Durability and Reliability of Materials and Components for Solid-Oxide Fuel Cells

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Acknowledgments

Collaborators

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Oak Ridge National Laboratory

W. Li and J. Lannutti
Department of Materials Science & Engineering
Ohio State University

E. Wachsman
U. of Florida

Diane England
Delphi

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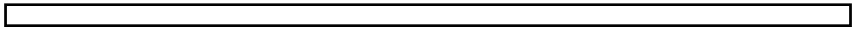
Outline

- Background
- Residual Stresses in SOFCs
  - Experimental Conditions
  - Results
  - Implications
- Interfacial Fracture Toughness
- Data Base
- Summary

Background

- Tools are being developed for predicting the durability and reliability of SOFC materials and components.
- The integration of mechanical property data with life prediction models requires the definition of a reference state of stress and understanding how stresses and strength evolve with time and operating conditions.

Background

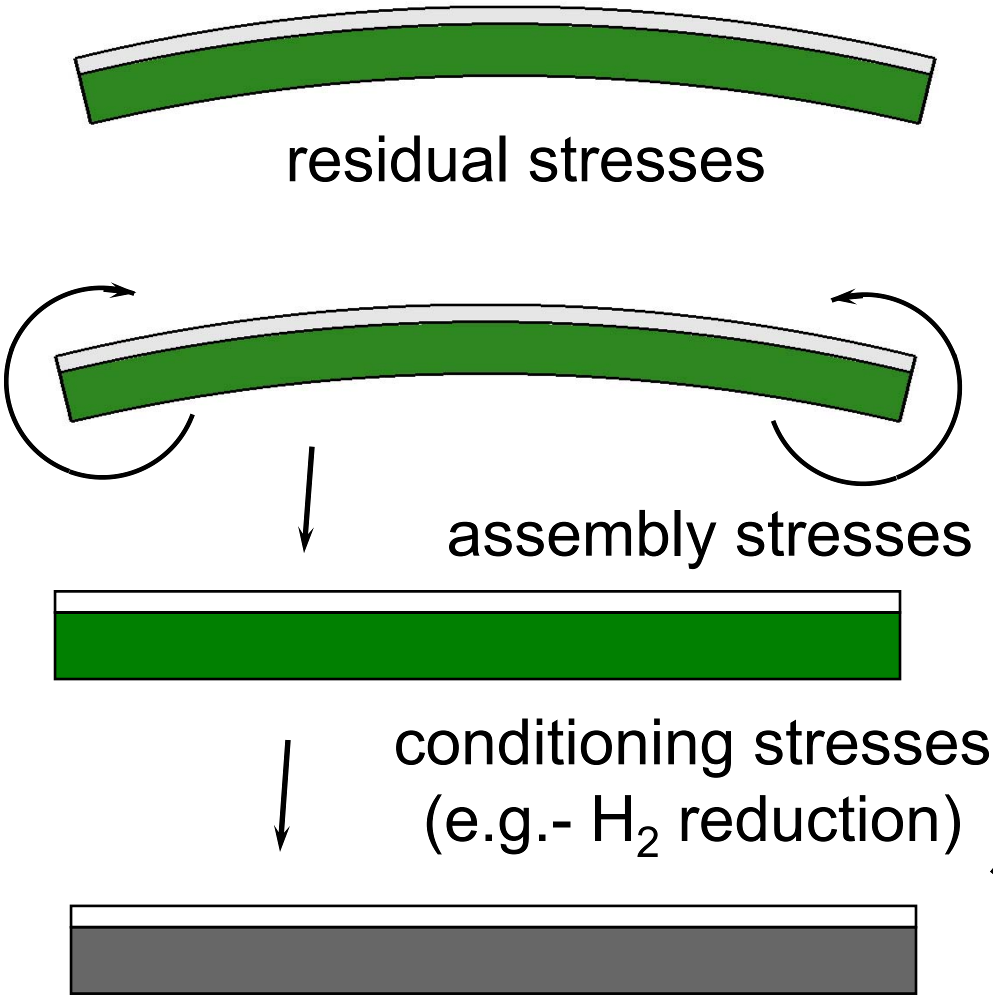


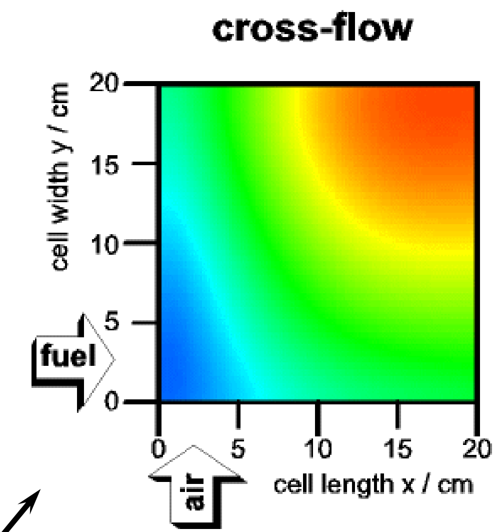
$$Reliability = \exp\left(-\frac{\sigma_1}{\sigma_{1o}}\right)^{m_1}$$

$$Reliability = \exp\left(-\frac{\sigma_2}{\sigma_{2o}}\right)^{m_2}$$

$$Reliability = \exp\left(-\frac{k_1(\sigma_1 + \sigma_{1res})}{\sigma_{1o}}\right)^{m_1} \exp\left(-\frac{k_2(\sigma_2 + \sigma_{2res})}{\sigma_{2o}}\right)^{m_2}$$

Background



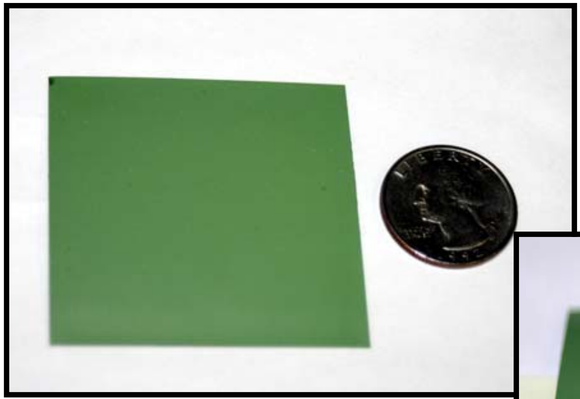


temperature gradients and gas pressure induce additional stresses

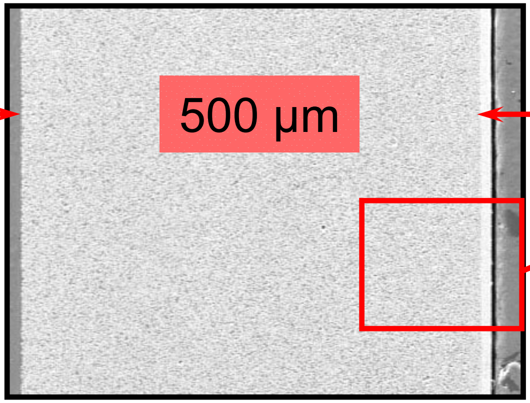
Background

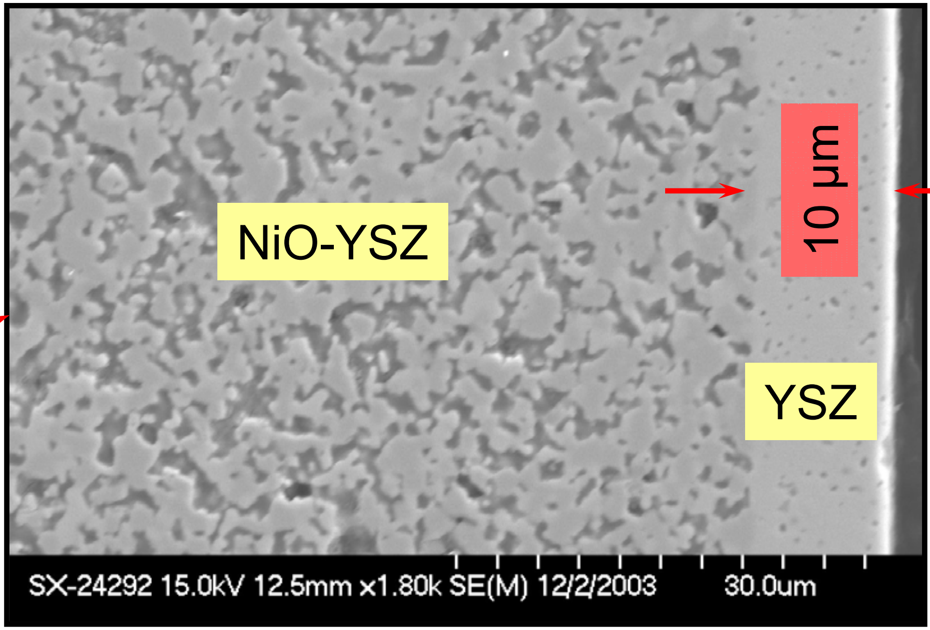
- Tools are being developed for predicting the durability and reliability of SOFC materials and components.
- The integration of mechanical property data with life prediction models requires the definition of a reference state of stress and understanding how stresses and strength evolve with time and operating conditions.
- The objective of this project is to determine the state of residual stresses in a NiO-YSZ/YSZ bilayer before and after reduction in H_2.

