USE OF THE ENERGY OF A STRONG PULSED MAGNETIC FIELD FOR POWDER COMPACTION

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A strong pulsed magnetic field may be used directly for pressing metallic and non-metallic powders. Pressure working utilizing the energy of a strong pulsed magnetic field belongs to the category of high-rate processes, which includes the detonation of high explosives, explosion of wires in a solid dielectric, discharge of an electric current in a liquid, etc. High-rate methods of powder compaction have certain advantages over static techniques. The principal characteristic of these processes is that high pressures are applied to a given area for an extremely short period of time (giving rates 20,000-30,000 times higher than those obtained on ordinary presses).

A pulsed magnetic field is generated with a pulsed current source. Usually, such a source is provided by a condenser battery of low self-inductance. During the discharge of the battery on to an inductive load (inductor), a pulsed magnetic flux of high concentration is generated in the latter. This magnetic flux induces eddy currents within the material to be pressed. As a result of interaction between the magnetic fields of the inductor and of the induced eddy currents, pressures are generated which may exceed 40,000 kg/cm^2. The material to be densified need not be magnetic or electrically conducting, because, as will be shown below, to improve pressing only a sheath from a conducting material is used.

Experimental work conducted both in the USSR and abroad established that the new technique has considerable advantages: It is flexible, the installation required is small, the process lends itself to automation, treatment may be carried out in a vacuum or a neutral atmosphere, etc.

Powder Compaction under a Magnetic Hammer

The magnetic hammer is the name given to a device in which a pulsed magnetic field of a plane inductor generates electromechanical forces in a conducting material which transmits these forces to the material being pressed. The arrangement and circuit of the magnetic hammer are illustrated diagrammatically in Fig. 1. An actuating pulse from a control button (not shown in the figure) is transmitted to the discharger 1 of a magnetic-pulse system. The discharger actuates and connects the plane inductor 2 of the hammer to the charged condenser battery 3. The discharge current flowing in the "battery-inductor" circuit has a damped sinusoidal character. The magnetic induction field $\vec{B}$ has the same character. This field penetrates through the electrically conducting surface of the moving plate 4 and generates in it electromechanical forces f. The pressure pulse of the magnetic field, which is distributed over the plate surface, is transmitted through the punches 5 to the powder 6 being pressed in the die 7.

For the pressing of powders under a magnetic hammer, of considerable interest is the magnitude of the energy developed by it, as well as the rate of travel of its moving part. The equivalent inductance L_i of the inductor can be approximately determined, taking into account the conducting surface of the moving plate, from the formula [1]:

$$L_i = \pi\mu_0\Delta_i w^2 \frac{\delta_1}{\delta_2}, \qquad (1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant, w is the number of inductor turns, and δ_1 and δ_2 are the inductor spiral pitch and turn width, respectively.

As the magnetic field in the plate is completely damped, an analogy may be drawn between the electromagnetic forces acting on the electrically conducting surface of the moving plate and a gas exerting a pressure p_m on this sheet. To determine the force F acting on the plate, it suffices to integrate the magnetic pressure p_m over the surface area S of the plate on which the pressure is distributed, i.e.,

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Leningrad Scientific-Research Institute of Machine-Construction Technology. Translated from Poroshkovaya Metallurgiya, No. 10 (82), pp. 24-31, October, 1969. Original article submitted March 11, 1968.

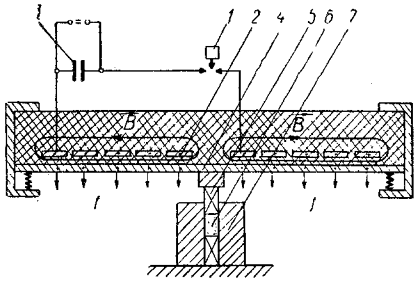

Fig. 1. Diagram of magnetic hammer. Description in text.

