Liquid Metal Embrittlement

An introduction

Véronique Ghetta, Dominique Gorse

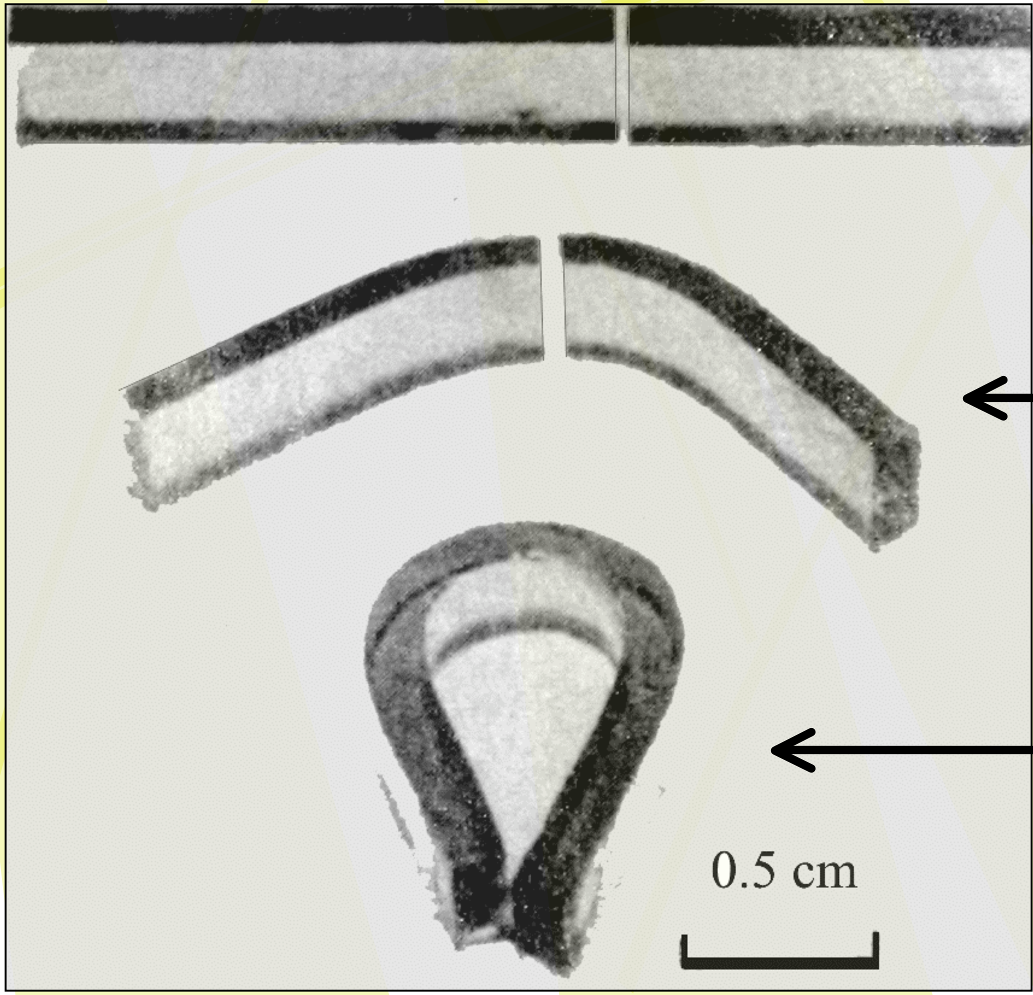
&

Vassilis Pontikis

Outline

- Environment & Mechanical behavior
- What is LME ?
- Fundamentals of mechanical failure
- Experimental facts
- Empirical criteria
- Modeling
- Conclusive remarks

