

Durability and Reliability of SOFC Materials and Components

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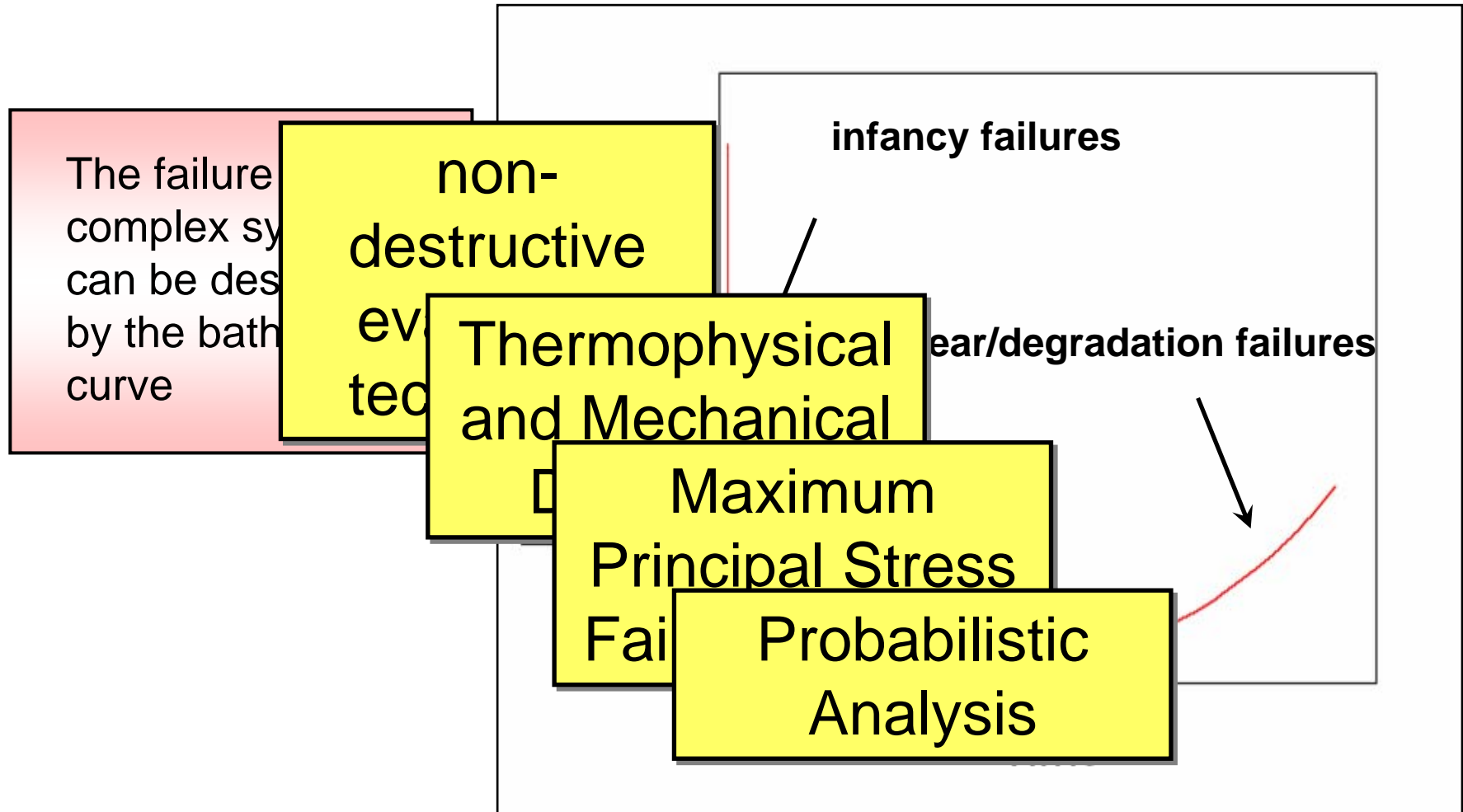
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Outline

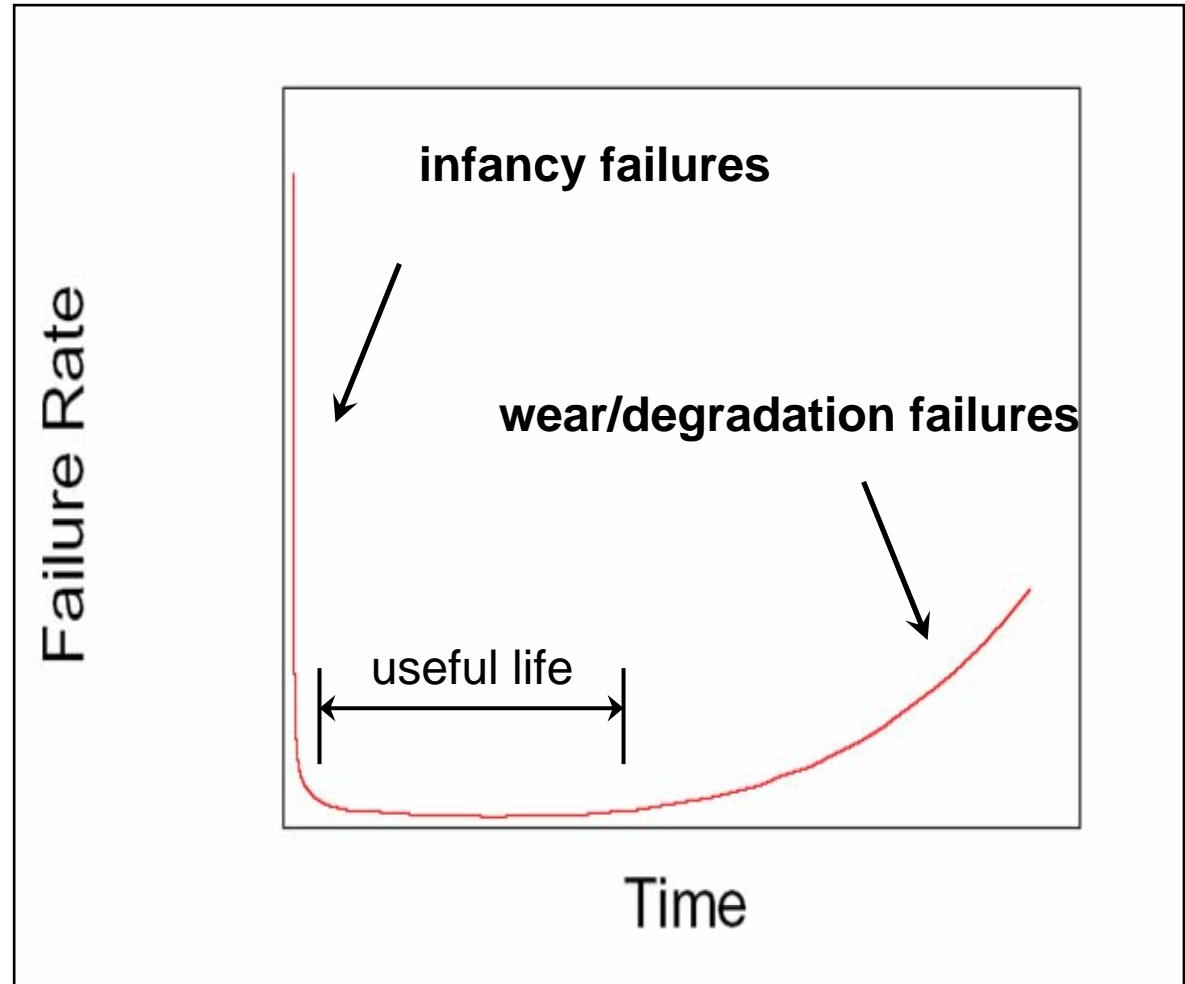
- Introduction
- Time-dependent deformation of Ni-YSZ
- Effect of thermal cycling & thermal aging on the properties and microstructure of SOFC materials
- Other
- Future work

Introduction: Reliability of Engineering Systems



Introduction: Reliability of Engineering Systems

The failure rate of complex systems can be described by the bathtub curve



Focus of today's presentation

- Time-dependent deformation of Ni-YSZ
- Effect of thermal cycling & thermal aging on the properties and microstructure of SOFC materials

Time-dependent Deformation/Dimensional Stability

Is creep
deformation good
or bad?

Time-dependent deformation

Creep deformation could be good

Creep deformation could be bad

Time-dependent deformation

most materials exhibit creep deformation when subjected to stresses at high homologous temperatures (T/T_M)

- thermal stresses (cte mismatch, temperature gradients)

Time-dependent deformation

most materials exhibit creep deformation when subjected to stresses at high homologous temperatures (T/T_M)

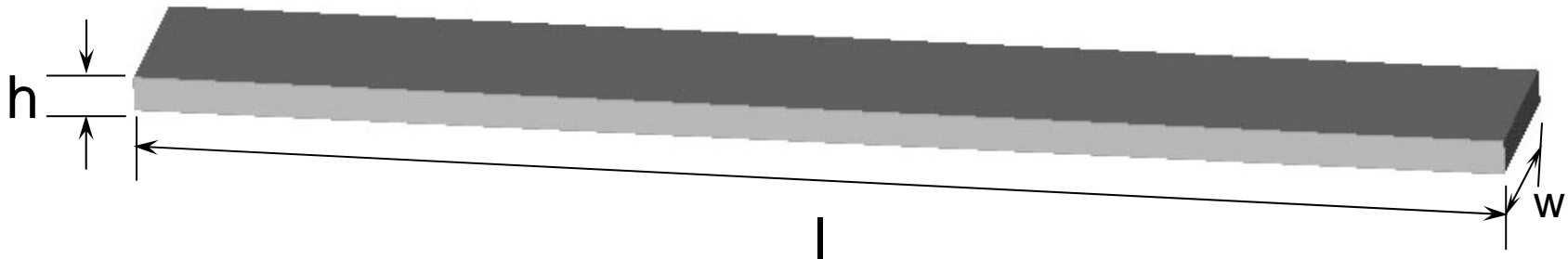
- thermal stresses (cte mismatch, temperature gradients)
- mechanical stresses (pressure)

Focus of today's presentation

- Time-dependent deformation of Ni-YSZ

Time-dependent deformation

Let's consider a beam of **thickness h , width w and length l** .



