The Influence of Porosity on the Elasticity and Strength of Alumina Ceramics

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1. Introduction

It is known that the porosity of brittle materials can have significant influence on their physical (mechanical, thermal, electrical) properties. Young’s modulus, shear modulus and Poisson’s ratio are essential parameters in the studies of advanced material mechanics [1-3]. In addition, the macroscopic behavior of ceramics can vary from brittle to quasi-plastic depending on the pore space volume [3]. That is why the investigation of the evolution of deterioration in a brittle porous material at different levels of scale and the subsequent damage depending on the deformation rate, constraint, etc. is of considerable interest [4-9] in terms of the emergence of a structural hierarchy of deformation and failure in similarbrittle materials (ceramics, stones).

The objective of the work is to study the relations between parameters such as porosity, compressive strength, Young’s modulus, shear modulus, measured in the process of mechanical loading under compression and shear, as well as structures of damage and deformation in alumina ceramics.

2. Experimental materials and methods

Al₂O₃ ceramics with different porosity values (18%-70%) were made of powders obtained via thermal decomposition of aqueous nitric-acid metallic salt solutions in high-frequency discharge plasma [10]. The initial powders and a 3% polyvinyl alcohol solution were pressed by a hydraulic press under 10 kN/cm² pressure in steel die molds in order to obtain cylindrical (10 mm in diameter, 15 mm in height) and cubic (10 mm each side) shapes.
Sintering was performed in air at temperatures ranging from 1000 to 1650 °C with an isothermal exposure time of one hour. The density of the sintered specimen was measured using the geometrical method. Residual porosity was calculated from the ratio of theoretical density to measured density, considering the phase composition of the obtained materials. The material structure after sintering was studied by optical metallography.

The specimens were exposed to mechanical tests in compression and shear by an universal testing machine Instron 1185, with simultaneous recording of the loading diagram. The traversal (loading) rate was 0.2 mm/min. On the σ-ε curves, a straight-line segment was outlined which corresponded with the phase composition of the obtained materials. The material structure after sintering was studied by optical metallography.

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Deformation diagrams of ceramics with porosity over 50% had a more complex behavior. The compression test curves mostly had a gradually descending stress arm (Fig. 2.c) which appear due to microdamages accumulated in the samples whereas the shear test curves had a slightly ascending arm after the stress fall curve portion which resulted from the stress growth (Fig. 2.d).

Observations of specimen structure after compression tests identified some differences in the nature of damage of ceramics with different porosities. In specimens with 18%-20% porosity, brittle fracturing of elastic specimens occurs after elastic energy accumulation. Due to elastic energy release, the specimen fully breaks down after reaching the compression strength limit. With a growth in pore space volume, damage of more localized nature is seen in ceramics and specimens do not fully break down after reaching the compression strength limit and, in general, do not lose the ability for future deformation. Specimens with a porosity near 40% after compression tests are shown in Fig. 3.a,b. With an increase in sintering temperature, along with decrease in pore space volume, an increase in the average pore size was observed (Fig. 1.c,d) due to the consolidation of fine pores into larger ones. According to X-ray structure analysis data, at all sintering temperatures Al₂O₃ is in a stable α-phase.

The comparison of σ-ε diagrams, obtained after testing ceramics with different porosity levels in compression, showed that their behavior depends on the pore space volume. The σ-ε curve analysis of 20% porous ceramics proved that they are linear functions until material destruction, (Fig. 2.a) while deviations from the linearity (Fig. 2.b) are observed in ceramics with a higher porosity of 20% to 50% in the area of high stresses.

3. Results and discussion

Investigations of ceramics structure after sintering showed that in specimens sintered at low temperatures, high porosity was observed and these pores were advantageously interpenetrating. The pore structure of Al₂O₃ ceramics sintered at 1400°C and 1600°C is shown in Fig. 1.a,b. With an increase in sintering temperature, along with decrease in pore space volume, an increase in the average pore size was observed (Fig. 1.c,d) due to the consolidation of fine pores into larger ones. According to X-ray structure analysis data, at all sintering temperatures Al₂O₃ is in a stable α-phase.

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The analysis of stress-strain curves of porous alumina ceramics (within the porosity range of 18% to 70%) showed
that during deformation in compression and shear, there was a transition from a typically brittle state for relatively dense ceramics (≤20% porosity), to a pseudo-plastic state with a high porosity level (over 50%).

The values of the modulus of elasticity, shear modulus and Poisson's ratio all decrease with an increase in pore space volume of Al₂O₃ ceramics, which correlates with the appearance of multiple cracking in the course of the deformation of highly porous ceramics.

It was shown that during deformation in compression, the failure process was controlled by shear stresses, which leads to the formation of damage in the shape of cones in the internal volume of the specimen, the size and location of which depend on the pore space volume.

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A porozitás hatása alumínium-oxid kerámikák szilárdságára és rugalmasságára

Jelen munkában a szerzők a 18%–70% porozitású alumínium-oxid kerámikák szilárdsági és deformációs tulajdonságait vizsgálták, nyírásuk nyomó és nyíró feszültségének hatását. A vizsgálatok során a porzítás néhány kiterjesztését jellemezte, hogy a nagy sűrűségű alumi

inum-oxid kerámikák rugalmassági és nyíró feszültségét csökkentik.

Külösszavak: alumínium-oxid, deformáció, rugalmassági modulus, feszültség, rugalmasság, porozitás, nyírás, szilárdság.