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Research Article

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Modeling of Materials Heating on Solar Furnace and Cooling of Melt

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Abstract
The possibilities of calculating the rate of heating and cooling of molten materials on the example of pyroxene rocks under the influence of concentrated solar radiation in the Big Solar Furnace are shown. The dependences of the microstructure of the material obtained from the cooled melt on the cooling rate of the melt are analyzed. It is shown that a different method of cooling the melt can achieve different cooling rates: 10^2; 10^3 and 10^4 deg/s.

Keywords: heating, cooling, concentrated solar radiation, Large Solar Furnace, modeling

Introduction
The properties of materials strongly depend on the method of their synthesis and are determined by the relationship: "synthesis method - morphology - properties". Recently, the area of material science has been intensively developing, relating to the quenching of the liquid state in order to obtain materials with a favorable combination of various properties.

Materials synthesized from the melt show high values of mechanical and dielectric properties, and thus widely used in various sectors of the economy. Melt is a state of matter at temperatures above the melting point. Unlike ordinary liquids, the structure of melts contains crystal-like groups - microcrystallines, whose structure is related to the structure of the crystalline phase. The morphology of such groupings in the melt strongly influences the structure and properties of the resulting material. In this aspect, one of the main technological factors determining the quality of the melt is the rate of heating of the substance to the melting point and higher, as well as the cooling rate of the melt. The use of solar technology allows hundreds of times to increase the heating rate and obtain a structure from clusters of a certain composition, applying fast (103 deg / s) and superfast (104 deg / s) quenching methods [1-6]. Thus, modeling of heating and cooling of materials under the influence of concentrated solar radiation is of scientific and practical interest.

Results and Discussion
a) The materials heating
The complete equation of the heating process is written in the form

$$\frac{dT_s}{dt} = -\frac{\alpha}{c\rho d}(T_s - T_0) - \frac{\varepsilon\sigma_0}{c\rho d}(T_s^4 - T_0^4) + \frac{(1-R)}{c\rho d}E \qquad (1)$$

where α is the coefficient of proportionality, called the heat transfer coefficient, W/(m^2 K); c - specific heat W/kgK; ρ is the density of g/cm^3; d is the thickness of the layer, m; T_s is the surface temperature of the body and T0 is the ambient temperature, K; ε is the degree of blackness, T_0 is the Stefan-Boltzmann constant, E is the flux density of concentrated solar radiation in units (W/m^2); R is the reflection coefficient of the heated material.

The first term in this equation is due to convective heat transfer, the second - corresponds to heat loss due to thermal radiation, the third - due to heating due to the absorption of solar radiation. Thus heating consists of three processes: heating to melting; melting, where the average temperature is assumed to be constant; heating of liquid material.

The melting time tm was determined from the following conditions:

$\frac{dT_s}{dt} = 0$, at T_s=T_m , (T_m is melt temperature, K)

The incoming heat Q is balanced with the heat of fusion of Qm, i.e.,

$$Q - Q_M = Q - \lambda m = Q - \lambda\rho S d = 0$$

$$Q = [(1-R)E - \propto (T_m - T_0) - \epsilon\sigma_0(T_m^4 - T_0^4)]St_m$$

$$t_m = \frac{\lambda\rho d}{[(1-R)I_s - \alpha((T_m - T_0) - \beta(T_m^4 - T_0^4)]}$$

Where, λ is the specific heat of fusion, J / kg; m is the mass of the material, kg; S- surface area absorbing solar radiation, m^2

The initial conditions for the materials studied (pyroxene rocks) are chosen as follows. c = 711 W / kgK, ρ = 3.2 g/cm^3; α = 100 W/(m^2 K); d: = 0.05 m; T_0: = 320K; E = 750 W/cm^2; R = 0.15; T_m = 1660K; λ = 4200 W / kg.

The calculation was carried out in the MATLAB program. Figure 1 shows the temperature dependence on the time of exposure to a concentrated flux of solar radiation.

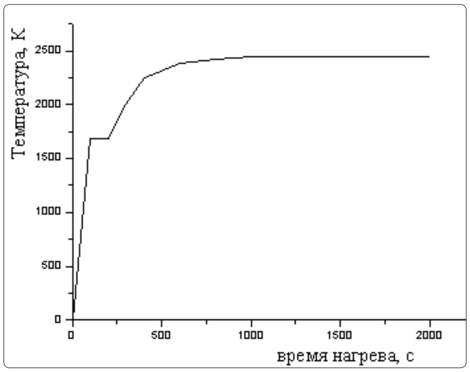

Figure 1: Dependence of temperature on the time of exposure to a concentrated flux of solar radiation.

