Metals and Cheeses: Unconventional Pairings

Lecture 8
22.033/22.33 – Nuclear Engineering Design Project
Nov. 21, 2011

What's the Deal?

Many of you are using metals in your designs

- Some are at very high temperatures
- Some are at very high stresses

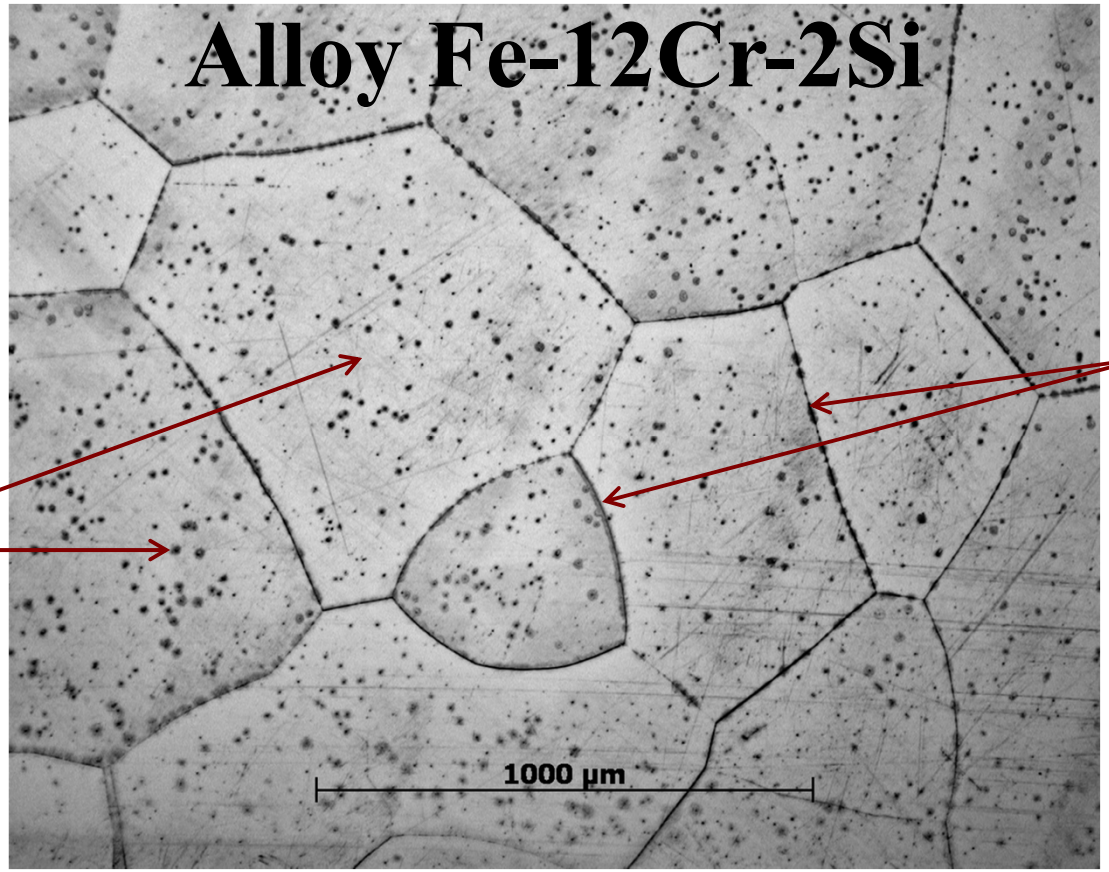
Understanding the structure and failure of metals is key to a successful design

Many concepts are hard to grasp, at first

- Hopefully this class will help you to remember them with cheese pairings

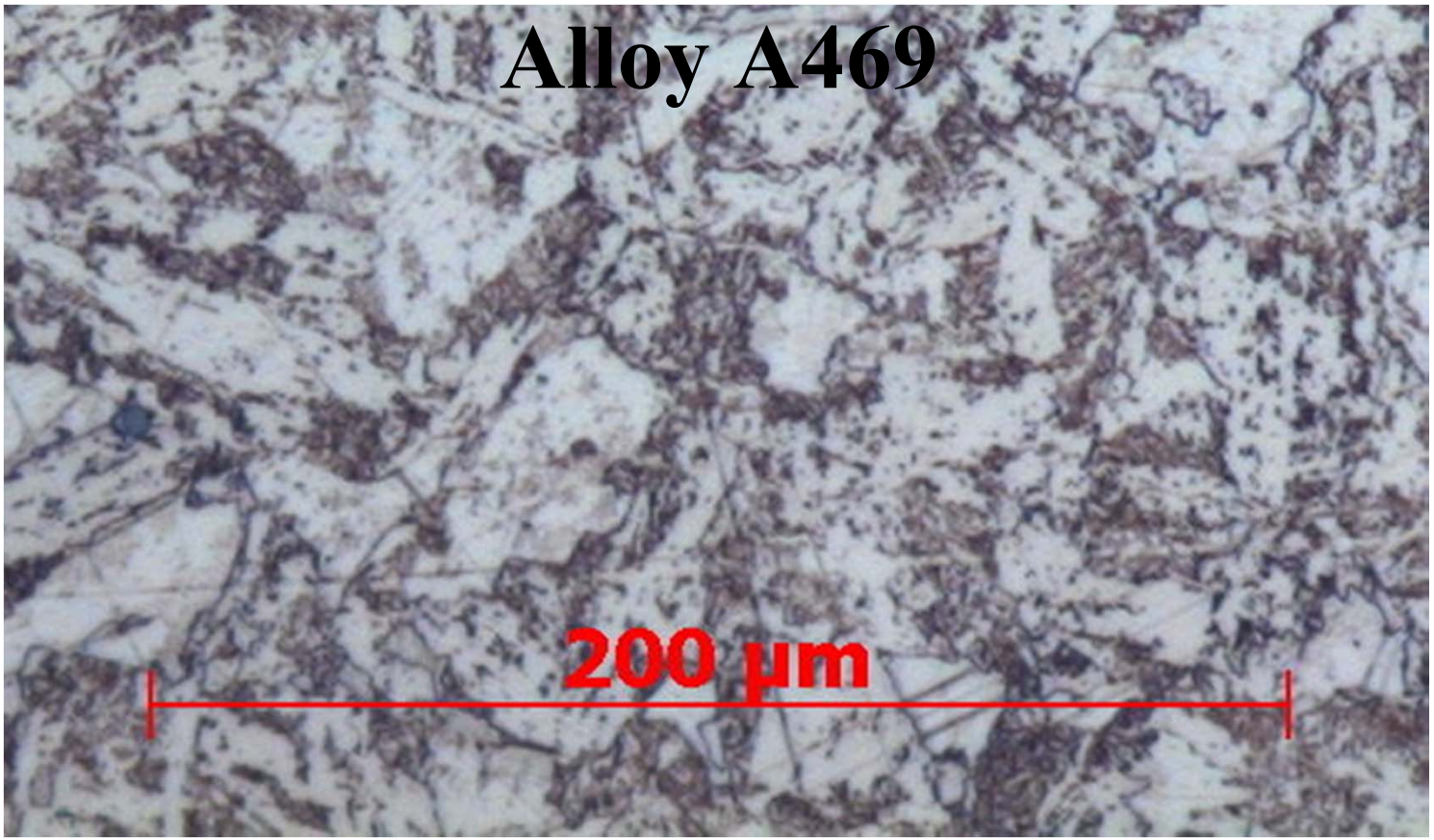
Metallic Crystal Structures

Cabot Clothbound Cheddar (Greensboro, VT, USA)



Grains: More Examples

Cabot Clothbound Cheddar (Greensboro, VT, USA)

