2. V. Herrmann, "Determining equations of porous sealing materials," in: Problems of Elasticity Theory [in Russian], Moscow (1976) (Mechanics. New Developments in Foreign Science, No. 7).
3. G. V. Belyakov, V. N. Rodionov, and V. P. Samosadnyi, "The heating of porous material upon shock compression," Fiz. Goreniya Vzryva, 13, No. 4 (1977).
4. G. V. Belyakov, "Shock deformation of granular media," Dokl. Akad. Nauk SSSR, 218, No. 6 (1974).
5. N. I. Matyushkin and Yu. A. Trishin, "Some effects which occur upon explosive compression of a viscous cylindrical shell," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1978).
6. S. Z. Dunin and V. V. Surkov, "The dynamics of pore closure in a shock wave front," Prikl. Mat. Makh., 43, No. 3 (1979).
7. A. A. Bakanova, I. P. Dudoladov, and Yu. N. Sutulov, "Shock compressibility of porous tungsten, copper, and aluminum in the low-pressure region," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1974).
8. F. A. Baum, L. I. Orlenko, et al., in: K. P. Stanyukovich (editor), The Physics of Explosion [in Russian], Nauka, Moscow (1975).
9. S. V. Dunin and V. V. Surkov, "The structure of the shock wave front in a solid porous medium," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1979).
10. V. V. Surkov, Theoretical Problems of Dynamic Loading of Microinhomogeneous Condensed Media, Dissertation for the degree of Candidate of Physicomathematical Sciences, MIFI, Moscow (1980).
11. R. K. Linde, L. Seaman, and D. N. Schmidt, "Shock response of porous copper, iron, tungsten, and polyurethane," J. Appl. Phys., 43, No. 8 (1972).
12. G. V. Stepanov, "The interrelationship of deformation resistance in the case of a uniaxial loaded state and the breaking loads in the case of cleavage of metals," Probl. Prochn., No. 12 (1978).

---

# EFFECT OF TEMPERATURE ON SPALL OF POLYMERIC MATERIALS

V. K. Golubev, S. A. Novikov,
and Yu. S. Sobolev

UDC 539.4:620.171.3

The results of an investigation of spall of some polymeric materials are given in [1-9]. The largest number of experimental results have been obtained for Plexiglas [1-6]; spall of polycarbonate has been investigated in detail [7, 8]. Concerning the question of the effect of temperature on spall, it has been experimentally investigated only for some metals (see, for example, [10, 11]), and with respect to polymeric materials one can mention only [12], in which the rate of growth of microdefects of Plexiglas at room and increased temperatures was estimated using the light-scattering method.

The results of an experimental investigation of spall of eight polymeric materials are given in this paper. Identical loading conditions and the use of methods of preliminary heating and cooling of the samples permit obtaining a realistic comparative picture of spall of the materials investigated and determining the nature of the effect of temperature on their spall resistance.

The layout of the experimental setup for investigation of the effect of temperature on spall of materials has been given in [11], and the testing scheme is shown in Fig. 1, where the numbers denote the following: 1) aluminum striker, 2) copper screen, 3) sample mounting, and 4) sample of the material being investigated. Samples 4 mm thick and 40 mm in diameter were loaded by the impact on a copper screen 12 mm thick of a plate made out of AMts aluminum alloy 4 mm thick, whose velocity w was specified with an accuracy of about 3%. Heating of the samples was accomplished through the copper screen by means of a Nichrome ribbon heater. The heating time did not exceed 10 min, and the temperature was recorded with the help of a Chromel—Copel thermocouple. Cooling to a temperature of —196°C was accomplished by submerging the screen with the sample in a vessel containing liquid nitrogen.

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 143-150, January-February, 1982. Original article submitted November 20, 1980.

