

Vertical sintering to measure the uniaxial viscosity of thin ceramic layers

Marco Cologna ^{*}, Vincenzo M. Sglavo

DIMTI, Università degli Studi di Trento, via Mesiano 77, I-38050 Trento, Italy

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Abstract

A novel method is proposed for the determination of the uniaxial viscosity of porous ceramic layers upon sintering. This approach is based on the application of a continuous but very low tensile stress to the densifying powder compact whose deformation is continuously monitored by an optical system. The viscosity of the system can be determined as a function of temperature and density from the sintering rate differences measured between loaded and unloaded samples. The uniaxial viscosity of porous Y_2O_3 doped ZrO_2 (YSZ) and NiO–YSZ composites was measured using the proposed approach. The results were used to predict the curvature evolution of bilayers used in solid oxide fuel cell applications, obtaining a fairly good agreement between the model and the data recorded experimentally. © 2010 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

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1. Introduction

Several technologies use multilayer materials to achieve specific functional requirements [1]. When ceramic materials are involved multilayers are often produced by powder processing technologies (e.g. tape casting, screen printing, spray coating), lamination and sintering. Co-sintering has attracted considerable attention in various industrial and technological fields. Some of the most important applications of the co-sintering technique include electronic packaging, such as low temperature co-fired ceramics (LTCC) [2,3], multilayer ceramic capacitors (MLCC), piezoelectric actuators [4], microfiltration membranes [5], coatings for thermal protection (TBC) [6,7] or for abrasion, oxidation and corrosion resistance, as well as solid oxide fuels cells (SOFC) [8,9]. A deep understanding of the underlying mechanisms that occur during the co-sintering process is important for its successful implementation in such technologies.

1.1. Elastic–viscous analogy

Sintering can be regarded as the response of a green body or powder compact to the sintering pressure. When a ceramic body portion shrinks at a different rate with respect to nearby regions (as is the case of rigid inclusion in a matrix, agglomerated powders, green ceramic multilayers or a coating on a rigid substrate), transient stresses are generated [10]. Viscous or plastic flow will try to relieve such stresses. In general, the response of the material to an applied stress consists of an almost instantaneous elastic strain and a time-dependent deformation due to plastic or viscous flow. The stresses associated with sintering are usually very low and the resulting elastic strain is much smaller than the strain observed during sintering. Since the observed deformation results virtually only from viscous flow, it is possible to consider only the viscous response [11]. Bordia and Sherer [12,15] suggested that a constitutive equation based on linear viscous deformation is more appropriate, and experimental measurements support that conclusion [10,16]. It has been shown that even considering a visco–elastic solution, the stresses generated are the same as for a purely viscous solution after a small transient increase in stress [17].

^{*} Corresponding author.

E-mail address: marco.cologna@ing.unitn.it (M. Cologna).

For an isotropic, linearly viscous material the elastic–viscous analogy can be applied. This approach involves solving equations for the elastic case and replacing the Young's modulus E with the uniaxial viscosity η , the Poisson ratio ν with the viscous Poisson ratio ν_p and the strain ε with the strain rate $d\varepsilon/dt$ [19,20]. Newton's law for principal stresses ($\sigma_1, \sigma_2, \sigma_3$) and principal strain rates ($d\varepsilon_1/dt, d\varepsilon_2/dt, d\varepsilon_3/dt$) can be written as:

$$\dot{\varepsilon}_1 = \dot{\varepsilon}_{f1} + \frac{1}{\eta} [\sigma_1 - \nu_p(\sigma_2 + \sigma_3)] \quad (1)$$

$$\dot{\varepsilon}_2 = \dot{\varepsilon}_{f2} + \frac{1}{\eta} [\sigma_2 - \nu_p(\sigma_1 + \sigma_3)] \quad (2)$$

$$\dot{\varepsilon}_3 = \dot{\varepsilon}_{f3} + \frac{1}{\eta} [\sigma_3 - \nu_p(\sigma_1 + \sigma_2)] \quad (3)$$

The subscript f refers to the strain rate observed in the case of unconstrained sintering ($\sigma_1 = \sigma_2 = \sigma_3 = 0$). In the special case of $\sigma_2 = \sigma_3 = 0$ one obtains:

$$\dot{\varepsilon}_1 = \dot{\varepsilon}_{f1} \frac{1}{\eta} \sigma_1 \quad (4)$$

