The problem considered in explosion physics, despite the considerable amount of empirical data from explosive practice, is presented as new by the authors. Because of this, there is still a large number of obscure questions here, and, in the first place, the role of scaling and time factors is unexplained.

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EXPERIMENTAL VERIFICATION OF THE DRUCKER POSTULATE

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The Drucker postulate can be formulated as the condition that the work of additional stresses with loading is not a negative value:

$$d\sigma_{ij}d\varepsilon_{ij} \geqslant 0. \quad (1)$$

This postulate is of great importance in the theory of plasticity; specifically, there follows from it the law of plastic flow [1, 2], as well as the fact that the creep surface must be convex. The postulate has been verified experimentally for a number of metals at room temperature [3, 4]. Since a great number of processes of plastic deformation of metals take place at high temperature, it is of interest to verify the postulate under precisely these conditions. Such a verification was carried out for a monaxial stressed state (elongation and compression) in a special device, i.e., a plastometer [5]. The following metals and alloys were tested: technical-grade copper; brass (B90, B68, B62); nickel (NPA1 and NPAN), Monel metal (NMZh, MTs-28-2.5); nickel silver (MNTs 65-15-20); German silver (MN19); carbon steels 20, 3, 45, 6 and U8; alloy steels 40Kh, 40KhN, 45G2, 12KhNZA, 35KhGS, 15KhSND, ShKh15, 14GN, 60S2, 1Kh13, 4Kh13, Kh17N2, Kh18N12M2TO, and R18; heat-resistant chrome-nickel alloys ÉI435, ÉI602, and VZh98; zinc; and lead. The samples for the elongation tests (diameter 6, length 30 mm with screw clamps) were heated simultaneously in four electric furnaces, in which the temperature was monitored by thermocouples. The elongation of a sample, arranged in the electric furnace, was effected using a cam, whose profile determines the law of deformation. The cam was driven through a flywheel, a reducer, and a chain clutch from a direct-current electric motor. The speed of the electric motor decreased during the deformation by not more than 2%. This speed was monitored by a tachogenerator.

The samples for compression tests (diameter 6 and height 9 mm) were heated together with the container in furnaces; they were then mounted in the plastometer and the test was carried out. The temperature was monitored by a thermocouple; during a test it did not vary by more than 5°C in view of the considerable mass of the container. The thermocouples were introduced into the furnaces through openings and were forced tightly to the middle of the sample using a spring.

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The temperature of the furnaces was monitored by ÉPD-17 electronic potentiometers with a scale of 0-1600°C, class 0.5. After testing series of 40-60 samples, the readings of the potentiometers were verified using a control potentiometer of class 0.2. Such attention to the exactness of the determination of the temperature is necessary, since it has a strong effect on the mechanical properties. In the present case, the exactness of the monitoring was equal to 3-4°C. The differences in the temperature in a deformed volume did not exceed 5°C. The container, the punch, and the clamps were made of alloy ÉI652. To decrease the friction of compression testing, a lubricant of three compositions was used for the temperature ranges 800-1000°C, 1000-1100°C, and 1100-1200°C. The composition of the lubricant, selected by D. Eller and W. Phillips for high-temperature deformation, is described in [6, 7]. The deformation stresses were measured with hydraulic dynamometers on wire strain gages with a PÉTZV electronic amplifier. The readings were recorded on an N102 oscillograph, using a vibrator with a frequency of its natural vibrations of 5000 Hz. The hydraulic dynamometers were cooled by circulating water to avoid their heating-up during a test. The photographic device on the oscillograph was switched on automatically by a contact cam before the start of a test. This device assured reliable recording of the readings with a velocity of the cam up to 900 rpm. The hydraulic dynamometers were calibrated directly in the plastometer using weights of known mass, which were suspended in the clamps by means of hinges and levers. The thermocouples were also calibrated periodically. The cam-type plastometer makes it possible to obtain different laws of the development of the deformation with time $\varepsilon_{11}(\tau)$ due to the shape of the cam against which a crosspiece with a roller was constantly pressed by springs. The function $\varepsilon_{11}(\tau)$ was monitored using a pickup of the displacements in the form of a cantilevered beam, whose resistance was equal to that of the strain gages. With displacement, the crosspiece bent the cantilevered end of the beam, whose deflection was equal to the displacement of the crosspiece. The calibration was carried out directly in the instrument, using an indicator.

