Optimization of ceramic thermal insulation behavior using the genetic algorithm

Amir Najah Saud[1,*], Hasan Shker Majdi[1], Safaa Najah Saud[2]

1. Dep. of Biomedical Engineering, Al-Mustaqbal University Collage, Babylon, Iraq

*2. Faculty of Information Sciences and Engineering,
Management & Science University, Shah Alam, Selangor, Malaysia*

amir.saud92@gmail.com

ABSTRACT. *The modified alumina has been classified as one of the best thermal insulation materials that able to reduce the solar radiation and enhance the working environment and thus, reduce the energy consumption. This paper emphasis the effect of the multi-variables, such as yeast cell ratio, pressing load, sintering temperatures, and socking time on the lower thermal conductivity of the modified alumina. The ceramic thermal insulation was prepared by semi-dry pressing method using alumina with different amount of the bioactive yeast cell as a pore-forming agent and 3 wt.% sugar. The optimization process was carried out via a genetic algorithm for 61 samples according to the chromosome-based. The microstructure results revealed that there are two types of pores were observed; micro and meso size pores. Furthermore, it was also found by depending on the analyzed input data that the thermal conductivity of 2.5× 10-1 watt/m.ºC was acquired at the optimal variables of 1200 ºC, 19.4 %, 66 MPa, 1.5 hrs. as sintering temperature, yeast cell, pressing load, and socking time, respectively.*

RÉSUMÉ. *L'alumine modifiée a été classée parmi les meilleurs matériaux d'isolation thermique capables de réduire le rayonnement solaire et d'améliorer l'environnement de travail, réduisant ainsi la consommation d'énergie. Ce document met l'accent sur l'effet des variables multiples, telles que le rapport de cellules de levure, la charge de compression, les températures de frittage et durée d'accrochage sur la conductivité thermique inférieure de l'alumine modifiée. L'isolation thermique en céramique a été préparée par un procédé de pressage semi-sec en utilisant de l'alumine avec une quantité différente de la cellule de levure bioactive en tant qu'agent porogène et 3% en poids de sucre.*

Le processus d'optimisation a été réalisé via un algorithme génétique pour 61 échantillons selon le chromosome. Les résultats de la microstructure ont révélé qu'il existe deux types de pores: pores de taille micro et méso. En outre, il a également été déterminé, en fonction des données d'entrée analysées, que la conductivité thermique de 2,5 × 10-1 watt/m.ºC avait été acquise aux variables optimales de 1200 ºC, 19.4 %, 66 MPa, 1.5 heures en tant que température de frittage, cellule de levure, charge de pressage et durée d'accrochage, respectivement.

KEYWORDS: *thermal insulation, semi-dry pressing, alumina, genetic algorithm.*

MOTS-CLÉS: isolation thermique, pressage semi-sec, alumine, algorithme génétique.

DOI:10.3166/ACSM.42.269-279

1. Introduction

Due to the energy costs and environmental concerns in recent years, the attention was paid to the development of the insulation materials. The main functions of these materials are mainly related to the temperature changes, in which are attributed to the porosity and density of the material that led to lower thermal conductivity, thus reduce overall energy consumption and heat losses. In addition, these materials can also play an important role in the controlling of the temperature in the industrial processes (Luyten *et al*., 2009; Arunachalam and Edwin, 2017), which can represent by the amount of heat transferred through the unit area of the material due to the difference of environment temperatures. Therefore, the porous alumina has been considered as one of the best materials for this purpose due to their low thermal conductivity, good thermal stability, low thermal capacity, low gas absorption, shock resistance, and good thermal cycling (Zhang *et al*., 2012). Moreover, increasing the percentage of porosity in the alumina materials can improve the thermal resistivity as consequences of the air trapped in the pores, which employ to improved thermal insulation and compressive strength. The main factors that affected the density of porosity in the alumina are the additives/pore-forming agents, sintering temperature, socking time, and manufacturing technique (Hirata *et al*., 2017; Dong *et al*., 2017; Tang *et al*., 2014; Xu *et al*., 2015). Yeast cell is considered one of the potential additives due to their solid cell wall structure which can harden and serve as biotemplated and withstand the pretreatment procedure (Nettleship, 1996; Lyckfeldt and Ferreira, 1998; Luo *et al*., 2015). On the other hands, it is well known that the addition of sugar to the yeast can produce a carbon dioxide (CO_2) and alcohol as a byproduct, thus led to form the micro-pores that associated with the individual clump of yeast grains (Amare and Bekalo, 2017; Pickrell *et al*., 2007). In spite of this, the technical investigation happens to be assessing the impact of limited numbers of parameters, whereby can cause elude a crucial effect in conjunction with time and cost consumption. Thus, performing the simulation engines combined with mathematical optimization algorithms variations of selected aspects tend to be interactively considered in relation to each other, to identify the optimum for a particular intention function for instance operating costs and annual energy use. One of the effectual optimization techniques is known as genetic algorithm (GA) that starts with a set of random generated individual variables called as chromosome, whereby these chromosomes are evaluated by a specific function known as fitness function. The GA operator with considering of selection, crossover and mutation based on the replacement techniques with repeating until an execution of the optimum solution (Boumaza *et al*., 2012). However, this model and algorithm was used for many optimization purposes but not yet been implemented to find out the thermal properties of the ceramic materials. Therefore, this work aims to optimize the best thermal conductivity for the modified alumina included 61 samples, were varied in terms of yeast cell concentrations, sintering temperatures, socking times, and press loadings.