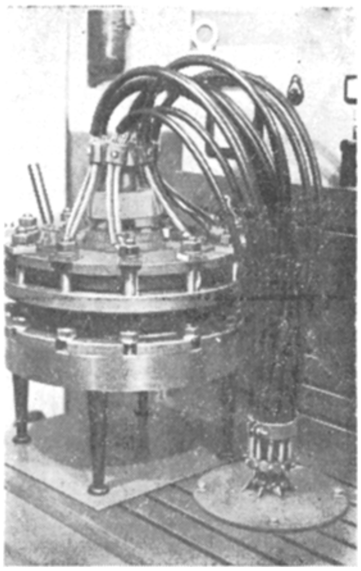

Fig. 2. Photograph of 400-ton laboratory magnetic hammer.

$$F=\int_s p_m \cdot ds. \tag{2}$$

The law of magnetic pressure distribution under an inductor on a current-conducting surface has a complex character. It depends on the design of the inductor, its turns, insulating gaps, the proximity effect, etc.; in the case of a multiturn inductor with a relatively uniform field, however, it may be taken that, to a first approximation:

$$F=p_m \cdot S, \tag{3}$$

where S is the surface area occupied by the inductor turns. The magnetic pressure is

$$p_m=\frac{\mu_0 H^2}{2}, \tag{4}$$

where H is the intensity of magnetic field in the gap between the inductor and the current-conducting plate under the middle inductor turns.

Considering that the intensity of magnetic field under each spiral turn is equal to the mean current density and that the current is sinusoidally damped, we have:

$$F=\frac{\mu_0 S}{2\delta_1^2} I_m^2 e^{-\frac{2t}{\tau}} \sin^2 \omega t, \tag{5}$$

where $\tau = 2L/R$ is the circuit time constant, I_m the maximum current intensity (first amplitude), δ_1 the inductor spiral pitch, ω the angular frequency of current oscillations, and L and R the total circuit inductance and active resistance, respectively.

Earlier experimental work [2] demonstrated that the motion of a part under the action of a pulsed magnetic field does not begin at once, but some time after the beginning of the discharge. For massive parts, this usually occurs after the first current maximum. It is conjectured that an energy build-up takes place during this time. As a result of a force pulse, the velocities of all points in the skin layer of the part undergo finite changes. Hence, during an infinitely short time, the displacements of these points must be infinitely small. It may be assumed that such points remain stationary, while their velocities are subject to stepwise, finite changes, so that the points experience impact.

Applying the pulse theory to our case, we obtain:

$$\vec{N}=\int_0^\infty \vec{F} dt, \tag{6}$$

where $\vec{N}$ is the force pulse and $\vec{F}$ is the vector of the resultant forces. Then, allowing for Eq. (5), we have:

$$N=\frac{\mu_0 S}{2\delta_1^2} I_m^2 \int_0^\infty e^{-\frac{2t}{\tau}} \cdot \sin^2 \omega t \cdot dt=\frac{\mu_0 S L I_m^2}{8\delta_1^2 R}. \tag{7}$$

The maximum value of discharge current is

$$I_m=\sqrt{\frac{E_c}{L_i+L_{par}}}, \tag{8}$$

where E_c is the energy stored up in the condensers:

$$E_c = \frac{U_0^2 C}{2}, \tag{9}$$

U_0 is the charge voltage, C is the total capacitance of the battery, $L_{par} = L_c + L_d + L_l$ is the parasitic inductance of the circuit, equal to the sum of the inductances of the condensers, discharger, and leads.

The initial velocity of the moving part of the magnetic hammer can be determined from the relationship:

$$v_0 = \frac{N}{m}, \tag{10}$$

where m is the mass of the moving part of the magnetic hammer.

The kinetic energy developed by the magnetic hammer is

$$E_k = \frac{mv_0^2}{2}. \tag{11}$$

The efficiency of the hammer is:

$$\eta = \frac{E_m}{E_k} \cdot 100\%. \tag{12}$$

From Eq. (10), it can be seen that the highest rate of travel of the moving plate and, consequently, the maximum energy of pressing will be attained at the least plate weight. Therefore, in the pressing of powders, use may be made of devices in which the part of the punch is played by an electrically conducting foil intended for a single application. The distribution of mechanical forces on the foil may be predetermined by choosing an appropriate magnetic-field configuration.

