Available online at www.sciencedirect.com

ScienceDirect

Journal of the European Ceramic Society 35 (2015) 267–275

www.elsevier.com/locate/jeurceramsoc

Fabrication and characterization of anorthite foam ceramics having low thermal conductivity

Ye Li, Xudong Cheng *, Lunlun Gong, Junjie Feng, Wei Cao, Ruifang Zhang, Heping Zhang *

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230027, PR China

Received 30 June 2014; received in revised form 22 August 2014; accepted 29 August 2014
Available online 13 September 2014

Abstract

Porous anorthite ceramics with low thermal conductivity were successfully prepared using fly ash and gypsum by direct foaming and slip casting method. Effects of dispersant and foaming process on the performance of the porous materials were investigated. The results show adiabatic anorthite ceramics with the highest open porosity (94%) and the lowest thermal conductivity (0.042 W/m K) can be fabricated by adding 10% content of gypsum, 0.8% content of SHMP and using two-step foaming process. High porosity and small pore size are the main factors resulting in the low thermal conductivity. Meanwhile, the thermal conductivity can be predicted with the proportionality coefficient χ obtained by fitting the experimental data based on previous Gong's model. The *a* and *b* values in the expression of the proportionality coefficient χ were further discussed. The results show that they are affected by the pore size and distribution, and then the thermal conductivity will change accordingly.

Keywords: Anorthite foam ceramic; Dispersant; Foaming process; Thermal conductivity; Microstructure

1. Introduction

Porous ceramics with outstanding performance such as low thermal conductivity, low density, high porosity, excellent thermal shock resistance and high strength have received wide attention and become one of the candidates for heat insulation.[1,2] As well as cordierite,[3] alumina[4] and mullite,[5] anorthite[6] also can be used as the matrix material of porous ceramics. What's more, anorthite has lower thermal conductivity than cordierite and mullite and thus is more suitable to fabricate thermal insulation material.

Numerous processing methods have been developed to produce porous ceramics, such as replica,[7] sacrificial template,[8] and direct foaming method.[9] The direct foaming method usually needs to be combined with other solidification method to obtain green bodies. For example, Marek Potoczek[10] fabricated alumina foams with 89% of porosity by gelcasting method. Ahmad Fadli[11] obtained porous alumina with 71% of porosity using protein foaming method. Gong et al.[5] prepared porous mullite ceramic with 86% of porosity by starch solidification method. And Hu et al.[12] produced ultra-high porosity zirconia ceramics through using freeze-drying process. However, the above methods for preparing highly porous materials are not cost-effective, and they are not suitable for large-scale industrial production. Slip casting method[13] as a traditional process has its strong advantage. Primachenko et al.[14] fabricated a microporous anorthite-based lightweight refractory using various aluminosilicates and calcium-containing components as raw materials by slip casting process. The thermal conductivity was below 0.25 W/m K at 650 °C. Furthermore, Priogov et al.[15] prepared microporous anorthite ceramics with a low thermal conductivity of 0.14 W/m K at 400 °C using direct foaming process. Though the thermal insulating performance of these materials is not sufficiently good for adiabatic application under the normal temperature, these two kinds of preparation methods are very suitable for industrial production because of their low cost and environmental advantage. In this study, the direct foaming and

* Corresponding authors. Tel.: +86 55163601665; fax: +86 55163602631.
E-mail addresses: chengxd@ustc.edu.cn (X. Cheng), zhanghp@ustc.edu.cn (H. Zhang).

http://dx.doi.org/10.1016/j.jeurceramsoc.2014.08.045
0955-2219/

Table 1
Elemental analysis of minerals using the XRF technique.

Fiy ash	SiO_2	Al_2O_3	CaO	SO_3	Fe_2O_3	TiO_2	K_2O	MgO	Na_2O	P_2O_5	Others
wt%	46.77	25.22	11.15	3.02	6.68	1.58	1.48	1.37	1.57	0.48	0.68

the slip casting method were combined for the material preparation and the thermal insulation property of the obtained material was examined.