NiO-YSZ/YSZ bilayer

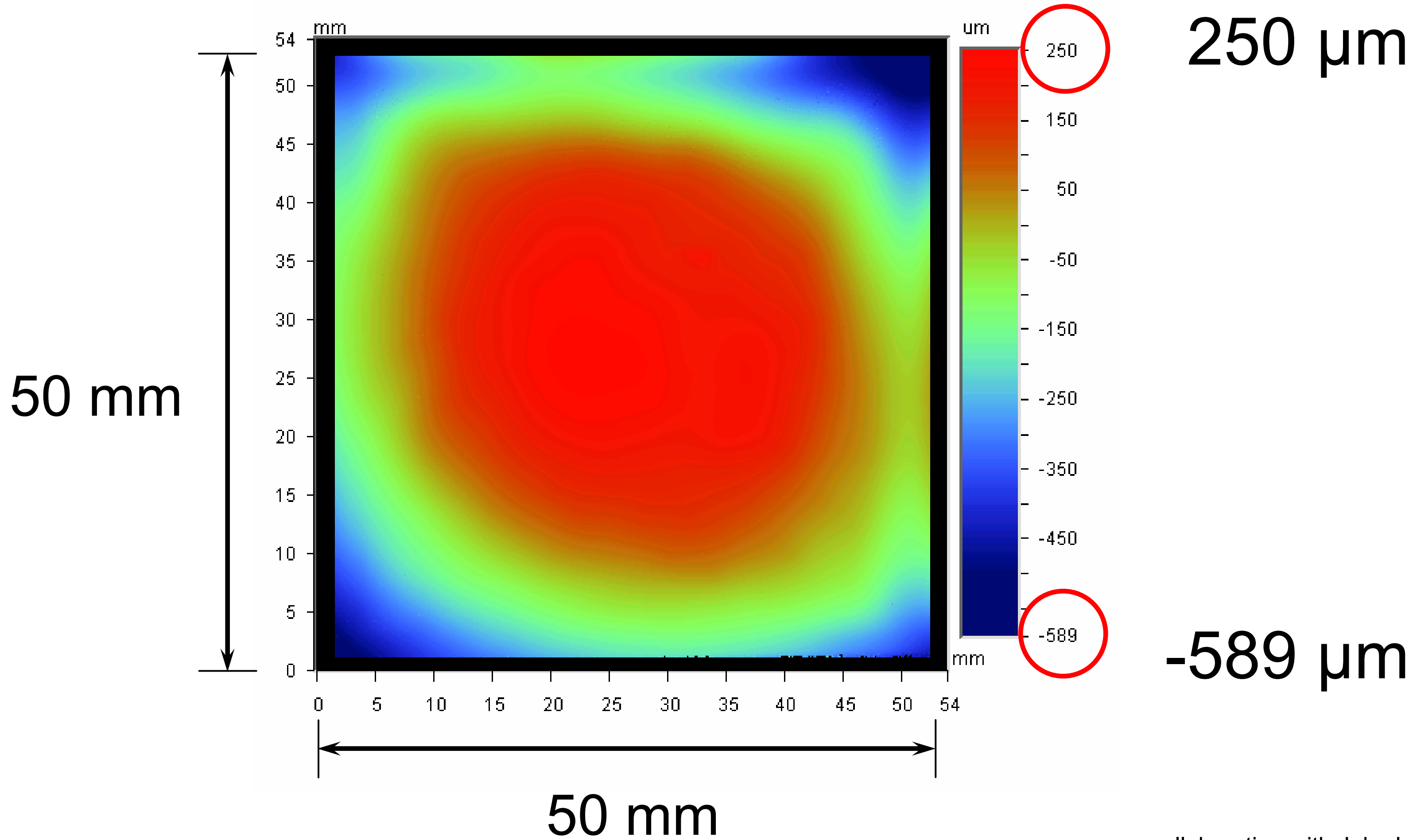


50 mm X 50 mm X 510 μm





Curvature of NiO-YSZ/YSZ bilayer: optical profilometry



collaboration with John Lannutti
Ohio State University

Residual Stresses in NiO-YSZ/YSZ bilayer

- 5 mm x 5 mm bi-layers of NiO-YSZ/YSZ
- 10 μm-thick YSZ layer
- scans between 139° and 142° 2θ
- 20°C, 400°C, 600°C, 800°C and 900°C
- Air

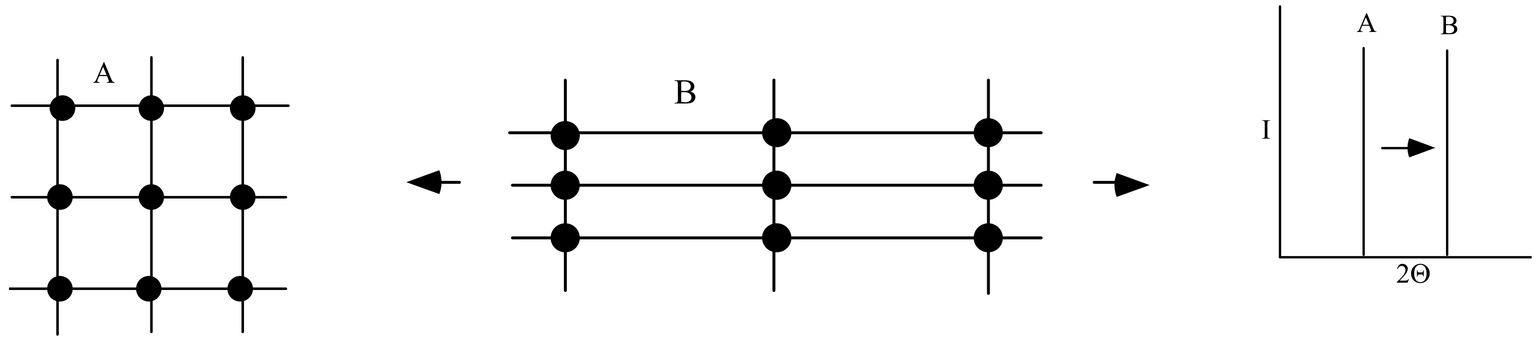
- 5 mm x 5 mm bi-layers of Ni-YSZ/YSZ (after reduction at 800°C using gas mixture of 4%H_2 and 96% Ar)
- 10 μm-thick YSZ layer
- scans between 139° and 142° 2θ
- 20°C, 400°C, 600°C, 800°C and 900°C
- Ar

High-temperature Diffractometer

Residual Stresses in NiO-YSZ/YSZ bilayer

Peak shift is converted into strain

•Strain/stress (applied or residual) changes the interplanar spacing Θ peak shift



