Thermophysical Properties and Numerical Prediction of Temperature Evolution in Mullite-Based Ceramics

A. B. Šaponjić[1], I. D. Tomanović[1], S. V. Belošević[1], S. M. Ilić[1], N. G. Manić[2], M. M. Vuksanović[1], M. S. Komatina[2]*

[1] Vinča Institute of Nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade, Mike Petrovića Alasa 12-14, 11000 Belgrade, Serbia

[2] University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade

Introduction

As a response to the call of the national environmental protection, energy saving and emission reduction utilization of abundant minerals tailings a well-known refractory material $Al_2O_3 \cdot SiO_2$ mullite using waste diatomite was synthesized. Using the eco-friendly, natural materials, consolidation techniques, generated by synthesis of ceramics at high temperatures, operate at lower sintering temperatures in the presence of a transient liquid phase. In this way, diffusion and mass transport at grain boundary/surface is accelerated, thus reducing the energy consumption and carbon footprint [1-4].

With the lack of literature data, a temperature field model was created to determine thermal conductivity in order to explore the effects of temperature on the thermal conductivities of mullite based compacts and validate an effective temperature field medium model incorporating these factors. As such, the modified transient plane source (MTPS) method technique was used to measure the bulk thermal conductivity of the mullite based compacts while changing temperature of the temperature field and to expand the available data set. Comparisons between the experimentally and model data set for the obtained materials based on mullite, will be presented and discussed.

The discretization of the governing partial differential equations was done by the Finite Element Method (FEM), regularly used in thermodynamics to analyze heat transfer within solid bodies [5]. The spatial domain is discretized into finite elements, in 3D geometry typically tetrahedra or hexahedra, and temperature distribution is approximated using shape functions within each element. The governing heat conduction equation is converted into its weak form and assembled into a global system.

Likewise,besides thermal conductivity, microstructural and mechanical stability properties (compressive strength) and SEM microstructure with image analysis software with measurements of crystallite size and diameter were followed.

Experimental measurements

Materials and Methods

The synthesis procedure of mullite based compacts has been previously reported [4], is followed by powder mixtures which were molded in a metal mold and uniaxially pressed at 50 MPa to form cylindrical compacts with 40 mm in diameter and about 10 mm in thickness. The green compacts were sintered in a chamber resistance furnace at 1300, 1400 and 1500°C for 4 h. The heating and cooling rates were 5°C/min, respectively.

Apparent density and open porosity

The apparent density and open porosity of sintered mullite samples were determined by the Archimedes method using water as the fluid.

SEM analysis

A TescanMira 3XMUFESEM (Field Emission Scanning Electron Microscopy, TESCAN, Kohoutovice, Czech Republic) was used for the microstructural characterization of the sintered mullite samples. The images obtained from the FESEM were also used to examine the porosity of the material. The assessment of the porosity of the material as well as the distribution of the pore diameters was performed using the Image Pro Plus software 6.0 (Media Cybernetics, Rockville, MD, USA).

Experimental measurements

Thermal conductivity measurements

The thermal conductivity of the considered samples was measured by a TCi thermal conductivity analyser (C-Therm Technologies, Canada), which is designed to operate by the modified transient plane source (MTPS) method. A protect ring and insulating layers encircle the spiral heating element in the TCi sensor, which allows the simultaneous measurements the sample interface's temperature and the heat input. To achieve the secure contact between the samples and the sensor, all samples were additionally prepared and flattened to ensure smooth and clean surfaces. Reaching thermal equilibrium for every sample was performed by maintaining samples at the constant room temperature and humidity for a minimum of one hour. The TCi sensor was placed on a level, vibration-free surface and, coated with a thin layer of thermally conductive material to eliminate minor air gaps before the measurement could be completed. The instrument's spring-loaded platform ensured that the prepared sample, delicately placed at the top of the sensor, remained under constant contact pressure achieved by weight of 500g . Each specimen was tested three times so that the sensor could return to its initial temperature setting in between each run, and the final thermal conductivity of the sample was calculated by averaging the values.