To obtain a lower thermal conductivity, a usual method is to increase the material porosity. Therefore, the relationship of the porosity and the thermal conductivity has been widely researched. As a general rule, a porous material is composed of a dense solid skeleton and air, which can be considered as a two-phase system.[16] Many analytical models have already been proposed to describe the effect of porosity on the thermal conductivity of this two-phase system, such as the Series and Parallel models,[17] Maxwell-Eucken models (two forms),[18,19] and EMT equation,[20,21] which are the five basic structural models. Moreover, Brailsford and Major[22] proposed the universal model, from which the basic structural models can be derived by suitable choice of parameters d_i and k'.

$$k_e = \frac{\sum k_i \upsilon_i((d_i k')/((d_i - 1)k' + k_i))}{\sum \upsilon_i((d_i k')/((d_i - 1)k' + k_i))} \tag{1}$$

Gong et al.[5] further developed the EMT model, introducing the proportionality coefficient χ which can be obtained from experimental data.

$$\sum_{i=1}^{w} \upsilon_i \frac{k_i - k_e}{k_i + 2\chi k_e} = 0 \tag{2}$$

However, despite the deep understanding of the influence of the porosity by researchers, there is no single model can be used to predict the thermal conductivity with universal applicability. That is to say, the porosity is not the only factor affecting the thermal conductivity. The nature of the pore itself cannot be overlooked, such as pore size and pore distribution. In spite of some efforts to investigate the relationship between the thermal conductivity and pore structure, in-depth works is needed.

In this work, different dispersants were added and different foaming processes were tested. The apparent porosity, microstructure, thermal conductivity at room temperature, phase composition and pore size distribution were investigated. Meanwhile, the pore structure of the porous anorthite ceramics was defined similarly as suggested by Carson.[23] The measured thermal conductivity were compared with Sutcu' results[24] and the predicted values derived from the universal model[22] and Gong' model.[5] Moreover, effects of pore size and distribution on the thermal conductivity were also discussed.

2. Experimental

Fly ash (Thermal power plant, Hefei, China) was used as the raw material to synthesize anorthite ($CaO \cdot Al_2O_3 \cdot 2SiO_2$). The chemical composition of the fly ash was determined by X-ray fluorescence spectroscopy (XRF-1800, SHIMADU, Japan) and is listed in Table 1. Gypsum (Hebei, China) was added (from 0 to 20 wt%) as a source of CaO and a binder. Moreover, Arabic gum (Cp, Shanghai, China) and sodium hexametaphosphate (Cp, Shanghai, China) were added as dispersants.

40 wt% concentrated slurry was chose to prepare the green bodies. For this purpose, the mixture and different amounts of dispersant were added into deionized water and ball-milled for 24 h at a rotation speed of 180 rpm. Then two different foaming procedures were executed. In Case I, the dodecyl sodium sulfate (K12, Cp, Shanghai, China) was directly added into the slurry and was stirred using a direct driven motor at a speed of 1500 rpm to produce wet slurry foams. In Case II, K12 was added into the deionized water to produce the foams firstly. Then the foams were poured into the ceramic slurry and stirred. Therefore, the two processes were named as one-step foaming process and two-step foaming process. After stirring for 3 min, the wet slurry foams were cast into plaster molds. Subsequently, the molds were dried at room temperature for 6 h before samples removal. The shrinkage, which occurs during drying, facilitates removal of the samples from the wet mold. Then the wet green bodies were dried at room temperature for 24 h and in a drying oven at 80 °C for 24 h. After drying, the specimens were sintered at 1100 °C for 2 h. A detailed flowchart of the process is shown in Fig. 1.

The types of crystalline phases of the sintered samples were identified from XRD patterns, using an X-ray diffractometer (X'Pert PRO, PHILIPS, 60 kV and 55 mA, α monochromatic Cu Kα radiation). The microstructure was observed on FEI Quanta FEG 450 scanning electron microscopy (SEM). The pore size distribution was obtained by analyzing SEM micrographs using an image analyzer (Nano measurer, China) with a total of at least 200 pores being counted on each image. The open porosity was determined by the Archimedes method using distilled water as liquid medium. And the thermal conductivity of the samples was measured by DRE-2C thermal conductivity tester.

3. Results and discussion

3.1. XRD

As shown in Fig. 2, anorthite is the main crystalline phase for all the four kinds of formulas and there are a small amount of the impurity phases. With 0 wt% content of gypsum, the other four observed crystalline phases are hematite, quartz, mullite and cristobalite. As the gypsum content increased, the content of the impurity phases changed a little. But when the gypsum exceeded 10 wt%, the crystalline phase of diopside started to appear and increased with the content of gypsum. Comparing the four kinds of formulas, with 10 wt% content of gypsum added, anorthite crystalline phase can be obtained with fewer impurity phases.