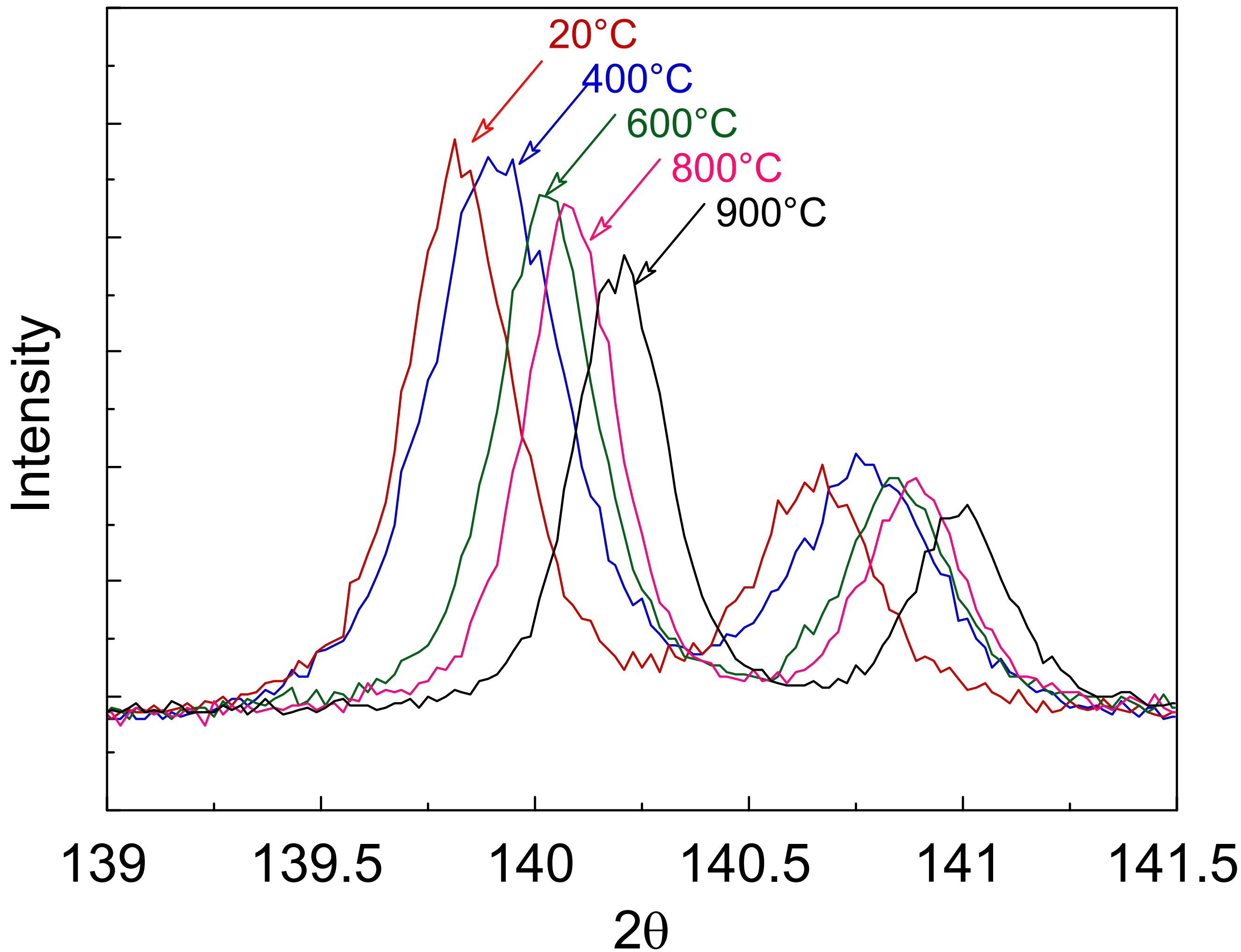
• Bragg’s Law

$$□\lambda = 2\, d \sin\theta$$

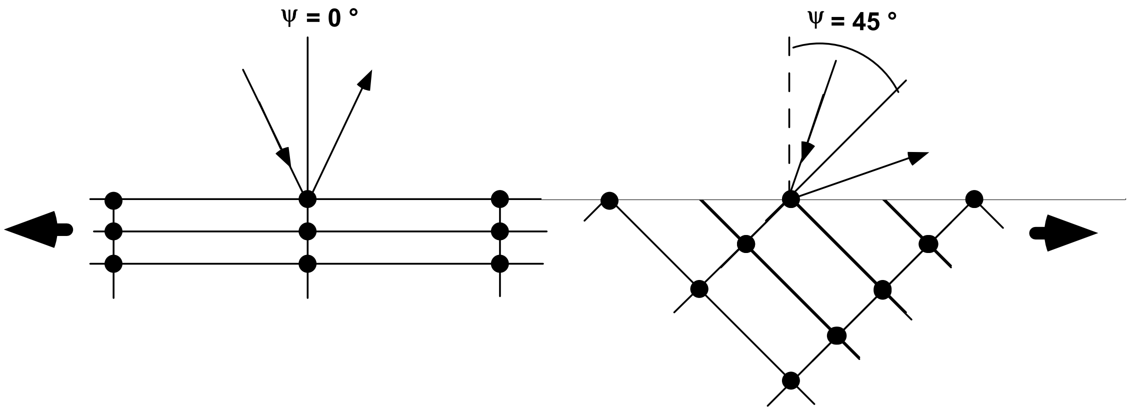
where	λ	=	wavelength
	d	=	interplanar spacing
	2θ	=	diffraction peak position

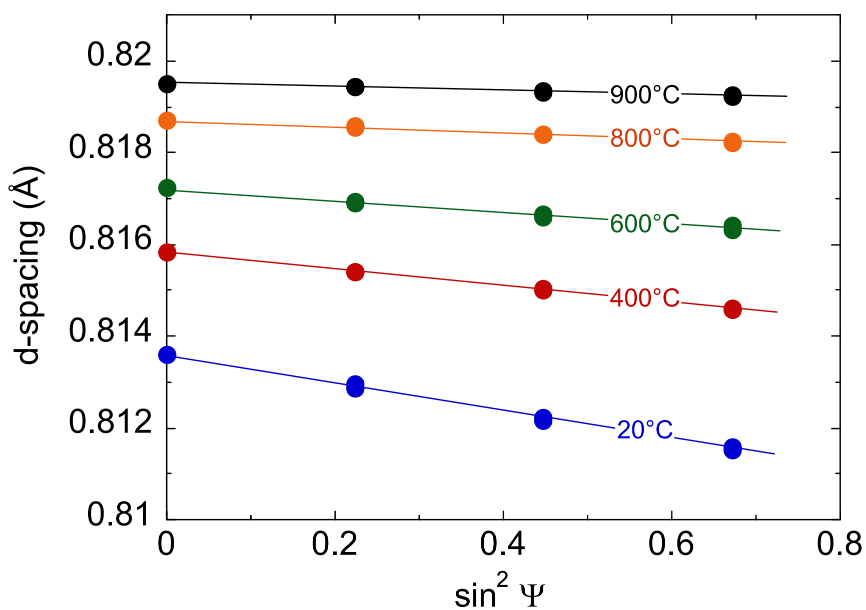
• Strain, $\varepsilon = (d_B - d_A)/d_A$

Residual Stresses in NiO-YSZ/YSZ bilayer



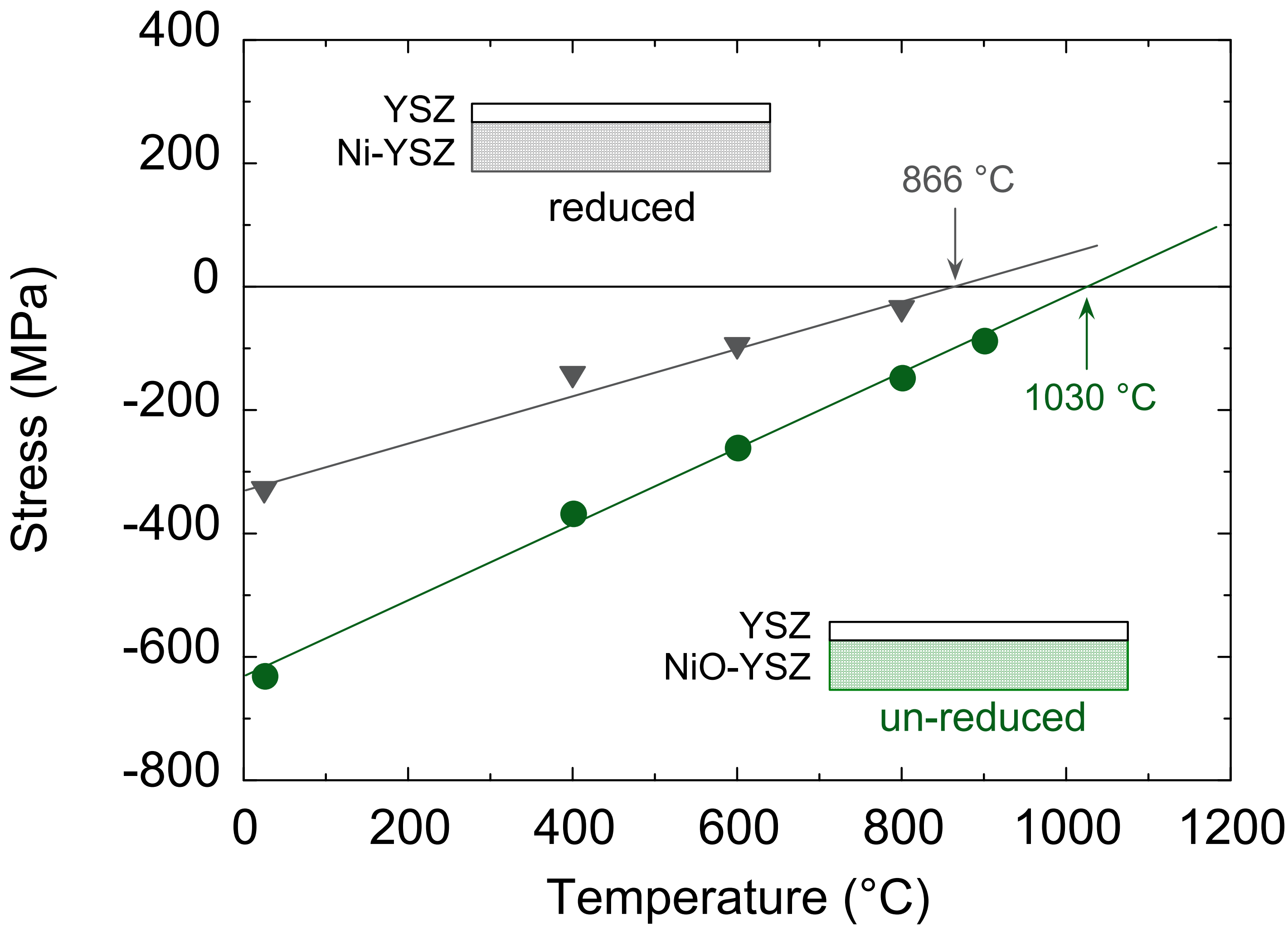
Residual Stresses in NiO-YSZ/YSZ bilayer



