THE POROSITY DEPENDENCE
OF MECHANICAL PROPERTIES OF SINTERED ALUMINA

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ABSTRACT

The mechanical behaviour of highly porous alumina has been investigated with special reference to the porosity (density) dependence of Elastic modulus, Flexural and Compressive strength. The tests were carried out on alumina specimens prepared using a hydrogen peroxide as a creator of pores with porosities ranging from 0.55 to 0.80. A number of models have been presented to predict the mechanical properties of cellular materials in terms of geometric parameters of an assumed unit cell. In this study the obtained mechanical properties were correlated with the relative density using the simple Gibson and Ashby’s mechanical model and with the porosity using semi-empirical expressions of exponential type. The measured values for E-modulus and Flexural strength are in good agreement with the calculated ones, but the Compressive strength deviated from predicted modeling behaviour.

Keywords: sintered alumina, porous materials, mechanical properties.

INTRODUCTION

In the development of pure oxide ceramics, sintered alumina and zirconia have been shown to possess high mechanical strength compared with other ceramic products. It is therefore of interest to consider them as construction materials. Construction materials, however, must be evaluated not only by their strength as such, but also by the ratio of the strength to the apparent specific mass of the material. The only expedient way of increasing this ratio is to lower the specific mass of the body. This can be achieved by producing ceramics with considerable porosity. It is evident, however, that with increased porosity the strength of the resulting body will decrease. The relative gain or loss will depend, then, on the rates at which the strength and the specific mass decrease [1]. In their review of cellular materials, Gibson and Ashby [2], point out that the porous materials can have higher specific mechanical properties relative to fully dense materials. Also, Brezny and Green [3] have considered a number of parameters for cellular ceramics and have shown that these materials can offer advantages in structural applications over dense ceramics.

However, there are many applications in which the use of porous materials can be advantageous, e. g., refractories, high temperatures filters, catalytic substrates, membranes, biomaterials, thermal insulations, gas burner materials, etc. Although the primary function of
these materials may not be structural, many of these applications require a high degree of mechanical reliability. Indeed, it is reasonable to suppose that improvements in the mechanical properties of porous ceramics will open up new technological applications [4].

The simplest classification of porous ceramics is with respect to the volume fraction (P) of the porosity. The ceramics with P>0.70 are called high porosity materials [4]. These materials are commercially available in two large groups: fibrous and cellular. Cellular ceramics are fabricated in two-dimensional (honeycombs) and three-dimensional (foams) macrostructures. Three-dimensional structures can be further sub-classified as open cell or closed cell depending on whether or not the individual cells possess solid phase [5]. There is clearly a possibility that foams can be partly open and partly closed.

In order to understand the mechanical behaviour of cellular materials, and be able to tailor the properties to specific applications, it is critical to understand the relationships between the properties and foam parameters such as porosity and relative density. Several expressions have been proposed for describing these relationships. Some of the models for mechanical properties of highly porous materials have a better theoretical basis. These apply elastic thin-beam to the idealized 2- and 3-dimensional structures and predict exponential or power law relationships between the fractional density and geometrical features of the cell structure in the porous material. The best known of the high porosity level models originate from Ashby’s group [6]. Other models have been proposed for limited ranges of porosity levels by Nielsen [7], Gent & Thomas [8], Rice [9], Wignier [10] and Green [11].

All of the expressions predict extremely sensitive relationships between properties and porosity levels. However, none apply over a wide density range, at best the constants are poorly related to microstructural features, and all of the constants change with relatively minor variations in the materials. In general, the modulus and hardness data are better behaved than strength, fracture toughness and fracture surface energy data which exhibit a great deal of variation about predicted values [12]. The models developed to describe the behaviour of porous materials are very general and shown only the basic relationships between the parameters in the model. So, when working with such materials whose properties are very sensitive to the microstructure one must be careful when using these simple models to predict mechanical properties.

**EXPERIMENTAL**

**Sample preparation**

As an initial material used for sintered alumina was chemically pure aluminum oxide powder, (TAIMICRON, TM-DR, Taimet, Japan). Its chemical composition and physical properties declared by the manufacturer are given in Table 1. The morphology of the powder is shown on a SEM micrograph, Fig. 1.

