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Modeling of thermal processes during electroconsolidation

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Practical application of mathematical modeling technologies of heat transfer processes in the main units of the installation for electroconsolidation of powder materials using FAST/SPS technology is considered. A mathematical model of the existing hot pressing unit with direct current transmission is created. The results on the heat distribution in the installation parts and in the compaction zone are obtained. Comparison of simulation results with experimental data is given. The significance of the data obtained by using similar techniques, both from the fundamental point of view and from the practical one, is shown.

Keywords: electroconsolidation, finite element simulation, thermal processes, Al_2O_3-SiC.

Розглянуто практичне застосування технологій математичного моделювання процесів теплопереносу в основних вузлах установки для електроконсолідації порошкових матеріалів за технологією FAST/SPS. Розроблено математичну модель існуючої установки гарячого пресування з прямим пропусканням струму. Отримані результати по розподілу тепла в деталях установки та в зоні компактування. Наведено порівняння результатів моделювання з експериментальними даними. Показана значимість даних, отриманих шляхом застосування подібних методик, як з фундаментальної точки зору, так і з практичної.

Ключові слова: електроконсолідація, скінченно-елементне моделювання, теплові процеси, Al_2O_3–SiC.

Introduction

As is known, the use of oxide ceramic, in particular, nanostructured and composite materials as instrumental is of great demand, because of their high physical and mechanical properties. But along with high hardness and temperature resistance, the use of such materials is limited by their low strength and crack resistance. It is not possible to solve this problem by traditional hot sintering. The reason for this is the rapid growth of grain, competing with the compaction of particles (Fig. 1).

The use of innovative technologies for the consolidation of ceramic materials, such as FAST (Field Activated Sintering Technology), SPS (Spark Plasma Sintering) and their combinations makes it possible to [1-5]. The advantage of these technologies is the obtain new materials with a submicron and nanostructure activation action of the electric field and current, which greatly intensifies the sintering process, in comparison with traditional methods. So, to obtain high-density Al_2O_3-SiC ceramics by hot pressing with direct current transmission (electroconsolidation) (Fig. 2), it was sufficient for about 3 minutes [6].

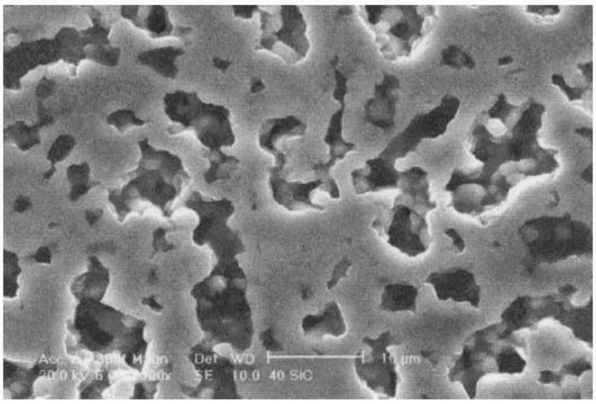


Fig. 1 Microstructure of ceramic sintered in argon atmosphere without activating additives [7]

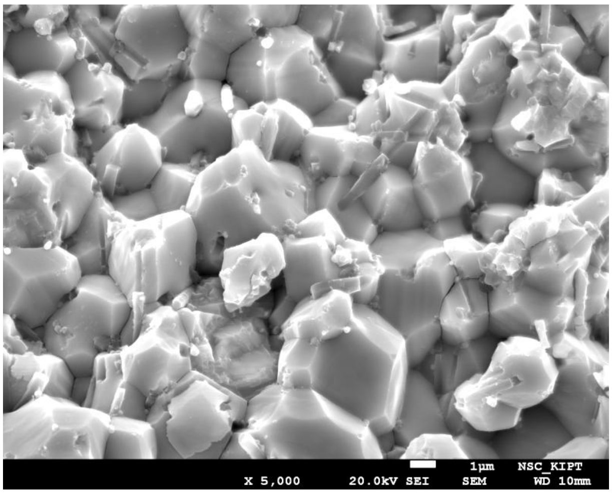
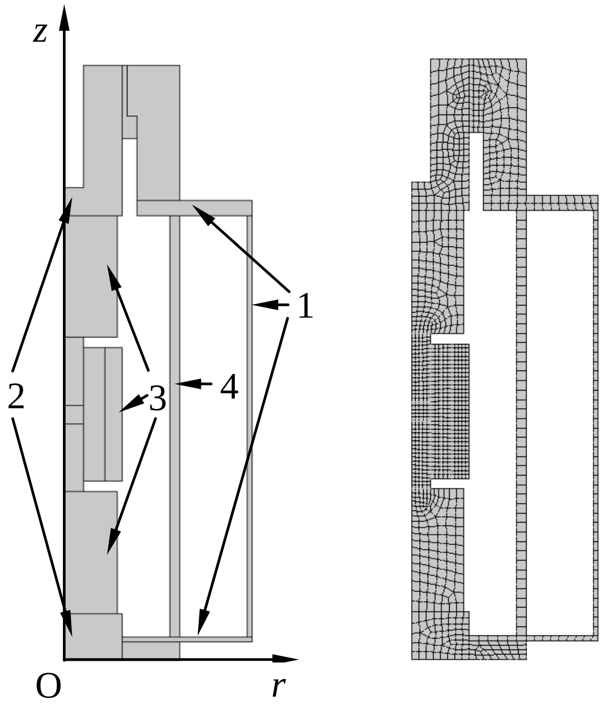