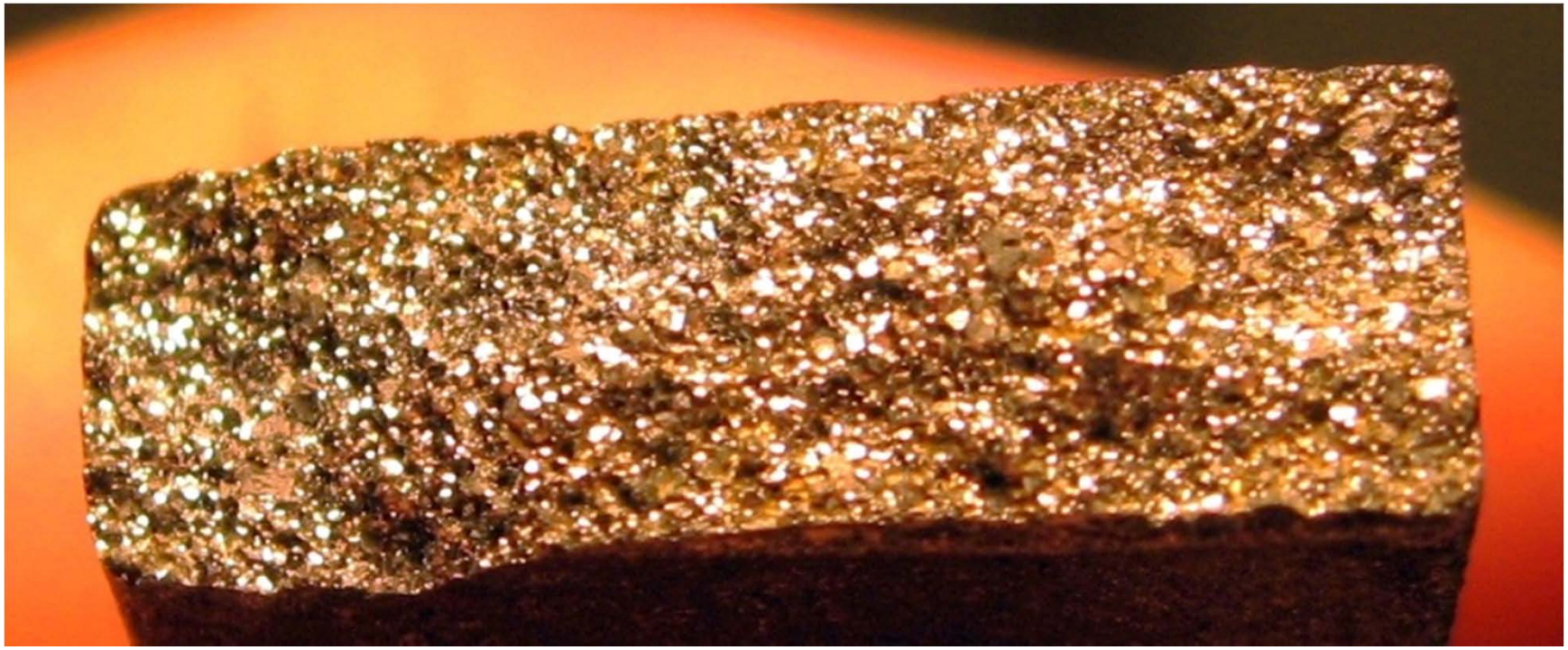


Grains: More Examples

Cabot Clothbound Cheddar (Greensboro, VT, USA)

Intergranular (IG) Fracture

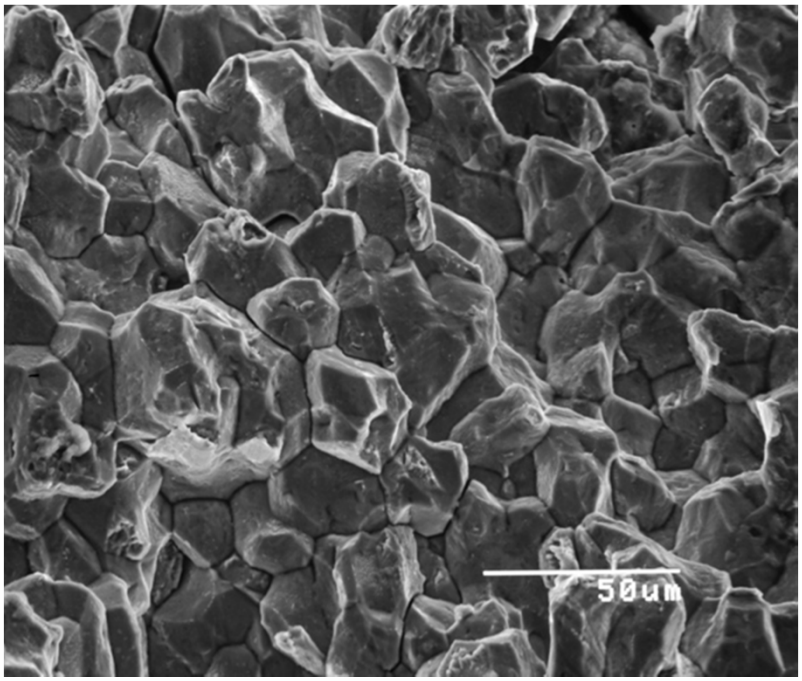
Cabot Clothbound Cheddar (Greensboro, VT, USA)



W1 tool steel, after quenching and breaking in a vise

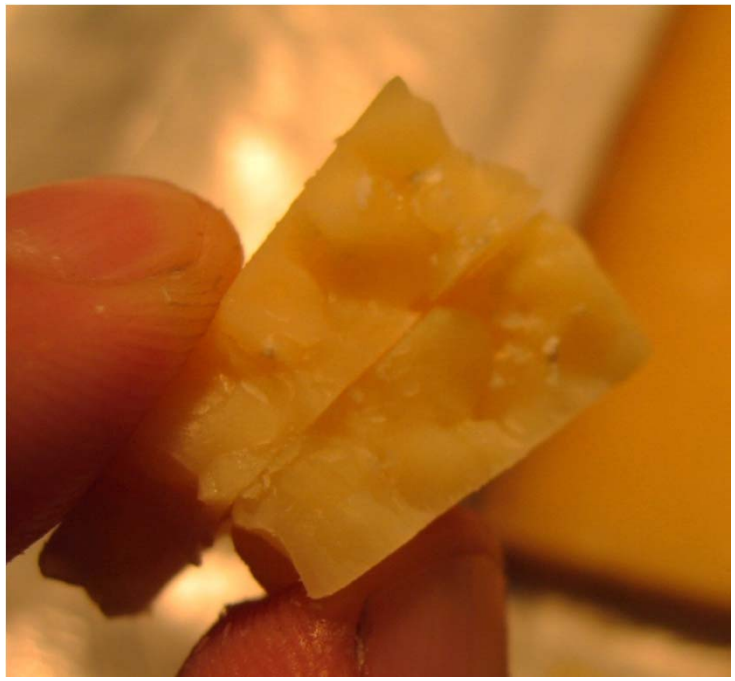
IG Fracture Side by Side

Cabot Clothbound Cheddar (Greensboro, VT, USA)



Courtesy of Christensen Materials Engineering. Used with permission.

IG fracture of sensitized 304 stainless steel
http://site.christensenmaterials.com/Services.html



IG fracture of Cabot cheddar cheese, showing matching fracture surfaces

Supersaturation, Precipitation

Comté Le Fort (Jura, France)

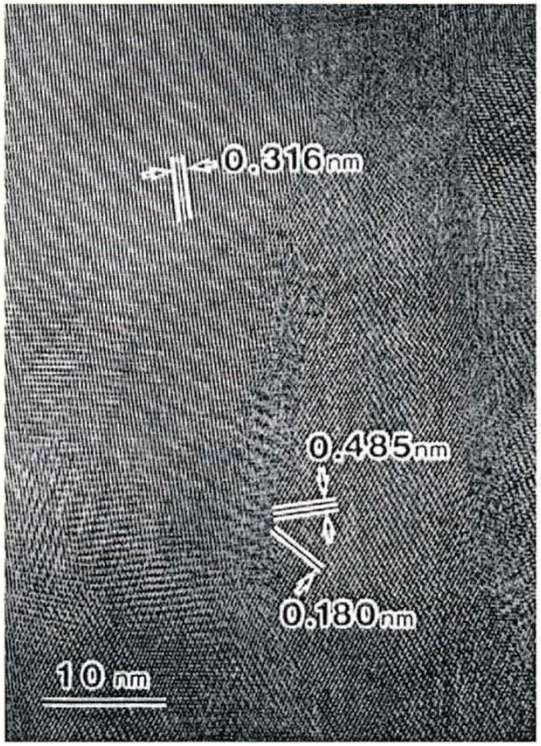
Especially relevant for Zircaloy fuel cladding

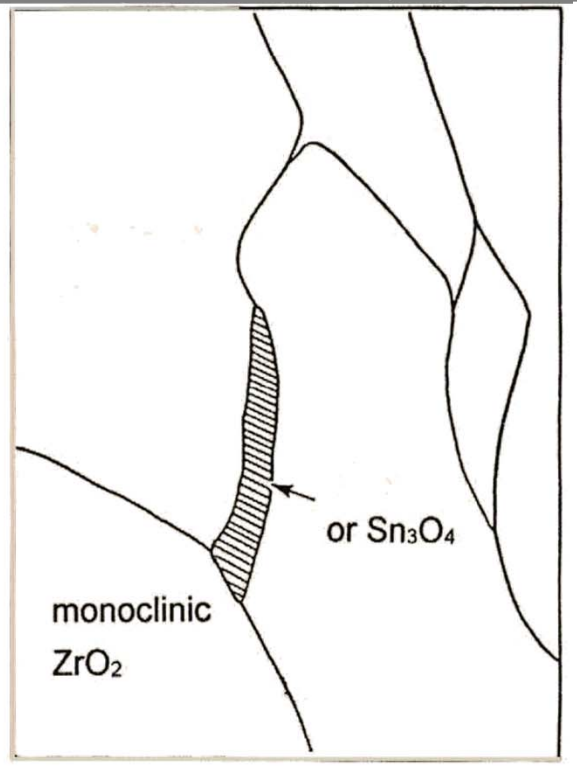
- Zircaloy is Zr with minor additions
  - Sn, Sb, Fe
- These form *secondary particle precipitates* (SPPs)
  - SPPs can guard against corrosion
- Dissolved elements increase strength

Comté cheese has lactic acid SPPs

Precipitation of SPPs

Comté Le Fort (Jura, France)





TEM image of tin oxide SPP in Zircaloy after oxidation

R. Adamson, F. Garzarolli, B. Cox, A. Strasser, P. Rudling. "Corrosion Mechanisms in Zirconium Alloys." IZNA7, Special Topic Report, ANT International, Skultuna, Sweden, 2007.

