Based on the developed model, one can derive the heat distribution in the parts of a press tool and in the sintered powder product. Choosing the optimum tooling material for electric sintering conditions greatly simplifies the mathematical modeling of the tooling heating process.

The numerical solution to the derived system of equations makes it possible to determine the temperature of the control volumes of the product and tooling in a random period. The calculations, similar to those described, allow the comparison of the progress of the activated process at various structural and material-science solutions for building a press-tool, as well as the quantification of the technical and economic evaluation of the entire technological link.

In the process of electric discharge processing of metal powders and alloys on their basis, there is a simultaneous effect exerted on the material of the press-tool by electric current, high temperatures, and pressure. This significantly complicates the task of selecting materials without preliminary calculations, which would make it possible to establish the technological principles for creating more resistant combined tooling elements for electric sintering [1]. The research into the development of materials for the mold is important for the practice of technological processes in powder metallurgy. Electric sintering allows for the compatibility of pressing and sintering processes, thereby freeing the production areas taken up by the equipment.
2. Literature review and problem statement

The use of modern methods of electrophysical treatment makes it possible to obtain materials with a new level of physical and mechanical properties, thus reducing the sintering temperature and aging time. The method of compacting of powdered products by electric sintering ensures the even distribution of density in the molds of complex shape without application of any plasticizers, which are the potential sources of impurities and additional porosity in would-be products [2]. The authors of papers [3, 4], to study the heating of porous materials, developed the methods for calculating a temperature distribution lengthwise the electrode-punches and a sintered product in contact with them. They considered a typical scheme to transmit electric current through a sample under the simplified assumption that there is no outflow of heat in the side directions. The specified methods provide an opportunity to derive formulae for one-dimensional temperature distribution in the resulting product and in the electrode-punches in contact with it. More complex temperature fields occur at the electric sintering of annular products [5]. It is of great importance, in this case, to mathematically model those complex temperature transformations that take place in the contact area of different materials of the mold [6].

The electric sintering should be considered a new, quite promising way that enables the use of heat, which is released as a result of micro discharges, as well as joule heating. A given technique intensifies the processes of thermal, electrostatic, and ionic diffusion in the area of inter-partial contact, which ensures short-term sintering of powder mixtures yielding the high-strength products [7]. However, electric sintering, as a kind of hot pressing, is characterized not only by the intensive mass transfer between the mixtures’ components but also between the powder particles and the molds’ components. The result of the mass transfer is the processes of baking the powder (adhesion) to the electrode-punches. In this connection, the task of the choice and development of materials for the press-tool is fundamental for the industrial implementation of this technique [8]. The main criterion for such materials is their resistance to sudden increases in temperature because, under the influence of electric current, their rapid heating occurs [9].

Paper [10] reports the results of studying the heating of porous materials with electric current; however, the heat and electrophysical processes in the electrode-punches are disregarded. In work [11], an equation for the temperature in metal between the electrodes was derived taking into consideration the heat transfer in the electrodes; however, no expression for the temperature field in electrodes is provided. When using a finite element method for the calculation of the temperature of the powder through which the electric current is passed [12], the electrodes-punches are accepted to be homogeneous in space but do not coincide with each other. The above papers do not take into consideration the porosity of a treated sample, as well as the thermal- and electrophysical parameters and densities with the temperature.

The reason for this may be the objective difficulties, which are associated with the high cost of conducting experimental research: this is especially true of the hardware that registers many parameters in the activated processes. Such factors make it impractical to conduct the above studies.

A variant for overcoming such difficulties can be those works that address the mathematical modeling of thermal processes in the process of passing an electric current through the system electrode-punch-sample-electrode-punch [13]. This paper formulates an assumption about the absence of real conditions to divert the heat from the areas of the electrode-punch in contact with a sample.

In the theory of heating complex electrical conductors [14], the temperature fields, which would make it possible to take into consideration all thermophysical processes in a sample and the electrode-punches in contact with it, were not calculated. Consequently, it is difficult to experimentally establish an accurate distribution of temperature in the press-tool elements, taking into consideration a different combination of their materials, which possess a wide enough range of thermophysical properties [15].