Tests were conducted on an experimental model of the above-described device with a six-turn spiral inductor and a 2-kg moving plate. The over-all dimensions of the model were 300 × 300 × 300 mm. Using this model, tungsten-powder compacts with a volume of more than 2 cm^3 and an average density of more than 14 g/cm^3 before sintering were obtained by discharging a condenser battery with an energy of 20 kJ and a voltage of 4.5 kV. Calculations with the aid of Eqs. (1)-(12) showed that, at $\Delta_1 = 2 \times 10^{-3}$ m, $\delta_2 = 5 \times 10 \times 10^{-3}$ m, $\delta_1 = 20 \times 10^{-3}$ m, $L = 530 \times 10^{-9}$ H, and $I_m = 250 \times 10^3$ A, the initial velocity of the moving plate was 32.5 m/sec and the efficiency was was 6.3%. Figure 2 shows a photograph of a laboratory magnetic hammer, 300 × 300 × 300 mm in size, developing a force of more than 400 tons. The initial velocity of its 2.5-kg moving plate is 36 m/sec.

By using a magnetic hammer, it is possible to subject the volume to be pressed to predensification in the same equipment and with the same source of electric energy. For the predensification of powder, series of charges and discharges of the condenser battery are performed automatically at low voltage. In this case, the moving plate repeatedly strikes the punch with a small force, consolidating the powder in a closed volume and deaerating it. When the required initial density has been reached, the battery is switched over for a single charge to the maximum voltage and discharge on the same inductor. In this way, the final powder densification is achieved.

Using the energy of a pulsed magnetic field, it is possible to perform double-ended pressing on powders. Other conditions being equal, double-ended pressing is the most advantageous and economical. A diagram of such a device is illustrated in Fig. 3. When the discharger 2 is actuated, the current from the condenser battery 1 flows in the opposite directions in two pairs of moving and stationary flat busbars. The moving busbars 3 are repelled from the stationary busbars 4 and drive the punches 5 against each other, thereby compressing the powder in the compaction volume 6 (split die). The total force exerted on one moving busbar can be determined from the expression:

$$F = \frac{\partial}{\partial \Delta}\left(\frac{L I_m^2}{2}\right), \tag{13}$$

where I_m is the first amplitude of the discharge current, obtained from Eq. (8), Δ is the distance between the busbars, and L is the equivalent inductance of one pair of busbars. According to Kalantarov and Tseitlin [3], L can be determined from the formula:

$$L = \frac{\mu_0 l}{d}\left(\Delta + \frac{2}{3} b\right). \tag{14}$$

Here, l and d are the busbar length and width, respectively, and b is the current-penetration depth:

$$b = \sqrt{\frac{2}{\omega\gamma\mu_0}}, \tag{15}$$

γ is the electrical conductivity of the busbars. Finally, we get:

$$F = \frac{I_m^2 \mu_0 l}{2d}. \tag{16}$$

The initial velocity of the moving busbar and the kinetic energy are calculated from Eqs. (10) and (11).

Pressing of Thin-Walled Tubes from Powders

One of the chief advantages of this technique is that it enables thin-walled tubes to be pressed from powders. The pressing of tubes can be performed in dies or on mandrels. The punch in either case is provided by a thin-walled electrically conducting tube which is used only once. Figure 4 shows a simple experimental device for pressing tubes from powder with a split die. The inductor is a multiturn cylindrical coil which is placed within the punch tube. The magnitude of the pressure acting on the punch tube can be calculated from Eq. (4), the maximum intensity of magnetic field in the gap between the inductor and the tube being:

$$H_m = \frac{I_m L_i}{\mu_0 w S}, \tag{17}$$

where L_i is the inductance of the inductor-tube-punch system. It has been found [4] that

$$L_i = \frac{\mu_0 w^2}{l} 2\pi R_0 \left(\Delta + \frac{3}{4} b\right). \tag{18}$$

Here, R_0 is the inner tube radius, w and l are the number of turns and the inductor length, respectively, Δ is the gap between the inductor and the tube, and b is the current-penetration depth, determined from Eq. (15).

It should be noted that the pressure acting on the punch tube is not transmitted directly to the powder, because the acceleration time of the tube is usually, as shown by experiment, about one half-period and is incommensurately small compared with the tube deformation time. Therefore, this is really a case of impact of an accelerated punch, provided by a tube, against powder. It is understandable that the intensity of this process will be characterized not by the pressure acting on the tube during the latter's acceleration, but by the accumulated kinetic energy per unit volume of the tube material:

$$e_m = \frac{\rho v^2}{2}, \tag{19}$$

where ρ is the density of the tube material and v is the tube velocity.