During the testing, oscillograms were obtained of the elongation (or contraction $\Delta l(\tau)$ and the stress $P(\tau)$, from which $\varepsilon_{11}(\tau)$ and $\sigma_{11}(\tau)$ were determined:

$$\varepsilon_{11}(\tau) = \ln\left[1 + \frac{\Delta l(\tau)}{l_0}\right], \quad \sigma_{11}(\tau) = \frac{P(\tau)}{F_0}\left[1 + \frac{\Delta l(\tau)}{l_0}\right]$$

(l_0 is the initial length of the sample). Here use was made of the condition of incompressibility, which, as experiments have shown, for $\varepsilon_{11} > 0.05$ is satisfied with a high degree of exactness.

To obtain small rates of deformation, in the plastometer it is convenient to use the invention [8]. This makes it possible to obtain deformation rates from 10^{-6} to 100 $\sec^{-1}$ in the same device without readjustment of the drive.

The degree of deformation was varied in the range 0.05-0.08. The temperature interval was taken equal to 900-1200°C for steels, 450-950°C for copper and brasses, 800-1250°C for nickel, 600-1250°C for Monel metal, 900-1100°C for nickel silver and German silver, and 50-340°C for zinc.

The above materials, as well as lead and aluminum, were also tested at room temperature. Figure 1a shows the functions σ_{11} (ε_{11}) for steel 60S2 for $\dot{\varepsilon}_{11}$ = 0.25 $\sec^{-1}$ and t = 1000°C (line 1); steel 45 for $\dot{\varepsilon}_{11}$ = 0.5 $\sec^{-1}$ and t = 1100°C (line 2); and copper for t = 950°C and a rate of deformation of 6 $\sec^{-1}$ (line 3) and 0.4 $\sec^{-1}$ (line 4). Figure 1b gives analogous diagrams for Monel metal for t = 1100°C and $\dot{\varepsilon}_{11}$ = 1.8 $\sec^{-1}$, (line 1); German silver for t = 1030°C and $\dot{\varepsilon}_{11}$ = 6 $\sec^{-1}$ (line 2); nickel for t = 1250°C and $\dot{\varepsilon}_{11}$ = 1.8 $\sec^{-1}$ (line 3); and brass L62 for t = 850°C and $\dot{\varepsilon}_{11}$ = 0.4 $\sec^{-1}$ (line 4).

Experimental curves of the stress $P(\tau)$ and the elongation $\Delta l(\tau)$, from which $\sigma_{11}(\tau)$ and $\varepsilon_{11}(\tau)$ were determined, are given in Fig. 2a, b for steel 45 for t = 1000°C and for copper for t = 950°C, respectively. The oscillogram was printed out on photopaper (magnification of four times) to which there was glued tracing paper with a marked-out grid, which simplified the analysis of the experimental data [6]. Simultaneously with the process of elongation or compression, on the oscillogram there were recorded vibrations obtained from a 3G-10 generator of sonic frequency. These vibrations, situated in the upper part of Fig. 2, increased the accuracy of the construction of $\sigma_{11}(\tau)$ and $\varepsilon_{11}(\tau)$ as functions of the time. The frequency of the generator was tuned in such a way that 1 mm of the oscillogram would correspond to a frequency of 1 Hz (for example, a rate of motion of the film of 200 mm/sec, corresponds to a frequency of 200 Hz).

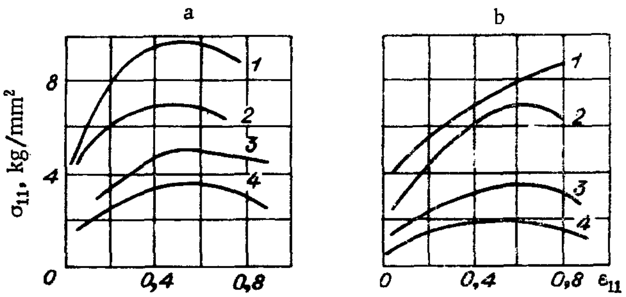

Fig. 1

The deformation process, taking place in the course of 0.024 sec, occupied 48 mm on the oscillogram; here there were 48 periodic vibrations from the generator. For the curves of Fig. 2a condition (1) is satisfied, while, for Fig. 2b, it breaks down for $\varepsilon_{11} > 0.6$.