Therefore, there are reasons to believe that the lack of certainty in the influence of additional parameters, namely, technological at electric sintering, and thermophysical, related to the materials, necessitates our research in this area.

3. The aim and objectives of the study

The aim of this study is to mathematically describe the heat transfer in the model holder-matrix-upper electrode-punch-sintered sample-bottom electrode-punch-stand.

To accomplish the aim, the following tasks have been set:
- to solve the problem of heating the tooling elements by a control volume method;
- to analyze the calculation results represented by graphic curves.

4. Materials and methods to study thermal effects arising in the tooling elements activated with electric current

4.1. The studied materials and the equipment used in the experiment

The estimation study in the model holder-dielectric matrix-electrode-punch-sintered ring-shaped product-electrode-punch-stand involved the application of a control volume method. It is one of the most effective among the difference methods to solve the problems of non-stationary thermal conductivity. The problem was solved in the cylindrical coordinate system.

The materials of the mold were made from:
- holder – steel 45;
- dielectric insert – asbestos-cement pipe VT-9;
- needle (hollow inside) – steel KhVG;
- top and bottom electrodes-punches – steel KhVG;
- stand – steel 3.

For experimental measurements:
- temperature – we used contact thermocouples TKhA (chromel-alumel), as well as the loop oscilloscope H 117;
- the pressure of additional pressing and final pressing the strain amplifier Topaz-3-01 and strain gauges;
- the raw material for the product – chopped BrAZh-9-4 alloy shavings.

5. Results of examining the proposed mathematical model

5.1. Analysis of thermal flux passage through a control volume

The problem of heat transfer in the model holder-dielectric matrix-electrode-punch-stand was solved by a control volume method. The problem of heating the tooling elements...
is solved by a control volume method [16]. A form whose sides are arranged such that the nodal points are in the middle of a square or rectangle is termed the control volume. When splitting an estimated region into a grid, three options for the location of the control volumes are possible [17]: control volume with a reference point is located in the middle, at the border, and in the corner of the estimated zone.

In the calculations, we accept that the thermophysical characteristics, body λ (coefficient of thermal conductivity), γ (density), and C (heat capacity) are constant.

The body temperature at the initial time (τ=0, s) is evenly distributed:

\[ t(r, \phi, z) = 20 \, ^\circ\text{C}. \]

We consider the axisymmetric problem; the coordinate origin is at the point of intersection of the axis and the plane of contact between a water-cooled plate and the upper electrode-punch. The dependence on the temperature in the contact area between the edge of the upper electrode-punch and a stand with water-cooled plates is represented analytically in the following form:

\[ t(r, \tau) = t_c = (1 - e^{-\alpha \tau}), \quad (1) \]

where \( t_c \) and \( \alpha \) are the constants (\( t_c = 200 \, ^\circ\text{C}, \alpha = 0.055 \, \text{s} \)).

The problem is solved in the cylindrical coordinate system; for the three-dimensional nonstationary thermal conductivity of solids, a general differential equation takes the following form:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial (r \phi, z)}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 (r \phi, z)}{\partial \phi^2} + \frac{1}{\partial z} \frac{\partial (r \phi, z)}{\partial z} \right] = \lambda + \alpha \frac{\partial \phi}{\partial \tau} + Q_v, \quad (2)
\]

where \( r \) is the radial coordinate, \( \phi \) is the angular coordinate, \( z \) is the axial coordinate, \( Q_v \) is the specific heat output of the internal sources of heat at the expense of joule heating.

The distribution of the heat flow has an axial symmetry, so equation (2) will take the following form:

\[
\gamma_c f_{i,j} \left( N - \frac{1}{2} \Delta R^2 \Delta z \Delta \rho \frac{t^+_{i,j} - t^-_{i,j}}{\Delta \tau} \right). \quad (3)
\]

In this case, the process of thermal conductivity can be considered two-dimensional, that is, \( t = t(r, z, \tau) \). Select a part of the hollow cylinder ABCDEFK (Fig. 1) with a small enough angle \( \Delta \phi \) in the plane of the sector OCD of height \( \Delta z \).

