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Thermal Conductivity Optimization of Porous Alumina Ceramics via Taguchi Model

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Abstract. A comparative analysis of the thermal conductivity for porous alumina using Taguchi method has been reported in the current research. Porous alumina is one of the most critical ceramics amongst those that are widely used in the thermal insulator industry; this is because of their physical properties. Thus, the investigation of these properties is highly desirable. Test variables were performed for the thermal conductivity studies-weight per cent of a pore-forming agent (yeast), sintering temperature, and soaking time. Through implementing the experimental design using the Taguchi method for thermal conductivity of porous alumina was statistically analyzed. The Signal-to-noise ratio and variance analysis investigated the influence of different parameters on the porous media's thermal conductivity. The result of research determines that the addition of the pore-forming agent obtained a higher thermal insulator. Based on the optimum conditions obtained from the Taguchi method factor was 20wt.% weight of yeast cell , sintering temperature at 1200 C , and the holding time 1.5 h. that give higher value of the S/N ratio.

Introduction

The porous ceramics have an aroused growing interest due to the diversity of areas in which it can be applied, such as catalytic supports, solid particle collectors, fuel and liquid metal filters, reactor membranes, and thermal insulation in furnace coatings [1-5]. The main properties make them suitable for a variety of applications, where the presence of high temperatures and chemical aggression does not allow the use of metallic or polymeric materials. Correctly, the forms as thermal insulators at high temperatures (above 1200 °C), It is used particularly vital as it combines the high refractoriness of the dense phase with lower thermal conductivity of the porous phase [6].

Notwithstanding this is an excellent performance, such systems still have two main limitations: a) the low thermomechanical resistance due to the high porosity (mainly in those materials with pore volume fraction above 50%) and b) the reduction of porosity caused by sintering and grain growth phenomena which intensify above 1100 °C [7]. Several studies demonstrate that it is appropriately combining raw materials and processing techniques; these negative aspects can be minimized [8-9]. Maintaining porosity at the high temperatures can be achieved via increasing the initial pore fraction in green material, with controlled heating and sintering ramps [10]. At the high temperatures, porous ceramics are the most promising. Two main characteristics are responsible for such efficiency: the low thermal conductivity of the porous phase, and the high refractoriness and chemical inertia of the dense matrix [11]. However, in addition to these requirements, there is also a need for the product to withstand mechanical stress, which may be a limiting factor if the porosity of the structure is very high. It is also important to mention that while having slightly lower thermal insulation efficiency than systems based on compacted ceramic fibers. But, the monolithic microporous ceramics do not have the same levels of complications related to exposure to toxic particles. Theoretical studies also indicate the possibility of developing porous structures that combine high mechanical strength and low thermal conductivity by controlling the average pore size [6]. The results point to a microstructure with a total porosity close to 80% and pore with an average diameter smaller than 20 μm [11]. Additionally, to their thermomechanical characteristics, thermally insulated porous ceramics must also have stable pores.

Taguchi method is a method of product optimisation that depends on specific stages of planning, conducting, and evaluating the results of matrix experiments to determine appropriate steps of optimal control factor levels [12-13]. Therefor, and various studies have been carried out successfully by using this technique to optimise the different processes. Because of primary goal is to make the output variance very low even in the presence of noisy input [14-19]. The Taguchi method involves determining sufficient control factors to get the process's best results. A selection of experiments is made using orthogonal arrays (OA). The results of those experiments are used to analyse the data and predict the output of the generated components. The main objective of the current work is to investigate the effect of parameters by selecting three factors such as (weight per cent of a pore-forming agent (yeast), soaking time, and sintering temperature on porous alumina's thermal conductivity behaviour using Taguchi's three-level process. The influence of parameters was studied via analysing the means and variance of experimental results. A mathematical equation was established to forecast the thermal conductivity of porous alumina ceramic by multiple linear regression.

Experimental Procedure

Using the slip casting the porous alumina was prepared as been described in [3]. There are different samples prepared based on the variation of the pore-forming agent (yeast) concentrations.