1.2. Co-sintering of bilayers

The stress solutions in the case of layered structures can be obtained by considering the integral of stresses and bending moments along the thickness to be equal to zero. If a laminate is asymmetric, the layer which densifies faster will be in tension, but the stresses will be partially relaxed by bilayer bending. The simple case of an alumina/zirconia bilayer was examined by Cai et al. [16,18]. The normalized curvature rate $\dot{k}$ is given by:

$$\dot{k} = \frac{6(m+1)^2 mn}{m^4 n^2 + 2mn(2m^2 + 3m + 2) + 1} \Delta \dot{\varepsilon} \quad (5)$$

where k is the normalized curvature (thickness over radius of curvature), $\Delta \varepsilon$ the difference in the strain rate between layers 2 and 1, $m = t_1/t_2$ the layer thickness ratio, with t_1 and t_2 being the layer thicknesses, $n = \eta_1(1 - \nu_2)/[\eta_2(1 - \nu_1)]$ the viscosity ratio, with η being the uniaxial viscosity and ν the viscous Poisson's ratio. For beam geometry the viscosity ratio reduces to η_1/η_2 . One can observe that the curvature rate has the same sign as the strain rate difference, i.e. the layer which tends to shrink faster tends to curve the bilayer towards its side.

1.3. Derivation of the viscous parameters for sintering

Viscous parameters, such as uniaxial viscosity and the viscous Poisson's ratio, can be measured on bulk specimens or calculated by theoretical models [10]. Nevertheless, theoretical prediction of such parameters during sintering has always posed serious challenges to ceramic scientists, and most of the developed models predict different dependency of the viscosity on relative density, as well as a negative viscous Poisson's ratio, in contradiction of the experimental data [13,14]. The empirical determination of such parameters

also represents a critical issue. Uniaxial viscosity and a viscous Poisson's ratio are obtained by measuring strain rates at a fixed applied stress. For a specific material they vary with density, grain size and temperature. Various techniques exist for measuring the mechanical parameters upon sintering and an excellent review can be found in Green et al. [10].

One of the first experimental techniques which was successfully employed is sinter forging. In this technique a compressive uniaxial load is applied to the specimen and the strain rate is measured. Equipment with high accuracy is now available (e.g. 2 μm for a cylinder of 20 mm height and 12 mm diameter) [21]. To obtain reliable data with minimum effect on the microstructure the uniaxial load should be applied long enough to obtain a signal above the background noise, but briefly enough to avoid anisotropy in the microstructure [22,23]. The stress amplitude is in the range of the sintering stresses [10], which can range from about 100 kPa in glasses or glass ceramic materials [24], to several megapascals for submicron polycrystalline oxides like Al_2O_3 or TiO_2 [10,25], and up to about 100 MPa for nanocrystalline oxides such as ZrO_2 [26,27]. Since hot forging can induce microstructural anisotropy, other techniques have been developed, such as cyclic loading dilatometry [18,28–30] and discontinuous hot forging [24,31,32]. The first allows the determination of many data points, since it uses only short loading cycles to reduce anisotropy; the latter uses the application of a load until unacceptable anisotropy is developed, thus producing only a few, but robust, values for single specimen. Two or three load applications may be feasible during one sintering run [10]. A recent approach suggested the use of a bending creep test and video imaging to measure the viscosity of porous materials during sintering [33,34].

1.4. Vertical sintering

The available analytical techniques for measuring uniaxial viscosity are not easily applicable to the direct measurement of viscosity of thin layers. The samples have to be massive and must possess a specific geometry (e.g. the height/diameter ratio should be larger than 1.5 for sinter forging) [10]. Pressed pellets or several layers stacked together have to be used and, clearly, this further processing step may result in a different (denser) green microstructure. The measured mechanical parameters will therefore be those of the processed samples and not of the intended original thin layer.

In the present paper we propose a novel method for measuring the uniaxial viscosity of green bodies during sintering. This approach is based on the application of a very low tensile stress to the green component. The uniaxial viscosity is obtained from two separate sintering experiments: in the first, the shrinkage rate of a green layer sintered while hanging on a rod (and, therefore, subjected to its own weight) is measured by an optical method; in the second experiment the shrinkage rate of an identical sample

sintered in a load-free configuration is measured. The viscosities of yttria-stabilized zirconia (YSZ) and a NiO–YSZ composite, typically used in solid oxide fuel cells as electrolyte and anode, respectively, were experimentally determined according to the proposed method.