To obtain the desired degree of porosity in ceramic body various methods were used. For this purpose a polystyrene, polyurethane foam and hydrogen peroxide as a creator of pores were used. The best re-

<table>
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<th>Table 1. Characterization of Alumina powder.</th>
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<tr>
<td>Mean particle size, μm</td>
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<td>Specific surface area, m² g⁻¹</td>
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<tr>
<td>Density, (non fired). g cm⁻³</td>
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<td>Fired density, at 1350 °C, 1h, g cm⁻³</td>
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<td>Dislocation density, cm⁻²</td>
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<td>Purity of Al₂O₃, %</td>
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<td>Impurities, ppm</td>
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Fig. 1. SEM micrograph of the Al₂O₃ powder (bar, 1μm).
sults were obtained using a definite quantity of hydrogen peroxide with concentration from 1 to 3%. After several preliminary experiments the slurry was prepared with constant mass ratio $\text{Al}_2\text{O}_3 : \text{H}_2\text{O}_2 = 10 : 3.5$. The other parameters of the procedure were: a temperature of evolution of oxygen from 20 to 50°C, drying at 100°C during total time of 12 h, a temperature of presintering was 1200°C and temperature of sintering from 1300 to 1500°C with constant time of isothermal treatment of 3 h. As a result of these operating conditions a ceramic bodies with porosities ranging from 0.55 to 0.80 were obtained. The densities (porosities) of sintered specimens were determined from their weights and dimensions. The relative density was estimated from the ratio of the density of the sample to the theoretical density (3.96 g cm$^{-3}$) of alumina.

**Mechanical tests**

To determine the Flexural strength and Young’s modulus the standard three points bending method was used. The practical measurements were conducted on an apparatus of type NETZCH 403. The specimens with dimensions of 6 mm x 5 mm x 30 mm were diamond machined from previously prepared blocks. The values for Flexural strength (sf) and Young’s modulus (E) were calculated according to the following relations:

$$\sigma_f = \frac{3FL}{2bh^2}$$  \hspace{1cm} (1)

where:

- $\sigma_f$ - Flexural strength, MPa,
- $F$ - applied force, N,
- $L$ - length of sample, mm,
- $b$ - width of sample, mm,
- $h$ - height of sample, mm.

$$E = \frac{FL^3}{4bh^3f}$$  \hspace{1cm} (2)

where:

- $E$ - Young’s modulus, GPa,
- $f$ - deflection, mm.

Compressive tests were performed at room temperature on an INSTRON 1343 machine with computer support. The specimens were cut into cubes having an unit length of approximately 10±1 mm. Before testing,
each specimen was carefully measured to the closest 0.1 mm and the area of the surface was calculated.

**RESULTS AND DISCUSSION**

The graphical presentations of the results obtained with highly porous sintered alumina are shown at Figs. 2, 3 and 4. The abscissa represents the porosity of specimens in a volume fraction; the ordinate indicates the strength in MPa for Flexural and Compressive strength and Young’s modulus in GPa, respectively. It is obvious that all characteristics decreased with the increasing of porosity because they are generally supposed to be contradictory properties.

The curves could be described with a simple well-known semi-empirical expression for $E$, based on load-bearing section arguments for a packing of solid spheres, given by:

$$\frac{E}{E_o} = \exp(-b_1 P)$$

where $b_1$ is a characteristic exponent that depends on the way the spheres are stacked, $P$ is volume fraction of porosity and $E_o$ is the Young’s modulus in the absence of any porosity [13]. For a simple cubic packing with coordination number of 6, the value of $b_1$ is about 6.

For high porosities, Rice [9], suggested a complementary relationship based on a model with spherical pores in a solid matrix:

$$\frac{E}{E_o} = 1 - \exp(-b_2 (1-P))$$

where $b_2$ is again a characteristic exponent with a value of about 0.5 for a simple cubic pore distribution.

The best fitting of our results is obtained in accordance with equation (3) although porosities range was 0.55 to 0.8, giving the following expressions for Flexural strength (5) and Young’s modulus (6):

$$\frac{\sigma}{\sigma_o} = \exp(-4.74 + P) \quad R = 0.94 \quad (5)$$

$$\frac{E}{E_o} = \exp(-5.25 + P) \quad R = 0.84 \quad (6)$$

It can be noted that there is a high level of matching of the results with the calculated ones according to the given equation for Flexural strength (5), (coefficient of correlation - 0.94). On the other hand, there is a slightly higher scattering of results for Young’s modulus (6), (coefficient of correlation - 0.84). Despite this, already given relations describe very well the change of Flexural strength and Young’s modulus with the porosity in even extensive interval of porosities (0.55–0.80). In this case the values for $E_o = 400$ GPa and $\sigma_o = 550$ MPa.

