SUPERHIGH-PRESSURE PRESS

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The article expounds the principles of the action of the superhigh-pressure press described in [1]. Its action reduces to the concentric pressing of pointed parts which, with compression, form a solid sphere with a high pressure at the center. Self-hardening of the parts of the press with compression plays an important role in achieving the effect.

The possibility, in principle, of containing as high a pressure as desired in a material of finite strength has been known for a long while. The possibility of the existence of a superstrong vessel is evident, for example, from [2], and consists in the following. Let the material of a thin-walled sphere be everywhere stressed to the yield point, i.e., at each of its points, the shear stress τ is equal to the strength. It acts in a plane forming an angle of 45° with the radius, and here

$$\tau = (p - \sigma) / 2 \tag{1}$$

where p and σ are the normal stresses in the sphere and the radial plane.

From the condition of the equilibrium of an element of the vessel (a hemispherical shell of radius r and thickness dr), hatched on Fig. 1, it follows that

$$2\pi r d r \sigma = \pi (r + dr)^2 p\,(r + dr) - \pi r^2 p\,(r)$$

whence

$$2\sigma = r^{-1} d\,(pr^2) / dr$$

Substituting here σ from (1), we obtain

$$dp / dr = -4\tau / r \tag{2}$$

whence, with a constant value of τ

$$p\,(a) = 4\tau \ln b / a$$

With $a \to 0$, the pressure is discharged, but only logarithmically, i.e., weakly. We note that $p \to \infty$ also indicates an infinite density of the energy at the center, i.e., a fundamentally new example of an infinite cumulation, that is to say, a static cumulation, not connected with any kind of motion.

In actuality, the strength does not remain constant, but, with compression, generally rises; therefore, the discharge of the pressure at the center can be stronger. Thus, in accordance with [3], with a pressure of 25 kbar, the compressive strength for steel increases by 18 kbar (from 29 to 47 kbar), while, in accordance with [4], for aluminum with p = 0.5E (E is the Young modulus), it increases by approximately 25 times (in spite of the heating-up in the shock wave with which the experiments were made).

A schematic diagram and the design of a superhigh-pressure press are described below. Its scheme was suggested by the figure in [1]; an analogous figure was published previously in [5], but no theory of cumulation, i.e., principle of action, was given.

Scheme of Device and Its Calculation

The device consists of a sphere made up of a large number of narrow pyramids, not filling it completely, but with a mean density K times less (Fig. 2a). With the pressing of such a porous sphere from

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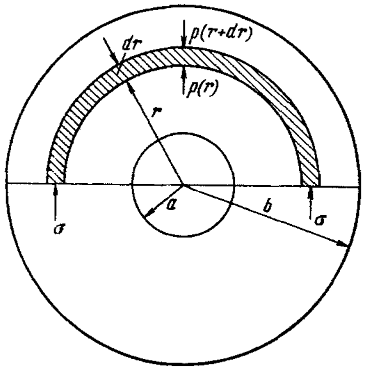

Fig. 1

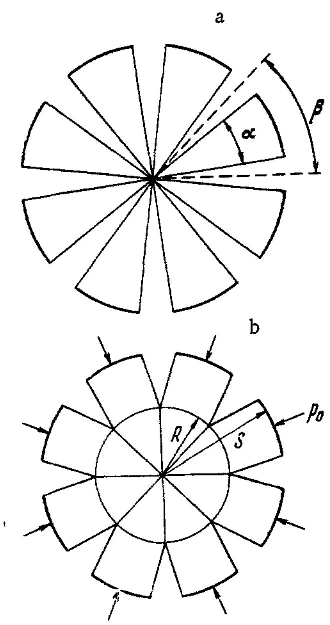

Fig. 2

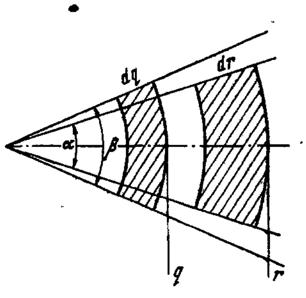

Fig. 3

without, in the middle of the sphere there is formed a solid compression zone, and the angle at the apex of a pyramid increases from α to β (Fig. 2b).

