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Approaches to Simulation of Interaction of Concentrated Solar Radiation with Materials

Muhammad S. Paizullakhanov* and Rasul Yu. Akbarov
Institute of Material Science
of SPA «Physics-Sun» AS RUz
Tashkent, Uzbekistan

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Abstract. The paper analyzes approaches to modeling the processes of interaction of concentrated solar radiation with materials. The experimental results obtained on the synthesis of materials from a melt in a solar furnace are presented. It is shown that when melting in a solar furnace under the influence of concentrated solar radiation of high density due to the acceleration of the recovery process, it is possible to obtain a fine-grained microstructure that gives the material enhanced mechanical and dielectric properties. It is shown that the relationship between the structure and properties of the materials obtained with the technological parameters of melting and cooling in a solar furnace can be used as an approach to modeling the interaction of concentrated solar radiation with materials.

Keywords: solar furnace, melts, synthesis, structures, hardening, microstructure, fine grain.

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Подходы к моделированию взаимодействия концентрированного солнечного излучения с материалами

М.С. Пайзуллаханов, Р.Ю. Акбаров
Институт материаловедения
НПО «Физика-Солнце» АН РУз
Узбекистан, Ташкент

Аннотация. В статье анализируются подходы к моделированию процессов взаимодействия концентрированного солнечного излучения с материалами. Приведены экспериментальные

* Corresponding author E-mail address: m.payzullakhanov@imssolar.uz

результаты, полученные по синтезу материалов из расплава в солнечной печи. Показано, что при плавлении в солнечной печи под воздействием концентрированного солнечного излучения высокой плотности за счет ускорения процесса восстановления можно получить мелкозернистую микроструктуру, придающую материалу улучшенные механические и диэлектрические свойства. Показано, что взаимосвязь структуры и свойств получаемых материалов с технологическими параметрами плавления и охлаждения в солнечной печи может быть использована как подход к моделированию взаимодействия концентрированного солнечного излучения с материалами.

Ключевые слова: солнечная печь, расплавы, синтез, структуры, закалка, микроструктура, мелкое зерно.

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The Big Solar Furnace (BSP) in the city of Parkent (Uzbekistan) is a unique tool for conducting full-scale research in the field of high-temperature synthesis of materials, conducting high-temperature research and testing of various materials and components of equipment. BSP is a complex optical-mechanical complex with automatic control systems, consisting of a heliostat field (62 heliostats) and a paraboloid concentrator, forming a stationary high-density energy flow in the focal zone of the concentrator (up to 600 W/cm^2). The reflecting surface area of the heliostatic field is 3020 m^2, the concentrator is 1840 m^2. The height of the concentrator is 54 m, the width is 47 m. The temperature at the focus of the rays of the concentrator exceeds 3000 °C. It is possible to cool the melt at different speeds.

To date, a systematic study of the synthesis of composition oxide systems of higher refractoriness from the melt has been carried out on the basis of BSP. The question of the synthesis of materials from a melt obtained by exposing a substance to high-density concentrated light radiation in which compounds are formed during reactions in melts is widely studied, and then this state is fixed by quenching [1–4]. Almost the entire group of materials of various classes – high refractory oxides, glasses, and glass metals – were synthesized on a BSP. This made it possible to identify the features of the effect of concentrated solar radiation (CSI) on the properties, and accordingly take a step along the path of directed synthesis.

It was revealed that as the flux density increases, an increase in the homogeneity of the melt is observed. With increasing flux density and melt holding time, the apparent density of the material increases. (Fig. 1 and 2).

A decrease in abradability was also observed with increasing flux density of concentrated solar radiation (Fig. 3). With increasing flux density during glass synthesis, mechanical strength and deformation under load are improved.

This may be due to the perfection of the structure, the type of crystalline and glass phases, and their relative amount. As a rule, during synthesis under the influence of concentrated solar energy, a more highly symmetric structure is stabilized.

Accordingly, prerequisites are created for the stability of materials at higher temperatures. The materials are characterized by high purity – during the melting process, purification occurs due to evaporation and diffusion into the skull area. The use of ultrafast hardening technique has shown the possibility of controlling the process of formation of the required crystalline structure and dispersion.

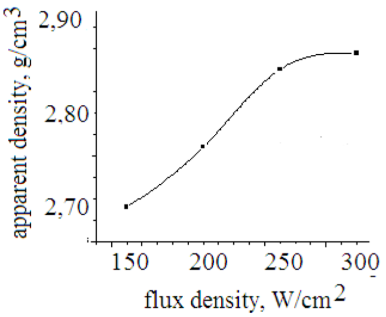

Fig. 1. Dependence of apparent density of pyroxene material samples on flux density

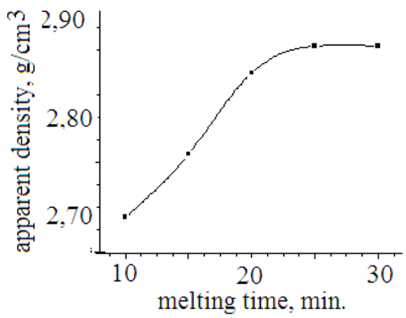

Fig. 2. Dependence of the apparent density of pyroxene material samples on the melt holding time at 300 W/cm^2

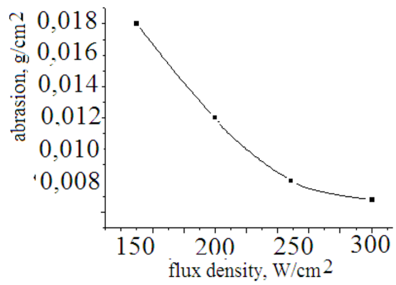

Fig. 3. Dependence of the abrasipn of the pyroxene material on the flux density

Powders <5 microns in size were obtained, and ceramics based on them are characterized by an unusual change in heat resistance and mechanical strength.