Time-dependent deformation

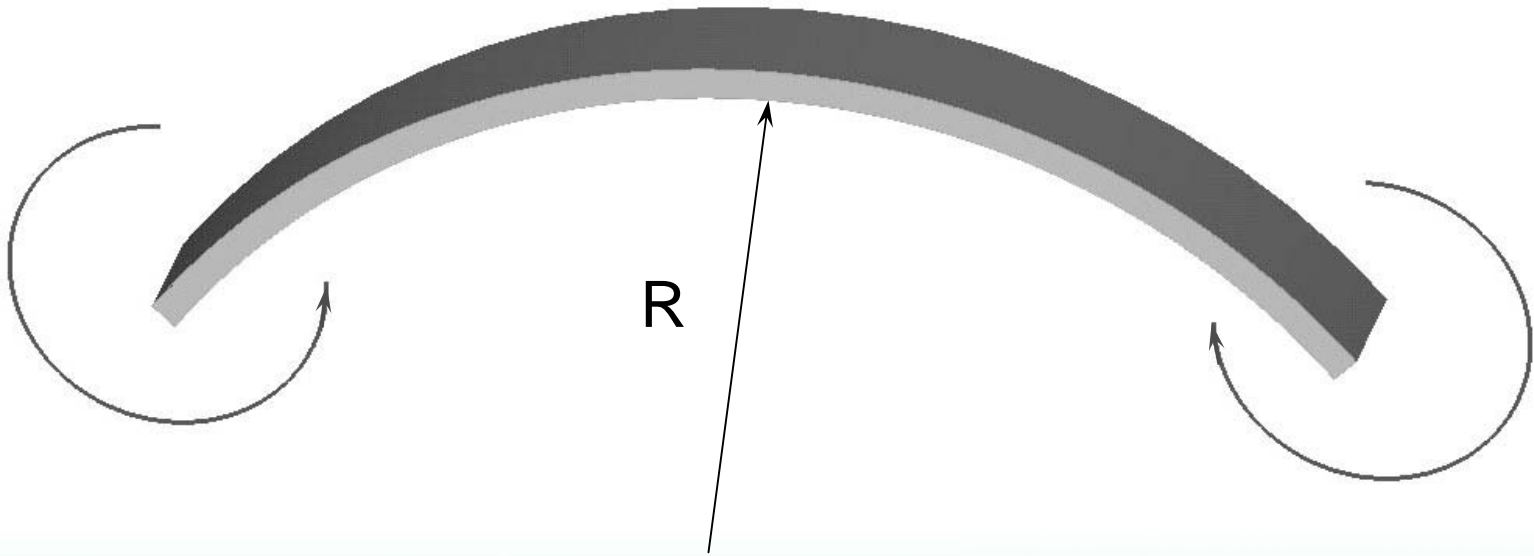
Let's subject the beam to **pure bending** within its **elastic limit**



Time-dependent deformation

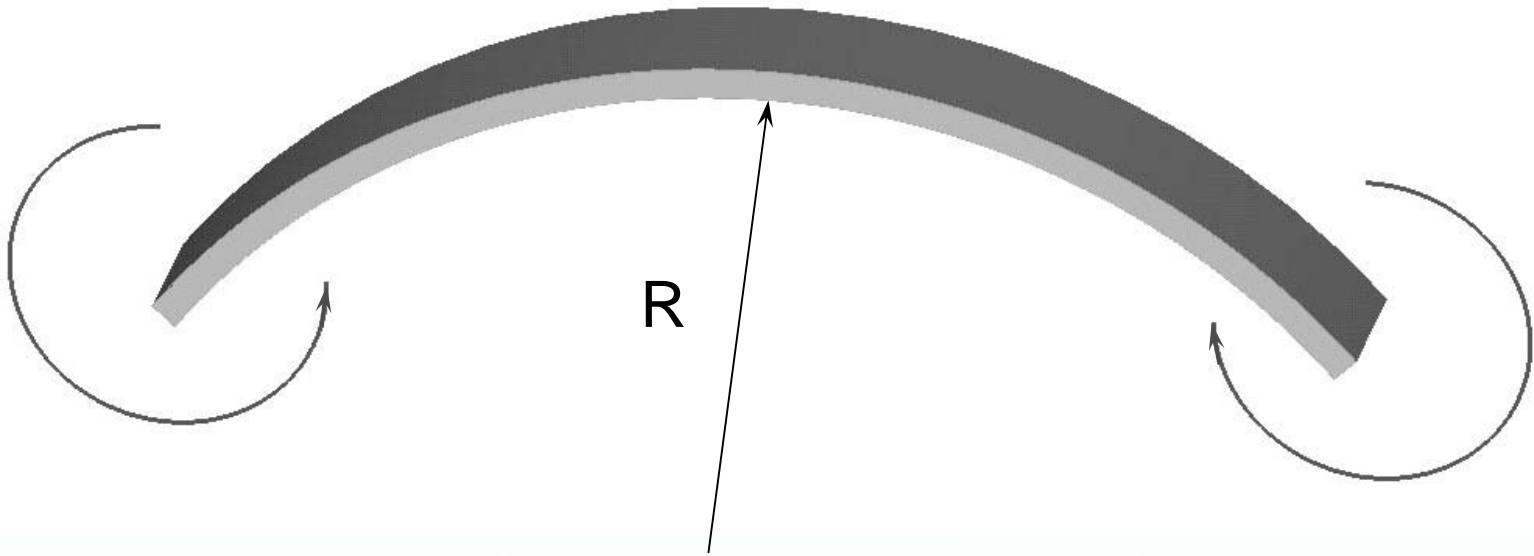
The maximum **strain** and **stress** will be related to the radius of **curvature** according to:

$$\sigma = E \varepsilon = \frac{E h}{2 R}$$



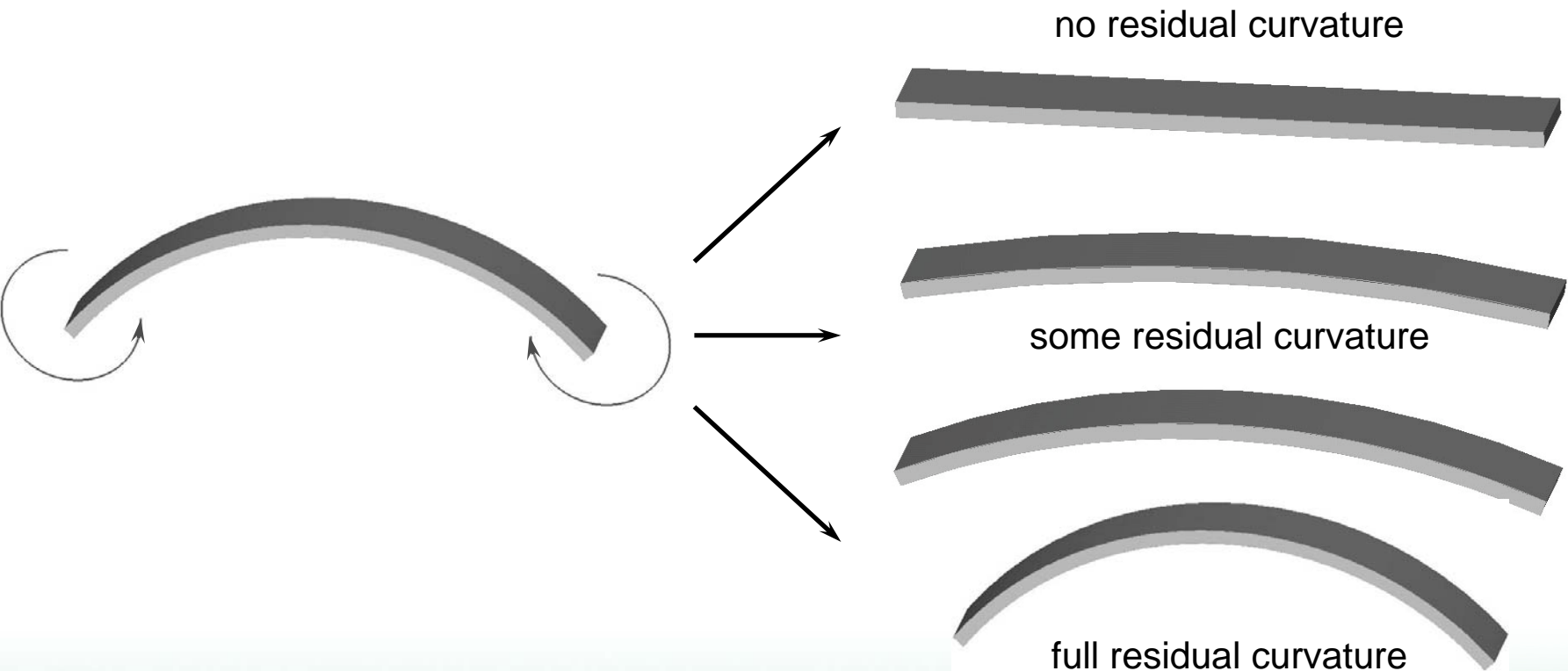
Time-dependent deformation

Now, let's subject the bent beam to **temperature T** , for a period of **time t** .