Let us find the distribution of the pressure in the zone of the compression. The dimensions of an element of a pyramid, α, r, dr, go over into β, q, dq (Fig. 3); under these circumstances, at the base of the pyramid there will act the pressure p, and, on the lateral face, $\sigma = p - 2\tau$. Let us calculate its dimensions, mentally loading it first with the uniform pressure p, and then decreasing the pressure from the sides by 2τ. We obtain

$$q\beta = r\alpha\delta^{-1/3}[1 + 2\tau(1-\mu)/E] \tag{3}$$

where E is the Young modulus; μ is the Poisson coefficient; $\delta = \rho/\rho_0$ is the relative density (it differs slightly from the true value of δ, since the lateral pressure is less than the radial). Further,

$$dq = dr\delta^{-1/3}(1 - 4\tau\mu/E)$$

whence

$$q = \int_0^r (1 - 4\tau\mu/E)\frac{dr}{\delta^{1/3}} \tag{4}$$

It is clear that $(\beta/\alpha)^2 = K$. Substituting here β/α from (3) and q from (4), we obtain

$$\frac{r}{\delta^{1/3}}\left[1 + \frac{2\tau(1-\mu)}{E}\right] = \sqrt{K}\int_0^r\left(1 - \frac{4\tau\mu}{E}\right)\frac{dr}{\delta^{1/3}}$$

Replacing τ in accordance with (2), we obtain

$$\frac{r}{\delta^{1/3}}\left[1 - \frac{1-\mu}{2E}r\frac{dp}{dr}\right] = \sqrt{K}\int_0^r\left(1 + \frac{\mu}{E}r\frac{dp}{dr}\right)\frac{dr}{\delta^{1/3}} \tag{5}$$

Further, we take the dependence of p on δ in the form

$$p = {}^1/_3\rho_0 c_0^2(\delta^3 - 1) \tag{6}$$

The Young modulus $E = \rho c^2 3(1-2\mu)$. Rounding off μ to $^1/_3$, we obtain $E = \rho c^2$. With a rise in the pressure, ρ increases, as well as the velocity of sound c; in this case, $c \sim \rho$, i.e., the Young modulus rises as ρ^3 or, neglecting the small difference of δ from the true compression, it can be assumed that

$$E = E_0\delta^3 \tag{7}$$

where E_0 is for an unloaded material.

Substituting (6) and (7) into (5), we obtain

$$\frac{r}{\delta^{1/3}}\left(1 - \frac{r}{3\delta}\frac{d\delta}{dr}\right) = \sqrt{K}\int_0^r\left(1 + \frac{r}{3\delta}\frac{d\delta}{dr}\right)\frac{dr}{\delta^{1/3}} \tag{8}$$

The solution of this equation is the exponential distribution of the density $\delta = A/r^n$, where n must satisfy the equation obtained from (8):

$$(1 + n/3)^2 = \sqrt{K}(1 - n/3) \tag{9}$$

whence, with a small porosity

$$n \approx (K-1)/2 \tag{10}$$

With K = 1 (a solid sphere), we obtain n = 0, i.e., there is no concentration of the pressure at the center; if K > 1, the pressure at the center rises, the more strongly the greater the value of K, but the value of K is limited by the strength (see below).

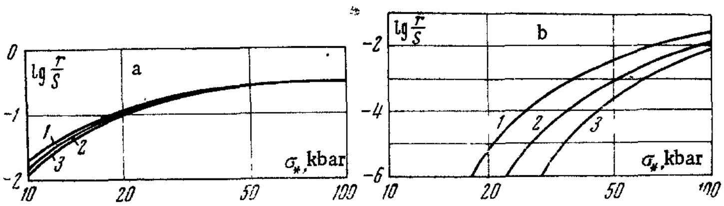

Fig. 4

We determine the value of A from the condition that, at the surface of the zone of continuous compression, the elements of adjacent pyramids are in contact, but still do not compress each other, i.e., $\sigma(R) = 0$ or $p(R) = 2\tau(R)$. Substituting here $p(R) = {}^1/_3\, E_0(A^3/R^{3n} - 1)$ and $\tau(R)$ in accordance with (2), we obtain

$$A = R^{3n} / (1 - {}^3/_2 n)$$

$$p(r) = \frac{E_0}{3}\left[\frac{1}{1 - {}^3/_2 n}\left(\frac{R}{r}\right)^{3n} - 1\right] \tag{11}$$

$$\tau(r) = \frac{E_0}{4}\,\frac{n}{1 - {}^3/_2 n}\left(\frac{R}{r}\right)^{3n} \tag{12}$$

