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PRINCIPLES OF DIELECTRIC MATERIAL FAILURE UNDER THE ACTION OF CONCENTRATED ENERGY FLUXES

A. B. Demidovich, G. S. Romanov,
Yu. A. Stankevich, and V. D. Shimanovich

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The process of failure of silicate material under the action of energy fluxes of $2 \cdot 10^6$-$1 \cdot 10^9$ W/m^2 is considered. Results of a numerical solution considering fusion, evaporation, and radiation are presented.

Creation of coatings by using lasers and electric arc generators have recently become a practical application, during which thermal fluxes above $1 \cdot 10^6$ W/m^2 are applied to surfaces of parts for lengthy periods under industrial conditions. Motion of the temperature front within a layer of silicate material during action of a flux $q = (1-2) \cdot 10^6$ W/m^2 was considered in [1]. It was found that the temperature of the part surface T_s could be significantly higher than the material fusion temperature T_l. However the experiments of [2] show that for such fluxes there is little surface fusion for action times of ∿1 sec, and consequently, T_s exceeds T_l only insignificantly. The disagreement between calculated and experimental results is apparently the result of [1]'s neglect of fusion and evaporation on the material surface.

In order to determine the possibilities of electric arc processing the present study will investigate heating of silicate materials under the action of thermal fluxes of $2 \cdot 10^6$-$1 \cdot 10^9$ W/m^2. Calculations will be presented for concrete q values with consideration of the phase transitions referred to above.

The process of coating formation upon a material during thermal processing is characterized by the temperature of the melt surface, the rate of growth of the coating, defined as the difference between the velocities of the fusion and evaporation fronts, and the efficiency, defined by ratio of the energy required for formation of the melt to the amount of energy supplied. Thus, the basic system of equations must describe heat propagation in the solid phase, fusion of the material, evaporation, and cooling of the melt by radiation. In the general case this problem is two-dimensional. However, if the characteristic dimensions of the interaction zone are significantly larger than the region of thermal front propagation in the material, it can be reduced to one-dimensional form. In practice this condition is satisfied both in use of large-size thermal sources and in scanning of limited size sources at a rate higher than the thermal front velocity.

In a coordinate system fixed to the surface separating the condensed and gaseous phases the thermal conductivity equation has the form [3]:

$$\frac{\partial T}{\partial t} - v_{\text{sub}} \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(a \frac{\partial T}{\partial x}\right), \qquad (1)$$

where v_{sub} is the evaporation rate, which depends on the surface temperature T_s and is given by Frenkel's expression [4]:

$$v_{\text{sub}} = v_0 \exp(-T_{\text{sub}}/T_s). \qquad (2)$$

Physics Institute, Academy of Sciences of the Belorussian SSR. A. V. Sevchenko Scientific-Research Institute for Applied Physics Problems. V. I. Lenin State University, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 5, pp. 817-822, May, 1987. Original article submitted February 26, 1986.

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The x-coordinate is measured from the boundary of the gaseous and condensed phases and is related to the coordinate in a fixed coordinate system x' by the expression

$$x = x' - \int_0^t v_{\text{sub}} dt. \tag{3}$$

The initial and boundary conditions for Eq. (1) have the form

$$T(x,\ 0) = T_{00}, \tag{4}$$

$$\lambda_1 \frac{\partial T}{\partial x} = -q_0 + \Delta H v_{\text{sub}} + \varepsilon \sigma T^4, \tag{5}$$

$$T(\infty,\ t) = T_{00}. \tag{6}$$

When the surface reaches the fusion temperature a new phase front appears — the fusion front, whereon the condition

$$\lambda_1 \frac{\partial T}{\partial x}\bigg|_{\text{T.T}} - \lambda_2 \frac{\partial T}{\partial x}\bigg|_{l} = \lambda_l (v_l + v_{\text{sub}}) \rho \tag{7}$$

