Aalto University
School of Engineering

COE-C2004 - Materials Science and Engineering

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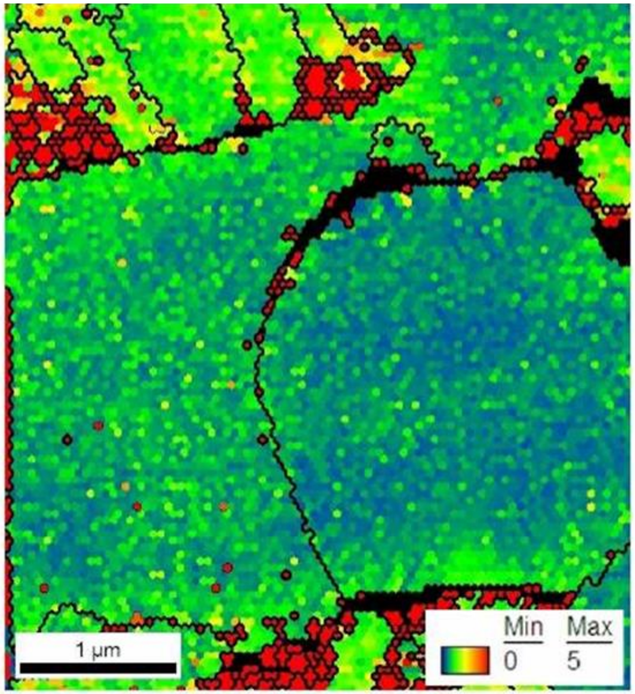
Ductile Fracture

Definition of Damage

Fracture of pressure vessel

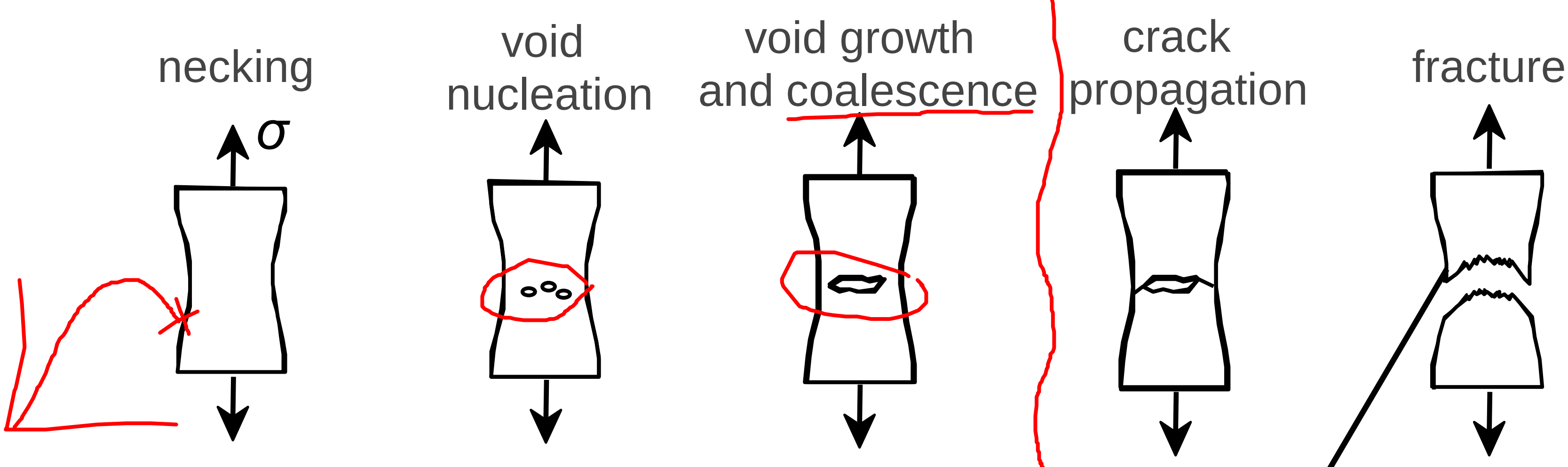
Damage: microstructure develops an irreversible degradation on a given length scale.
e.g. void formation



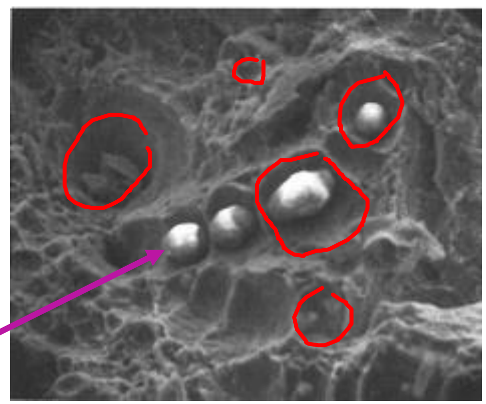
Microvoids

Fracture: Separation of a body into two or more pieces in response to a load.

Stages of Moderately Ductile Failure

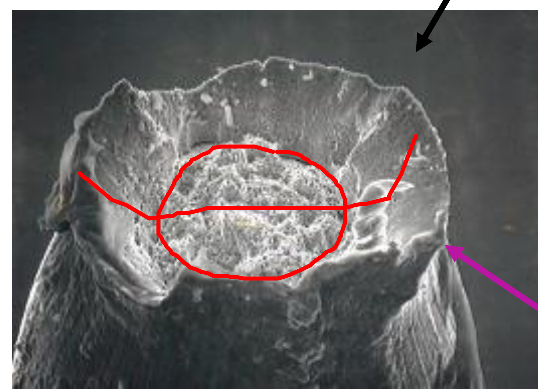


Electron micrographs of fracture surfaces (steel)



From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)

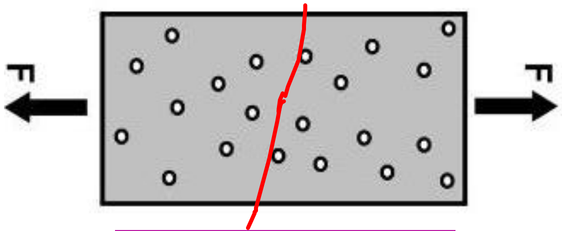
Acorn particles serve as void nucleation sites.



Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

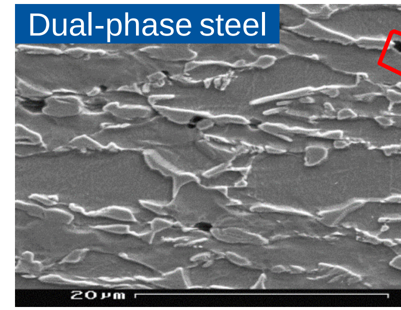
cup and cone fracture surface

Ductile Fracture Mechanism

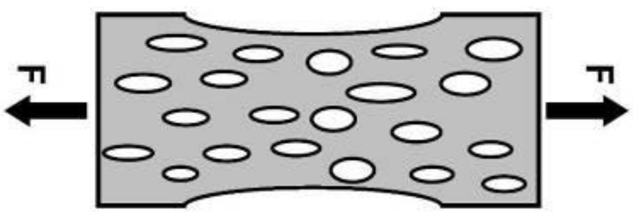


Void nucleation

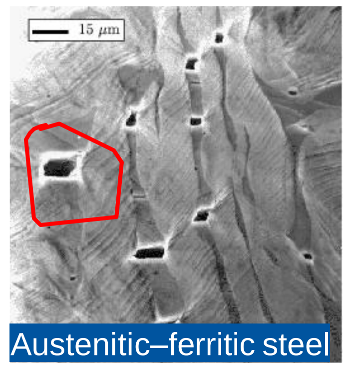
Tasan et al., Mechanics of Materials, 2009



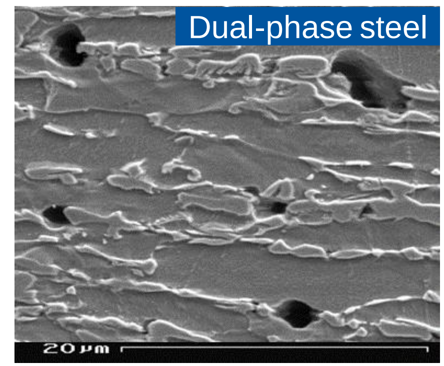
Lian et al., *Computational Material Science, 2014*



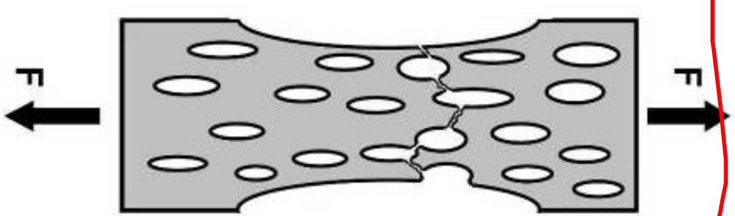
Void growth



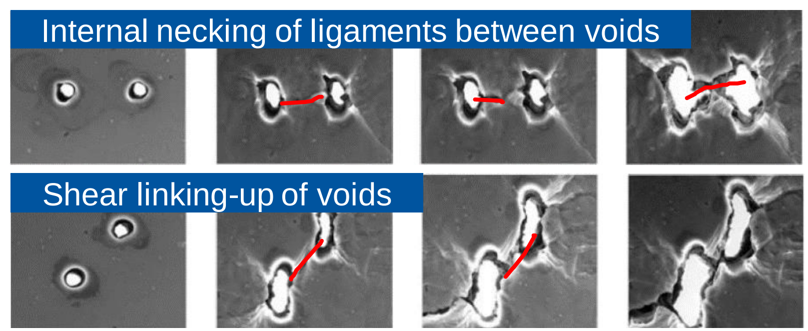
Besson, et al., *Engineering Fracture Mechanics, 2000*

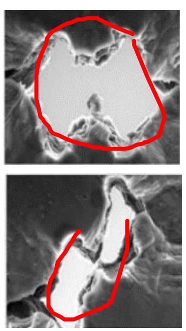


Lian et al., *Computational Material Science, 2014*



Void coalescence





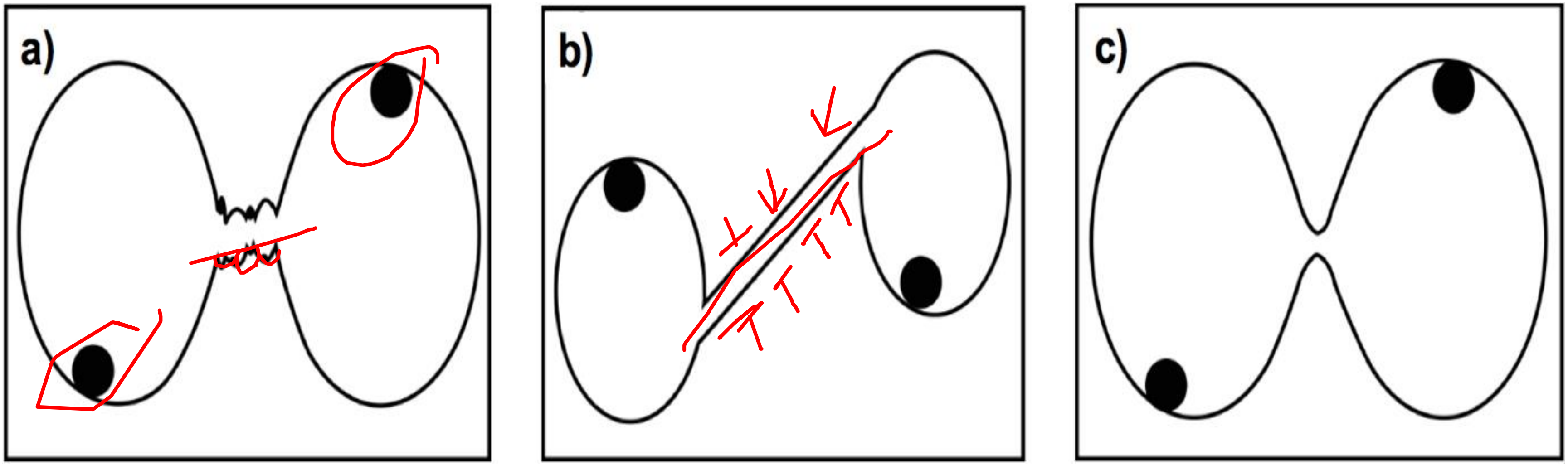
Weck and Wilkinson, *Acta Materialia, 2008*

Void coalescence

Secondary pores
Formation of a second pore population in between bigger primary pores, mostly at hard particles of small size

Shear bands
Formation of shear bands in between to primary pores due to strain localization

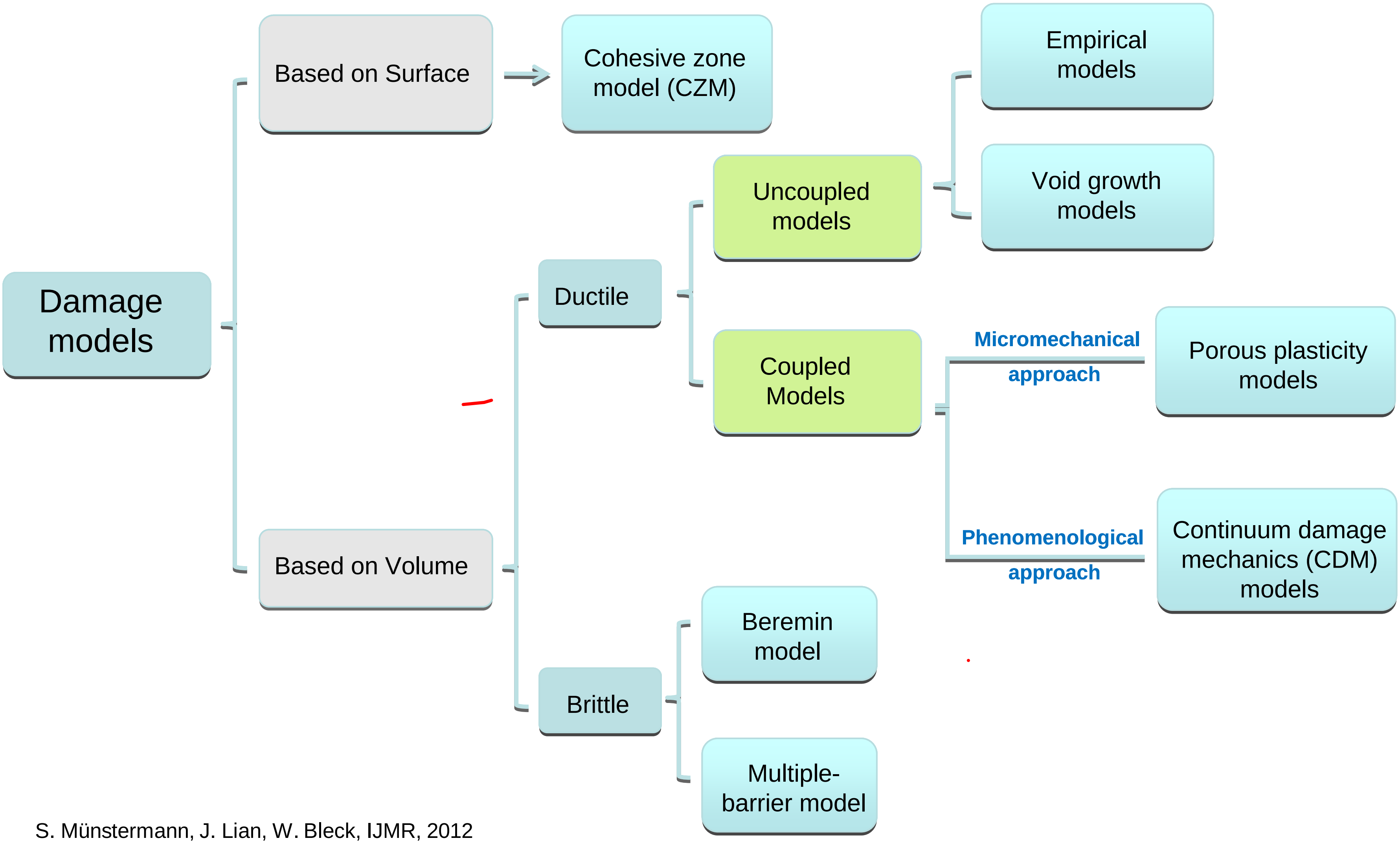
Coagulation
Coalescence of two primary pores which are close by