Joffe effect, irradiated KCl, Rebinder et al., 1944

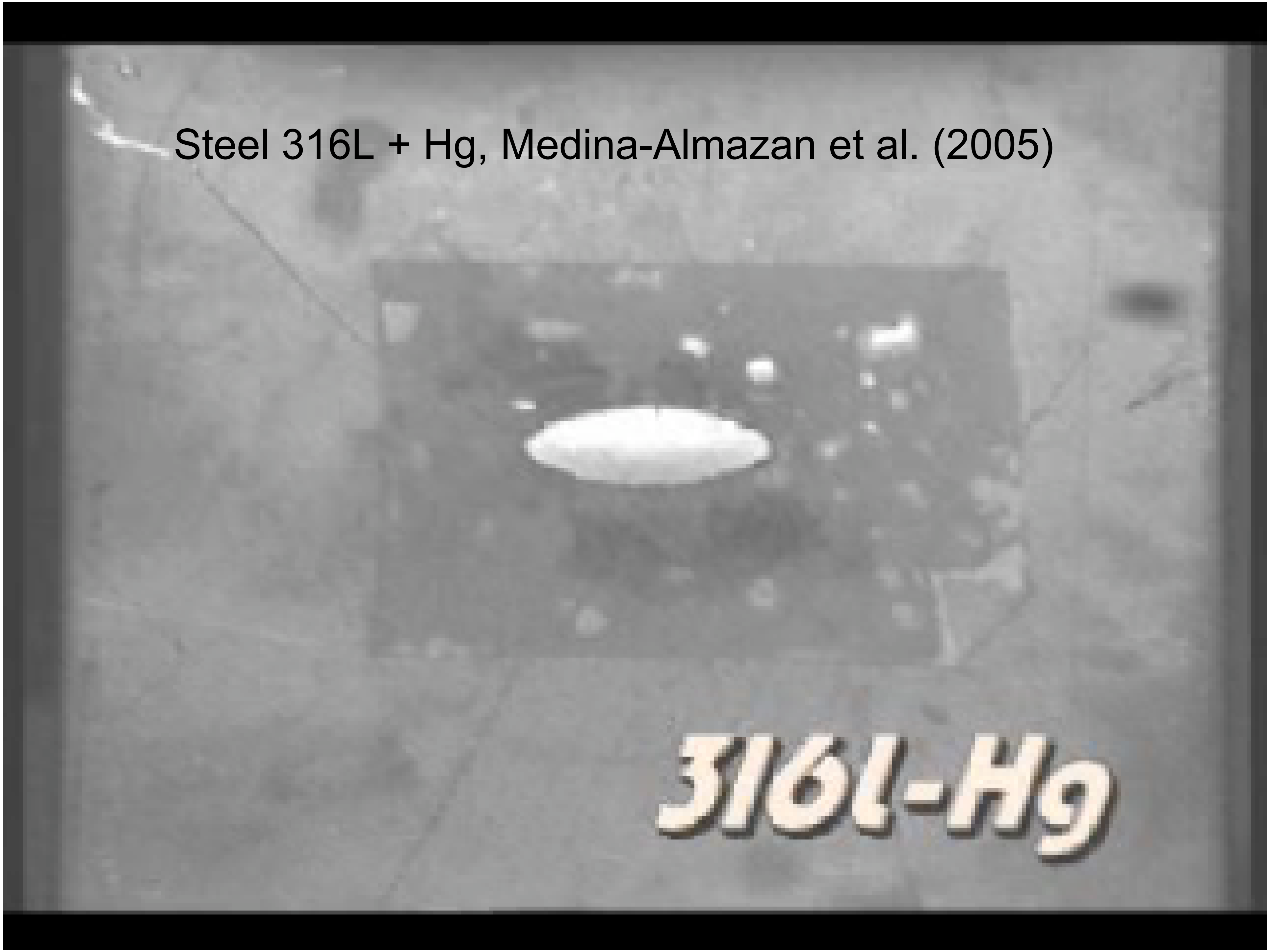


air

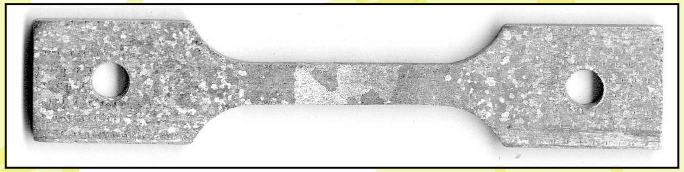
60 s H_2O, dried, air

H_2O

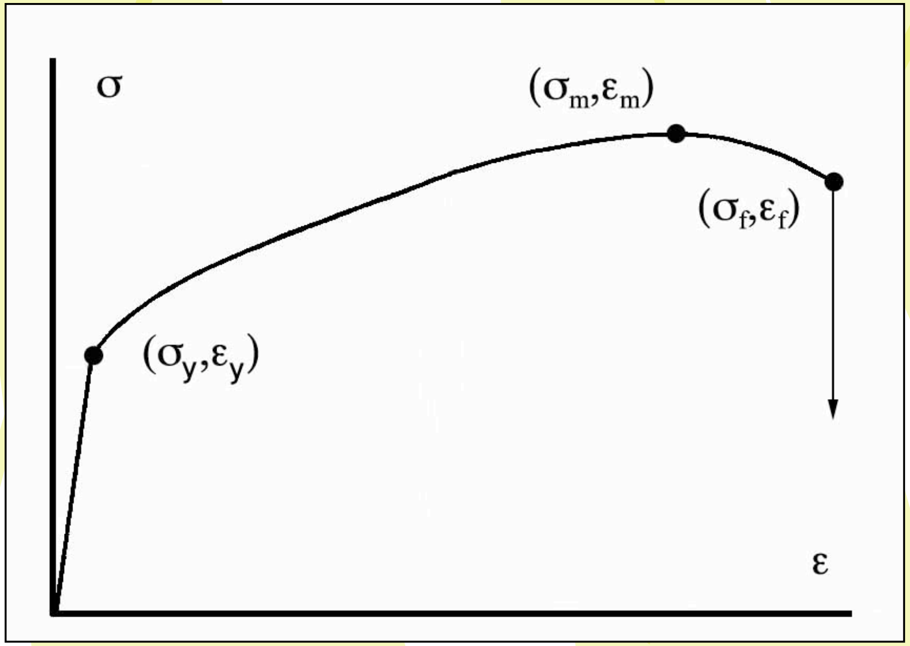
Steel 316L + Hg, Medina-Almazan et al. (2005)