Phase Precipitation Side by Side

Comté Le Fort (Jura, France)

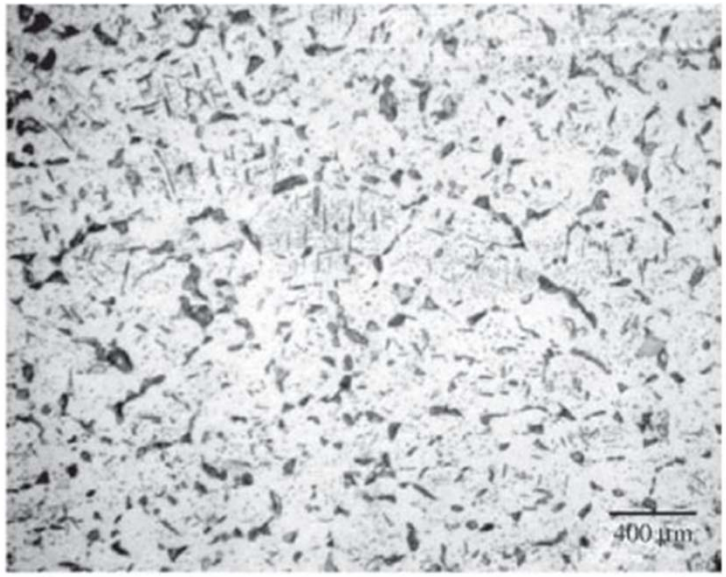


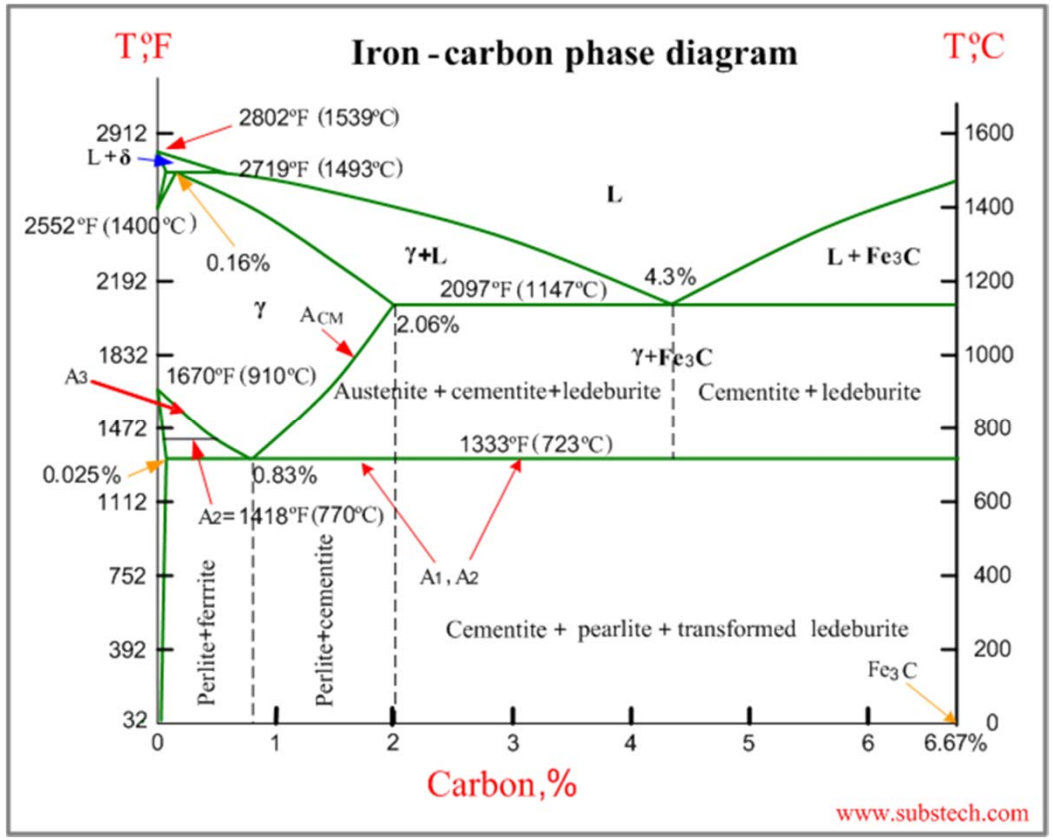
Figure 4. Grain boundary and intragranular precipitation at the hot side of the hot gas casing of a gas turbine. Material: 321 stainless steel. Etched successively in Vilella's reagent, methanolic aqua regia, and Groesbeck's reagent to darken carbides.

Source: H. C. Furtado, I. L. May. "High temperature degradation in power plants and refineries." *Materials Research* 7, no. 1.1 (2004): 103-110. License CC BY-NC

Lactic acid SPPs on the cut surface of Comté cheese

Phase Precipitation in Steel

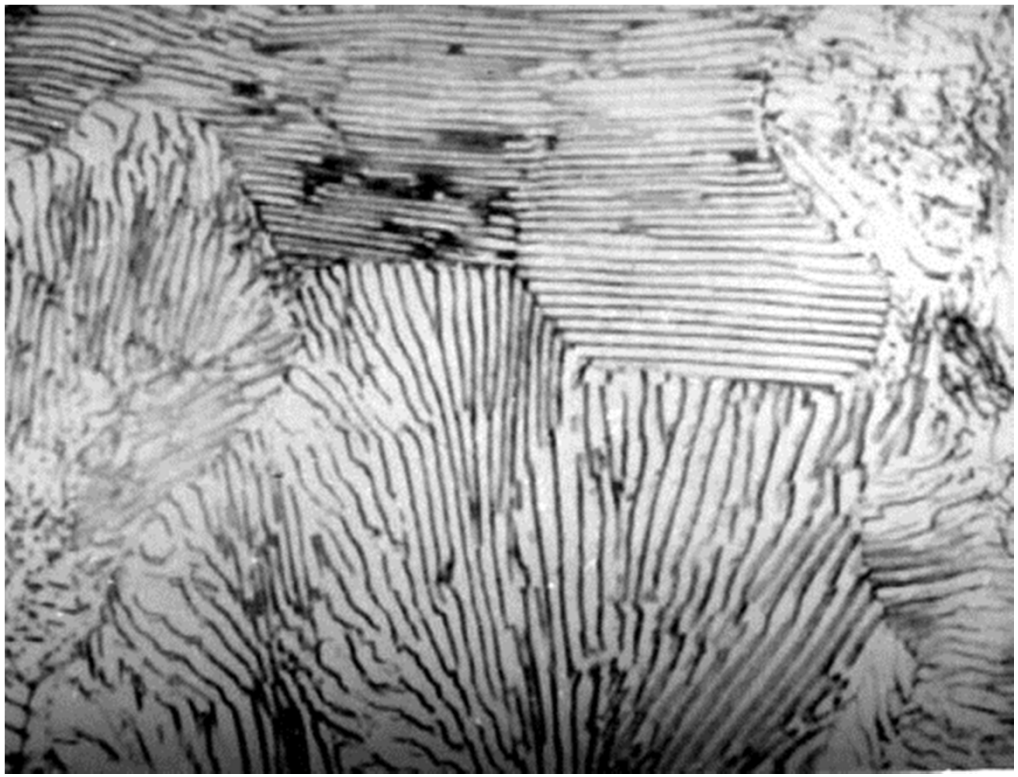
Comté Le Fort (Jura, France)



Courtesy of Dimitri Kopeliovich. Source: Kopeliovich, D. "Iron-carbon phase diagram." SubsTech.