2. Experimental

YSZ and NiO–YSZ composite layers with thickness of approximately 200 μm were produced by the tape casting method. The procedure for obtaining such samples has been described in detail elsewhere [35]. The ceramic powders consisted of YSZ ($d_{50} = 0.7 \mu\text{m}$, FYT13-002H, Unitech, Stafford, UK) in the solely YSZ sample, and 58 wt.% NiO ($d_{50} = 1 \mu\text{m}$, J.T. Baker Inc., Phillipsburg, NJ) + 42 wt.% YSZ ($d_{50} = 0.3 \mu\text{m}$, TZ8-YS, Tosoh, Tokyo, Japan) in the NiO–YSZ composite. The initial relative densities were 54.2% and 40.3% for the YSZ green tape and NiO–YSZ composite, respectively. The micrographs in Fig. 1 show the microstructure of the green samples. Green tapes were cut into half dumb-bell shapes with a sharp blade. The initial constant cross-section of the sample was $30 \times 8 \text{ mm}^2$. The sintering schedule was 1°C min^{-1} to 600°C , 5°C min^{-1} to 1450°C and a 4 h isotherm at 1450°C . The sample dimensions upon sintering were measured by an optical method, as described in detail elsewhere [36]. Fig. 2 shows an example of a hung NiO–YSZ specimen at 1200°C .

The experimental set-up consisted of a thin ceramic layer hanging from a support made from a MoSi_2 rod. The flexible ceramic tape was wrapped around the support rod, while the portion with a constant cross-section was left hanging downwards, as shown in Fig. 3. The length of constant cross-section was measured from images acquired at 60 s intervals. The sample dimensions were recorded from room temperature up to 1450°C . Any macroscopic dimensional change was observed during the binder burnout between 200°C and 400°C .

3. Data analysis

It has previously been shown that a porous body undergoing densification can be treated as linearly viscous at stresses below 1 MPa. For such materials it is expected that

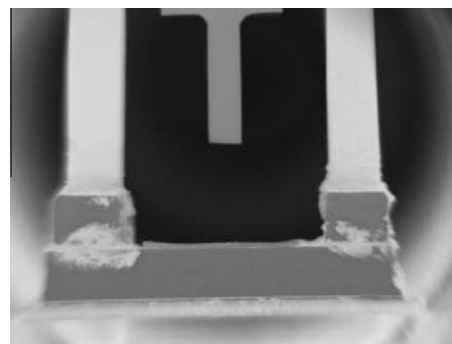


Fig. 2. Photograph of a hung NiO–YSZ specimen being sintered at 1200°C .

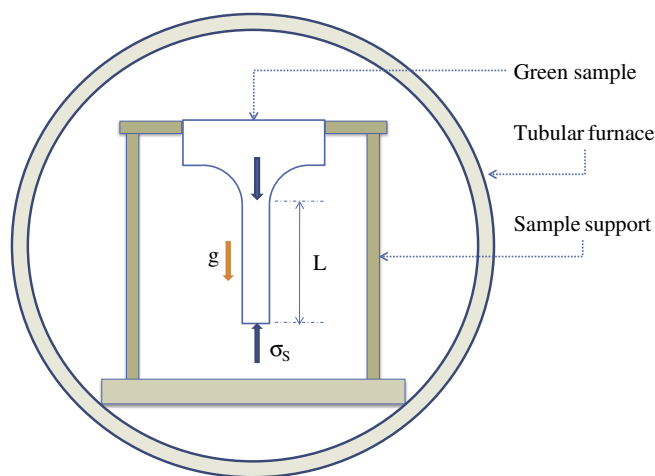


Fig. 3. Set-up for the vertical sintering experiment.

the creep rates in slight uniaxial tension or uniaxial compression are the same [14,33]. If a tensile load is applied to the sintering body its effect will be to reduce the effective sintering stress and the observed strain rate will be reduced. A similar concept was employed by Gregg and Rhines [37] and Cheng and Raj [25], who measured the sintering pressure in ceramic films as the external load required to have zero axial strain rate.

For the hanging specimen the applied stress was always very low, the only mechanical effect being related to the green tape's own weight. Based on results presented in Section 4, we conclude that this minimal stress is not inducing

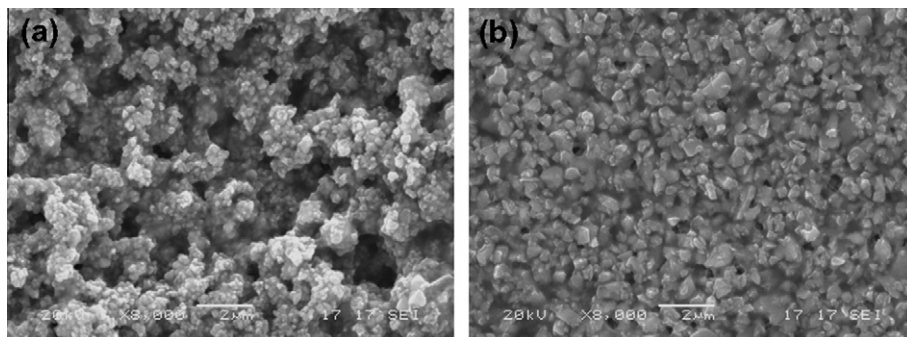


Fig. 1. Microstructure of the green tapes: (a) anode; (b) electrolyte.

anisotropy in the material microstructure and, therefore, it can be applied continuously from the beginning to the end of the sintering cycle.

