Journal of Applied Mechanics and Technical Physics, Vol. 36, No. 3, 1995

STRENGTH AND VISCOSITY OF METALS IN A WIDE RANGE OF STRAIN RATE VARIATION

V. A. Ogorodnikov, E. S. Tyun'kin, and, A. G. Ivanov

UDC 539.374; 662.215.2

At present a number of mathematical models have been suggested and investigated for describing the behavior of metals under conditions of nonstationary high-rate strain. As a rule,use is made of continuum mechanics equations which are closed by relations of stress and strain tensors with thermodynamic and kinematic medium parameters. Methods for describing the spherical constituents of the corresponding tensors depending on specific volume and temperature parameters, or means of constructing equations of state are known and generally accepted [1]. Methods for describing deviator constituents of tensors or methods for constructing defining relations depend on the rheologic behavior of a solid body in the process of deformation. This accounts for the diversity of mathematical models used in phenomenological description of the resistance of impact-loaded materials to forming, and for the modifications of mathematical models of elastoplastic, viscoplastic, and relaxing media [2].

For a large class of problems of high-rate straining of metallic shells driven in one way or another toward the center or axis of symmetry, mathematical modeling of dynamic processes is carried out according to the scheme of nonstationary straining of a compressible viscoplastic medium in a region with free boundaries. The difficulties emerging in this case are due to the absence of reliable experimental data on the behavior of the dynamical yield limit σ_s and the dynamical viscosity coefficient μ for many metals in a wide range of the strain rates $\dot{\varepsilon} \simeq 10^3$–$10^6$ sec^{-1}. In this paper we suggest a new technique for determining these characteristics of metals with the use of experiments on compressed cylindrical shells [3].

1. High-rate deformation of cylindrical shells is usually performed by explosion products (EP) of a high explosive (HE) located on their outer surface. As a rule, however, in these experiments the shells converge toward the symmetry axis and then fly apart [4] or there arise conditions leading to spallation of the shell [5] or to loss of its stability [6]. The possibilities of the method are substantially increased in the case of inertial axisymmetric compression of the shell at a relatively low initial velocity when its initial kinetic energy completely dissipates in the compression process, and the shell is stopped at a certain radius retaining its symmetric shape and integrity (absence of spalls).

These conditions of shell compression can be provided by applying additional shields of thickness Δ_2 comparable to the thickness Δ_1 of the shell. The shields are placed on the outer surface of the HE layer. This makes it possible to use HE layers of smaller thickness ($\Delta_0 \ll \Delta_1,\ \Delta_2$), i.e., to create loading conditions closer to instantaneous detonation, to press a shell under the conditions of inertial compression, and to greatly simplify the computational scheme for determining the shell's initial velocity [7, 8]. It can be stated that the initial kinetic energy E of these shells is completely transformed to the work of plastic deformation A^*, i.e., to the work directed against the strength forces of the shell material, characterized by its dynamic yield limit σ_s. Assuming the constancy of the yield limit ($\sigma_s = \text{const}$) during the compression or plastic deformation of a shell and taking its material to be incompressible, we can define the value of A^* by the relation [9]

$$A^* = \frac{\pi\sigma_s}{\sqrt{3}}\left[R^2 \ln\frac{R_b^2}{R} - a^2 \ln\frac{b^2}{a^2} + (b^2 - a^2)\ln\frac{R_b^2}{b^2}\right], \tag{1.1}$$

Research Institute of Experimental Physics, Arzamas-16 607200. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 36, No. 3, pp. 134–140, May–June, 1995. Original article submitted May 6, 1994.

where b is the outer and a the inner radii of the shell before loading; R_b is the outer and $R = (R_b^2 + a^2 - b^2)^{1/2}$ the inner radius after loading. For practical calculations it is more convenient to use this formula in the form

$$A^* = \frac{\pi\sigma_s b^2}{\sqrt{3}}\left[\frac{R_b^2}{b^2}\ln\frac{R_b^2}{b^2} - \left(\frac{R_b^2}{b^2} + \frac{a^2}{b^2} - 1\right)\ln\left(\frac{R_b^2}{b^2} + \frac{a^2}{b^2} - 1\right) + \frac{a^2}{b^2}\ln\frac{a^2}{b^2}\right].$$