Tensile deformation & failure-I



$$\sigma_E^{th} \approx \frac{\mu}{10}$$



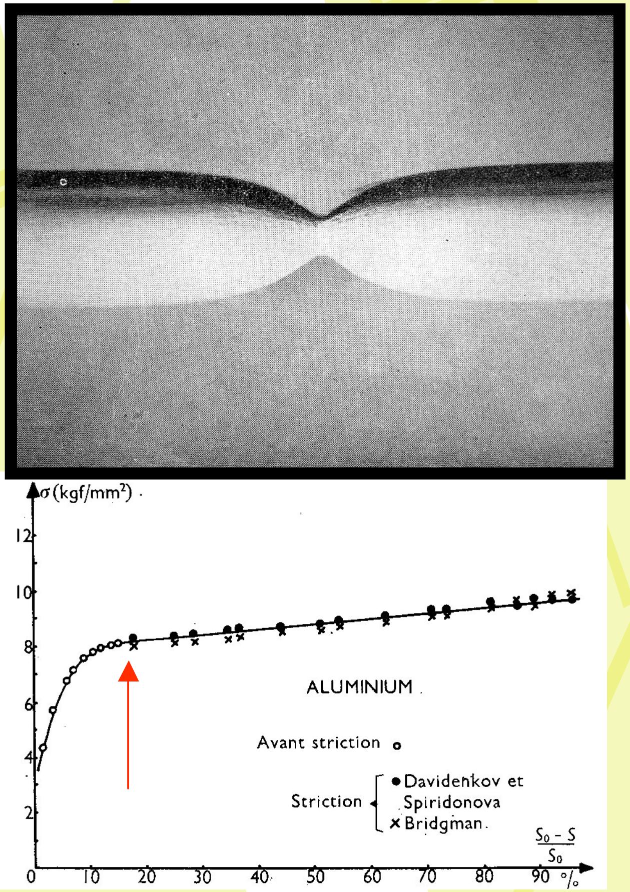
Dislocations

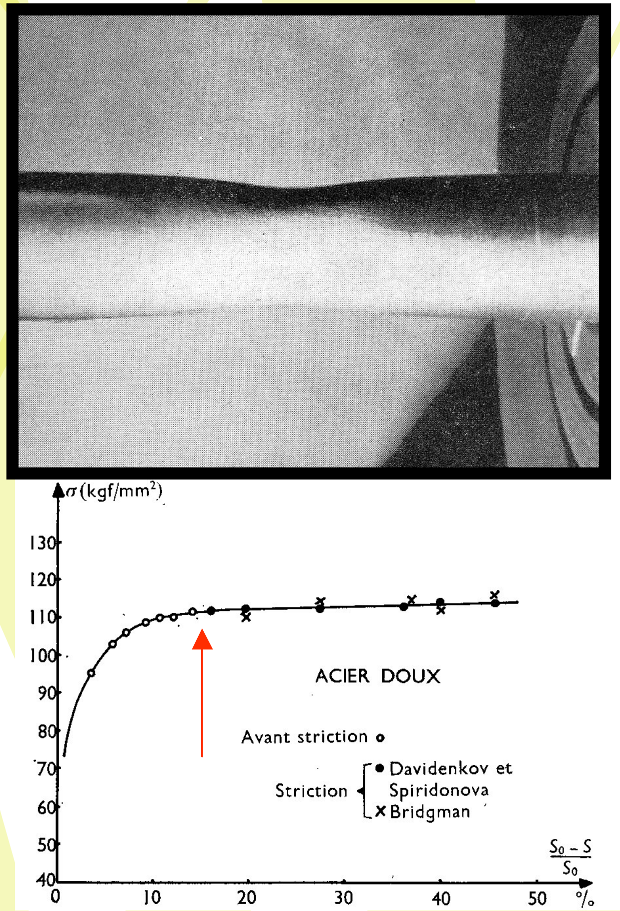
$$\begin{cases} \sigma_E^{exp-fcc} \approx 10^{-5}\mu \\ \sigma_E^{exp-bcc} \approx 10^{-3}\mu \;\; (T-dependent) \end{cases}$$

Instability

$$\sigma_m = \frac{d\sigma}{d\varepsilon} \quad (Considère)$$

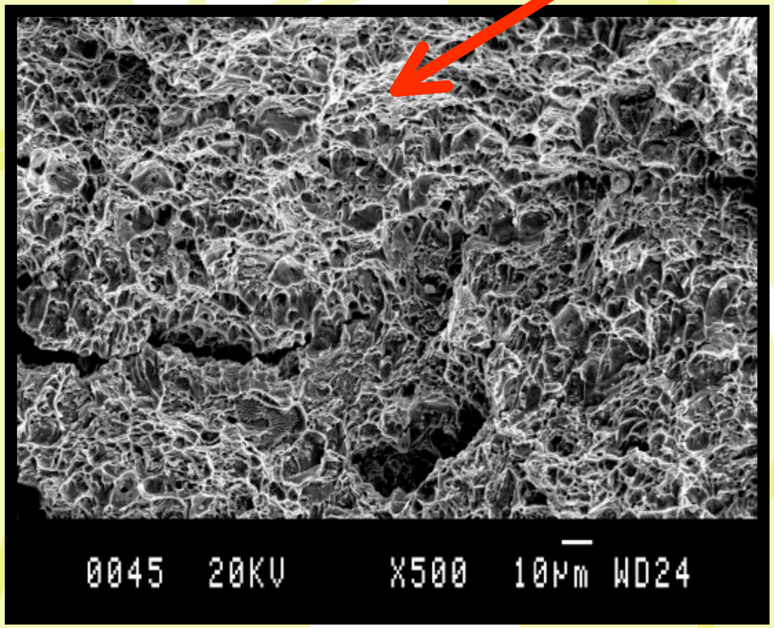
Tensile deformation & failure-II





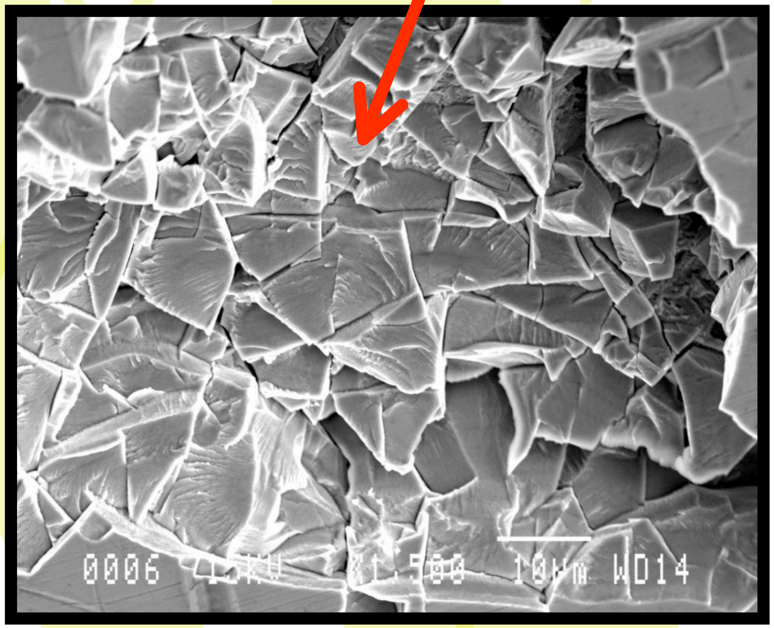
$$Creep: \quad \dot{\varepsilon} \approx \sigma^n \ , \quad n\dot{\varepsilon}_i t_f = 1 \quad (Monkman - Grant,\ 1956)$$