Phase Precipitation in Steel

Comté Le Fort (Jura, France)



Pearlite forms when dissolved carbon in austenite precipitates out

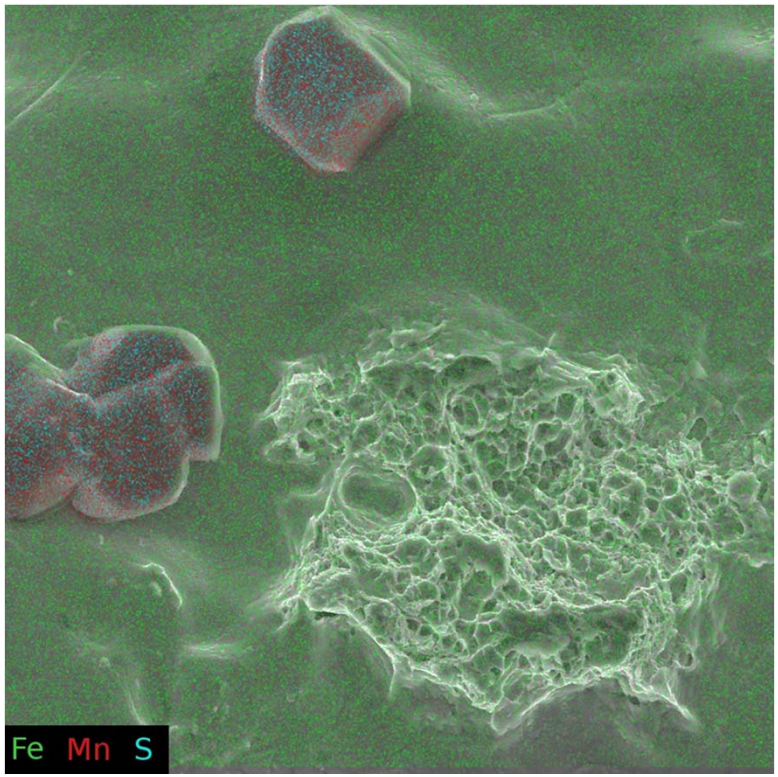
Two phases: ferrite (mostly Fe, light) and cementite (Fe_3C, dark)

Note how grains of pearlite are still aligned

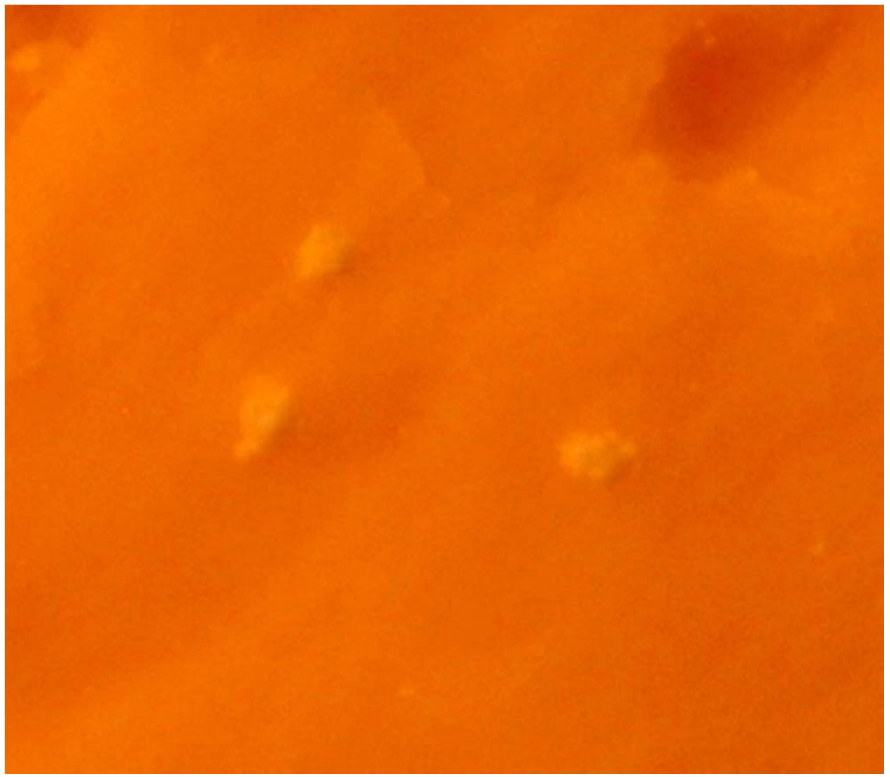
http://hsc.csu.edu.au/engineering_studies/application/civil/1-1/answers.html

SPPs and Fracture Surfaces

Comté Le Fort (Jura, France)



MnS particles on the fracture surface of alloy A469 from Alcator C-Mod



Lactic acid SPPs on the fracture surface of Comté cheese

Creep Lifetime and Failure

Brebis Abbaye de Belloc (Aquitaine, France)

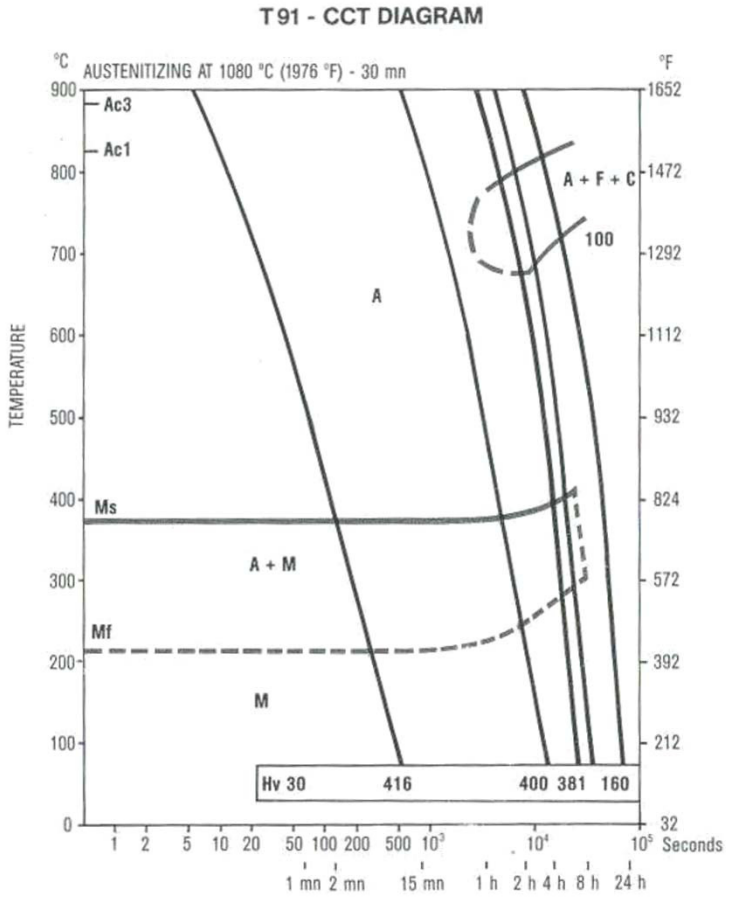
Metals can deform under a static (constant) load well below their rated failure strengths

- This is called *creep*
- Proceeds via a number of mechanisms
  - Most involve vacancy or dislocation mvmt.
- Generally speeds up with temperature

Creep lifetime can limit reactor performance

Creep Lifetime and Failure

Brebis Abbaye de Belloc (Aquitaine, France)



T91 requires a delicate balance between creep lifetime (harder is better) and toughness (softer is better)

The precise heat treatment is key to dialing in T91's properties

Deviations can be disastrous!

G. Guntz, M. Julien, G. Kottmann, F. Pellicani, A. Pouilly, and J. C. Vaillant. The T91 Book. Vallourec Industries, France, 1990.

Creep Lifetime and Failure

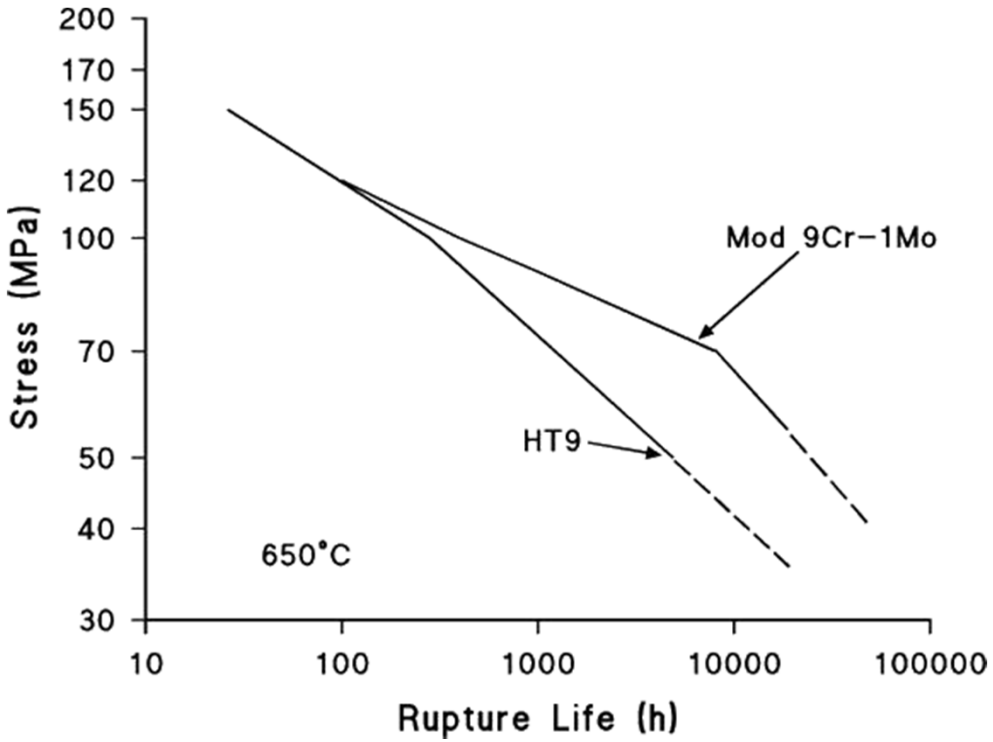
Brebis Abbaye de Belloc (Aquitaine, France)