is satisfied, $T(z) = T_l$, where z is the position of the fusion boundary and $v_l = \frac{\partial z}{\partial t}$ is the velocity of the fusion front in the moving coordinate system. Therefore, the system of equations defining the temperature distribution within the material has the form

$$\frac{\partial T_i}{\partial t} - v_{\text{sub}} \frac{\partial T}{\partial x} = \frac{\partial}{\partial x} \left(a_i \frac{\partial T}{\partial x} \right),$$

where for i = 1 z < x < 0, the solid phase region with boundary condition (7) and $T(\infty,\ t) = T_{00}$ for i = 2; 0 < x < z is the liquid phase region with boundary conditions (5) and (7), where

$$\Delta H = \lambda_{\text{sub}} - \lambda_l + \frac{5}{2} \frac{kT_{00}}{m} - c_1 T_l - c_2 (T_{00} - T_l).$$

To solve (1)-(6) the flowing drive system of [5] with explicit separation of the fusion front was used. The calculation was performed for a silicate material: SiO_2, 92.5%; Al_2O_3, 0.5%; CaO, 2.5%; MgO, 1.5%; K, 1.5% for flux densities of $200\text{-}2 \cdot 10^4$ W/cm^2 and action times $\tau = 10^3\text{-}10$ sec.

Usually the material being processed has a complex chemical composition and structure, with the size of material inhomogeneities being of the same order of magnitude as the thicknesses of the fused layers formed. Consideration of these factors by selecting several temperatures and heats of fusion, introduction of a cellular material structure into the difference system, etc. greatly complicates the basic system of equations. Analysis has shown that creation of more precise solutions by this approach is impossible because of increasing errors, especially as a result of lack of precise values of the thermophysical characteristics and their temperature dependences In the proposed model chemical reactions in the material before its transition to the liquid state will be considered by choosing an elevated value for the heat of fusion, equal to the heat of fusion of the basic material — amorphous quartz, and the specific heat of the chemical reaction of decomposition of the binder — calcium hydrosilicate.

The following thermophysical parameter values were used: $\rho = 1.81 \cdot 10^3$ kg/m^3, $T_l = 1400$°K, m = 59, $T_{00} = 300$°K, $\lambda_l = 4.75 \cdot 10^5$ J/kg, $C_1 = 2.75 \cdot 10^3$ J/(kg•K), $\lambda_1 = 1.1$ W/(m•K), taken from [6] for silicate brick. For the liquid phase the thermophysical parameters of the material being studied are unknown, although since it is more than 90% SiO_2, the values $\lambda_2 = 0.175$ W/(m•K), $C_2 = 3.75 \cdot 10^3$ (J/kg)/K, $\lambda_{\text{sub}} = 4.72 \cdot 10^5$ J/kg, $T_{\text{sub}} = 6.8 \cdot 10^4$ K, $v_0 = 5.7 \cdot 10^3$ m/sec were used, these being values corresponding to quartz [7].

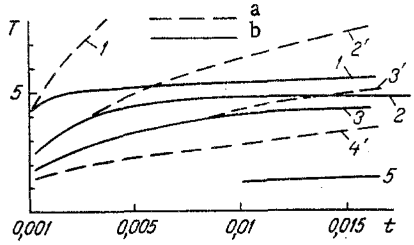

Fig. 1

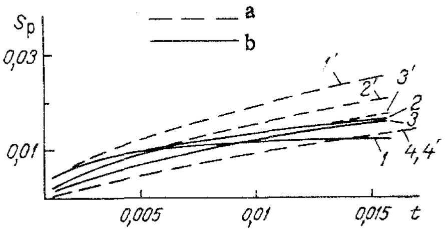

Fig. 2

Fig. 1. Material surface temperature vs time of thermal action q: 1, 1') $2\cdot10^8$; 2, 2') $1\cdot10^8$; 3, 3') $6.3\cdot10^7$; 4') $4\cdot10^7$; 5) $1\cdot10^7$ W/m²; a) without; b) with consideration of radiation. T) 10^3 K; t) sec.