2. Experimental

Alumina powder was used with an average particle size of 7µm, whereby the yeast cell and sugar were used as pore forming agents and the sodium polyphosphate as defloccunts. Alumina powder was weighed and dry mixed thoroughly in a mortar pestle with the required amount of yeast cell and defloccunts (5 batches), then followed by addition of desired volume of sugar solution so that final sugar content of the batch was 3%. The sugar solution was thoroughly blended with alumina by mixing it in agate mortar for 30 minutes, the samples were produced by semi-dry pressing in a hydraulic press (Carver Press USA) at a various load 70, 111, 143, and 213 MPa with soaking time of 90 seconds. The sample size of 20 mm Φ× 6 mm thickness was prepared and then dried in an oven at 50 °C overnight. Then the green samples were sintered in different conditions of 1200,1300, 1400, and 1500 °C and socking time of 1.5, 2, 2.5 and 3 hours.

3. Design of experimental

Five batches with different concentrations of alumina powder and yeast cell were prepared to produce the porous alumina samples. The experimental population consisted of 61 samples with each sample regarded as a chromosome and each chromosome consists of several genes. These genes were characterized by the input parameters, in the current paper; four input parameters with four levels were utilized as shown in Table 1. The fitness function or regression equation was created using a Minitab 17 software program. The regression equation obtained for thermal conductivity can be expressed as follows:

$$Thermal\ conductivity = -303 - 1.377x_1 + 0.69x_2 + 30.8x_3 + 0.219x_4 + 0.0255x_1^2 - 0.000524x_2^2 - 14.3x_3^2 + 0.00189x_4^2 + 0.000678x_1 \times x_2 + 0.0367x_1 \times x_3 - 0.00049x_2 \times x_3 - 0.000689x_1^3 + 0.000001x_2^3 + 2.17x_3^3 - 0.000005x_4^3$$

Where x_1, x_2, x_3 *and* x_4 *are* concentration of yeast cell, sintering temperature, socking time, and pressing load, respectively.

4. Results and discussion

4.1. Physical and thermal properties

The true porosity for the samples without addition yeast cell was in the range of 12.63 to 32.51 %. The data was shown that the porosity increases from 57.12 to 81.25 % with increase in the yeast cell ratios from 5 to 20 wt.% as an illustrated in Table 1. This indicates that the most of the organic addition was removed with the sintering process. The indicated results in Table 1 have shown also the same behavior in increasing the true porosity with decrease in the sintering temperature, socking time and amount of the pressing. On the other hand, the thermal conductivity changes with the variation in the volume fraction of true porosity. Moreover, it was affected by pore size, pore morphology, and the interconnectivity of the pores. There is a decrease in the thermal conductivity from 3.2 to 0.22 Watt/m.°C with increase in the amount of the yeast cell additions. This is because of the formed closer pores from the reaction of the yeast with sugar would produce carbon dioxide (CO_2) and alcohol as a byproduct. Figure 1 shows the main effect plot for thermal conductivity, compressive strength, true porosity, and bulk density to examine differences between level means for one or more factors based on value from Table 1.