Microvoid coalescence & Cleavage



$T > T_{BDT}$

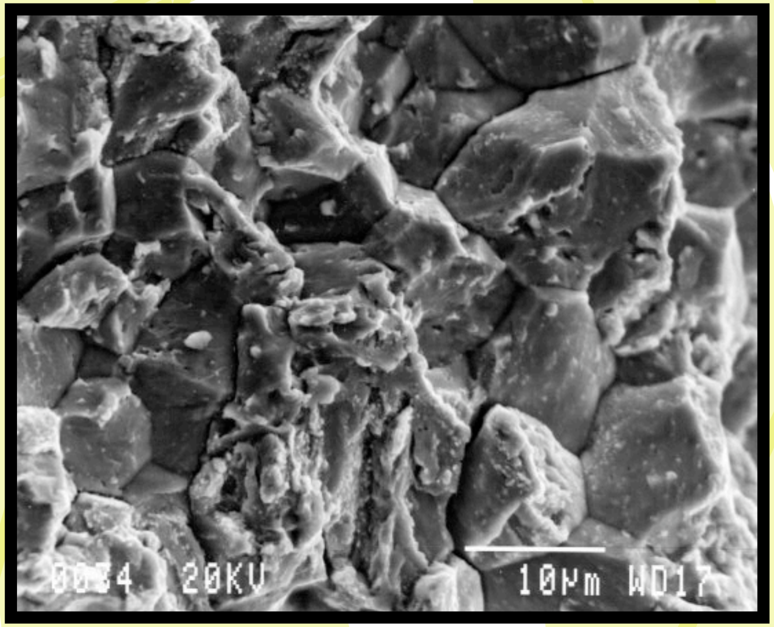
Mechanism of ductile transgranular fracture (1040 carbon steel *[1]*)

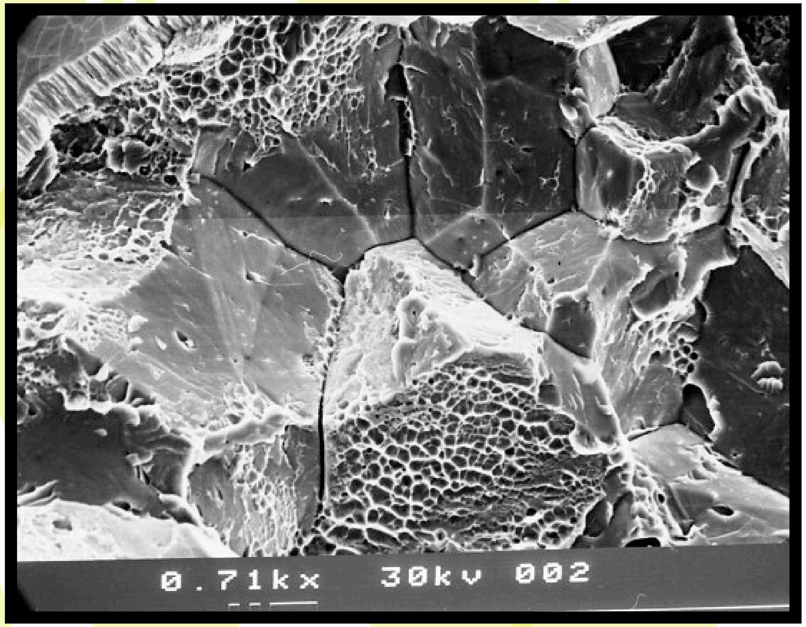


$T < T_{BDT}$

Mechanism of brittle transgranular fracture: cleaving of the crystals along crystallographic planes (bcc Cr *[1]*).