0021-8944/82/2301-0134$07.50

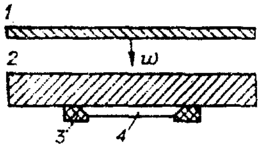

Fig. 1

TABLE 1

| No. | Investigated polymeric materials | Shock adiabats of the materials | | | Critical conditions of spall at normal temperature | | |
|---|---|---|---|---|---|---|---|
| | | $\rho$, g/cm$^3$ | $c_0$, km/sec | $\lambda$ | $w$, m/sec | $p$, GPa | $\sigma$, GPa |
| 1 | Plexiglas | 1,18 | 2.57 | 1,54 | 95 | 0,16 | 0,15 |
| 2 | Teflon-4 | 2,19 | 1,53 | 1,95 | 125 | 0,24 | 0,20 |
| 3 | Polycarbonate | 1,20 | 1,74 | 1,72 | 115 | 0,14 | 0,12 |
| 4 | Vinyl plastic | 1,40 | 1,95 | 1,66 | 93 | 0,14 | 0,13 |
| 5 | VK-3 adhesive | 1,10 | 2,27 | 1,70 | 77 | 0,11 | 0,10 |
| 6 | Polyethylene | 0,92 | 2,05 | 1,95 | 128 | 0,14 | 0,12 |
| 7 | Caprolan | 1,15 | 3,30 | 1,32 | 93 | 0,19 | 0,18 |
| 8 | Polystyrene | 1,05 | 2,51 | 1,36 | <69 | <0,10 | <0,09 |

The critical velocities of the aluminum plate on the copper screen were determined in the experiments conducted, which when exceeded by an insignificant amount resulted in the visually observable initial stage of spall of the materials being investigated. The onset of spall was observed under a microscope at small magnification (20×) by transillumination in transparent materials and on a polished section surface in opaque materials. The following polymeric materials were investigated in this paper: type TOSP Plexiglas, Teflon-4, type 2 polycarbonate diflon, type VN vinyl plastic, VK-3 adhesive based on phenoloformaldehyde resin, type PÉVD polyethylene, V-1 Caprolan, and polystyrene made out of PSÉ-1 powder.

Knowledge of the shock adiabats of the striker materials, the screen, and the samples permits a computational comparison of the velocities of the aluminum striker and the value of the pressure in the loading compression pulse reaching the free surface of the sample. The shock adiabats of the materials were taken in the form of linear relationships between the wave and bulk velocities, $D = c_0 + \lambda u$; it was assumed that expansion of the materials is also satisfactorily described by their shock compression adiabats, including the region of small negative pressures. The shock adiabats of polymeric materials necessary for computational estimates are taken from [13-18] and given in Table 1, and the shock adiabats for aluminum and copper are taken in the form $D = 5.25 + 1.39u$ and $D = 3.95 + 1.50u$, respectively. One should note that some nonlinearity of the D–u relationships is observed in the low-pressure region of shock-wave compression for polymeric materials [14, 16, 19]; therefore the approximate D–u relationships used are based, as a rule, on results obtained at small values of u. In order to determine the pressure in the compression pulse at an elevated temperature, one should take account of the lowering of the density and the volume elasticity modulus of the material. Estimates made for Plexiglas and polystyrene using the results of [20] show that heating by 50° results in a decrease in the pressure in the loading pulse by approximately 4%. This value of the pressure decrease has been adopted in the computational estimates for all the materials under investigation. The characteristic loading time $\tau$ is estimated to be 1.5 μsec as the circulation time of a plastic wave in the aluminum striker. Pressure measurements in polymeric materials using the procedure of a manganin detector [21] were made to check the competence of the method used for the computational estimate. The measurements were made with a striker velocity of 150 m/sec for all the materials except polycarbonate and VK-3 adhesive. One of the detectors was placed between the copper screen and the sample, and the other one was placed at a distance of 4 mm from the first one between the two samples. This permitted simultaneously recording the wave velocity and pressure in the compression pulse on two baselines. The experimentally recorded loading compression pulses in the materials under investigation were more or less bell-shaped and their characteristic duration at half-height was about 1.5 μsec.

An oscillogram obtained in connection with the measurement of the loading parameters of Plexiglas is given in Fig. 2. The peculiarity of the leading front in the form of a precursor also observed for Caprolan, may be related to some asymmetry of the shock loading as well as with the effect of the gap at the place where the detector is mounted, which was