Experimental Design

The implementation of the Taguchi method can be illustrated with the help of a flow diagram shown in Fig. 1. Experiments were performed according to a conventional orthogonal array. The selection of the orthogonal matrix is made based on complaints that the degree of freedom of the orthogonal array must be greater than or equal to those of thermal conductivity control or control parameter/factor sum. The thermal conductivity factors (control parameters) selected for the experiments. E-each row in the L16 orthogonal array represents individual experiments, and the columns were allocated to different factors or parameters [14-15].

The experimental results are converted into S/N ratio in Taguchi's method to be used in the calculation of quality features. The "lowest" mass characteristic was used in the current study to evaluate the thermal conductivity of porous alumina because it provided the minimum thermal conductivity value. Calculate the S/R of each process factor level, based on the S/R analysis. Furthermore, the Statistical Variance Analysis (ANOVA) was applied to determine the statistically significant parameters [16].

The S/N ratio for thermal conductivity specified by Taguchi as given below:

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\right)\{y_1^2 + y_2^2 + - - - - - - - + y_n^2\} \quad (1)$$

Wherein, the thermal conductivity response is represented by y_1, y_2,.... y_n, and n is representing the number of observations. The "better" characteristics and conversion of the signal-to-noise ratio are suitable for minimizing thermal conductivity. The control parameters were statistically analyzed and an ANOVA model was applied to predict the best relation between the thermal conductivity and achieve the best level of accuracy along with implementing the signal-to-noise ratio [17-19] and the extracted data are tabulated in Table 1 with an average of specific features at each factor level. The obtained data are shown depending on the incremental statistics, which match the relative values of the effects. The signal-to-noise ratio is a response that combines the impact of recursion and noise levels into a specific data point.

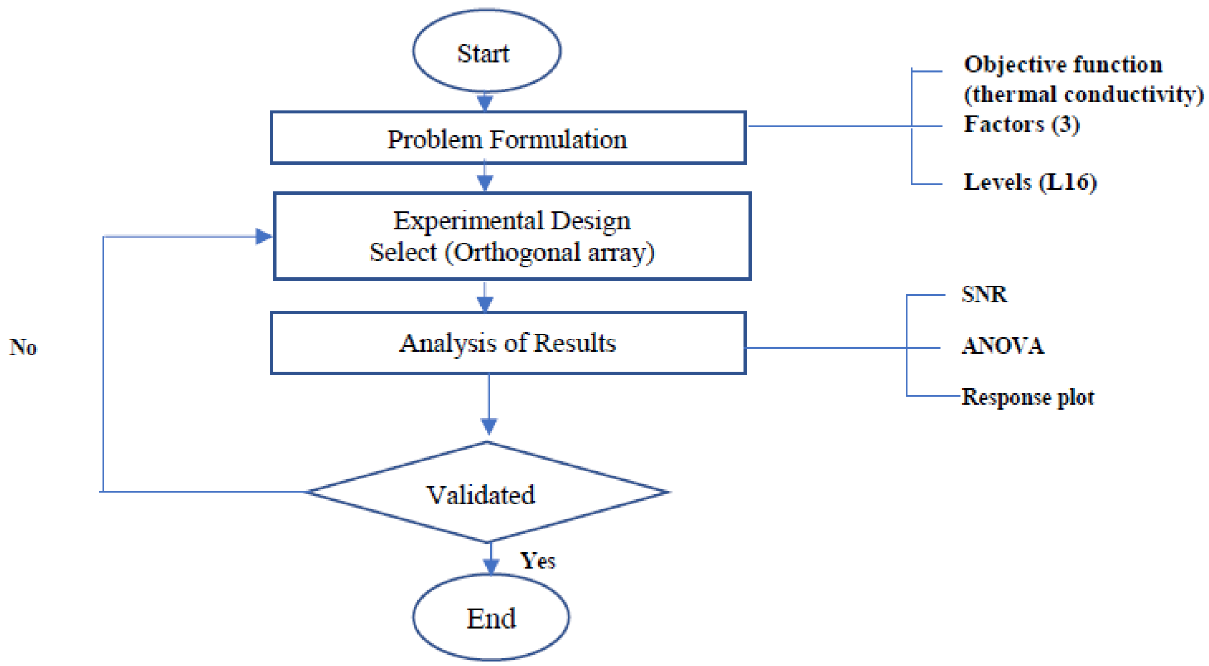

Fig. 1. Flow diagram of Taguchi method.

