AN ULTRAHIGH-PRESSURE PRESS

Yu. I. Fadeenko

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The principle of the strengthening of materials at increased density (bulk strengthening) is referred to in [1] as a general principle of the action of ultrahigh pressure presses. An analysis of a special scheme for a spherical press shows that the increase in pressure toward the center of the press is relatively slow and therefore doubt is raised in [1] as to the possibility of producing megabar static pressures in any significant volume. In the present paper we solve the problem of the state of stress in a sphere of bulk-strengthened material corresponding to an extremely fast increase in pressure toward the center of the press. As $r \to 0$ the asymptotic law $p \sim r^{-\mu}$ holds. Theoretical estimates and a collection of experimental data show that at high pressures $0.15 \leq \mu \leq 0.75$ for typical materials. However, for a number of materials in certain pressure ranges values of $\mu \gtrless 1$ are noted. The alternation of layers of appropriately selected materials makes it possible to maintain megabar pressures in a spherical press in technically acceptable volumes.

We consider the problem of the state of stress in a spherical press corresponding to an extremely rapid increase of pressure toward the center of the press in general form, i.e., without any restrictions peculiar to the specific technical schemes.

The equation of the equilibrium of stresses in spherical coordinates r, φ, θ for central symmetry has the form

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{2(\sigma_{rr} - \sigma_{\varphi\varphi})}{r} = 0, \tag{1}$$

where

$$\sigma_{\theta\theta} = \sigma_{\varphi\varphi}, \quad \tau_{r\varphi} = \tau_{\varphi\theta} = \tau_{\theta r} = 0.$$

Suppose the Mises yield criterion is satisfied:

$$(\sigma_{rr} - \sigma_{\varphi\varphi})^2 + (\sigma_{\varphi\varphi} - \sigma_{\theta\theta})^2 + (\sigma_{\theta\theta} - \sigma_{rr})^2 + 6(\tau_{r\varphi}^2 + \tau_{\varphi\theta}^2 + \tau_{\theta r}^2) = 6Y^2,$$

then the condition $-Y\sqrt{3} \leq (\sigma_{\varphi\varphi} - \sigma_{rr}) \leq Y\sqrt{3}$ must be satisfied, where the inequality sign corresponds to the elastic state of the material and the equality sign, to the plastic state. The maximum rapid rise of pressure toward the center of the press occurs for

$$\sigma_{\varphi\varphi} - \sigma_{rr} = Y\sqrt{3}. \tag{2}$$

Ordinarily, it is assumed that Y = const; then for condition (2) the solution of (1) has the form

$$p = p_0 + 2\sqrt{3}Y \ln\frac{r_0}{r}, \tag{3}$$

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where p_0 is the hydrostatic pressure in the material at the surface of the press, related to the radial stress σ_0 at the surface by the equation

$$p_0 = -\sigma_0 - Y\sqrt{\frac{4}{3}}, \quad (\sigma_0 \geqslant -\sqrt{3}Y),$$

and r_0 is the radius of the press. It follows from (3) that as $r \to 0$ the pressure increases indefinitely, but this increase is too slow and cannot be used in practice to obtain ultrahigh pressures.

We limit ourselves to a linear law of bulk strengthening:

$$Y(p) = Y_0 + \alpha p, \tag{4}$$

since any function Y (p) can be represented with sufficient accuracy in broken line form. Under condition (4) the solution of (1) has the form

$$\frac{Y_0 + \alpha p}{Y_0 + \alpha p_0} = \left(\frac{r_0}{r}\right)^{\mu}, \tag{5}$$

where

$$\mu = \frac{6\sqrt{3}\alpha}{3 + 2\sqrt{3}\alpha}.$$

At very high pressures ($p \gg Y_0/\alpha$)

$$p \simeq \left(p_0 + \frac{Y_0}{\alpha}\right)\left(\frac{r_0}{r}\right)^{\mu}.$$