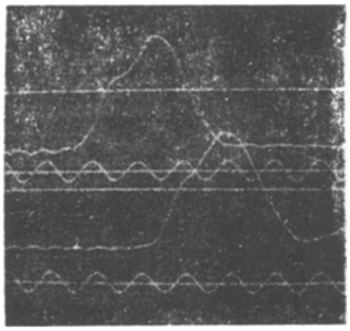

Fig. 2

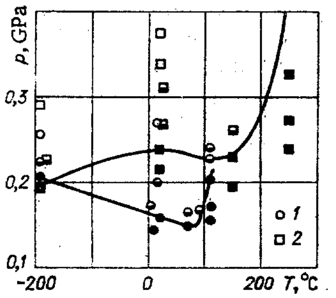

Fig. 3

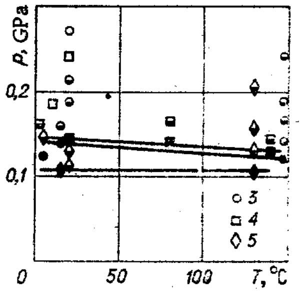

Fig. 4

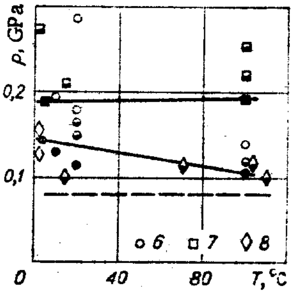

Fig. 5

filled with vacuum grease. Equality of the pressures in the compression pulse on both measurement base lines was observed for Plexiglas, Caprolan, and vinyl plastic. An inappreciable decrease of the pressure amplitude was observed for the remaining materials, but the size of this decrease is less than the error of the procedure, which is estimated to be 10%, and its average value was taken as the pressure in the loading pulse. Good agreement of the calculated and experimental results is observed for Plexiglas, Teflon, polyethylene, and polystyrene. The calculated and experimental values of D practically coincide for them, and the experimental values of p somewhat exceed the calculated values (by no more than 7%). The experimental values of D and p for Caprolan are less than the calculated values by 3 and 10%, respectively. An excess of the experimental value of D over the calculated value by 17% is observed for vinyl plastic with the same good agreement of the pressures. It should be noted that the information given in this paper permits conducting a more detailed analysis of the results if one uses an elastoplastic computational program and more exact and refined equations of state of the materials.

The experimental results are given in Figs. 3-5, in which the state of the sample after a test is placed in conformity with the pressure in the compression pulse and the temperature T; the state is arbitrarily subdivided into three types: The filled symbols denote the absence of visually observable damage, the partially filled symbols denote partial spall, which is characterized by the presence of individual flaws or aggregates of them in the spall zone, and the open symbols denote total spall, which is characterized by the presence of a main spall crack passing through all the section surfaces of the sample, covering of the entire cross section of the sample with aggregates of flaws, or direct splitting off of part of the free surface of the sample. We will dwell in detail on the results obtained for each of the materials under investigation (the numbers of the points in Figs. 3-5 correspond to the numbers of the materials in Table 1).

For Plexiglas at normal temperature and with loading pressure pulses of 0.17 and 0.2 GPa the relative area of the damaged material S (relative to the area of the free surface of the sample) is approximately 2 and 60%, and complete splitting off of a spall zone 1.8 mm thick occurs for a loading pressure of 0.27 GPa. An increase of the testing temperature to 110° results in an increase in the critical value of p, and the value of S amounts to 20 and 40%, respectively, at pressures of 0.23 and 0.24 GPa. A reduction of the temperature to −196° also leads to an increase in the critical value of p, and the value of S for $p = 0.23$ GPa is 5%, and at $p = 0.26$ GPa splitting off of about 70% of the free surface of the sample occurs.

For Teflon at normal temperature and for loading pressure pulses of 0.27 and 0.31 GPa separate small cracks are observed on the section surface of the samples, at $p = 0.34$ GPa a main spall crack passes through almost all the section surfaces, and at $p = 0.37$ GPa complete splitting off of a spall layer 1.15 mm thick occurs. An increase of the temperature to 150° hardly changes the critical value of p, and a further increase to 250° results in the fact that at $p = 0.43$ GPa onset of spall is still not observed, and at $p = 0.68$ GPa significant cracking of the material is now noticeable on the section surface of the sample over a rather wide (more than 1 mm) spall zone. Cooling to −196° results in some lowering of the critical value of p, at $p = 0.23$ GPa several small cracks are observed on the section surface, and at $p = 0.29$ GPa splitting off of about 60% of the free surface occurs.

For polycarbonate at normal temperature and loading by 0.16, 0.19, 0.21, 0.27, and 0.38 GPa pressure pulses the following nature of damage to the samples occurs: Individual minute flaws, $S = 40$ and 60%, and aggregates of flaws span the entire cross section of the samples in the last two cases. At a temperature of 150° and loading by 0.14, 0.17, 0.19, and 0.24 GPa pressure pulses the quantity S is 5, 20, 20, and 60%, respectively.

