speed of sound in quartz; k, Boltzmann's constant; m, atomic mass of material; c_1 and c_2, specific heats of solid and liquid phases; σ, Stefan–Boltzman constant; t_a and t_{opt}, action time and optimum action time; ρ, density of material; v_∞, quasisteady-state rate of isotherm translation; δ_T, depth to which material is heated; S_m, thickness of melt layer; z, position of fusion front; λ_1, λ_2, specific heats of solid and liquid phases.

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CHOICE OF THE OPTIMUM THICKNESS OF HEAT INSULATION IN THE HOT COMPACTION OF POROUS MATERIALS

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Calculations are made of the thickness of the heat-protective shell of a system for sintering powder mixtures which will ensure a quasiuniform temperature distribution over a given period of time.

In the high-temperature compaction of powdered materials, it is only possible to obtain high-quality products when certain necessary conditions are satisfied. One of the main conditions is to maintain a uniform temperature field, regardless of how the latter is initially set up, in the system material — working surface of the instrument over the period of time which is necessary for carrying out the technological operation. Failure to satisfy this condition, especially in the compaction of powdered alloys with low thermal conductivities, leads to nonuniformity of the plastic deformation, the appearance of thermal stresses in the material, and the formation of macrocrystalline rims with poorer mechanical properties.

It is obvious that a high degree of uniformity of an initial temperature field obtained as a result of the use of internal heat sources, for instance as a result of the passage of an electrical current, can be achieved either by setting up an adiabatic shell, or (what is equivalent) by carrying out the heating sufficiently rapidly ($\sim 10^{-6}$-10^{-3}sec). However, these conditions are not sufficient for maintaining the uniformity of the field which is obtained after the source is turned off. It is possible to ensure quasiuniformity of the temperature field within required limits over the course of a specified interval of time for sintering $\hat{\tau}$

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by significantly reducing the heat flow from the object in the pressure mold to the latter and from the latter to the surrounding medium. One of the technologically accessible solutions of this problem is the setting up of a multilayer metal-ceramic composite of the "sandwich" type which fulfills the function of a barrier in the path of the heat flow and which is placed in a strong metallic housing which provides the compressive stress required to prevent the rupture of the construction. Naturally, it would be preferable to use the ceramic material directly as the heat-insulating insert, but the low thermal stability of these materials makes it necessary to go the "sandwich" route. This then leads to the problem of selecting the thickness of the shell as a function of the geometric dimensions of the briquet R, the thermophysical properties of the material being compacted and of the shell, the heat transfer conditions at the outer boundary, etc.

1. The problem will be considered within the framework of a very simple model of a three-layered cylinder of infinite length (see Fig. 1), where the thickness of the steel housing Δ_2 is related to the thickness of the "sandwich" Δ_1 and to the radius of the zone being compacted R by the relationship $\Delta_2 = 10^{-2}(R + \Delta_1)$. The materials in each of the three media will be characterized by the effective parameters: λ_i, the thermal conductivity; c_i, the heat capacity; ρ_i, the density, where i = 1, 2, 3, which all depend in general on the temperature (the corresponding dependences are given in Sec. 3). The conditions at the outer boundary, $r_3 = R + \Delta_1 + \Delta_2$, obey Newton's law, and are characterized by a heat-transfer coefficient α. The temperature field in the composite medium being considered is described by the following conditions after the heat source is cut off:

$$c_i(T_i)\rho_i(T_i)\frac{\partial T_i}{\partial t} = \nabla(\lambda_i \nabla T_i),\quad i = 1, 2, 3,\quad 0 < t \leqslant \hat{\tau},$$

$$T_i(r, 0) = \varphi_i(r),\quad T_j|_{r=r_j} = T_{j+1}|_{r=r_j}\quad (j = 1, 2;\ r_1 = R,\ r_2 = R+\Delta_1), \tag{1}$$

$$\lambda_j \frac{\partial T_i}{\partial r}\Big|_{r=r_j} = \lambda_{j+1}\frac{\partial T_i}{\partial r}\Big|_{r=r_j},\quad -\lambda_3\frac{\partial T}{\partial r}\Big|_{r=r_3} = \alpha(T_3|_{r=r_3} - T_{\text{amb}}),$$

where T_{amb} is the temperature of the surrounding medium; $\varphi_i(r)$ is the initial temperature distribution, which is assumed to be piecewise linear, such that $\varphi_1(r) \equiv T_0$ = 1200°C, and for $j = 2, 3$ $\varphi_j(r) = T_{j-1} - \frac{T_{j-1} - T_j}{\Delta_{j-1}}(r - r_{j-1})$, $T_1 = 400$ °C, $T_2 = 50$ °C.