The elastic solution for a strip that is hanging freely, and is therefore subjected to its own weight only, can be easily derived as [38]:

$$L - L_0 = \frac{\rho g L_0^2}{2E} \quad (6)$$

where L_0 is the initial strip length, L the final length, ρ the material density, g the gravity constant and E Young's modulus. The total elongation of the strip was therefore identical to that produced by a concentrated load equivalent to half of the strip weight. By applying the elastic–viscous analogy, the Young's modulus is replaced by the uniaxial viscosity η , while the strain is replaced by the strain rate ε . By considering the sintering stress σ_s as well, one obtains:

$$\varepsilon = \frac{\rho g L_0^2}{2E} + \frac{\sigma_s(1 - 2\nu)}{E} \quad (7)$$

and, since

$$\sigma_s = \frac{\eta \dot{\varepsilon}_f}{(1 - 2\nu_p)} \quad (8)$$

the following relationship is obtained:

$$\eta = \frac{\rho g L_0}{2(\dot{\varepsilon} - \dot{\varepsilon}_f)} \quad (9)$$

The uniaxial viscosity of a ceramic strip can therefore be determined from two separate sets of experiments: first the sintering rate of the ceramic body is determined in the absence of any applied load (e.g. laying on a horizontal support); then the sintering rate is also recorded while the sample is sintered while hanging (i.e. under the effect of its own weight). The strain rates in Eq. (9) have to be calculated as a function of the relative density. For a material that undergoes isotropic sintering the relative density can be calculated as follows:

$$\rho_{free}(t) = \rho_0 e^{-3\varepsilon_f} \quad (10)$$

And, from Eqs. (1)–(3):

$$\rho_{vertical}(t) = \rho_0 e^{-\left(2\varepsilon_f + \varepsilon_1 - 2 \int_0^t \frac{\nu_p}{\eta} \rho g L dt\right)} \quad (11)$$

The last term in Eq. (11) can be neglected, as will be explained in more detail in the following section. This implies that the sintering rate in the horizontal direction is not significantly affected by application of the vertical load. As a matter of fact, Gregg and Rhines reported that the strain rate in the width direction in a hanging sample is very close to that of a sample sintering freely [37]. Also, in the present experiment the shrinkage in the width was found to be very close to free shrinkage.

4. Results and discussion

4.1. Viscosity of the YSZ and NiO–YSZ composite tapes

The strain of the YSZ sample sintered freely and in the hanging configuration is reported in Fig. 4, and the corre-

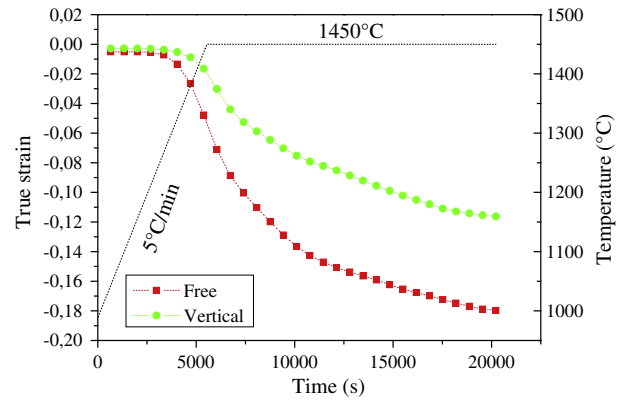


Fig. 4. Strain upon sintering for YSZ sintered freely and vertically hung.

sponding strain rate is shown in Fig. 5. The uniaxial viscosity of the YSZ compact calculated as a function of relative density is plotted in Fig. 6. The uniaxial viscosity was calculated only up to a maximum relative density of 0.83.