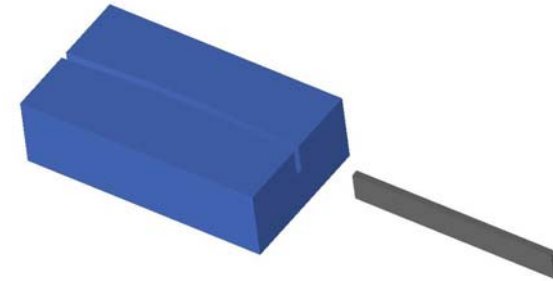


Time-dependent deformation

At the end of the thermal treatment, let's remove the bending moment and measure the residual curvature of the beam by laser profilometry.



Time-dependent deformation Ni-YSZ (30% porosity)



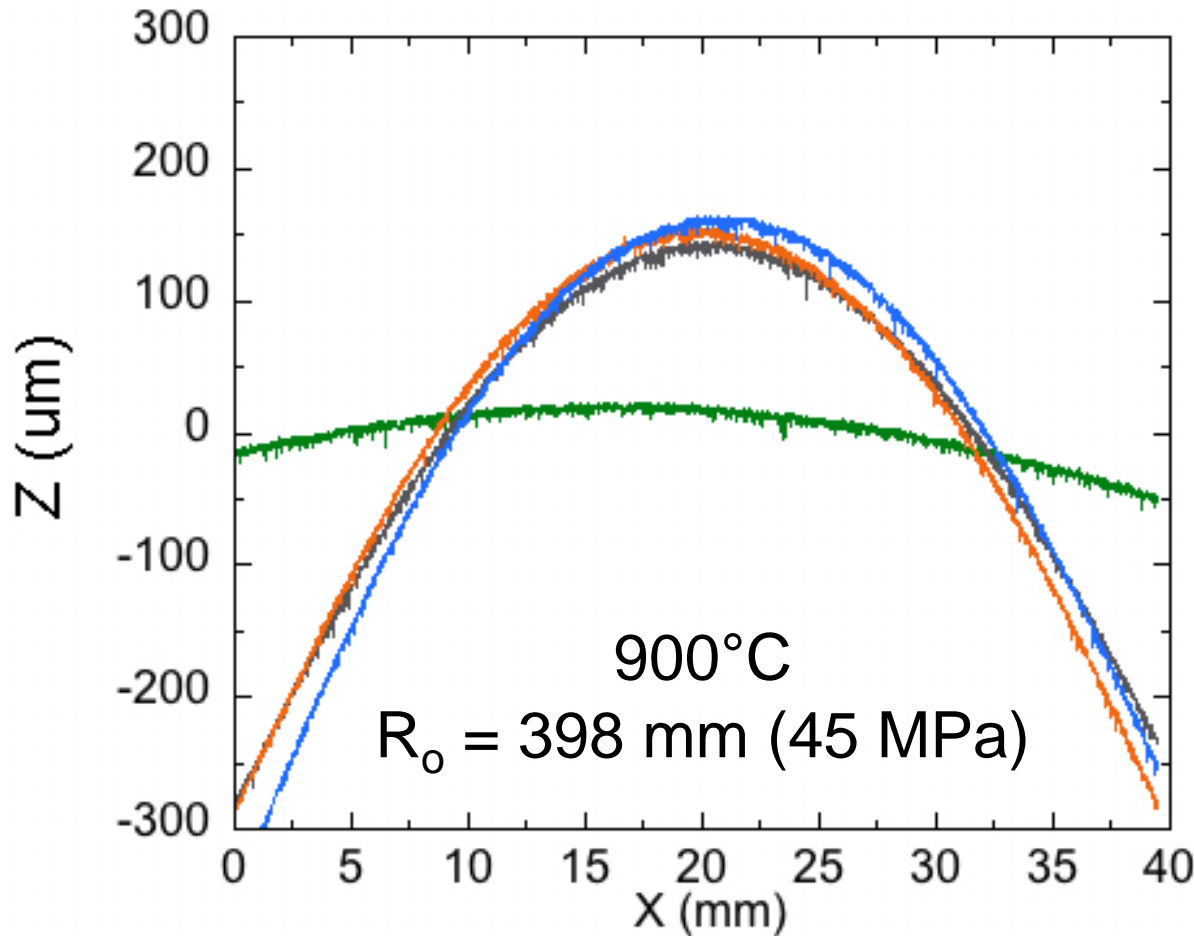
machinable alumina fixtures

- 600°C
- 800°C
- 900°C
- 15, 30 and 45 MPa
- 4%H₂+96%Ar

sample dimensions:

- 0.7 mm
- 4 mm
- 40 mm

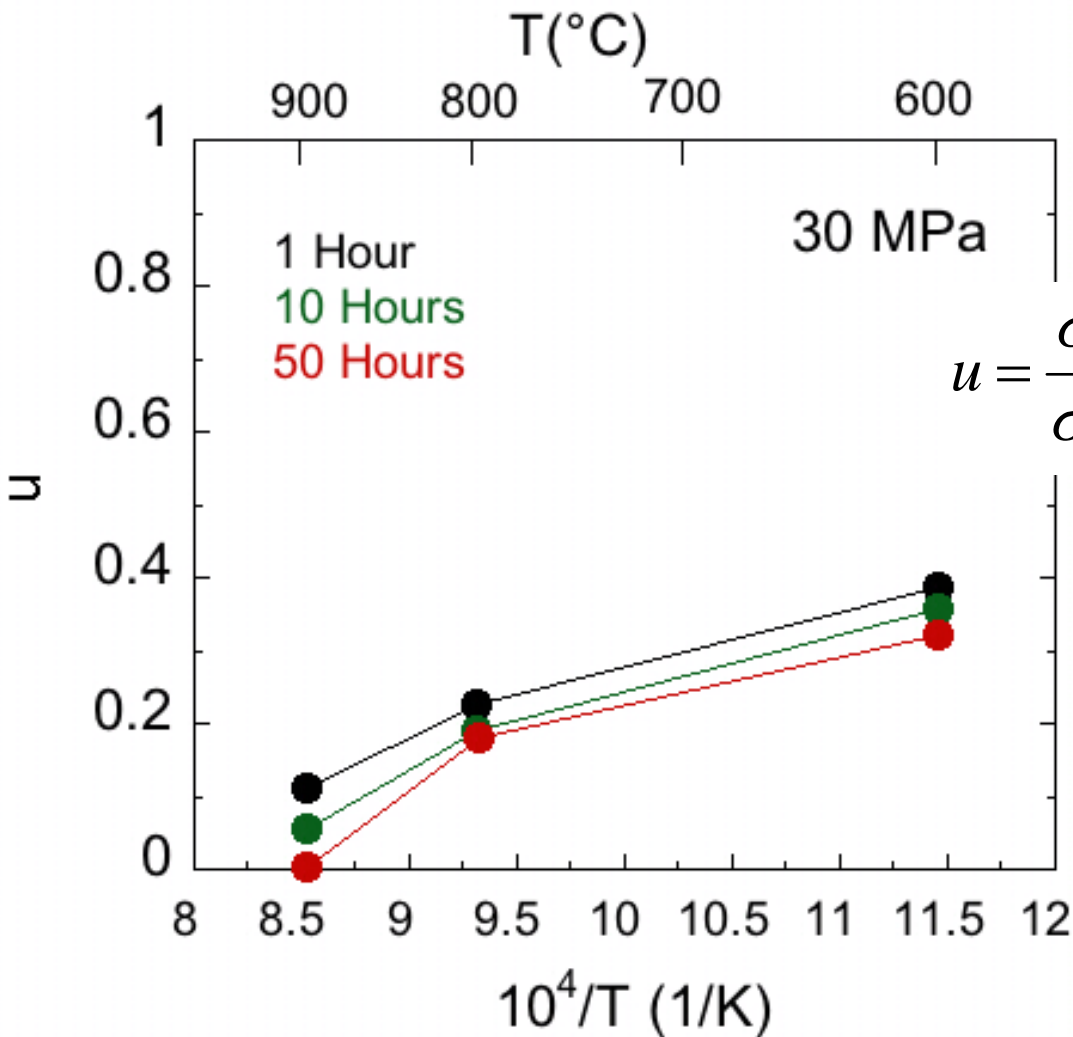
Time-dependent deformation of Ni-YSZ



Time (hrs)	R(t) (mm)
0	3724
1	474
10	436
50	413



Time-dependent deformation of Ni-YSZ



$$u = \frac{\sigma(t, T, \varepsilon_o)}{\sigma(0, T, \varepsilon_o)} = \frac{M_b(t)}{E(T)} = 1 - \frac{R}{R_o}$$

$$Q = R \ln\left(\frac{t_2}{t_1}\right) \left(\frac{1}{\frac{1}{T_1} - \frac{1}{T_2}} \right)$$

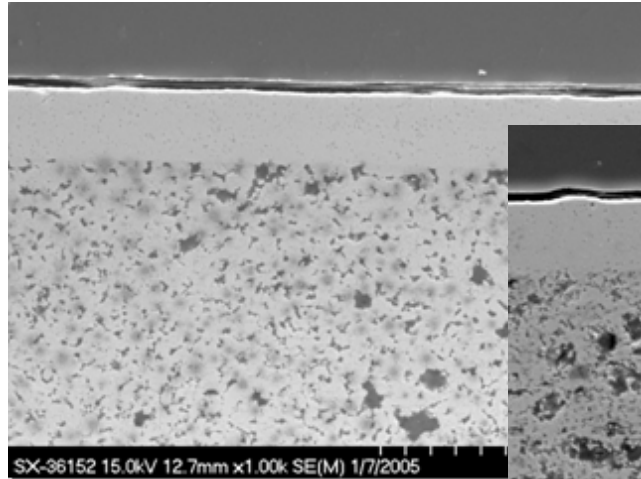
Time-dependent deformation of Ni-YSZ

- Ni-YSZ exhibits time-dependent deformation when subjected to stress at temperatures between 600°C and 900°C
- Thermally-activated process
- Implications:
 - during service thermal stresses will be relaxed.
 - beware of
 - mechanical stresses
 - redistribution of stresses during cool-down process
- Whenever possible, take advantage of creep deformation to enhance reliability