The problem (1) has been made the basis of a computer program for the temperature field using a conservative finite-difference scheme [1] which solves the layer in each interval of time by a stepping method [2] and which includes internal iteration loops in order to take into account the nonlinearity of the equations.

2. The minimum amount of information on the temperature field provided by the probe which is required for solving the problem within the framework of the model which has been assumed for the construction being considered consists of the following values: $\chi_1 \equiv T_1(0, \hat{\tau})$, which is the characteristic level of the temperature field in the working zone at the moment at which the holding period ends, $\chi_2 \equiv \chi_1 - T_1(R, \hat{\tau})$, which is an estimate of the uniformity of of the temperature field in the working zone, $\chi_3 \equiv T_3(r_2, \hat{\tau})$, which is a characteristic of the level of heating of the shell. Analogous characteristics can also be easily introduced in more detailed descriptions of the process, for example in two- and three-dimensional models. Each of these is obviously a function of a combination **p** of several parameters governing the process.

For the given materials of the working zone and the shell it is natural to select the following quantities as the governing parameters: the dimension of the briquet being sintered, R, the length of the holding time, $\hat{\tau}$, and the heat transfer coefficient from the outer surface, α; then $\mathbf{p} = \{R, \hat{\tau}, \alpha\}$. It should be noted that the last of the parameters mentioned can also be varied over a wide range by making use of regulation of the external cooling system.

The required value of the thickness of the shell Δ_1 will be regarded as a function of **p**: $\Delta_1 = \Delta_1(\mathbf{p})$, which is determined by the conditions written to take into account the functional relationship mentioned above:

$$\chi_1(\Delta_1, \mathbf{p}) \geqslant T^*,\quad \chi_2(\Delta_1, \mathbf{p}) \leqslant \delta,\quad \chi_3(\Delta_1, \mathbf{p}) \leqslant T_*. \tag{2}$$

These conditions express the inherent requirements for the process to be effective. In the calculations which have been carried out, T^* = 1200°C, δ = 30°C, T_* = 400°C.

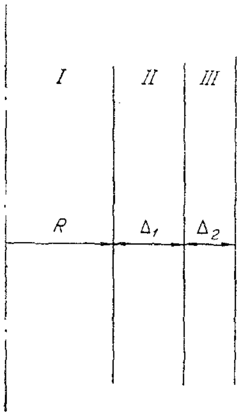

Fig. 1

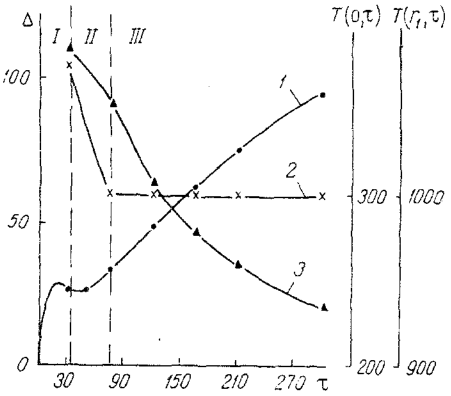

Fig. 2

Fig. 1. Cross section of device.

Fig. 2. Effect of various criteria on the selection of the shell thickness: 1) shell thickness; 2) $T(0, \hat{\tau})$; 3) $T(r_1, \hat{\tau})$; I) zone in which criterion $(2)_1$ has an effect; II) zone in which criterion $(2)_2$ has an effect; III) zone in which criterion $(2)_3$ has an effect. Δ is given in mm, and $\hat{\tau}$ in seconds.

In view of the monotonic dependence of χ_i on Δ_1 with the other parameters fixed, the optimum selection of Δ_1 at which an upper estimate of this quantity is obtained is completely automated in the computer program. For this purpose, an initial approximation is made for Δ_1, namely $\Delta_1^{(0)} = R$, after which the calculation of the problem itself and the verification of the conditions (2) is carried out. If at least one of the conditions is not satisfied, then the value of Δ_1 is doubled, while in the opposite case the value of Δ_1 is halved. As a result of the monotonic nature of the dependence of the function χ_i on Δ_1, it will be possible to bracket the value after a certain number of steps, $\Delta_1^{(k)} < \Delta_1^{(k+1)}$: at the point $\Delta_1^{(k)}$ the conditions (2) will not be satisfied, while at the point $\Delta_1^{(k+1)}$ they are already satisfied. Further refinement of the value of Δ_1 is carried out by subdividing the section $[\Delta_1^{(k)}, \Delta_1^{(k+1)}]$ into halves (dichotomy) [3] until the required precision is attained.