Considering that the path of travel of the punch tube is a function of time alone and that the magnetic field in the gap is uniform, the rate of travel of the punch-tube wall can be determined from a pressure-equilibrium equation [5], which, to a first approximation, may be expressed as:

$$\frac{\mu_0 H^2}{2} = \rho\delta \frac{d^2\Delta}{dt^2} + \frac{\delta}{R_0}\sigma_t, \tag{20}$$

where σ_t is the hoop stress generated in the tube wall in the circumferential direction and δ is the tube-wall thickness.

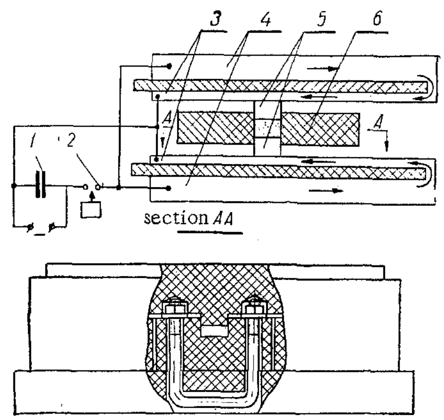

Fig. 3. Diagram of device for double-ended pressing of powder. Description in text.

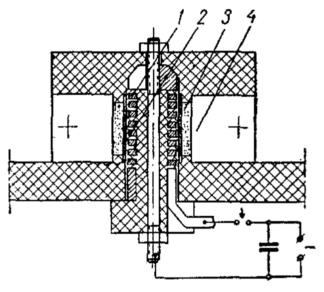

Fig. 4. Device for pressing thin-walled tubes in split die: 1) cylindrical inductor; 2) punch tube; 3) powder being pressed; 4) split die.

In the pressing of powders by the energy of a pulsed magnetic field, the intensity of the latter in the gap between the tube and the inductor is more than 100 kA/cm, while the punch tube is usually made of a soft material (copper, aluminum). As a result, the expression $\delta / R_0 \cdot \sigma_t$ is small enough to be ignored. Then the velocity acquired by the tube wall during its displacement in a radial direction will be:

$$v = \frac{d\Delta}{dt} = \frac{\mu_0 H^2}{2\varrho\delta} t, \tag{21}$$

and its path of travel:

$$\Delta_1 = \frac{\mu_0 H^2}{4\varrho\delta} t^2. \tag{22}$$

From Eqs. (21) and (22), we can find the maximum velocity at the end of the whole deformation path:

$$v_{max} = H_m \cdot \sqrt{\frac{\mu_0 \Delta_1}{\varrho\delta}}, \tag{23}$$

where H_m = const is the amplitude value of the intensity of magnetic field.

It is interesting that when the tube has traveled a distance equal to its thickness the kinetic energy of the tube per unit volume of its material (allowing for the assumptions made) will be:

$$\frac{\varrho v_{max}^2}{2} = \frac{\mu_0 H^2}{2}.$$

The efficiency of the device can be determined from the expression:

$$\eta = \frac{e_m V}{E_k} \cdot 100\%, \tag{24}$$

where V is the volume of the tube material.

Pulsed magnetic fields may also be employed for the production of thin-walled tubes with lengths of up to 800 mm or even more from powders. A device in which discharge currents flow in the opposite directions in two coaxial tubes has been described [6]. As the inner thin-walled tube is repelled from the massive outer tube, it undergoes deformation and presses the powder on a mandrel.

The above-described powder-compaction techniques employ, to varying extents, intermediate metal components such as punch plates or tubes. It would be advantageous if a pulsed magnetic field could be applied directly to a powder, yielding compacts with a density close to theoretical. The magnetic field can also exert a considerable influence on the properties and structure of a pressed part. So far, it has been found impossible to press loosely-poured powders by the direct action of a pulsed magnetic field. The principal difficulty lies in establishing closed paths of induced currents within the powder volume. The problem can partially be solved by using powders of current-conducting materials which are subjected to predensification by any existing technique (or incipient melting) and then placed in a strong pulsed magnetic field. This method has been employed for pressing copper cylinders, 10.7 mm in diameter and 42 mm long, prepared by the powder metallurgy process. The cylinders were inserted in pairs into a cylindrical inductor having 19 turns. The discharge of a condenser battery (4 kV, 2700 μF) on to this inductor increased the density of the cylinders from 6.84 to 8.2 g/cm^3.

Pulsed magnetic fields can be utilized for comminuting materials with a spongy or porous structure to ultrafine powders with particles under 1 μ in size, as well as for layering fiber materials [7].

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