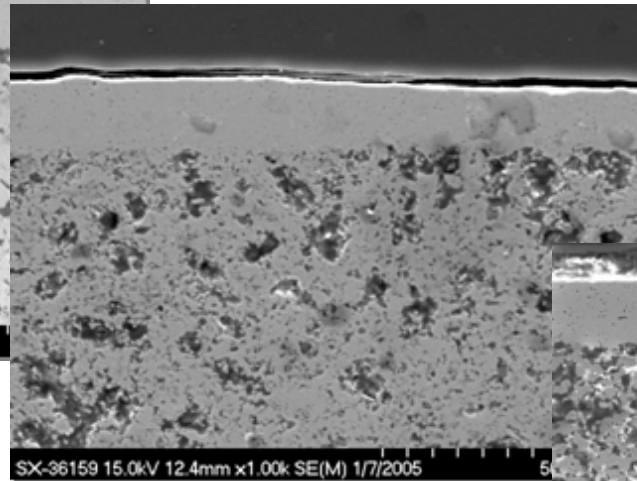
Focus of today's presentation

- Time-dependent deformation of Ni-YSZ
- Effect of thermal cycling & thermal aging on the properties and microstructure of SOFC materials

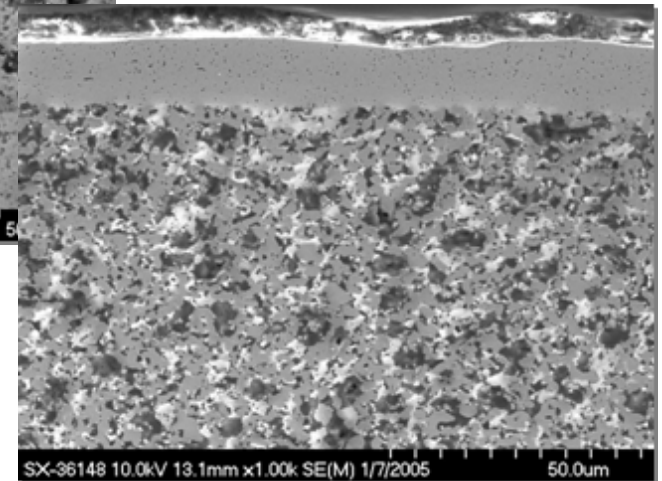
Thermal cycling and thermal aging



27-bilayer
0% pore former



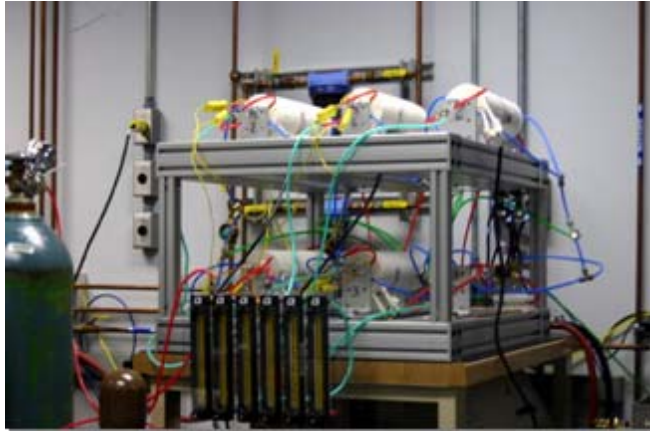
34-bilayer
15% pore former



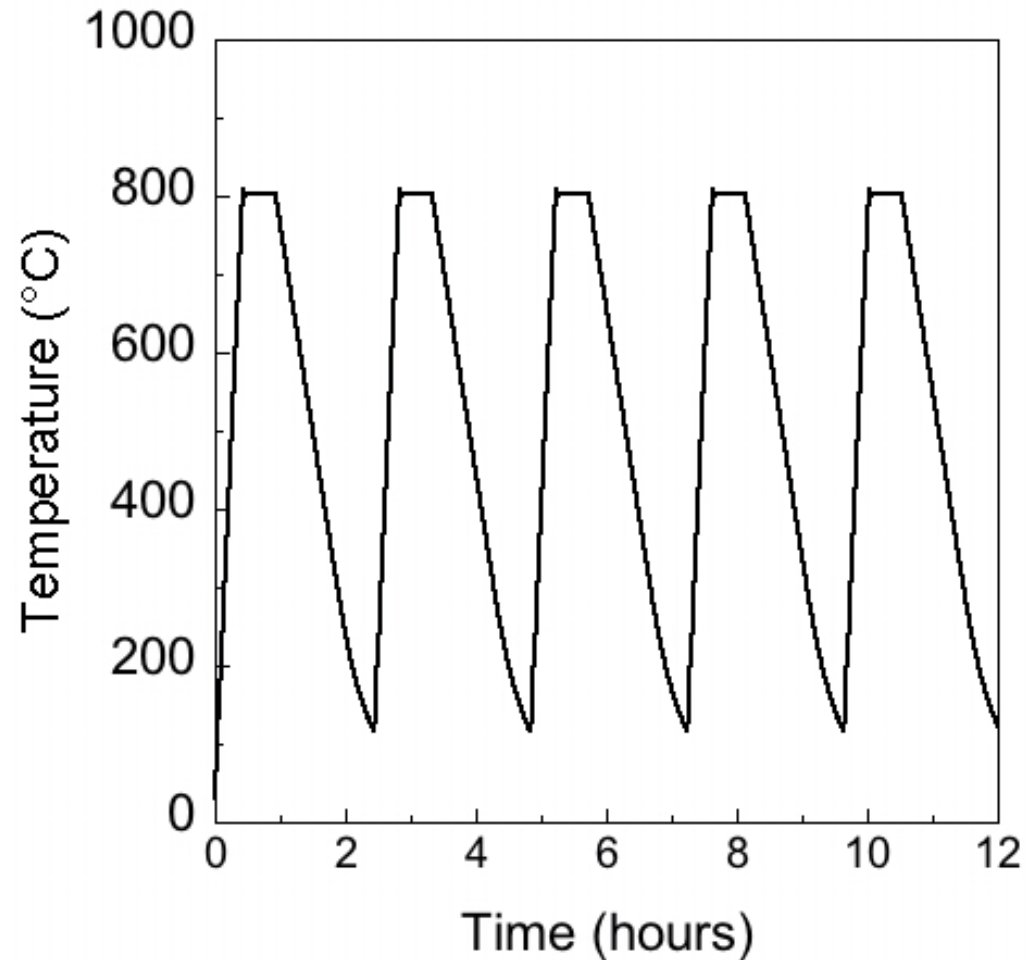
40-bilayer
30% pore former

- Ni-YSZ substrate
- 10- μ m thick YSZ layer

Thermal cycling and thermal aging



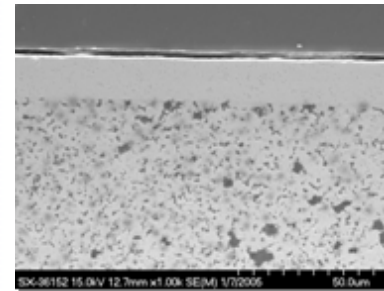
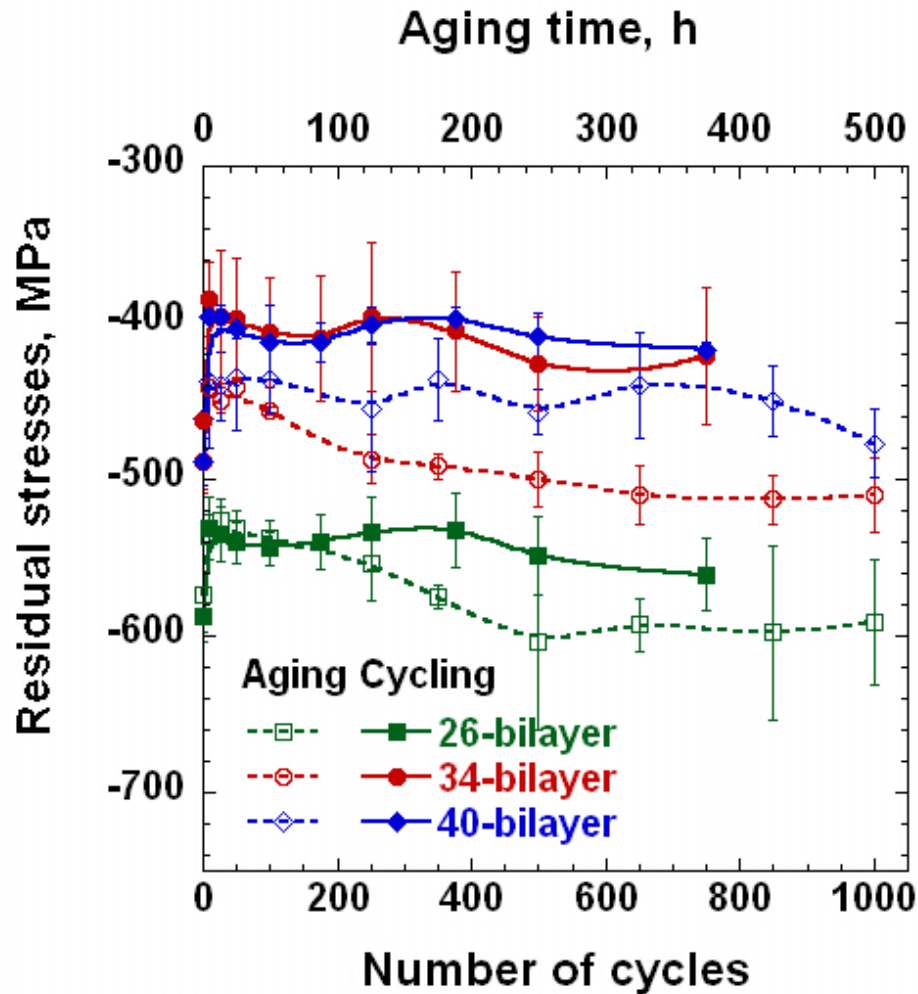
- H₂ (4%)-Ar (96%)
- tubular furnaces



