Residual Stresses in SOFC Materials and Components

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Outline

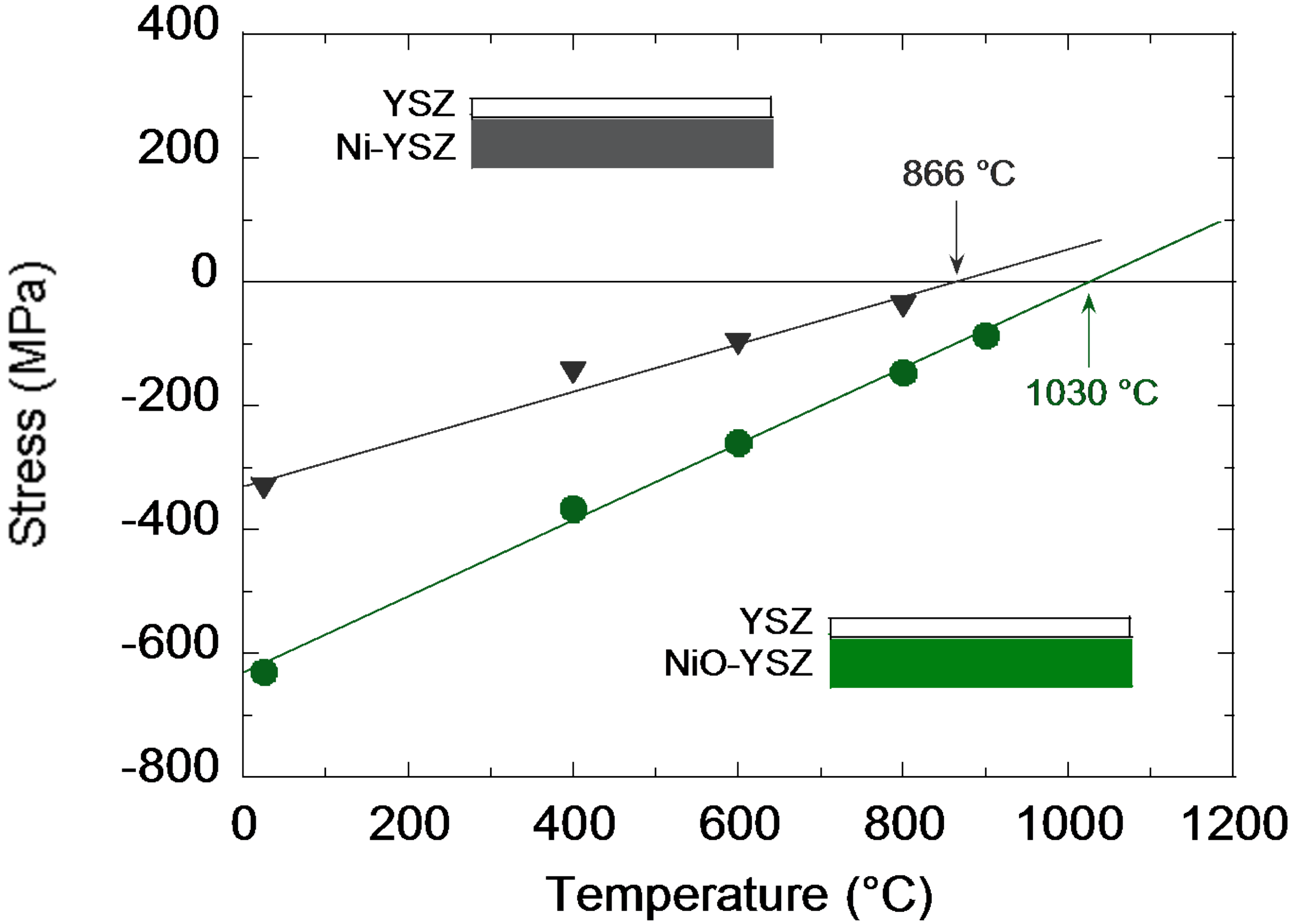
- Background
- Techniques for measuring Residual Stresses
  - Diffraction (x-rays, neutrons)
  - Raman Spectroscopy
  - Piezospectroscopy
  - Digital image correlation
- Summary and Future Work

Background

- The reliability of materials and components for SOFCs is determined by their state of stress, which includes contributions from:
  - residual stresses

Residual and “Reduction” Stresses (X-ray diffraction)

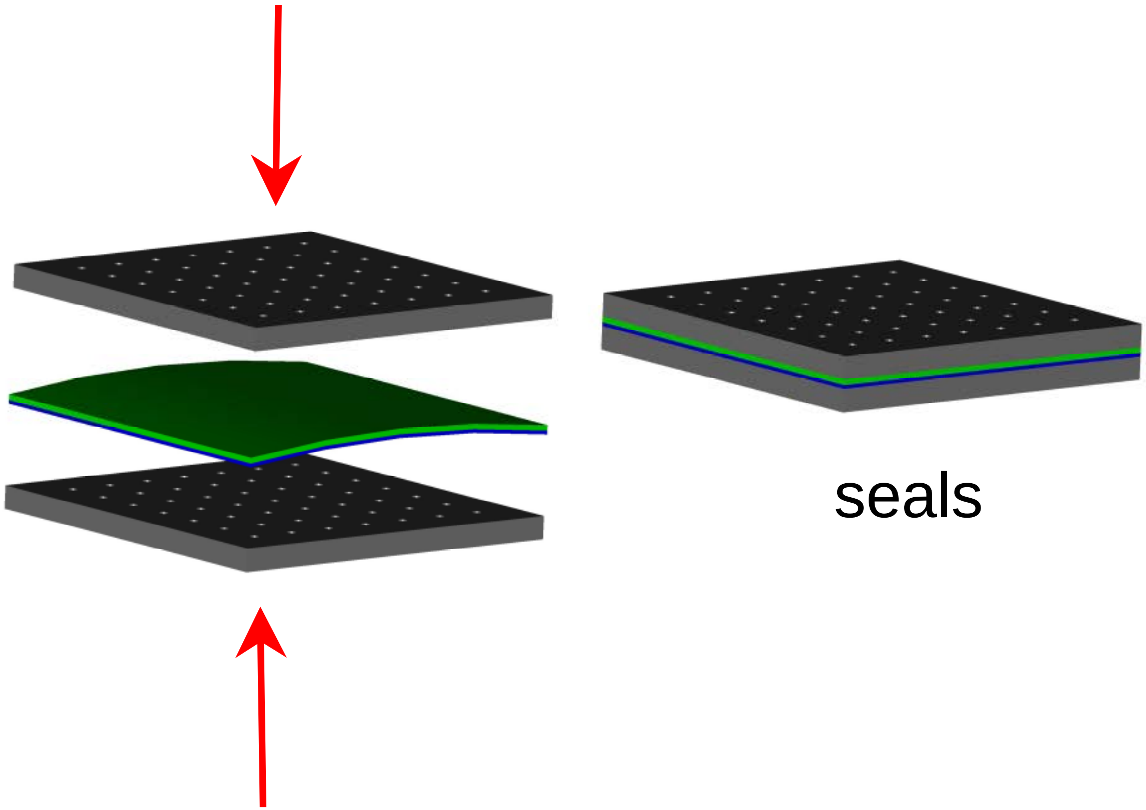
800°C Reduction in 4%H_2-96%Ar



Background

- The reliability of materials and components for SOFCs is determined by their state of stress, which includes contributions from:
  - residual stresses
  - assembly stresses