The speed of changing the heat capacity of the control volume ABCDEFK (in Fig. 2: numbers \( i-1, j=3 \)) over time \( \Delta \tau \) is determined from the ratio

\[
\gamma_c f_{i,j} \left( N - \frac{1}{2} \Delta R^2 \Delta z \Delta \rho \frac{t^+_{i,j} - t^-_{i,j}}{\Delta \tau} \right). \quad (4)
\]

where \( \gamma_c \) is the heat capacity of the material of control volume; \( f_{i,j} \) is the density of the control volume’s material; \( \Delta R \) is the step along the radial coordinate; \( \Delta z \) is the step along the axial coordinate; \( \Delta \tau \) is the step in time; \( n \) is the sequential number of a time step; \( t^\pm_{i,j} \) is the unknown control volume’s temperature over time \( \tau^\pm(n+1) \Delta \tau \); \( t^\pm_{i,j} \) is the known control volume’s temperature over the preceding period (Fig. 4).

The heat balance in closed spaces in the tooling’s elements is described by the following equation:

\[
c_v \gamma_c V_{ai} \frac{\partial t}{\partial \tau} = \alpha \left[ F_1 (t_1 - t_{\phi}) + F_2 (t_1 - t_{\phi}) \right] + \frac{F_3 (t_1 - t_{\phi})}{+ F_4 (t_1 - t_{\phi})}, \quad (5)
\]

where \( c_v \gamma_c V_{ai} \) is the heat capacity, density, volume of air; \( F_1 - F_4 \) is the area of contact of the tangent layers of air with the inter-
nal walls of the tooling elements, forming the enclosed spaces 1, 2, and 3, respectively; \( \alpha \) is the heat transfer coefficient; \( t_1 - t_3 \) is the temperature of the internal walls of closed volumes.

\[
Q_1 = N \Delta R \Delta z \Delta \varphi \left( t_1 - t_3 \right),
\]

where

\[
t_3 = t_A + \frac{\Delta \tau F}{V} \left( t_{in} - t_{tr} \right)
\]

– the difference expression, where \( t_A \) is the air temperature during the sintering process. The amount of heat \( Q_2 \), released from a given volume through the right edge LKCД (Fig. 2) of area \( S_2 = \left( N + 1 \right) \Delta R \Delta z \Delta \varphi \) due to thermal conductivity, equals

\[
Q_2 = \left( N + 1 \right) \Delta R \Delta z \Delta \varphi \frac{\left( t_1^* - t_3^* \right)}{\Delta R + 2 \lambda_{ij}},
\]

where the following expression

\[
\left( \frac{\Delta R}{2 \lambda_{ij}} + \frac{\Delta R}{2 \lambda_{ij+1}} \right)
\]

is derived based on the following considerations (Fig. 3).

The heat flows per unit area of two control volumes (1 and 2) will take the form of the following equation:

\[
Q_{un} = \lambda_{ij} + \frac{\Delta R}{2}, \quad \lambda_{ij}, \quad \frac{\Delta R}{2}
\]

subject to the condition of the heat flow discontinuity at the interface of the distribution of the heated (1) and unheated (2) zones of the body intersection.