Ductile Fracture Modeling

(Seminar)

Quantify Ductile Fracture – Damage Mechanics



S. Münstermann, J. Lian, W. Bleck, IJMR, 2012

Damage measurement for Copper

Lemaitre, Nuclear Engineering and Design, 1984

$$D = \left(1 - \frac{\tilde{E}}{E_0}\right)$$

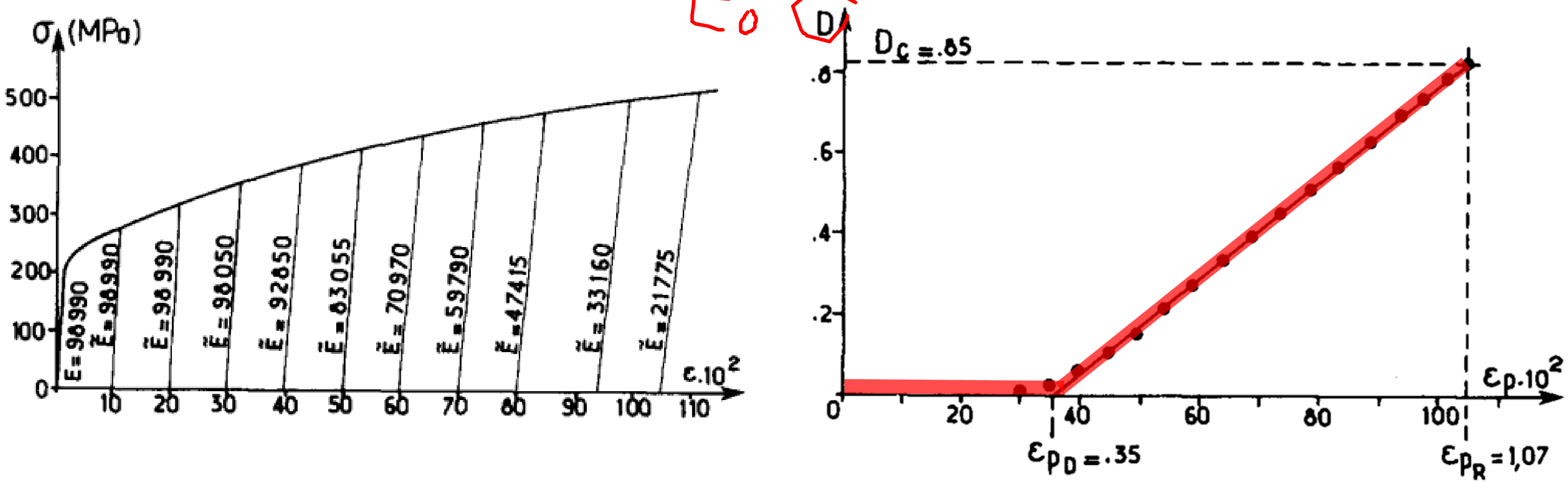


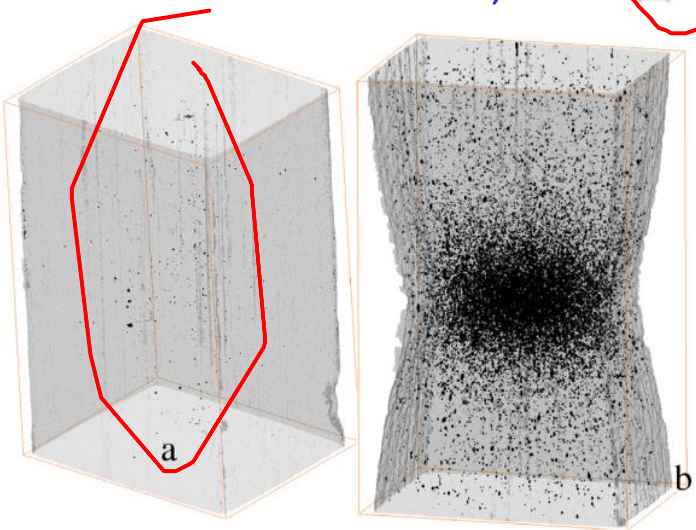
Fig. 2. Ductile plastic damage of copper 99.9%.

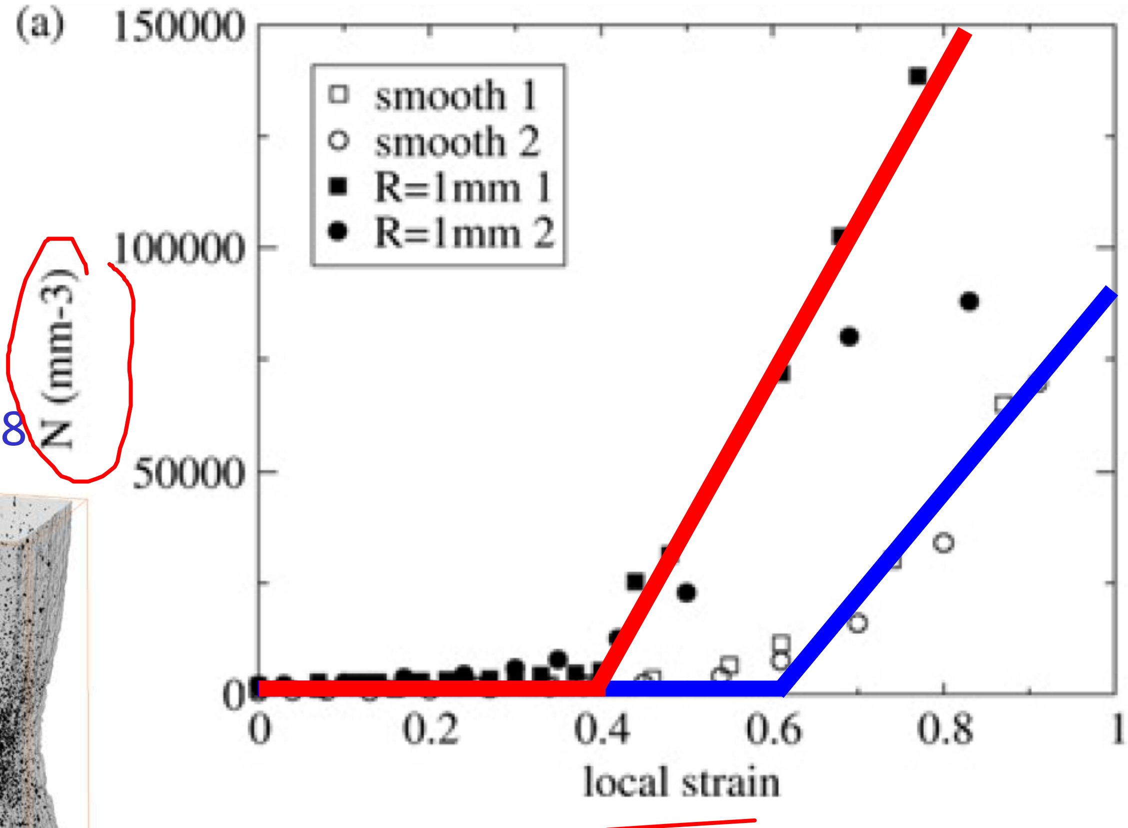
Damage measurement in DP600

Landron et al., Scripta Mat., 2010

X-ray microtomography

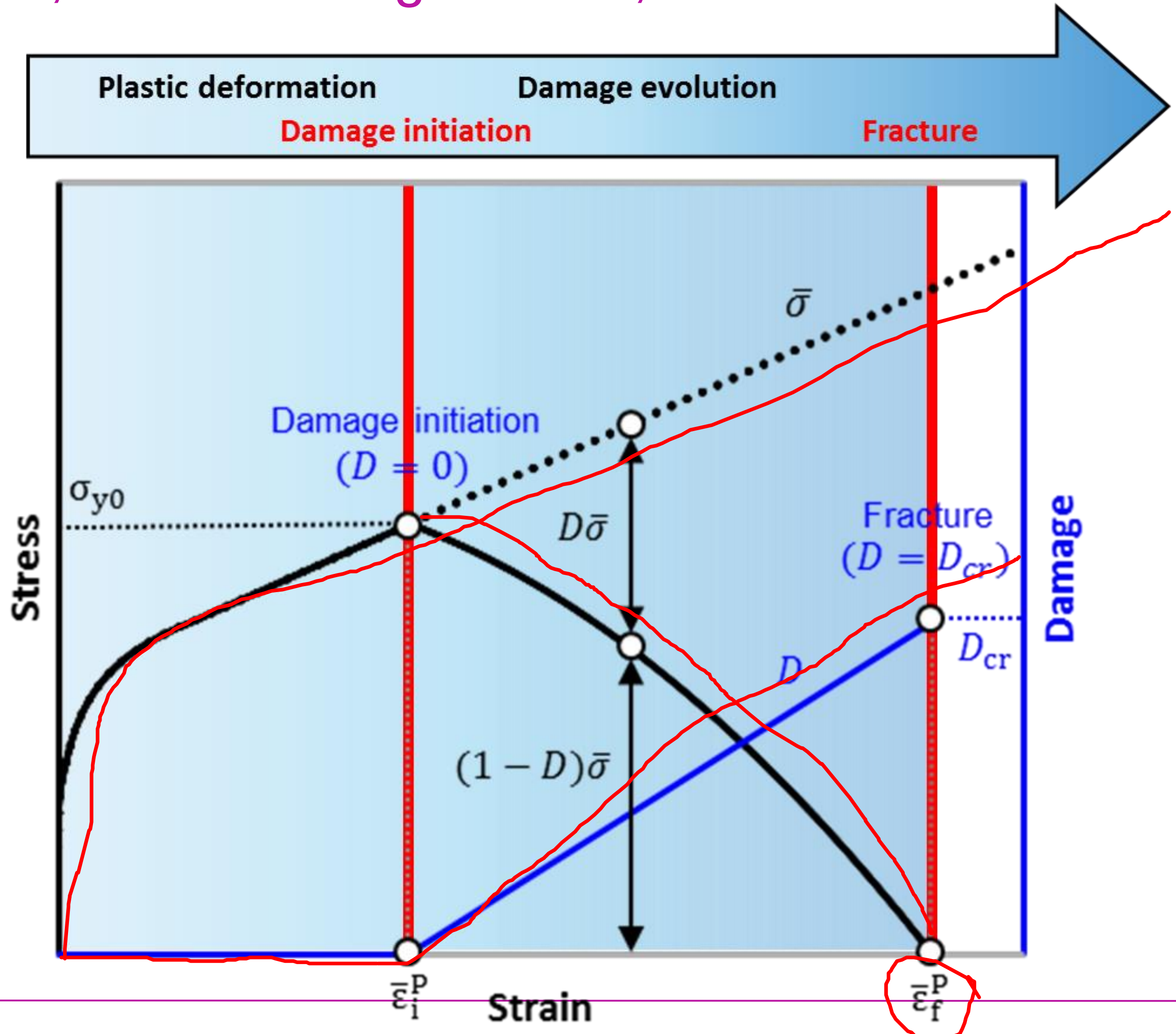
Maire et al. Acta Mat., 2008



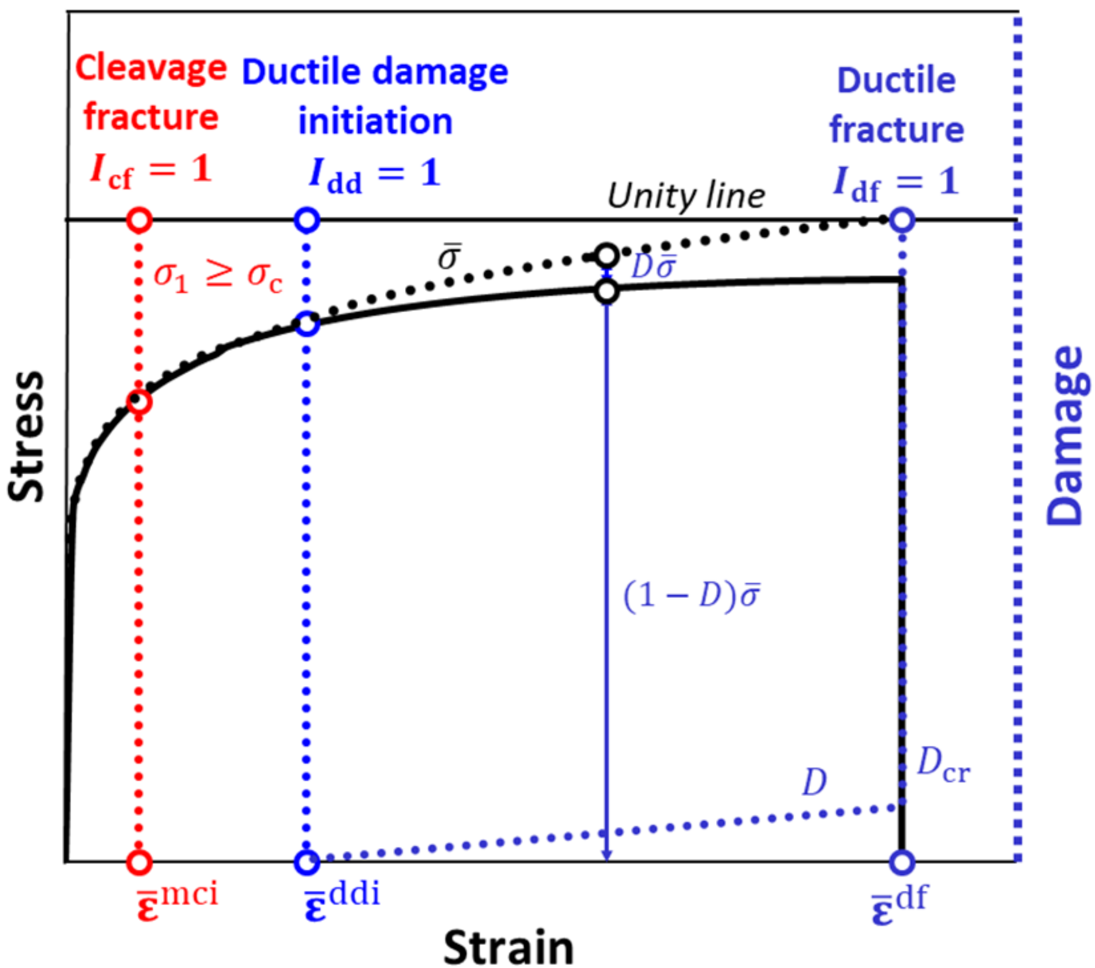


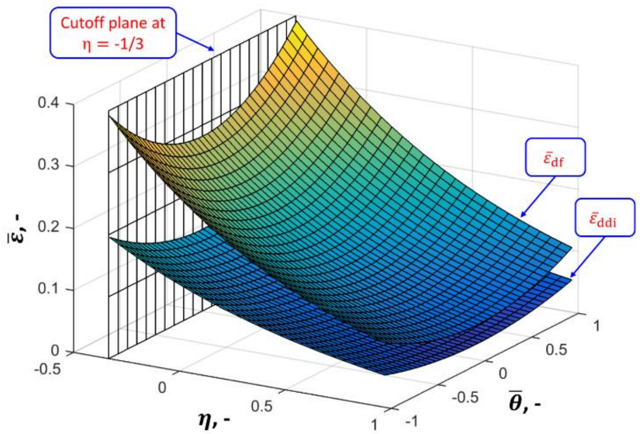
A hybrid damage mechanics model

Lian et al., Int. J. Damage Mech., 2013 & 2015



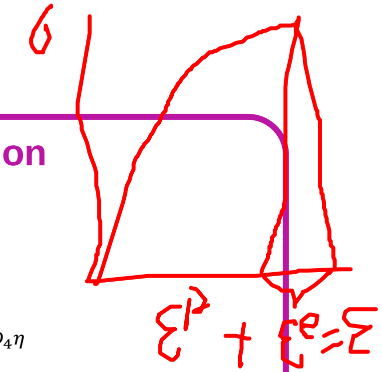
Extension of the model





- Non-proportional loadings
  Wu, Lian, et al., FFEMS, 2017
- Cleavage fracture
  He, Lian et al., EFM, 2017
- Non-local formulation
  Aravas, Lian et al., IJSS, 2019
- Dynamic loading
  Liu, Lian et al., IJMS, 2020