Fig. 2. Thickness of melt layer S_m vs action time of thermal flux q: 1, 1') $2\cdot10^8$; 2, 2') $1\cdot10^8$; 3, 3') $6.3\cdot10^7$; 4, 4') $4\cdot10^7$ W/m²; a) without; b) with consideration of radiation. S_m) cm.

The results obtained from the calculations are shown in Figs. 1-3. The rate of the thermophysical processes occurring during heating of the silicate material depends strongly on the density of the incident flux. The time required for heating the surface to the fusion point T_l = 1400°K for q = $2\cdot10^4$ W/cm², while for q = $1\cdot10^3$ W/cm² is $1.5\cdot10^{-2}$ sec. After this fusion of the material and evaporation occur. The role of evaporation is quite significant: as is evident from Fig. 1, its neglect can lead to severe temperature evaluation.

The dependence of fusion front velocity v_f and evaporation front velocity v_{ev} on the flux q and interaction time τ is quite complex. In the initial stage $v_f = 2\text{-}3\cdot10^{-2}$ m/sec and $v_{ev} = 1.5\cdot10^{-2}$ m/sec, after which the values fall to 0.5 and 0.2-0.4 m/sec respectively. Thereupon v_{ev} changes only slightly: for increase in q by an order of magnitude the velocity only doubles.

Over the entire q range considered after passage of $\tau = 10^{-2}$ sec a quasisteady-state regime sets in, characterized by a practically constant surface temperature T_s. Relative change in surface temperature and flux power q in the quasisteady-state regime decrease with increasing flux, comprising $5\cdot10^3$ and $1\cdot10^3$ (K·m²)/W at $1\cdot10^7$ and $1\cdot10^8$ W/m². Surface temperature stabilizes with passage of time due to cooling of the surface by evaporation and radiation. In the present calculations radiation was considered using an emissivity coefficient $\varepsilon = 0.5$, chosen by analysis of data presented in [8]. The role of radiation reduces to a reduction in the effective flux density and increase in the steady-state value of the fused-layer thickness.

The quasisteady-state regime indicates that the rate of displacement of all isotherms within the body is equal to the linear velocity of disintegration of the exterior surface, while the temperature field shifts in an equidistant manner through the portion of the material being heated, so that at any moment the depth of heating remains constant.

For q = $6\cdot10^7$ W/m² the quasisteady-state condition sets in the melt layer after $3\cdot10^{-1}$ sec (Fig. 2). This value agrees with the characteristic formation time for the fused layer on the surface of the silicate material for the q range considered as obtained in [9] for action of a plasma flux. In all processing regimes involving fusion a quasisteady-state regime is established, which permits evaluation of the depth to which the material is penetrated [10]:

$$\delta_T = \frac{a}{v_\infty} \ln[(T_V - T_{00})/(T_l - T_{00})].$$

The calculations performed permitted estimation of energy losses to heating, fusion, and evaporation for various thermal action times. Figure 3 shows the ratios of thermal energy of the layer E_t, fusion energy E_f, and evaporation energy E_{ev} to the incident energy. The fraction of energy expended in fusion has a maximum in time. Its value is independent of the flux density and comprises 6% of the energy supplied. With increase in interaction time energy losses to evaporation increase. However the thickness of the melted layer S_m also increases, since the time for exit to the steady-state regime (where the value of S_m is maximum, Fig. 2) is much greater than the optimal action time as regards energy losses to fusion (where E_f/E_i is maximal, Fig. 4).