Fig. 2 Microstructure of Al_2O_3-SiC ceramics sintered by electroconsolidation at a temperature T = 1400˚C, pressure P = 30 MPa.

Experiment

The use of such technologies is associated with the need to carefully design equipment that directly participates in the consolidation processes, because the accuracy and predictability of consolidation parameters such as temperature, pressure, etc. is important in order to achieve the necessary material properties. The priority in this case is obtaining information on the temperature distribution in component parts of the installation, as well as the distribution of electric current in the components involved in its transport. The most accurate source of information necessary for this is computer simulation using specialized software.

For the calculations, a universal software system of finite element analysis ANSYS was used. In Fig. 3 shows the design area in the form of a two-dimensional model of a hot vacuum pressing unit. To solve this problem, the finite element method was used together with the radiosity method, and the computational domain was divided into a grid of 923 eight-node elements with quadratic approximation.



a *b*

Fig. 3. Calculation area (a) and its decomposition into a finite element grid (b). Oz - axis of pressing; Or is the radial axis of the installation. 1 - body (steel); 2 - water-cooled current leads (brass); 3 - mold and punches (graphite); 4 - lining (thermo-expanded graphite).

The simulation was performed according to the original electrosparking system developed by us [8]. An alternating voltage of the order of 5 V with a frequency of 50 Hz is applied to the surfaces of brass current leads. A distinctive feature of such plants is a short synthesis time, due to the current flow of the order of several kA. The distribution of the heat produced was carried out taking into account convective heat transfer with the heat carrier and the environment, as well as radiant heat exchange inside the installation. The calculations take into account the temperature dependences of the properties of the materials from which the parts of the installation are made. The volume of the material to be compacted (Al_2O_3 powder) is small relative to the whole installation, and its physical properties change during compaction (they depend not only on temperature), they are taken to simplify calculations. The values of the contact electrical and thermal properties and their dependence on the temperature and pressure of pressing are obtained from the literature [9-14].

Results

In Fig. 4 shows the temperature dependence at different points of the sintering zone as a function of time. The time interval from 0 to 400 s corresponds to intensive heating, and from 400 s – approach to the temperature regime and the beginning of sintering. As can be seen from the graph, in pairs of points s1-s4 and s2-s3, the temperature coincides over the entire time interval, which means that there is no axial temperature gradient between the upper and lower punch. The presence of such a balance of heat dissipation speaks about the correctness of calculations of the components of the installation and the cooling system of the upper and lower current leads.

When the sintering temperature is reached, a small temperature divergence is observed at the points s1 and s2 (s3 and s4) due to heat removal through the outer part of the mold by radiation. Despite the presence of a radial gradient, the temperature difference between the center and the periphery of the compact does not exceed 10K, which in this case corresponds to 0.6% of the sintering temperature.

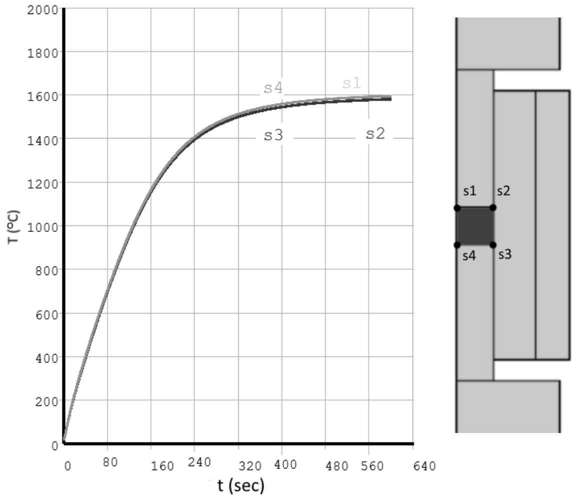


Fig. 4. Change in temperature at points on the surface of the volume being compacted. s1-s2 - upper, s3-s4 - lower plane.