Since there are no absolutely rigid testing machines, to take account of the elastic deformation of the construction of the plastometer itself, in place of the samples, the deformations were carried out using springs, working in the region of elastic deformations with a known dependence of the elongation on the stress. Under these circumstances, measurements were made of the elastic deformation of the plastometer, whose effect is less than 3%, and the measuring devices were calibrated.

The error in determination of the value of ε_{11} did not exceed 6%, while that in the determination of σ_{11} at room temperature did not exceed 8% and 15% at high temperatures; this was determined by an analysis of the scatter of the data and a determination of the mean-square deviation. For zinc, the deviations were considerable and reached 20-25%. With small rates of deformation ($\dot{\varepsilon}_{11} < 0.5$ sec^{-1}) and room temperature, for zinc there were observed "deformation jumps" with stops; this kind of deformation is not described or analyzed; we point out only that, in this case, the scatter of the data rises considerably (up to 50%).

In the examples shown in Fig. 1, with the exception of Monel metal, there are sections where the inequality (1) is not satisfied. It must be pointed out that, for titanium, the inequality (1) also breaks down for $t > 300$°C and $\varepsilon_{11} = 0.6$-0.8 [7]. In the range 20-300°C the Drucker postulate for titanium is in agreement with the experimental data.

An analysis was made of the possibility of softening of the metal due to heating, i.e., of deviations from an isothermal process. Under these circumstances, the work of deformation was determined from the area of the diagram of $\sigma_{11}(\varepsilon_{11})$, and it was assumed that it all goes over to heat, which in actual fact is not accurate; 0.85-0.90 of the work of deformation goes over into heat. In addition, the process was assumed to be adiabatic, so that high values of the possible changes in the temperatures were determined, but they are insignificant (with the exception of zinc, which must obviously be examined separately). Measurements using thermocouples show that even for rates of deformation of 80-100 sec^{-1} the increase in the temperature is not more than 15-25°C, while for $\dot{\varepsilon}_{11} < 40$ sec^{-1} it does not exceed 5°C; consequently, heating of the metal with deformation cannot be the reason for the breakdown of condition (1). The thermal deformations for the tested metals are small. They are determined by the coefficient of linear expansion. This quantity (depending on the temperature) for copper is equal to $(1.6$-$1.9)\cdot 10^{-5}$ 1/deg; for brasses $(1.7$-$2.2)\cdot 10^{-5}$ 1/deg; for carbon steels $(1.0$-$1.5)\cdot 10^{-5}$; for alloy steels $(1.0$-$1.3)\cdot 10^{-5}$ 1/deg; for nickel $(1.3$-$1.6)\cdot 10^{-5}$ 1/deg; for lead $(2.8$-$3.2)\cdot 10^{-5}$ 1/deg; for Monel metal $1.5\cdot 10^{-5}$ 1/deg; and for zinc $(3.9$-$4.1)\cdot 10^{-5}$ 1/deg.

With heating by 25°C, the thermal deformation for copper, steels, nickel, German silver, and Monel metal does not exceed $25\cdot 2.2\cdot 10^{-5} = 5.5\cdot 10^{-4}$. For lead it attains $8\cdot 10^{-4}$ and for zinc $4.1\cdot 25\cdot 10^{-4} = 10^{-2}$.

With regard to thermal deformation before the start of deformation during the course of heating from room temperatures to the working temperature, before the start of a test all the gaps were selected using a special flywheel (controlled by hydraulic dynamometers) and the measurement of the deformation was begun with testing of the sample starting from zero.

Thus, the process is affected only by thermal deformation due to the change in the temperature during the testing process. As has been shown above, with fluctuations of the temperature up to 25°C this value does not exceed 10^{-3}, which is 300-600 times less than the measured values of ε_{11}.