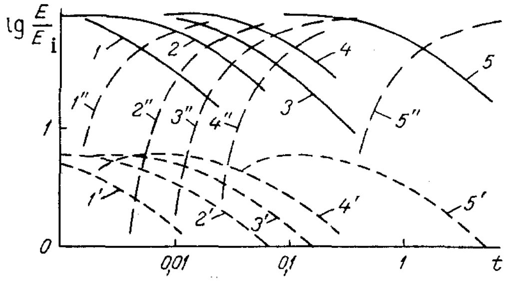

Fig. 3

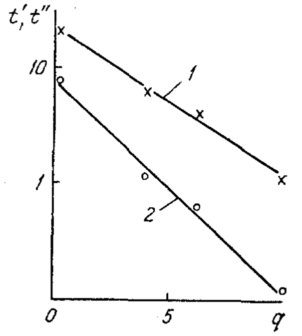

Fig. 4

Fig. 3. Ratios of layer thermal energy E_t, fusion energy E_f, and evaporation energy E_{ev} to incident energy E_i vs time: 1', 1'') $2 \cdot 10^8$; 2, 2', 2'') $1 \cdot 10^8$; 3, 3', 3'') $6.3 \cdot 10^7$; 4, 4', 4'') $4 \cdot 10^8$; 5, 5', 5'') $1 \cdot 10^7$ W/m^2.

Fig. 4. Optimum thermal action time for fusion $t'_{opt}(1)$ and evaporation $t''_{opt}(2)$ of silicate material. t', t'') 10^{-3} sec; q) 10^7 W/m^2.

With decrease in flux density the quasisteady-state value of fused layer thickness S_m increases (Fig. 2), however to attain a given melt thickness for small flux densities requires a long action time. Optimization of the processing regime is then possible by selecting action time and flux density for a specified melt thickness on the basis of Fig. 2 such that energy losses to fusion are maximal (Fig. 3).

The applicability of the proposed calculation model to surface processing of other materials is controlled by the admissability of the assumption of independence of thermophysical characteristics from temperature and choice of a phase transition temperature when several phase transitions are present, as well as the degree of inhomogeneity present in the original material as compared to the thickness of the fused layers produced. In light of the difficulty of considering the effect of these factors, the validity of calculations results obtained for a concrete real process can only be established by comparing calculated and measured parameters. Unfortunately, the required concrete experimental data is lacking in the literature. In connection with this the present study analyzed results of an investigation of arc fusion of silicate material [11], performed previously with participation of one of the present authors.

Upon heating by an arc with i = 450-540 A of a slot (d = 6 mm) in a wall of silicate material the surface temperature of the zone heated most by the arc comprised 2300°K according to spectral measurements. Considering the weak dependence $T_s(i)$ it can be proposed that at i = 400 A T_s will also equal 2300°K. From the data of [9] this regime corresponds to a flux into the wall of $q = 2 \cdot 10^7$ W/m^2. Thus, experimental measurements indicate that the surface temperature of the silicate material $T_s = 2300$°K at a flux of $2 \cdot 10^7$ W/m^2. In accordance with data from the calculations of the present study, such a temperature T_s is reached at $q = 2.5 \cdot 10^7$ W/m^2, indicating agreement of the theoretical and experimental results within the limits of measurement and calculation uncertainty. The same satisfactory agreement is found for the other characteristic parameters of the technological process (fusion time, thickness of fused layer, etc.).

On the basis of the data presented it can be stated that the calculation results correspond to experiment on fusion of silicate material and therefore the proposed model can serve as the basis for a method of determining thermal processing regimes of a silicate surface. Obtaining more reliable quantitative thermophysical properties of the material. The calculation results are also of interest in designing plasmochemical reactors with a working medium formed by evaporation of refractory materials. The method and calculation programs developed could find application in studies of materials with different thermophysical properties.

NOTATION

T_{00}, initial temperature of body; T_s, surface temperature; x, t, coordinate and time; T_{sub}, T_l, evaporation and fusion temperatures; a, thermal diffusivity; q, thermal flux; ΔH, specific enthalpy of evaporation; λ_{sub} and λ_l, specific heats of evaporation and fusion; v_0, 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

E. A. Vishnevskaya, V. B. Glasko,
A. I. Malokostov, S. G. Popov,
M. K. Trubetskov, and O. P. Chernyaev

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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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