Simulation of the temperature distribution in semi-finished products of combined abrasive tools during their microwave heating

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Abstract. When producing of the abrasive tool using one of the most reliable operations is the thermal processing operation. Heating nonuniformity during the thermal processing adversely affects the quality of the abrasive tool and can lead to it being rejected. In this paper there are computational simulation results of the heating process of semi-finished products of combined abrasive tools in the microwave field presented and recommendations on the uniformity improvement of the temperature distribution along the whole volume of the heating object are provided.

1. Introduction

At the present time there is a substantial severization of requirements imposed on performance characteristics of abrasive tools based on organic thermoreactive bonds, particularly, on their strength, residual stresses, g-ratio and the existence of microcracks. Properties mentioned above are primarily formed during the most time-consuming operation of thermal processing of semi-finished products carried out to polymerize the bond. At factories producing abrasive tools based on the bakelite bond a classic thermal processing technology of their semi-finished products based on the convective heat transfer in ovens-bakelizators is applied. Production cycles of thermal processing of tools using these technologies are extremely longstanding and last in average for 13 - 40 hours (depending on the typical size and the characteristic of the tool). Specific energy consumption reaches 2.5 ... 3 kW*h/kg of the abrasive tool mass [1 - 3]. Furthermore these technologies are not up-to-date taking into consideration the ecological cleanness.

Thermal processing cycle time reduction of abrasive tool semi-finished products and intensification of their performance characteristics due to the microwave heating suggest themselves. Time of heating and the whole thermal processing operation of abrasive tool semi-finished products and other products based on organic thermoreactive bonds can be reduced by 8 times due to microwave technologies exhibiting the series of unique properties: 1) the heating selectivity when components with the greatest loss-angle tangent are heated intensively in the multicomponent mixture of dielectrics; 2) heating uniformity because of the fact the the electric field immediately and deeply penetrates dielectric materials directly associated with the radiating wave length providing the uniform distribution of the generated heat along the whole volume of the object being heated notwithstanding its thermal conductivity; 3) high conversion ratio of the radiated energy into the heating energy: bakelization
energy density using the microwave energetics – up to 0.3 kW-h per one kg of the sime-finished product mass against 2.5...3 kW-h/kg when bakelizing using the convective approach. An additional point is that under the influence of the electromagnetic radiation the series of chemical transformations course differently than in normal conditions which opens wide perspectives of using concentrated energy flows of variable electric and magnetic fields to control and to stimulate chemical reactions and to bake when producing abrasive tools based on the bakelite bond [4 - 6]. However, it should be noted that the microwave heating often does not provide the necessary uniformity of the temperature distribution because of the heat exchange by outer surfaces of heat-treated semi-finished products with relatively cold environment [7]. One more issue is the absence of the special industrial equipment for the microwave bakelization of abrasive tools in the market. Moreover, at the present time there is no opportunity to heat-treat combined abrasive tool semi-finished products consisting of parts with different composition and properties in the microwave field because the part of the semi-finished product with greater radiation-absorbent properties will be heated faster than other parts which will lead to the nonuniform polymerization of the bond (overbakelization of one parts and unfinished bakelization of others). For example, power snagging wheels produced at the Kosulinsky abrasive factory consist of two parts – operating and nonoperating. Molding compound of the operating part consists of the almost radiotransparent mixture of zirconium oxide and aluminium oxide. As far as the nonoperating part is concerned, it consists of silicone carbide with strong radiation-absorbent properties. These wheels are produced of the great typical size (600 mm). Their structure is almost pore-free which substantively raises up the risk of rejection during the convective thermal processing. Along with that, domestically made wheels of this category are worse in comparison with foreign made ones taking into consideration the g-ratio. Findings of the study will give occasion to resolve the issue related to the production technology improvement of abrasive tool semi-finished products based on organic thermoreactive bonds: firstly, to prevent the negative influence of volatile substances on geometrical parameters of semi-finished products; secondly, to provide the uniform microwave heating of semi-finished products by their thermal regulation; thirdly, provide the opportunity for the thermal processing of combined abrasive tool semi-finished products using radiation-absorbent fillers and "level" radiation-absorbent properties of abrasive tool components. These solutions open doors to the substantial speed increase of the microwave heating and the further performance improvement of the thermal processing operation and the quality improvement of abrasive tools.

2. Materials and methods
We simulated the heating of combined abrasive tool semi-finished products based on the bakelite bond in the microwave field (frequency 2450 MHz). Semi-finished product consisted of two coaxial cylinders with holes. These cylinders had different composition of the molding compound. Molding compound of the internal cylinder included abrasive powders of silicone carbide (black) and electrolytically produced corundum (white). Molding compound of the external cylinder included only electrolytically produced corundum (white).

