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Ongoing research at Lund University, Invited talk given at University of Parma, Italy. Orationem Meam.

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UNIVERSITÀ DEGLI STUDI DI PARMA

DIPARTIMENTO DI INGEGNERIA CIVILE, DELL'AMBIENTE, DEL TERRITORIO E ARCHITETTURA



AVVISO SEMINARIO

Mercoledì 21 dicembre 2016, ore 10:30-12:30

(aula 8, Plesso Ingegneria Didattica)

Ongoing research at Lund University (Per Ståhle, Lund University, Sweden)

The presentation will give an overview of ongoing research at Lund University. Four projects will be reviewed. 1) The necking type of fracture that occur in elastic plastic materials with a sub-critical thickness that reduces the fracture process to pure necking is described. Laminate applications will be discussed. 2) Stress corrosion crack growth with a moving mesh is described. A single chemical criterion for removal of matter replaces the crack growth, crack path and crack branching criteria. 3) A phase field model of delayed hydride cracking. The mechanics of surface blister hydrides forming at cold spots on zirconium surfaces and hydrides at crack tips will be presented. 4) Bone growth controlled by stress driven diffusion will be demonstrated. Both a switch of state and an alternative, a set of coupled PDEs derived for a phase field model are used to trace the growth of a bone exposed to mechanical load.

Biosketch

Per Ståhle addresses problems in the theoretical and applied mechanics of solids. His research involves stress corrosion, hydrogen embrittlement and materials testing. He has a focus on the mechanical conditions leading to dissolution of materials, instabilities at material surfaces, growth of precipitates and initiation and growth of cracks. He became honorary doctor and professor at Uppsala University 1986, Professor of Mechanics of Materials at Malmö University and is since 2009 Professor of Solid Mechanics at Lund University.

Per was visiting Professor at Brown university 1989/90, University of California Santa Barbara 1992, Tokyo Institute of Technology and Academy of Science Beijing 1997. From 2004 to 2009 he was the chairman of the National Committee for Theoretical and Applied Mechanics at the Swedish Royal Academy of Science, correspondent of EuroMech, expert for the Swedish Research Council, the NATO Collaborative Research Council and the Royal Society of London. He is presently Swedish representative in The International Union of Theoretical and Applied Mechanics since 2012, the official blogger for the Elsevier publication Engineering Fracture Mechanics and a member of the executive committee of the European Society of Structural Integrity.

Mercoledì 21 dicembre 2016, ore 10:30-11:30 (aula 8, Plesso Ingegneria Didattica)

Ongoing Solid Mechanics Research at Lund University

Per Ståhle, Lund University, Sweden

Necking Type of Fracture of Laminates
 Stress Corrosion Crack Growth - a Moving Boundary Mod.
 Modelling of delayed hydride cracking
 Bone Growth Controlled by Stress Driven Diffusion



A Strong Toughening Mechanism in an Elastic Plastic Laminate

P. Ståhle¹, C. Bjerkén², J. Tryding³ and S. Kao-Walter⁴

¹Lund University, Lund ²Malmö University, Malmö ³TetraPak AB, Lund ⁴Blekinge Technical University, Karlskrona

Necking vs fracture

Fracture toughness of aluminium is ≈ 24 MPa m^{1/2}. Measured toughness of an 9 μ m aluminium foil is 3.5 MPa m^{1/2} due to necking.

The stress intensity factor is

 $K \sim \text{sheet thickness}^{1/2}$

A sheet thickness > 400 μ m is needed to restore K_{lc} fracture control.

The largest load per unit of length

 $P \sim {
m sheet \ thickness}^{3/2}$

A sheet thickness $> 32\mu$ m is needed to provide the strength of a non necking 9μ m aluminium foil.

Layers and laminate properties

Metal foil (fully annealed AA1200 aluminium) Stiff and Brittle

 $t_A = 9\mu$ m, $E_A = 71$ GPa, $\sigma_{bA} = 73$ MPa, $\nu_L = 0.33$, $F_A = 12.5$ N

Polymer (PolyEthene LDPE, LD270) Weak and Soft

 $t_L = 27 \mu m$, $E_L = 126 MPa$, $\sigma_{bL} = 8 MPa$, $\nu_L = 0.45$, $F_L = 2 N$

The laminate (homogenized, plane stress) Stiff and Ductile

 $t_{lam} = 36 \mu$ m, $E_{lam} = 18$ GPa, $\sigma_{b \ lam} = 27$ MPa, $\nu_{lam} = 0.3$, $F_{lam} = 22.5$ N

Test results (Kao-Walter et al., 02, Macionczyk and Bruckner, 99) 20 laminate 15 Load [N] independent layers 5 alum. polymer 2 3 0 Δ Extension [mm] Fracture mechanical test Load displacement curves

Test results



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Work of failure



Strip yield zone ahead a crack tip. a) the crack geometry in the plane z = 0. b and c) the slip region as seen in a plane x = const.