For vinyl plastic at normal temperature and loading by 0.16, 0.19, and 0.24 GPa pressure pulses the following nature of sample damage is observed: a main crack passing through half of the section surface, total splitting off of a spall layer 1.9 mm thick, and total spall with splitting off from the spall layer and the remaining material of layers 0.65 mm thick, which indicates that the samples were made out of a sheet obtained by hot pressing of thin layers, and the value obtained for the spall resistance corresponds to the dynamic strength of the bonding of these layers. At $T = 80°$ and $p = 0.18$ GPa and at $T = 140°$ and $p = 0.14$ GPa splitting off of 40 and 5% of the free surface of the samples occurs.

For VK-3 adhesive at normal temperature and a pressure of about 0.15 GPa flaw accumulations cover about 50% of the section, and at $T = 130°$ and $p = 0.2$ GPa more minute flaws are scattered over the entire cross section of the sample.

For polyethylene at normal temperature and pressures of 0.15, 0.17, and 0.19 GPa the value of S is 2, 40, and 100%, respectively, but complete splitting off of the spall layer does not occur, although the pressure was increased to 0.42 GPa. At $T = 100°$ and pressures of 0.12 and 0.14 GPa the value of S is 20 and 100%, respectively.

For Caprolan at normal temperature and loading by 0.21, 0.27, and 0.31 GPa pressure pulses, there is the following pattern of sample damage: individual minute flaws, a main crack passing through 60% of the section surface, and a main crack intersecting the entire section surface. At $T = 100°$ and pressures of 0.22 and 0.25 GPa individual minute flaws are visible in the section surface.

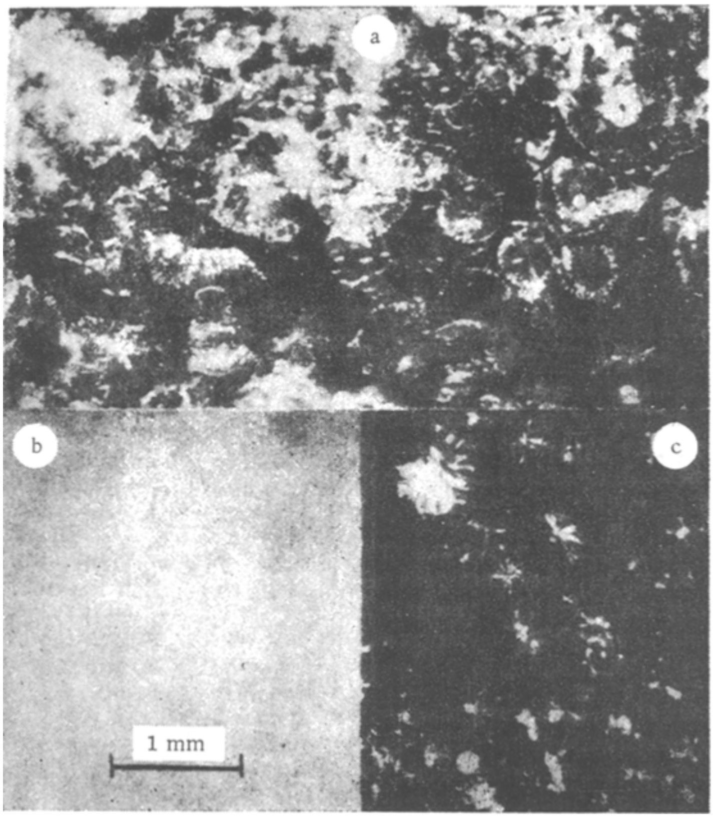

Fig. 6

For polystyrene at normal temperature and loading by 0.10 and 0.13 GPa pressure pulses the value of S is 40 and 100%, and for loading by a pressure of 0.15 GPa a spall layer 1.7 mm thick is completely split off. At T = 70° and p = 0.11 GPa, T = 100° and p = 0.12 GPa, and T = 110° and p = 0.10 GPa the value of S is 40, 60, and 40%, respectively. The critical conditions for the origin of spall in polystyrene were not obtained in connection with the limited possibilities of the loading method employed ($w \geqslant 70$ m/sec), but observing the nature of the sample damage, one can intuitively assume that the critical value of p is about 0.08 GPa.