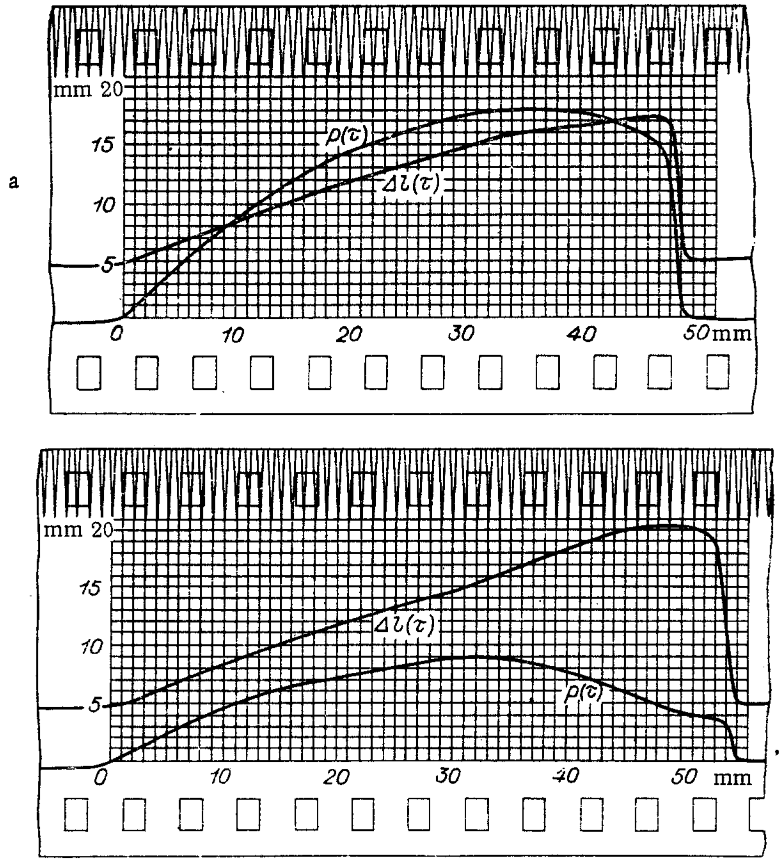

Fig. 2

Thermal deformations can change the $\sigma_{11}(\varepsilon_{11})$ diagram with small degrees of deformation $\varepsilon_{11} < 10^{-3}$ if here the deformation process deviates from isothermal.

The deformation due to creep was determined from the results of experiments in which the stress remained constant. In this partial case calculation of the deformation due to creep and its isolation from the total deformation are simplified [9].

Here it was assumed that the rate of deformation due to creep is a function only of the stress $v(\sigma)$ and that the deformation due to creep $\varepsilon_c = \int v(\sigma)d\sigma$. In the case where the time of a test was less than 2 sec for copper, brass, zinc, nickel, and carbon steels, less than 3-4 sec for steels 1Kh13, 4Kh13, Kh18N9T, Kh18N12M2TO, and R18, and less than 5-6 sec for alloys ÉI435, ÉI602, and VZh98, the deformation due to creep was insignificant (less than 2%). For alloys ÉI435, ÉI602, and VZh98 and Monel metal the section of established creep ($\dot{\varepsilon}_{11}$ = const, σ_{11} = const) is small; therefore, here the deformation due to creep was determined in accordance with the theory of hardening (see [9]). The deformation due to creep can be left out of consideration when the deformation is less than 2-4 sec and $\dot{\varepsilon}_{11} > 0.5$ sec^{-1}. With small deformation rates, where the loading process lasts more than 2-3 sec, deformation due to creep must be taken into account at high temperatures.

With small degrees of deformation (less than 10^{-2}) account must also be taken of elastic deformation. Elastic deformations and deformations due to creep are subtracted from the values of the total deformation when constructing the function $\sigma_{11}(\varepsilon_{11})$.

Samples cut from the deformed metal were also verified for their anisotropy. Tests were made of samples oriented along three mutually perpendicular directions. In distinction from tests at low temperatures, at high temperatures deformation did not lead to the development of anisotropy, and the difference in the yield points and other mechanical properties did not exceed 10-15%, which is close to the accuracy of the experiment. The sole exception among the investigated materials was zinc, for which the difference attains 50-100%, and the round cross section of the samples becomes elliptical during the deformation process. Within the limits of accuracy of the experiment, the remaining materials can be regarded as isotropic. An analysis of the experimental data shows that for copper and brasses there are

TABLE 1.