For certain fixed values of the parameters, Fig. 2 illustrates the role of the various criteria in (2) in different ranges of the values of $\hat{\tau}$. The zones in which they are effective are indicated by the corresponding Roman numerals and the sequence of behavior $\chi_i = \chi_i(\hat{\tau})$ (i = 1, 2, 3) is followed and represented graphically. The graph for the optimum shell thickness $\Delta_1 = \Delta_1(\hat{\tau})$ for this variant is also given in the figure.

3. The results are given below for a mathematical experiment which was carried out for materials characterized by the following parameters ($c\rho$ kJ/(m³·K); T, K; λ(T), W(m·K):

layer I:

$$c_1\rho_1 = 2690 + 1{,}47T,$$

$$\lambda_1(T) = \begin{cases} 17{,}2\cdot 10^{-3}, & T < 900, \\ -3{,}4 + 21{,}0\cdot 10^{-3}T, & 900 < T < 1109, \\ -6{,}9 + 23{,}8\cdot 10^{-3}T, & 1109 < T < 1210, \\ -14{,}7 + 30{,}6\cdot 10^{-3}T, & T > 1210; \end{cases}$$

layer II:

$$c_2\rho_2 = \begin{cases} 3070 + 0{,}52T, & T < 1478, \\ 3220 + 0{,}28T, & T > 1478, \end{cases}$$

$$\lambda_2(T) = \left(\frac{10{,}5}{148 - 0{,}036T} + \frac{1}{3{,}6 + 0{,}00078T}\right);$$

layer III:

$$c_3\rho_3 = 3540, \quad \lambda_3 = 66.$$

The special mathematical experiment showed that when the thermophysical parameters of the

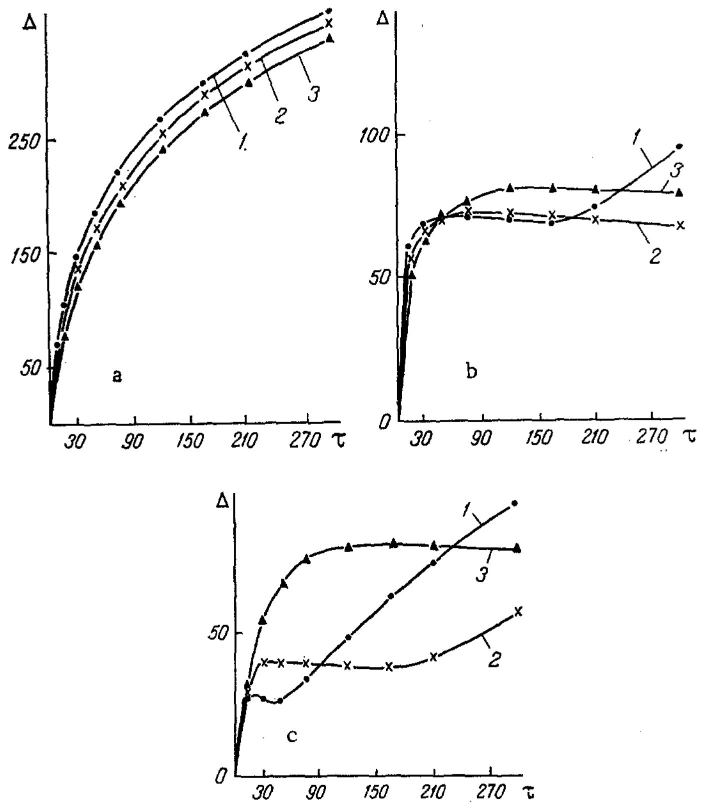

Fig. 3. Thickness of the heat-protecting shell as a function of $\hat{\tau}$ for $\alpha = 15$ W/(m^2·K) (curve (a)); $\alpha = 100$ W/(m^2·K) (curve (b)); and for $\alpha = 250$ W/(m^2·K) (curve (c)). 1): R = 10 mm; 2): R = 25 mm; 3) R = 50 mm.