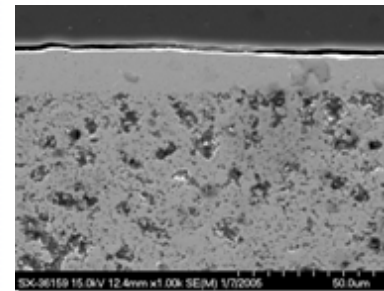
Thermal cycling and thermal aging

- Residual stresses (X-ray diffraction)
- Elastic modulus
- Biaxial strength
- Density
- Microstructure

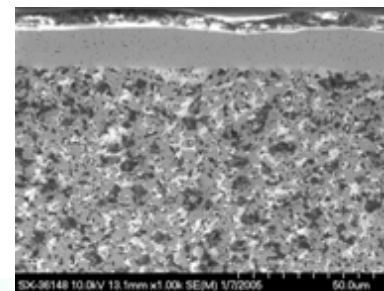
Thermal cycling and thermal aging



27-bilayer

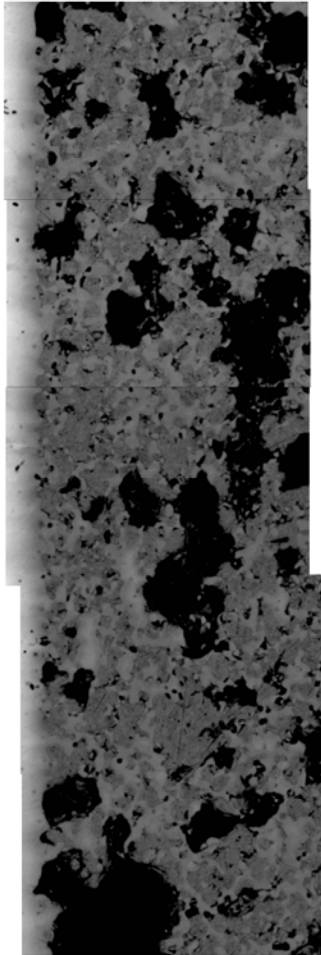


34-bilayer

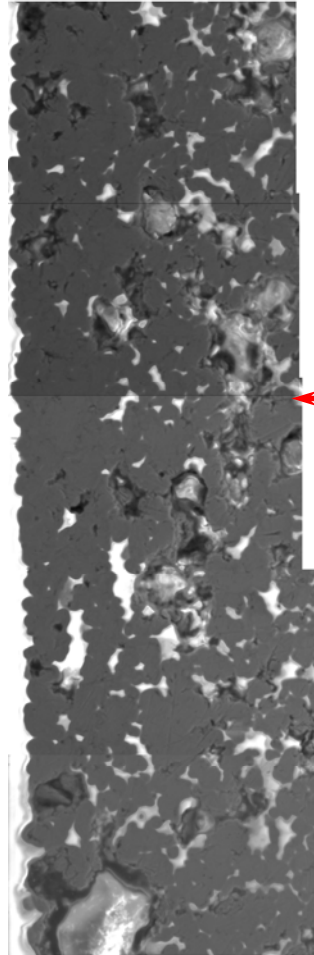


40-bilayer

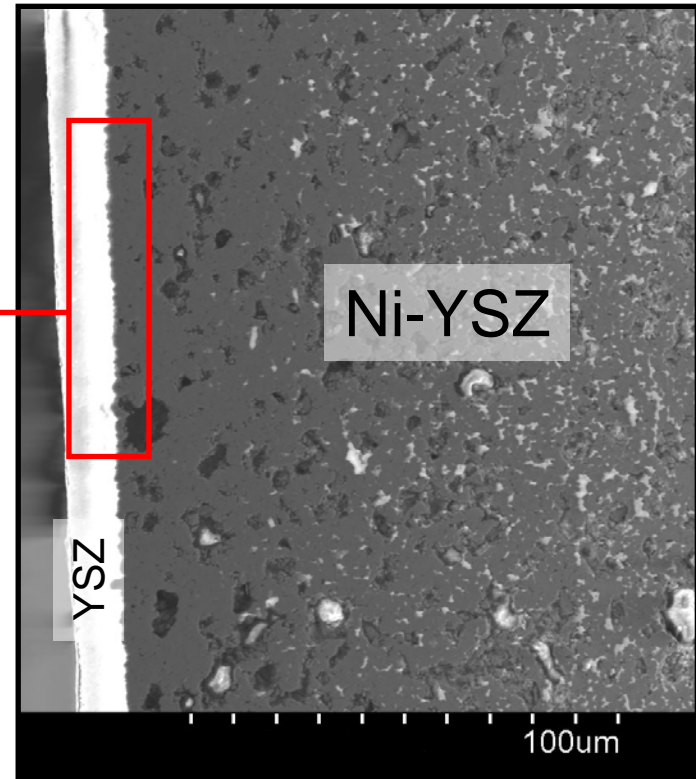
Microstructural evolution during thermal aging