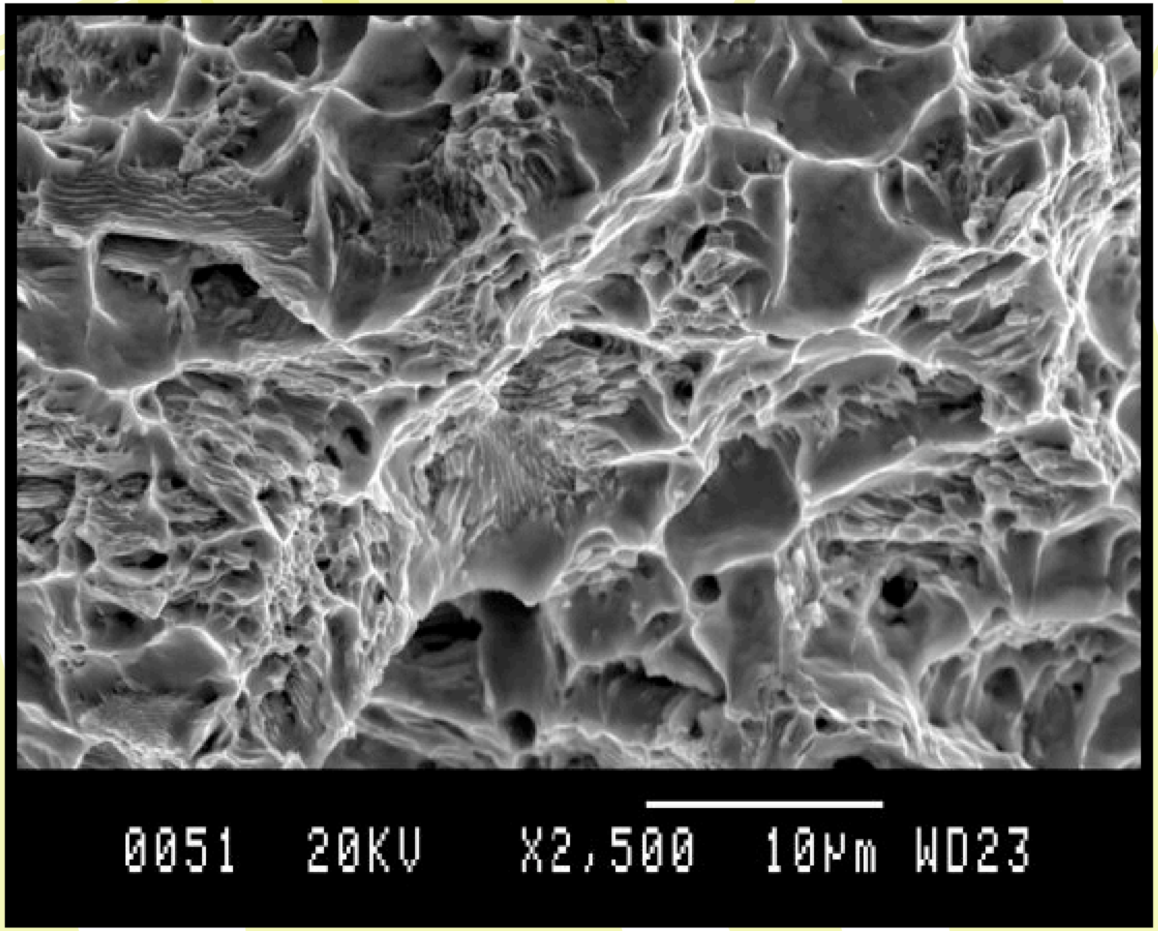
Intergranular fracture





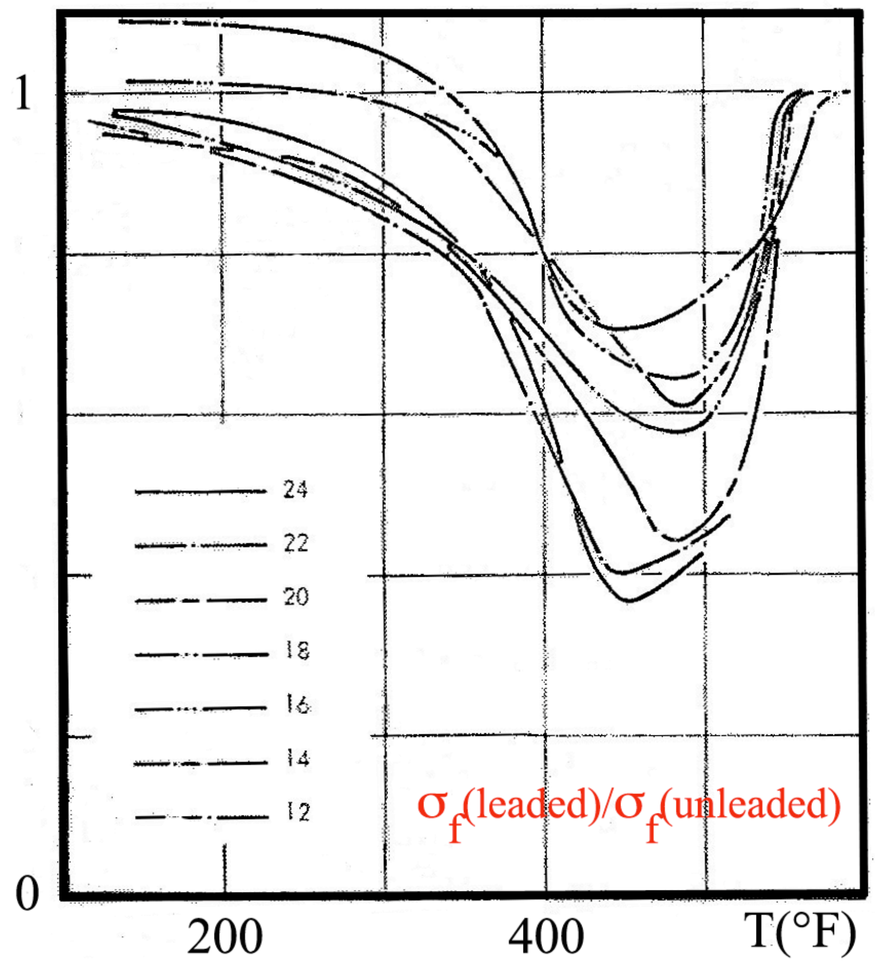
Steel, *from ref. [1]*

Mixed fracture: cleavage + MVC



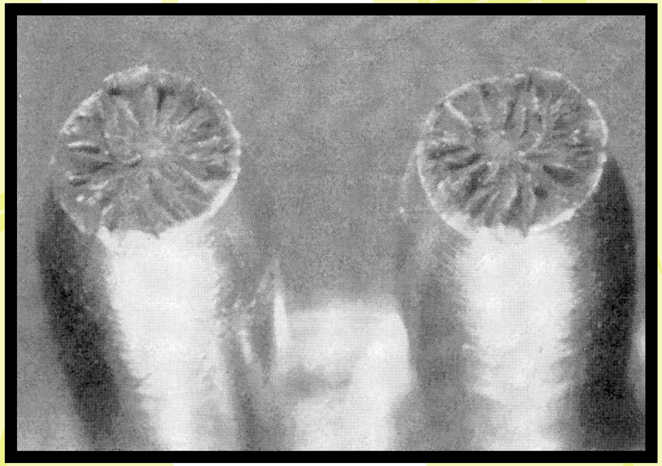
Steel *[1]*

Macroscopic features - I

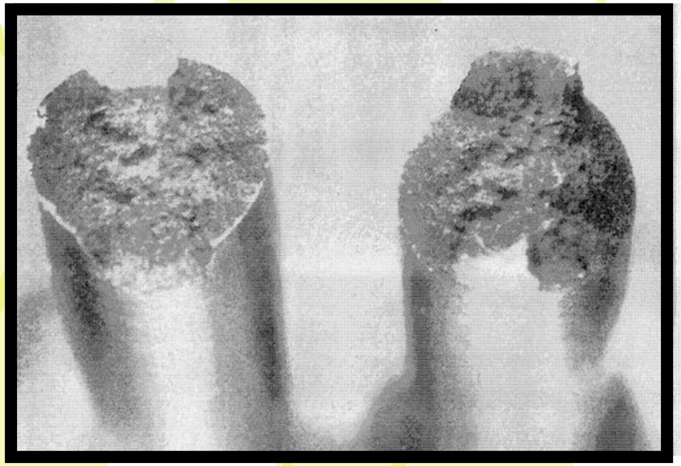


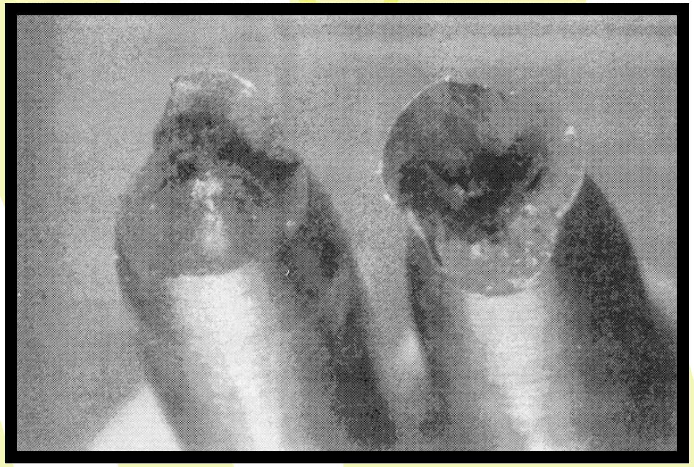
Ratio of fracture stresses of 4145 steel with & without Pb(0.3%)