Note that there are certain reasons in assuming σ_s to be constant in this case, as distinct, e.g., from the method of expanding rings [10], . Firstly, as the shell is being compressed (particularly at the first stage of the process), the plastic deformation rate remains constant, $\dot{\varepsilon} = V/r_*$, since the shell velocity V and its mass center radius $r_* = ((a^2 + b^2)/2)^{1/2}$ decrease concurrently. Secondly, during the shell compression, at the stage of stopping, the processes of changes of resistance of a material to deformation, due to decreasing $\dot{\varepsilon}$ and increasing strain hardening, have opposite signs. This circumstance leads to partial compensation and to a decrease in the effect of these factors on resistance to deformation.

In the absence of energy losses on fracture and bending deformations, with regard to smallness of mass m_0 of the HE layer as compared with the masses m_1 of a shell and m_2 of a shield, the initial kinetic energy E_1 of a shell can be determined from conservation laws for energy E and impulse I. For the closed shield–HE layer–shell system

$$E_0 = E_1 + E_2, \qquad I_1 = I_2. \tag{1.2}$$

Taking into account that $E = I^2/2m$, we find

$$E_1 = \frac{m_2}{m_1 + m_2} E_0 = \varphi E_0.$$

Here φ is the energy take-off coefficient; $E_0 = m_0 D^2/2(n^2 - 1)$; D is the detonation rate; n the polytropic exponent of the EP.

In the general case where the mass of the HE, as compared to that of a shield or a shell, cannot be neglected, in solving the problem of the energy take-off by a shell, account must be taken of the HE mass. This amounts to taking into account the kinetic energy and the impulse of the EP moving toward the shell and the shield whose velocities are limited by the corresponding velocities of the shell and the shield. The equations of the conservation laws (1.2) take the form

$$E_0 = E_1 + E_1^{\mathrm{EP}} + E_2 + E_2^{\mathrm{EP}}, \qquad I_1 + I_1^{\mathrm{EP}} = I_2 + I_2^{\mathrm{EP}}. \tag{1.3}$$

If we assume, just as in [11], that the distribution of the EP velocities along the radius is linear (Fig. 1), then the velocities can be written as

$$V_{\mathrm{EP}} = \frac{V_b}{R_0 - b}(R_0 - r), \qquad R_0 \leqslant r \leqslant b,$$

$$V_{\mathrm{EP}} = \frac{V_A}{A - R_0}(r - R_0), \qquad A \leqslant r \leqslant R_0.$$

For cylindrical geometry the equation of continuity on the shell boundaries meets the condition $V_a a = V_b b$. Taking into account this and the "lacing" of the velocities of the shield and the shell on the A and b radii with those of the EP, we obtain expressions for the terms contained in (1.3) and write

$$E_1^* = \varphi_* E_0 = \varphi_* \frac{\pi\rho_0\Delta_0 D^2}{n^2 - 1} b\left(1 + \frac{\Delta_0}{2b}\right), \tag{1.4}$$

where

$$\varphi_* = \left\{1 + \frac{\rho_2 \ln(B/A)}{\rho_1 \ln(b/a)}\left(k\frac{A}{B}\right)^2 + \frac{1}{12}\frac{\rho_0\Delta_0}{\rho_1 b \ln(b/a)}\left[\left(1 + \frac{A}{B}\right)(k-1)^2 + 2\left(1 + \frac{A}{B}k^2\right)\right]\right\}^{-1};$$

$$k = \frac{2\left(3\frac{\rho_1\Delta_1}{\rho_0\Delta_0} + 1\right) + \frac{A}{b}}{2\frac{A}{b}\left(3\frac{\rho_2\Delta_2}{\rho_0\Delta_0} + 1\right) + 1}; \qquad B = b + \Delta_0 + \Delta_2;$$