backscattered
electrons image



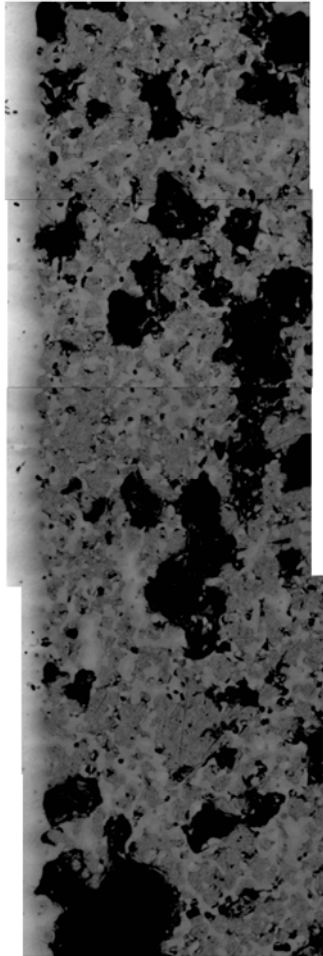
secondary
electrons image



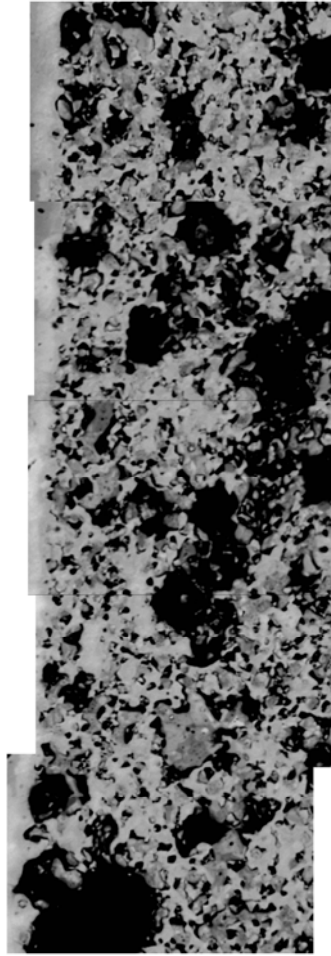
40-bilayer

Microstructural evolution during thermal aging

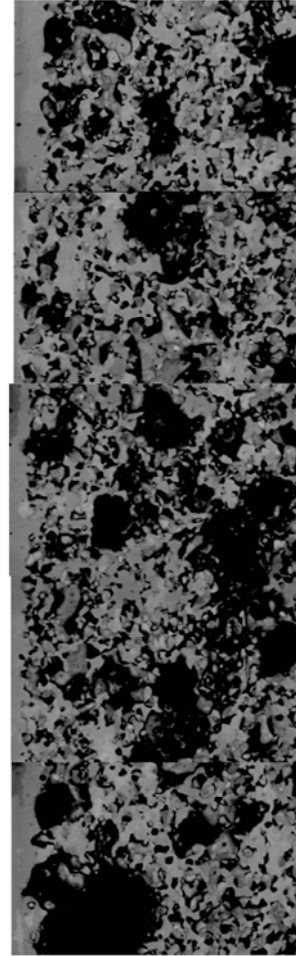
backscattered electron images



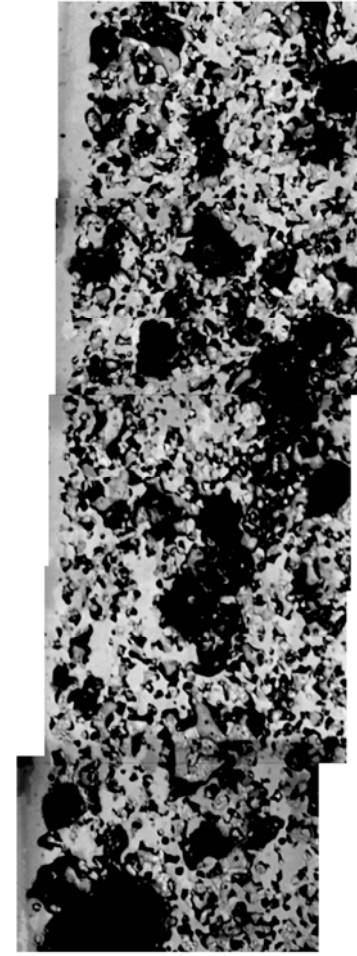
0 hrs



5 hrs

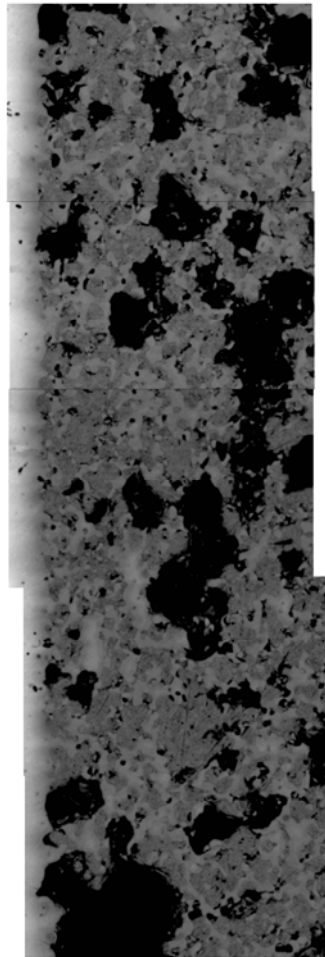


12.5 hrs

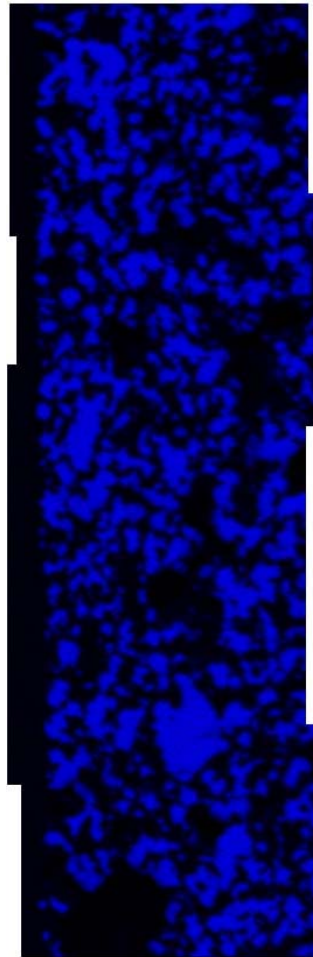


25 hrs

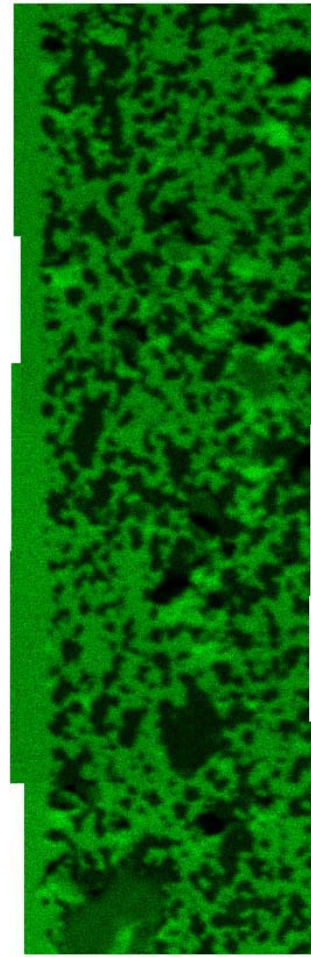
Microstructural evolution during thermal aging 0 hrs.



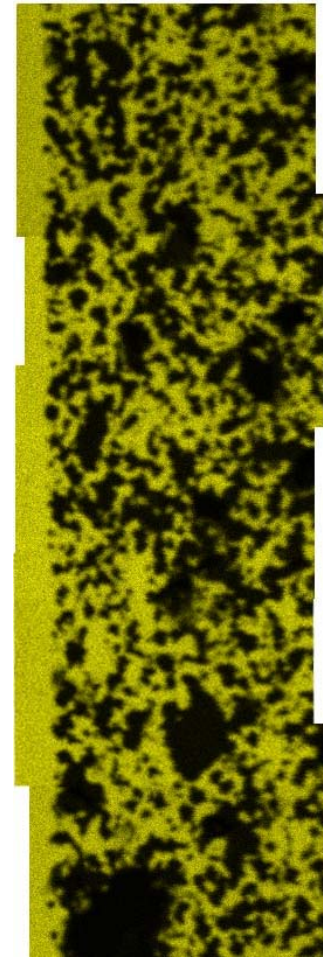
elemental maps



Ni

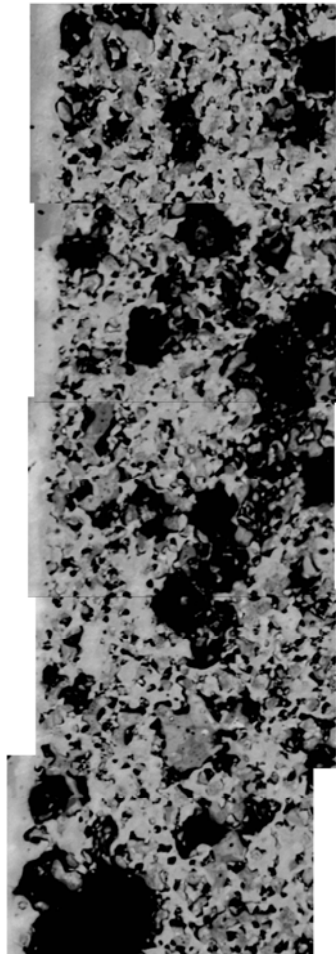


O

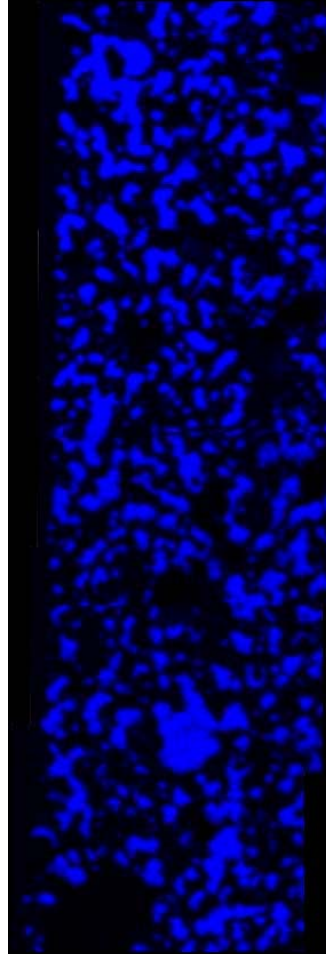


Zr

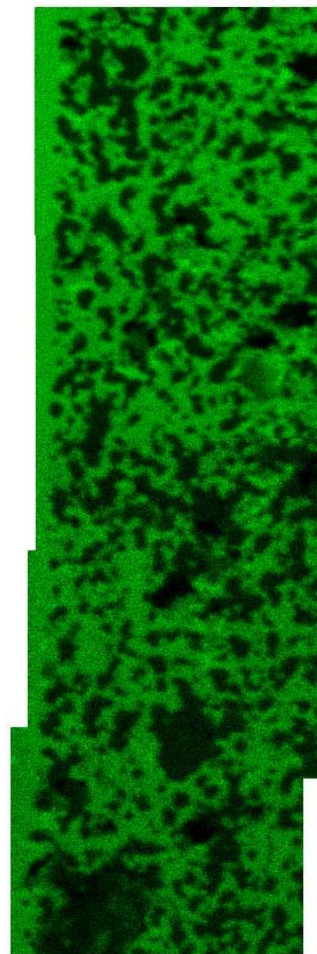
Microstructural evolution during thermal aging ^{5 hrs.}



