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Compilation of mechanical properties for the structural analysis of solid oxide fuel cell stacks. Constitutive materials of anode-supported cells

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Abstract

The mechanical failure of one cell is sufficient to lead to the end of service of a solid oxide fuel cell (SOFC) stack. Therefore, there is growing interest in gaining knowledge on the mechanical properties of the cell materials for stress analysis.

This study compiles available data from the literature on the mechanical properties of the most common materials used in intermediate-temperature anode-supported cells: nickel and yttria-stabilized zirconia (Ni–YSZ) anodes, YSZ electrolytes, yttria (YDC) or gadolinia-doped ceria (GDC) compatibility layers and lanthanum strontium manganite (LSM) or lanthanum strontium cobalt ferrite (LSCF) cathodes. The properties for the simulation of stresses, i.e. coefficient of thermal expansion (CTE), Young's modulus, Poisson's ratio, creep behaviour and strength are reported, with an emphasis on temperature and porosity dependence and the evolution upon aging or cycling when available. Measurements of our Ni(O)–YSZ anode material includes the CTE (oxidised and reduced state), Young's modulus and strength at room temperature (oxidised and reduced) and 1073 K (oxidised).

Keywords: C. Creep; C. Mechanical properties; C. Strength; C. Thermal expansion; Solid oxide fuel cell

1. Introduction

Structural reliability of solid oxide fuel cells (SOFC) is a salient issue, which currently impedes their large-scale commercialisation. The in-series assembly of the single repeating units (SRU) to build a stack and the use of brittle ceramic materials for the manufacturing of the cells are striking weaknesses. The mechanical failure of one single cell usually quickly leads to the end of life of the stack, as it induces a succession of detrimental effects that act in a coupled manner. For instance, delamination or cracking of the electrode layers breaks the ionic and/or electronic conduction paths to the reaction sites. The ensuing local loss of performance induces a harmful redistribution of the current density [1,2]. Once cracked, the electrolyte does not any longer ensure the separation of the fuel and air compartments to the fullest extent. The local and unsteady combustion provokes a local increase of the temperature, as well as diverse chemical alterations of the cell layers, such as the reduction and re-oxidation (redox) of the nickel in the composite anode and the reduction of the cathode material [3]. All these undesirable chemical and electrochemical phenomena promote in turn additional stresses, which reach critical values in an accelerated manner.

SOFC stacks with a few hours of operation can fail because of improper control strategy. They incur in the longer term repeated full or partial thermal cycles and variations of the electrical load, which reduce the lifetime of any energy

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Nomenclature

Latin letters

b_E	constant
b_G	constant
b_σ	constant
d_g	particle diameter (m)
d^{crp}	creep particle exponent
D	diameter (m)
D^e	diffusion coefficient ($m^2\ s^{-1}$)
E	Young modulus (Pa)
E_a	activation energy ($J\ mol^{-1}$)
G	shear modulus (Pa)
h	thickness (m)
k_o	kinetic constant
m	Weibull modulus
m^{crp}	creep stress exponent
n	porosity
N	mechanical load (N)
R	universal gas constant 8.314 ($J\ mol^{-1}\ K^{-1}$)
T	temperature (K)
$\mathcal{V}_r$	reference volume (m^3)

Greek letters

α^{th}	coefficient of thermal expansion (K^{-1})
ϵ	strain
ϕ	scalar field variable
ν	Poisson's ratio
ρ	density ($kg\ m^{-3}$)
σ	stress (Pa)
σ_o	characteristic stress (Pa)
σ_u	threshold stress (Pa)

Indices

o	initial, dense state
cr	critical or failure
eq	equivalent
lr	loading ring
sp	sample
sr	supporting ring
th	thermal
RT	room temperature, 298 (K)

Superscripts

th	thermal
crp	creep
$*$	foam

Acronyms

BOR	ball-on-ring
CTE	coefficient of thermal expansion
GDC	gadolinia-doped ceria
LSM	lanthanum strontium manganite
LSCF	lanthanum strontium cobaltite ferrite
Ni–YSZ	nickel YSZ anode in reduced state
NiO–YSZ	nickel YSZ anode in oxidised state
ROR	ring-on-ring
SRU	single repeating unit
TBC	thermal barrier coating
XRD	X-rays diffraction
YDC	yttria-doped ceria
YSZ	yttria-stabilised zirconia
4PB	4-point bending

conversion device. The aggressive environment during constant output electrical power mode already entails detrimental alterations of the materials and interfaces. Coarsening of the microstructure [4–9], localised modifications of the composition of the materials close to the interfaces [10–12], development of insulating phases, such as lanthanum (LZO) or strontium zirconates (SZO) [13–15] or phase transformations [16,17] are commonly reported during aging, under polarisation or not. These phenomena can affect the mechanical behaviour of the cell layers, hence the ability of the cell to resist thermal cycling and/or electrical demand following.

Stresses in a cell embedded in a stack originate from different phenomena. Residual stresses build up after the sintering phase of the manufacturing process due to the mismatch between the coefficients of thermal expansion (CTE) of the materials of the cell. Stresses in the cell then arise from mechanical load due to the stacking and the joining with the components of the SRU frame by a glass sealant or compressive gaskets. The reduction of the nickel oxide in the anode takes place when fuel is fed for the first time, which ensures a suitable electrical conductivity and electrochemical activity. This last manufacturing step results in an increase in porosity, hence induces a change in mechanical properties and a shrinkage of the anode. During operation, the uneven temperature distribution causes additional stresses in the cell.

The stress state in the different layers of anode-supported cells follows typical patterns, depending on the range of possible variations of the CTE of the materials, which can be controlled to some extent by varying their composition. The anode support withstands tensile stress, while compressive stress shields the thin electrolyte, if their magnitude is properly controlled [18]. The use of separate or graded functional electrodes [19] and anode backside compensating layers to limit the cell curvature and to facilitate the assembly [20] does not modify this trend. The situation is less well defined in the cathode and possible compatibility layers. The two most widely used cathode materials, composite lanthanum strontium manganite and yttria-stabilised zirconia (LSM–YSZ) and single solid phase lanthanum strontium cobaltite ferrite (LSCF), have very different CTEs. LSM–YSZ can be subjected to either compressive or tensile stress, depending on the materials and temperature [21,22]. In the case of LSCF cathode, a compatibility layer made of gadolinia (GDC) or yttria-doped ceria (YDC) is required to prevent undesirable reactions at the interface between the cathode and the electrolyte [23,24]. Their CTE matches that of the anode; hence stress can possibly turn from tensile to compressive, or vice versa, depending on the