Table 1. Experimental design.

yeast %Wt.	temperature °C	Soaking time (hrs.)	True porosity	Density	Thermal cond.	S/N Ratio for thermal cond. (db)
0	1200	1.5	42.580	1.825	0.7000	-32.5841
0	1300	3.0	28.280	2.315	1.1300	-29.0296
0	1400	3.0	22.390	2.656	1.2700	-27.0011
0	1500	3.0	14.260	3.600	4.1900	-23.0824
5	1200	2.0	69.170	1.217	0.4010	-36.7984
5	1300	1.5	67.550	1.196	0.4002	-36.5925
5	1400	3.0	62.570	1.122	0.5540	-35.9273
5	1500	2.5	61.370	1.333	0.5370	-35.7591
10	1200	2.5	69.370	1.000	0.3630	-36.8234
10	1300	2.5	69.053	1.117	0.3760	-36.7837
10	1400	1.5	66.430	1.355	0.4880	-36.4473
10	1500	2.0	66.290	1.235	0.5210	-36.4290
20	1200	3.0	71.520	1.197	0.3280	-37.0886
20	1300	2.5	67.320	1.254	0.4770	-36.5629
20	1400	2.0	71.200	1.211	0.3050	-37.0496
20	1500	1.5	66.220	1.227	0.4210	-36.4198

Results and Discussion

The primary purpose of understanding the experiment is to determine the highest dominant factor and a mix of factors that have an extreme effect on the thermal conductivity to minimize its value. Tests were performed based on orthogonal arrays, which correlate the influence of control parameters on the properties of porous alumina ceramics.

To establish the influence of specific factors, experimentally obtained values were converted into the S/N ratio. Also, the investigated were effects of the thermal conductivity control factors that are weight % of a pore-forming agent (yeast), soaking time, and sintering temperature on the thermal insulator to obtain the S/N ratio. The main factor that affects the thermal conductivity is weight % of a pore-forming agent (yeast) followed by soaking time and lastly, by sintering temperature depending on the ranking in Table 2.

Table 2. Response of S/N for thermal conductivity.

Level	yeast %Wt.	Temperature °C	Soaking Time (hrs.)
1	-27.92	-35.82	-35.51
2	-36.27	-34.74	-36.76
3	-36.62	-34.11	-36.48
4	-36.78	-32.92	-30.43
Delta	8.86	2.90	6.33
Rank	1.00	3.00	2.00

Fig. 2 (a, b) shows the main effects of different test factors on thermal conductivity. In the main impact, if the line of a particular factor is close to the surface, it means that the factor has no substantial effect. On the other hand, the coefficient of the maximum slope of the line has a great influence. The most significant effect on the thermal conductivity is shown by the weight% of the pore-forming factor (yeast), while other factors show lighter results. The thermal conductivity decreases with the weight% of the pore-forming agent (yeast), while it increases with the temperature sintering. The lowest thermal conductivity is shown at the highest percentage of pore-forming factor (yeast) and the lowest sintering temperature. Fig.3 shows the relevant interactions of all the analyzed factors and their effect on thermal conductivity