Obtaining predictable and reproducible results in the compacting of powder materials requires precise control of the main parameters of consolidation: temperature, pressure, holding time. The most difficult is the precise control of the temperature in the pressing zone, since access to it is difficult. A relatively simple solution to this problem is the option of controlling the temperature at the periphery of the mold. In Fig. 5 shows the change in temperature at points on the transverse axis, obtained by mathematical modeling. Thus, it can be seen from the graph that when monitoring the temperature at the periphery of the mold (point c3), the temperature difference ΔT≈200K must be taken into account.

The efficiency of the model can be estimated by comparing the simulation results with the actual measured parameters. In Fig. 6 shows the time dependences of the temperature measured at the periphery of the mold during the electroconsolidation and the simulation results. The differences in the preliminary stage are associated with different initial currents and, correspondingly, the heating rate. The termination of the effect of the electric field for the real process corresponds to the instant of time t = 1100 s, and for the model it was terminated at the time t = 1000 s. If the differences in the magnitude of the current flowing at the initial stage to a minimum are reduced, then the simulation results fully correspond to the real nature of the temperature behavior at the monitored point, which confirms the reliability of the results obtained by modeling.

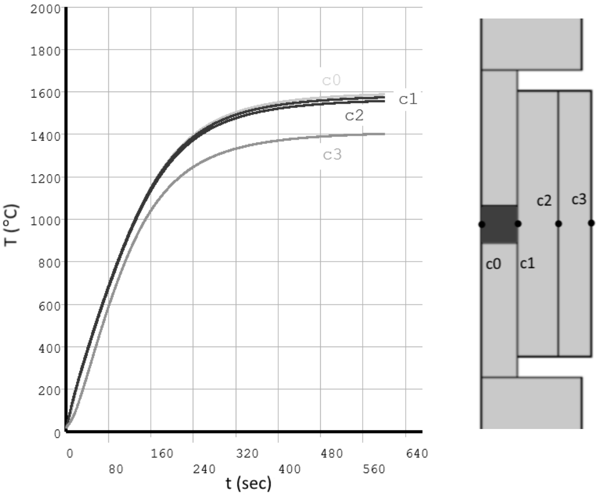


Fig. 5. Change in temperature at points on the transverse axis, *c0* is the center of the volume being compacted, *c1* is the border with the mold, *c2* is the border of the mold and composite shell, *c3* is the outer part of the shell.

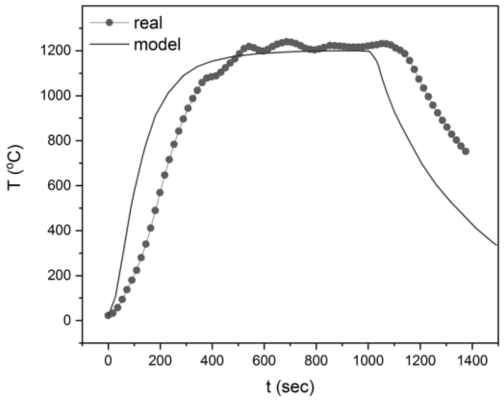


Fig. 6. Dependence of mold shell temperature on time. Points are real measurements, a solid line is the result of modeling.

Conclusions

Accurate understanding of the processes occurring during the consolidation of nanomaterials allows us to create a theoretical foundation for the development of innovative technologies for the production of new materials with increased physical, mechanical and operational properties. With the use of FAST/SPS technologies, all processes take place quite quickly, and the consolidation time is reduced to several minutes, in such conditions the control of current, temperature and mechanical stress distribution is practically unattainable problem, which, however, is easily solved by using mathematical models and mathematical calculations. This approach allows us not only to determine the magnitude of important parameters of consolidation, but also to observe their dynamics in the process of synthesis. In addition, the use of such solutions at the design stage makes it possible to simplify the development of equipment for electroconsolidation, and the results of modeling the temperature distribution in the volume of the mold-simplify temperature control in the sintering zone, which can significantly reduce the cost of manufacturing it.

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