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Super-tough Thin Film Laminates

Sharon Kao-Walter, Rickard Hägglund, Eskil Andreasson



Summary





 $N_A = N_B = 0.1$ and $h_A/h_B = 2$ (Hutchinson, 2013) $\sigma_B/\sigma_A = 0.002$ or $\sigma_A/\sigma_B = 0.002$



Material parameters

Comparison of structural and material parameters for the different test speciemens.

	Al-foil	LDPE	laminate
$h[\mu m]$	9,0	27	36
E [GPa]	71,0	0.126	17.9
v[-]	0.33	0.45	0.30
$\sigma_b \ [MPa]$	73.0	8.0	26.6
$J_c [N/m]$	188	82.6	109
F_{max} [N] {2a=45mm}	14,0	9,4	24,4

$$\sigma_{c} = \sqrt{J_{c} \frac{E}{\pi a}} \frac{1}{\phi\left(\frac{a}{W}\right)} = \sqrt{\frac{1}{\sqrt{3}} \left(\frac{\sigma_{bA} h_{A}^{2} + \sigma_{bL} h_{L}^{2}}{h_{A} + h_{L}}\right) \frac{E}{\pi a}} \frac{1}{\phi\left(\frac{a}{W}\right)}.$$
 (13)

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Stress Corrosion Crack Growth

Per Ståhle, Andrey Jivkov and Christina Bjerkén Malmö University, Sweden



Competing mechanisms

SD - surface diffusion

SC - stress corrosion



Organisms believed to cause SC

Anaerobic Bacteria: *Desulfovibrio, -maculum, -monas* Aerobic Bacteria: *Thiobacillus* Fungi, Algae, Protozoans



Surface with different levels of pitting



Corrosion in stainless steel in the presence of Gallionella Bacillus

Corroding environment leads to:

1. Continuous loss of mass

2. Pitting

- ... and with mechanical stress present
- 3. Surface roughening







- 4. Evolving pits5. Formation of cracks6. Crack growth
- 7. Crack branching



Growing crack in a polycarbonate exposed to acetone (Hejman 2011)



Cr/zone six charge related of land and groove substrate erosion through a micro-crack at the 12:00 bore origin. (Sopok *et al.* 2005)

Corrosion Crack crossing a bi-material interface



Corrosion crack penetrating a bimaterial interface between austenitic and pressure vessel steel of type SA533C11. The tip of one of the crack branches. Crack length 7 mm, notch width 10 µm. *Reproduced with permission from Vattenfall AB.* Surface Morphology: Surface Wave Spectrum

Crack Initiation: Pit, Cusp and Crack

Crack Growth: Crack Growth, Blunting and Branching

Evolving Surface Morphology

Asaro-Tiller (1972), Grinfeld (1986, 1993), Srolovitz (1989), Freund (1995), Kung-Suk (2000)

Chemical potential,

$$\Phi = U_c + U$$

 U_c surface energy, U elastic strain energy



Governing equations:

Evaporation-condensation $\frac{\partial h}{\partial t} = L_1 \left(\gamma \frac{\partial^2 h}{\partial t} - \frac{k}{\partial t} \frac{\partial h}{\partial t} \right)$

$$\frac{1}{\partial t} = L_1 \left(\gamma \frac{1}{\partial x^2} - \frac{\kappa}{2} \mu \frac{\partial n}{\partial x} \right)$$

or surface diffusion

$$\frac{\partial h}{\partial t} = L_2 \frac{\partial^2}{\partial x^2} \left(-\gamma \frac{\partial^2 h}{\partial x^2} + \frac{k}{2} \mu \frac{\partial h}{\partial x} \right)$$

10(99)



Competing mechanisms

SD - surface diffusion

SC - stress corrosion





AFM image of corroded EBM surface (Hejman 06)