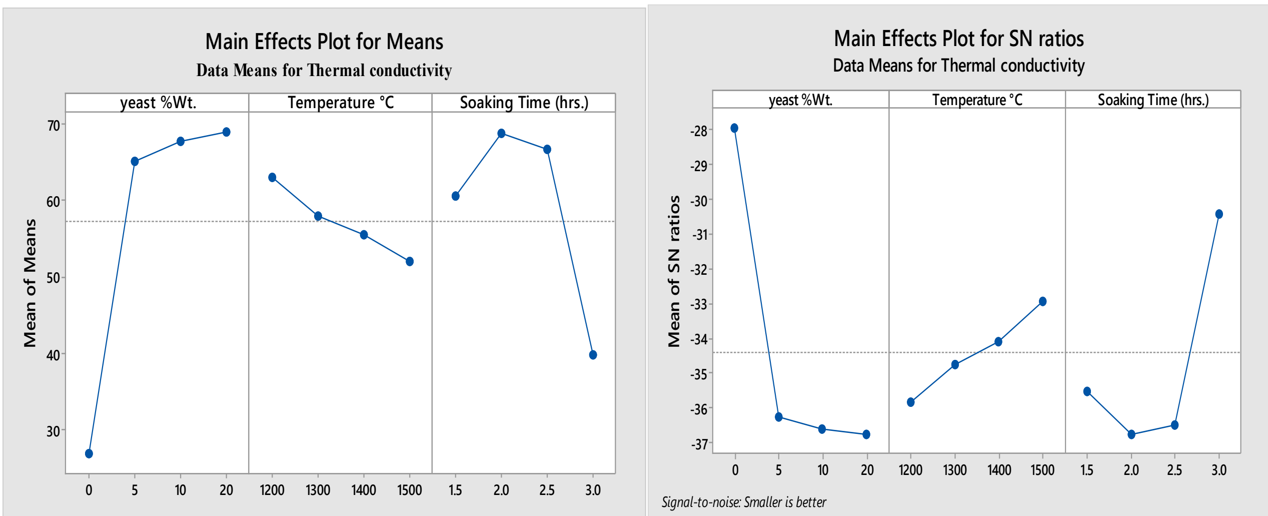

Fig. 2. (a) Main effect plots for means and (b) Main effect plots for S/N ratio for thermal conductivity for porous alumina.

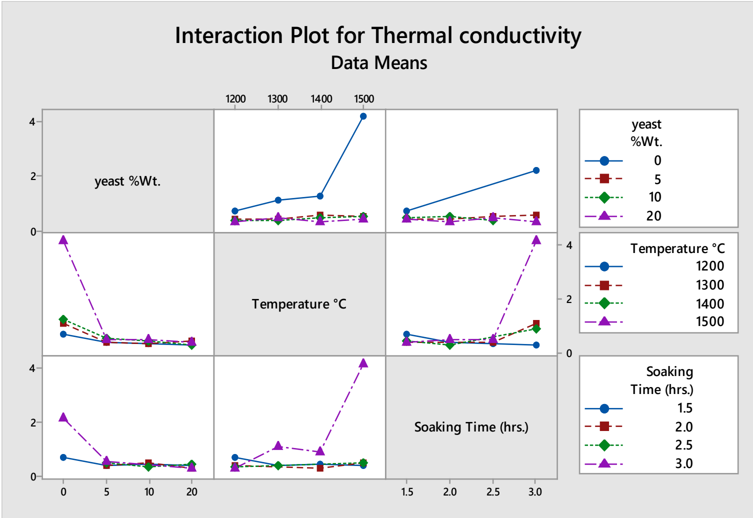

Fig. 3. Interactions plots for means- for thermal conductivity for porous alumina.

ANOVA Technique

The Taguchi test can't cause adverse effects, and therefore the experimental results were evaluated using variance analysis (ANOVA). The ANOVA is practical to investigate the effect of factors, like weight % of a pore-forming agent (yeast), sintering temperature and Soaking Time, as well as their optimal level. Within the ANOVA method, you can also determine the effect of specific factors on thermal conductivity and the percentage of that effect. The results of ANOVA are listed in Table 3 for the thermal conductivity, and three factors analyses, which differ at different levels and their interactions.

The significance level for this analysis was 0.05, which is a 95% confidence level. Sources with a P value of less than 0.05 are considered to have a statistically significant impact on performance indicators. The proportional effects of each factor and the extent to which they affect the overall result are introduced.

Table 3. The ANOVA results of compounds in terms of thermal conductivity in this research, it can be observed that the most influencing factor on thermal conductivity is applied by weight% of the pore-forming agent (yeast) (P = 75.42%). The second-largest effect is the sintering temperature (P = 13.45%). The least specific is socking time to take (P = 3.20%). The remaining error in the ANOVA table was about 7%.