Constitutive equations



Elastoplastic deformation

- Elastoplastic strain split: $\boxed{\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}}$
- Elastic law: $\boldsymbol{\sigma} = (1-D)\mathbf{C}:\boldsymbol{\varepsilon}^{\mathrm{e}}$
- **Yield criterion:**

$$\boldsymbol{\Phi} = \bar{\boldsymbol{\sigma}} - (\mathbf{1}-\boldsymbol{D})\cdot\boldsymbol{\sigma}_{\mathbf{y}}\left(\bar{\boldsymbol{\varepsilon}}^{\mathbf{p}},\dot{\bar{\boldsymbol{\varepsilon}}}^{\boldsymbol{p}}\right)\cdot\mathbf{f}(\boldsymbol{T})\cdot\boldsymbol{f}(\bar{\boldsymbol{\theta}}) \leq \mathbf{0}$$

$$\boldsymbol{\sigma}_{\mathbf{y}}\left(\bar{\boldsymbol{\varepsilon}}^{\mathbf{p}},\dot{\bar{\boldsymbol{\varepsilon}}}\right) = \boldsymbol{\sigma}_{\mathbf{y}}(\bar{\boldsymbol{\varepsilon}}^{\mathbf{p}})\cdot\left(\mathbf{1}+\boldsymbol{c}_{\mathbf{1}}^{\dot{\bar{\varepsilon}}}\cdot\mathbf{ln}\frac{\dot{\bar{\boldsymbol{\varepsilon}}}^{\boldsymbol{p}}}{\dot{\bar{\boldsymbol{\varepsilon}}}_{\mathbf{0}}}\right)+\boldsymbol{c}_{\mathbf{2}}^{\dot{\bar{\varepsilon}}}\cdot\bar{\boldsymbol{\sigma}}_{\mathbf{0}}\left(\frac{\dot{\bar{\boldsymbol{\varepsilon}}}^{\boldsymbol{p}}}{\dot{\bar{\boldsymbol{\varepsilon}}}_{\mathbf{0}}}-\mathbf{1}\right)$$

$$\boldsymbol{f}(\boldsymbol{T}) = \boldsymbol{c}_{\mathbf{1}}^{\boldsymbol{T}}\cdot\mathbf{exp}\left(\boldsymbol{c}_{\mathbf{2}}^{\boldsymbol{T}}\cdot\boldsymbol{T}\right)+\boldsymbol{c}_{\mathbf{3}}^{\boldsymbol{T}}$$

$$\boldsymbol{f}(\bar{\boldsymbol{\theta}}) = \left[\boldsymbol{c}_{\theta}^{\mathbf{s}}+\left(\boldsymbol{c}_{\theta}^{\mathbf{ax}}-\boldsymbol{c}_{\theta}^{\mathbf{s}}\right)\cdot\left(\boldsymbol{\omega}-\frac{\boldsymbol{\omega}^{\mathbf{m+1}}}{\boldsymbol{m}+\mathbf{1}}\right)\right]$$

$$\boldsymbol{\omega} = \frac{\sqrt{\mathbf{3}}}{\mathbf{2}-\sqrt{\mathbf{3}}}\left[\mathbf{sec}\left(\frac{\bar{\boldsymbol{\theta}}\boldsymbol{\pi}}{\mathbf{6}}\right)-\mathbf{1}\right]$$

- Flow rule: $\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}} = \dot{\gamma}\frac{\partial\Phi}{\partial\boldsymbol{\sigma}}$

Cleavage fracture initiation

- Cleavage fracture initiation:

$$(\cdot)_{\mathrm{avg}} = \frac{1}{\bar{\varepsilon}^{\mathrm{p}}}\int_0^{\bar{\varepsilon}^{\mathrm{p}}}(\cdot)(\bar{\varepsilon}^{\mathrm{p}})\mathrm{d}\bar{\varepsilon}^{\mathrm{p}}$$

$$\bar{\varepsilon}^{\mathrm{mci}}\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) = f\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right)$$

$$f\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) = \left[C_1e^{-C_2\eta}-C_3e^{-C_4\eta}\right]\bar{\theta}^2+C_3e^{-C_4\eta}$$

- Cleavage fracture initiation indicator:

$$I_{\mathrm{cf}} = \int_0^{\bar{\varepsilon}^{\mathrm{p}}}\frac{\mathrm{d}\bar{\varepsilon}^{\mathrm{p}}}{\bar{\varepsilon}^{\mathrm{mci}}\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right)}$$

Ductile damage initiation

- Ductile damage initiation:

$$\bar{\varepsilon}^{\mathrm{ddi}}\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) = \begin{cases}+\infty & \text{for } \eta\leq\eta_{\mathrm{c}}\\ g\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) & \text{for } \eta>\eta_{\mathrm{c}}\end{cases}$$

$$g\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) = \left[D_1e^{-D_2\eta}-D_3e^{-D_4\eta}\right]\bar{\theta}^2+D_3e^{-D_4\eta}$$

- Ductile damage initiation indicator:

$$I_{\mathrm{dd}} = \int_0^{\bar{\varepsilon}^{\mathrm{p}}}\frac{\mathrm{d}\bar{\varepsilon}^{\mathrm{p}}}{\bar{\varepsilon}^{\mathrm{ddi}}\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right)}$$

- Characteristic strain @ ddi for non-proportional loading:

$$\bar{\varepsilon}_{\mathrm{c}}^{\mathrm{ddi}} = \bar{\varepsilon}^{\mathrm{p}}(I_{\mathrm{dd}}=1)$$

Ductile fracture

- Critical ductile damage accumulation function:

$$D_{\mathrm{cr}}\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) = \begin{cases}+\infty & \text{for } \eta\leq\eta_{\mathrm{c}}\\ h\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) & \text{for } \eta>\eta_{\mathrm{c}}\end{cases}$$

$$h\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right) = \left[E_1e^{-E_2\eta}-E_3e^{-E_4\eta}\right]\bar{\theta}^2+E_3e^{-E_4\eta}$$

- Ductile damage propagation rule:

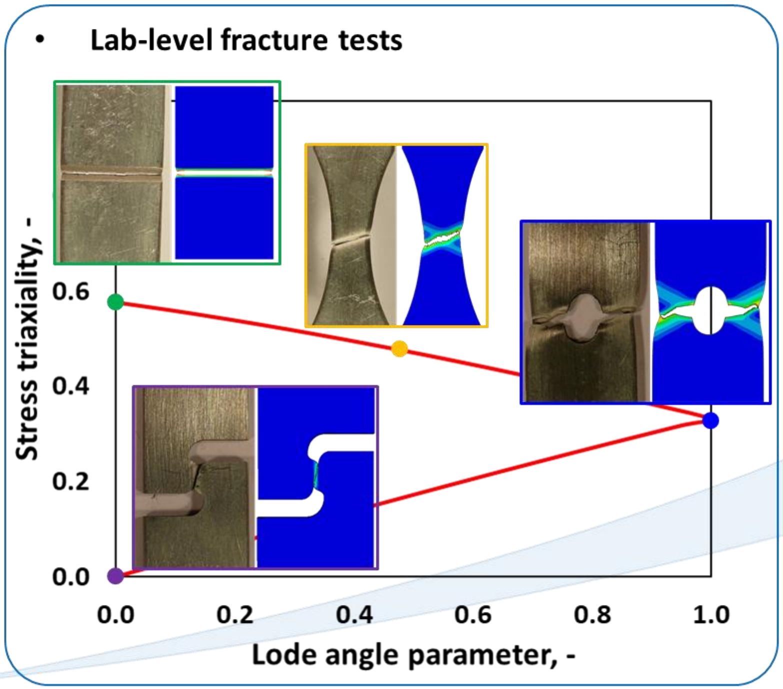
$$P_{\mathrm{dd}} = \int_{\bar{\varepsilon}_{\mathrm{c}}^{\mathrm{ddi}}}^{\bar{\varepsilon}^{\mathrm{p}}}\frac{\sigma_{\mathrm{yi}}/G_{\mathrm{f}}}{D_{\mathrm{cr}}\left(\eta_{\mathrm{avg}},\bar{\theta}_{\mathrm{avg}}\right)}\mathrm{d}\bar{\varepsilon}^{\mathrm{p}}$$

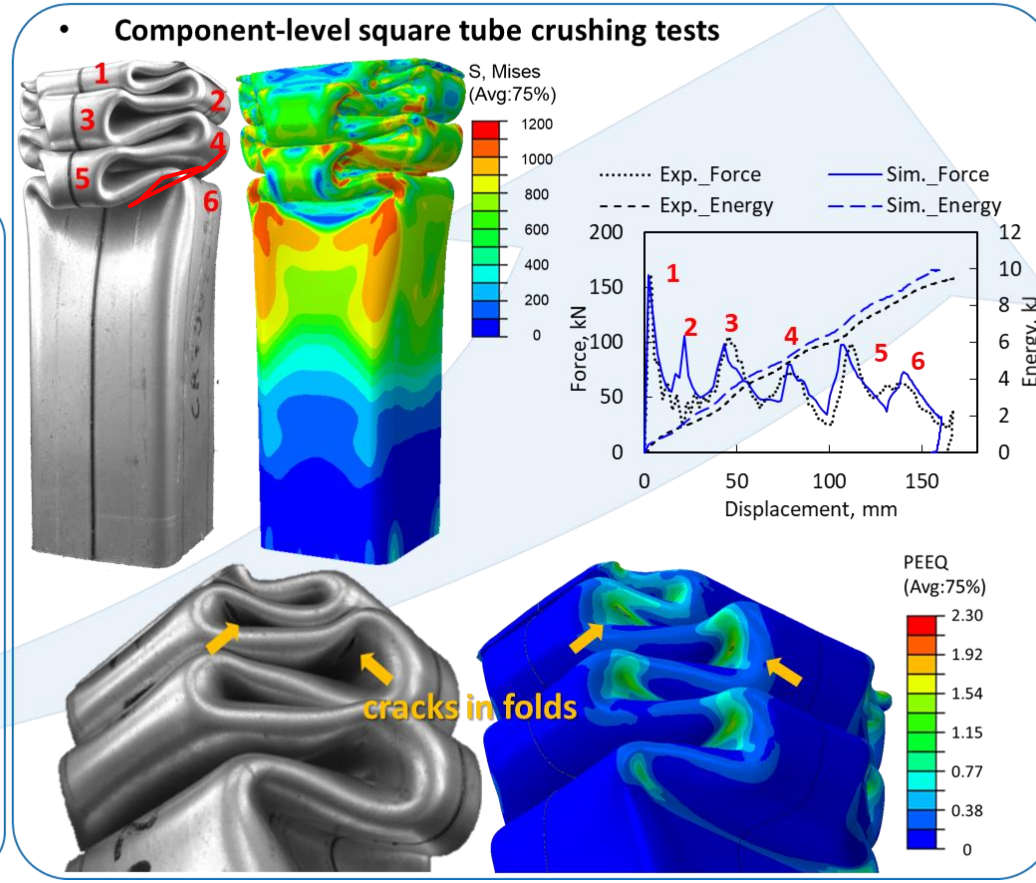
Ductile & cleavage interaction

- Cleavage and ductile damage:

$$D = \begin{cases}0 & \text{for } I_{\mathrm{cf}}<1\wedge I_{\mathrm{dd}}<1\\ 0 & \text{for } I_{\mathrm{cf}}\geq1\wedge\sigma_1<\sigma_{\mathrm{c}}\wedge I_{\mathrm{dd}}<1\\ 1 & \text{for } I_{\mathrm{cf}}\geq1\wedge\sigma_1\geq\sigma_{\mathrm{c}}\wedge I_{\mathrm{dd}}<1\\ P_{\mathrm{dd}} & \text{for } I_{\mathrm{dd}}\geq1\ \wedge P_{\mathrm{dd}}<1\\ 1 & \text{for } I_{\mathrm{dd}}\geq1\ \wedge P_{\mathrm{dd}}\geq1\end{cases}$$