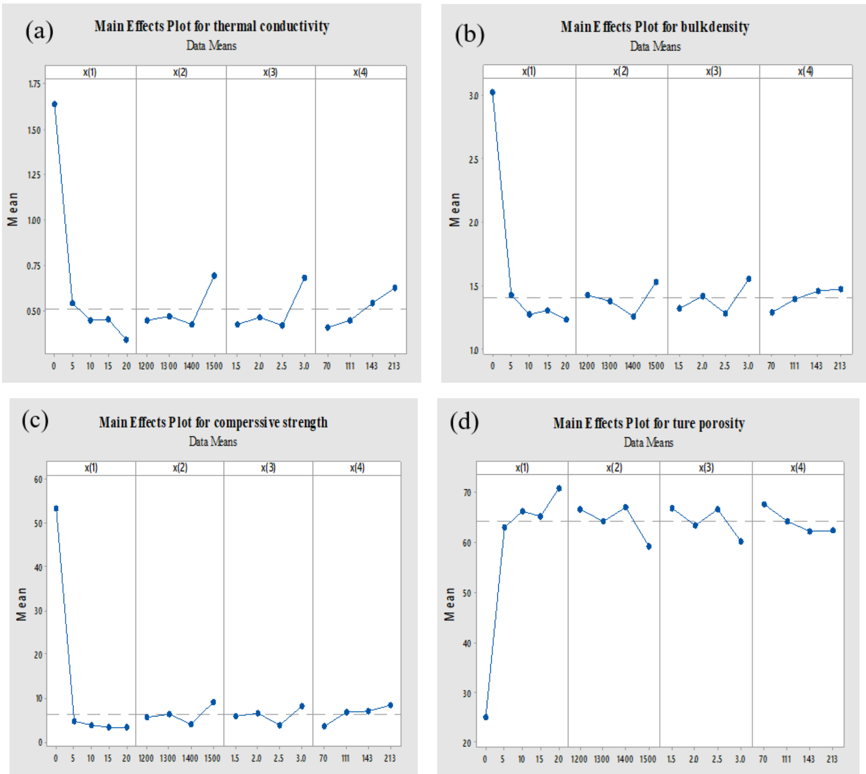

Figure 1. Main effects plot of a) thermal conductivity, b) bulk density, c) compressive strength, d) true porosity

Table 1 The experimental variables with the correspondence results

Yeast wt.%	Temperature (°C)	Socking time (hr.)	Pressing load (MPa)	True porosity (%)	Bulk density (mg/cm^3)	Compressive strength (MPa)	Thermal conductivity (Watt / m. °C)
Batch 1 (0 %	1200	2	111	32.51	2.5	39.5	0.82

	1300	1.5	143	30.24	2.75	44.61	0.9
	1500	3	213	12.63	3.82	75.89	3.2
Batch 2 (5 %)	1200	1.5	70	64.51	1.349	3.383	0.433
	1200	2	143	63.51	1.39	4.89	0.54
	1200	2.5	143	62.33	1.479	5.07	0.62
	1200	2.5	111	65.01	1.421	4.21	0.41
	1200	3	213	57.21	1.853	5.68	0.75
	1200	3	143	62.15	1.8	5.47	0.65
	1300	3	143	60.81	1.425	5.13	0.68
	1300	2.5	213	62.89	1.31	4.78	0.5703
	1300	1.5	70	66.93	1.235	4.23	0.4
	1300	1.5	111	63.64	1.3	4.39	0.534
	1300	3	70	61.25	1.51	5.11	0.62
	1400	2	70	65.76	1.328	4.62	0.411
	1400	1.5	213	63.22	1.32	4.56	0.567
	1400	3	143	58.17	1.37	5.33	0.735
	1500	1.5	70	65.04	1.36	4.32	0.42
	1500	1.5	111	67.47	1.368	4.97	0.397
Batch 3 (10 %)	1200	3	213	64.21	1.333	3.07	0.422
	1200	3	70	69.22	1.496	2.95	0.38
	1300	1.5	143	76.69	1.127	2.42	0.31
	1300	3	213	64.82	1.266	3.39	0.418
	1300	2.5	213	71.41	1.139	3.27	0.35
	1400	3	213	64.8	1.263	3.41	0.424
	1400	2.5	111	68.43	1.241	4.2	0.398
	1400	2.5	70	69.95	1.118	4.05	0.388
	1400	3	213	67.74	1.296	4.6	0.407
	1500	3	143	57.38	1.46	5	0.74
	1500	1.5	213	56.41	1.35	4.81	0.758
	1500	2.5	111	65.11	1.258	4.5	0.413
Batch 4 (15 %)	1200	1.5	70	78.71	1.101	1.51	0.29
	1200	2	143	71.03	1.211	3.06	0.36
	1200	2.5	111	68.21	1.22	2.51	0.381
	1300	2	213	66.08	1.372	3.07	0.405
	1300	3	143	66.14	1.33	2.98	0.399
	1300	2	70	68.19	1.329	2.87	0.381
	1300	2.5	70	64.44	1.428	3.12	0.413
	1400	3	70	70.8	1.122	2.93	0.379
	1400	1.5	213	68.67	1.187	3.2	0.3733
	1400	2.5	143	63.93	1.31	3.86	0.44