Macroscopic features - II



Room T





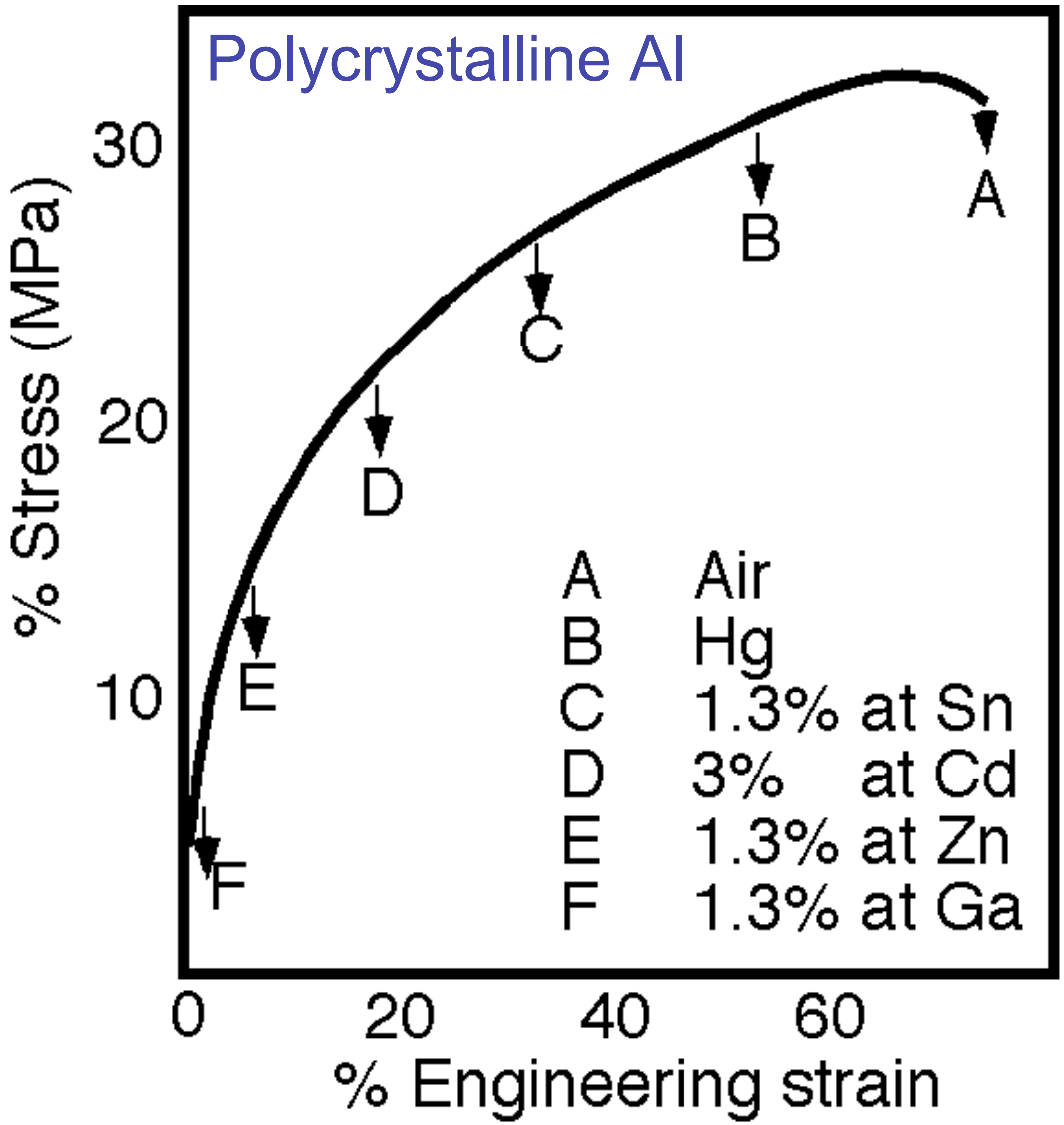
400 < T < 620 °F

Steel 4145

Mostovoy & Breyer, (1968)