Creep failure in T91 pipe due to prolonged heat treatment and oversoftening

R. Swanekamp. Handling Nine-Chrome Steel in HRSGs. Power Engineering, Vol 100:2, 2006.

Creep Lifetime Can Limit LFRs

Brebis Abbaye de Belloc (Aquitaine, France)

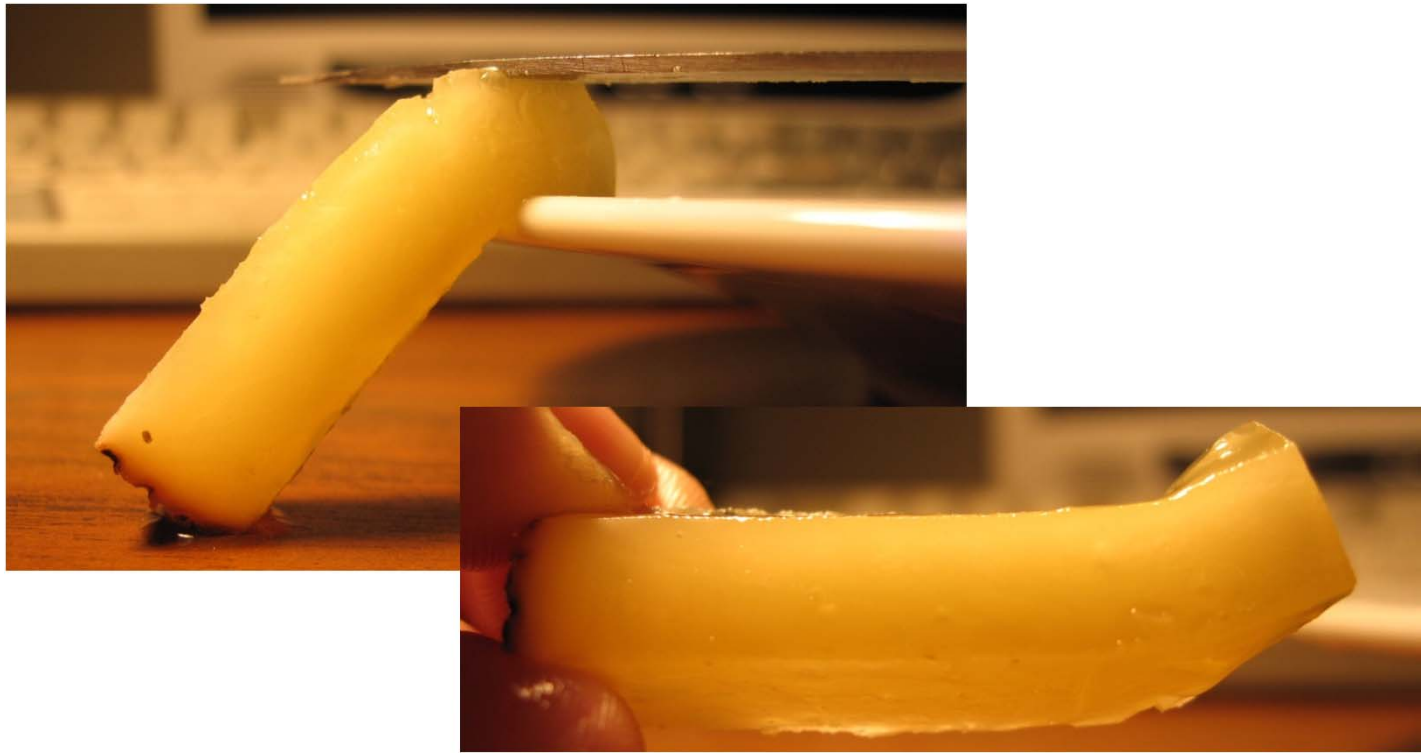


Creep rupture lifetimes of HT9 and T91 steels at 650 Celsius

R.L. Klueh and A.T. Nelson. Ferritic/martensitic steels for next-generation reactors. Journal of Nuclear Materials, 371(1-3):3752, September 2007.

Creep Lifetime and Failure

Brebis Abbaye de Belloc (Aquitaine, France)



Creep deformation of Abbaye de Belloc under static gravity load at room temperature

Defects and Stress Concentration

Sottocenere al Tartufo (Lombardy, Italy)

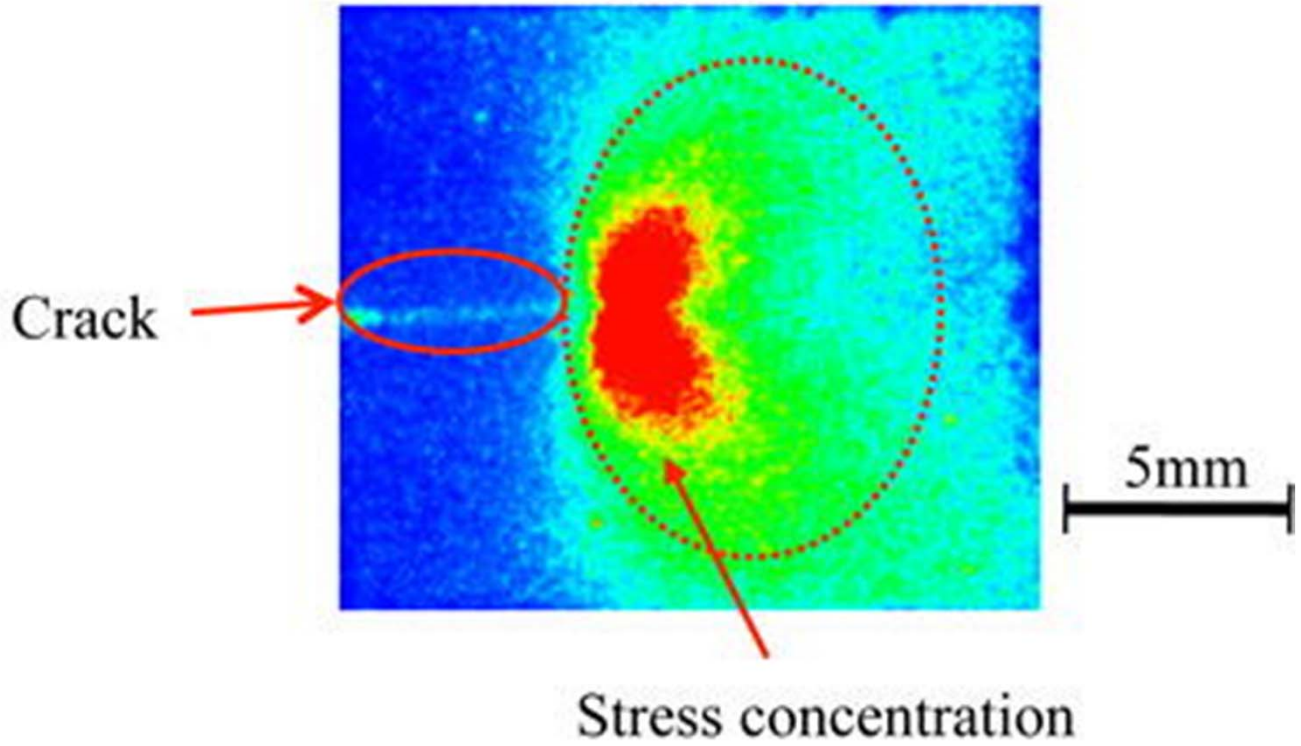
Defects (voids, inclusions, cracks, scratches) locally increase stresses in materials

- Dependent on the **geometry**, NOT the total size
- Proportional to the *ratio* of the major & minor flaw axes, or the *radius of curvature* of a flaw tip

The sharper the flaw, the worse it is!