It can be seen from Fig. 1 that the heating curve of the material is non monotonic and consists of three sections. In the first section, the material is heated in a solid state to the melting point. This process lasts for 80 s, which corresponds to a speed of 1385 deg/min.

When any solid is heated, when a certain temperature is reached, it turns into a liquid. This phenomenon is due to the fact that as the temperature of the body increases, the rate of thermal motion of its molecules increases, and the atoms move away from each other for long distances. Owing to the increase in the amplitude of the vibrations of atoms, the destruction of the crystal lattice begins - long-range order disappears - the solid melts. The fusion process corresponds to the second section in Fig. 1, and it flows for about 100 s, during which the equilibrium thermodynamic state of the liquid is established. The third section corresponds to the heating of the liquid material. Such a process, as can be seen from Fig. 1, goes to saturation associated with the boundary value of the flux density of the incident solar radiation.

b) The melt cooling

The fixation of the amorphous state of the melts during quenching is related to the cooling rate, which is influenced by such parameters as heat transfer conditions, melt temperature, quenching system material, etc.

The critical cooling rate Vc depends on the level of the thermodynamic properties of the material and the nature of the inter particle interaction. Depending on the nature of the material, it varies over a wide range (from 10^2 deg / s for inorganic glasses and some metallic melts to 10^6-10^8 deg / s for metals). Achieving high cooling rates is possible with a small thickness of the cooled melt and minimal time of the quenching process itself.

Cooling of the liquid material was carried out by three methods

- Collapse of the melt by the "hammer-anvil" principle between water-cooled baits ("cracker"), which allowed hardening of the melt with high speed.
- dropping drops of liquid into the water;
- cooling on the water-cooled surface of the substrate.

To describe the cooling process, we use the Newton-Richmann law. In general, heat transfer of the melt to the surrounding medium is carried out by heat conduction, convection and radiation.

According to the Newton-Richmann law, the amount of heat delivered through the surface of the body S per unit time is proportional to the difference between the surface temperature Ts and the ambient temperature T_0 (T_s>T_0):

$$\frac{dQ}{dt} = -\alpha(T_s - T_0)S \qquad (2)$$

We assume that the temperature inside the droplet is uniformly distributed and, given that the temperature is related to the amount of heat

$$\Delta Q = cm\Delta T$$

Equation (1) can be rewritten as:

$$\frac{dT_s}{dt} = -\frac{\propto}{cm}(T_s - T_0)S \qquad (3)$$

Where c and m are the specific heat and droplet mass, respectively

Since in the case under consideration the contact surface varies in time-when the liquid contracts, its shape changes from spherical to plate. Hence S in (2) is a function of time S = S (t).

To determine this dependence, we use the following assumption. In the process of compression between two bikes moving towards each other with a relative (average) velocity v, the drop of the formation of a ball with volume V acquires the form of a disk (due to the wetting effect, for example) with a radius R and height h, depending on the time. Then, taking into account the fact that the volume V is conserved and h (t) = d-vt, the area of the contact surface, that is, the end area of the disk S, can be written in the following form:

$$S(t) = \frac{V}{h(t)} = \frac{V}{d - vt} \qquad (4)$$

Where d is the diameter of the sphere.
Substituting (4) into (3) and taking into account that the heat is transferred simultaneously from the two ends of the disk, that is, replacing S by 2S, we obtain

$$\frac{dT_s}{dt} = -\frac{\propto}{cm}(T_s - T_0)\frac{2V}{d - vt} \qquad (5)$$

For the solution we need to find the following integral

$$I = \int_0^t \frac{d\tau}{d - v\tau} = -\frac{1}{v}\ln\left(\frac{d - vt}{d}\right)$$

Thus, for the general solution of equation (5), we obtain

$$T_s = \begin{cases} T_0 + (T_{s0} - T_0)e^{-\frac{2\alpha V}{cmv}\ln\left(\frac{d}{d - vt}\right)} & \text{при } t \le t_0 \\ T_0 + (T_{s1} - T_0)e^{-\frac{2\alpha V\, t}{cm\, h_k}} & \text{при } t > t_0 \end{cases}$$

Where

$$T_{s1} = T_0 + (T_{s0} - T_0)e^{-\frac{2\alpha V}{cmv}\ln\left(\frac{d}{h_k}\right)},$$

and h_k is the finite thickness of the disk, t_0 = (d-hk)/v

Figure 2 shows the cooling curves of a melt in a solar furnace by the "cracker" method, with the following values of the heat transfer coefficient: 1 - α = 500 W/(m^2K), 2- α = 1000 W/(m^2K).