The strain on the NiO–YSZ composite sintered freely and in the hanging configuration is reported in Fig. 7, and the corresponding strain rate is shown in Fig. 8. While the freely sintered sample started shrinking in the first stages of sintering, the hanging sample showed a length increase that could be accounted for by the effect of its

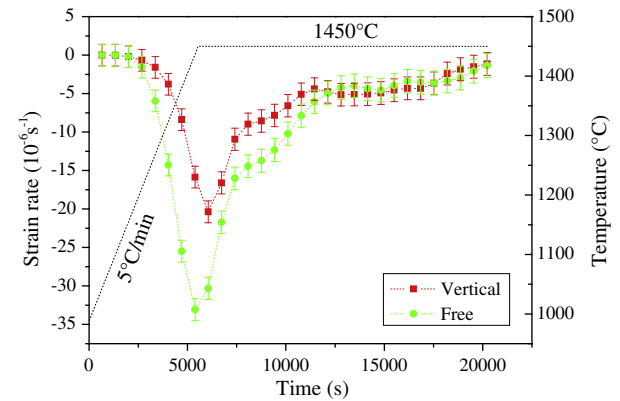


Fig. 5. Sintering strain rate for YSZ sintered freely and vertically hung.

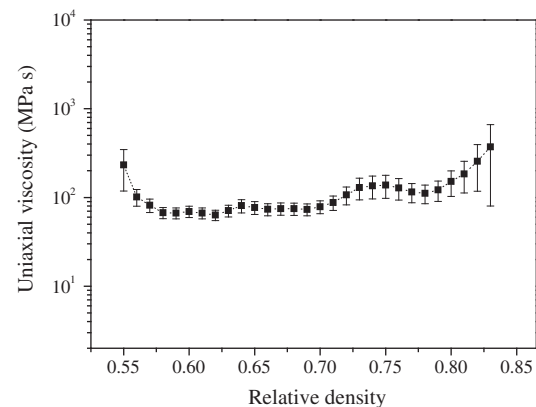


Fig. 6. Calculated uniaxial viscosity for YSZ.

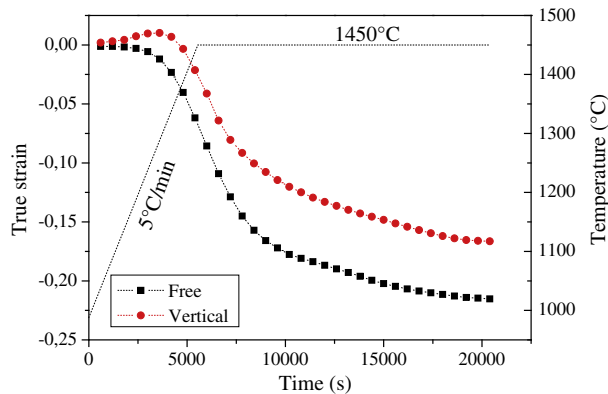


Fig. 7. Strain upon sintering for NiO-YSZ sintered freely and vertically hung.

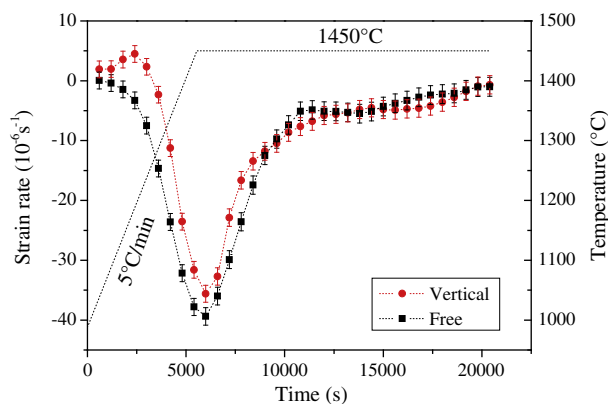


Fig. 8. Sintering strain rate for NiO-YSZ sintered freely and vertically hung.

own weight. Correspondingly, the strain rate was initially positive, thereafter becoming negative. The strain rate curve for the sample subjected to the low tensile load was always above that of the freely sintered sample up to around 1 h at 1450 °C, then the two samples started to shrink at similar rates. This is consistent with the fact that a very small load was applied. This can also be considered as proof that such a load does not influence the microstructure substantially: the low applied load affected the sintering rate only when the ceramic compact showed very low density and creep resistance. As sintering proceeded and density increased, more necks were formed and the small load was ineffective in producing observable differences in strain rate. The microstructure of the stressed sample did not therefore retain a memory of the applied load.

The uniaxial viscosity of the NiO-YSZ compact as a function of relative density, calculated by Eq. (9), is reported in Fig. 9. At low temperature and low density the viscosity was high, but then it decreased due to the increasing temperature. As the sample became more dense the viscosity again increased. The graph is limited to the zones where the viscosity can be effectively calculated. The viscosity at high density cannot be evaluated with