Transform equation (10)

\[
\lambda_{ij} \frac{t_1^* - t_3^*}{\Delta R} = \lambda_{ij+1} \frac{t_1^* - t_3^*}{\Delta R}
\]

or

\[
\frac{\left( \lambda_{ij} + \lambda_{ij+1} \right) t_1^*}{\Delta R} = \lambda_{ij} t_1^* + \lambda_{ij+1} t_3^*.
\]

From (12), we find the desired value

\[
t_1^* = \frac{\lambda_{ij} t_1^*}{\lambda_{ij} + \lambda_{ij+1}}.
\]

Substitute the value

\[
t_1^* = \frac{1}{\lambda_{ij} + \lambda_{ij+1}}
\]

using (6), into the expression for the summary flow \( Q_{un} \) of two control volumes:

\[
Q_{un} = 2 \lambda_{ij} \left( \frac{1}{\Delta R} \left( \lambda_{ij} t_1^* + \lambda_{ij+1} t_3^* \right) \right) =
\]

\[
= 2 \lambda_{ij} \left( \frac{\lambda_{ij} t_1^* + \lambda_{ij+1} t_3^*}{\lambda_{ij} + \lambda_{ij+1}} \right)
\]

\[
= 2 \lambda_{ij} \frac{t_1^* - t_3^*}{\lambda_{ij} + \lambda_{ij+1}}
\]

\[
= \frac{\Delta R}{2 \lambda_{ij}} \frac{t_1^* - t_3^*}{\lambda_{ij} \lambda_{ij+1}}
\]

\[
= \frac{\Delta R}{2 \lambda_{ij}} \frac{t_1^* - t_3^*}{\lambda_{ij} \lambda_{ij+1}}
\]

\[
= \frac{\Delta R}{2 \lambda_{ij}} \frac{t_1^* - t_3^*}{\lambda_{ij} \lambda_{ij+1}}
\]

\[
= \frac{\Delta R}{2 \lambda_{ij}} \frac{t_1^* - t_3^*}{\lambda_{ij} \lambda_{ij+1}}
\]
where $\lambda_{i,j}$ and $\lambda_{i,j+1}$ are the thermal conductivity of two control volumes (Fig. 6).

The amount of heat $Q_3$, which arrives due to the thermal conductivity in a vertical direction through the upper edge ABCD (Fig. 2, 3) of area

$$S_j = \left(N + \frac{1}{2}\right) (\Delta R)^2 \Delta \phi$$

equals

$$Q_j = \left(N + \frac{1}{2}\right) (\Delta R)^2 \Delta \phi \frac{\Delta x_j - \Delta x_{i+1}}{2 \Delta x_j + 2 \Delta x_{i+1}}$$

5.2. Analysis of the internal sources of heat by joule heating

The amount of heat that is released inside the control volumes by Joule heating $Q$ can be represented as follows:

$$Q = k' UI \tau,$$

where $U$ is the voltage applied to other elements of the tooling (the upper and bottom electrode-punch, needle, and stand), $I$ is the amperage, $\tau$ is the time of the progress of electric current, $k'$ is the parameter that takes into consideration the level of usable heating (we accept it equal to 0.6).

On the other side

$$Q = Q_1 + Q_2,$$

where $Q_1$ is the amount of heat released in the elements of the metal tooling, $Q_2$ is the amount of heat released in the sintered products.

Proceeding from the equivalent replacement scheme of the metal tooling unit (electrodes-punches and needle) and the sintered product shown in Fig. 7, we derive the following formula:

$$Q_1 + Q_2 = q_1 + q_2 + q_3 + q_4,$$

where $q_1 - q_4$ is the amount of heat that is released on each electrical resistance $R_1 - R_4$ by joule heating (here, $R_1$ is the resistance of the upper electrode-punch, $R_2$ is the electrical resistance of the sintered product, $R_3$ is the electrical resistance of the needle's area, tangent to the sintered product, $R_4$ is the electrical resistance of the bottom electrode-punch and the needle's area in contact with it).