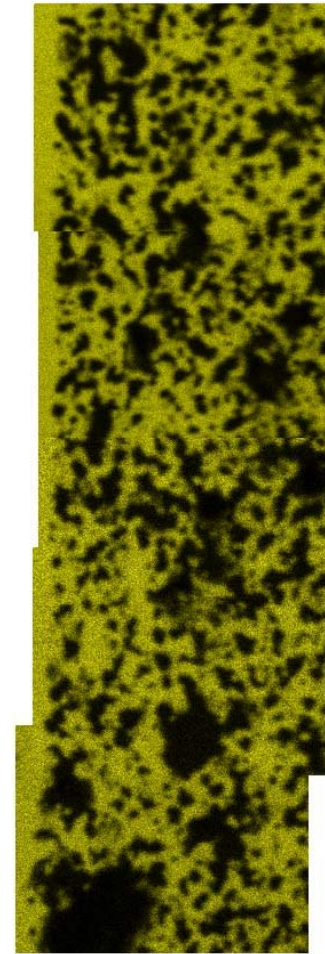
elemental maps



Ni

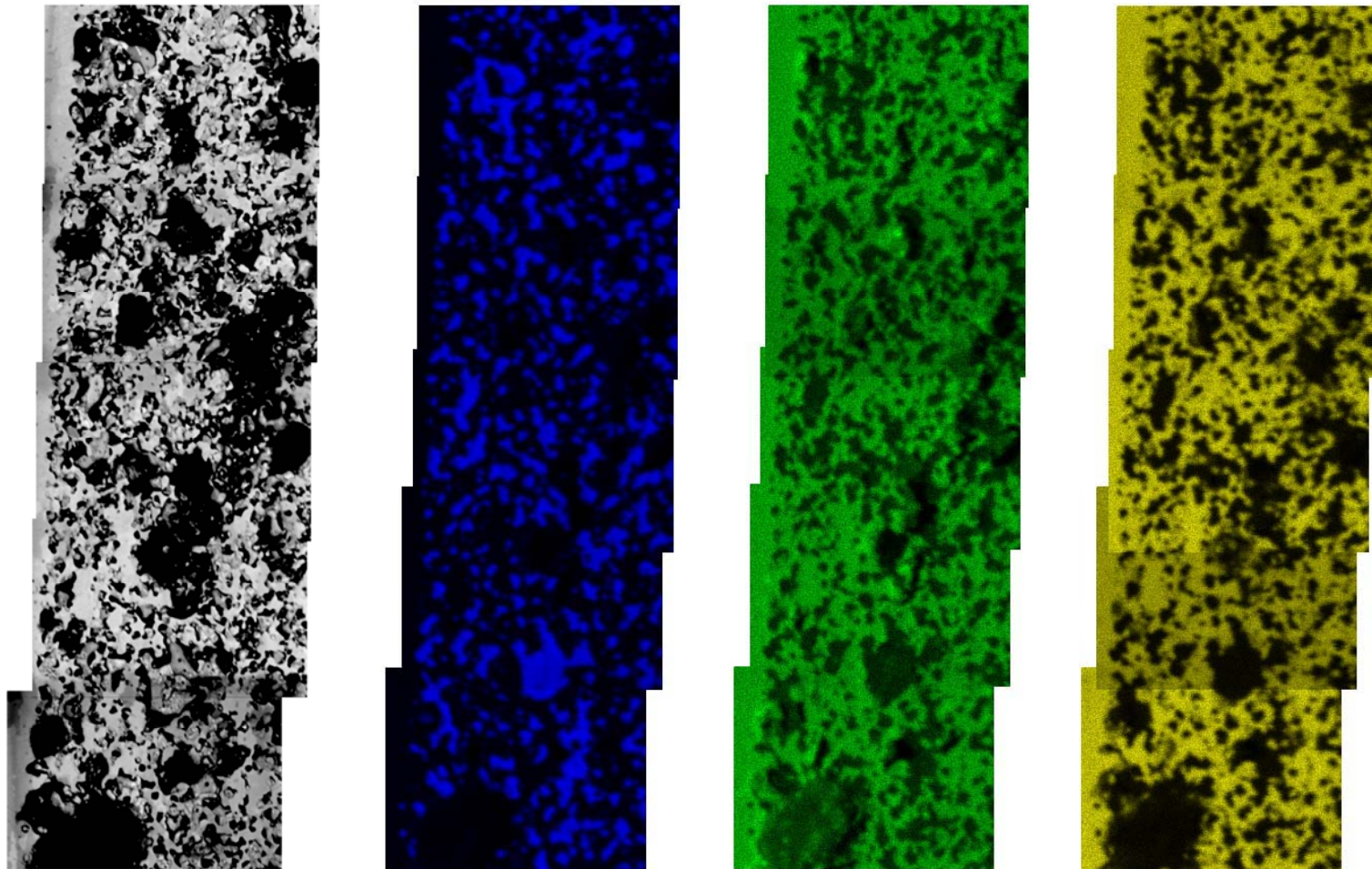


O



Zr

Microstructural evolution during thermal aging ^{25 hrs.}



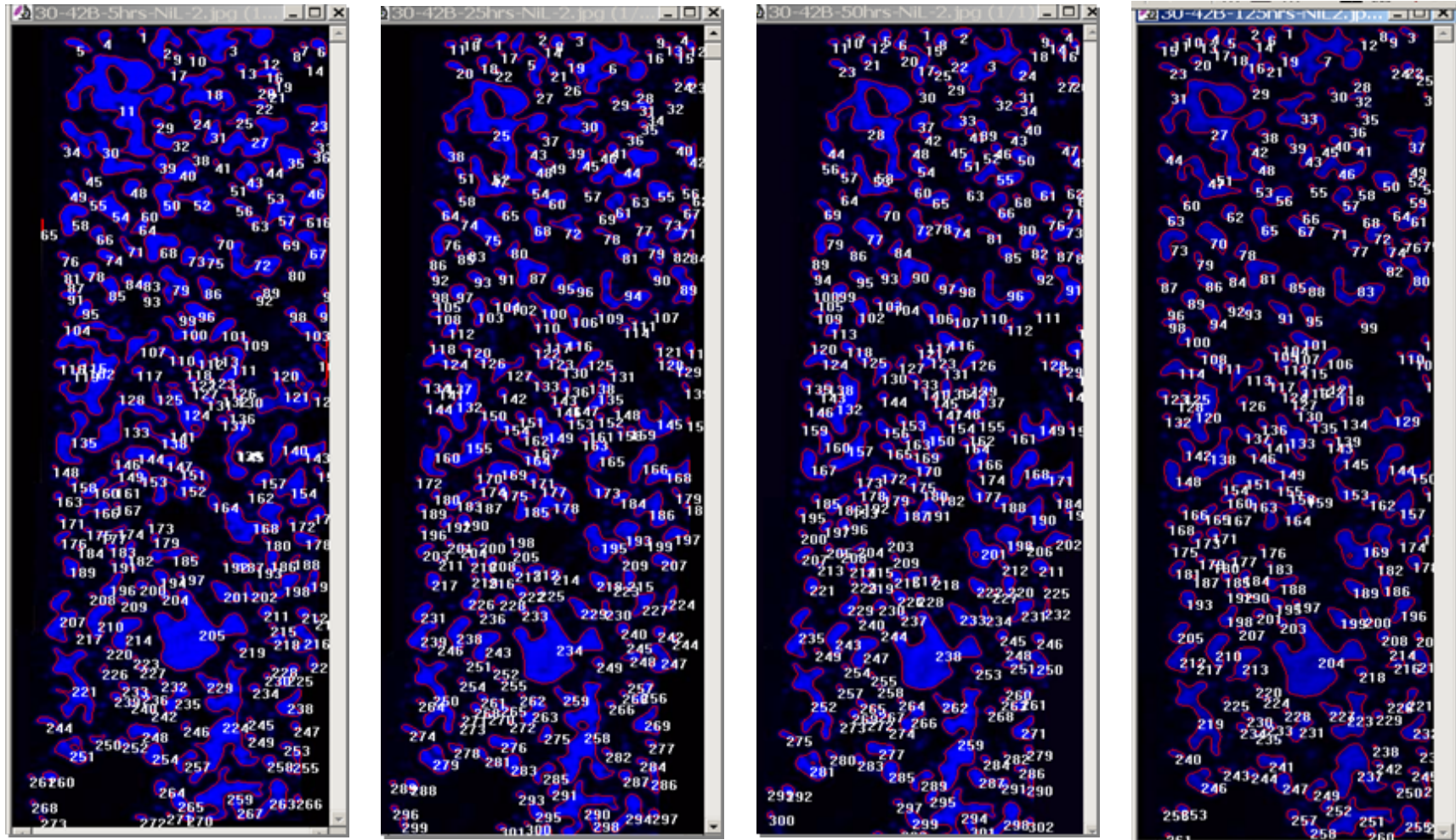
elemental maps

Ni

O

Zr

Microstructural evolution during thermal aging



0 hrs

5 hrs

12.5 hrs

25 hrs

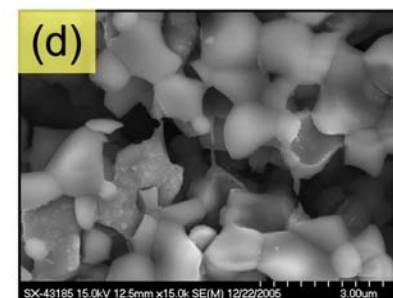
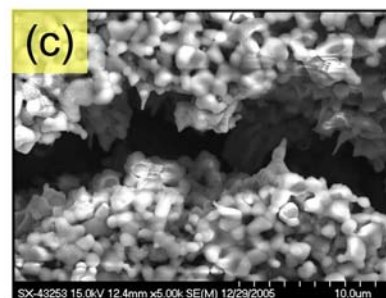
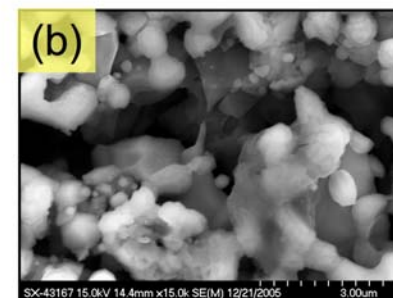
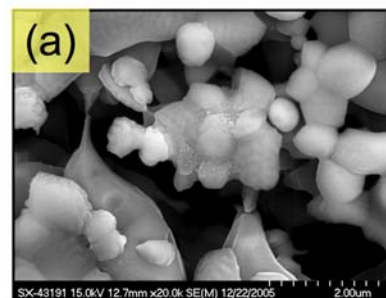
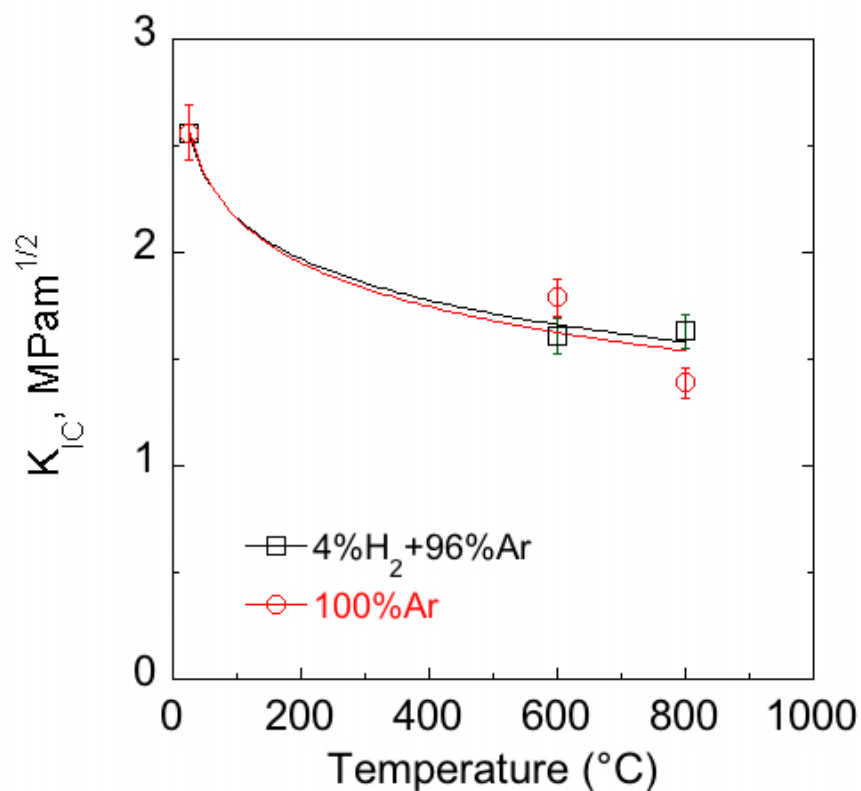
Microstructural evolution during thermal aging