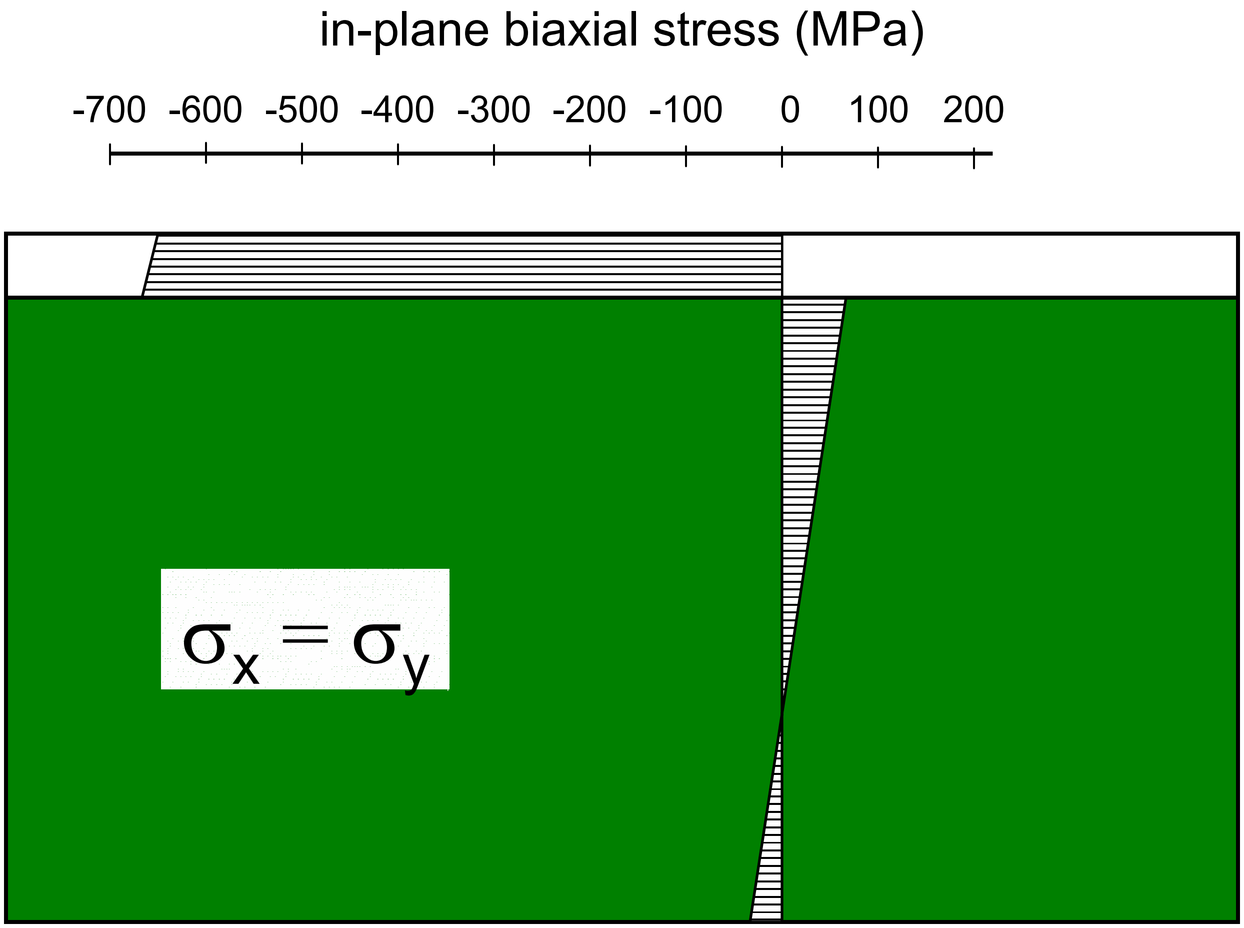


- Sample tilting is required for accurate strain measurement with x-rays
- Peak position as a function of tilt angle, ψ
- Slope of d (interplanar spacing) vs. $\sin^2\psi$ is used to calculate strain.