One should note the peculiarities of the spall flaws, which it is especially convenient to observe by transillumination in transparent materials. Actually, the flaws for all the materials are disk-shaped cracks, which were observed upon the spall of polycarbonate [7, 8], although their sizes were somewhat smaller as a rule, which is related in part to the shorter loading time, but the density over the sample section is larger. Several fragments from observations of the nature of spall of the materials are given in Fig. 6 as an example [a) Plexiglas, T = 15°, p = 0.2 GPa; b) Caprolon (section surface), T = 100°, p = 0.22 GPa; c) VK-3 adhesive, T = 130°, p = 0.16 GPa]. Measuring the crack radius r and knowing the characteristic loading time $\tau$, one can estimate the average velocity of the crack, $v = r/\tau$. For Plexiglas (Fig. 6a) at normal temperature the average velocity of the larger cracks is about 330 m/sec, for polystyrene (p = 0.13 GPa) 300 m/sec, and for polyethylene (p = 0.19 GPa) 360 m/sec. One can also note the effect of temperature on the value of v. For polycarbonate at T = 15° and p = 0.16 GPa, v = 470 m/sec, and at T = 150° and p = 0.17 GPa, v = 330 m/sec, i.e., some decrease of the crack velocity is present, which is observed for other materials. The crack velocity can be estimated also for opaque materials by the method of observing the section surface of a sample. For Caprolan (Fig. 6b) v = 200 m/sec. For VK-3 adhesive, which is a modified phenoloformaldehyde resin and is, in contrast to the other materials investigated, a thermoreactive polymer, a clear change in the damage mechanism occurs upon heating to 130°. If at normal temperature the flaws are larger than in other materials and disk-shaped cracks are spaced at lower density (at T = 20° and p = 0.13 GPa, v = 730 m/sec), then at T = 130° the flaws are star-shaped volume spallations (Fig. 6c) spaced with appreciable density over the entire sample section. The estimate of the maximum rate of damage development in this case is 200 m/sec.

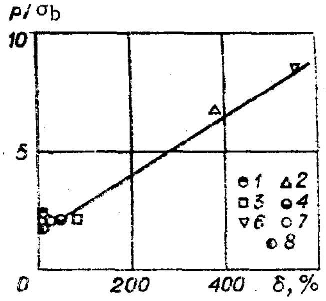

Fig. 7

The critical conditions for damage obtained and presented in Table 1 for the polymeric materials under investigation (including σ, the maximum tensile stress in the cleavage plane estimated by extrapolation of the shock adiabats into the region of small negative pressures) give a real comparative picture of the strength of polymeric materials for a characteristic loading time of ∿1 μsec. The results obtained for Plexiglas and polycarbonate are in good agreement with the results of [3, 4, 7], and the results for VK-3 adhesive and polystyrene are similar to the results given in [9] for epoxy resin and ABC plastic, which is similar to polystyrene in its properties. Making a comparison with the results obtained with explosive loading is difficult in connection with the imposition of additional effects associated with a higher loading intensity on the pattern of the phenomenon. The question of the effect of the loading time on the spall of polymeric materials has also still not been definitely solved. If some dependence of the breaking stress on the loading time has been noted in the 0.75-2.1-μsec time range in [3], then no effect of the loading time on the breaking stress in Lucite was observed in the 0.2-5-μsec time range in [1]. Concerning [4], here the experimental loading procedure evidently simply did not permit varying the loading time significantly, for which a variation within appreciable limits of the scale of the striker—sample system is necessary.

It is also interesting to compare the results obtained on the dynamic loading of the polymeric materials investigated with the data for their strength under static conditions of uniaxial tension [22]. The results are given in Fig. 7 in the coordinates $\delta$ and $p/\sigma_b$, where $\delta$ is the relative tensile elongation, which serves as the main engineering characteristic of the plasticity of the material, and $\sigma_b$ is the breaking tensile stress. Since the tabular values given have some scatter, the upper value was taken for $\sigma_b$ in order that we obtain the minimum effect of dynamic strengthening in pure form, and the average value was taken for $\delta$. An increase in plasticity of the material from polystyrene to polyethylene results in its dynamic strengthening from 1.8 to 8.4, i.e., a clear connection between the processes of plastic deformation and fracture of polymeric materials is present under the conditions of the impulsive loading mechanism. One can observe a similar picture for metals by systematizing the results obtained under identical loading conditions (see, for example, [11]). This phenomenon also qualitatively explains the significant difference in the behavior of the temperature dependences of the cleavage strength of polymeric materials and metals in comparison with the temperature dependences of their strength under static conditions of uniaxial tension and gives some prerequisites for a quantitative solution of this problem.