- Effectively **no significant changes** in the microstructure of Ni-YSZ after thermal aging or thermal cycling
- Changes in residual stresses?
- Techniques applicable to characterize potential microstructural changes in other components

Other

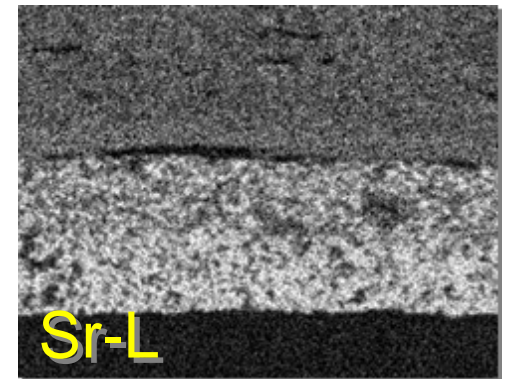
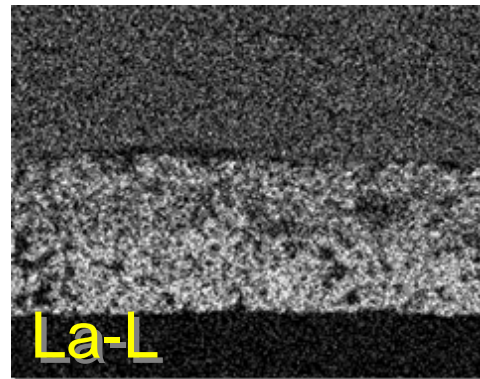
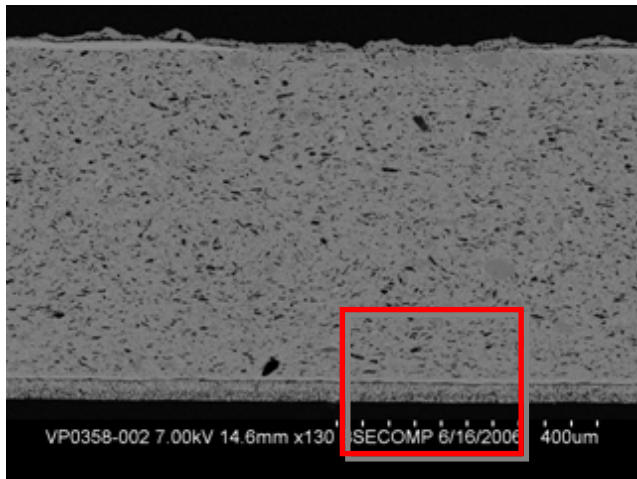
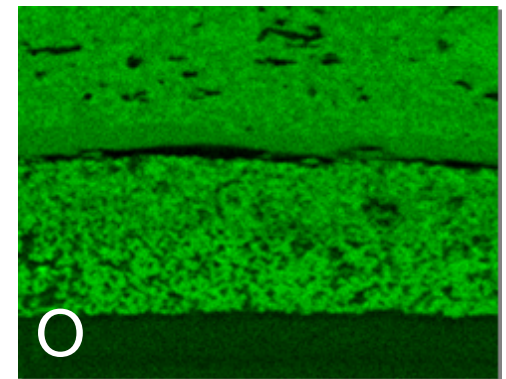
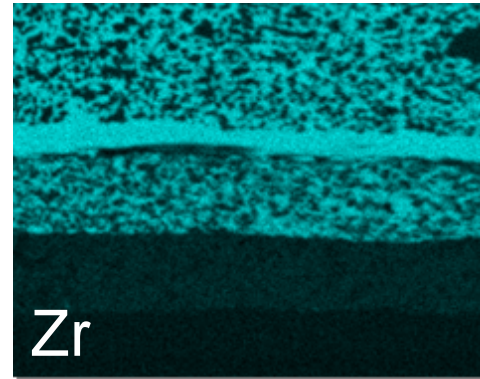
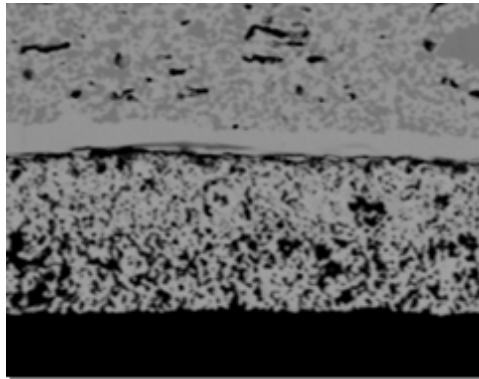
Fracture behavior of Ni-YSZ

- No effect of hydrogen on fracture behavior of Ni-YSZ



Other

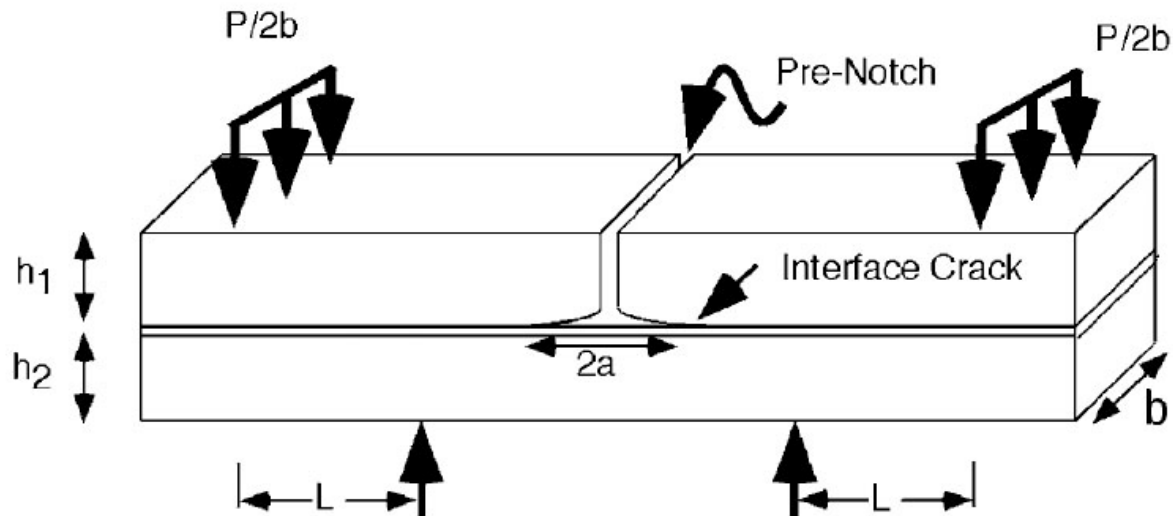
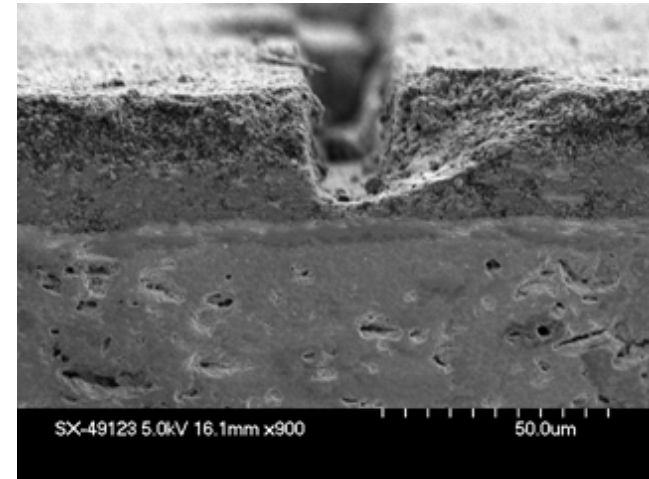
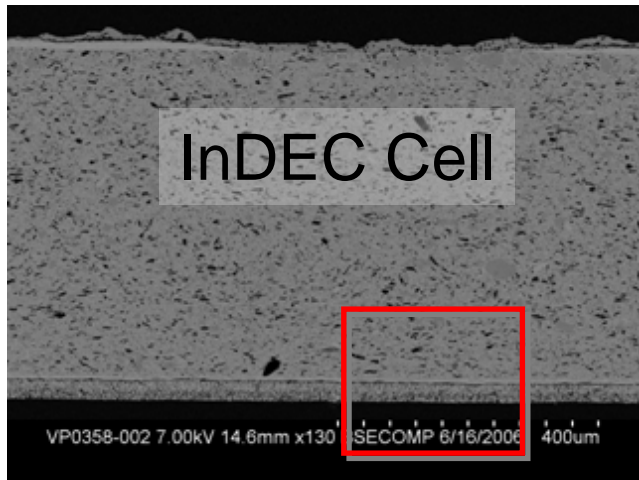
Interfacial fracture properties



InDEC Cell

Other

Interfacial fracture properties



Summary & Future Work

- Degradation mechanisms (electrochemistry-thermomechanical-environmental)
- ASME design handbook
- Scaling of SOFCs
- Databases
- Other