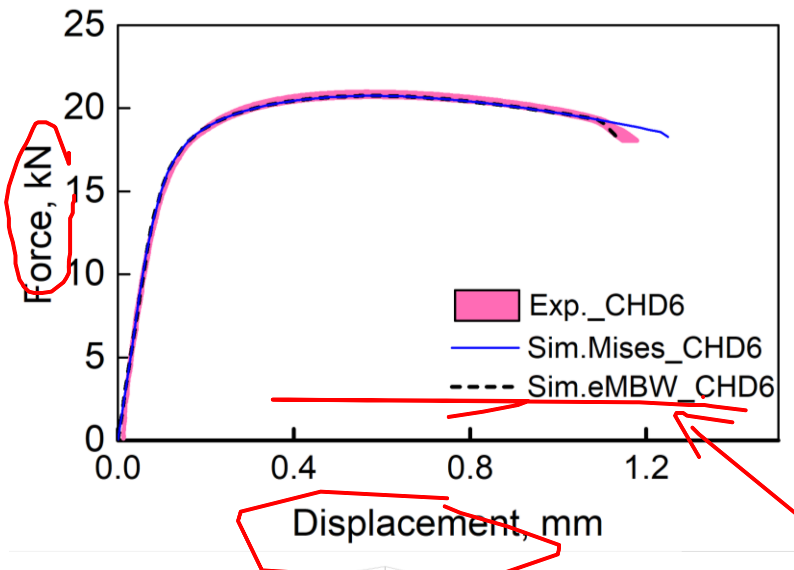
Case study: crashworthiness prediction

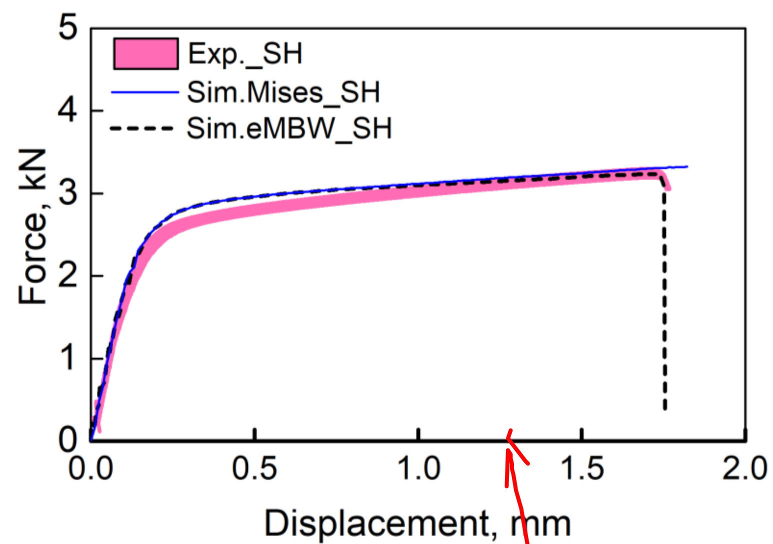


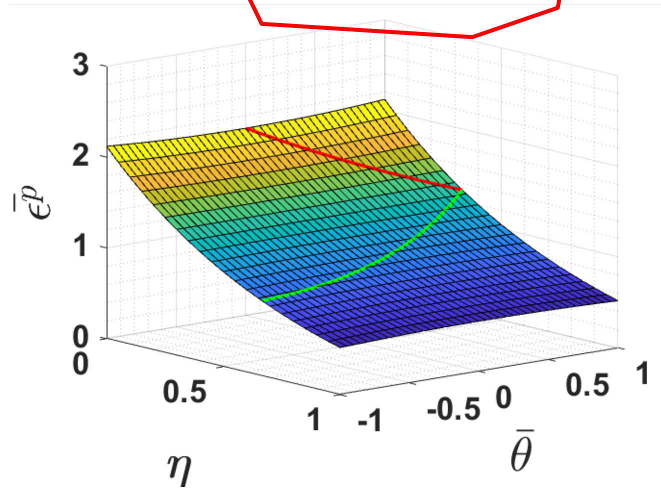


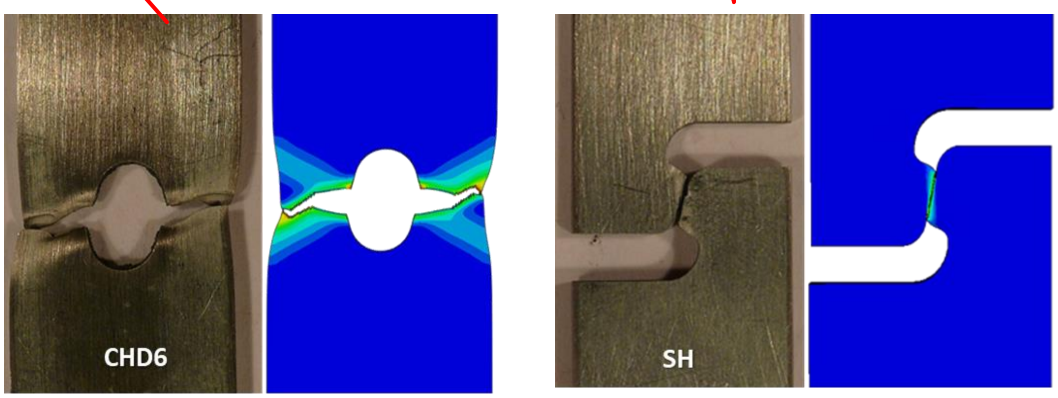
Liu, Lian, et al., Prediction of crack formation in the progressive folding of square tubes during dynamic axial crushing, IJMS, 2020

Fracture parameters calibration



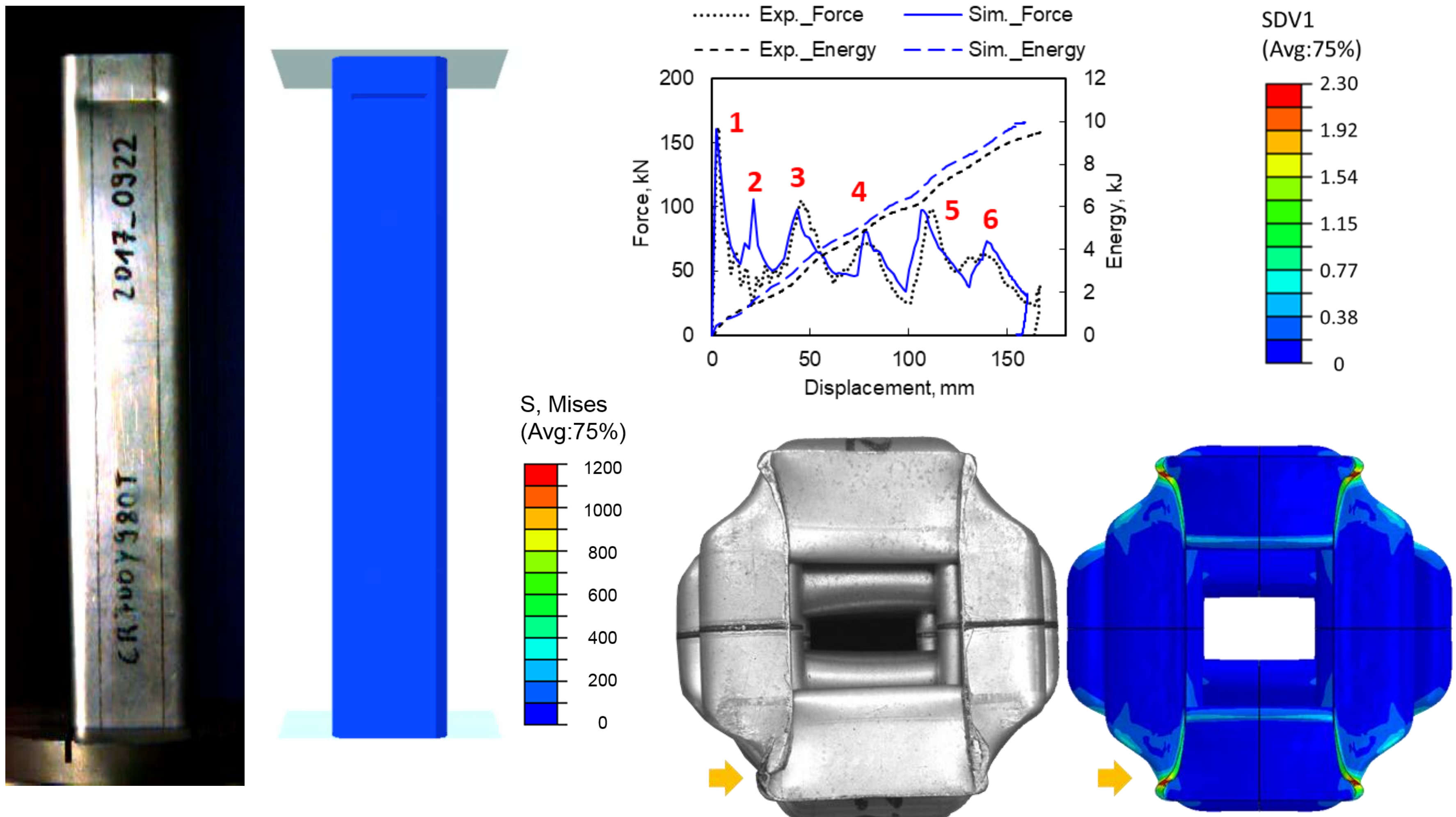






Liu, Lian, et al., Prediction of crack formation in the progressive folding of square tubes during dynamic axial crushing, IJMS, 2020

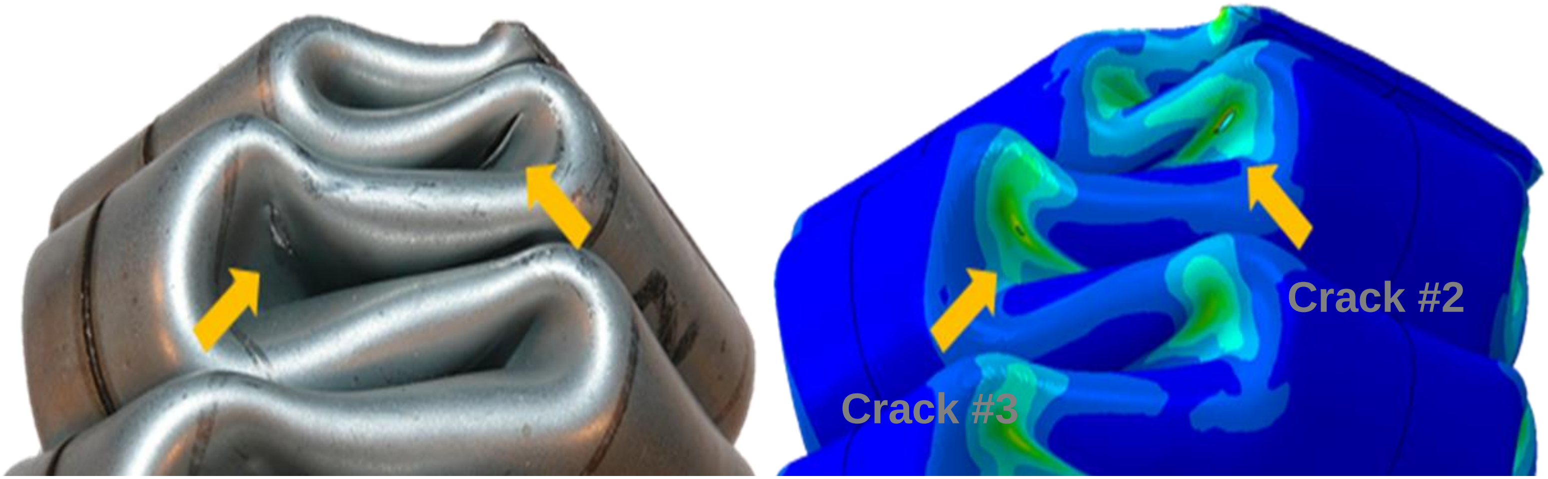
Model application – prediction of crack formation during tube crushing

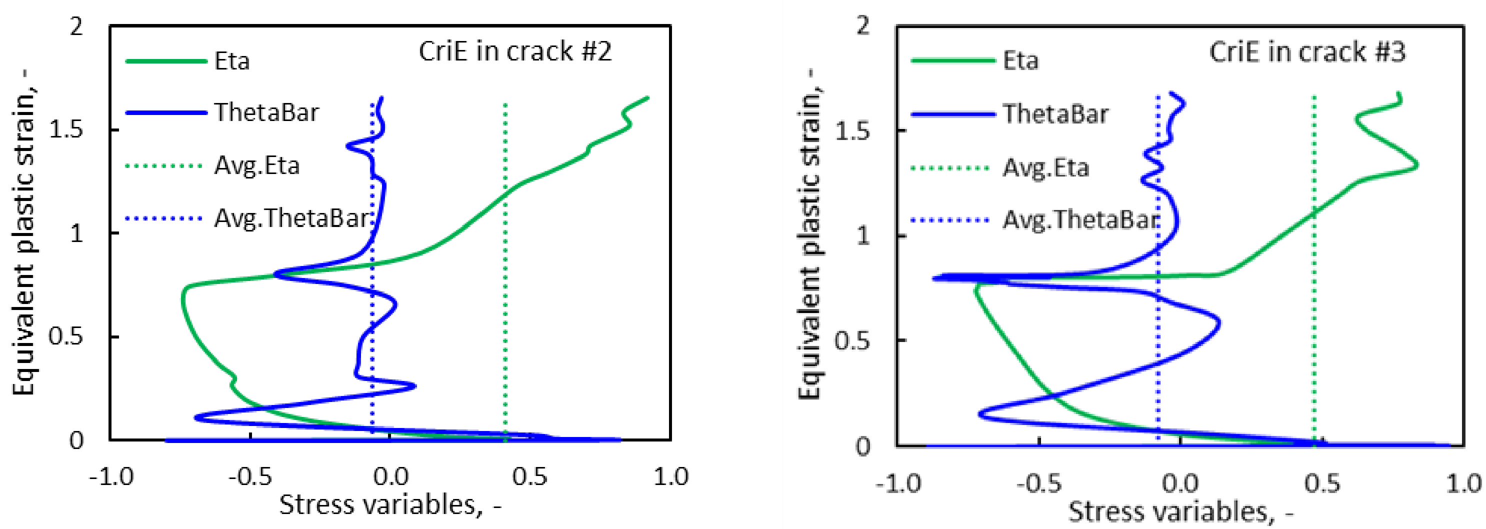


**Supported by TKSE*

Liu, Lian, et al., Prediction of crack formation in the progressive folding of square tubes during dynamic axial crushing, IJMS, 2020

Model application – prediction of crack formation during tube crushing





Liu, Lian, et al., Prediction of crack formation in the progressive folding of square tubes during dynamic axial crushing, IJMS, 2020

GTN Damage Model

- **Elastoplastic strain split:** $\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}$
- **Elastic law:** $\boldsymbol{\sigma} = (1 - D)\mathbf{C}\colon \boldsymbol{\varepsilon}^{\mathrm{e}}$
- **Yield criterion:** $$\Phi = \left(\frac{\sigma_V}{\sigma_y}\right)^2 + 2 \cdot q_1 \cdot f^* \cdot \cosh\left(\frac{3}{2} \cdot q_2 \cdot \frac{\sigma_H}{\sigma_V}\right) - \left(1 + q_3 \cdot f^{*2}\right) = 0$$
- **Flow rule:** $$\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}} = \dot{\gamma}\frac{\partial \Phi}{\partial \boldsymbol{\sigma}}$$
- **Damage evolution:** $$\dot{f} = \dot{f}_{GROWTH} + \dot{f}_{NUCLEATION}$$ $$f(t_0) = f_0$$
- **Loading/unloading condition :** $$\dot{\gamma} \geq 0;\ \Phi \leq 0;\ \dot{\gamma}\Phi = 0$$

GTN Damage Model

Modified von Mises yield potential:

$$\Phi_{GTN} = \left(\frac{\sigma_v}{\sigma_y}\right)^2 + 2 \cdot q_1 \cdot f^* \cosh\left(\frac{3}{2} \cdot q_2 \cdot \frac{\sigma_H}{\sigma_y}\right) - \left(1 + q_3 \cdot f^{*2}\right) = 0$$