Crack Stress Concentration Map

Sottocenere al Tartufo (Lombardy, Italy)



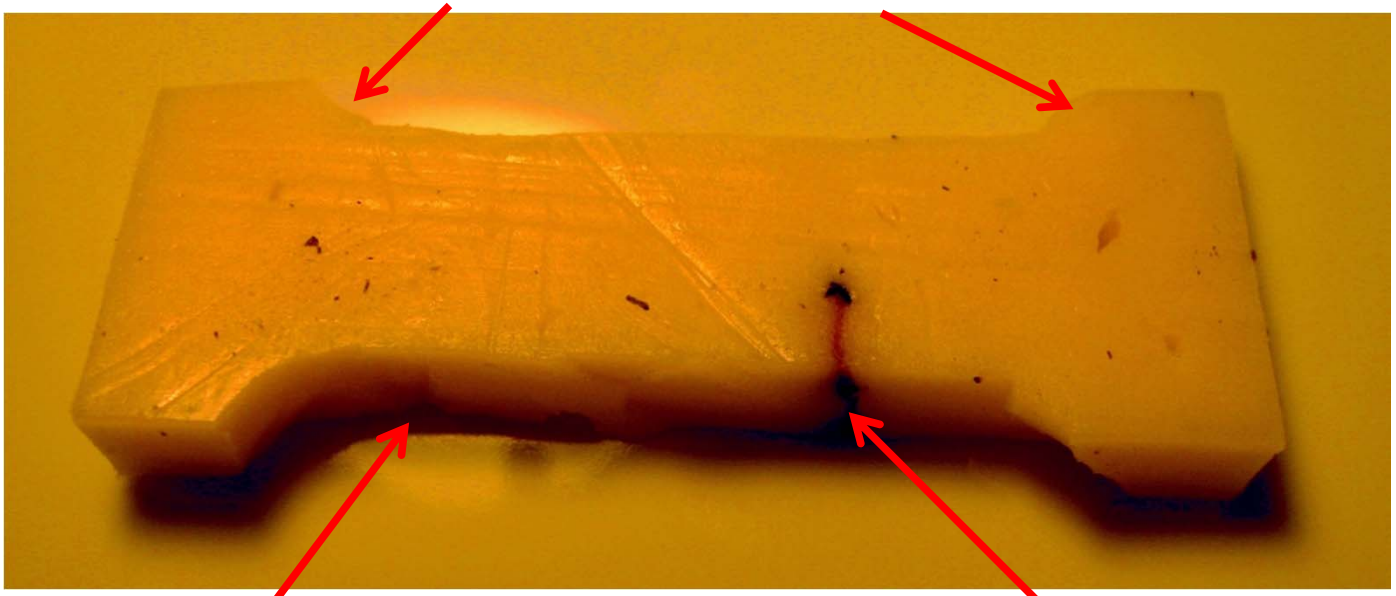
Stress concentration map near a crack tip using elasto-luminescent coating

AIST. Diagnosing damages in structures and their danger level at the same time using elastico-luminescent materials. Accessed at http://www.aist.go.jp/aist_e/latest_research/2009/20090107/20090107.html.

Uniaxial Tensile Cheese Specimen

Sottocenere al Tartufo (Lombardy, Italy)

Rounded corners to avoid other stress concentrators



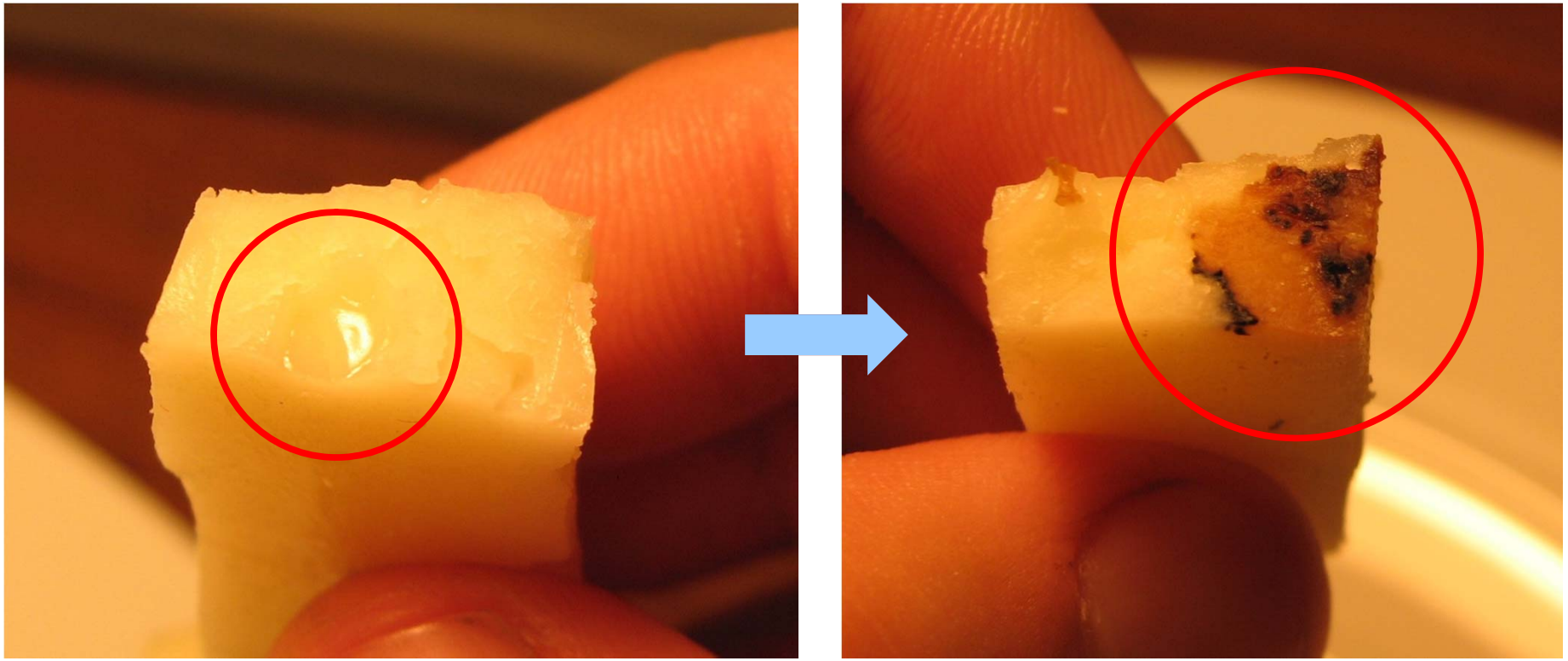
Void (gas bubble)

Inclusion (truffle)

Uniaxial tensile specimen fabricated from Sottocenere al Tartufo

Cheese Fracture Surface

Sottocenere al Tartufo (Lombardy, Italy)