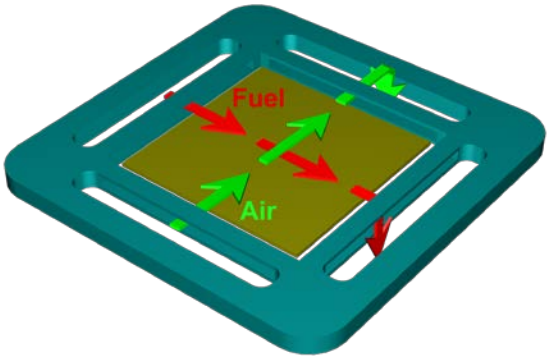
Reliability of SOFCs (Assembly Stresses)

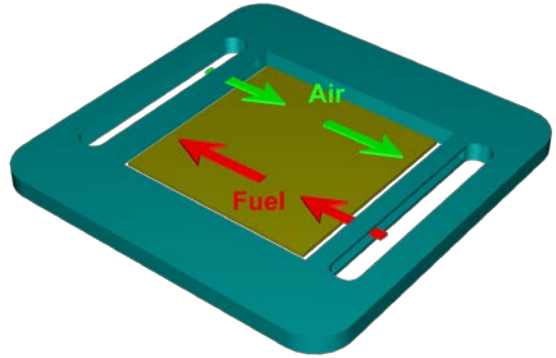


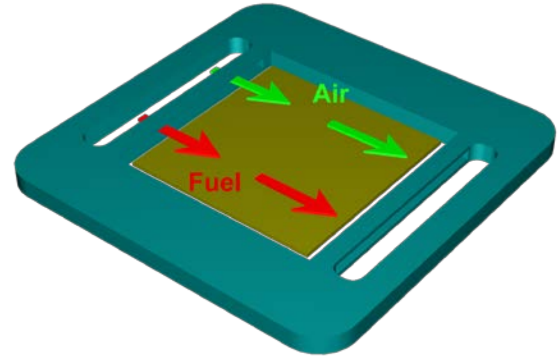
Background

- The reliability of materials and components for SOFCs is determined by their state of stress, which includes contributions from:
  - residual stresses
  - assembly stresses
  - operational stresses

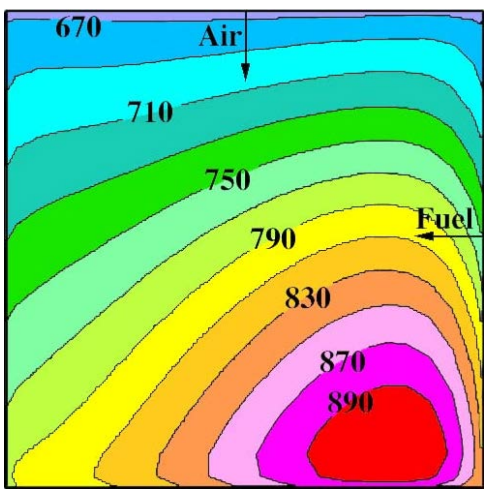
Reliability of SOFCs (Operation-induced Stresses)

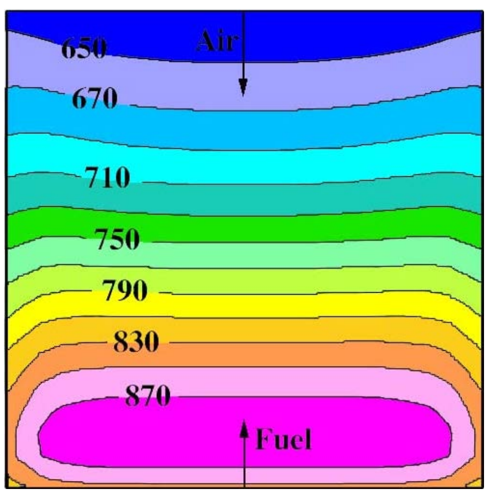


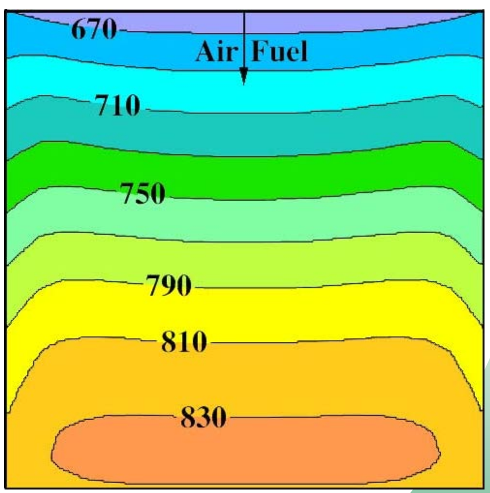




Cross-Flow | Counter-Flow | Co-Flow







Background

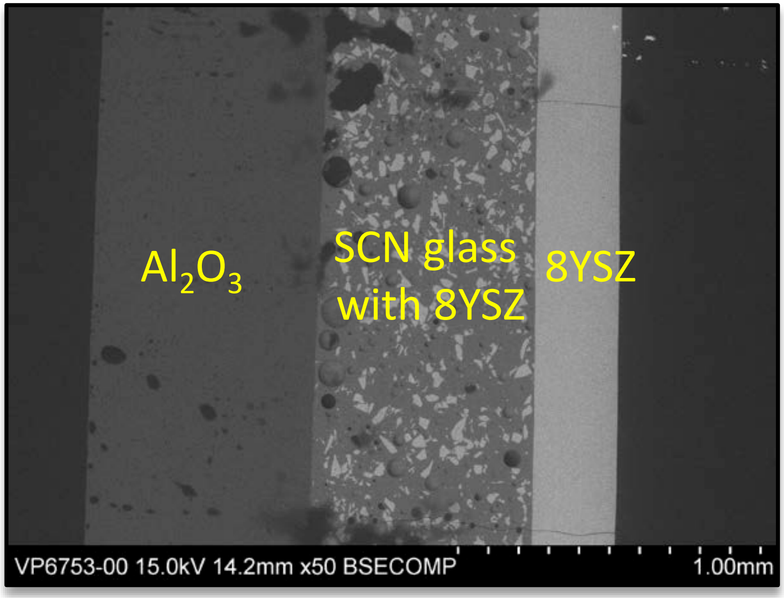
- Residual stresses arise from differences in the thermoelastic properties of materials when these are constrained to expand-contract as a function of temperature.
- The objective of this exercise is to identify and apply techniques to quantify residual stresses in SOFC materials and components and studying how these stresses evolve as a function of time and operational history.

Techniques for Measuring Residual Stresses

- Diffraction (x-rays, neutrons)
- Raman Spectroscopy
- Piezospectroscopy
- Digital image correlation

Experimental

sandwich specimen processed at 850°C



Layer	Thickness (µm)	CTE (ppm/°C)	Young's Modulus (GPa)
Al_2O_3	760	8.1	400
8YSZ	290	8.5 (100°C) 10.5 (950°C)	200
SCN+8YSZ	870	9.97	70