Notation

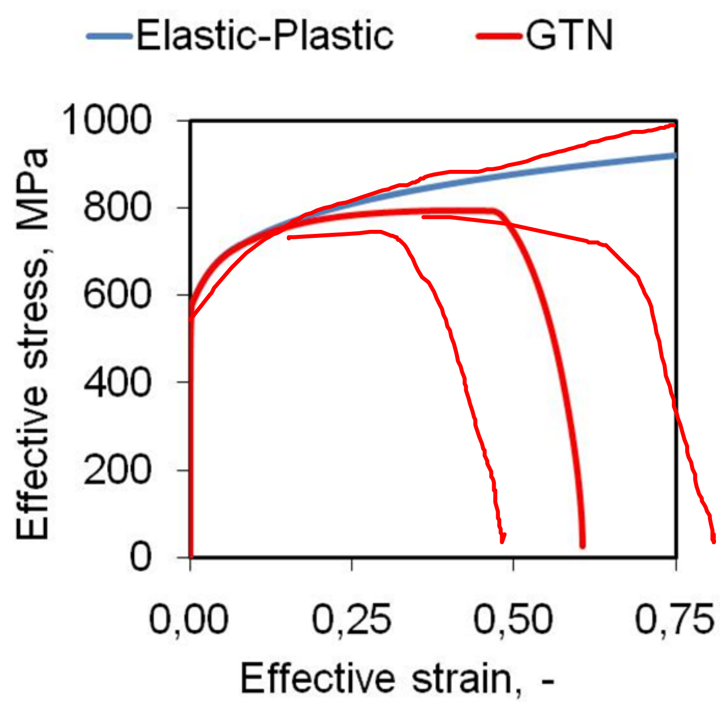
q_1, q_2, q_3: parameter for description of yield locus curve

f^*: from the calculated void volume f modified void volume f^*

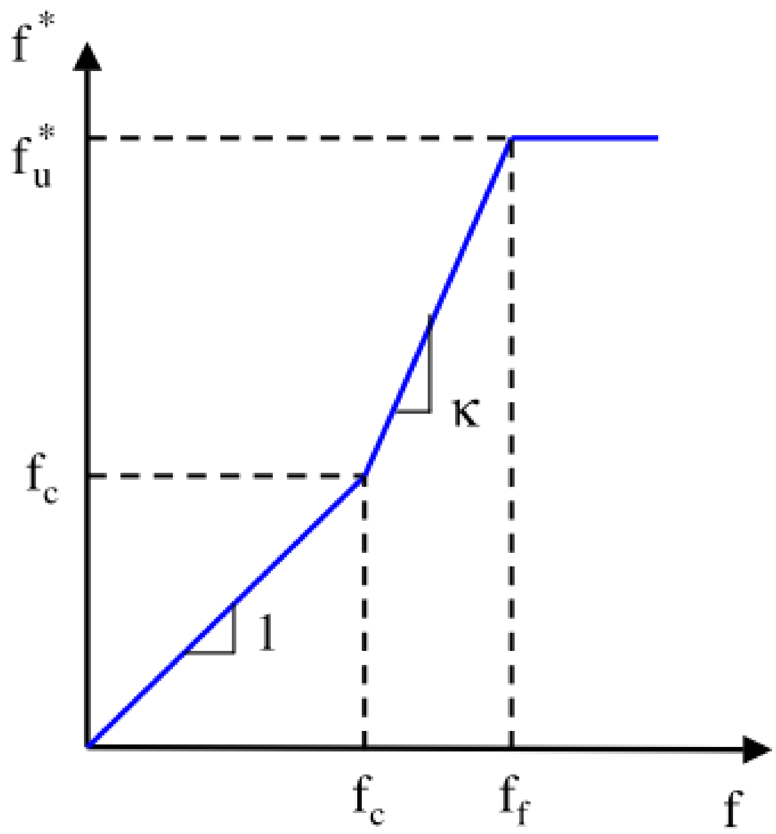
σ_H: hydrostatic stress

σ_V: von Mises effective stress

σ_y: flow stress of matrix material



GTN Damage Model



$$f^*(f) = \begin{cases} f; & f \le f_c \\ f_c + \kappa(f - f_c); & f > f_c \end{cases}$$

f_c	Critical void volume fraction
κ	Factor of accelerated void growth

GTN Damage Model

$$\dot{f} = \dot{f}_{GROWTH} + \dot{f}_{NUCLEATION} \quad \text{with} \quad f(t_0) = f_0$$

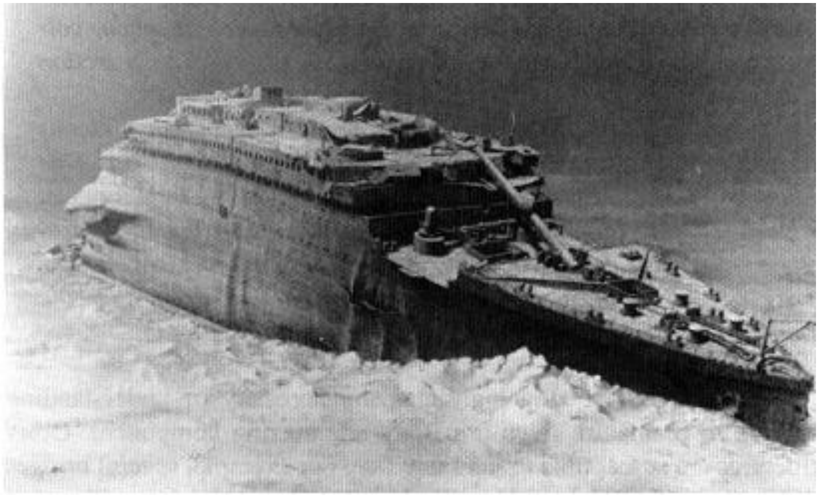
$$\dot{f}_{GROWTH} = (1-f)\cdot\dot{\varepsilon}_{kk}^{pl} \qquad \dot{f}_{NUCLEATION} = \frac{f_N}{S_N\cdot\sqrt{2\pi}}\cdot\exp\left[-\frac{1}{2}\left(\frac{\bar{\varepsilon}^{pl}-\varepsilon_N}{S_N}\right)^2\right]\cdot\dot{\bar{\varepsilon}}^{pl}$$

Material dependent GTN-parameters	
f_0	Initial void volume fraction
f_N	Volume fraction of secondary voids
ε_N	Characteristic plastic strain of secondary void nucleation
S_N	Standard deviation of ε_N
q_1, q_2, q_3	Model parameter by Tvergaard and Needleman
f_c	Critical void volume fraction
κ	Factor of accelerated void growth

Brittle to Ductile Transition

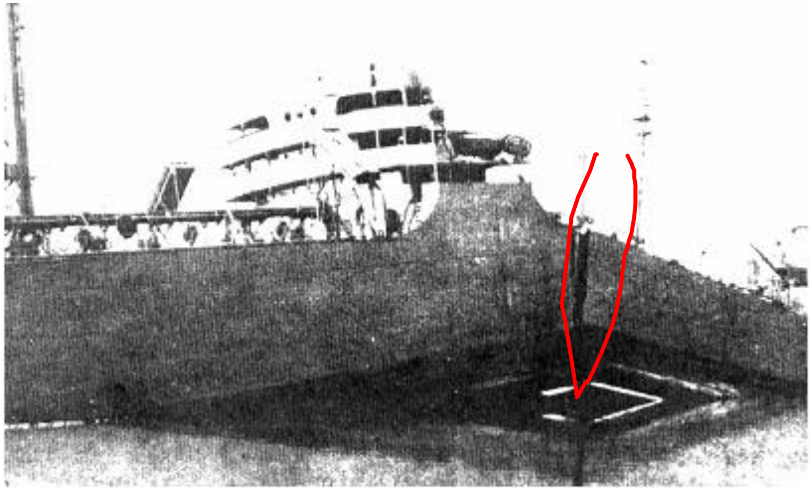
Brittle Fracture of Ductile Materials

- **Pre-WWII: The Titanic**



Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(a), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Dr. Robert D. Ballard, *The Discovery of the Titanic*.)

- **WWII: Liberty ships**



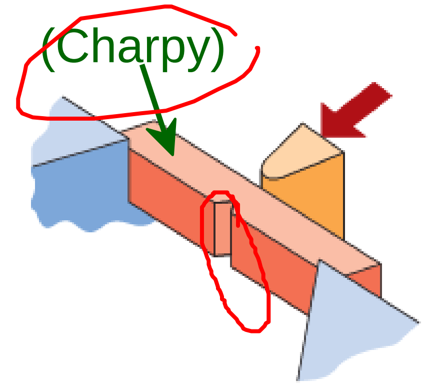
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc., NY, 1957.)

- Ships failed in a brittle manner though constructed of steel that, from tension tests, is normally ductile

Testing Ductile Materials for Brittle Failure

Impact Test

- Test conditions promoting brittle fracture:
  - -- High strain rate
  - -- Deformation at low temperatures
  - -- Presence of a notch



Impact energy computed from difference between initial height *h* and final height *h*’

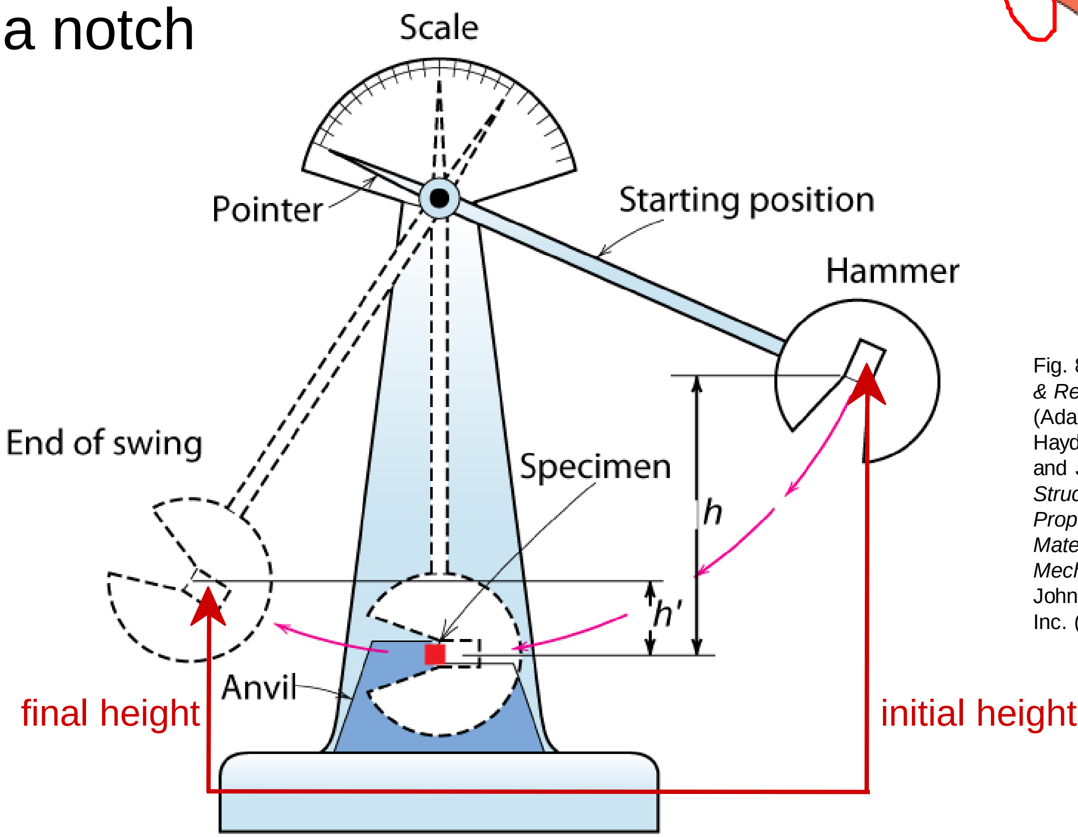


Fig. 8.13(b), *Callister & Rethwisch 10e.* (Adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

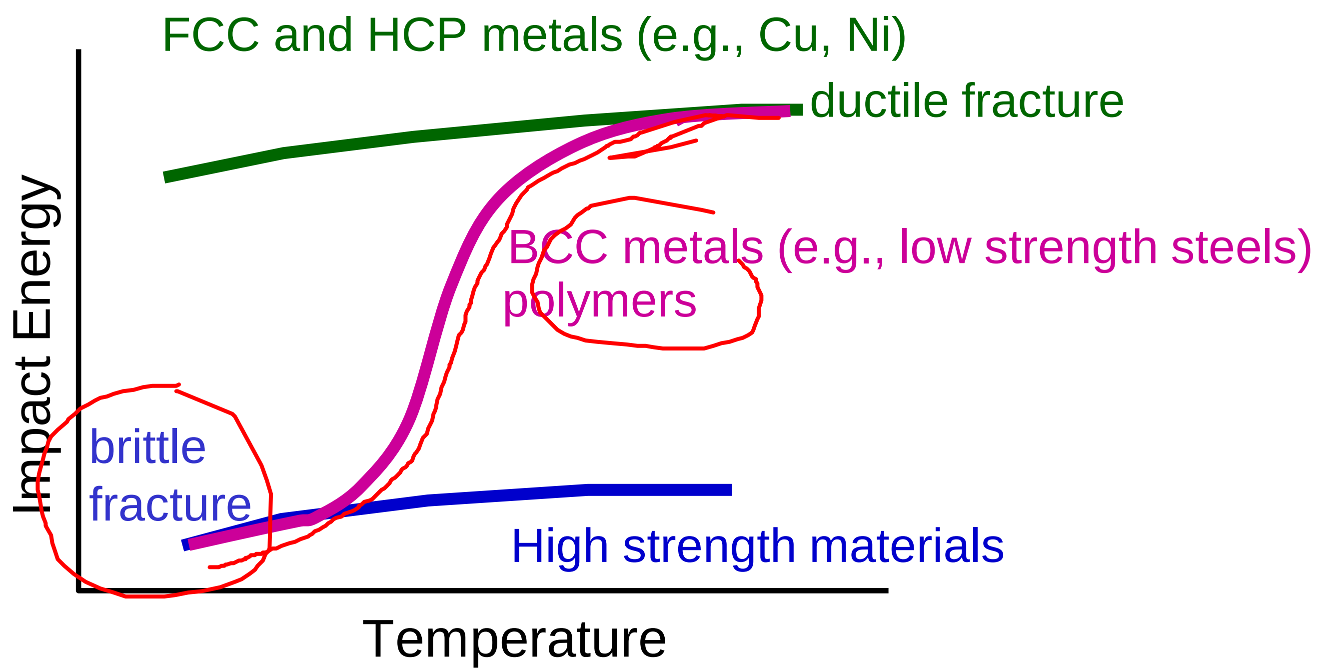
Testing Ductile Materials for Brittle Failure

https://youtu.be/tpGhqQvftAo

Influence of *T* on Impact Energy

- When impact tests conducted as function of temperature—three kinds of behavior observed for metals
- Some BCC metals exhibit Ductile-to-Brittle Transition Temperature (DBTT)

Adapted from Fig. 8.16, *Callister & Rethwisch 10e.*



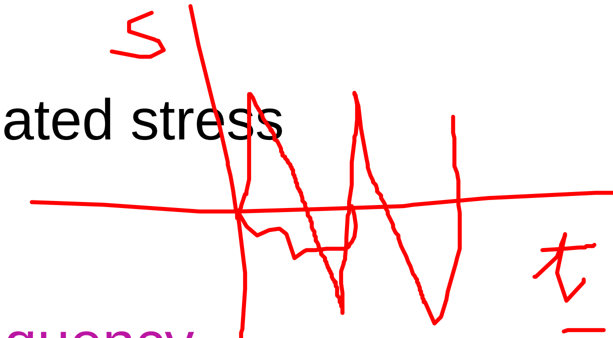
Metals having DBTT should only be used at temperatures where ductile.