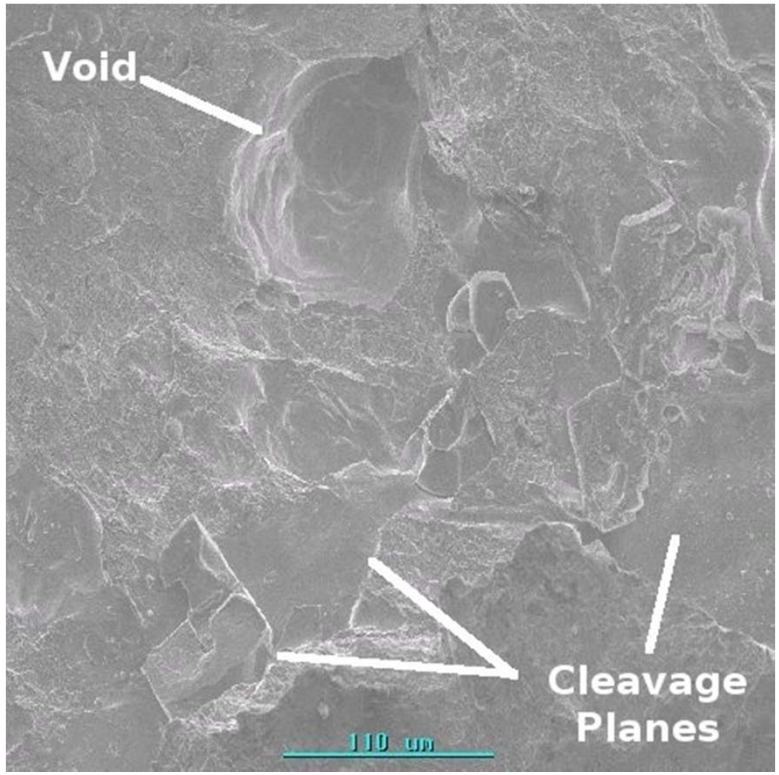


Fracture occurred in plane with the void

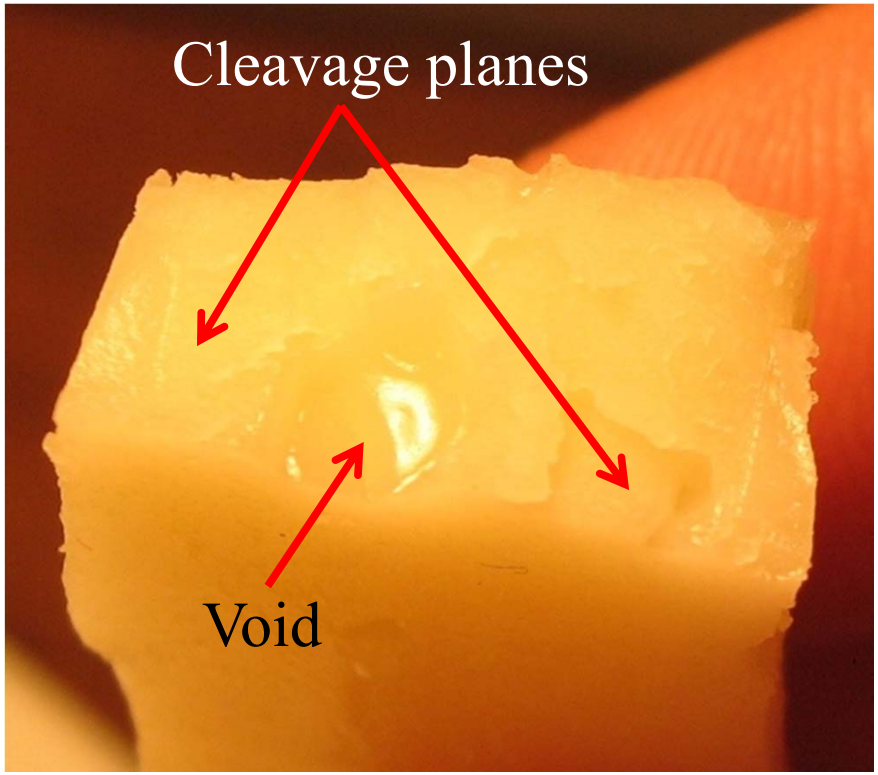
Further testing fractured on the inclusion

Fracture Surfaces Side by Side

Sottocenere al Tartufo (Lombardy, Italy)



Void-induced fracture in A469



Void-induced fracture in Sottocenere

Sensitization, IG Corrosion

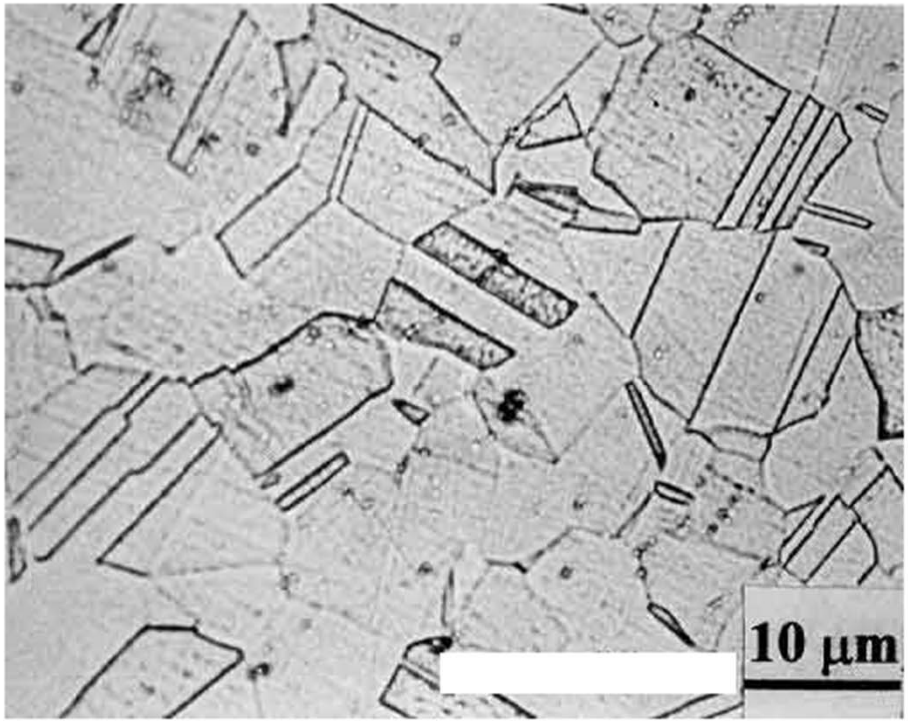
Queso Azul de Valdeon (Valdeon, Spain)

Various things can cause grain boundaries to become weak and susceptible to attack

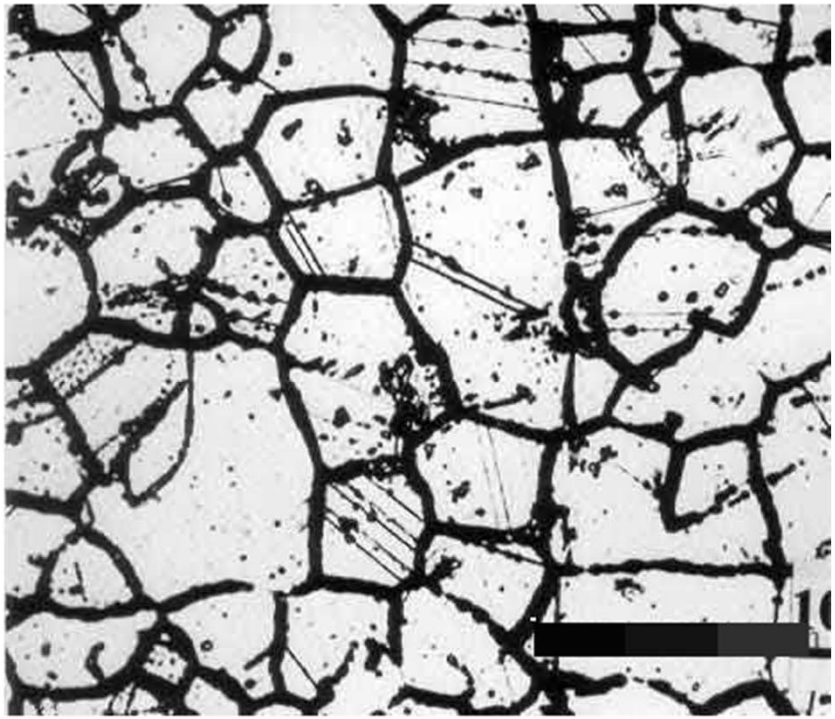
- Heating stainless steel between 400-850 Celsius causes Cr-carbides to grow on grain boundaries
  - Depletes Cr from the surrounding matrix
- Radiation, heat can cause Cr segregation away from grain boundaries (Alloy 600)

Sensitization of Stainless Steels

Queso Azul de Valdeon (Valdeon, Spain)



Unsensitized structure for 304 stainless steel

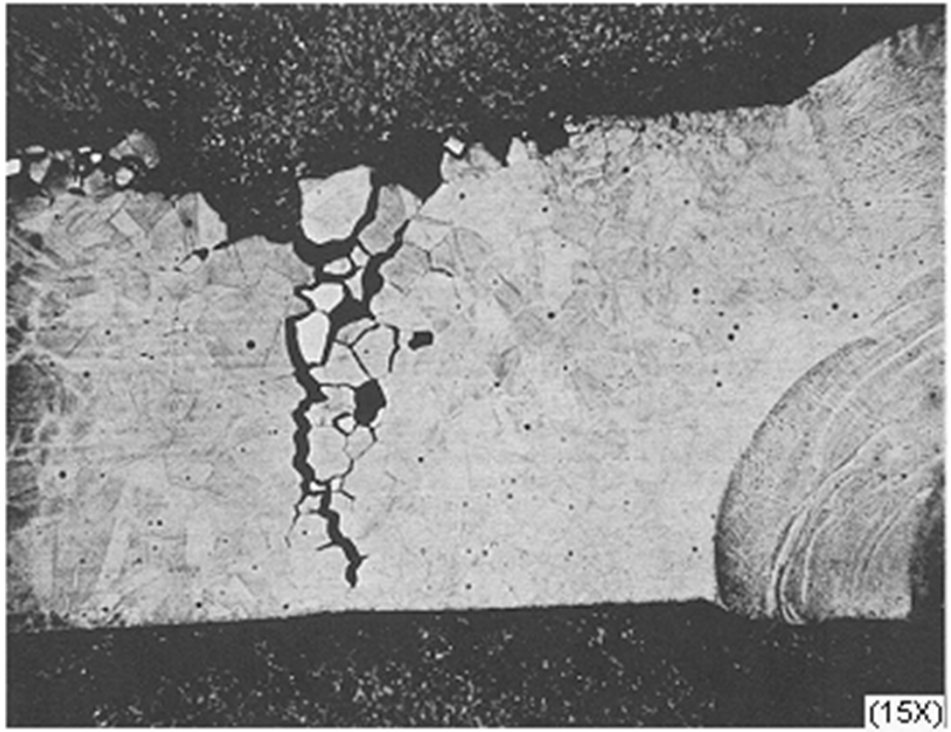


Sensitized structure of 304 stainless steel

Image source: http://www.solidmetals.net/2011/05/02/sensitization-of-stainless-steel/