	1500	2	143	62.66	1.4	3.9	0.52
	1500	2	111	59.21	1.3	3.4	0.578
	1500	2	70	60.11	1.315	3.37	0.5309
	1500	3	70	56.74	1.423	3.9	0.66
	1500	3	143	55.19	1.55	5.56	0.689
Batch 5 (20 %)	1300	1.5	143	67.49	1.1	4.95	0.387
	1300	2.5	213	66.54	1.12	2.9	0.39022
	1300	3	70	69.11	1.298	5.4	0.351
	1400	1.5	70	70.1	1.244	3.1	0.343
	1400	1.5	213	68.76	1.297	5.2	0.366
	1500	2.5	213	65.38	1.411	5.8	0.391
	1500	1.5	70	69.33	1.263	3.4	0.355
	1500	1.5	143	68.28	1.315	5.35	0.361
	1200	1.5	70	80.25	0.99	1	0.232
	1200	1.5	213	78.41	1.22	1.96	0.28
	1200	2	111	78.93	1.15	1.21	0.25
	1400	2.5	111	72.84	1.27	2.31	0.321
	1500	3	111	66.33	1.33	2.52	0.44

4.2. Microstructure examination

The micrographs of the porous alumina were formed by the semi-dry pressing in the different conditions as shown in Figure 2(a-d). It can be observed that the porous microstructure varies depending on the manufacturing conditions. Furthermore, the formed macro-porous of d >50nm with the pore size ranging from the several micrometers to the nanometers. It can be clearly observed that there are pores with size of about 0.237-0.705 um which was formed by the volatility of the yeast that created pores of approximately regular and circular in shape. The pore size was decrease with increased the sintering temperature and decreased the amount of the yeast as shown in Figure 2 c and d, there are some small irregular pores with size of 0.160-0.578 um.

The porous sources are different from which the yeast was burned during the sintering process. The binder combustion and the decomposition process, and due to the evaporation of the moisture content contributed to produce pores that lead to formed open porous. Whilst, there are closed pores due to the reaction between the yeast cell and sugar lead to forming carbon dioxide gas bubbles that were formed closed the porous (Ma *et al.*, 2008).

This is because the high temperatures are associated with excessive grain growth and decomposition of the alumina powder. It was reported that the processing of alumina sample at the higher temperatures (exceeding 1400-1500 °C). The result in the exaggerated grain growth and decomposition, while the large pores were produced in the sintering bodies at 1200 °C (Honda *et al.*, 2016).