AFM image of shallow etched aluminium (Kim et al. 2000)



FEM calculation of an evolving surface

14(99)

Surface Roughness



From Kim Kung Suk













Steady State Crack-tip Shape





From Cladding to Grey Material



83(99)

Steady-state Advancing Crack Tip


Missing lengthparameter => Selfsimilar growth



2. Cusp solutions

Spencer and Meiron(94), Chiu and Gao (95), Yang Xiang and Weinan (02)





FEM stress corrosion

	$\varepsilon_{f}/\varepsilon_{\infty} = 0$	0.3	0.5	0.75	1	1.2
σ_x/σ_y = 0						4
0.5		\leq				
0.7	4	\leq		\leq	$\left \right $	
0.9	\langle		4			\leq





Crack-tip Load






















































































































Crack-tip load



effective stress



Before branching $K_{\rm I} = K_{\rm I}$, $\rho = \rho$

After branching $K_{\rm I} \approx 0.7 K_{\rm I}$, $\rho = \rho$ '/2

Crack-tip Load



Phase Field Modelling of Stress Corrosion

Per Ståhle, Eskil Hansen LU, Lund Sweden Contributions to the free energy (Ginzburg & Landau, 1950)

$$\mathcal{F} = \mathcal{F}_{el} + \mathcal{F}_{ch} + \mathcal{F}_{gr}$$

Volume totals:

Elastic energy
$$\mathcal{F}_{el} = \int \frac{G(\psi)}{2} (\nabla w)^2 dV$$

Chemical energy $\mathcal{F}_{ch} = \int U(\psi) dV$
Gradient energy $\mathcal{F}_{gr} = \int \frac{g_b}{2} (\nabla \psi)^2 dV$

88(99)

Antiplane deformation => Two free variables

Displacements w and phase (density) ψ

$$\frac{\partial \psi}{\partial t} = -L_{\psi} \frac{\delta \mathcal{F}}{\delta \psi} \quad , \quad \frac{\partial w}{\partial t} = -L_{w} \frac{\delta \mathcal{F}}{\delta w}$$

Ginzburg, Landau (50)

Double-well chemical potential $U(\psi) = p \psi^2 (1 - \psi)^2$





Evolution of the phase

$$\frac{\partial \psi}{\partial t} = -L_{\psi} \left[\frac{1}{2} G'(\psi) (\nabla w)^2 + p \psi (\psi^2 - 1) - g_b \triangle \psi \right]$$

Evolution of the displacements

$$\frac{\partial w}{\partial t} = L_w \nabla \cdot [G(\psi) \nabla w]$$

At equilibrium: $\nabla \cdot [G(\psi)\nabla w] = 0$

Steady state solution

$$\psi = -\tanh(\sqrt{\frac{p}{2g_b}}x_2 + \frac{3}{4}L_{\psi}G_o(\nabla w)^2\sqrt{\frac{2g_b}{p}}t)$$



Dissolution Rate vs. Tensile Stress




$$\left(\frac{\mathrm{d}}{\mathrm{d}x_2} - 2\beta\right)(f' + f^2 - 1) = 0$$

$$\psi = -\tanh(\sqrt{\frac{p}{2g_b}}x_2 + \frac{3}{4}L_{\psi}G_o(\nabla w)^2\sqrt{\frac{2g_b}{p}}t)$$





Red is remaining material

Effective Stress

Effective Stress

96(99)



Red is remaining material

Effective stress

97(99)



Without general corrosion

with general corrosion

98(99)

Formation and growth of hydrides

Per Ståhle

Solid Mechanics, Lund University, Sweden

Collaborators: Wurigul Reheman, Ram N Singh, Martin Fisk, Srikumar Banerjee, Ali Massih, Christina Bjerkén



Hydride Blister section



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.

The basis of radial hydride formation is the stress field of blister in the matrix surrounding it.