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Experimental

$$\sigma_s = \frac{2}{t_s^2}\left(3z + 2t_s - \frac{2}{E_s}\sum_{j=1}^{n} E_j t_j\right)\sum_{i=1}^{n} E_i t_i(\alpha_i - \alpha_s)\Delta T$$

$$= \frac{E_s}{3r}(3z + 2t_s) - \frac{2}{3r}\sum_{i=1}^{n} E_i t_i ,$$

$$\sigma_i = E_i\left[\alpha_s - \alpha_i + 4\sum_{j=1}^{n} \frac{E_j t_j(\alpha_j - \alpha_s)}{E_s t_s}\right]\Delta T$$

$$= -\frac{E_s t_s^2}{6 t_i r_i} + \frac{2E_i t_s}{3r} .$$

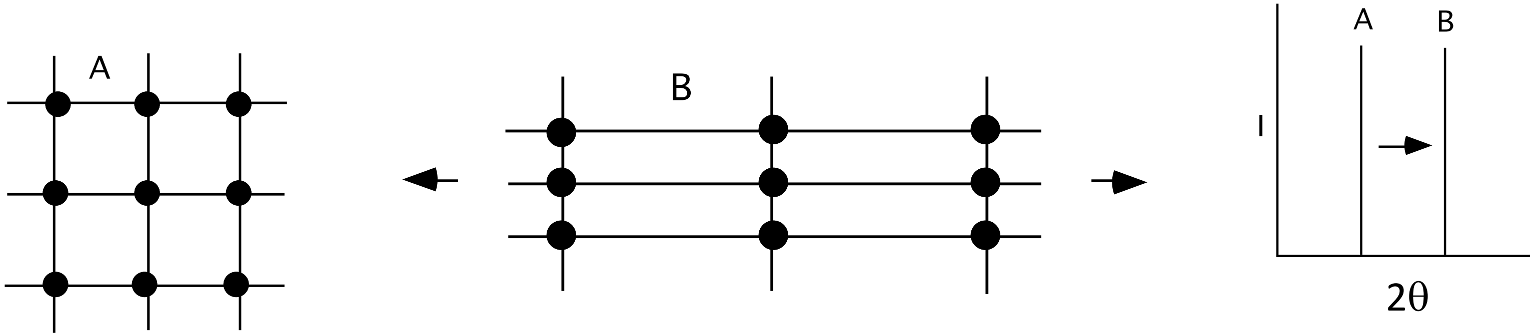
C. H. Hsueh, J. Appl. Phys., Vol. 91, No. 12, 15 June 2002

X-ray Diffraction

- Strains in a crystal lattice are measured (with respect to a stress-free condition) and the associated residual stress is determined from the elastic constants assuming a linear elastic distortion of the crystal planes.

X-ray Diffraction

Strain (applied or residual) changes the interplanar and spacing θ peak shift



- Bragg's Law

$$\lambda = 2\ d \sin\theta$$

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

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

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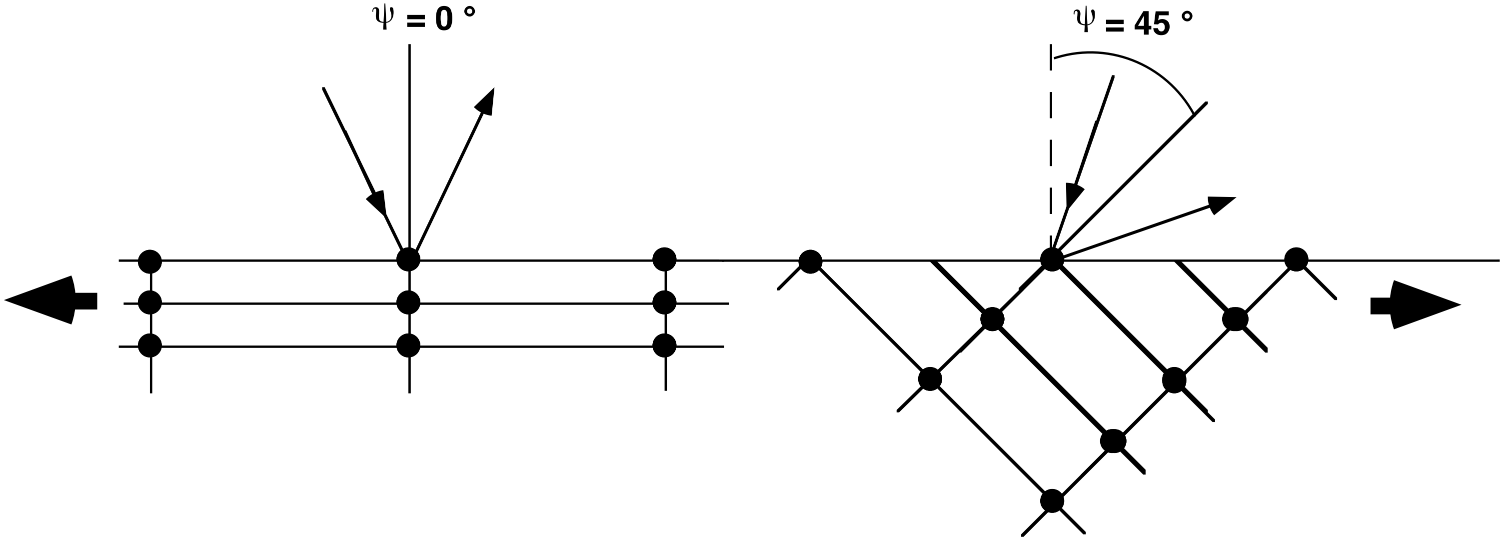
X-ray Diffraction

- 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.



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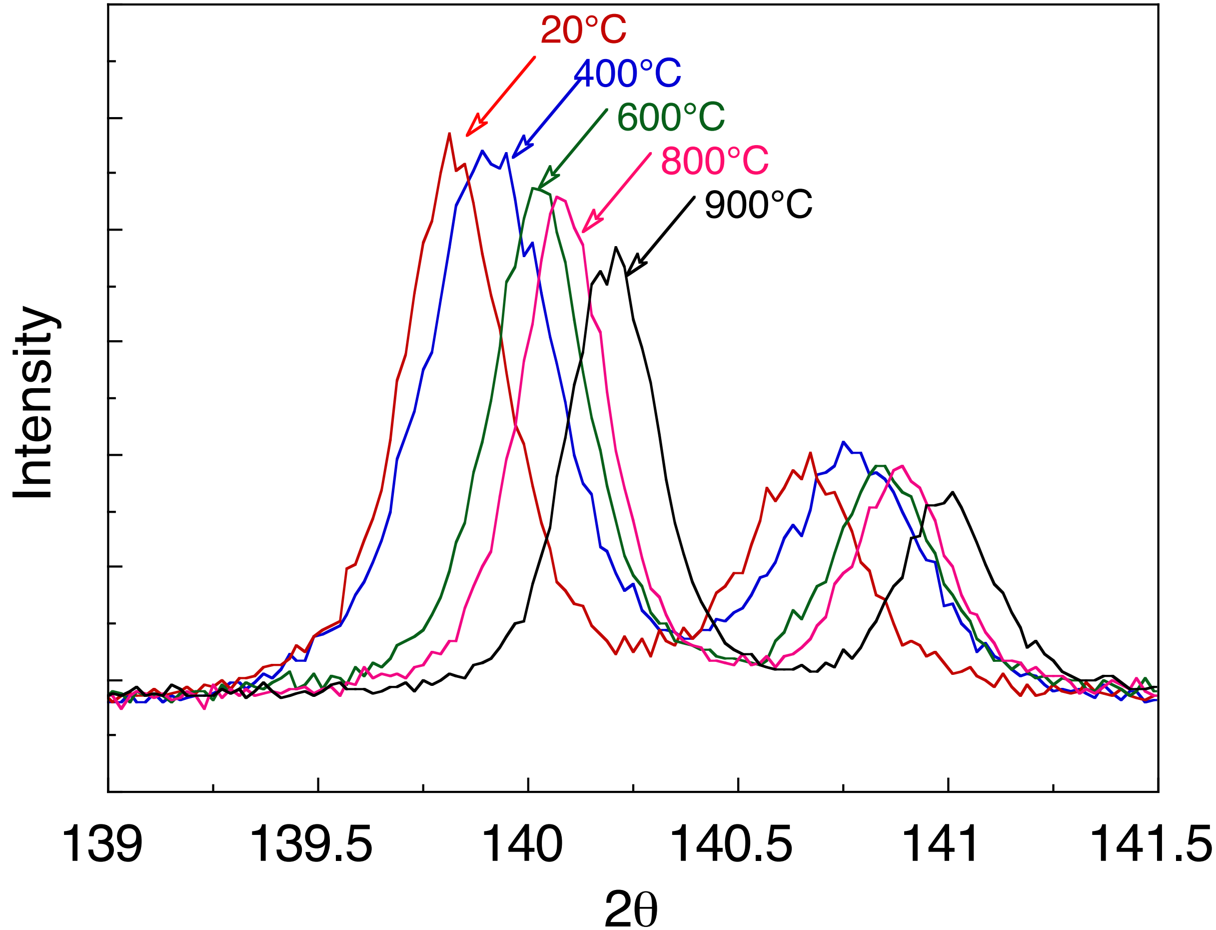
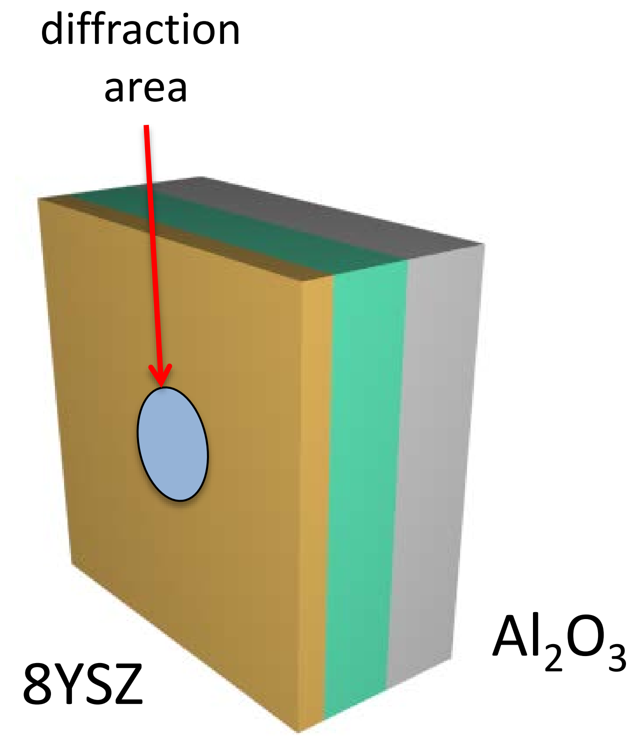
X-ray Diffraction





