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CUMULATION EFFECT IN DYNAMIC PRESSING OF POWDERED MATERIALS

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One of the promising methods of pressing powdered materials is the passage of a high-density electrical current through the powder [1, 2]. This method produces high-density materials with required characteristics. The density of the pressed materials is controlled by choice of pressing parameters: the mechanical loading applied, and the amplitude and duration of the current pulses. It has been established experimentally that certain parameter values exist, at which the pressing process becomes unstable — "spattering" of material from the press form occurs [1]. The present study will consider the possible cause of such "spattering" and define the range of parameter values within which this phenomenon occurs. The behavior of powdered material subjected to compression by applied pressure can be described with the aid of the "hollow sphere" model [3]. At values of the deformation rate tensor components in the range 10^3-10^5 sec^{-1} the rheological behavior of the powder material corresponds quite well to that of a viscoplastic material with hardening [3, 4]. In this case the equation describing the change in porosity of the pressed material $\alpha = v/v_m$, where v is the specific volume of the powder and v_m is the specific volume of the bulk material forming the powder ($\alpha > 1$), has the form [3]

$$-\frac{1}{3}(\alpha_0-1)^{-2/3}\frac{d}{d\alpha}\left\{\frac{\dot\alpha^2}{2}\left[(\alpha-1)^{-1/3}-\alpha^{-1/3}\right]\right\} = 1-\frac{2}{3}\beta\times$$
$$\times\left\{\ln\frac{\alpha}{\alpha-1}+3m\int_1^{\left(\frac{\alpha}{\alpha-1}\right)^{1/3}}\left[\frac{2}{3}\ln\left(1+\frac{\alpha_0-\alpha}{(\alpha-1)x^3}\right)\right]^n\frac{dx}{x}\right\}+\frac{4}{3\,\mathrm{Re}_0}\frac{\dot\alpha}{\alpha(\alpha-1)}, \quad (1)$$

where $\mathrm{Re}_0 = (a_0/\nu)\sqrt{p/\rho}$; $\beta = Y_0/p$; $\tau = a_0\sqrt{\rho/p}$; a_0 is the characteristic size of the pores, ν is viscosity, ρ is the density of the powder material, p is the external pressing pressure, α_0 is the initial porosity value. The dot indicates differentiation with respect to dimensionless time t/τ. The material hardening law is chosen in the form [3]

$$Y = Y_0\left(1+m\left(\bar\varepsilon^p\right)^n\right),$$

where Y_0 is the initial yield point; m, n are hardening parameters; $\bar\varepsilon^p$ is the accumulated plastic deformation.

Depending on the value of the parameters Re_0 and β, Eq. (1) produces two qualitatively different types of solution $\alpha(t)$: the first consists of solutions defining a finite porosity value for pressing with $\alpha > 1$, while the second produces a final porosity of $\alpha = 1$ (poreless material) with $\alpha \neq 0$ (at the moment $\alpha = 1$). The solutions of the second type can be analyzed conveniently by commencing from the corresponding equation for change in internal radius of a "hollow sphere", $a(t)$, which can be obtained from Eq. (1), considering that

$$\xi = \frac{a(t)}{a_0} = \left(\frac{\alpha(t)-1}{\alpha_0-1}\right)^{1/3}, \quad u = \frac{d\alpha}{dt}\sqrt{\frac{\rho}{p}},$$

where u is the dimensionless rate of motion of the internal radius of the "hollow sphere" and ξ is the dimensionless internal radius of the same "hollow sphere."

With such notation Eq. (1) takes on the form

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$$\frac{du}{d\xi}+\frac{u}{\xi}\left(2-\frac{1}{2}\frac{1-\varphi^{-1/3}}{1-\varphi^{-1/3}}\right)+\frac{1}{u\xi}\left\{1-\frac{2}{3}\beta\left[\ln\varphi+3m\times\right.\right.$$
$$\left.\left.\times\int_1^{\varphi^{1/3}}\left[\frac{2}{3}\ln\left(1+\frac{1-\xi^3}{\xi^3x^3}\right)\right]^n\frac{dx}{x}\right]\right\}(1-\varphi^{-1/3})^{-1}+\frac{4}{\mathrm{Re}_0}\frac{1}{\xi^2}\left[\varphi(1-\varphi^{-1/3})\right]^{-1}, \quad (2)$$

where $\varphi = 1 + 1,\xi^3(\alpha_0 - 1)$.

The initial condition for Eq. (2) (at t = 0) is $\xi = 1$, $u = 0$. The singular point of this equation ($\xi = 0$, $u^{-1} = 0$) is a complex one, analogous to the singular point of the equation describing collapse of a bubble in a viscous liquid [5]. Pore collapse in a viscoplastic material may occur in two ways: 1) over an infinite time, with $u \to 0$ and $\xi \to 0$; 2) over a finite time with accumulation of energy at the point $\xi = 0$, with $u \sim \xi^{-3/2}$. The separatrix separating the various families of solutions in the phase plane, itself a special solution of Eq. (2), defines the law of velocity change $u = -8\xi^{-1}$. Energy accumulation leads to an unlimited increase in pressure at the moment of collapse and formation of a divergent shock wave.