Find $q_1 - q_4$:

$$q_1 = I_1^2 R_1 \tau,$$

$$q_2 = I_2^2 R_2 \tau,$$

$$q_3 = I_3^2 R_3 \tau,$$

$$q_4 = I_4^2 R_4 \tau,$$

where, according to the Kirchhoff law

$$I_2 = \frac{IR_j}{R_j + R_s}$$

$$I_3 = \frac{IR_j}{R_s + R_j}$$

Define $Q_1$ and $Q_2$ from the values of $q_1 - q_4$:

$$Q_1 = q_1 + q_3 + q_4,$$

$$Q_2 = q_2.$$

The specific heat output of internal heat sources in the elements of metal tooling $Q_{V1}$ and the sintered product $Q_{V2}$ is equal to:

$$Q_{V1} = \frac{Q_1}{V_s},$$

where $V_s$ is the total volume of the electrodes-punches and needle;

$$Q_{V2} = \frac{Q_2}{V_s},$$

where $V_s$ is the volume of the sintered product.

5.3. Deriving a general heat balance equation

Thus, we obtain the equation of heat balance of the control volumes in a general form:
The thermophysical characteristics of the tooling elements and a sintered product

| Tooling element          | Material | Density, kg/m³ | Heat capacity, J/kg, °C | Heat conductivity, J/m·s·°C | Specific electrical resistance, Ohm·m²/m |
|--------------------------|----------|----------------|--------------------------|------------------------------|-----------------------------------------|
| Upper electrode-punch    | Steel KhVG | 7,800         | 571.2                    | 29.4                         | 0.271                                   |
| Needle                   | Steel KhVG | 7,800         | 571.2                    | 29.4                         | 0.271                                   |
| Bottom electrode-punch   | Steel KhVG | 7,800         | 571.2                    | 29.4                         | 0.271                                   |
| Matrix-insert            | Asbestos-cement | 2,500       | 815                      | 0.37                         | −                                        |
| Holder                   | Duralumin | 2,700         | 940                      | 155                          | −                                        |
| Stand                    | Steel 45  | 7,800         | 470                      | 48                           | −                                        |
| Sintered product         | BrAZh-9-4 | 7,500         | 400                      | 88                           | 0.125                                   |
| (shavings from a cast    | copper    | 8,900         | 380                      | 410                          | 0.169                                   |
| rod) with alloying powder | graphite | 2,300         | 836                      | 0.4                          | 10                                       |
| additives                |           |               |                          |                              |                                         |
| Sintered product         | −ε−       | 6,433         | 370                      | 68                           | 0.171                                   |
| considering porosity     |           |               |                          |                              |                                         |

Table 1

We show the numerical calculation for a regime with the sintering time of 90 s, with the amount of heat released due to joule heating per unit volume of the elements of metal tooling $Q_{	ext{v1}}=3,250$ J/cm, per unit of product volume $Q_{	ext{v2}}=3,080$ J/cm.

Fig. 8. Time dependence of the temperature of the upper electrode-punch at heating with electric current
Fig. 9. Spatial dependence of the upper electrode-punch temperature at heating with electric current

Fig. 10. Time dependence of the needle temperature at heating with electric current

Fig. 11. Spatial dependence of the needle temperature at heating with electric current

Fig. 12. Time dependence of the temperature of an asbestos-cement matrix-insert when heating with electric current the sintered part and metallic components of the press tool
Fig. 13. Spatial dependence of the temperature of an asbestos-cement matrix-insert at heating with electric current

Fig. 14. The radial spatial dependence of the temperature of an asbestos-cement matrix-insert at heating with electric current

Fig. 15. Time dependence of the steel stand temperature at heating with electric current

Fig. 16. Spatial dependence of the steel stand temperature at heating with electric current
Fig. 17. The axial spatial dependence of the steel stand temperature for the region with coordinates $j=17; i=23$.

Fig. 18. The radial spatial dependence of the steel stand temperature.
Fig. 19. The spatial dependence of temperature at a fixed time value (t=90 °C) for region 14≡23

Fig. 20. The time dependence of the sintered product temperature at heating with electric current
6. Discussion of results of studying the modeling of the process of heating the tooling elements

The calculation results are represented in Fig. 8–24. As the heat is spread to the sintered object relative to the height of the upper electrode-punch (Fig. 8) (coordinates $j=3$, $i=15$),
1=9), the temperature gradually increases in sections 1–7 and reaches its maximum, which is 845 °C. There is a further noticeable tendency towards decreasing in the areas close to the product (curves 8,9), to temperature 823 °C. This might be due to the complex influence between the electric- and thermophysical properties of the electrode-punch material and the sintered powder and the balance of heat-generating processes, its inflow and outflow [20]. Fig. 8 shows the time-based and, in Fig. 6, space-based dependences of the upper electrode-punch temperature.