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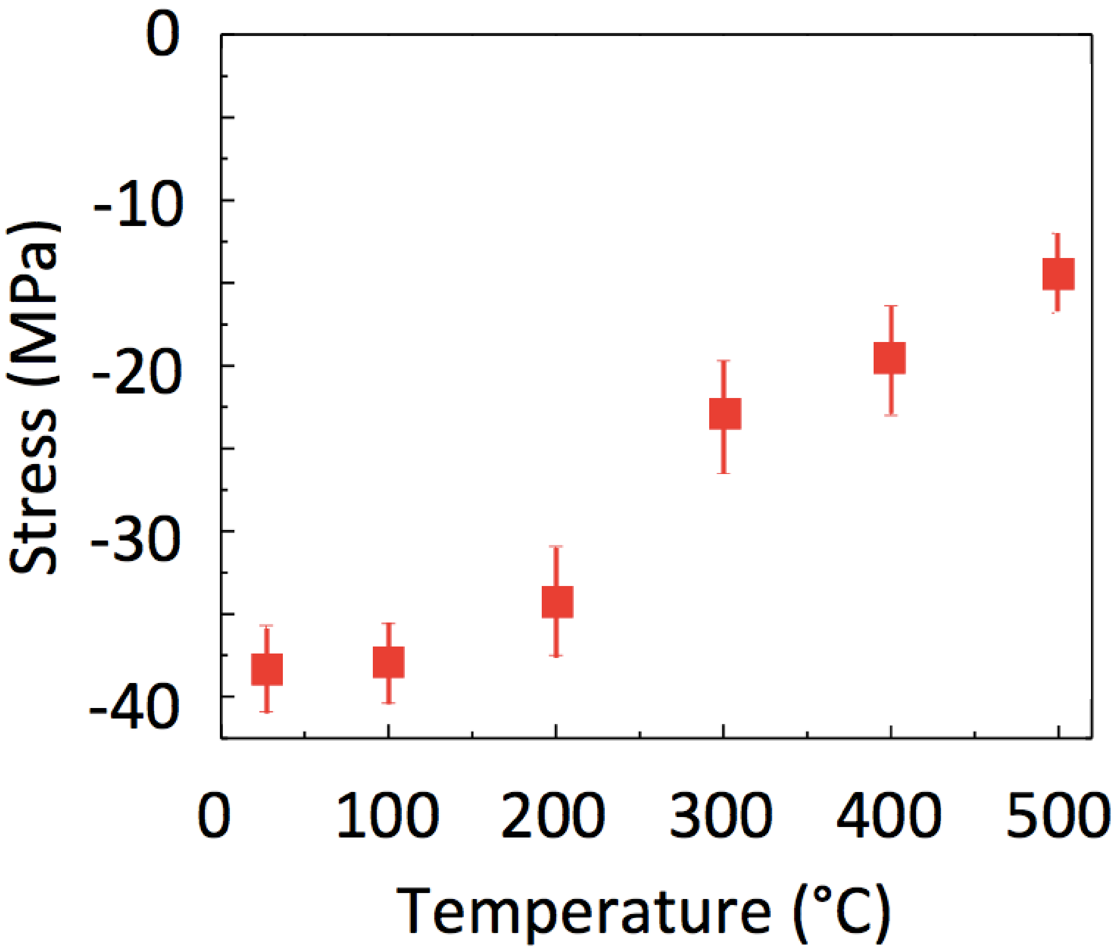
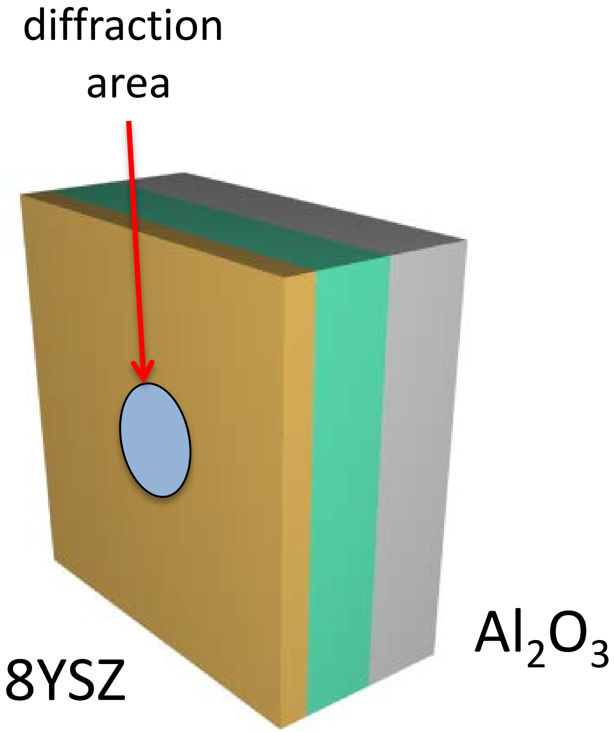
X-ray Diffraction





