thermal shock initiated by x-rays of a nuclear explosion can be used in design and development of elements and units of new power and radiation installations, development of experimental techniques, and further study of strength of solids.

REFERENCES

1. S. Eliezer, I. Gilath, and T. Bar-Noy, "Laser-induced spall in metals: Experiment and simulation," *J. Appl. Phys.*, **67**, No. 2, 715–724 (1990).
2. *Physics of Nuclear Explosion*, Vol. 2: *Explosive Action* [in Russian], Fizmatlit, Nauka (1997).
3. V. N. Aptukov, "Deformation and failure of a plate under a thermal shock," *Probl. Prochn.*, No. 12, 82–87 (1987).
4. E. K. Bonyushkin, B. L. Glushak, N. I. Zavada, et al., "Mechanisms of spalling of metals in the fast space-heating regime in submicrosecond and submillimicrosecond ranges of durability," *J. Appl. Mech. Techn. Phys.*, **37**, No. 6, 862–870 (1996).
5. V. K. Golubev, K. G. Rabinovich, and A. K. Chernyshev, "Special features of failure of copper foil under intense x-ray irradiation," *Zh. Tekhn. Fiz.*, **68**, No. 2, 116–117 (1998).
6. A. M. Molitvin, I. P. Borin, and V. S. Bosamykin, "Durability of copper, nickel, titanium, brass, and bronze under impulsive irradiation," *J. Appl. Mech. Tech. Phys.*, **37**, No. 6, 871–875 (1996).
7. I. P. Borin, V. S. Bosamykin, and A. M. Molitvin, "Durability of copper and its alloys under a pulsed electromagnetic action," *Fiz. Met. Metalloved.*, **81**, No. 5, 170–175 (1996).
8. A. M. Molitvin and I. P. Borin, "Special features of spalling fracture of metals under a thermal shock," *Metally*, No. 3, 93–98 (1998).
9. A. M. Molitvin, "Kinetic and energy approaches to the description of spalling fracture of copper and nickel under a thermal shock," *Metally*, No. 3, 101–108 (2001).
10. A. M. Molitvin, "Kinetic and energy approaches to the description of spalling fracture of structural steels under a thermal shock," *Metally*, No. 4, 66–71 (2002).
11. A. M. Molitvin, "Strength and specific fracture energy of metals subjected to a thermal shock," in: V. E. Fortov (ed.), *Physics of Extremal States of a Substance* [in Russian], Chernogolovka (2002), pp. 121–123.
12. A. M. Molitvin, I. P. Borin, and V. S. Bosamykin, "Some geometrical effects of thermomechanical failure of metallic specimens under pulsed radiation," *J. Appl. Mech. Tech. Phys.*, **37**, No. 5, 751–755 (1996).
13. E. N. Donskoi, "Algorithm and program ÉLIZA for solving problems of compatible transfer of γ-radiation, electrons, and positrons by the Monte Carlo method," *Vopr. Atom. Nauki Tekh., Ser. Mat. Model. Fiz. Prots.*, No. 1, 3–6 (1993).
14. G. G. Ivanova, N. F. Gavrilov, V. I. Selin, and V. N. Safonov, "UP-OK program for solving one-dimensional problems of mechanics of continuous media in the one-dimensional complex," *Vopr. Atom. Nauki Tekhn. Ser. Met. Progr. Chisl. Resh. Zad. Mat. Fiz.*, No. 3, 11–14 (1982).
15. I. P. Borin, S. A. Novikov, A. P. Pogorelov, and V. A. Sinitsyn, "Kinetics of fracture of metals in the subsecond range of durability," *Dokl. Akad. Nauk SSSR*, **266**, No. 6, 1377–1380 (1982).
16. A. G. Ivanov and V. N. Mineev, "Scale criterion of brittle fracture of structures," *Dokl. Akad. Nauk SSSR*, **220**, No. 3, 575–578 (1975).
17. V. A. Ogorodnikov, A. G. Ivanov, V. I. Luchinin, et al., "Scaling effect in dynamic fracture (spallation) of brittle and ductile materials," *Combust. Expl. Shock Waves*, **35**, No. 1, 97–102 (1999).