LME&Chemistry

The effect of impurities

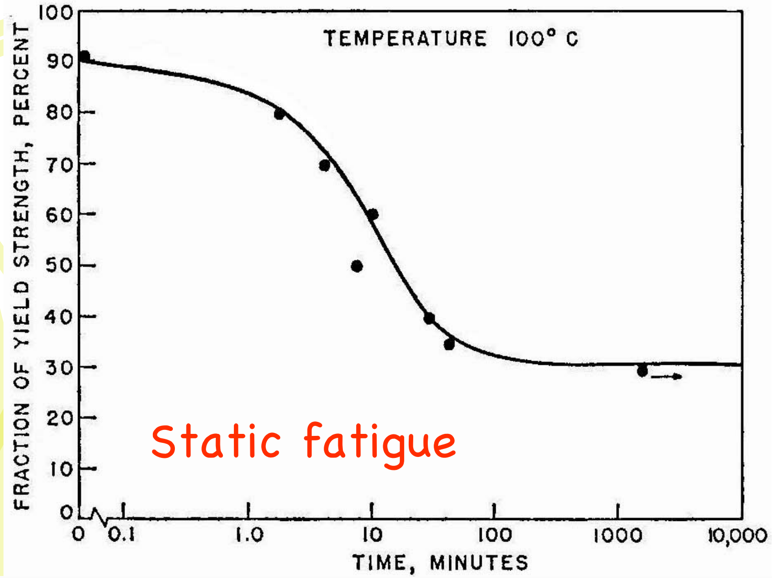


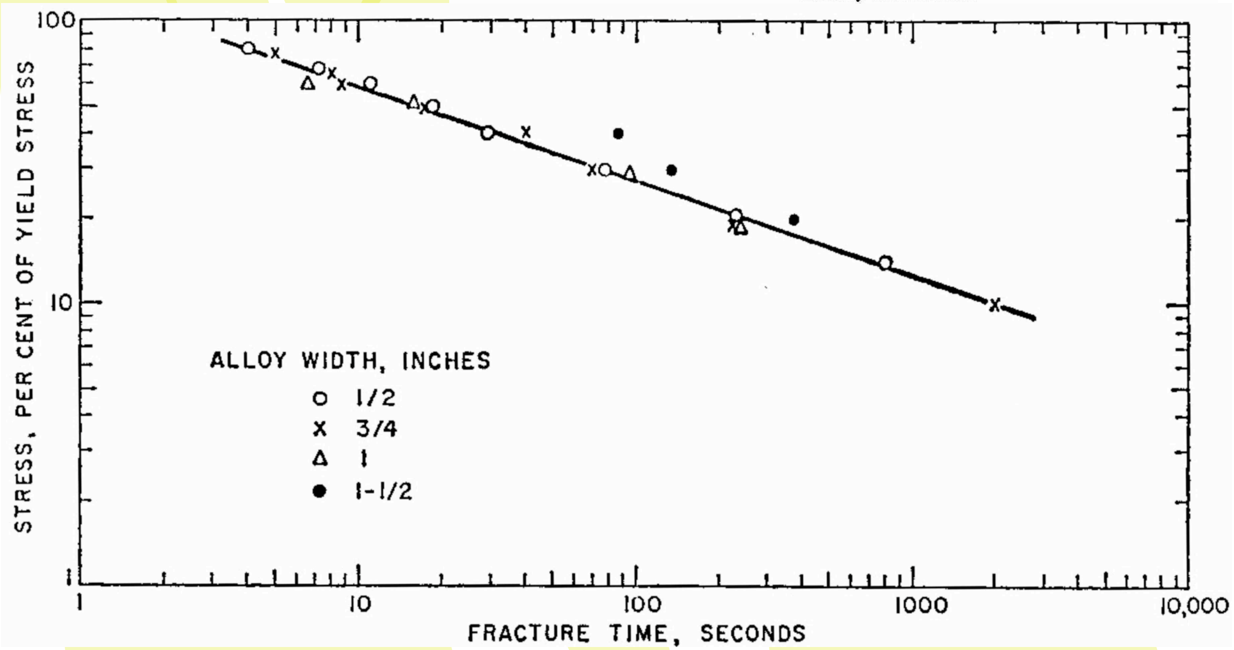
Westwood et al., (1971)