Table 3. Analysis of Variance by (ANOVA) for thermal conductivity.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-Value
yeast %Wt.	3	1.38773	75.42%	0.73608	0.24536	10.13	0.009
Temperature °C	3	0.24798	13.458%	0.25114	0.08371	3.46	0.092
Soaking Time (hrs.)	3	0.05881	3.20%	0.05881	0.01960	0.81	0.533
Error	6	0.14537	7.90%	0.14537	0.02423		
Total	15	1.83990	100.00%				

Multiple Linear Regression Models

The multi-linear regression model of vehicle wear rates was developed with the help of the MINITAB 17 Statistical Program. The generated model provides linear dependency for the non-specified variable over the selected variables. In the current investigation, the direct dependence of the thermal conductivity on the weight % of a pore-forming agent (yeast), soaking time, and sintering temperature. A linear regression equation was obtained with the aid of ANOVA analysis, and the values of weight pore-forming agent (yeast), sintering temperature, and socking time were given:

$$\textbf{Thermal conductivity} = (5.52 + 0.0768 \text{ Yeast \%Wt.} - 0.00255 \text{ Temperature °C} - 0.317 \text{ Soaking Time (hrs.)})^{-1} \quad (2)$$

The analytical expressions of relevance to model and equation. As shown in Fig. 4, the individual probability plot of the residuals has been used to confirm the acceptability of the model characterized by Eq. 2. These points are very close to the standard probability line. Therefore, there is considerable evidence that the model is acceptable. Accordingly, as characterized by Eq. 2, the model is configured to calculate the thermal conductivity of porous alumina ceramics.

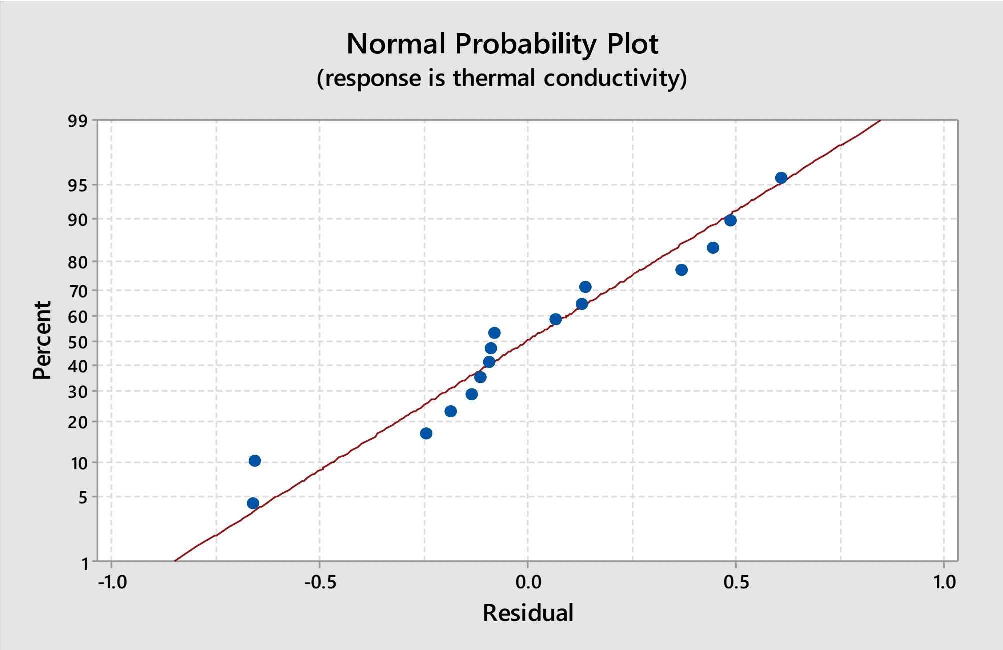

Fig. 4. Normal probability plots of residuals for thermal conductivity for porous alumina.

Conclusions

Taguchi's robust orthogonal matrix design, as described in the study, can be used to analyse the thermal conductivity of porous ceramic alumina. Below are the conclusions to be drawn:

1. The thermal conductivity decrease with increasing the weight of pore-forming agent, while its increase with increase the sintering temperature and socking time

2. The Taguchi method's factor design provides a simple, systematic and efficient way to improve the thermal conductivity of porous ceramic alumina factors. Based on the optimum factor was 20wt.% weight of yeast cell , sintering temperature at 1200 C , and the holding time 1.5 h. that give higher value of the *S/N* ratio.

3. The best thermal conductivity investigation parameters can be used to calculate the estimated S / N ratio, and good agreement has been observed between the expected and actual thermal conductivity of 99.5% confidence.

4. The linear regression equation used for the current study was used to calculate thermal conductivity and is well compatible with experimental data.

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