One can also note with respect to the effect of temperature on the spall resistance of polymeric materials that heating does not actually reduce their dynamic strength, and it can often even lead, as in the case of Plexiglas and especially Teflon, to a very significant strengthening, whereas for metals an increase in the temperature leads only to a decrease, although to a different extent, of their spall resistance [10, 11]. It is interesting that an explicit correlation is observed for Plexiglas between the results on the effect of temperature on spall resistance and the impact viscosity [22], which is a very sensitive parameter to a change in the fracture mechanism. The experimental estimates made in [12] for the microdamage rates in the subcritical stage of growth (a size up to $2 \cdot 10^{-4}$ mm) in connection with the spall of Plexiglas give values of 1.3 and 3.8 m/sec for temperatures of 22 and 73°C. In the supercritical stage of growth of flaws in the form of disk-shaped cracks, whose characteristic size is about 1 mm, a decrease in their growth rate with increasing temperature occurs for all the polymeric materials investigated, which is evidently associated with the fact that the nature of the damage becomes more viscous in the sense of an increase of the zone of local plasticity at the tip of a growing crack. The characteristic values of the crack velocities lie within the range from 100 m/sec to 1 km/sec, which was observed in [8] for polycarbonate. It is impossible to extend the conclusion drawn to the thermoreactive VK-3 polymeric adhesive, the nature of whose fracturing becomes even less high-speed upon heating, but the visually observable volume cracking of the material creates the impression of a more brittle fracturing of it, nor is it possible to extend the conclusion drawn above to vinyl plastic, whose fracturing occurs along the boundary of compressed layers of the material and is not observed very clearly visually.

We note in conclusion that the heating of polymeric materials to temperatures exceeding their design temperatures under conditions of static loads does not reduce their resistance to the action of strong impulsive mechanical loads of short duration.

## LITERATURE CITED

1. D. V. Keller and J. G. Trulio, "Mechanism of spall in Lucite," J. Appl. Phys., 34, No. 1 (1963).
2. B. A. Tarasov, "The temporal dependence of the strength of plastic under shock loading," Probl. Prochn., No. 12 (1972).
3. B. A. Tarasov, "A quantitative description of cleavage flaws," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1973).
4. E. P. Evseenko, E. L. Zil'berbrand, et al., "The dynamic branch of the temporal dependence of the strength of polymethylmethacrylate," Pis'ma Zh. Tekh. Fiz., 3, No. 14 (1977).
5. A. N. Dremin, G. I. Kanel', and S. A. Koldunov, "An investigation of cleavage in water, ethyl alcohol, and Plexiglas," in: Combustion and Explosion [in Russian], Nauka, Moscow (1972).
6. V. K. Golubev, S. A. Novikov, and L. M. Sinitsyna, "The fracturing of materials under loading by the explosion of a sheet explosives charge," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1981).
7. D. R. Curran, D. A. Shockey, and L. Seaman, "Dynamic fracture criteria for a polycarbonate," J. Appl. Phys., 44, No. 9 (1973).
8. J. F. Kalthoff and D. A. Shockey, "Instability of cracks under impulse loads," J. Appl. Phys., 48, No. 3 (1977).
9. L. Davison and R. A. Graham, "Shock compression of solids," Phys. Rep., 55, No. 4 (1979).
10. R. M. Schmidt, F. W. Davies, et al., "Temperature-dependent spall threshold of four metal alloys," J. Phys. Chem. Solids, 39, No. 4 (1978).
11. V. K. Golubev, S. A. Novikov, et al., "The effect of temperature on the critical conditions of spall of metals," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1980).
12. L. D. Volovets, N. A. Zlatin, et al., "The effect of temperature on the fracture kinetics of polymethylmethacrylate in the microsecond longevity range," Pis'ma Zh. Tekh. Fiz., 6, No. 11 (1980).
13. R. MacQueen, S. Marsh, et al., "The equation of state of solid bodies based on the results of investigations of shock waves," in: High-Speed Shock Phenomena [Russian translation], Mir, Moscow (1973).
14. L. V. Kuleshova and M. N. Pavlovskii, "Dynamic compressibility, electric conductivity, and speed of sound behind a shock wave front in Caprolan," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1977).
15. I. P. Dudoladov, V. I. Rakitin, et al., "Shock compressibility of polystyrene with various initial densities," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1969).
16. N. G. Kalashnikov, L. V. Kuleshova, and M. N. Pavlovskii, "Shock compression of polytetrafluorethylene up to pressures of 1.7 Mbar," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1972).
17. I. Mills, "A comparison of the Hugoniot empirical equations of state for plastics," RTK, 3, No. 4 (1965).
18. M. N. Pavlovskii, "Measurement of the speed of sound in shock-compressed quartzite, dolomite, anhydrite, sodium chloride, paraffin, Plexiglas, polyethylene, and Teflon-4," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1976).
19. L. M. Barker and R. E. Hollenbach, "Shock-wave studies of PMMA, fused silica, and sapphire," J. Appl. Phys., 41, No. 10 (1970).