Results

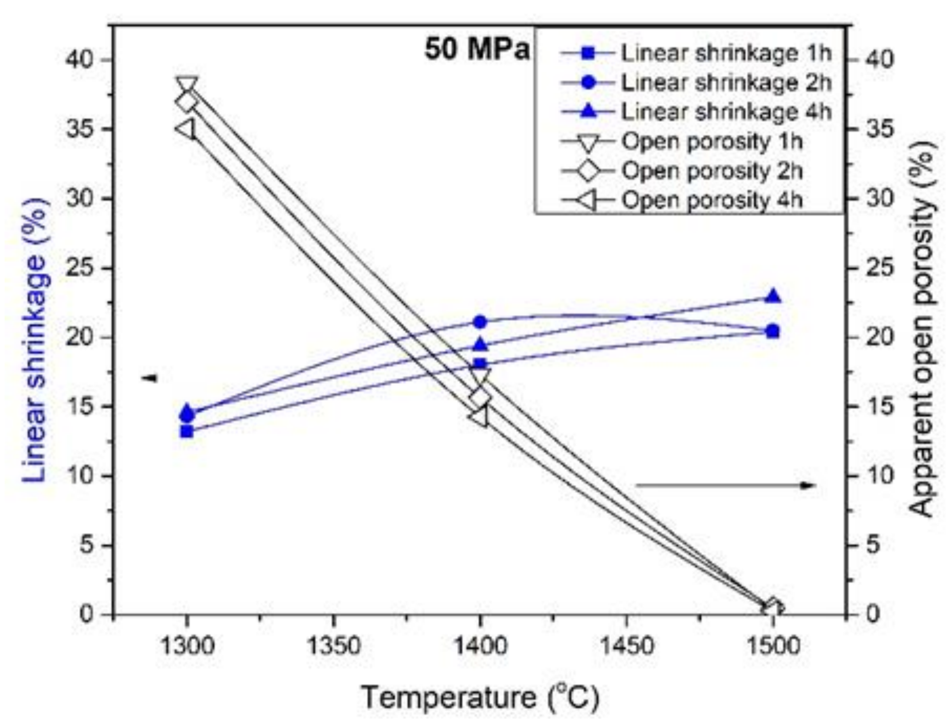

Fig. 1. Lenear shrinkage and apparent open porosity as a function of sintering temperature.

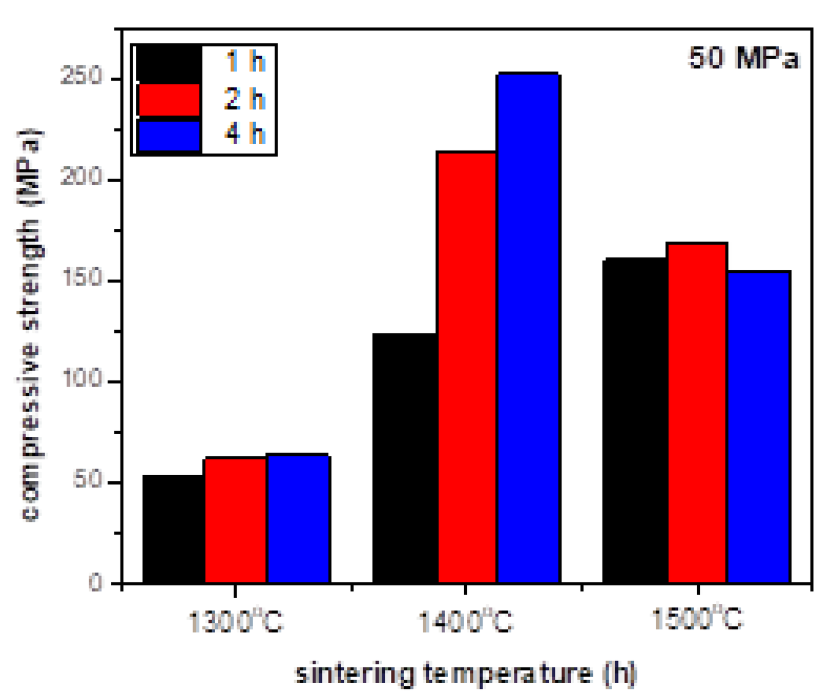

Fig. 2. Compressive strength as a function of sintering temperature.

The effect of sintering temperature between 1300°C and 1500°C on the linear shrinkage and open porosity of the sintering products sintered for different dwell time is shown in Figure 1. Increasing sintering temperature leads to slow increase in linear shrinkage and abrupt decrease in apparent open porosity.

The effect of sintering temperature between 1300°C and 1500°C on the compressive strength of the sintering products sintered for different dwell time is shown in Figure 2. The maximum obtained value for the compressive strength was obtained for the samples sintered for 4h at 1400°C (252 MPa).