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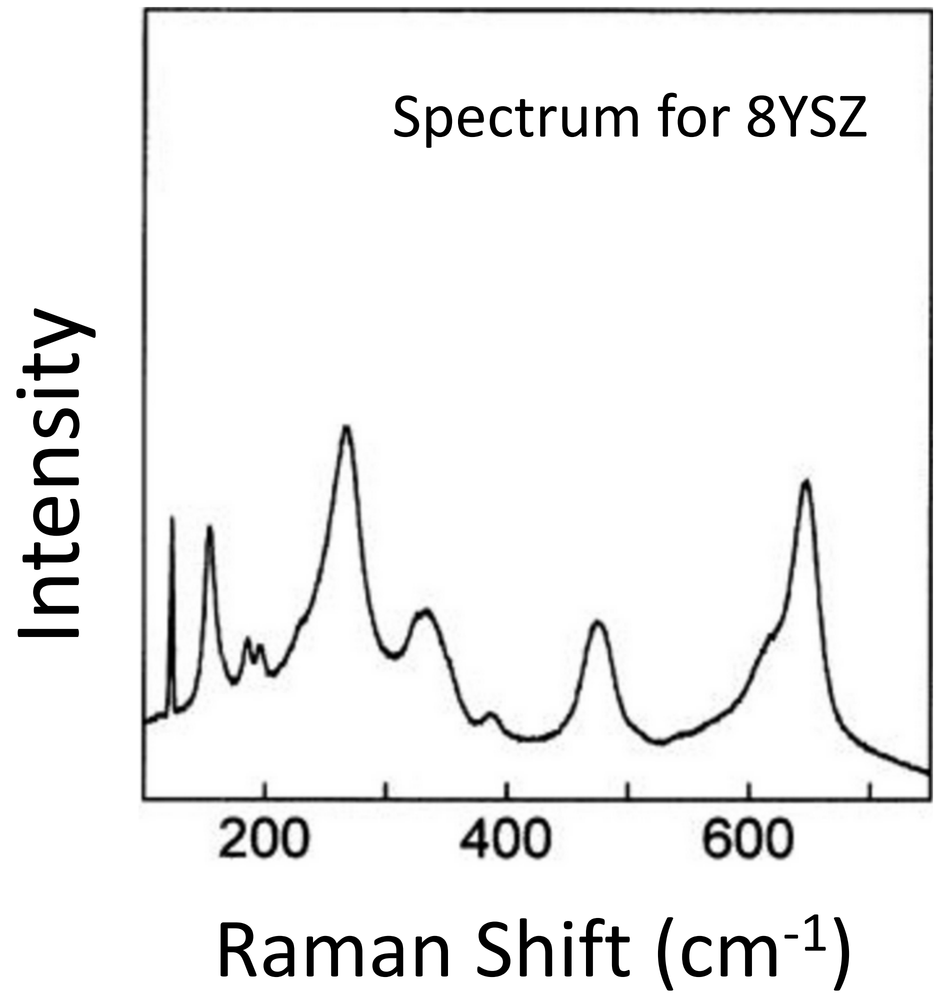
Techniques for Measuring Residual Stresses

- Diffraction (x-rays, neutrons)
- Raman Spectroscopy

Raman Spectroscopy

- Raman scattering arises from the inelastic interaction between photons and phonons
- The frequency of the Raman signal, ν, is related to the frequency of the lattice vibrations of the probed material

Raman Spectroscopy



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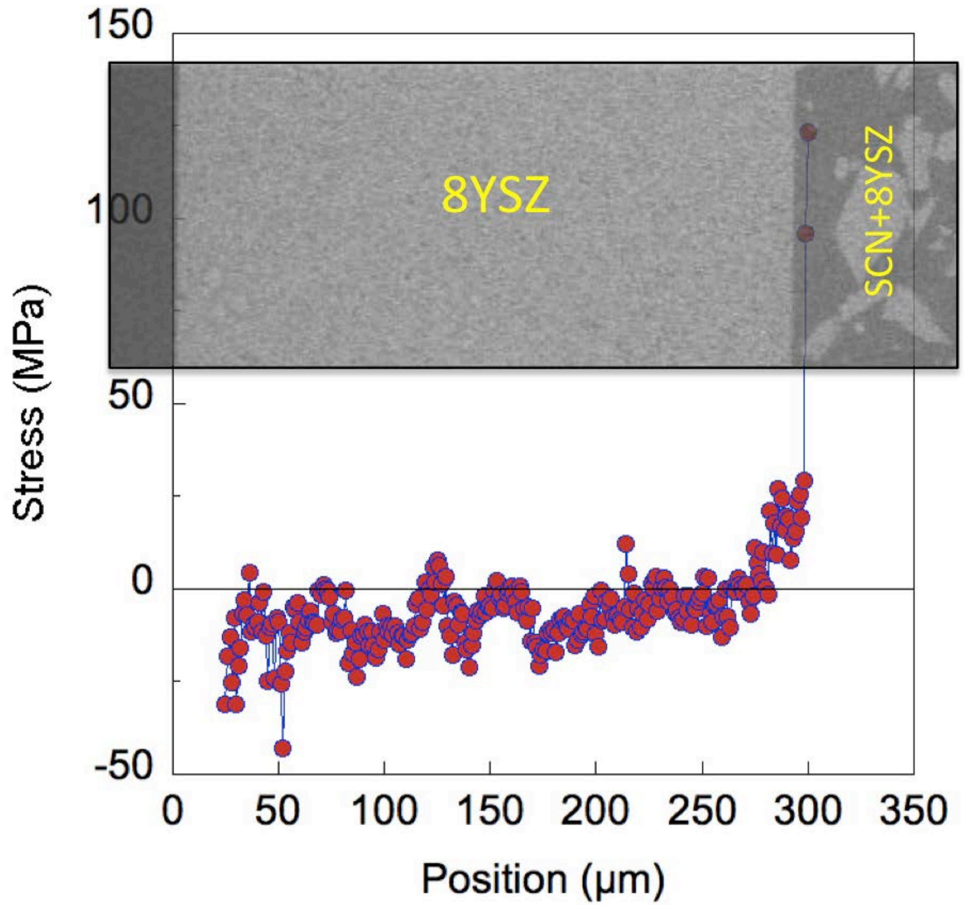
Raman Spectroscopy

- Raman scattering arises from the inelastic interaction between photons and phonons
- The frequency of the Raman signal, ν, is related to the frequency of the lattice vibrations of the probed material
- Because strain changes the frequency of the lattice vibrations, it will also shift the Raman frequency. By mapping the frequency shift, $\Delta\nu$, of Raman peaks at different positions on the sample, information on the local stress can be obtained

Raman Spectroscopy

- µRaman spectroscopy has high spatial resolution



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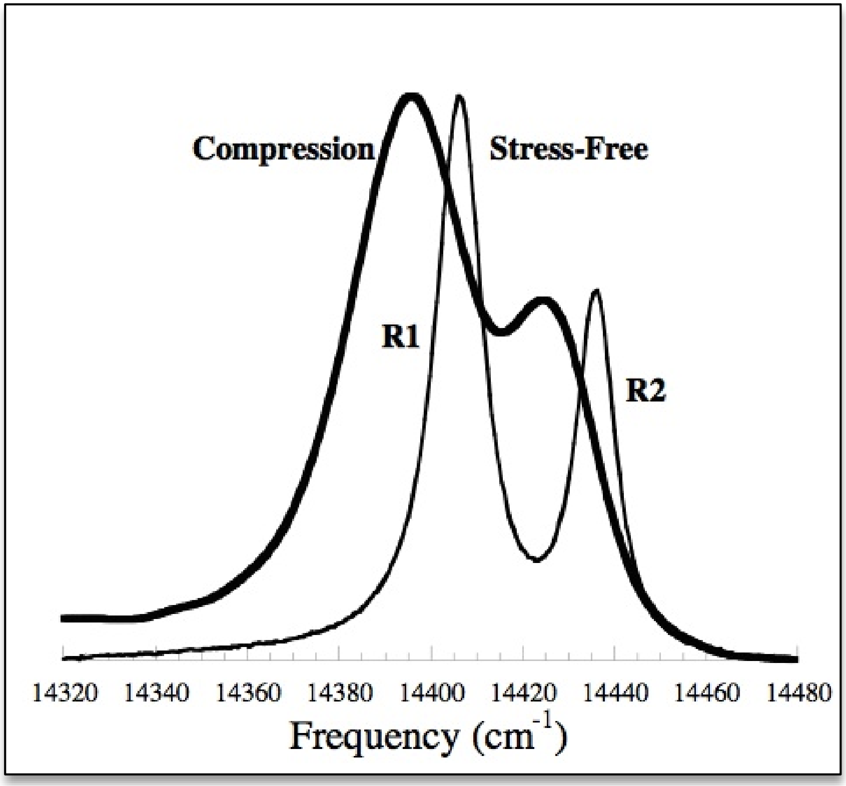
Techniques for Measuring Residual Stresses

- Diffraction (x-rays, neutrons)
- Raman Spectroscopy
- Piezospectroscopy

Piezospectroscopy

Unfortunately the intensity of the Raman lines is very weak for many materials, with zirconia being an exception. Alternative approaches to measure local stresses using stimulated luminescence associated with Cr^{3+} have been proven successful.



