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#### Spontant brott vid expanderande fasomvandling

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#### SMD 2013

### Spontant brott vid expanderande fasomvandling

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# Zr-H solid solution and hydride

Hydrogen occupies tetrahedral sites in Zr-H solid solution  $\alpha$ -lattice distorts to match the  $\gamma$  and  $\delta$  structures Interstitial ordering results in periodic occupation of tetrahedral sites







Zr exhibits two allotropic modification: low T hcp ( $\alpha$ ) and high T bcc ( $\beta$ ) phases Two stable hydrides ( $\delta$  and  $\epsilon$ ) and one metastable ( $\gamma$ ) hydride forms in this system Under optical microscope the traces of hydrides appears as dark lines At higher magnification the hydride plates reveal several smaller entities Hydride plate comprises of platelets stacked side by side Each platelet comprises of sub-platelets stacked end to end

## **Multi-scale Structural Mechanics**





Thermocouples for temperature monitoring

## Top view of hydride blister

**Experimental setup** 



# Top view of a hydride blister grown in Zr–2.5wt%Nb pressure tube alloy (Singh *et al.*, 2001)



#### **Examination of a section of blister** (grown in Laboratory)

Figure : Optical micrograph of hydride blister section, grown in Zr-2.5wt.% Nb pressure tube material. Three regions -Region I - matrix & circumferential hydrides, region II - matrix containing both radial and circumferential hydrides and region III mainly of δ-hydride.





#### Expanding elastic-plastic inclusion (Hill, 1950)





## Blister formation - Stress field computation - Multi step



#### Essential result of FEM and present solution



Strains

#### Equilibrium

$$\epsilon_r = \frac{\partial u_r}{\partial r}, \quad \epsilon_\theta = \frac{1}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r},$$
  
$$\epsilon_{r\theta} = \frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r} + \frac{1}{r} \frac{\partial u_r}{\partial \theta}.$$

$$\frac{\partial \sigma_r}{\partial r} + \frac{1}{r} \frac{\partial \sigma_{r\theta}}{\partial \theta} + \frac{1}{r} (2\sigma_r - \sigma_\theta - \sigma_\psi + \sigma_{r\theta} \cot \theta) = 0.$$
$$\frac{\partial \sigma_{r\theta}}{\partial r} + \frac{1}{r} \frac{\partial \sigma_\theta}{\partial \theta} + \frac{1}{r} [(\sigma - \sigma_\psi) \cot \theta + 3\sigma_{r\theta}] = 0.$$

Decomposed strains

Plast. strain prop. to deviatoric stress

$$\epsilon_r = \epsilon_r^e + \epsilon_r^p + \epsilon^s,$$
  

$$\epsilon_\theta = \epsilon_\theta^e + \epsilon_\theta^p + \epsilon^s,$$
  

$$\epsilon_\psi = \epsilon_\psi^e + \epsilon_\psi^p + \epsilon^s \text{ and } \epsilon = \epsilon_{r\theta}^e + \epsilon_{r\theta}^p$$

$$\frac{\epsilon_r^p}{\sigma_r - \sigma_h} = \frac{\epsilon_\theta^p}{\sigma_\theta - \sigma_h} = \frac{\epsilon_\psi^p}{\sigma_\psi - \sigma_h} = \frac{\epsilon_{r\theta}^p}{\sigma_{r\theta}},$$

DE: 
$$\frac{\mathrm{d}^2 u_r}{\mathrm{d}r^2} + 2\frac{\mathrm{d}u_r}{r\mathrm{d}r} - 2\frac{u_r}{r^2} - \frac{1-2\nu}{1-\nu}\left(\frac{\mathrm{d}\epsilon^p}{\mathrm{d}r} + 3\frac{\epsilon^p}{r}\right) = 0$$

Displacements: 
$$u_r = \epsilon_s r - \frac{2(1-2\nu)}{3} \left(1+3\ln\frac{r_p r}{R^2}\right) \frac{\sigma_o r}{E}$$
 in  $r \le \mathbb{R}$ .



Fig. 2 Different characteristic regions of the solution. In  $r > r_p$  the material is elastic; in  $r \le r_p$  the material is plastic; in  $r_{c1} < r < R$  no tensile stress; in  $r_o < r < r_{c1}$  tensile radial stress; in  $r_{c2} < r < r_o$  tensile radial stress and hydrostatic stress; in  $r < r_{c2}$  all stresses are tensile.

$$r < r_{c1} = \frac{R^2}{r_p e^{1/3}}, \quad r < r_o = \frac{R^2}{r_p e^{2/3}} \text{ and } r < r_{c2} = \frac{R^2}{r_p e^{5/6}}$$

#### Essential result of FEM and present solution



Radial pressure, - $\sigma_r/k$ , versus vs. distance r/R



# Hoop Stress



# Radial Displacement





# Hoop Stress



# Crack Surface Displacement





v Mises Stress, Incremental Growth Expanding Cylinder ahead of a Crack



Deformation, Simultaneous Growth Expanding Cylinder ahead of a Crack



### Deformation, Incremental Growth Expanding Cylinder ahead of a Crack



v Mises Stress, Simultaneous Growth Expanding Cylinder ahead of a Crack



## Conclusions

• Precipitates that grow at its edges obtain reduced pressure in its interior.

• At self-similar growth, stresses become logarithmically singular for all precipitates shapes.

• The mechanical state of the matrix of homogeneously growing precipitates matches the present solution exactly but for larger expansion.

• Spontaneous crack growth may occur