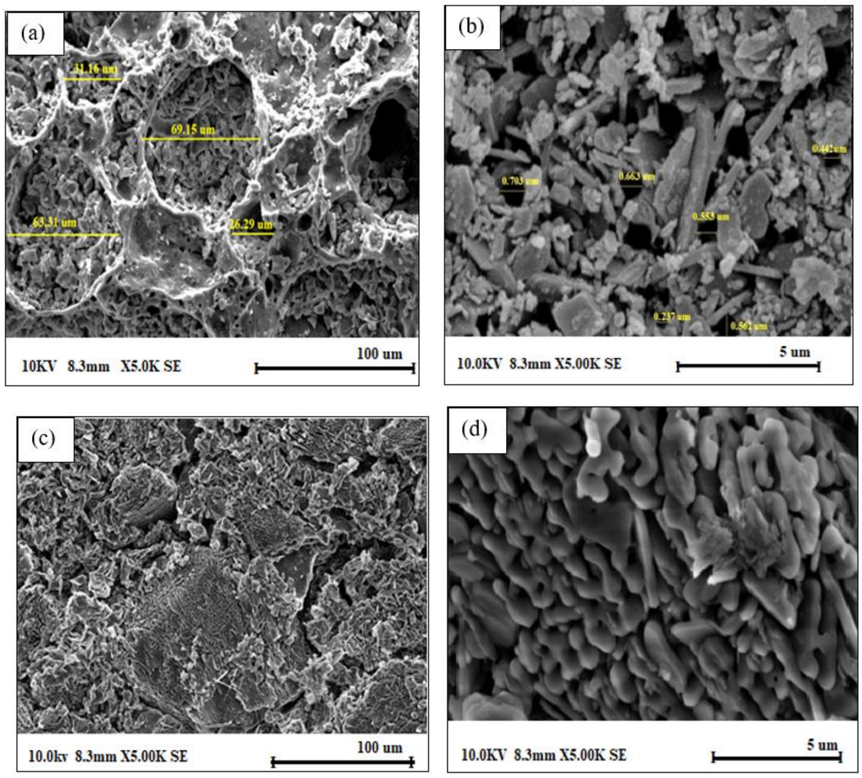

Figure 2. Micrographs of porous alumina formed by semi dry pressing of sample a) cross section with 20 wt.% calcined at 1200°C, b) at surface with 20 wt.% calcined at 1200°C, c) cross section with 20wt.% calcined at 1500°C, and d) at surface with 20 wt.% calcined at 1500°C

4.3. Porosity features

The pore size distribution, specific surface area and the isotherm type were measured by Brunauer-Emmett-Teller (BET) for meso or macro porous in range of 20 Å to below ~1500 Å. Figures 3 and 4 illustrate the N_2 adsorption/desorption isotherms for sample synthesized by semi-dry pressing at different sintering temperature. The N_2 adsorption/desorption isotherms corresponding confirm the type III isotherm with a hysteresis loop located at the relative pressure (P/P_0) range of 0.15 to1, with the average pore size of 86.6364 nm, which represent to macro-porous as shown in Figure 3. While, the type II isotherm with the hysteresis loop at the relative pressure range (0.01-1), with average pore size (3.7905 nm) which hints mesoporosity shown in Figure 4. The increase of the sintering temperature lead to decrease the pore volume. Correspondingly, at the high sintering temperature the particles become more regular and some inter-particle pores may be disappearing.

While, at the low sintering temperature was shown the high adsorption that indicate to the large surface area. The adsorption capacity of the synthesized samples decreases with the increases of the sintering temperature (Han *et al.*, 2017).

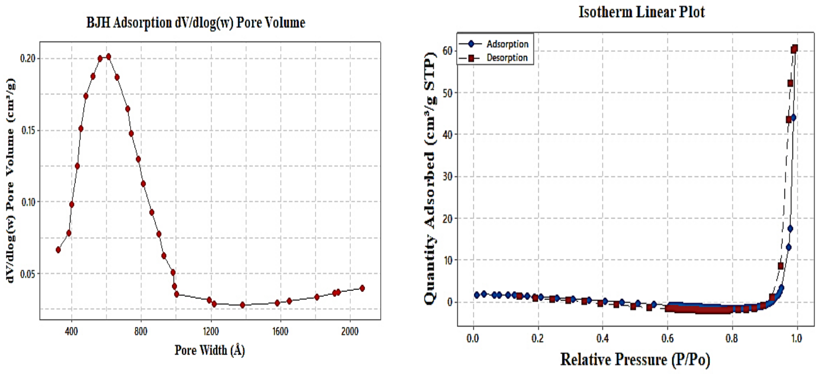

Figure 3. BET result of porous alumina prepared by semi-dry pressing of sample with 20wt% and calcined at 1200 °C

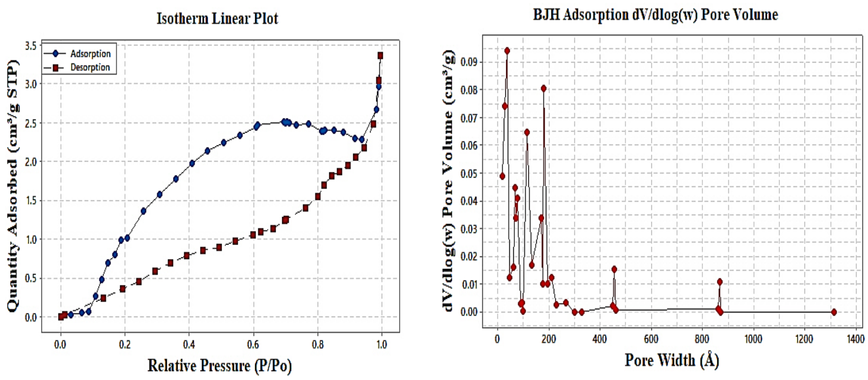

Figure 4. BET result of porous alumina prepared by semi-dry pressing of sample with 20wt% and calcined at 1500 °C

5. The objective function and parameter of genetic

The first step of the genetic algorithm is design of initial population with individual while the individual represents as a chromosome. Then the individuals were using the fitness function. The next step was to operate the population three genetic algorithm operators (reproduction, crossover, and mutation) to create new population (Faoite *et al.*, 2013).