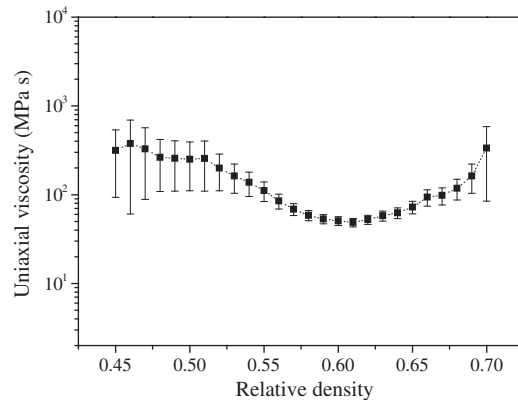


Fig. 9. Calculated uniaxial viscosity for NiO-YSZ.

the present method, because the very low applied load does not cause any appreciable difference in the strain rates. The viscosity is in fact proportional to the applied stress over the strain rate difference between the loaded sample and the load-free sample. When this difference tends to zero, i.e. at very high viscosities (low temperature or high density), the error becomes too high.

In Figs. 6 and 9 the viscosities were also calculated during the heating stage. Since the samples had different densities, the comparison is not strictly accurate. Nevertheless, deformations and, consequently, differences in densities were still low (just before the isothermal hold the density difference between the free and overhung sample was less than 3% and 4% for YSZ and NiO-YSZ, respectively) and, therefore, the temperature difference between the free and hanging samples at the same density did not exceed 25 °C.

4.2. Evolution of NiO-YSZ/YSZ bilayer upon sintering

As an important technological application, the data can be used to determine the curvature evolution of an asymmetric bilayer upon sintering. A typical case of such a bilayer is a fuel cell consisting of a thin YSZ electrolyte and a thick NiO-YSZ anode support. The normalized curvature rate can in fact be calculated from Eq. (5), once the viscosities of the layers and their free sintering rates are known (16). The thickness ratio $m = t_1/t_2$ is calculated as (where $i = 1$ or 2):

$$t_i = t_{i0} e^{\epsilon_{i,free}} \quad (12)$$

Three half cells (bilayers formed by a thin electrolyte and a thick anode support) were built to validate the predicted curvature rate and evaluate the consistency of the measured uniaxial viscosities. Samples were produced by a sequential casting method [35]. The green electrolyte thickness was $12 \pm 2 \mu\text{m}$; the anode thickness was 180, 278 or $408 \pm 5 \mu\text{m}$. In the following description a positive curvature refers to a half cell which is curved towards the anode side.

The curvatures measured experimentally for the three half cells with different anode thicknesses are reported in

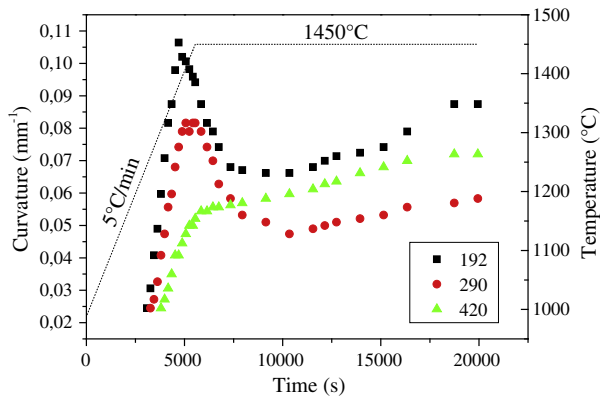


Fig. 10. Measured curvature of the half cells of thickness 192, 290 and 420 μm .

Fig. 10, and the corresponding curvature rates are plotted in Fig. 11. For all samples the curvature rates were positive in the first stage of sintering (i.e. the cells are curving toward the anode side) and reached a peak at around 1300–1350 $^{\circ}\text{C}$, after which its magnitude quickly decreased. The cell possessing the highest peak in the curvature rate

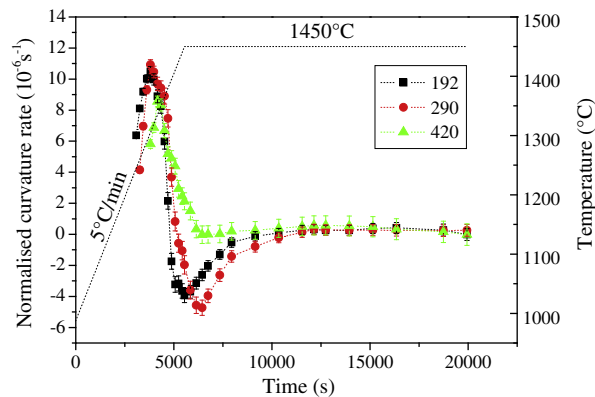


Fig. 11. Measured normalized curvature rate of the half cells of thickness 192, 290 and 420 μm .