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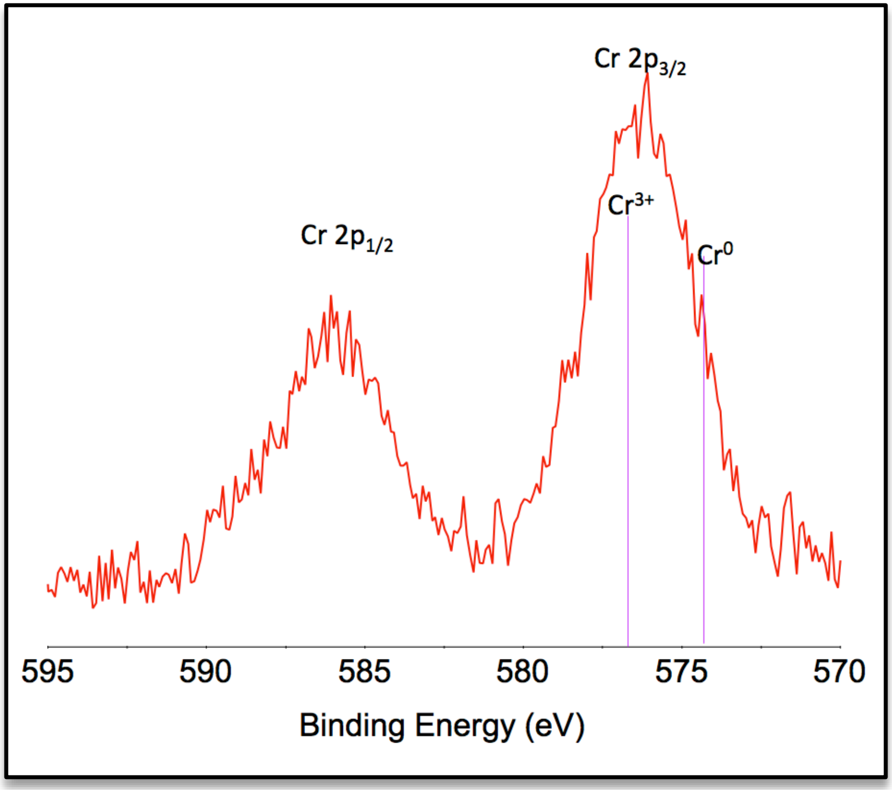
Piezospectroscopy

This XPS spectrum corresponds to 8YSZ after exposure to Cr_2O_3 powders in air at 800°C for 1 hour, demonstrating the feasibility of doping oxides with chromium



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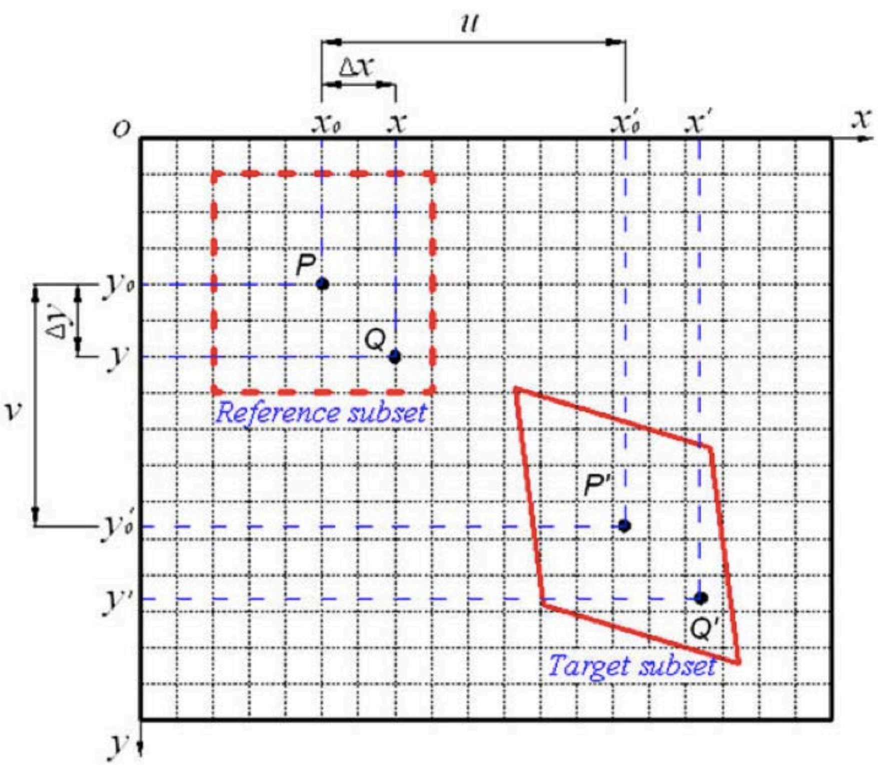
Techniques for Measuring Residual Stresses

- Diffraction (x-rays, neutrons)
- Raman Spectroscopy
- Piezospectroscopy
- Digital image correlation

Digital Image Correlation

DIC directly provides full-field in-plane deformation fields of the test planar specimen surface by comparing the digital images of the specimen surface acquired before and after deformation



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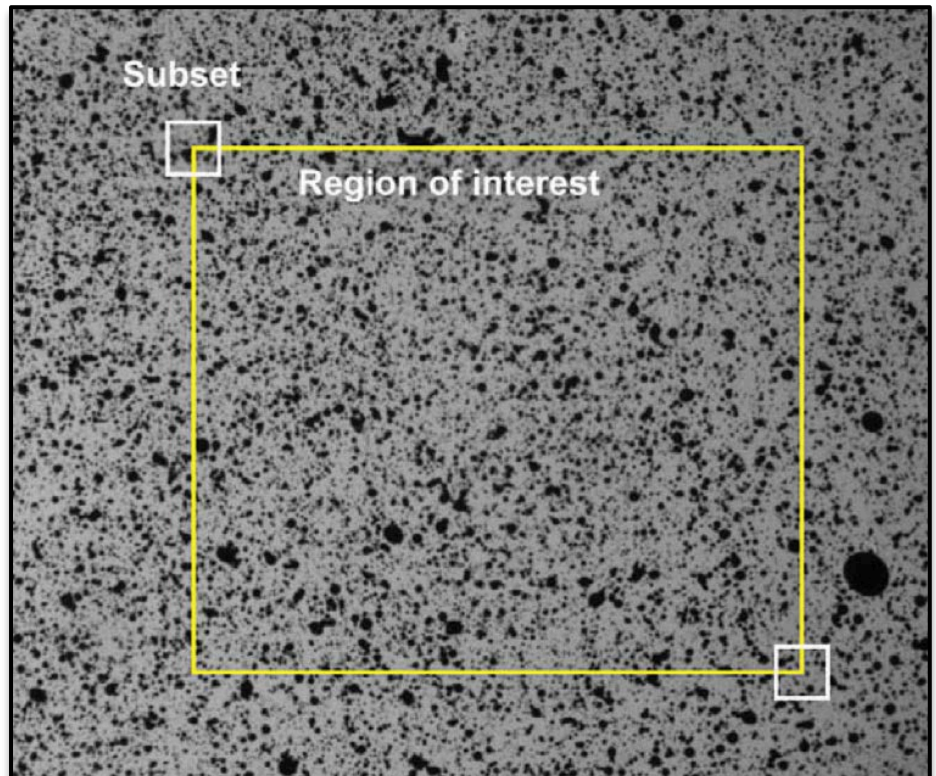