Material	Temperature range, °C	σ_0, kg/mm²	n	m	p, deg⁻¹
Technical-grade copper	450—950	73	0,40	0,11	0,0023
Brass B90	450—950	105	0,40	0,11	0,0030
B70	450—900	190	0,57	0,11	0,0035
B68	$t<600$	99	0,57	0,11	0,0028
B68	$t>600$	97	0,38	0,11	0,0028
B62	$t<750$	127	0,50	0,11	0,0040
B62	$750\geqslant t\geqslant 600$	105	0,50	0,11	0,0070
B62	$t<600$	150	0,50	0,11	0,0040
Nickel	800—1250	270	0,50	0,11	0,0028
German silver	600—900	174	0,40	0,15	0,0025
"	900—1100	390	0,40	0,15	0,0035
Nickel silver	600—950	485	0,50	0,15	0,0040
Monel metal	600—1000	200	0,45	0,11	0,0022
"	1000—1250	200	0,45	0,11	0,0024
Aluminum	300—500	18	0,37	0,14	0,0017
Steel 45	900—1200	166	0,25	0,14	0,0025
St. 12KhNZA	900—1200	290	0,25	0,14	0,0029
St. 4Kh13	900—1200	550	0,28	0,09	0,0037
St. Kh17N2	900—1200	900	0,28	0,09	0,0037
St. Kh18N9T	900—1200	415	0,28	0,09	0,0028
Alloy ÉI435	900—1200	1200	0,35	0,10	0,0032
Alloy ÉI602	900—1200	1490	0,35	0,10	0,0032
Alloy VZh98	900—1200	1040	0,35	0,10	0,0028

cases where $d\sigma_{11}/d\varepsilon_{11} < 0$ for $t > 750$°C and $\varepsilon_{11} > \varepsilon^\circ_{11}$, where $\varepsilon^\circ_{11} = 0.50$-$0.65$. The value of ε°_{11} rises with an increase in the deformation rate. For German silver for $t > 900$°C, $\varepsilon^\circ_{11} = 0.60$-$0.70$; for nickel for $t > 1100$°C, $\varepsilon^\circ_{11} = 0.65$-$0.75$; for carbon steels $\varepsilon^\circ_{11} = 0.40$-$0.50$ for $t > 1000$°C, and, with a deformation rate greater than 50 sec⁻¹, it increases up to 0.60-0.70. For alloy steels 40Kh, 40KhN, 15KhSND, etc., $\varepsilon^\circ_{11} = 0.40$-$0.50$ for $t \geq 1100$°C, while for high alloy steels 1Kh13, 4Kh13, Kh17N2, Kh18N9T, and Kh18N12M2TO for $t = 1100$-1200°C and $\dot{\varepsilon}_{11} < 5$ sec⁻¹, $\varepsilon^\circ_{11} = 0.35$-$0.55$. For fast-cutting steel R18 in the range 900-1200°C, $\varepsilon^\circ_{11} = 0.25$-$0.40$. For heat-resistant alloys ÉI435, ÉI602, and VZh98 and Monel metal the value of $d\sigma_{11}/d\varepsilon_{11}$ is positive in the whole range of change in the degree of deformation, the deformation rate, and the temperature.

At room temperature condition (1) broke down for zinc and lead for $\varepsilon^\circ_{11} = 0.45$-$0.55$, while for the remaining materials, indicated above, in the studied range of the degree and rate of deformation condition (1) was satisfied.

Deformation softening [10] plays a considerable role at high temperatures. For $\varepsilon_{11} \leqslant 0.30$-$0.40$ the results of the tests make it possible to describe the function $\sigma_{11}(\varepsilon_{11}, \dot{\varepsilon}_{11}, t)$ by the formula (for ε_{11} = const)

$$\sigma_{11} = \sigma_0 \varepsilon_{11}^{n} \dot{\varepsilon}_{11}^{m} \exp(-pt),$$

where σ_0, m, n, and p are constant quantities for a given material, listed in Table 1. What has been set forth shows that, even with relatively large deformation, the Drucker postulate does not contradict the experimental data.

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