Fatigue

Fatigue loading and testing

https://youtu.be/LhUclxBUV_E

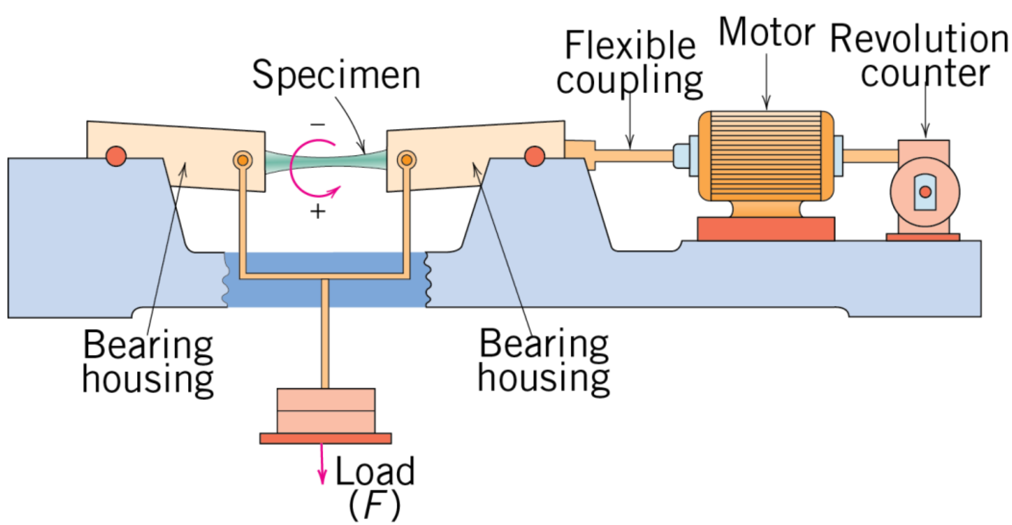
Fatigue Failure



- Fatigue = failure under lengthy period of repeated stress or strain cycling
- Stress varies with time.
  -- key parameters are S, σ_m, and cycling frequency
- Key points: Fatigue... $\bar{\varepsilon}$ ε_M
  --can cause part failure, even though applied stress $\sigma_{max} < \sigma_y$.
  --responsible for **~ 90%** of mechanical engineering failures.

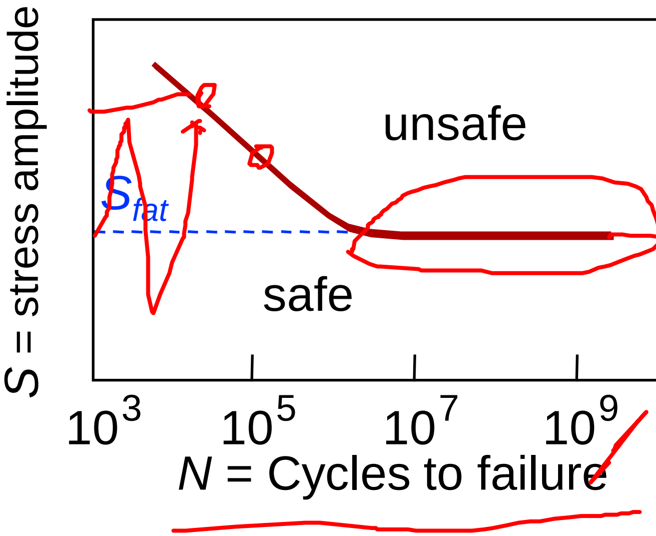
Schematic diagram of an apparatus for performing rotating-bending fatigue tests

Adapted from Fig. 8.19(a), *Callister & Rethwisch 10e.*



Fatigue Types

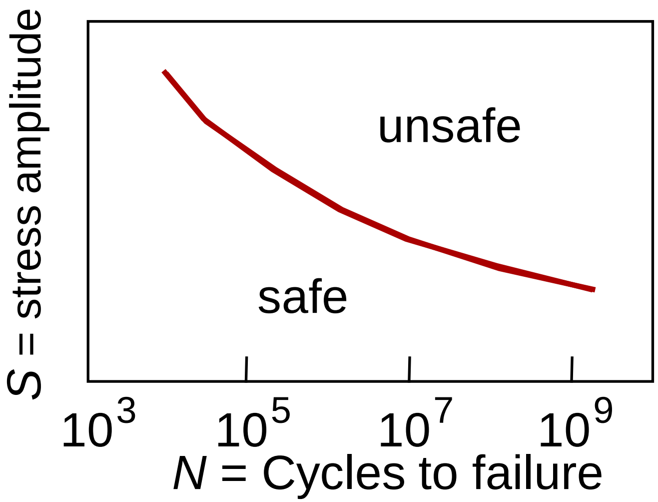
- Fatigue data plotted as stress amplitude S vs. log of number N of cycles to failure.
- Two types of fatigue behavior observed
  - Fatigue limit, S_{fat}: no fatigue if $S < S_{fat}$
  - For some materials, there is no fatigue limit!



case for steel (typ.)

Adapted from Fig. 8.20(a), *Callister & Rethwisch 10e.*

- Fatigue Life N_f = total number of stress cycles to cause fatigue failure at specified stress amplitude

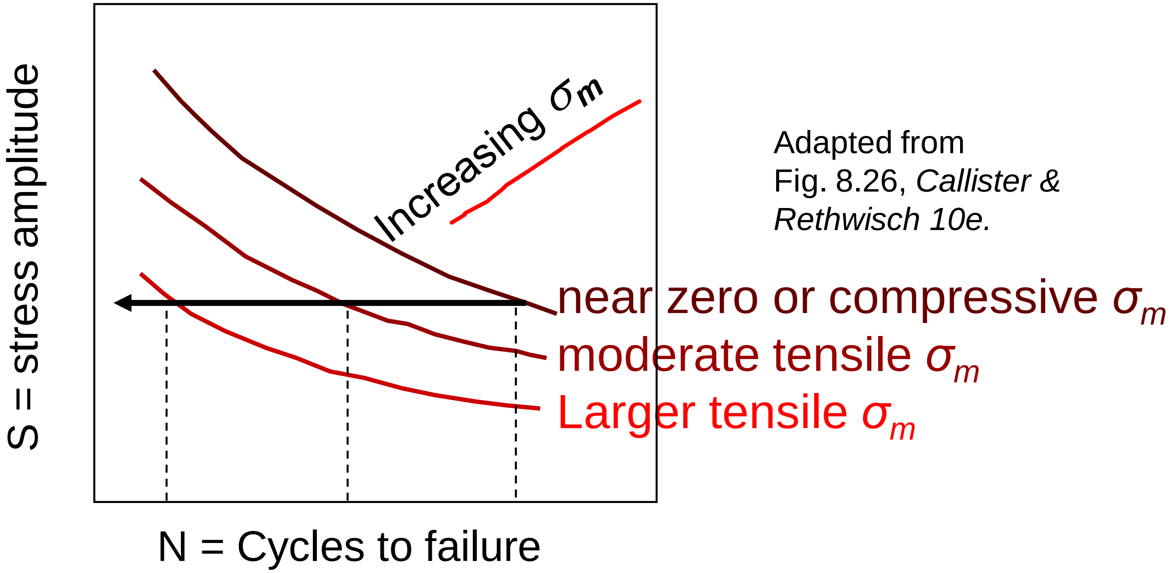


case for Al (typ.)

Adapted from Fig. 8.20(b), *Callister & Rethwisch 10e.*

Improving Fatigue Life

- Three general techniques to improve fatigue life
  1. Reducing magnitude of mean stress
  2. Surface treatments
  3. Design changes



Adapted from Fig. 8.26, *Callister & Rethwisch 10e.*

Decreasing mean stress increases fatigue life

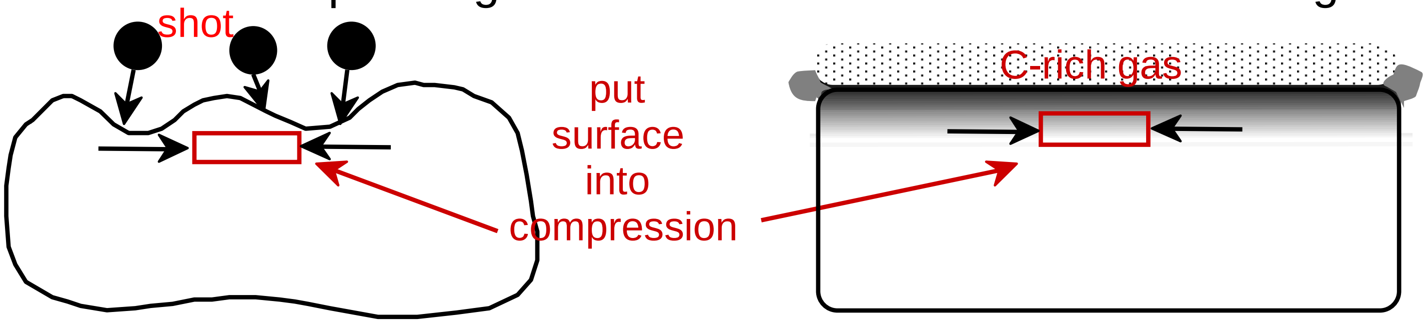
Improving Fatigue Life

- Three general techniques to improve fatigue life
  1. Reducing magnitude of mean stress
  2. Surface treatments
  3. Design changes

  Imposing compressive surface stresses increases surface hardness – suppresses surface cracks from growing

--Method 1: shot peening

--Method 2: carburizing



surface compressive stress due to plastic deformation of outer surface layer

surface compressive stress due to carbon atoms diffusing into outer surface layer

Improving Fatigue Life

- Three general techniques to improve fatigue life
  1. Reducing magnitude of mean stress
  2. Surface treatments
  3. Design changes

     Remove stress concentrators

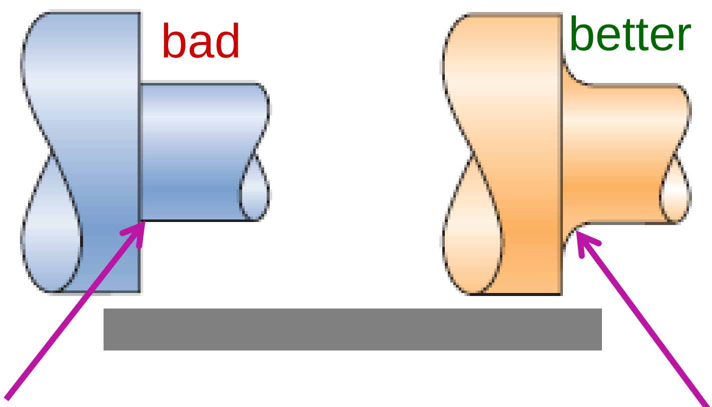


Fig. 8.27, *Callister & Rethwisch 10e.*

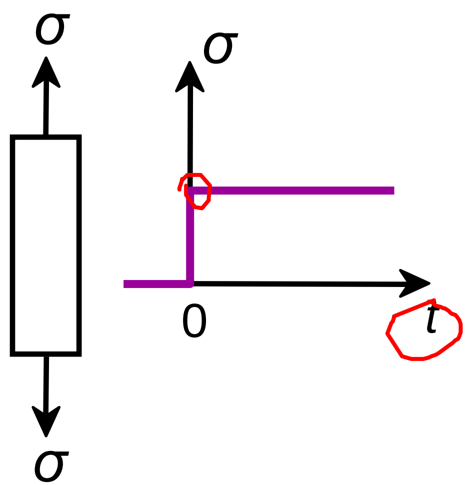
sharp corner – point of stress concentration

rounding corner reduces stress concentration

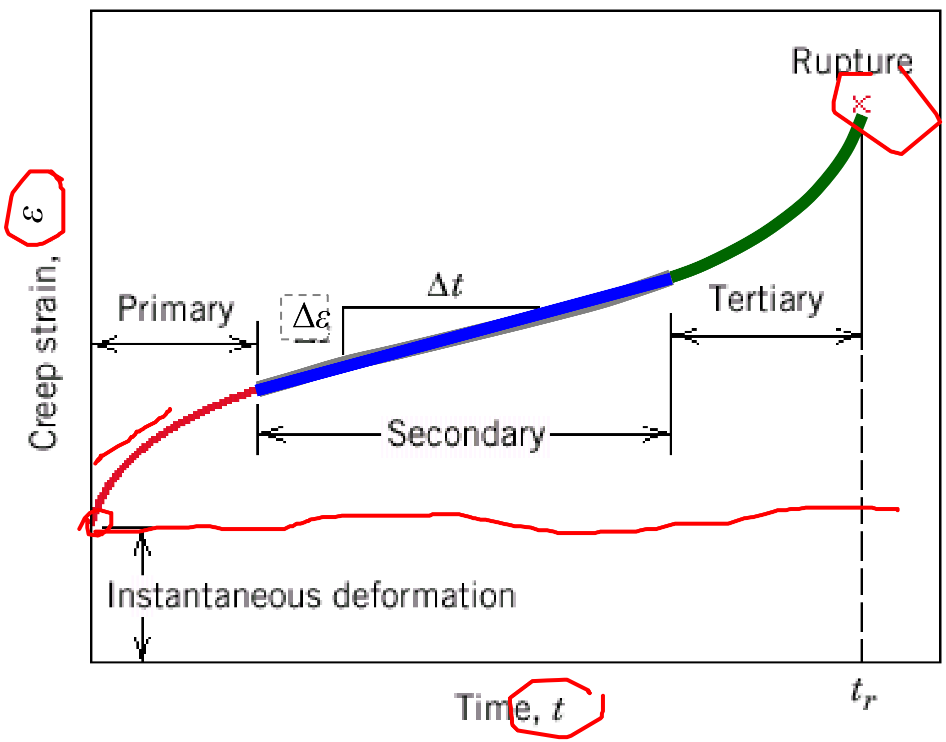
Creep

Creep

Measure deformation (strain) vs. time at constant stress



Occurs at elevated temperature for most metals, $T > 0.4\ T_m$ (in K)