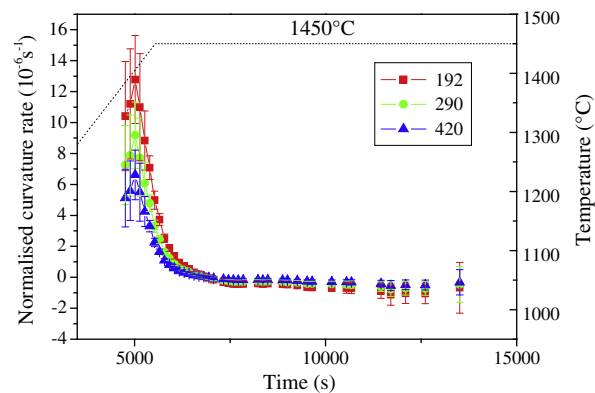


Fig. 12. Calculated normalized curvature rate of the half cells of thickness 192, 290 and 420 μm .

was that produced with the thinnest anode. The curvature rate for the same samples, as calculated using Eq. (5), is reported in Fig. 12. Such graphs are limited to the points where the uniaxial viscosity of the layers could be effectively calculated. Fig. 13 shows a direct comparison between the calculated and experimental data for the thicker sample only.

The agreement between the measured and calculated strain rates was better for the thicker bilayer. On decreasing the total thickness to 290 and 192 μm the mismatch between the theoretical and experimental data increased. A possible explanation for this observation could be as follows. The bilayers considered here show an initial positive curvature (anode on the concave side) during the sintering process, particularly at low viscosities (and low densities). The weight of the sample tends to flatten the cell, thus acting against the curvature due to faster sintering of the anode. This simulates the effect of a faster sintering electrolyte. The thicker the bilayer, the lower the flattening effect due to gravity. For very thin layers (290 and 192 μm) this effect is more prominent.

The differences between the experimental and measured curvature rates can also be attributed to the necessary approximations introduced in the calculations of viscosities and curvature rate. The agreement between the experimental and calculated curvature rates improved during the isothermal hold. This may reflect the fact that viscosity values during the heating stage are biased by a temperature difference between the free and constrained samples, as discussed above.

As anticipated in the previous section, calculation of the hung sample density was performed by neglecting the last term in Eq. (10), which approximation could represent a source of error. To estimate the magnitude, the integral in Eq. (9) was calculated, by considering a constant viscosity of 100 MPa, an average value for v_p equal to 0.1 (the hypothesis was made that it ranged from 0 to 0.2 in the considered density interval) and, as integration limits, t_0 , the time of densification onset, and t , the time to reach the final density. The differences in the final relative densi-

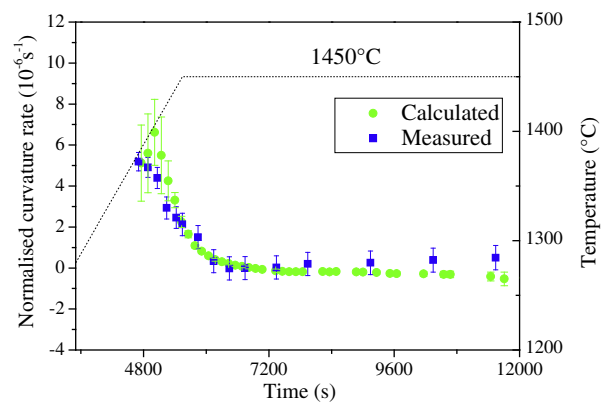


Fig. 13. Comparison between calculated and measured curvature rate for the 420 μm thick sample.

ties calculated from Eq. (9) with and without the contribution of the integral are 0.006 and 0.009 for the NiO–YSZ composite and for YSZ, respectively, corresponding to a maximum error of less than 1%. The error will always be lower, being equal to zero at the beginning and increasing as sintering proceeds.

The constitutive equations suppose that the viscosity is a function only of density and temperature, whereas the properties of crystalline materials depend also on the microstructure, as demonstrated by Mikeska et al. [39]. The measured viscosities include the influence of grain growth and the values apply only during a particular thermal cycle. It is therefore important to use the same heating cycle for the viscosity measurements and the bilayer sintering to obtain reliable results.

5. Conclusions

A new experimental method for measuring the uniaxial viscosity of thin porous ceramic layers is proposed. This method consists of applying a low tensile load to the ceramic compact that is undergoing densification. The resulting reduction in the strain rate is used to calculate the viscosity. The tensile load is derived from the sample weight. For ceramics of few tens of millimeters in length the stress magnitude is of the order of 0.1 kPa. The limited load does not induce any anisotropy in the ceramic microstructure.

The calculations are restricted to the zones of low viscosity: the applied load being very low, its effect on the shrinkage rate is, in fact, measurable only at low viscosities (i.e. when interparticle contacts are small).