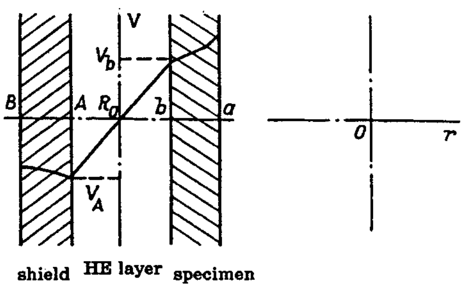

Fig. 1

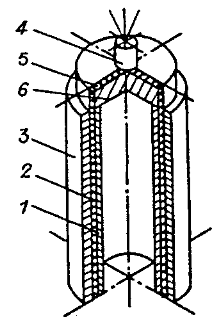

Fig. 2

$A = b + \Delta_0$; ρ_1, ρ_2, ρ_0 are the densities of the material of the shell, the shield and the HE layer, respectively. From the equality $A^* = E_1{}^*$ and Eqs. (1.1), (1.4) we obtain the expression for the dynamic yield limit of the shell material:

$$\sigma_s = \frac{\sqrt{3}\rho_0 \Delta_0 D^2 b\left(1 + \frac{\Delta_0}{2b}\right)\varphi_*}{(h^2 - 1)\left[R^2 \ln \frac{R_b^2}{R^2} - a^2 \ln \frac{b^2}{a^2} + (b^2 - a^2) \ln \frac{R_b^2}{b^2}\right]} . \tag{1.5}$$

For a thick-walled cylindrical converging shell the kinetic energy has the form [9]

$$E_1 = \pi \rho_1 (V_r)^2 \ln \frac{b}{a} . \tag{1.6}$$

Equating expressions (1.4) and (1.6) we determine the initial velocity of a shell and the strain rate of its material. For the shell wall center-of-mass radius $r_* = \left(\frac{a^2+b^2}{2}\right)^{1/2}$ we write

$$V_0 = D\left[\frac{2\varphi_* \rho_0 \Delta_0 b\left(1 + \frac{\Delta_0}{2b}\right)}{(n^2 - 1)\rho_1 (a^2 + b^2) \ln (b/a)}\right]^{1/2} ; \tag{1.7}$$

$$\dot{\varepsilon} = \frac{V_0}{r_*} = D\,\frac{2}{a^2 + b^2}\left[\frac{\varphi_* \rho_0 \Delta_0 b\left(1 + \frac{\Delta_0}{2b}\right)}{(n^2 - 1)\rho_1 \ln (b/a)}\right]^{1/2} \tag{1.8}$$

Having thus determined σ_s and $\dot{\varepsilon}$, we can construct from the experimental data the relation $\sigma_s = \sigma_s(\dot{\varepsilon})$ and, in accordance with this dependence, calculate the dynamic viscosity coefficient of the shell material. In particular, for a cylindrical shell at $\sigma_s = \sigma_0 + (2\mu/\sqrt{3})\,\dot{\varepsilon}$ we have

$$\mu = \frac{\sqrt{3}}{2}\,\frac{d\sigma_s}{d\dot{\varepsilon}} . \tag{1.9}$$

The relations thus obtained are used below to process the experimental data on cylindrical shell compression with the aim of clarifying the rheological properties of the shell material in the range $\dot{\varepsilon} = 10^3$–$3 \cdot 10^5\ \text{sec}^{-1}$.

2. In experiments conducted according to the scheme given in Fig. 2 we used cylindrical shells made of steel St. 3 and Armco iron in the as-delivered condition. On the lateral surface of a shell (specimen) of the metal *1* a layer *2* of HE charge was applied which was placed into a shield *3* rigidly bound with the specimen along the lateral surface. To eliminate any clearance the conjugate surfaces of the shell and shield had a slight taper along the cone element ~ 0.5–2^0; their surfaces finally had a class six clearance, and to secure a tight bearing between them and eliminate any clearance due to variations of HE layer thickness the

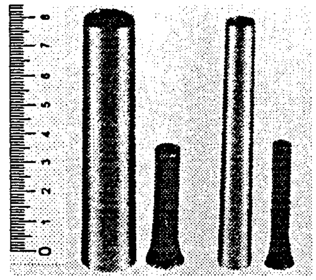

Fig. 3

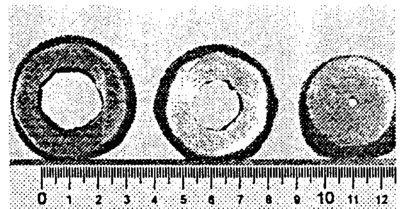

Fig. 4

inner surface of the shield was wetted with condenser oil. The HE charge was detonated by means of the detonating cap *4* which initiated an additional HE charge *5* located on the technological plug *6* fitted to the end of the cylindrical specimen which made it possible to detonate the main HE charge concurrently over the entire circle [4].