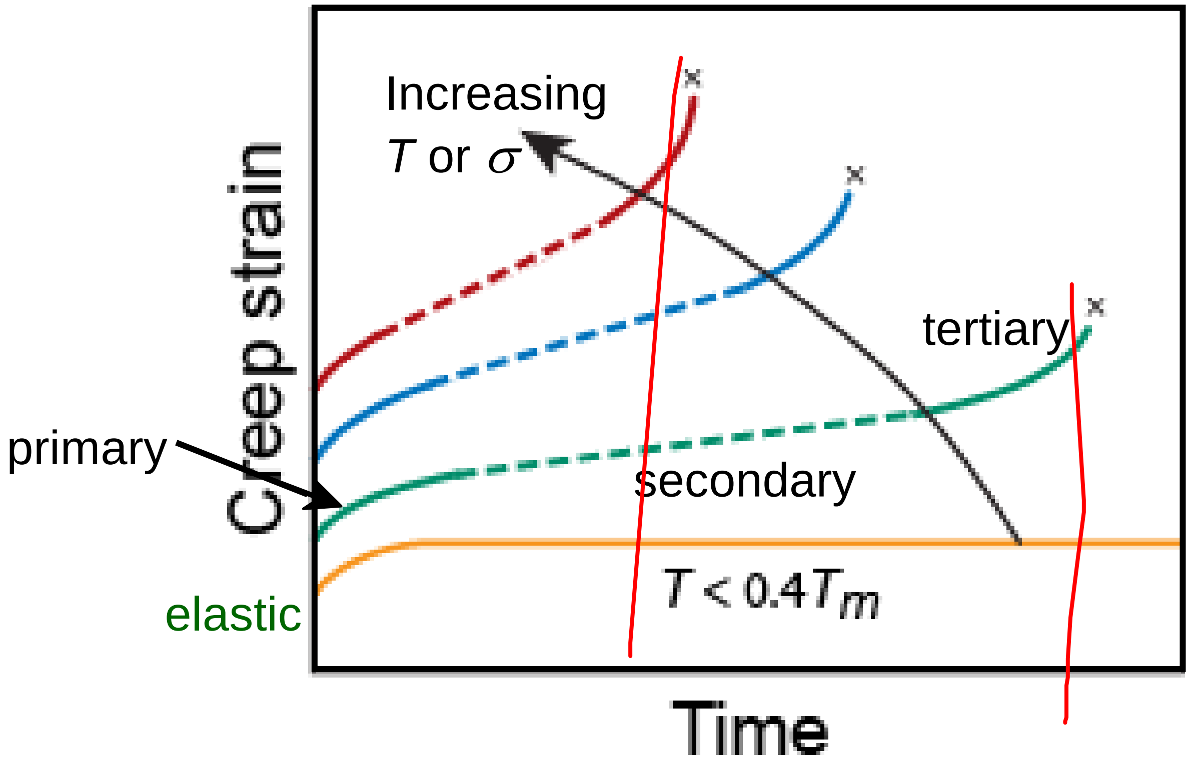


Adapted from Fig. 8.30, *Callister & Rethwisch 10e.*

Stages of Creep

- Primary Creep: slope (creep rate) decreases with time.
- Secondary Creep: steady-state i.e., constant slope ($\Delta\varepsilon / \Delta t$).
- Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

Creep: Temperature Dependence



Figs. 8.31, *Callister & Rethwisch 10e.*

- Steady-state creep rate ($\dot{\varepsilon}_s$) increases with increasing T and σ
- Rupture lifetime (t_r) decreases with increasing T and σ

Steady-State Creep Rate

- $\dot{\varepsilon}_s$ constant for constant T, σ
  -- strain hardening is balanced by recovery
  -- dependence of steady-state creep rate on T, σ

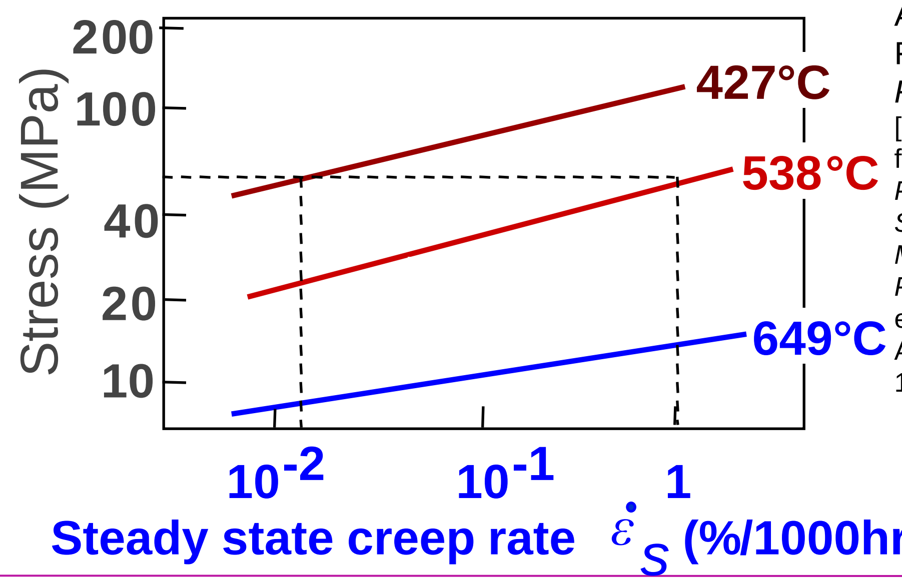
stress exponent (material parameter)

$$\dot{\varepsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

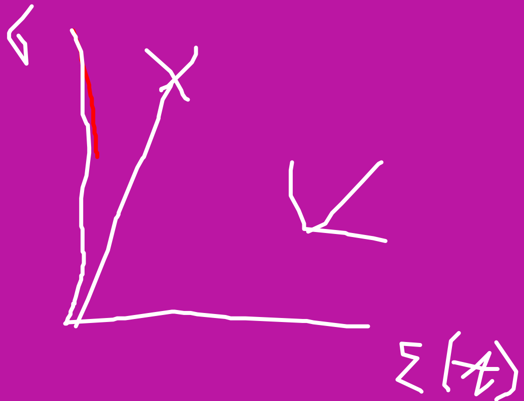
activation energy for creep (material parameter)

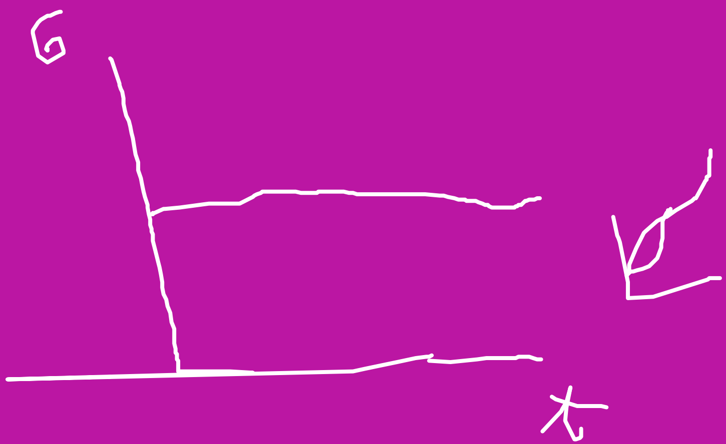
material const. applied stress

- Steady-state creep rate increases with increasing T, σ



Adapted from Fig. 8.31, *Callister & Rethwisch 7e.* [Reprinted with permission from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), ASM International, 1980, p. 131.]



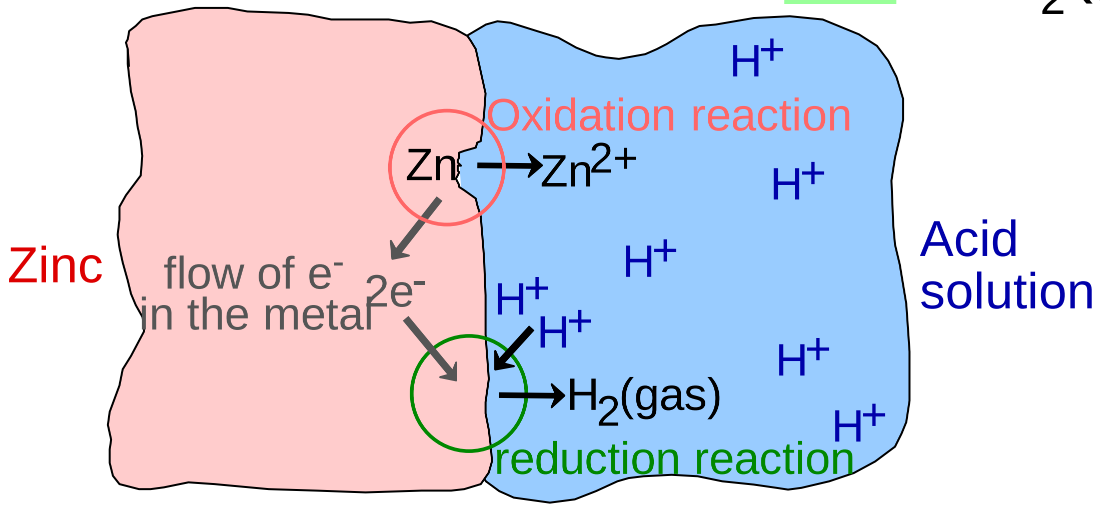


Corrosion

Electrochemical Corrosion

Ex: consider the corrosion of zinc in an acid solution

- Two reactions are necessary:
  - -- oxidation reaction: $Zn \rightarrow Zn^{2+} + 2e^-$
  - -- reduction reaction: $2H^+ + 2e^- \rightarrow H_2(gas)$

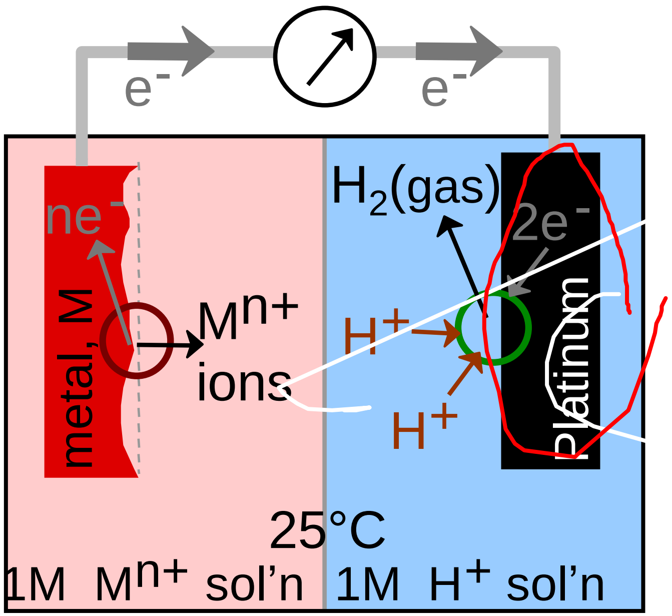


- Other reduction reactions in solutions with dissolved oxygen:
  - -- acidic solution: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
  - -- neutral or basic solution: $O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$

Standard Hydrogen Electrode

- Two outcomes:

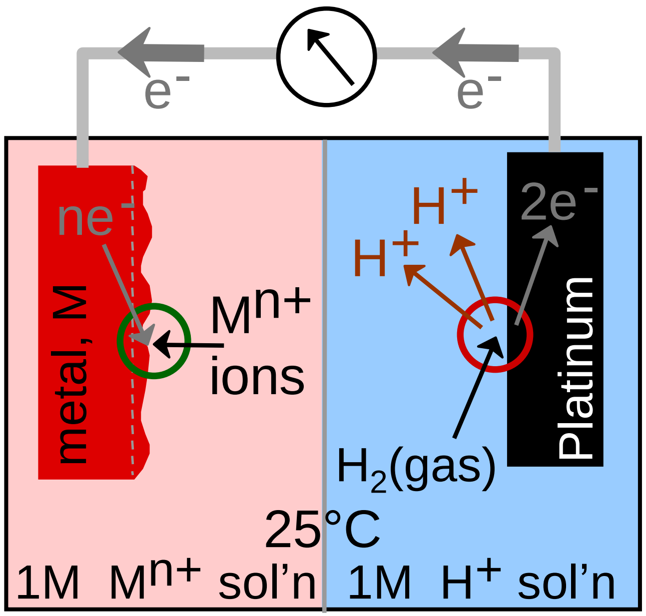
-- Corrosion



-- Metal is the anode (-)

$V^{o}_{metal} < 0$ (relative to Pt)

-- Electrodeposition



-- Metal is the cathode (+)

$V^{o}_{metal} > 0$ (relative to Pt)

Standard Electrode Potential

Standard EMF Series

- Electromotive force (EMF) series

metal	V^o_{metal}
Au	+1.420 V
Cu	+0.340
Pb	- 0.126
Sn	- 0.136
Ni	- 0.250
Co	- 0.277
Cd	- 0.403
Fe	- 0.440
Cr	- 0.744
Zn	- 0.763
Al	- 1.662
Mg	- 2.363
Na	- 2.714
K	- 2.924

more cathodic

more anodic

$\Delta V^o =$ 0.153V

Data based on Table 17.1, *Callister 10e*.

- Metal with smaller V^o_{metal} corrodes.
- Ex: Cd-Ni cell

$V^o_{Cd} < V^o_{Ni}$ $\therefore$ Cd corrodes

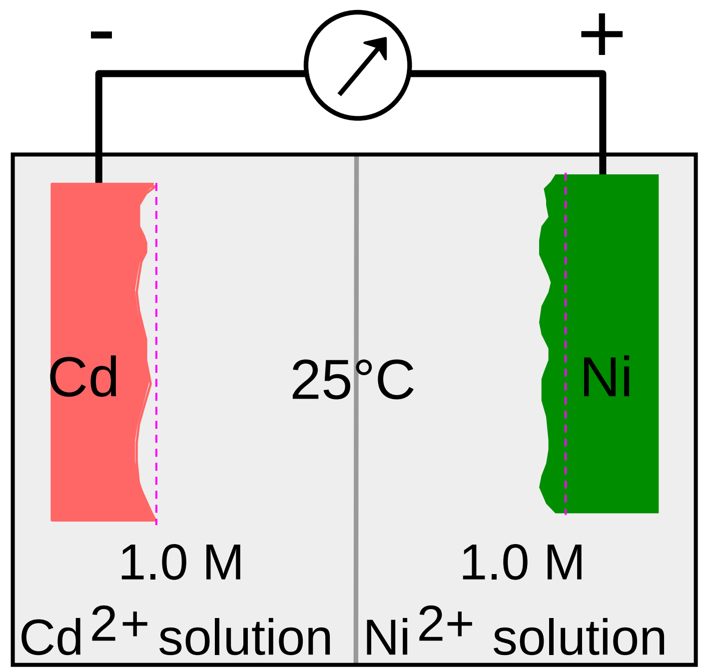
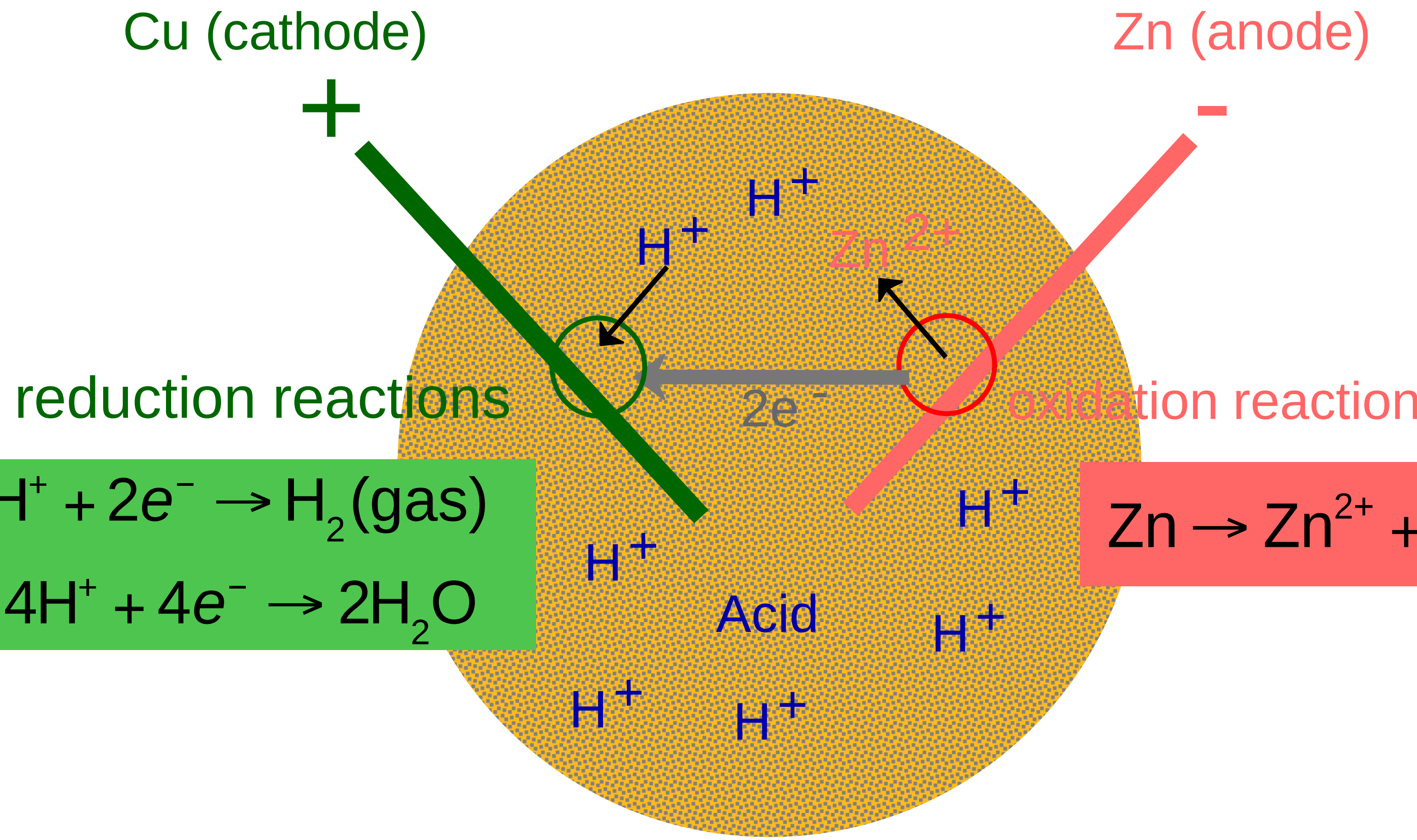