With a small porosity, these formulas assume the form

$$p(r) = \frac{E_0}{3}\left[\frac{1}{1 - {}^3/_4 (K-1)}\left(\frac{R}{r}\right)^{3(K-1)/2} - 1\right] \tag{13}$$

$$\tau(r) = {}^1/_8\, E_0(K-1)(R/r)^{3(K-1)/2} \tag{14}$$

With $r \to 0$, the pressure p and the tangential stress rise infinitely, the more strongly, the greater the value of K. We find the dimensions of the zones of high pressure, assuming that the press does not fail, i.e., that the rise in the strength outruns the increase in τ. This is probably valid even very close to the center, which is argued by the enormous pressure (2 Mbar) attained in the Japanese press.

From (13) and (14) we obtain

$$\tau = {}^1/_8\,(K-1)(E_0 + 3p) \tag{15}$$

We so select K that, at the boundary of the zone of continuous compression, the material will be at the yield point, i.e., the pressure p will be equal to the compressive strength σ_*: $p(R) = \sigma_*$.

Substituting this equality into (15), and taking into account that $\tau(R) = \sigma_*/2$, we obtain the maximal permissible porosity

$$K - 1 = 4\sigma_* / (E_0 + 3\sigma_*) \tag{16}$$

Substituting (16) into (15), as well as the equality $p_0/\sigma_* = (S/R)^2$, where p_0 is the pressure of the liquid surrounding a press of radius S (the gaps between the pyramids are closed to the liquid, i.e., the pressure p_0 does not act in them), after transformation, we obtain

$$\lg\frac{r}{S} = \lg\sqrt{\frac{p_0}{\sigma_*}} - \frac{E_0 + 3\sigma_*}{6\sigma_*}\lg\frac{E_0 + 3p}{E_0 + 3\sigma_*} \tag{17}$$

(here the logarithmic form is convenient, since r/S varies over very wide limits).

The value of r/S depends on four variables: p_0, E_0, σ_*, and p. We fix one of them, setting $p_0 = 10$ kbar, i.e., we assume that the vessel embracing the press contains this pressure. The dependence on the remaining parameters is shown on Fig. 4, on which curves 1, 2, and 3 relate to the values $E_0 = 1000$, 2000, and 5000 kbar; p = 100 kbar for *a*, and p = 1000 kbar for b.

It can be seen from the figure that very high pressures can be achieved, but that the volumes in which they are reached are small (1 Mbar is developed with $r/S = 2 \cdot 10^{-4}$, i.e., in a press with a radius greater than 100 mm only with r = 0.02 mm). Therefore, the surprising pressure of 2 Mbar supposedly attained in the Japanese press is developed only with $r/S = 10^{-7}$ or $r = 10^{-5}$ mm.

With a fixed value of E_0, a greater strength σ_* is advantageous, which is natural, but, with same strength, a lower value of the modulus E_0 is advantageous (i.e., a lower rigidity), which was difficult to foresee.

The radius of the compression zone $R \sim \sqrt{p_0}$; under these circumstances, the distributions of the pressures and the other quantities with respect to r are similar and differ only in the scale with respect to r, i.e., the whole phenomenon is self-similar.

It is obvious that the real number of pyramids cannot be too great: in the scheme in [1] there are only eight and, in the outer part of the sphere, only six.

We note that another kind of sample at the center of the press changes the distribution of the pressure, and a new calculation will be required (which is lacking in the given article). Without this it can be indicated only in order of magnitude.

Thus, from a material of finite strength it is possible to make a device which will develop and contain a large, possibly an infinite, pressure in a small volume. It can be developed in a system of congruently approaching pyramids, where the pressure at the center is discharged in accordance with an exponential law, and is probably not limited by the strength. The question of the physical limitations on the dispersion at the center of the press remains open.

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