The shield prevented the free scattering of the EP; as a result the pressure impulse shape in the specimen was transformed from triangular to nearly rectangular and this contributed to the elimination of spalling. In some experiments, where justified, no shield was used. The stability of the shell compression was attained by the appropriate choice of the relative shell thickness $\delta = \Delta_1/b > \delta_*$, where δ_* is the critical relative shell thickness (percentage). When the shell thickness exceeded this value, the shell compression was stable. By virtue of the cylindrical symmetry of the experimental assemblies during the explosive compression of specimens no special steps had to be taken to conserve them for subsequent analysis (presence of spalling, shape symmetry, radius measurements, etc.). The shell radii before and after the compression (b, R_b) were measured in the cross section under study with a micrometer at $\sim$ 10 points and then averaged. In the experiments we used plastic HE with $\Delta_0 = 0.3$–1.0 mm; $\rho_0 = 1.51$ g/cm^3, $D = 7.8$ km/sec, and $n = 3$. The shells had the following standard sizes: $\varnothing$ 6×1, 9×0.9, 14×0.9, 16×0.9, 21×2, 21×3, 45×3, 45×5, 70×3 mm, while the ratio of the shell length to its diameter $L/2b \geqslant 5$. The initial shell wall velocities varied from 45 to 800 m/sec due both to the variations in the thickness of the HE layer and to those in the thickness or material of the shield. This made it possible to realize the range of strain rate variation from 10^3 to $3 \cdot 10^5$ sec^{-1}. The relative averaged strains $\varepsilon = (b - R_b)/b$ of the shells in the experiments varied from 1 to 50%.

As an illustration, in Fig. 3 are shown typical photographs of shells made of steel St.3 $\varnothing$ 16×0.92 and 9×0.93 mm before loading and the view of their middle cross section after loading at initial wall velocities of 640 and 730 m/sec, respectively. In Fig. 4 is presented for comparison a photograph of lead shell cross sections of $\varnothing$ 42×6.3 mm after loading at initial velocities of 20.3, 36.3, and 56.6 m/sec. To prevent shells from spalling in this case, a 2.8 mm air clearance was introduced between the HE layer and the shell. The initial velocities of shell wall motion were determined experimentally. In Fig. 5 are plotted the dependences $\sigma_s = \sigma_s(\dot{\varepsilon})$, derived from measured initial and final sizes of shells using relations (1.5), (1.6), and(1.8) for steel St. 3 and Armco iron.

3. The course of the relationships $\sigma_s = \sigma_s(\dot{\varepsilon})$ for steel St. 3 and Armco iron in the range of $\dot{\varepsilon} = 10^3$–$3 \cdot 10^5$ sec^{-1} has a piecewise linear form. This relationship points to the viscoplastic character of behavior of metals during shell deformation, which is the reason for using relationship (1.9). In this case, in the vicinity of the value $\dot{\varepsilon} \simeq 10^4$ sec^{-1} the the values of the dynamic viscosity coefficients vary from $\mu_1 = 6.7 \cdot 10^{-1}$ kg·sec/cm^2 to $\mu_2 = 1.4 \cdot 10^{-2}$ kg·sec/cm^2 for steel St. 3 and from $\mu_1 = 3.4 \cdot 10^{-1}$ kg·sec/cm^2 to $\mu_2 = 4.8 \cdot 10^{-2}$ kg·sec/cm^2 for Armco iron.