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





The Phase Field



Contributions to the free energy

$$\mathcal{F} = \mathcal{F}_{el} + \mathcal{F}_{ch} + \mathcal{F}_{gr}$$

Elastic energy
$$\mathcal{F}_{el} = \int \sigma_{ij} \mathrm{d}\epsilon_{ij}$$

Chemical energy
$$\mathcal{F}_{ch} = U(\psi)$$

Gradient energy
$$\mathcal{F}_{gr} = \frac{g_r}{2} \left(\psi_{,i} \right)^2$$

Double-well chemical potential $U(\psi) = p \psi^2 (1 - \psi)^2$





Plane cases. Unknown:
$$\psi, u_1, u_2$$

Phase:
$$\frac{\partial \psi}{\partial t} = -L_{\psi} \left(\frac{\partial \mathcal{F}}{\partial \psi} - \nabla \frac{\partial \mathcal{F}}{\partial (\nabla \psi)} \right)$$

Displ.:
$$\frac{\partial u_i}{\partial t} = -L_{u_i} \left(\frac{\partial \mathcal{F}}{\partial u_i} - \nabla \frac{\partial \mathcal{F}}{\partial (\nabla u_i)} \right)$$

Heat transfer with heat generation

$$\psi_{,ii} - \frac{\partial \psi}{\partial \tilde{t}} = \left\{ 3\epsilon^{el}_{ii} \tilde{\epsilon}_s + 2(1 - 2\psi) \right\} (1 - \psi)\psi$$

Mechanical equilibrium with thermal expansion

$$\tilde{u}_{i,jj} + \frac{1}{1-2\nu}\tilde{u}_{j,ij} - (\tilde{\epsilon}_s)_{,j} = 0$$

In analogy with a fully coupled thermal-stress

Surface energy
$$\gamma = \sqrt{2pg_b}$$
 [F/L]

Strain energy density $W = \sigma_{ii}\epsilon_s$ [F/L²]

Length parameter γ/W [L]





Noisy interface

$$\epsilon_{11} = 0.45\epsilon_s$$







Noisy interface $\epsilon_{11} = 0.55 \epsilon_s$ x_2 x_1



Noisy background $\epsilon_{11}=\epsilon_{22}=0.5\epsilon_s$











Noisy background $\epsilon_{11} = 0.5 \epsilon_s$











Evolution of the phase

$$\frac{\partial \psi}{\partial t} = -L_{\psi} \left(\left\{ 3\sigma_{ii}\epsilon_s + 2p(1-2\psi) \right\} (1-\psi)\psi - g_b\psi_{,ii} \right) \quad \stackrel{0.4}{\underset{0.2}{\longrightarrow}} \quad \stackrel{0.4}{\underset{0.2}{\longleftarrow}} \quad\stackrel{0.4}{\underset{0.2}{\longrightarrow}} \quad \stackrel{0.4}{\underset{0.2}{\longrightarrow}} \quad \stackrel{0.4}{\underset{0.2}{\longrightarrow}} \quad \stackrel{0.4}{\underset{0.2}{\longrightarrow}} \quad \stackrel{0.4}{\underset{0.2}{\longrightarrow}} \quad\stackrel{0.4}{\underset{0.2}{\longrightarrow}} \quad\stackrel{0.4}{\underset{0.2}{\underset{0.2}{\longleftarrow}} \quad\stackrel{0.4}{\underset{0.2}{\underset{0.2}{\underset{0.2}{\longrightarrow}} \quad\stackrel{0.4}{\underset$$

Evolution of the displacements

$$\frac{\partial u_i}{\partial t} = -L_u(\mu u_{i,jj} + (\mu + \lambda)u_{j,ij} - (2\mu + 3\lambda)\epsilon_{,i}^s)$$





Osteoporosis



100.000 fractures related to osteoporosis each year in Sweden.

(Sweden has a population of 9 million people)

Observations of exercise stimulated bone growth





(Lanyon and Rubin, 84) Experiments performed on the left wing, while the right wing was used as reference for each turkey.

The flow \boldsymbol{J} , and the concentration \boldsymbol{c} ,

$$J = -D\nabla c + B\nabla \sigma_h$$
$$\nabla J = -\dot{c}$$

Hooke stress tensor

$$\sigma_{ij} = 2\mu\epsilon_{ij} + \lambda\delta_{ij} - \beta\delta_{ij}c$$

=>
$$-\nabla D \nabla c + \nabla B \nabla \sigma_h = -\dot{c}$$



Left wing, dynamic load



Right wing, no load

The dynamic load was applied at a frequency of 1 Hz during 100s per day during 8 weeks. Max force 525 N.



Landau phase field model



Amplitude, A, as a function of load frequency ω

$$C = C(x, t) = A f(x) \sin(\omega t), \quad f(L) = 1$$



Concentration per unit of area