20. D. L. Lamberson, J. R. Asay, and A. H. Guenther, "Equation of state of polystyrene and polymethylmethacrylate from ultrasonic measurements at moderate pressures," J. Appl. Phys., 43, No. 3 (1972).
21. Yu. V. Bat'kov and E. D. Vishnevetskii, "Instrumentation for the measurement of pulse pressures in the 0.1-20 GPa range with piezoresistive detectors," in: Abstracts of Lectures of the Second All-Union Symposium on Pulse Pressures [in Russian], VNIIFTRI, Moscow (1976).
22. V. M. Kataeva, V. A. Popova, and B. I. Sazhina (editors), Handbook on Bulk Plastics [in Russian], Vols. 1 and 2, Khimiya, Moscow (1975).

---

# EFFECT OF STRAIN RATE ON THE CHARACTERISTICS OF ELASTOPLASTIC DEFORMATION OF METALLIC MATERIALS

G. V. Stepanov

UDC 539.4

One of the main problems of the mechanical testing of materials is the determination of their strength and deformation characteristics as a function of the temperature and time conditions of loading. For a fixed temperature and strain rate the strength of the material under investigation is determined by its structural state (conventionally denoted by C), which changes during deformation as a result of the combined action of processes related to the growth of plastic deformation and processes developing with them. Their effect on the shear strength τ can be estimated by the strain-hardening modulus $M_D = \partial\tau/\partial e_p$ $(\partial\tau/\partial t = 0)$ and the strain softening modulus $R = -\partial\tau/\partial t$ $(\partial\tau/\partial e_p = 0)$ [1], so that for a fixed plastic shear rate $\dot{e}_p$

$$\tau_{\dot{e}_p = \mathrm{const}} = \tau(C_0, \dot{e}_p) + \int_{e_p^0}^{e_p} \left[M_D - \frac{R}{\dot{e}_p}\right] de_p \qquad (1)$$

where the subscript zero denotes the initial state.

A change of the strain rate for a fixed structure of the material leads to a change of the ductile component of the strength. Characterizing the effect of rate by the viscosity factor μ — the proportionality factor between increments of rate and the ductile component of the strength — we find

$$\tau_{C=\mathrm{const}} = \tau(C, \dot{e}_p^0) + \int_{\dot{e}_p^0}^{\dot{e}_p} \mu(C)\, d\dot{e}_p. \qquad (2)$$

By taking account of Eqs. (1) and (2) we obtain the dependence of the strength on the history of previous deformation $e_p$ in the form

$$\tau = \tau(C_0, \dot{e}_p^0) + \int_0^t \left[M_D \frac{de_p(t)}{dt} - R\right] dt + \int_{\dot{e}_p^0}^{\dot{e}_p} \mu(C)\, d\dot{e}_p.$$

The results of experiments with a combined loading regime are commonly processes by using integral equations of nonlinear hereditary viscoplasticity, e.g., of the form [2]

$$\tau = \varphi(e_p) - \int_{(t)} Q_1(t-\zeta)\, \tau(\zeta)\, d\zeta \qquad (3)$$

In this procedure the effect of rate on the ductile component of the strength is not separated from its effect on the change of the structural state, since the strain-hardening and relaxation processes interact. This approach encounters serious difficulties in describing

---

Kiev. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 150-156, January-February, 1982. Original article submitted December 11, 1980.