The parameters of genetic algorithm were as follow:

(1). The objective function: The objective is minimizing the thermal conductivity. Equation 1 represents the fitness function.

(2). Initial population and number of generations: The population involves the chromosomes that form the mating pool, the chromosome represented by parameters of problem, in this case concentration of yeast, sintering temperature, socking time, and amount of pressing load represents the parameters of the problem. The population type was double vector and their size was 25 individuals.

(3). Selection crossover and mutation: The selection type was Roulette, and the new population created by combining the genes from a pair of new population selected on count of fitness. The constraint dependent was used as crossover type.

Figure 5a and b display the fitness value versus generation and the best chromosome at this value of thermal conductivity, respectively. The result agrees with experimental value of $2.32*10^{-1}$ Watt/m.°C, whereas this different in value due to some factors of uncontrolled condition, such as presence of agglomerate, moisture, and type of pores (Mohammed *et al.*, 2017).

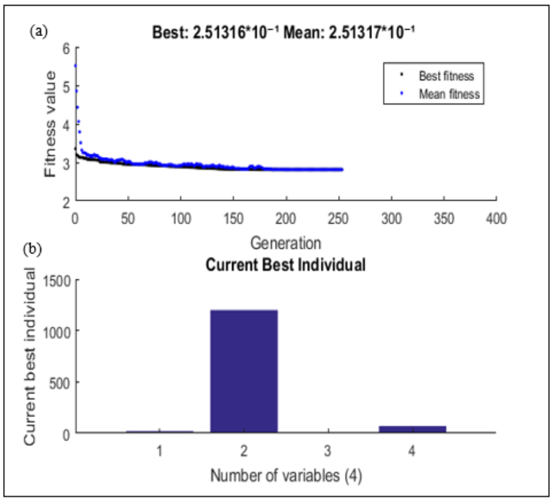

Figure 5. a) The generation versus the fitness value, b) the best individual for thermal conductivity

6. Conclusions

In this present work, the ceramic thermal insulation was fabricated by semi-dry pressing using yeast cell and sugar as pore forming agent, and the genetic algorithm was implemented to optimize the process parameters which include the ratio of yeast additive, sintering temperature, socking time, and pressing load. The closed pores with diameter larger than 100 nm dispersed in the final sintering sample that formed due to the reaction between of the yeast cell and sugar whereby led to the formation of the carbon dioxide gas bubbles that were formed closed the porous or due to volatility of the yeast. When the additive amount of yeast cell was (20wt%), the true porosity of ceramic thermal insulation of 81.25 % with the increasing the true porosity of ceramic thermal insulation, the thermal conductivity decreases from 3.2-0.232 Watt/m.°C at room temperature. The best thermal conductivity using genetic algorithm of $2.5*10^{-1}$ Watt/m. °C was agreed with the experimental result of 2.32 $*10^{-1}$ Watt/m.°C, with a slight difference between these values due to the uncontrolled conditions.

Reference

Amare Z. E., Bekalo T. B. (2017). Clay ceramic filter for water treatment. *Materials Science and Applied Chemistry*, Vol. 34, No. 1, pp. 69-74. http://dx.doi.org/10.1515/msac-2017-0011

Arunachalam U. P., Edwin M. (2017). Theoretical investigation of a ceramic monolith heat exchanger using silicon carbide and aluminium nitride as heat exchanger material. *International Journal of Heat and Technology*, Vol. 35, No. 1, pp. 645-650. http://dx.doi.org/10.18280/ijht.350323

Boumaza A., Djelloul A., Guerrab F. (2010). Specific signatures of α-alumina powders prepared by calcination of boehmite or gibbsite. *Powder Technology*, Vol. 201, No. 2, pp. 177-180. http://dx.doi.org/10.1016/j.powtec.2010.03.036