P. Bing et al. / Polymer Testing 28 (2009) 75–83

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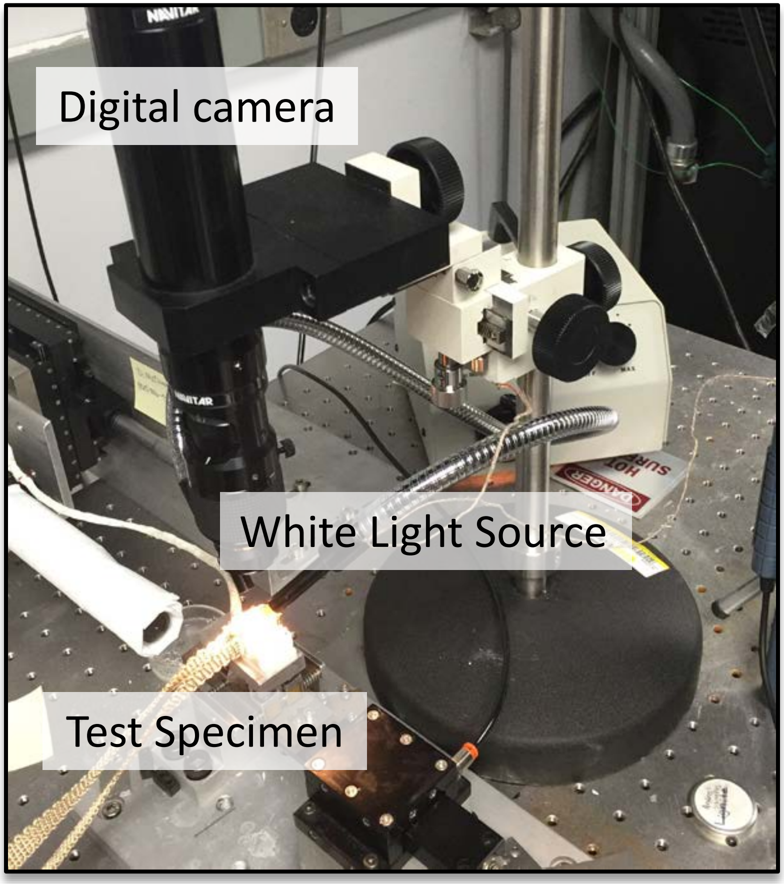

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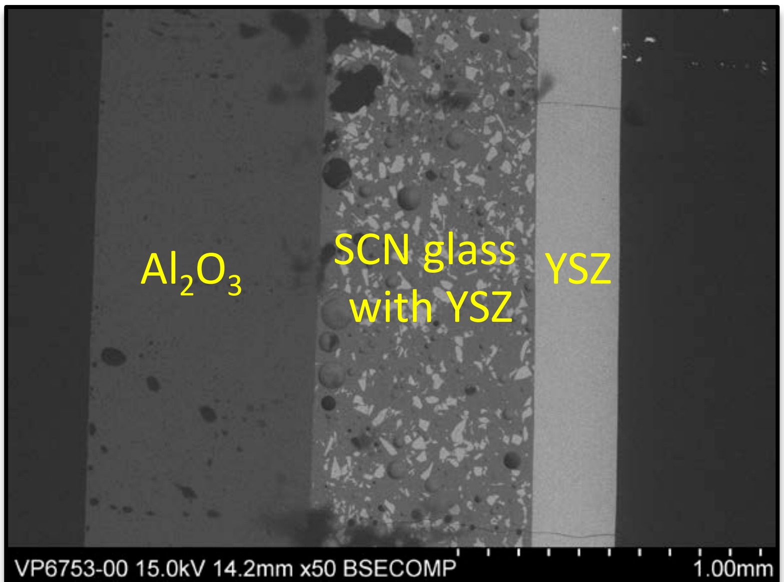
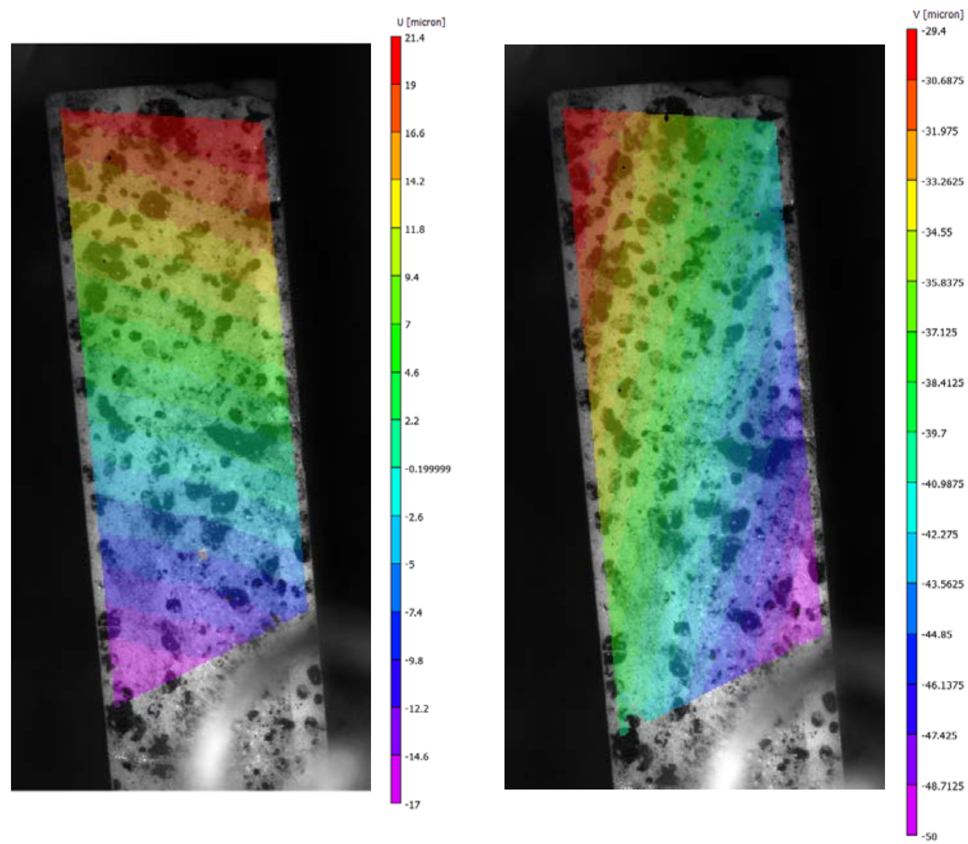
Digital Image Correlation



Displacement Fields (u, v)