The experimentally observed "splattering" of material from the press form [1] is apparently related to accumulation of energy upon pore collapse in the process of electrical pulse pressing.

It is thus important to establish the parameter ranges which lead to accumulation in pressing. We note that for a viscous liquid the critical regime is determined by a single parameter, the critical value of the Reynolds number Re* [5]. For a viscoplastic material which manifests hardening the critical region is determined by both the parameters Re*, β* and the hardening parameters m and n. It will be convenient to consider the condition for development of accumulation in the plane of the parameters $(1/\mathrm{Re}_0)$, β. Figure 1 shows the regions corresponding to parameters for various pressing regimes ($\alpha_0 = 1.89$). Region I corresponds to the regime with accumulation, while region II is the conventional pressing regime with final material porosity unequal to unity ($\alpha > 1$). The line $(1/\mathrm{Re}^*) = f(\beta^*, \alpha_0, m, n)$ bounds the region of parameter values leading to accumulation. The point $(1/\mathrm{Re}_0) = 0$, $\beta = 0$ corresponds to the Rayleighan case of bubble collapse in an ideal liquid. The point $(1/\mathrm{Re}_0) = 0$, $\beta = \beta_*^0$, where

$$\beta_*^0=\frac{3}{2}\left\{\ln\frac{\alpha_0}{\alpha_0-1}+\frac{\ln\alpha_0}{\alpha_0-1}+\frac{3m}{\alpha_0-1}\int_1^{\alpha_0\left(\frac{\alpha}{\alpha-1}\right)^{1/3}}d\alpha\int_1^{}\left[\frac{2}{3}\ln\left(1+\frac{\alpha_0-\alpha}{(\alpha-1)x^3}\right)\right]^n\frac{dx}{x}\right\}^{-1},$$

corresponds to the critical accumulation regime in a plastic powdered material with hardening without consideration of the effect of viscosity. In the general case the function $f(\beta^*, \alpha_0, m, n)$ is defined by numerical integration of Eq. (2) for $u(\xi)$ by a method analogous to that presented in [5].

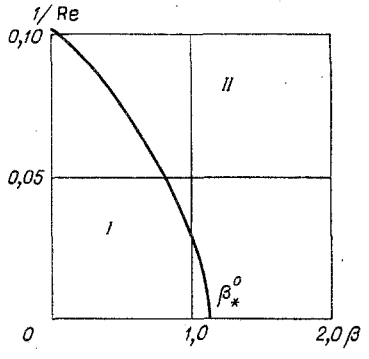

Fig. 1

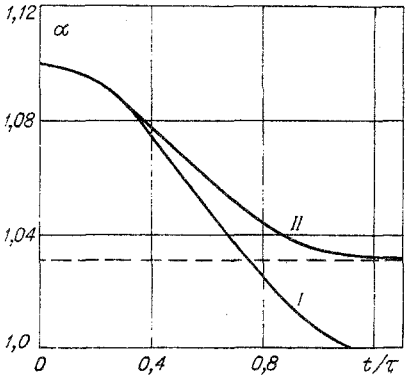

Fig. 2

The effect of hardening on the pressing process is illustrated by Fig. 2, where porosity is shown as a function of time $\alpha(t)$, as obtained by numerical integration of Eq. (1) for parameter values $Re_0 = 10$; $\beta = 0.2$; $\alpha_0 = 1.1$; $m = n = 0$ (curve I); $m = 4.8$, $n = 0.8$ (curve II, corresponding to pressing of aluminum [3]). Hardening of the material increases the final porosity of the pressed specimens obtained under identical pressing conditions, and the time for reaching final porosity also increases somewhat.

The results presented in Figs. 1, 2 were obtained for the case of steplike change in pressure and temperature, varying the viscosity ν and yield point Y of the material. For continuous change of the parameters Re(t) and $\beta(t)$ in time the condition for development of accumulation contains time characteristics. In this case it is convenient to use the equation defining the change in Reynolds number $Re = -a\dot{a}/\nu$. The following condition follows directly from Eq. (2):

$$\frac{1}{\nu}\frac{d\,\mathrm{Re}}{dt} = \frac{\mathrm{Re}^2}{a^2}\left(1 - \frac{1}{2}\frac{1-a^4/b^4}{1-a/b}\right) + \frac{p - \frac{2}{3}Y_0\left[\ln(b/a)^3 + 3m\int_a^b (2\ln r/r_0)^n \frac{dr}{r}\right]}{\rho\nu^2(1-a/b)} - \frac{4\,\mathrm{Re}}{a^2}\frac{1-a^3/b^3}{1-a/b} \tag{3}$$