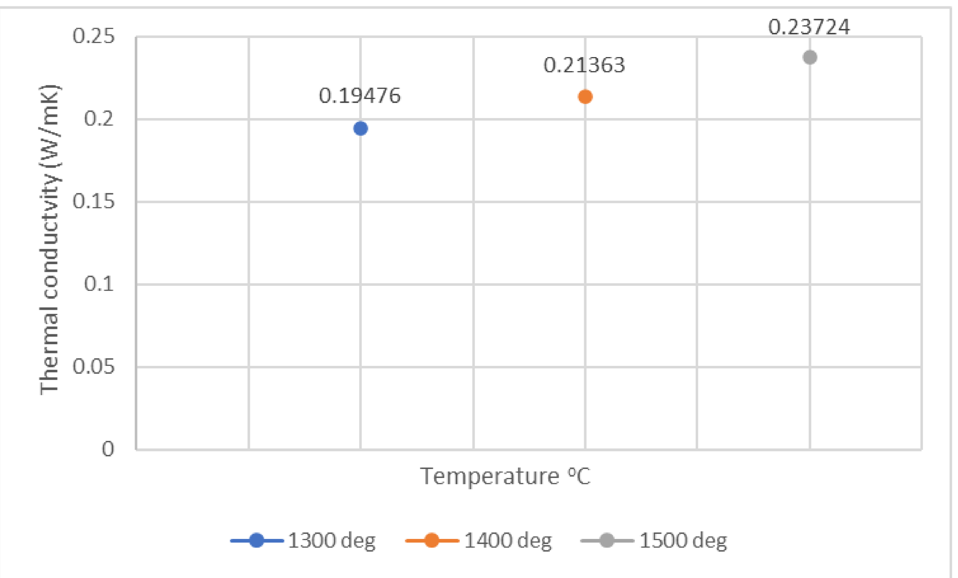

Fig. 3. Thermal conductivity as a function of sintering temperature.

The effect of sintering temperature between 1300°C and 1500°C on the thermal conductivity of the sintering products sintered for dwell time of 2h, is shown in Figure 3. As with the sintering process in general, the higher the sintering temperature, causing thermal conductivity gradually to rise, while the open porosity, abruptly decreases and for the 1500 °C sample, approaches nearly zero at 1500°C.

Numerical model

Numerical simulations were set up to resemble the experimental setup around the sample – bottom side of the disk has circular contact with measuring instrument, figure 1. This circular contact is 18 mm in diameter. It has 2 heating elements – the main heating plate which is smaller in diameter, and a ring heating element which ensures even conditions over the entire cross-section [6-8].

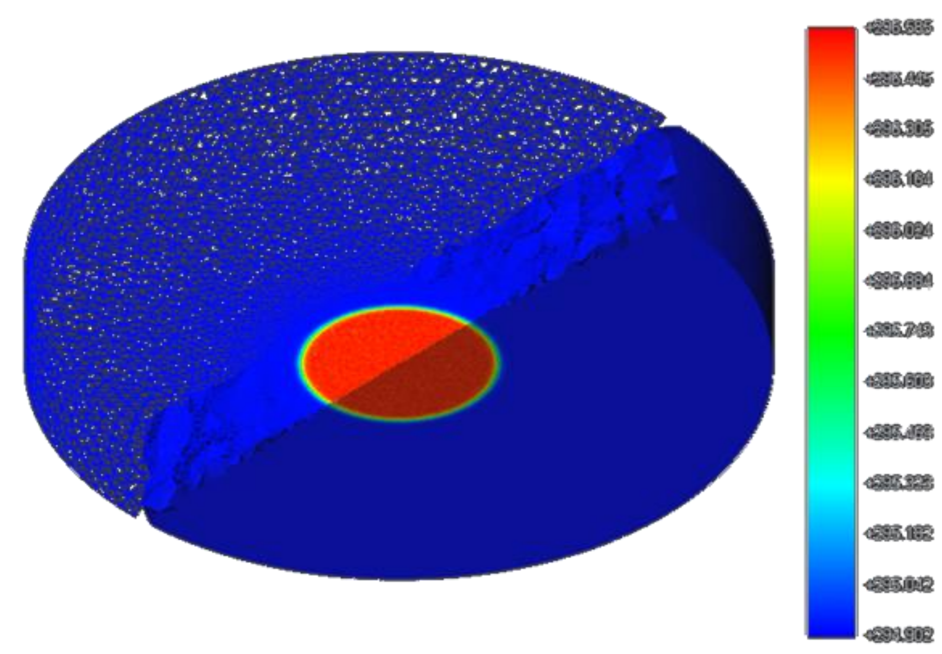

Fig. 4. Numerical model of simulated disc.

Conclusions

The main conclusions drawn from all these work are:

- Increasing sintering temperature leads to slow increase in linear shrinkage and abrupt decrease in apparent open porosity.;
- The maximum obtained value for the compressive strength was obtained for the samples sintered for 4h at 1400°C (252 MPa).;
- As with the sintering process in general, the higher the sintering temperature, causing thermal conductivity gradually to rise;
- A temperature field model was created to determine thermal conductivity in order to explore the effects of temperature on the thermal conductivities of mullite based compacts and validate an effective temperature field medium model incorporating these factors.

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