Figure 5 shows the experimental results (dashed lines) obtained by G. V. Pisarenko et al. [12] on $\sigma_s(\dot{\varepsilon})$ for annealed Armco iron at $\dot{\varepsilon} \leqslant 5 \cdot 10^4$ sec^{-1} under high-velocity rod tension on a set-up with a powder accelerator. Within this range of $\dot{\varepsilon}$ variation the data we obtained during dynamic shell compression differ from

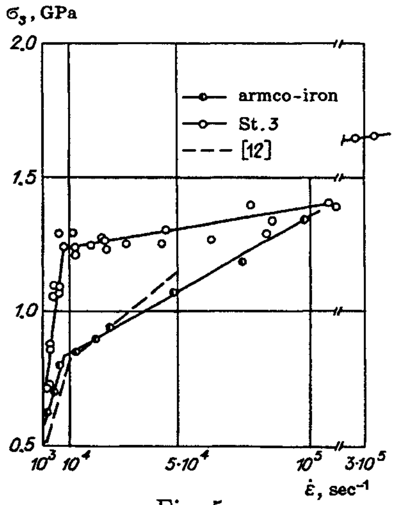

Fig. 5

those of [12] by no more than 15%. In addition, G. V. Pisarenko et al. [12] have discovered and interpreted, in terms of dislocation dynamics, a characteristic break in the course of the relationship of $\sigma_s(\dot{\varepsilon})$ at $\dot{\varepsilon} \simeq 10^4$ sec^{-1} observed both in Armco iron and in steel St. 45. We have observed a similar break at $\dot{\varepsilon} \simeq 10^4$ sec^{-1} in steel St. 3 and Armco iron. A comparison of values of σ_s obtained for steel St. 3 and Armco iron at $\dot{\varepsilon} = 10^3$ sec^{-1} with the data of [13] shows entirely satisfactory agreement.

Thus, it may be concluded that the method we proposed for determining the dynamic yield limit in the range of $\dot{\varepsilon} = 10^3$–$3\cdot10^5$ sec^{-1} at comparatively low values of material compression ($\sigma = \rho/\rho_{00} \simeq 1$) and, due to the specificity of behavior of metals in this range of $\dot{\varepsilon}$, of the dynamic viscosity coefficient makes it possible to obtain results which quantitatively and qualitatively agree with those obtained using other methods [12, 13].

In [14, 15] different methods of determining the dynamic yield limit of metals are described. Analysis shows that each of these methods is applicable, as a rule, within one or two orders of strain rate variation. With respect to the proposed method,* the range of variation of $\dot{\varepsilon}$ can be widened, say, in the direction of increasing $\dot{\varepsilon}$, by the definition of $\dot{\varepsilon} = V_0/r_*$, via an increase of the shell velocity and a decrease in its dimensions. We were able to compress shells made of steel St. 3 ⌀ 4×1 and 2×0.5 mm with $\dot{\varepsilon}$ up to $2 \cdot 10^6$ sec^{-1}. There is a tendency for a sharper increase of σ_s in the range $\dot{\varepsilon} = 3 \cdot 10^5$–$2 \cdot 10^6$ sec^{-1} which in principle does not contradict the results of [15] for soft steel. However, for shells whose percentage amounts to 50% there emerge difficulties in defining the quantities σ_s and $\dot{\varepsilon}$ due to the small radius of a shell. Hence for Armco iron and steels the value $\dot{\varepsilon} = (1$–$3) \cdot 10^5$ sec^{-1} should apparently be considered limiting.

It can be noted that steel St. 3 and Armco iron used as a material for specimens (classed with these are a number of other marks of steel, titanium alloys, and uranium) have relatively high values of shear strength, spall strength, and plasticity. This would secure stable and compact compression of specimens at shell strain values in the range of 1 to 50% which made it possible to realize a wide range of variation of $\dot{\varepsilon} = 10^3$–$3 \cdot 10^5$ sec^{-1}. For a number of metals, such as copper, magnesium, aluminum, and its alloys, whose shear and spall strengths are small, there arise difficulties in compressing the shell to a certain fixed stopping radius by using the scheme given in Fig. 2 with the shell shape retaining its stability and integrity. One can overcome these difficulties by using energy sources that are weaker and have smaller critical diameters of HE (e.g., liquid HE) or other energy sources, e.g., laser radiation. Another way of overcoming the above difficulties is introducing an air clearance between the layer of plastic HE and a tested shell. The application of the latter technique permitted us, e.g., to measure σ_s even in lead (see Fig. 4). The values of σ_s for $\dot{\varepsilon} = (1.1$–$3.1) \cdot 10^3$ sec^{-1} amounted to 23–30 MPa, which is in satisfactory agreement with the data of [17] for these strain rates.