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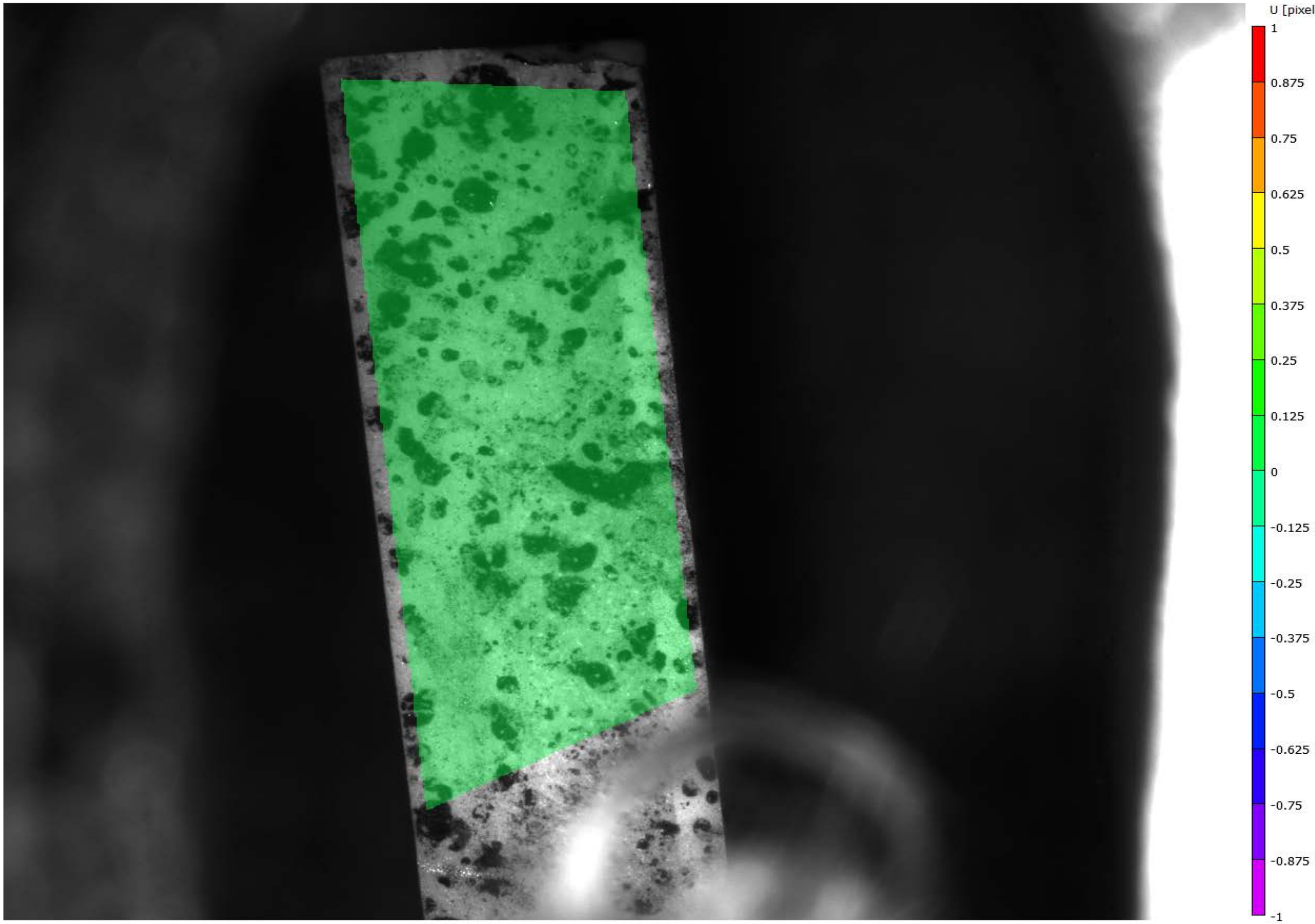
Digital Image Correlation



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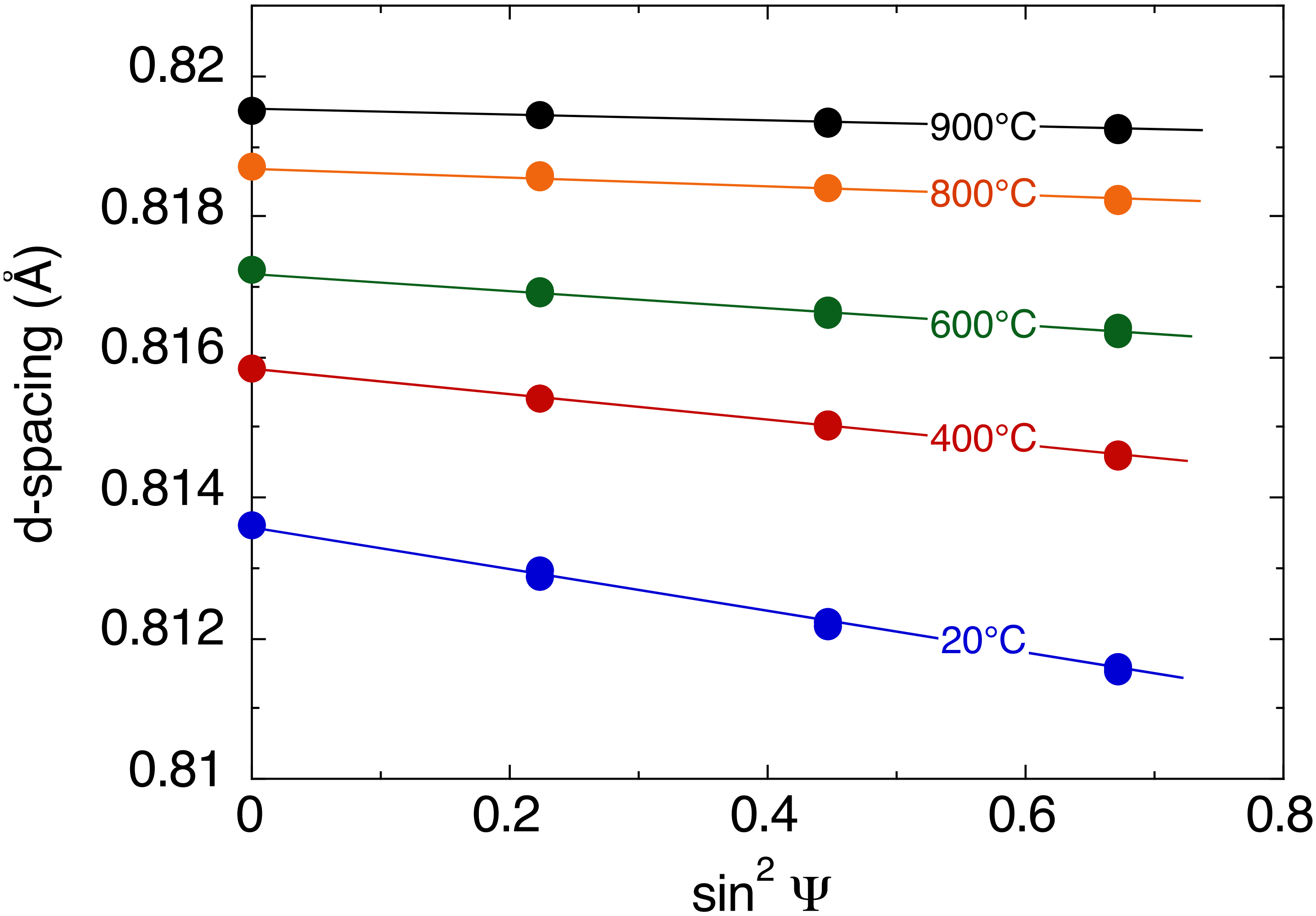
Summary

- Different techniques for measuring residual stresses are being investigated and adapted to SOFC materials and components. Some of these techniques have high spatial resolution, while others can be adapted to measure residual stresses as a function of temperature or, on the surface of components with complex geometries.
- Using a model system, the precision, advantages and disadvantages of these techniques will be determined
- Determination of residual stresses is essential to ensure the manufacturing of durable and reliable SOFCs

X-ray Diffraction



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