An estimate of the order of magnitude of α for typical solids at very high pressures can be obtained by taking account of the fact that the dislocations are pinned by the barriers and the strength of the material must approach the theoretical value,

$$Y = \frac{G}{k} = \frac{E}{2k(1+\nu)},$$

where G is the shear modulus, E is Young's modulus, and ν is Poisson's ratio. The magnitude of the coefficient of proportionality k depends on the contribution of the central binary interactions to the binding energy; at zero pressure $k \approx 30$ for tungsten and molybdenum $k \simeq 10$ [2]. As the contribution of the central interactions increases, the value of ν approaches the limiting value $\nu = 0.25$ [3]. For a material with a zero isotherm

$$p = A\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right]$$

the relations

$$E = 3n(1 - 2\nu)(p + A),$$
$$Y = \frac{3n}{2k}\frac{1 - 2\nu}{1 + \nu}(p + A).$$

are valid. Thus,

$$\alpha \simeq \frac{3n}{2k}\frac{1 - 2\nu}{1 + \nu}. \tag{6}$$

In the region of megabar pressures $n \approx 3$-5 [4]. Setting $n = 3-5$, $k = 10-30$, $\nu = 0.25-0.33$, from (6) we obtain

$$\alpha \simeq 0.04 - 0.30, \quad \mu \simeq 0.14 - 0.77.$$

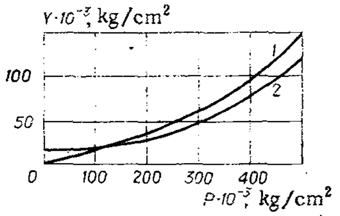

Fig. 1

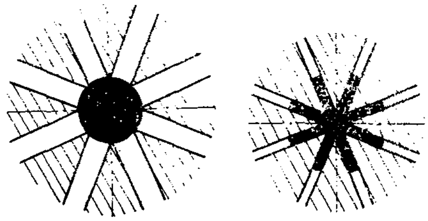

Fig. 2

TABLE 1

Material	α	Pressure range, kbar	Source
Pyrophillite		10—40	[7]
lump	0,47		
powder	0,25		
Lithium	0,275	50—100	[6]
Steel 45	0,5	400—500	[6]
Tungsten	0,33	100—175	[6]
Copper 1B	0,056	0—25	[8]
"	0,33	50—100	[8]
Copper, pure	0,016	50—150	[8]
Copper	0,165	10—40	[7]
Lead	0,09	20	[7]
Boron carbide	0,4	25	[7]

This estimate is in good agreement with the theoretical value $\alpha \approx 0.1$ for an ideal fcc lattice [5].

We compare the estimates obtained with the known experimental data. Figure 1 shows Y as a function of p for two kinds of steel (1, St 45; 2, 2Kh18N9) obtained in [6]; it is clear from these data that as the pressure increases, α increases to approximately 0.5 and at 0.5 Mbar it shows no tendency to stop increasing. Table 1 lists values of α for a number of materials at high pressures. These data are in good agreement with estimates (7), but for certain materials and pressure ranges the values of α and μ are considerably above typical.

The following conclusions can be drawn from the above: the alternation of layers of properly chosen materials makes it possible to maintain a state of stress in a spherical press with a rapid increase in pressure toward the center; megabar pressures can be maintained in practically acceptable volumes. We illustrate this conclusion by a numerical example. Let Y_0 = 10 Kbar, $\sigma_{\varphi\varphi}(r_0)=0$, $\alpha=0{,}5$, $\mu \simeq 1{,}1$, $Y_0+\alpha p_0= 3Y_0/(3-\alpha\sqrt{3}) \approx 14{,}1$ kbar, $\sigma_0 = -24.4$ kbar. Then for $r = 0.01\, r_0$ a pressure of about 4.5 Mbar is maintained.

In connection with the problem of a possible specific structure of ultrahigh pressure presses we note the scheme of Fig. 2 which was pointed out to the author by G. V. Ivanov. In this scheme high pressure is produced by the extrusion of a plastic filler through gaps between pyramidal dies. The radial distribution of pressure arising in this flow is described approximately by the equation

$$\frac{dp}{dr} = -\frac{2Y^*}{h},$$

where h (r) is the width of the gap and Y^* (p) is the pure shear strength of the filler. By an appropriate choice of gap it is possible in principle to produce any possible state of stress in the pyramids, including the optimum state (5).

A cylindrical press can be treated similarly; a problem close to the one posed is solved in [9].

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