Dong X., Wang M., Guo A., Zhang Y., Ren S., Sui G., Du H. (2017). Synthesis and properties of porous alumina ceramics with inter-locked plate-like structure through the tert-butyl alcohol-based gel-casting method. *Journal of Alloys and Compounds*, Vol. 694, pp. 1045-1053. http://dx.doi.org/10.1016/j.jallcom.2016.10.153

Faoite D. D. B., David J., Stanton, K. T. (2013). Regression analysis of temperature-dependent mechanical and thermal properties of dielectric technical ceramics. *Journal of Materials Science*, Vol. 48, No. 1, pp. 451-461. http://dx.doi.org/10.1007/s10853-012-6759-6

Han M., Yin X., Cheng L., Ren S., Li Z. (2017). Effect of core-shell microspheres as pore-forming agent on the properties of porous alumina ceramics. *Materials & Design*, Vol. 113, pp. 384-390. http://dx.doi.org/10.1016/j.matdes.2016.10.043

Hirata Y., Fujita H., Shimonosono T. (2017). Compressive mechanical properties of partially sintered porous alumina of bimodal particle size system. *Ceramics International*, Vol. 43, No. 2, pp. 1895-1903. http://dx.doi.org/10.1016/j.ceramint.2016.10.149

Honda S., Hashimoto S., Yase S., Daiko Y., Iwamoto Y. (2016). Fabrication and thermal conductivity of highly porous alumina body from platelets with yeast fungi as a pore forming agent. *Ceramics International*, Vol. 42, No. 12, pp. 13882-13887. http://dx.doi.org/10.1016/j.ceramint.2016.05.196

Luo Y. (2015). Effect of yeast cell morphology, cell wall physical structure and chemical composition on patulin adsorption. *PloS One*, Vol. 10, No. 8, pp. e0136045. http://dx.doi.org/10.1371/journal.pone.0136045

Luyten J. S., Mullens J., Cooymans A. Wilde D. M., Thijs I., Kemps R. (2009). Different methods to synthesize ceramic foams. *Journal of the European Ceramic Society,* Vol. 29, No. 5, pp. 829-832. http://dx.doi.org/10.1016/j.jeurceramsoc.2008.07.039

Lyckfeldt O., Ferreira J. M. F. (1998). Processing of porous ceramics by 'starch consolidation'. *Journal of the European Ceramic Society,* Vol. 18, No. 2, pp. 131-140. http://dx.doi.org/10.1016/S0955-2219(97)00101-5

Ma C., Chang Y., Ye W., Shang W., Wang C. (2008). Supercritical preparation of hexagonal γ-alumina nanosheets and its electrocatalytic properties. *Colloid Interface Sci*., Vol. 317, pp. 148-154. http://dx.doi.org/10.1016/j.jcis.2007.07.077

Mohammed A. Ahmed A. D., Shaker J. (2017). Hasanain Nadhim Abbas: Preparation of HA/β-TCP scaffold and mechanical strength optimization using a genetic algorithm method. *Journal of the Australian Ceramic Societ*. http://dx.doi.org/10.1007/s41779-016-0007-5

Nettleship I. (1996). Applications of porous ceramics. *Key Engineering Materials,* pp. 122-124, 305-324. https://doi.org/10.4028/www.scientific.net/KEM.122-124.305

Pickrell G. R. (2007). Porous ceramic, polymer and metal materials with pores created by biological fermentation. *U.S. Patent,* No. 7. http://dx.doi.org/10.1016/US7157115 B2

Tang Y. F., Miao Q., Qiu S., Zhao K., Hu L. (2014). Novel freeze-casting Fabrication of aligned lamellar porous alumina with a Centro symmetric structure. *Journal of the European Ceramic Society,* Vol. 34, No. 15, pp. 4077-4082. https://doi.org/10.1016/j.jeurceramsoc.2014.05.040

Xu G., Li J., Cui H., He Q., Zhang Z., Zhan X. (2015). Biotemplated fabrication of porous alumina ceramics with controllable pore size using bioactive yeast as pore-forming agent. *Ceramics International,* Vol. 41, No. 5, pp. 7042-7047. https://doi.org/10.1016/j.ceramint.2015.02.007

Zhang L., Du J. H., Gan G. Y., Yan J. K., Yi J. H. (2012). Preparation and characterization of porous alumina insulation materials by gel-foaming. *In Advanced Materials Research,* Vol. 412, pp. 207-210. http://dx.doi.org/10.4028/www.scientific.net/AMR.412.207