Power-weight ratio of the thermal energy qmw released in the material of the semi-finished product after the impact of the microwave field (W/m²) was calculated using the following dependence [3]:

\[ q_{mw} = 0.5\varepsilon_0\varepsilon''_0\omega E^2 = \pi\varepsilon_0\varepsilon''_m/\varepsilon E^2 \]  

(1)

where \( E \) is the amplitude of the electric field intensity; V/m, \( \varepsilon'' \) is the imaginary component of the relative dielectric permittivity, \( \varepsilon_0 \) is the dialectic vacuum permittivity, F/m; \( f \) is the frequency of the applied field, Hz, \( \omega \) is the circular frequency, rad/s.

To calculate the complex dielectric permittivity of separate parts of abrasive tool semi-finished products we used the Nielsen formula [4]:

\[ \varepsilon_{comp} = \varepsilon_m \frac{1 + AB\gamma}{1 - B\Psi \gamma} \]  

(2)
where

\[
B = \frac{\varepsilon_n \varepsilon_m^{-1} - 1}{\varepsilon_n \varepsilon_m^{-1} + A};
\]

\[
\Psi = 1 + \frac{1 - \nu}{\nu^2};
\]

(v) is the maximum possible volume ratio of the dispersed component of the solid phase characterizing laying and the form of particles; \(\nu\) is the volume ratio of the dispersed component; \(\varepsilon_n\) is the complex dielectric permittivity of the dispersed component; \(\varepsilon_m\) is the complex dielectric permittivity of the continuous component, \(A\) is the coefficient of influence of the dispersed component particles form changing its value from 1.5 (for spherical particles) to 4 (particles in the form of shells).

Basic data for the calculation of the complex dielectric permittivity please ref. Table 1.

**Table 1.** Electric and physical characteristics of some substances under normal conditions on the frequency of 2 – 3 GHz.

| Substance                          | Real part of the relative dielectric permittivity | Imaginary part of the relative dielectric permittivity | Loss-angle tangent |
|-----------------------------------|--------------------------------------------------|------------------------------------------------------|-------------------|
| Electrolytically produced corundum (white) | 10                                               | 0.005                                                | 5·10^{-4}         |
| Silicone carbide (black)         | 7.5 – 12                                          | 3.75 – 13.2                                          | 0.5 – 1.1         |
| Bakelite                          | 4.5                                               | 0.17                                                 | 0.038             |
| Finely-divided graphite           | 34.3                                              | 13.4                                                 | 0.391             |
| Carbon nanotubes                  | 62.2                                              | 12.4                                                 | 0.2               |

To estimate the temperature distribution in the cross-section of the abrasive tool semi-finished products pile we carried out the mathematical simulation of the heating process in the microwave field. Temperature filed in various cross-sections going through the axis of the abrasive tool semi-finished products pile at any time of the microwave heating does not change. That is why it will be enough to plot the 2D mathematical model. 2D nonstationary mathematical model was based on the Fourier differential equation of the thermal conductivity for the isotropic solid in the Cartesian coordinates which appears as follows [1]:

\[
\frac{\partial T}{\partial \tau} = \chi \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{q_v}{c \rho},
\]

where \(\chi\) is the temperature conductivity coefficient, m^2/s; \(\tau\) is the time, s; \(T\) is the temperature, °C; \(c\) is the specific thermal capacity, J/(kg·°C); \(q_v\) is the specific internal heat release in the volume \(dV = dx dy dz\), W/m^3; \(x, y, z\) are the Cartesian coordinates, m; \(\rho\) is the density, kg/m^3.

As an initial condition we took the uniform temperature distribution in all bodies at the reference time:

\[
T(r, z, 0) = T_0.
\]

Convective and radiative heat exchange between open surfaces of the body and the environment were taken into consideration using boundary conditions of third kind which appear as follows:

\[
-(\lambda_r(T) \frac{\partial T}{\partial r}) = \alpha_f \left( T_{w_1} - T_f \right) + \varepsilon_{r_f} \sigma_0 \left( T_{w_1}^4 - T_f^4 \right); \quad r = R_1; \quad z \in [0; l];
\]

\[
\lambda_r(T) \frac{\partial T}{\partial r} = \alpha_f \left( T_{w_2} - T_f \right) + \varepsilon_{r_f} \sigma_0 \left( T_{w_2}^4 - T_f^4 \right); \quad r = R_2; \quad z \in [0; l];
\]
\[
\lambda_r(T) \frac{\partial T}{\partial r} = \alpha_f \left( T_{w1} - T_f \right) + e_{pl} \sigma_0 \left( r_{w1}^4 - T_f^4 \right); \quad r = -R_1; \quad z \in [0; l]; \quad (9)
\]

\[
-\lambda_r(T) \frac{\partial T}{\partial r} = \alpha_f \left( T_{w2} - T_f \right) + e_{pl} \sigma_0 \left( r_{w2}^4 - T_f^4 \right); \quad r = -R_2; \quad z \in [0; l]; \quad (10)
\]