Fig. 17.2, *Callister & Rethwisch 10e*.

Corrosion In A Grapefruit



$$2H^+ + 2e^- \rightarrow H_2(gas)$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

$$Zn \rightarrow Zn^{2+} + 2e^-$$

Corrosion Prevention (I)

- Materials Selection

  -- Use metals that are relatively unreactive in the corrosion environment -- e.g., Ni in basic solutions

  -- Use metals that passivate

  - These metals form a thin, adhering oxide layer that slows corrosion.

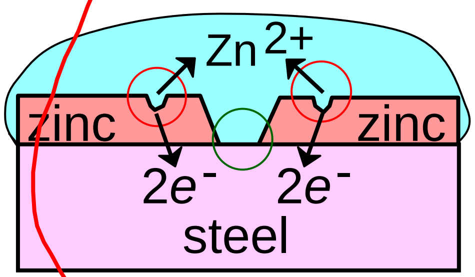
- Lower the temperature (reduces rates of oxidation and reduction)
- Apply physical barriers -- e.g., films and coatings

Corrosion Prevention (II)

- Add inhibitors (substances added to solution that decrease its reactivity)
  -- Slow oxidation/reduction reactions by removing reactants (e.g., remove O_2 gas by reacting it w/an inhibitor).
  -- Slow oxidation reaction by attaching species to the surface.

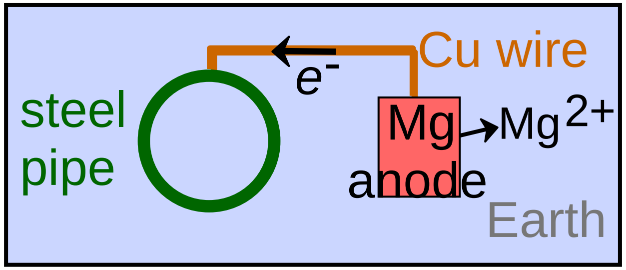
- Cathodic (or sacrificial) protection
  -- Attach a more anodic material to the one to be protected.

Galvanized Steel



e.g., zinc-coated nail

Using a sacrificial anode



e.g., Mg Anode

Summary

- **Ductile fracture** behavior
  - Ductile fracture is different from **damage**
  - The mechanism of ductile fracture is **void nucleation**, **growth**, and **coalescence**.
- **Damage mechanics models** are developed to quantify and predict ductile fracture.
- Ductile materials may experience brittle fracture – e.g. low temps. **Ductile to brittle transition** is measured by Charpy impact tests.
- **Fatigue** failure – at cyclic and repeated loading.
- **Creep** failure – at elevated temperatures and constant stress.
- **Corrosion** – metallic corrosion involves electrochemical reactions.

Mid-term Review

Course Grade

- 10 points for participation
  - 0.5 points x 12 **lectures/seminars**
  - 0.5 points x 6 **exercises**
  - 1 point for **forum** activities
- 40 points quality of tasks
  - (5-7) points x 6 weekly **assignments**
- 50 points on **exam**
- 10 points on **extra activities**
  - 5 points on a computational task (details given on MyCourses)
  - 5 points on an essay task (details given on MyCourses)

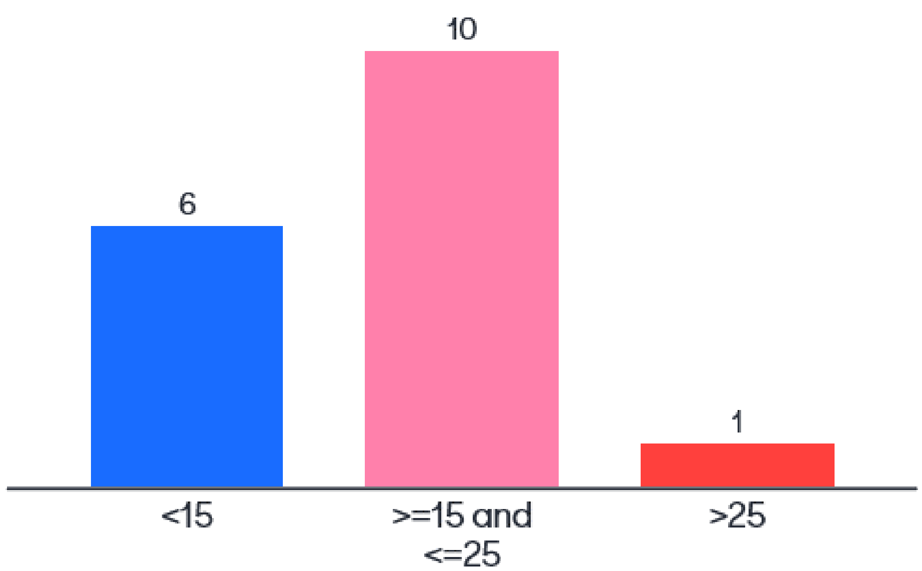
Total	Grade
≥90	5
≥80	4
≥70	3
≥60	2
≥50	1
<50	0

Course feedback

Go to **www.menti.com** and use the code **9345 3415**

Mentimeter

How many hours did you spend on the studying and working on assignmens?



Course feedback

Go to **www.menti.com** and use the code **9345 3415**

Mentimeter

How do you feel like the course? Use three adjectives to describe.

12

Announcements

Reading: Textbook **Ch. 8, 17**

Assignment: Open; DL: **18:00 Sunday**

Q&A time: **Tuesday 16:30**

Exercise: **Thursday 10:15 – 12:00**

Preparation of your computational environment is needed before the exercise sessions.

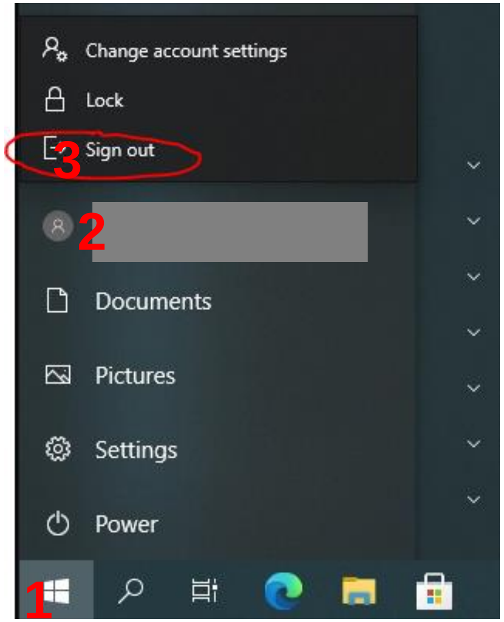
Software preparation

Input data download: 'E3flowcurve.txt' on MyCourses

Abaqus: free student version (https://edu.3ds.com/en/software/abaqus-student-edition)

Aalto VDI system: **mfavdi.aalto.fi**, or VMware Horizon Client **vdi.aalto.fi**, for more information, please refer to [Remote access to Windows classroom computers](#).

IMPORTANT! Please remember to do '**Sign Out**' after the session (NOT Disconnect). Click your username in Start and click 'Sign Out'.

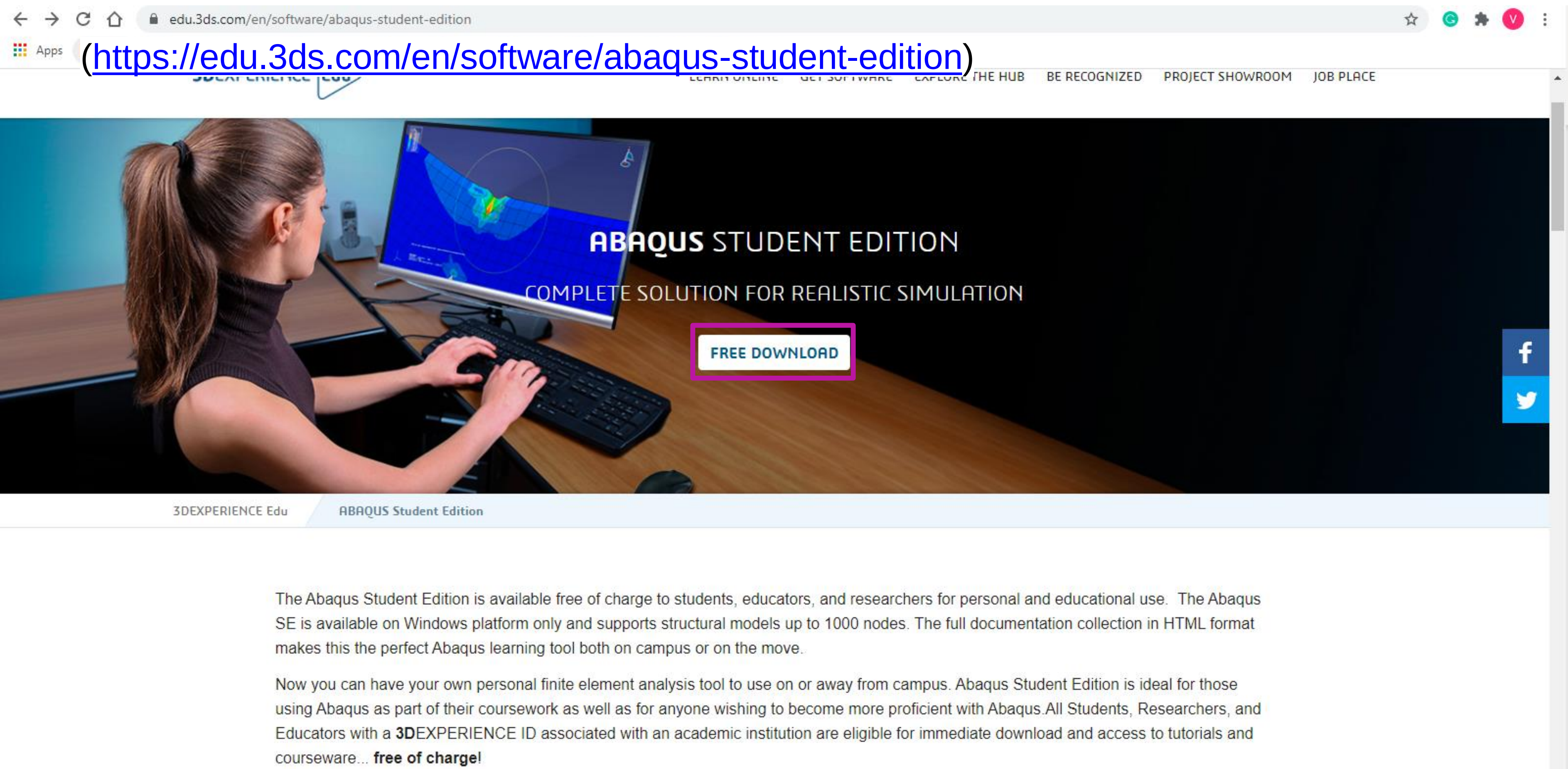


Basic Rule: Please use DOT as the decimal separator, **NO COMMA!**
Contribution from Mr Binh Nguyen: For those who use win 10, go to control panel > region > additional settings > choose dot . as decimal separator.

The Abaqus student version has been installed in the VDI windows 10 3D, but it would be too slow if too many people are using VDI at the same time. You can also install the software on your own computer.
Make sure that you have downloaded the data file 'E3flowcurve.txt' from MyCourses.

Abaqus student version installation

(https://edu.3ds.com/en/software/abaqus-student-edition)



Abaqus student version installation

3DEXPERIENCE Edu

(https://edu.3ds.com/en/software/abaqus-student-edition)

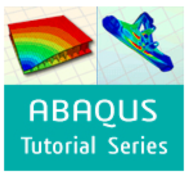
ABAQUS Install instructions

PDF 1.26 MB

Abaqus 2020 Student Edition Installation Instructions & known issues

Download

Install Abaqus according to the 'Install instructions', if you have questions, contact Abaqus service or Aalto IT.



ABAQUS Tutorials

To get started, ABAQUS Tutorials are available here

See more

Tutorials

Learning Ressources

Tutorials and learning resources for Abaqus and other SIMULIA products are available at the

> SIMULIA Learning Community

Contact Abaqus for download problem

Download Issues

For download issues only (no other support for Abaqus), please contact us here

System requirements

ABAQUS Student Edition is not available on 32bits configurations

Note: The Microsoft Visual C++ 2010 SP1 Redistributable Package (x64) is required for successful execution of the Abaqus Student Editions.

▶ Abaqus Student Edition 2020 (latest release): This version installs this package automatically and no additional steps are required.

▶ Abaqus Student Edition 2019: This release does not install this package automatically, and the user must download and install the Microsoft Visual C++ 2010 SP1 Redistributable Package (x64) using this link: https://www.microsoft.com/en-us/download/details.aspx?id=13523. Failure to install this package will produce the following fatal runtime error with

Questions?