Residual Stresses in NiO-YSZ/YSZ and NiO-YSZ/YSZ bilayers

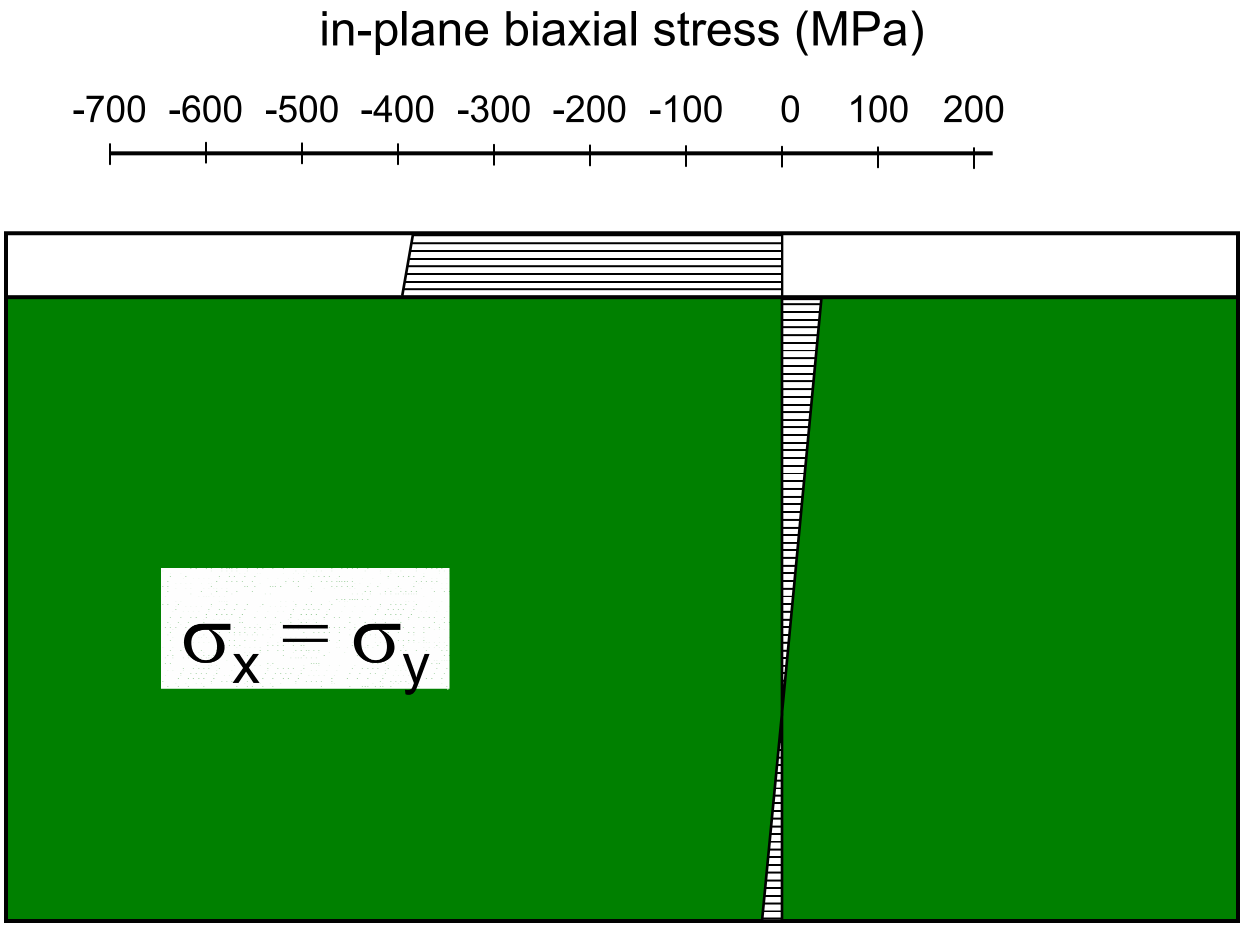


Residual Stresses in NiO-YSZ/YSZ bilayer



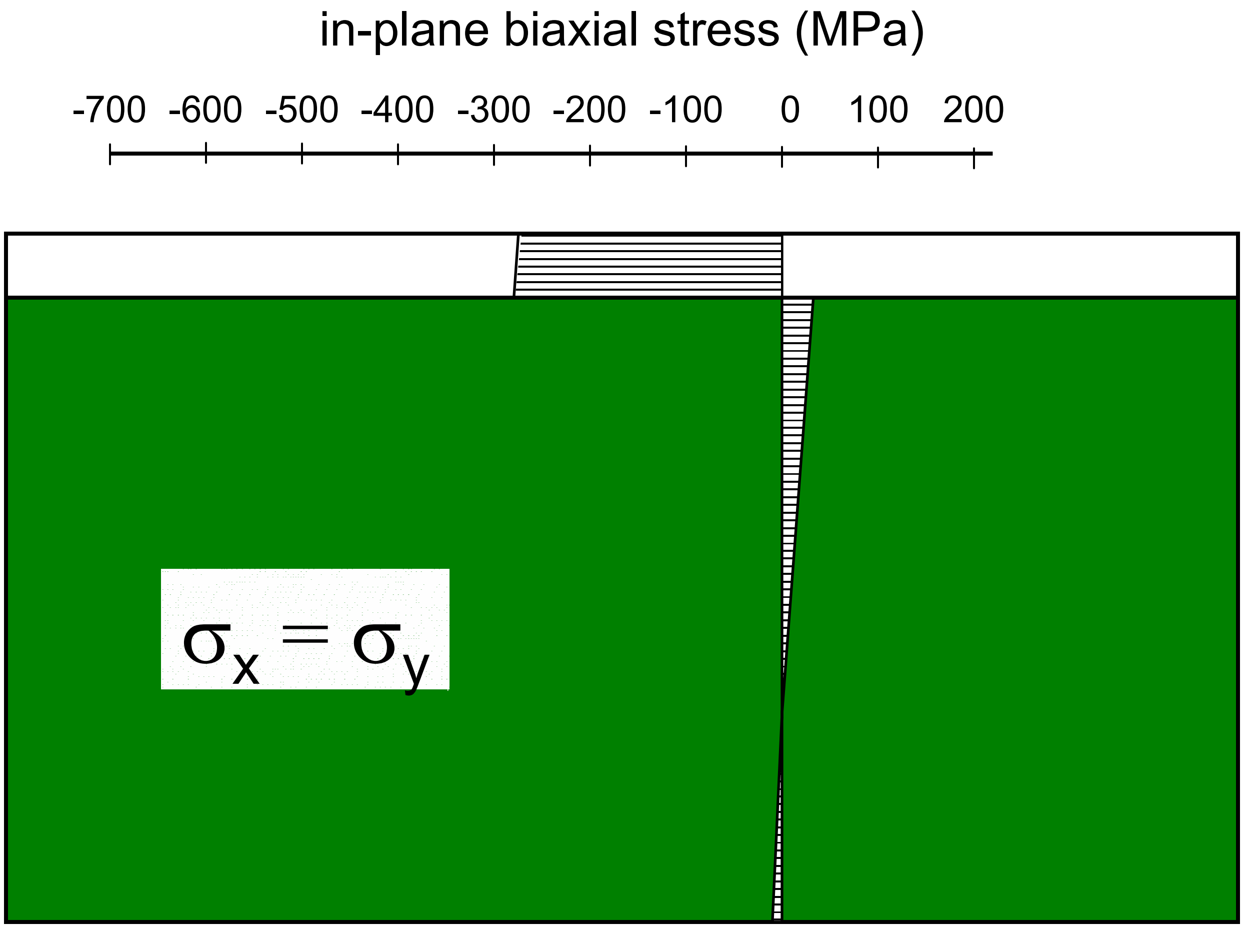
20°C

Residual Stresses in NiO-YSZ/YSZ bilayer



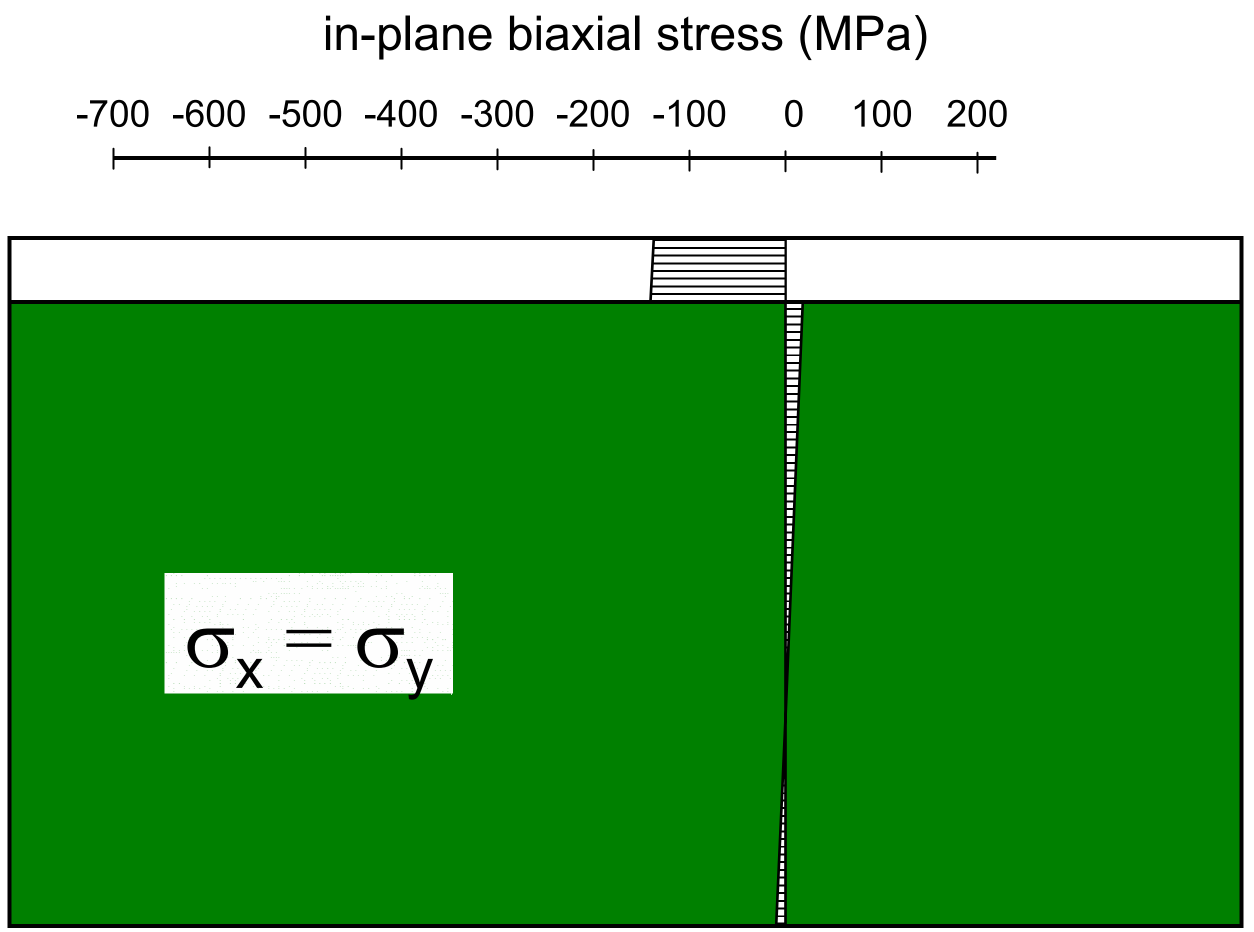
400°C

Residual Stresses in NiO-YSZ/YSZ bilayer



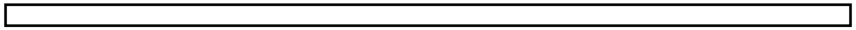
600°C

Residual Stresses in NiO-YSZ/YSZ bilayer



800°C

Implications



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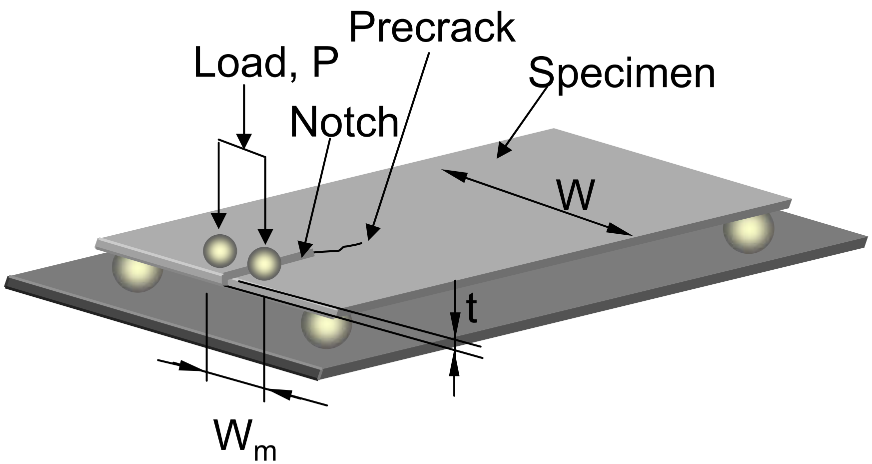
Summary

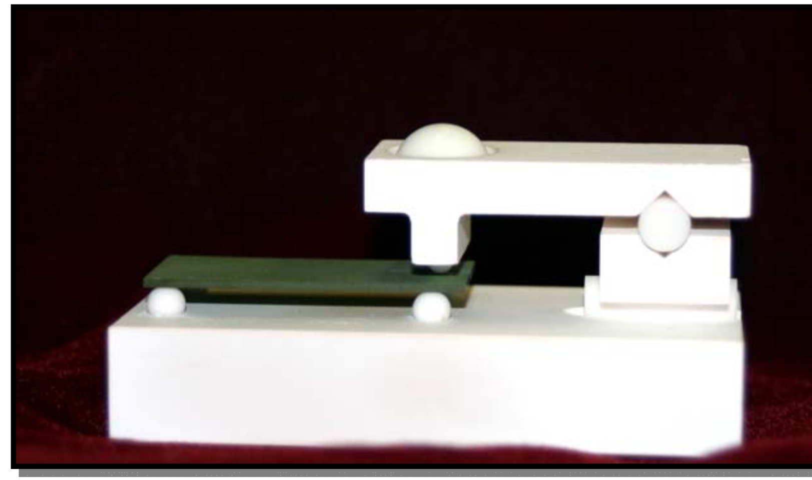
- Large residual compressive stress in zirconia layer at room temperature.
- The magnitude of residual stresses decreases linearly with temperature.
- The magnitude of residual stresses in both zirconia and Ni-YSZ layers decreases after NiO-YSZ reduction in H_2.
- The zero-stress temperature was found to be lower than the sintering temperature.
- Model predictions are consistent with curvature measurements and X-ray diffraction determined values.