The results for compressive strength as a function of volume fraction of porosity are shown in Fig. 4. It is obvious that there is a high dispersion of experimental results. Despite that, an attempt was made for setting in order the results for compressive strength, excluding the results that show enormous error. Thus ordered results can be approximated with the following analytical dependence of exponential type:

$$\sigma = 459.857 \exp(-4.46 + P) \quad R = 0.48 \quad (7)$$

The low coefficient of correlation proved the previously mentioned. The samples exhibited significantly different behaviour as a function of porosity due to their sensitivity to the method of load application, which means the uniformity of load distribution over the entire contact surface. This disagreement is attributed to the dramatically different failure mode which is characterized by a damage accumulation process [5].

One of the more recent models was developed by Gibson and Ashby and has been applied to metal, polymer and ceramic systems. The simple geometry of the G-A model for open-cell materials has allowed the development of a large number of mechanical property relationships for both elastic-brittle and plastic systems. Using standard beam theory Gibson and Ashby determined the deflection of the cell struts in the unit cell, and by relating the applied stress to the force acting on the struts, by substitution and assuming $C_t = 1$, one can relate the modulus to the normalized density as:

$$\frac{E}{E_o} = C\left(\frac{\rho}{\rho_i}\right)^n$$

where $E$ and $E_o$ are the Young’s modulus of the porous structure and the struts, respectively. $(\rho/\rho_i)$ is relative
density i.e. the density of porous structure ($\rho$) normalized by the theoretical density of solid, $(\rho_s)$, $C$ is a geometric constant and $n$ is density exponent. Comparing this equation with experimental data on open-cell materials, Gibson and Ashby conclude that $C \approx 1$ (0.65) and $n = 2$ (1.5).

The results of the Flexural strength and Young’s modulus were analyzed according to this model with relative density as independent parameter. In this case there is not reason to analyze the results for Compressive strength due to enormous dispersion of data.

The graphs are presented in Figs. 5 and 6 and show straight-line relationships on a logarithmic scale.

In both equations, there is disagreement between the measured values of the geometric constant $C$ and those suggested by Gibson and Ashby. This discrepancy can be explained in terms of microstructure complexity resulting from the processing of specimens. The GA model is based on a cubic unit cell where the deformation is controlled by the bending of the individual struts within the unit cell. In fact, this model assumed an idealized open-cell structure. The obtained porous bodies in this study are characterized with different cell size and showed considerable inhomogeneity of the macrostructure. On the other hand, all specimens used in the study were found to contain both open- and closed- or partially closed cells. Finally, due to capability of apparatus, the specimens were limited to maximum height of 6 mm, which additionally influences on the measured values.

The obtained dependences are expressed with equations (9) and (10), respectively.

The values of the exponent on the relative density term in both expressions are given by the slope of the data. Although there is considerable scatter from theoretical exponent of 2, these values are in good agreement with the work of Gibson and Ashby for open-cell materials.

**CONCLUSIONS**

The dependence of strength characteristics with volume fraction of porosity (relative density) of highly porous sintered alumina bodies was investigated. In this study the obtained mechanical properties were correlated with the total volume porosity using semi-empirical expressions of exponential type and with the relative density using the simple Gibson and Ashby’s mechanical model.

In both cases the experimental data for Flexural strength and Young’s modulus have indicated good agreement with predicted ones. The compressive strength as a function of porosity (relative density) was observed to deviate from predicted behaviour and shows a substantial discrepancy between the experimental data and that by the models.

The deviations from the predicted behaviour can be due to a number of factors such as an incorrect assumption in the deformation mode in these materials, deviation from fully open-cell geometry due to presence of partially closed or filled cells, the size of samples

![Graph](image1)

Fig. 5. Normalized Flexural strength as a function of relative density.

$$\frac{\sigma}{\sigma_0} = 0.42 \left( \frac{\rho}{\rho_s} \right)^{2.1} \quad R = 0.96 \quad (9)$$

![Graph](image2)

Fig. 6. Normalized Young’s modulus as a function of relative density.

$$\frac{E}{E_0} = 0.23 \left( \frac{\rho}{\rho_s} \right)^{1.8} \quad R = 0.83 \quad (10)$$
or the inability of the models to accurately describe samples in this porosity (density) range.

Therefore, there is no single model which appears capable of describing the mechanical behaviour of cellular materials as a function of the single parameter characterizing the volume fraction of the porosity or the relative density.

REFERENCES