*Note that in view of the cylindrical geometry of the specimens the method is free of the limitations typical of, say, quasi-static methods (rod specimens) due to the effects of radial inertia [16].

REFERENCES

1. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena [in Russian], Nauka, Moscow (1966).
2. L. V. Al'tshuler and B. S. Chekin, "Structure of shock waves and defining equations for metals," Prikl. Mekh. Tekh. Fiz. No. 6, 119–128 (1987).
3. Inventor's Certificate No. 1624410, "Method of determining dynamic characteristics of material (E. S. Tyun'kin, V. A. Ogorodnikov, and A. G. Ivanov, Applied for on June 26, 1989)," Inventions, No. 18 (1993), p. 197.
4. N. I. Matyushkin and Yu. A. Trishin, "Some effects arising during explosive compression of a tough cylindrical shell," Prikl. Mekh. Tekn. Fiz., No. 3, 99–112 (1978).
5. A. G. Ivanov, V. N. Sofronov, and E. S. Tyun'kin, "Properties of axisymmetric compression of spalled layers in cylindrical steel shells," Prikl. Mekh. Tekh. Fiz., No. 3, 125–127 (1984).
6. A. G. Ivanov, V. A. Ogorodnikov, and E. S. Tyun'kin, "Behavior of shells under impulsive loading. Small perturbations," Prikl. Mekh. Tekh. Fiz., No. 6, 112–115 (1992).
7. A. G. Ivanov, L. I. Kochkin, V. A. Ogorodnikov, and E. S. Tyun'kin, "Properties of the acceleration of plates by grazing detonation waves with combined or lumped masses," Fiz. Goreniya Vzryva, **26**, No. 5, 127–129 (1990)
8. V. A. Ogorodnikov, A. A. Sadovoi, V. N. Sofronov, and E. S. Tyun'kin, "Experimental-numerical investigation of the compression of cylindrical shells by explosions, taking dissipation processes into account," Works of the 5th All-Union Conference on Detonation, Krasnoyarsk, August 5–12, 1991; Vol. 2, Chernogolovka (1991).
9. A. A. Ilyushin and N. M. Ogibalov, Elastoplastic Deformations of Hollow Cylinders [in Russian], Izd. MGU, Moscow (1960).
10. C. R. Hoggatt and R. F. Recht, "Stress-strain data on rates using an expanding ring," Exp. Mech. **9**, No. 10.
11. F. A. Baum, L. P. Orlenko, K. P. Stanyukevich, et al., The Physics of Explosion [in Russian], Nauka, Moscow (1975).
12. G. V. Pisarenko, V. G. Petushkov, G. V. Stepanov, and N. A. Fot, "Mechanical properties of some metals during high-velocity tension," Probl. Prochnosti, No. 7, (1970)
13. V. K. Borisevich, V. P. Sabel'kin, S. N. Solodyankin, et al., Dynamic Characteristics of Some Metals and Alloys. Impulsive Processing of Metals by Pressure [in Russian], Khark. Aviats. Inst., **9** (1981).
14. J. A. Zukas, T. Nicholas, H. F. Swift, et al., Impact Dynamics [in Russian]. Mir, Moscow (1985).
15. G. V. Stepanov and V. V. Kharchenko, "Dynamic plasticity of metals at strain rates of 10^5–10^7 1/sec," in: High Energy Fabrication, Proc. X Intern. Conf., Ljubljana, Yugoslavia, S. l., s. a. (1989).
16. G. V. Stepanov, Elastic-Plastic Deformation of Materials under the Action of Impulsive Loads [in Russian], Naukova Dumka, Kiev (1979).
17. M. Malatynski and J. Klepaezko, "Experimental investigation of plastic properties of lead over a wide range of strain rates," Int. J. Mech. Sci. **22**, No. 3, 173–184 (1980).