To reduce the weight of the tooling and to warm faster its components (the upper electrode-punch and needle), the latter are executed hollow. A movable needle forms the inner wall of the sintered bushing and warms up at the end of the process in this area to a mean temperature of 73 °C. Fig. 10 shows the monotonous decrease in temperature along the needle height (j=4; 10=12) over time. The temperature of the needle in the area surrounded by air decreases less intensively due to the slight convective heat exchange caused by the hot air within a closed volume (Fig. 11).

In the contact area of the internal walls of an asbestos-cement matrix with the upper electrode-punch (j=7; 1=9) for time dependences (Fig. 12) including the control volume with the coordinate i=6, the temperature rises; its maximum value reaches 248 °C. When approaching the sintered product, it begins to fall (curves 7–9) and, in the area of the contact between the wall and the bottom electrode-punch, the temperature reaches 166 °C (curve 13).

A high-quality pattern is demonstrated by the axial and radial spatial dependences of the asbestos-cement matrix-insert when heating with electric current (Fig. 13, 14).

It is known that asbestos fibers undergo a series of changes during thermal treatment that affect their physical properties [21]. In the case of prolonged aging at a temperature of 110 °C, a significant part of the adsorptive water is released, whereby decreasing the mechanical strength of asbestos fibers, thus predetermining the wear of the matrix. When moving in the radial direction from the object of sintering, the heating of an asbestos-cement insert becomes less intense; the temperature of its internal layers reaches 20–35 °C (Fig. 14).

The temperature of the steel stand (j=6;14=i=23) at the end of the process, when moving away from the lower electrode-punch (Fig. 15), varies in the range of 279 °C to 147 °C (curves 1–6). Then there is a gradual increase in it when approaching the lower water-cooling plate (curves 7–10). A very pronounced indication of the change in the temperature of the stand is provided by its spatial dependence (Fig. 16) for each time interval. Fig. 17 shows a temperature change for a series of control volumes (j=17; 14=i=23) of the stand. In this case, the temperature of the control volume (j=17; i=14) in the area of contact with a duralumin holder (between them is an air gap of thickness 2...3 mm), due to the lack of joule heating, is slightly less and, over time, changes from 150 to 35 °C. Th stand contacts the bottom electrode-punch, asbestos-cement matrix-insert, and holder; the distribution of temperature in the radial direction in these areas is characterized by the curves that monotonously descend (Fig. 18).

The dependences of temperature on the axial coordinate in a steel stand near the inner air cavity demonstrate maxima; as the distance grows, towards the periphery, the curves acquire a monotonous ascending character (Fig. 19).

For the vertical zone j=6, in the contact area with the lower electrode-punch, the maximum temperature is observed, 278 °C. As the distance from the source of joule heating grows, the temperature monotonously decreases in the area 14=i=21 to 146 °C, and, in the zone in contact with the bottom water-cooled plate (21=i=23), there is a tendency to increase to 158 °C. It seems this is due to the mass of the stand and scattering of the heat flow [22, 23].

The estimated value of temperature in the upper and lower layers of the sintered product (chip powder BrAZh-9-4) (Fig. 20, curves 1.2) with coordinates j=5; 10=i=11 changes at the end of the process from 747 °C to 714 °C [24]. Curve 3 illustrates the experimental dependence of temperature on time, the value of which reaches 750 °C. The character of the curve is the same as that in the estimated dependences. After 90 s, the final pressure was applied over 20 s and the temperature fell to 635 °C [25].