Sensitization of Alloy 600

Queso Azul de Valdeon (Valdeon, Spain)



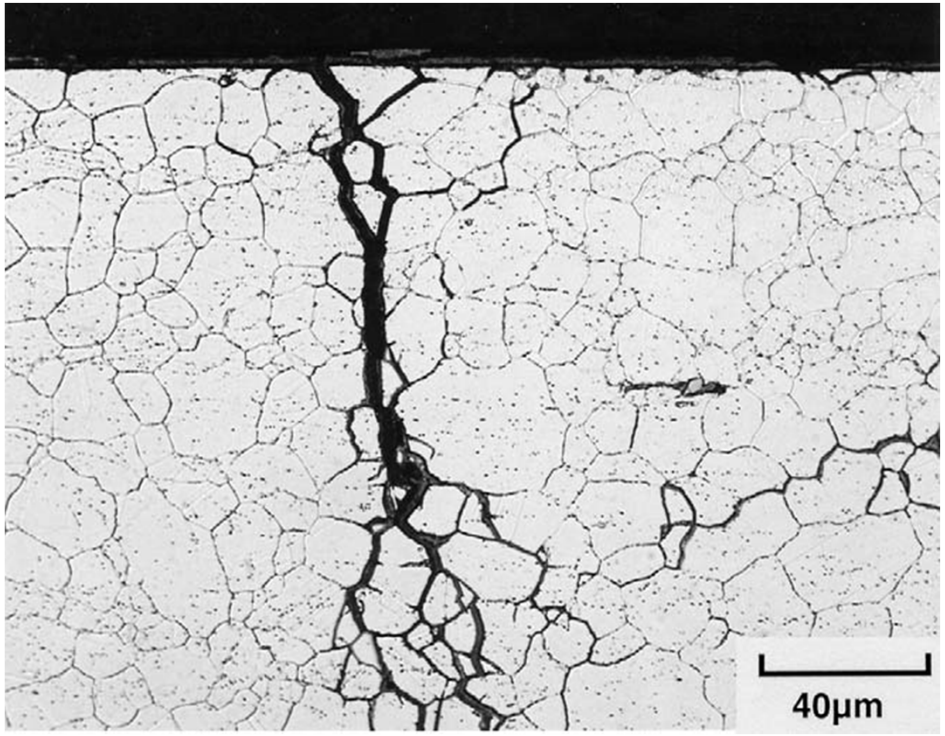
Courtesy of Materials Technology Institute. Used with permission.

Corrosion and cracking of sensitized Alloy 600 piping in sour water service containing H_2S and cyanides, due to the formation of a low-melting nickel-sulfide eutectic during welding

Image source: http://sirius.mtm.kuleuven.be/Research/corr-o-scope/hcindex2/sulfur.htm

IGSCC of Alloy 600TT

Queso Azul de Valdeon (Valdeon, Spain)



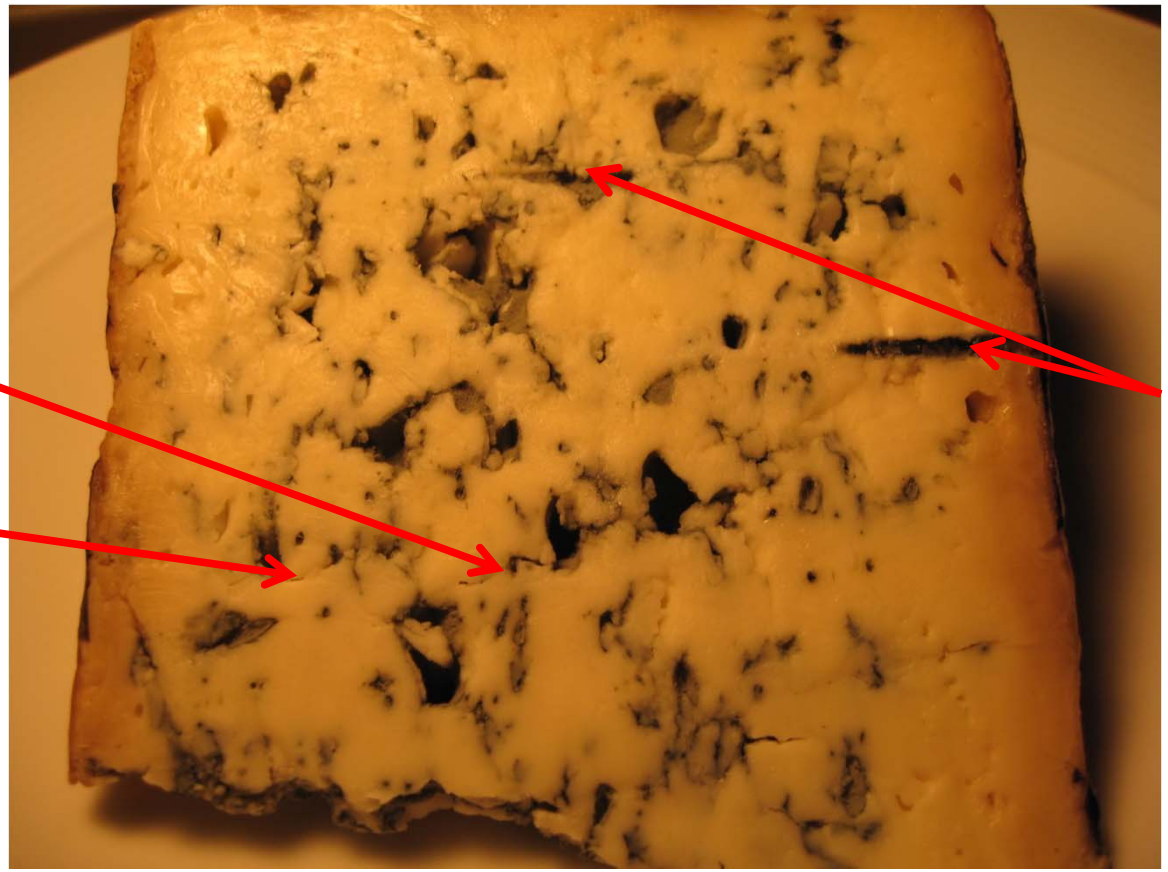
IGSCC in Alloy 600TT tested at open circuit with solution containing 500 ppm Pb, 500X

J. Lumsden, A. McIlree, R. Eaker, R. Thompson, S. Slosnerick. "Effects of Pb on SCC of Alloy 600 and Alloy 690 in Prototypical Steam Generator Chemistries." 12th Env. Deg. Mat. Conf., TMS, 2005.

The Structure of Blue Cheese

Queso Azul de Valdeon (Valdeon, Spain)

Mold attacks the intercurd (IC) regions of the cheese



Piercings to allow oxygen ingress

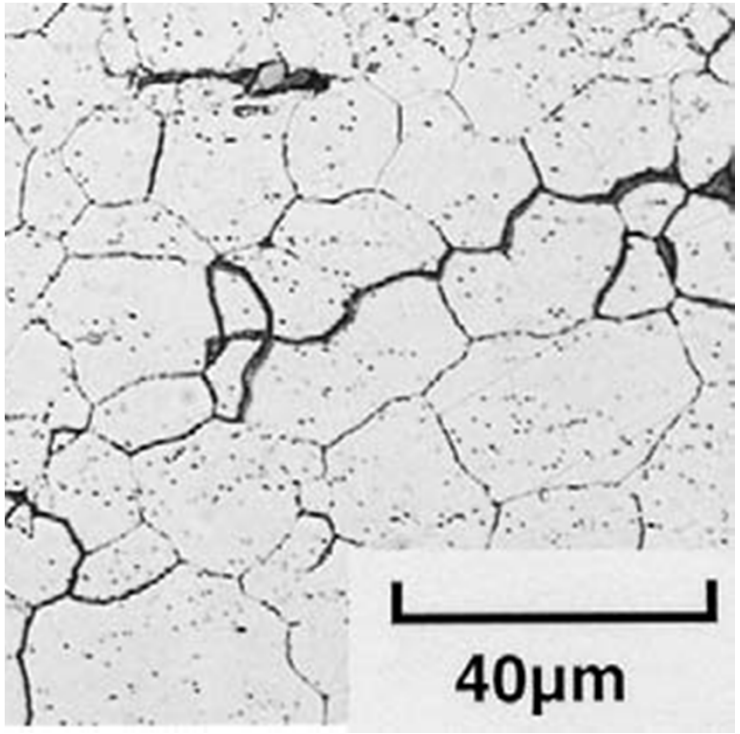
IG Attack of Blue Cheese

Queso Azul de Valdeon (Valdeon, Spain)

Note regions of intercurd attack by mold, exhibiting "sensitization-like" behavior

IG Attack of Metals and Cheese

Queso Azul de Valdeon (Valdeon, Spain)



Alloy 600TT

Queso Azul de Valdeon

22.033 / 22.33 Nuclear Systems Design Project

Fall 2011