Fracture Toughness

Fracture Toughness

Double Torsion

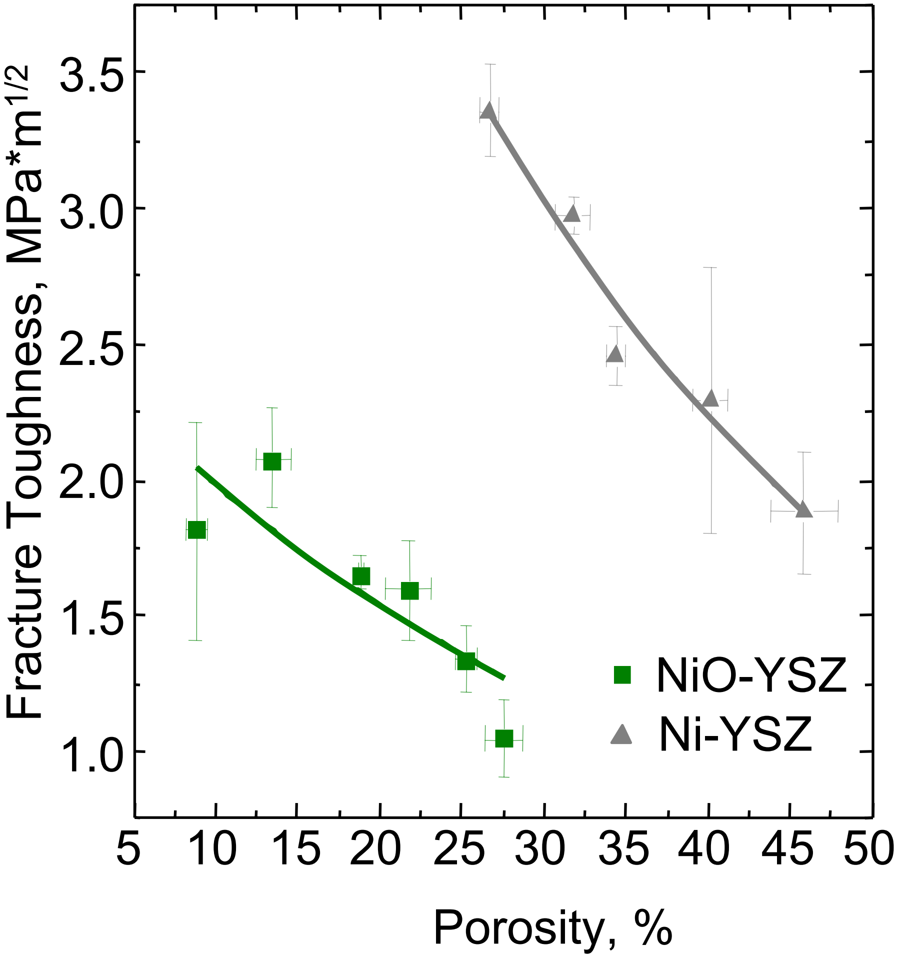


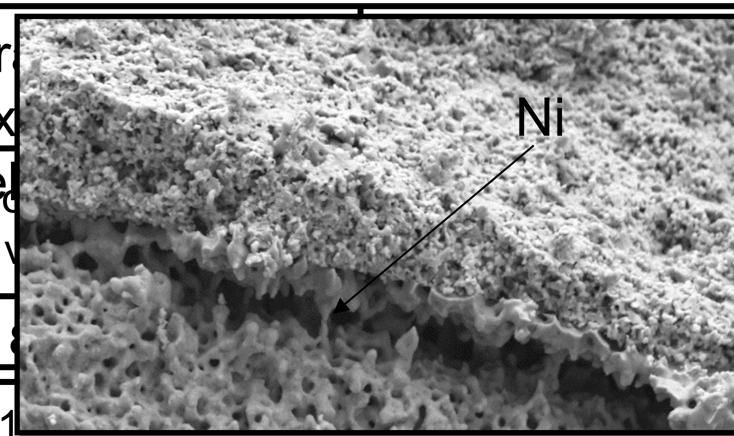


$$K_I = PW_m \left[\frac{3(1+v)}{Wt^4\xi}\right]^{1/2}, \xi = 1 - 1.26(t/W) + 2.4(t/W)\exp[-\pi W/(2t)]$$

P-maximum load, v – Poisson's ratio
Precracked @ 0.02 mm/min and tested @ 1 mm/min

Fracture Toughness

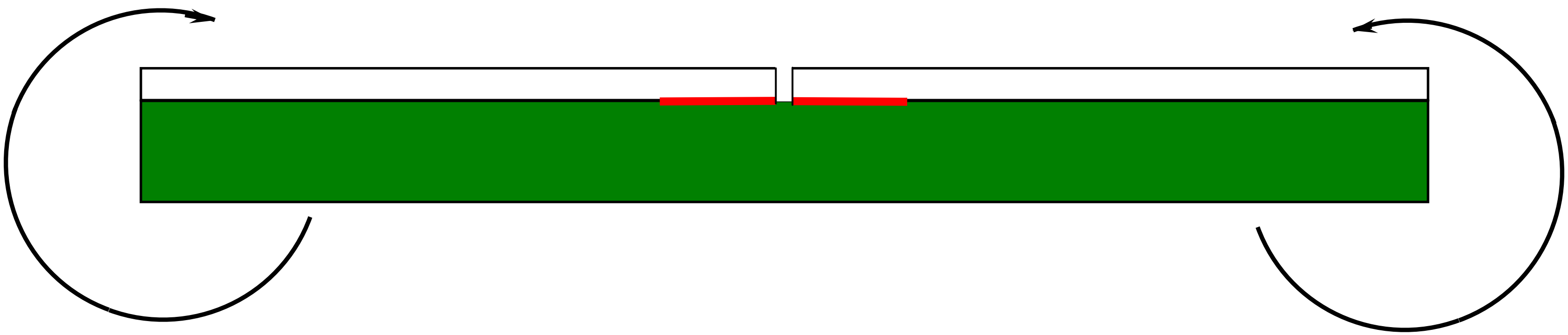




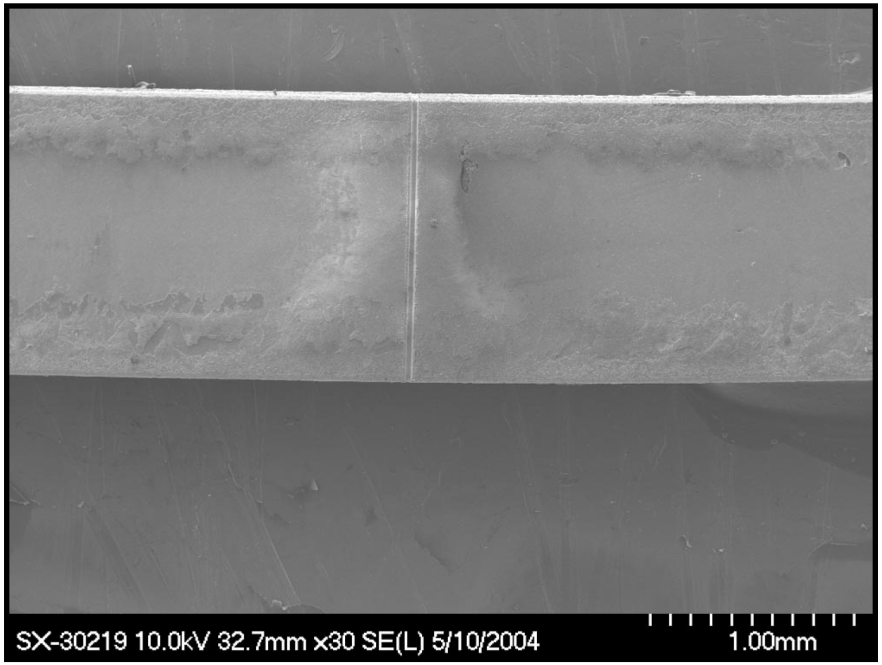
Fracture Toughness increases due to the formation of Ni ligaments as a result of H_2 reduction.