\[
\lambda_z(T) \frac{\partial T}{\partial z} = \alpha_f \left( T_{h2} - T_f \right) + e_{pl} \sigma_0 \left( r_{h2}^4 - T_f^4 \right); \quad z = l; \quad r \in [-R_2; -R_1]; \quad r \in [R_1; R_2]; \quad (11)
\]

\[
-\lambda_z(T) \frac{\partial T}{\partial z} = \alpha_f \left( T_{h1} - T_f \right) + e_{pl} \sigma_0 \left( r_{h1}^4 - T_f^4 \right); \quad z = 0; \quad r \in [-R_2; -R_1]; \quad r \in [R_1; R_2]; \quad (12)
\]

where \( T \) is the temperature inside the body, °C; \( \lambda_r \) is the thermal conductivity of the body in the direction of the axis \( 0r \), W/(m·°C); \( \lambda_z \) is the thermal conductivity of the body in the direction of the axis \( 0z \), W/(m·°C); \( T_{wk} \) is the temperature of the body surface perpendicular to the direction of the axis \( 0r \), °C; \( T_{bk} \) is the temperature of the body surface perpendicular to the direction of the axis \( 0z \), °C; \( \varepsilon \) is the emissivity factor if the body surface; \( k \) is the sequence number of the body surface in the direction of coordinates; \( R_1 \) is the radius of the fitment hole of the semi-finished product, m; \( R_2 \) is the outer radius of the semi-finished product, m; \( l \) is the height of the semi-finished product, m.

3. Results
Simulation of the temperature distribution in combined abrasive tool semi-finished products during their microwave heating was carried out using the numerical method (ECM). At the first stage we plotted the 3D geometrical model of the abrasive tool semi-finished product with the outer diameter of 600 mm, the height of 75 mm, the fitment hole diameter of 305 mm. The interface region of the operating and nonoperating parts of the semi-finished product with different molding compound was in the diameter of 410 mm. Then we scheduled thermal and physical characteristics for every part of the semi-finished product calculated using analytical dependences as for composite materials. Thermal conductivity and thermal capacity of materials were set as dependence functions on the temperature. At the next simulation stage, we set initial and boundary conditions. Further we applied thermal loads to the semi-finished product. Power-weight ratio of the heat radiation from the influence of the electromagnetic radiation was calculated using the dependence (1). To that effect we preliminarily calculated the complex dielectric permittivity of the material from every part of the semi-finished product using dependences (2) – (4). Duration of the microwave heating was 4 hours. Simulation results please ref. Figure 1.

As can be seen from Figure 1 the greatest heat radiation was in the nonoperating part of the semi-finished product because of the presence of silicone carbide (black) with great radiation-absorbent properties. Consequently, the temperature gradient in the combined abrasive tool semi-finished product after heating in the microwave filed was ± 25 %. To uniform radiation-absorbent properties of parts of the semi-finished product with various recipes of the molding compound it is possible to inject special radiation-absorbent fillers into the molding compound. As such fillers, for example, finely-divided graphite adn carbon nanotubes can be used.

Using dependences (1) – (4) we determined that to uniform radiation-absorbent properties of parts of the abrasive tool semi-finished product it is necessary to modify its operating part using finely-divided graphite in the amount of 2.3 %. Simulation results of heating of the modified semi-finished product please ref. Figure 2.
Figure 1. Temperature distribution in the abrasive tool semi-finished product during the heating process under the influence of the microwave radiation.

Figure 2. Temperature distribution in the abrasive tool semi-finished product modified using the radiation-absorbent filler during the heating under the influence of the microwave radiation.

As can be seen from Figure 2 the temperature gradient in the modified abrasive tool semi-finished product after the heating in the microwave field reduced by ±15%. This value of the temperature gradient is conditional upon thermal losses from outer surfaces of the semi-finished product during the heating process. Further considerable reduction of the temperature gradient when heating in the microwave field of the modified abrasive tool semi-finished product can be reached when using the efficient radiotransparent thermal isolation of the heated object.

4. Conclusions
1. We received numerical models for the temperature distribution in combined abrasive tool semi-finished products based on the bakelite bond when heating in the microwave field.
2. We identified that when heating the combined abrasive tool semi-finished product in the microwave field the nonuniformity of the temperature distribution can reach ±25%. This fact allows to this type of heating for the thermal processing of abrasive tools. It is possible to increase the heating uniformity using special radiation-absorbent fillers providing the decrease of the heating
nonuniformity by ± 15%. In addition to the above, when radiation-absorbent properties of the semi-finished product are levelled, the opportunity to additionally increase the heating uniformity using the efficient radiotransparent thermal isolation will appear.

3. Simulation results can be used to correct recipes of molding compounds when producing combined abrasive tools based on organic thermoreactive bonds to provide the opportunity for the thermal processing in the microwave field.

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