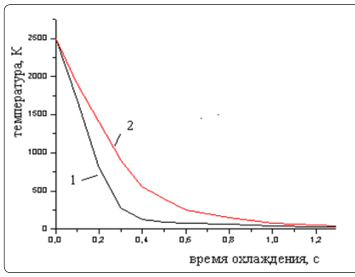

Figure 2: Curves of melt cooling on a solar furnace by the "cracker" method, with heat transfer coefficients 1 - α = 500 W/(m^2K), 2- α = 1000 W/(m^2K).

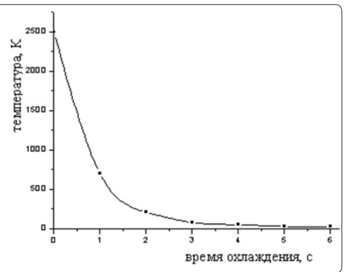

Figure 3: The curve of cooling the melt on a solar furnace by draining droplets of liquid into water at α = 1000 W/(m^2K).

Analysis of the curves in Fig. 2 shows that the cooling rate of the melt on a solar furnace by the "cracker" method is of the order of 10^4 deg/s.

Figure 3 shows the cooling curve of a melt in a solar furnace by draining liquid droplets in water at α = 1000 W/(m^2K).

Analysis of the curve in Fig. 3 shows that the cooling rates of the melt on a solar furnace by draining liquid droplets in water are about 10^3 deg/s.

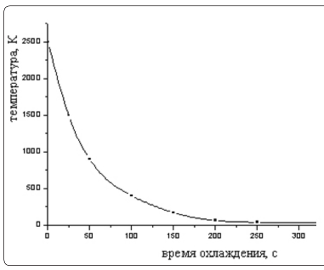

Figure 4: The cooling curve of the melt on a solar furnace by cooling on the surface of a water-cooled furnace at d = 0.1, α = 1000 W/(m^2K).

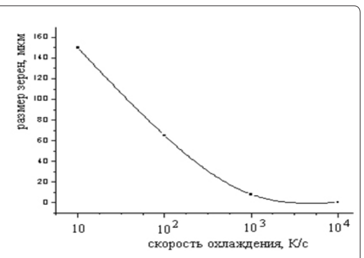

Figure 5: Dependence of the size of the material particles on the quenching rate.

Figure 4 shows the cooling curve of a melt in a solar furnace by cooling on the surface of a water-cooled substrate at d = 0.1, α = 1000 W / (m^2K). It is clear that the cooling rate of the material (melt) depends on the mass of the melt, the water temperature and the rate of its flow.

Analysis of the curve in Fig. 4 shows that the cooling rate of the melt on a solar furnace by cooling on the surface of the water-cooled substrate is about 20 deg/s. Thus, choosing a method of cooling the melt, it is possible to achieve different cooling rates: 10^2; 10^3 and 10^4 deg/s.

For melts of pyroxenes at high cooling rates T> 10^3 K/s the condition of homogeneous nucleation and growth of crystal grains is satisfied. The grain size is determined by diffusion [7].

$$d \sim \tau U \sim C\left(\frac{\Delta T^3}{T_m^2}\right)\exp\left(-\frac{E}{kT_{cr}}\right)$$

where τ is the average time of grain growth corresponding to the crystallization time, s; U is the growth rate of grain μm/s; C is a quantity that depends on the cooling rate, temperature and melting enthalpy, surface tension, specific volume of the solid phase, and Debye frequency μm; Tcr is the crystallization temperature of the melt, K; ΔT is the super cooling quantity ($\Delta T = T_m - T_{cr}$), K; E is the effective activation energy of diffusion, eV.

Figure 5 shows the dependence of the grain size of the material on the quenching rate. It is seen from Fig. 5 that the approximation of such a dependence on the maximum high quenching rate makes it possible to determine the sizes of clusters of the liquid state of matter. To produce a hardened material with nanoscale particles, it is necessary to cool the melt at a rate higher than 10^6 g/s.

Conclusion

Consequently, the modeling of the processes of heating and cooling of materials (pyroxene rocks) on the Big Solar Furnace was carried out. It is shown that within the framework of the model, taking into account the assumptions and initial conditions, it is possible to describe the processes of heating and cooling of pyroxene rocks under the influence of concentrated high-density solar radiation. The obtained results of the calculation are in good agreement with the experimentally observed ones. It is shown that the rate of cooling of the melt, which has a strong effect on the dispersion of the resulting material, is determined by the method of its implementation. To produce a hardened material with nanoscale particles, it is necessary to cool the melt at a rate higher than 10^6 g/s.

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