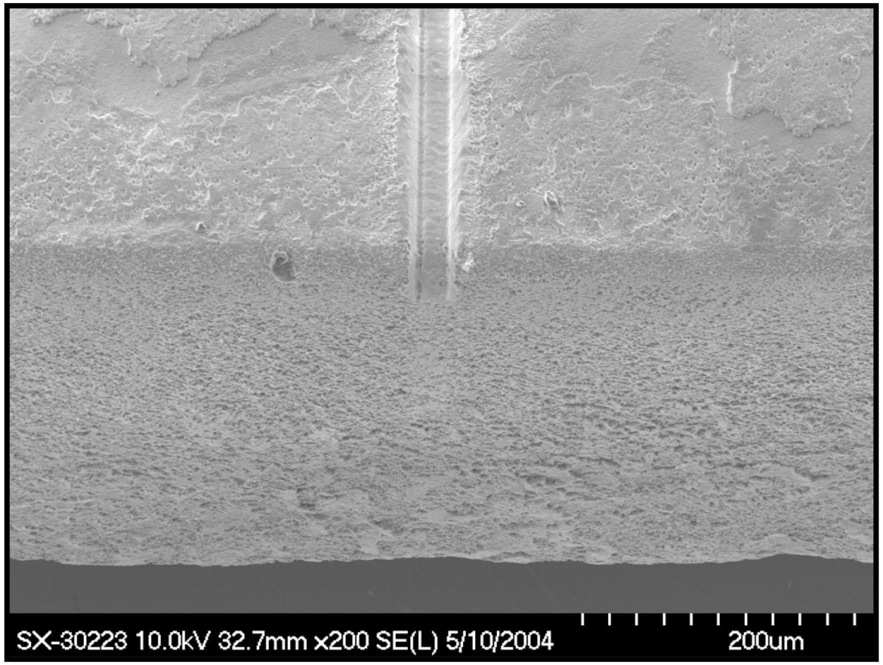
27.6 ρ_K	1.05	±0.83	45.87	±0.36 1.38

Interfacial Fracture Toughness



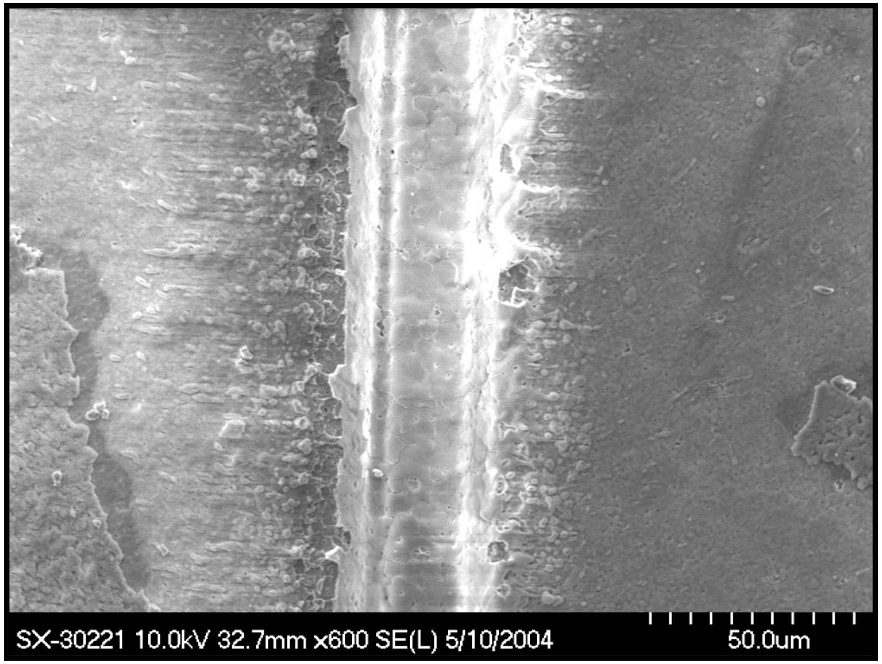
Interfacial Fracture Toughness



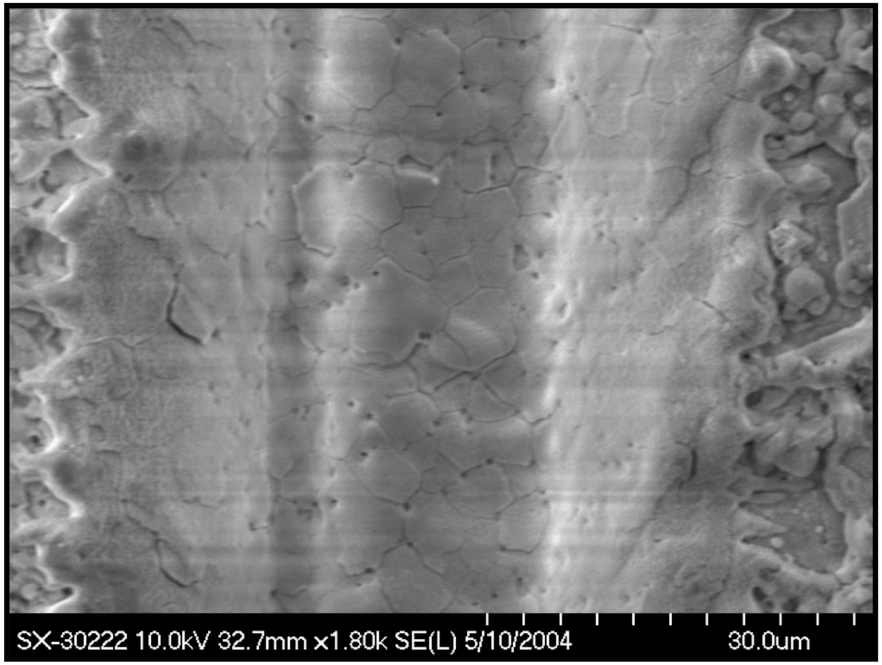


Notches machined
with laser beam

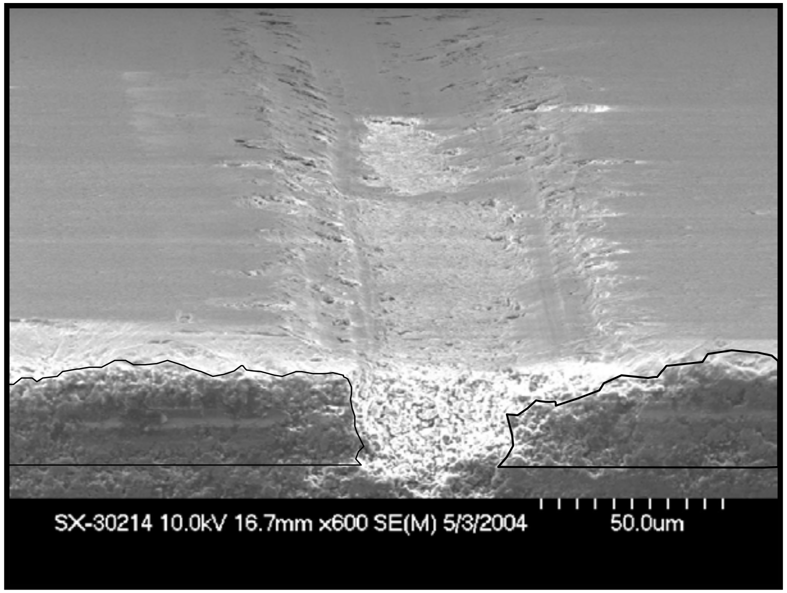
Interfacial Fracture Toughness

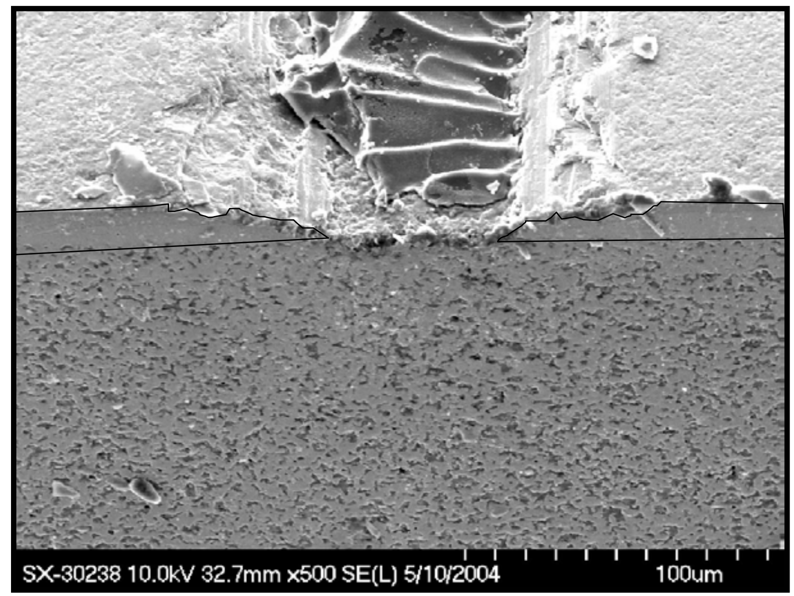


Notches machined
with laser beam



Interfacial Fracture Toughness





Notches machined with diamond blade

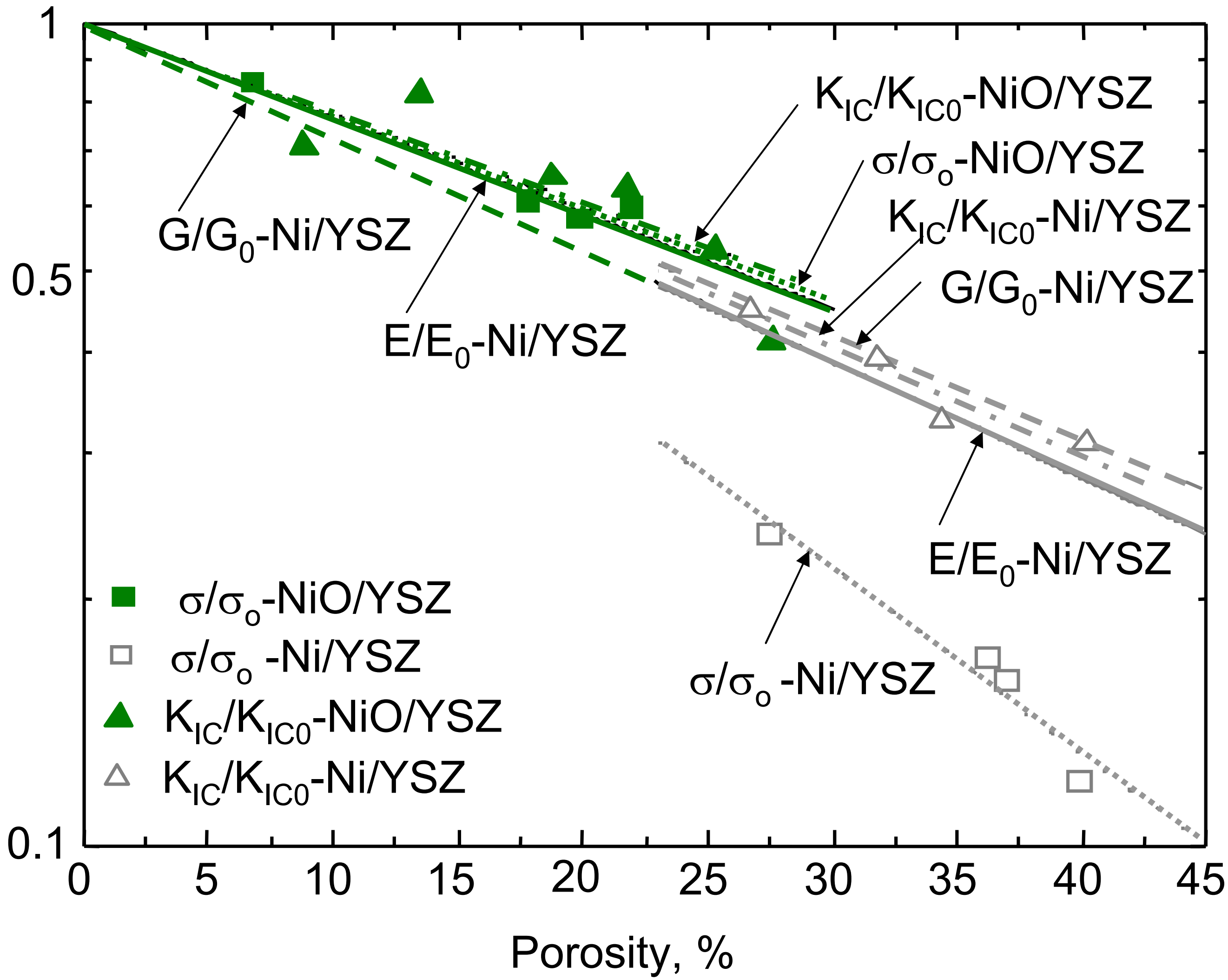
Interfacial Fracture Toughness

- Work in progress to optimize sample preparation.
- Tests will be carried out under a microscope or using a special test fixture inside an SEM.
- Collaboration with J. Qu et al. (Ga. Tech)