(where b is the external radius of the hollow sphere). For $Y_0 = 0$, $b \to \infty$ Eq. (3) transforms to the equation describing change in Reynolds number for collapse of a bubble in a viscous liquid [6]. We combine Eq. (3) with the equations of motion and incompressibility

$$\frac{1}{\nu}\frac{da}{dt} = -\frac{\mathrm{Re}}{a}, \qquad b^3 = a^3 + (b_0^3 - a_0^3), \tag{4}$$

where b_0, a_0 are the external and internal radii of the hollow sphere at t = 0. Numerical integration of Eqs. (3), (4) with initial conditions t = 0, Re(0) = 0, $\alpha(0) = a_0$ for a given law of change of external parameters permits determination of the critical accumulation parameters.

An estimate of the critical Reynolds number value at which cumulation is possible can be obtained by using the quasistatic approximation. At the initial moment of time the Reynolds number issmall, so that the inertial terms in Eq. (3) may be neglected. Integration of Eqs. (3), (4) with this assumption gives the change in Reynolds number with time

$$\mathrm{Re}(t) \simeq \frac{a^2(t)\left[p(t) - \frac{2}{3}Y_0(t)\left[\ln(b/a)^3 + 3m\int_a^b (2\ln r/r_0)^n \frac{dr}{r}\right]\right]}{4\rho\nu^2(t)(1-a^3/b^3)}. \tag{5}$$

Equation (5) also permits determination of $\alpha(t)$. For constant pressure $p(t) = p_0$ and variation of $\nu(t)$ and $Y_0(t)$ connected with heating of the powder, for $\beta \ll 1$ Eq. (5) gives

$$\mathrm{Re}(t) \simeq \frac{a_0^2 p_0}{4\rho\nu^2(t)} \exp\left(-\frac{p_0}{4\rho}\int_0^t \frac{d\tau}{\nu(\tau)}\right). \tag{6}$$

The time τ_T over which the viscosity changes from the low temperature value [7] to that of the liquid metal can be estimated with the aid of the expression

$$\rho c_p(\Delta T/\tau_T) \sim \frac{j_0^2}{\sigma}, \tag{7}$$

where j_0 is the current density; σ is the conductance of the powder; c_p is the heat capacity of the powder material; and ΔT is the temperature change.

We will now use Eqs. (6), (7) to estimate the values of Reynolds number corresponding to the two qualitatively different pressing regimes of [1] with similar values of pressing parameters. The pressing regime with "splattering" of the material from the form had a pressure of 39 MN/m² (regime 6), while the conventional regime without splattering occurred at a pressure of 26 MN/m² (regime 5). Remaining pressing parameters were identical for both cases: Current density $j_0 = 5\cdot10^8$ A/m², $a_0 = 100$ μm, $1/\sigma = 10^{-6}$ Ω·m, $\rho = 7.6$ g/cm³. The temperature change $\Delta T \sim 500$°C, and the low-temperature viscosity ($\nu = 0.3$ m²/sec) was taken

from [7]. The regime designation is that of [1]. For the regime with "splattering" the estimate gives Re ∿ 11; for the regime without "splattering" Re ∿ 7.

We note that the change in the parameters Re and β is apparently related not only to Joulean heating of the powder, but also the electroplastic effect of current pulse action [8], which reduces the yield point of the material.

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INFLUENCE OF TEMPERATURE ON THE CRITICAL CONDITIONS OF SPALLING FRACTURE OF METALS

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The question of the influence of temperature on the spalling fracture of metals has still been studied insuficiently at this time. The results of a few experimental investigations of this equation [1-4] are extremely limited and quite contradictory. If a reduction in the spalling strength of steel St.3 and copper M1 with the temperature rise to 500°C is noted in [2, 4], then no influence of the temperature on the spalling fracture of aluminum was noted in [1, 3].

Results of an experimental investigation of the influence of temperature on the critical spalling fracture conditions for a number of construction metals are represented in this paper: AD1 aluminum, D16 and AMg6 aluminum alloys, St.3 and 12Kh18N10T steels, VT14 titanium, M1 copper, and NP2 nickel in a broad temperature range (—196- +800°C). The experimental method used is based on determining the critical velocity of impact of a plate on the specimen of material being investigated, that results in the formation of macroscopic spalling fracture, and was successfully used to investigate the time regularities of spalling fracture ([5, 6], for instance). In application to the problem posed in this paper, the method of determining the critical impact velocity permits us to obtain a clear boundary between the spalling fracture zones, and to conserve the macroscopic continuity of the material in the temperature range under study for identical time conditions of the impulsive mechanical loading.

Knowledge of the mechanical properties of the specimen and impactor materials under shockwave loading permits a comparison between the critical impact velocity and the magnitude of the critical tensile stress in the specimen. The selection of a geometry of the impactor—

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