The use of solar energy in relation to the production of materials of higher refractoriness was first carried out by Japanese and French scientists. For this purpose, small-capacity Solar Furnaces were built in Japan, and subsequently, taking into account this experience, the Large Solar Furnace was created in France. The results obtained by French researchers were quite interesting and promising from both a scientific and a practical point of view. In the scientific plan, oxide and some non-metallic systems with melting points above 2000 °C in an oxidizing atmosphere were studied, which is difficult to achieve using traditional techniques. It was found that as a result of exposure to solar radiation, the mechanical, optical characteristics and a number of other functional parameters of materials are significantly improved.

Despite the many years of experience and sufficient scientific and experimental material in this area, little attention has been paid to the study of the physical foundations of the processes of interaction of concentrated solar radiation with matter and the mathematical modeling of these processes.

Studies and literature analysis showed that knowledge of the physical basis of the processes of interaction of concentrated solar radiation with matter plays an important role in the synthesis and heat treatment of materials. However, due to the complexity, this problem has not been practically studied; there is very scarce data both in terms of interpreting physical processes and in terms of constructing a mathematical model. Therefore, the study of this problem is an urgent task of our time.

It should be noted that the structure of substances cannot yet be fully described, statistical parameters (enthalpy, entropy) do not allow tracking the local evolution of a substance under the influence of radiation, although it has long been proposed to transfer the formalism of the coherence theory to the description of matter [5]. For radiation, in such experiments as interference, diffraction, polarization, dispersion, the wave properties of light are manifested and wave characteristics are used to describe light: λ, ν (spectral composition of radiation). In the effects of quantum optics, such as thermal radiation, the photoelectric effect, the photochemical effect of light, the pressure of light, the Compton effect, light manifests itself as a particle and particle characteristics are used to describe it – mass, momentum. The development of optics, the totality of optical phenomena, showed that the continuity properties characteristic of the electromagnetic field of a light wave should not be opposed to the discrete properties characteristic of photons. Light has complex wave-particle properties, i.e. possesses both wave and quantum properties – particle-wave duality (duality) of the properties of light. As for matter, in some cases its quantum nature is manifested – under the influence of the radiation field, transitions occur between the energy levels of the particles of which this substance consists. This usually occurs when the radiation frequency coincides with the transition frequency.

The same effects occur during interband absorption in semiconductors and dielectrics, when electron-hole pairs are produced, or during impurity absorption, when an electron is generated in the conduction band or a hole in the valence band. In this case, one has to resort to a quantum-mechanical description. If the quantum nature of the substance does not appear, then it is much easier to consider on the basis of the classical description, using macroscopic characteristics, such as dielectric constant, magnetic constant, conductivity, etc. When it comes to the interaction of radiation with matter, a semi-classical description is often used: the substance is considered as a quantum system and the corresponding physical quantities are replaced by operators, and the radiation field is considered classically, based on Maxwell's equations.

The main problem is, of course, the lack of a single formalism for the simultaneous description of both matter and radiation. This is especially true for the situation when the phenomenon occurs in the region that is transitional from quantum-mechanical to classical scales, which is characteristic of most optical phenomena, as was recently shown in the modern theory of quantum measurements [6]. Hence the complexity of the problem. In this sense, the problem of creating a theory of the process of the interaction of radiation with matter is very far from its solution.

It is well known that the electromagnetic field in any medium in the classical description is determined by setting the vectors of electric strength E and magnetic H fields, as well as vectors of electric D and magnetic induction B (Maxwell's equation). The Maxwell equations themselves do not form a closed system, on the basis of which it would be possible to calculate the fields in the crystal. These equations reflect only the influence of the crystal on the propagation of electromagnetic radiation in it. In its most general form, this dependence is determined by the equations of quantum mechanics that describe the effect of an electromagnetic field on the motion of crystal charges. However, the solution of these equations and finding on their basis the functional relationship between the physical characteristics of the crystal and the field strengths is a very difficult task.

One of the options for constructing the achievement of such a goal may be to use the formalism of statistical physics and fluid theory. By the way, we note that the use of the theory of integral, and, in particular, Fourier, transformations in statistical physics and fluid theory allows us to talk about an analogy between the phenomena described in them with the processes of wave field formation in Fourier optics and apply a number of results , for example, in computer optics [7].

Thanks to the advent of lasers, the theory of the interaction of radiation with substances received a certain impetus to development. For some types of lasers and substances, mathematical models of these processes have been developed. The literature contains the development of a mathematical model and an algorithm for calculating the temperature distribution in complex multilayer systems under the influence of laser radiation. These models are based on the finite-difference method and take into account the anisotropy of the optical and thermal parameters of the structure of materials. Typically, the model is two-dimensional and non-stationary and allows you to simulate the interaction of various types of laser with substances.

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