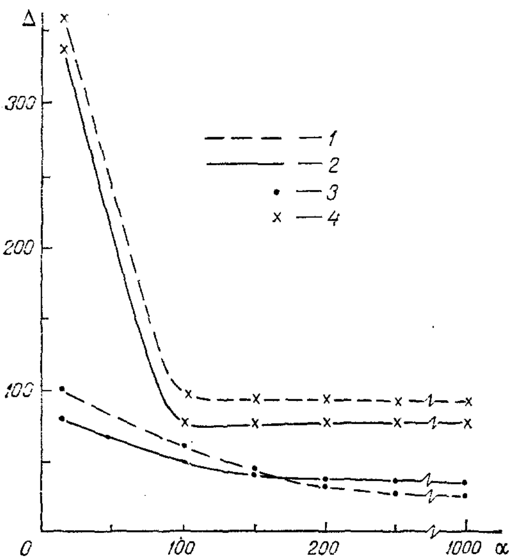

Fig. 4. Thickness of the heat-insulating shell as a function of the heat transfer coefficient: 1) R = 10 mm; 2) R = 50 mm; 3) $\hat{\tau}$ = 15 sec; 4) 300 sec. α is given in W/(m^2·K).

shell were measured to ±10%, the variation in the selection of its thickness over the time range $\hat{\tau}$ = 30-210 sec did not exceed ±0.5-5%. This indicates that the results are stable relative to unavoidable errors in the determination of the thermophysical characteristics of the composite material and that the accuracy is sufficiently high.

Figure 3 shows a nomogram of the process which expresses the relationship $\Delta_1 = \Delta_1(\tau)$ determined by the combination of criteria in (2) for various values of α and R.

An analysis of the results of the calculation shows that when α_1 = 15 (free convection, air) the thickness of the "sandwich" Δ_1 for the briquet radii investigated is a monotonic function of the compaction time $\hat{\tau}$, and reaches values $\Delta_1 \gg$ R at large values of $\hat{\tau}$. At the values of $\hat{\tau}$ being considered, the criterion which governs the behavior of Δ_1 is the condition $(2)_3$. On increasing the heat transfer coefficient to α_2 = 100 (forced convection, air) a "plateau" appears on the curve $\Delta_1 = \Delta_1(\hat{\tau})$ at the level of 70-80 mm. The effect of the criterion $(2)_3$ becomes smaller as R increases, and the criteria $(2)_1$ and $(2)_2$ begin to have an effect, and for $25 \leqslant R \leqslant 50$, the behavior of Δ_1 is determined exclusively by the criterion $(2)_2$. It should be noted that $\Delta_1(\alpha_1) \gg \Delta_1(\alpha_2)$ in all cases when $\hat{\tau} \geqslant$ 15 seconds. A further increase of the heat transfer coefficient to α_3 = 250 (forced convection, water) leads to an increase in the effect of criterion $(2)_1$ for $10 \leqslant R \leqslant 25$, and when $R \geqslant 25$ mm the effect of criterion $(2)_2$ becomes smaller. The trend towards an increased thickness of the shell is simplified for briquets of small dimensions at quite large holding times. It can therefore be concluded that the role of the effectiveness criteria shifts in the direction $(2)_3 \to (2)_1$ as α increases, and that in the working range of $\hat{\tau}$

$$\Delta_1(\alpha_1) \gg \Delta_1(\alpha_2) \gg \Delta_1(\alpha_3).$$

The results which have been obtained make it possible to provide practical recommendations for the construction of the heat-protective shells. From Fig. 4, which represents the thickness Δ_1 as a function of α for various radii and holding times, it follows that there is an optimum (but not a very sharply marked one) in the conditions of cooling at which a sufficiently small thickness of the "sandwich" is reached.

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THERMOOPTICAL PROCESSES IN MIRROR–LENS OBJECTIVES. I. SCHEME FOR SYNTHESIS OF A THERMOSTABLE TELESCOPE

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Special features of the designing of a thermostable telescope are discussed on the example of the objective for the narrow-angle television camera of the Vega spacecraft.

A new scientific discipline, which can be called thermooptics for short, has taken shape in recent years. The sphere of consideration of the latter includes the joint analysis of thermal and optical phenomena arising in the passage of light through condensed and uncondensed media. Up to now these phenomena have been studied in sufficient detail in gaseous lenses, controlling strong fluxes of laser radiation [1], as well as in the active elements of solid lasers, in resonators, etc. [2-4]. Relatively long ago, opticians turned attention to the influence of thermal processes on the quality of the image produced by an optical system [5-7]. In the investigation of optical systems, however, there has been insufficiently full allowance for the mutual thermal influence of the construction elements on each other, the thermooptical models have not been adequate to the object being studied, as a rule, and the

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