Data Base

A study to determine the effect of porosity, temperature and test specimen thickness on the elastic properties, strength, fracture toughness and thermophysical properties of NiO-YSZ, Ni-YSZ and YSZ has been completed.

Data Base

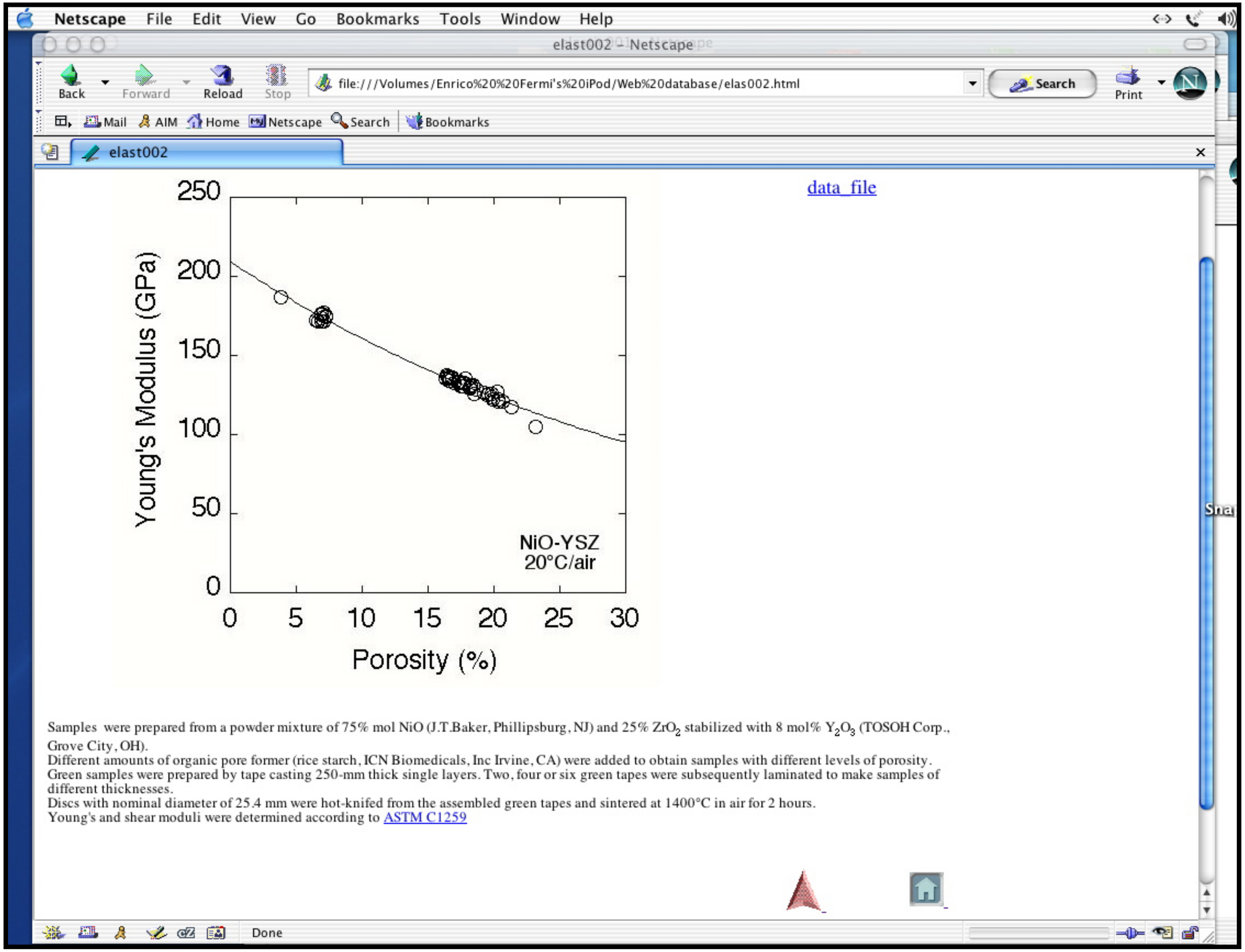


1
0.5
0.1
0
5
10
15
20
25
30
35
40
45
Porosity, %
K_{IC}/K_{IC0}-NiO/YSZ
σ/σ_o-NiO/YSZ
K_{IC}/K_{IC0}-Ni/YSZ
G/G_0-Ni/YSZ
G/G_0-Ni/YSZ
E/E_0-Ni/YSZ
E/E_0-Ni/YSZ
σ/σ_o -Ni/YSZ
σ/σ_o-NiO/YSZ
σ/σ_o -Ni/YSZ
K_{IC}/K_{IC0}-NiO/YSZ
K_{IC}/K_{IC0}-Ni/YSZ

Data Base


SOFCs – Netscape
Back
Forward
Reload
Stop
file:///Volumes/Enrico%20%20Fermi's%20iPod/Web%20database/MENU.html
Search
Print
Mail
AIM
Home
Netscape
Search
Bookmarks
SOFCs
Solid State Energy
Conversion Alliance (SECA)
Physical and Mechanical Properties of SOFC Materials & Structures
Elastic Properties
Monotonic Strength
Fracture Toughness
Residual Stresses
Thermal Conductivity
Thermal Cycling
Thermal Shock
Creep Deformation
NiO Reduction
Thermal Expansion
Links

Data Base



Netscape File Edit View Go Bookmarks Tools Window Help
elast002 – Netscape
Back Forward Reload Stop
file:///Volumes/Enrico%20%20Fermi's%20iPod/Web%20database/elas002.html
Search
Print
Mail AIM Home Netscape Search Bookmarks
elast002
data file
Young's Modulus (GPa)
250
200
150
100
50
0
0 5 10 15 20 25 30
Porosity (%)
NiO-YSZ
20°C/air
Samples were prepared from a powder mixture of 75% mol NiO (J.T.Baker, Phillipsburg, NJ) and 25% ZrO_2 stabilized with 8 mol% Y_2O_3 (TOSOH Corp., Grove City, OH).
Different amounts of organic pore former (rice starch, ICN Biomedicals, Inc Irvine, CA) were added to obtain samples with different levels of porosity.
Green samples were prepared by tape casting 250-mm thick single layers. Two, four or six green tapes were subsequently laminated to make samples of different thicknesses.
Discs with nominal diameter of 25.4 mm were hot-knifed from the assembled green tapes and sintered at 1400°C in air for 2 hours.
Young's and shear moduli were determined according to ASTM C1259
Done

Data Base

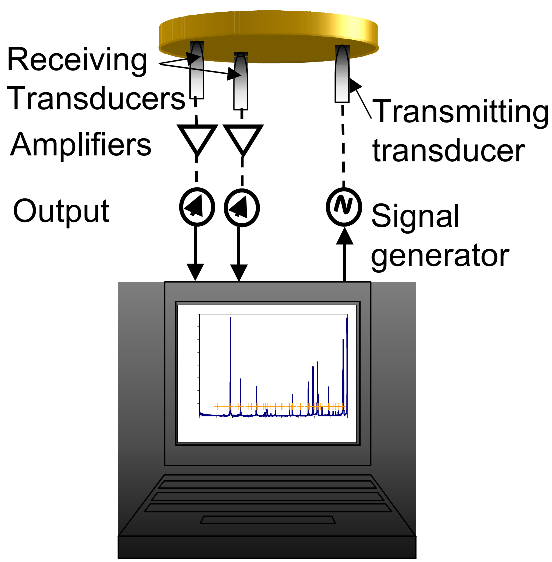
- Thermophysical and mechanical properties of SOFC materials.
- Data generated at ORNL
- Data reported in open literature
- To be distributed to SECA Industrial Teams

Summary

- A methodology has been developed to determine the magnitude of residual stresses in SOFC layered systems as a function of temperature by means of X-ray diffraction.
- Information necessary for determining zero-stress reference temperature, for verifying thermoelastic models and for predictions of reliability and durability.
- Work is in progress to determine the fracture toughness of relevant SOFC interfaces.
- A data base has been assembled containing physical and mechanical properties of SOFC materials.
- All elements are in place for predicting reliability of SOFC assemblies.

Elastic Modulus of GDC

Resonant Ultrasound Spectroscopy (RUS)



In collaboration with Eric Wachsman
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