The time dependence of the lower electrode temperature is similar to the above dependence (Fig. 21; j=5; 12=i=13), however, at the end of the process, it is heated to a slightly lower temperature: for i=12, to 650 °C; for i=13, to 575 °C. The mold has a closed inner space, inside which there is a certain amount of air. The exchange of air with the environment is almost absent. Because of the very weak convective heat exchange, the mass of air heats up quickly (Fig. 22), which plays its role in the heating of the tangent parts of the metal tooling. Thus, at the end of the process, the air is heated to a temperature of 378 °C.

A change in the temperature of the holder is insignificant and the estimated value reaches 22–23 °C in the zone in contact with a steel stand, 32 °C. Experimental measurements showed that in the upper half of the holder the temperature increases from 25 to 26 °C (Fig. 23, curve 1); at the bottom – from 27 to 29 °C (curve 2).

The thermocouples helped register the temperature of the asbestos-cement matrix at points with coordinates j=8; i=2 and j=9; i=2 240 and 60 °C (Fig. 23, curves 3 and 5). For example, the estimated value of the temperature at point (j=8; i=2) is 240 °C; at the same time, experimental – 223 °C.

The steel stand at a point with coordinates j=14; i=18, the estimated temperature was 123 °C, experimental – 120 °C (Fig. 23, curve 4).

Based on the derived heat balance for the control volumes in a general form, we have the distribution of the latter in the tooling elements (Fig. 24).

The advantage of a control volume method (CVM) is that it is based on the macroscopic physical laws, it includes the exactly integrated preservation of values such as mass, pulse, and energy, in any group of control volumes. A solution that is obtained using a CVM will always keep the energy balance over the entire estimated area, which cannot be said about the solutions derived by using other methods. The absolute advantages of a given method are the high efficiency and simplicity of implementation, as well as the visibility of the sampling rate procedure, which makes it possible to construct the high-order precision schemes. However, these benefits are realized only when applying a regular enough (structured) grid – almost orthogonal and with smoothly changing cell sizes. Consequently, most CVM applications are limited to the cases of estimated areas that are quite simple in terms of geometry.

The current study is to be advanced by using more wear-resistant materials, specifically the replacement, in
the future, of an asbestos-cement insert with materials with dielectric coatings. Constraints in obtaining future experimental results may await researchers at the stage of registering control parameters at electric sintering because of the possibility of the occurrence of undesirable electro-physical effects.

Preliminary modeling of the process of the activated treatment with an electric current of powder products would allow a more expedient choice of tooling materials and the optimization of a future technological cycle.

This research is not a continuation of an earlier one; however, we are going to improve it in the future.

7. Conclusions

1. Our analytical research has solved the problem of heating in the elements of the mold: holder-asbestos-cement insert-upper electrode-punch-sintered sample-lower electrode-punch-stand, by deriving a heat balance equation for the latter in a general form. The resulting expression for the tooling control volumes makes it possible to describe the heat distribution in all elements of the tooling, as well as to optimize the choice of materials that could promote the concentration of usable heating in the zone of a sintered product.

2. Our mathematical description of heat distribution in the considered model has made it possible to establish the overall pattern of changes in temperature fields according to the graphic curves shown in Fig. 8–24. Special features of their formation are as follows:
   - the spatial and time dependences of the upper electrode-punch temperature are nonlinear in character, it mostly increases; there is probably an intensive heat outflow in areas close to the product;
   - a decrease in the temperature of the movable needle occurs throughout the entire process of sintering; in the part surrounded by air, it is less intense;
   - for the case of prolonged aging in the matrix at a temperature of 110 °C, a significant portion of the adsorptive water is released, the mechanical strength of asbestos fibers decreases, thus causing the wear of the matrix;
   - the estimated values of temperature in the upper and lower layers of the sintered product are quite close and differ little from experimental; they change at the end of the process from 747 °C to 714 °C;
   - the sintered product concentrates 24% of the thermal energy released from the entire “node” (press-tool-product).

The considered mathematical model enables the targeted adjustment of temperature fields by preliminary calculation and choosing the tooling materials based on the thermal-physical characteristics.

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