The method was applied to the measurement of the viscosity of anode and electrolyte tape cast layers typically used in solid oxide fuel cells. The results were used to model the curvature rate of a half cell upon sintering. The calculated and experimental data were in fairly good agreement in the case of relatively thick samples during the isothermal hold.

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References

- [1] Evans AG, Hutchinson JW. *Acta Metall Mater* 1995;43:2507.
- [2] Jean J-H, Chang C-R. *J Mater Res* 1997;12:2743.
- [3] Hagymási M, Roosen A, Karmazin R, Dernovsek O, Haas W. *J Eur Ceram Soc* 2005;25:2061.
- [4] Hall A, Akdogan EK, Safari A. *J Appl Phys* 2006;100:094105.
- [5] Feng J, Fan Y, Qi H, Xu N. *J Membr Sci* 2007;288:20.
- [6] Lu X-J, Xiao P. *J Eur Ceram Soc* 2007;27:2613.
- [7] Zubacheva O, Malzbender J, Steinbrech RW, Singheiser L, Schulz U. *Ceram Eng Sci Proc* 2005;26:29.
- [8] Ye G, Ju F, Lin C, Gopalan S, Pal U, Seccombe D. *Ceram Eng Sci Proc* 2005;26:25.
- [9] Muecke R, Menzler NH, Buchkremer HP, Stoever D. *J Am Ceram Soc* 2009;92:95.
- [10] Green DJ, Guillon O, Rödel J. *J Eur Ceram Soc* 2008;28:1451.
- [11] Rahaman MN. *Ceramic processing and sintering*. New York: Marcel Dekker; 2003.
- [12] Sherer GW. *J Am Ceram Soc* 1987;70:719.
- [13] Bordia RK, Scherer GW. *Acta Metall* 1988;36:2393.
- [14] Bordia RK, Scherer GW. *Acta Metall* 1988;36:2397.
- [15] Bordia RK, Scherer GW. *Acta Metall* 1988;36:2411.
- [16] Cai PZ, Messing GL, Green DJ. *J Am Ceram Soc* 1997;80:445.
- [17] Riedel H, Zipse H, Svoboda J. *Acta Metall Mater* 1994;42:445.
- [18] Cai PZ, Messing GL, Green DL. *J Am Ceram Soc* 1997;80:1929.
- [19] Scherer GW. *J Non-Cryst Solids* 1979;34:239.
- [20] Skorokhod VV. *Powder Metall* 1963;12:188.
- [21] Aulbach E, Zuo R, Roedel J. *Exp Mech* 2004;44:71.
- [22] Zuo R, Aulbach E, Roedel J. *Acta Mater* 2003;51:4563.
- [23] Bordia RK, Zuo R, Guillon O, Salamone SM, Roedel J. *Acta Mater* 2006;54:111.
- [24] Zuo R, Aulbach E, Roedel J. *J Mater Res* 2003;18:2170.
- [25] Cheng T, Raj R. *J Am Ceram Soc* 1988;71:276.
- [26] Kanters J, Eisele U, Roedel J. *J Am Ceram Soc* 2001;84:2757.
- [27] Zuo R, Aulbach E, Roedel J. *Adv Eng Mater* 2005;7:949.
- [28] Chang J-C, Jean J-H. *J Am Ceram Soc* 2006;89:829.
- [29] Mohanram A, Lee S-H, Messing GL, Green DJ. *J Am Ceram Soc* 2006;89:1923.
- [30] Gillia O, Jossierond C, Bouvard D. *Acta Mater* 2001;49:1413.
- [31] Ollagnier JB, Guillon O, Roedel J. *J Am Ceram Soc* 2004;87:192.
- [32] Ollagnier JB, Guillon O, Roedel J. *Int J Appl Ceram Technol* 2006;3:437.
- [33] Lee S-H, Messing GL, Green DJ. *J Am Ceram Soc* 2003;86:877.
- [34] Blaine DC, Bollina R, Park S-J, German RM. *Comput Ind* 2005;56:867.
- [35] Cologna M, Contino AR, Montinaro D, Sglavo VM. *J Power Sources* 2009;193:80.
- [36] Cologna M, Bertoldi M, Sglavo VM. *Int J Appl Ceram Technol*; 2009. doi:10.1111/j.1744-7402.2009.02390.x.
- [37] Gregg RA, Rhines FN. *Metall Trans* 1973;4:1365.
- [38] Beer FP, Johnston Jr ER. *Mechanics of materials*. New York: McGraw-Hill; 1992.
- [39] Mikeska KR, Scherer GW, Bordia RK. *Ceram Trans* 1990;7:200.