LME

Delayed failure

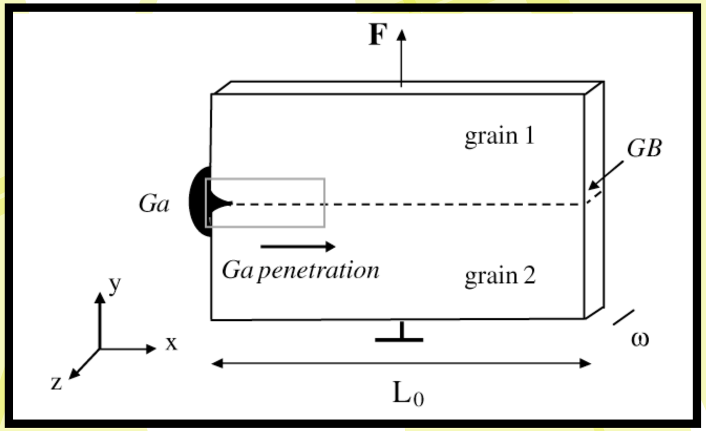
2024-T4 Al alloy + Hg amalgam

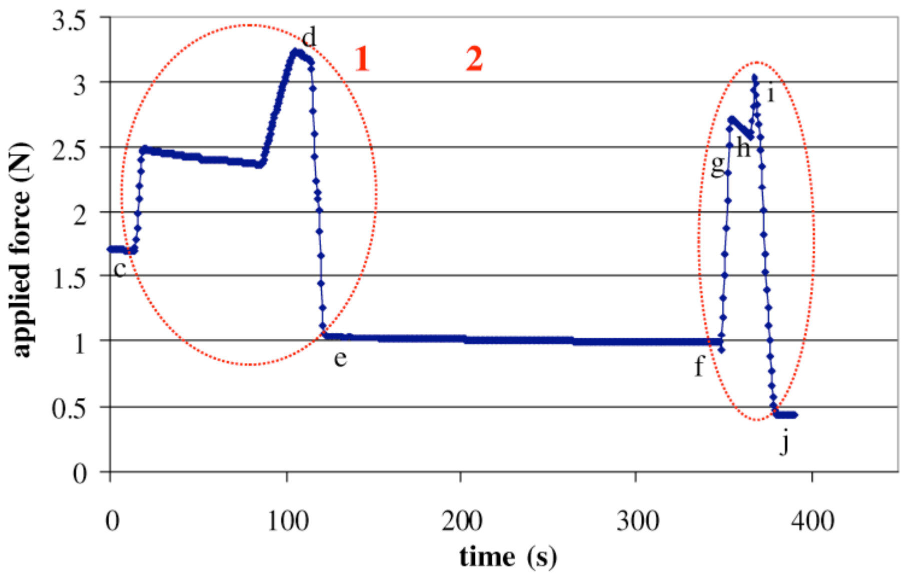


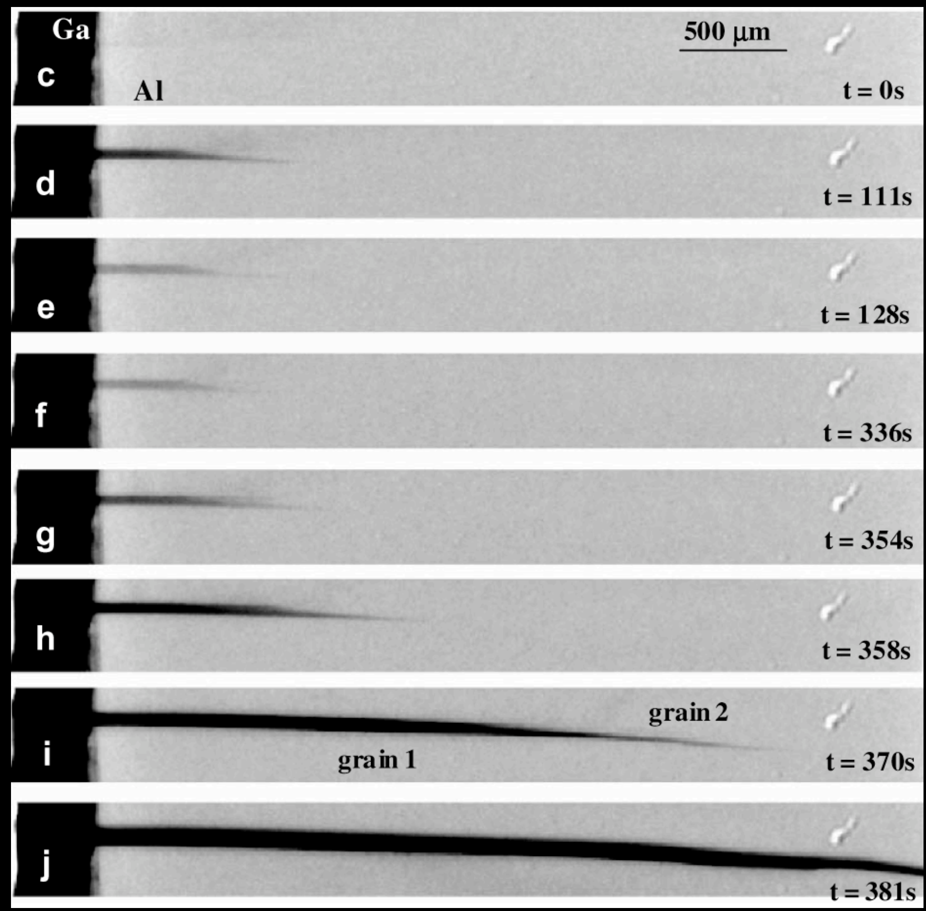


Rostoker et al. (1960)

LME and Grain Boundaries: Al/Ga

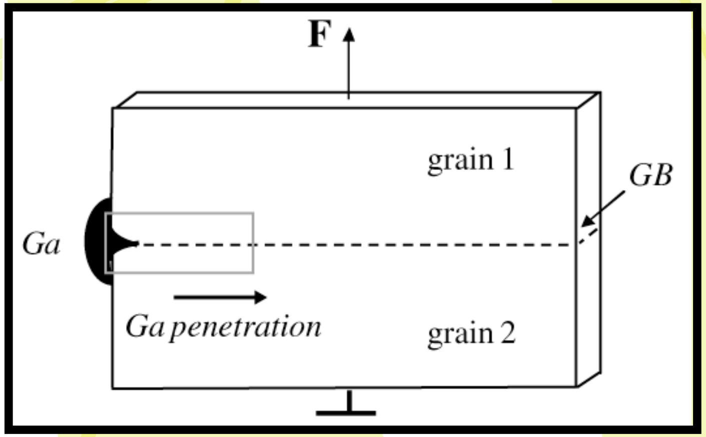


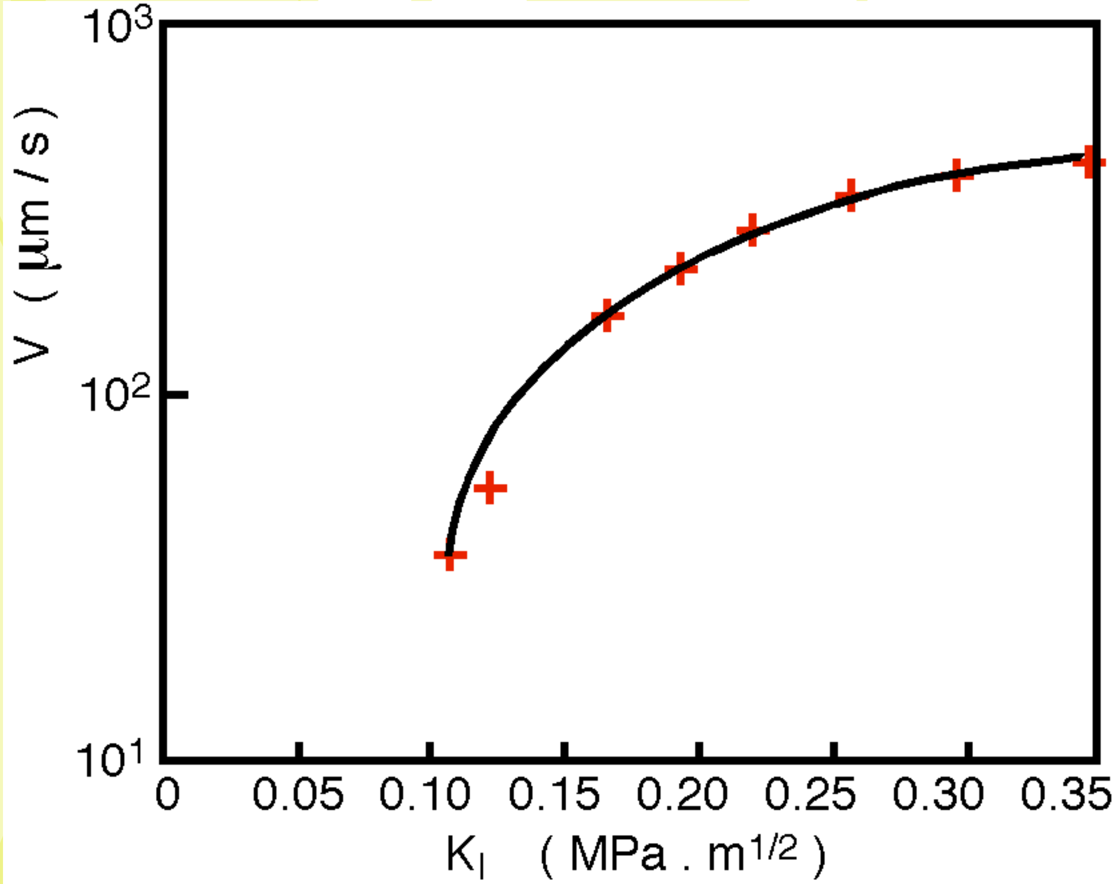




Ludwig et al. (2006)

LME and Grain Boundaries





LME: consensus about facts

- Instantaneous failure under applied or residual stresses
- Delayed failure at a static stress level below the tensile strength
- Microstructure is important BUT LM's embrittle amorphous alloys too ! Ashok et al. (1981)
- Plasticity is often present
- Stress independent (?) grain boundary penetration
- High temperature "corrosion"

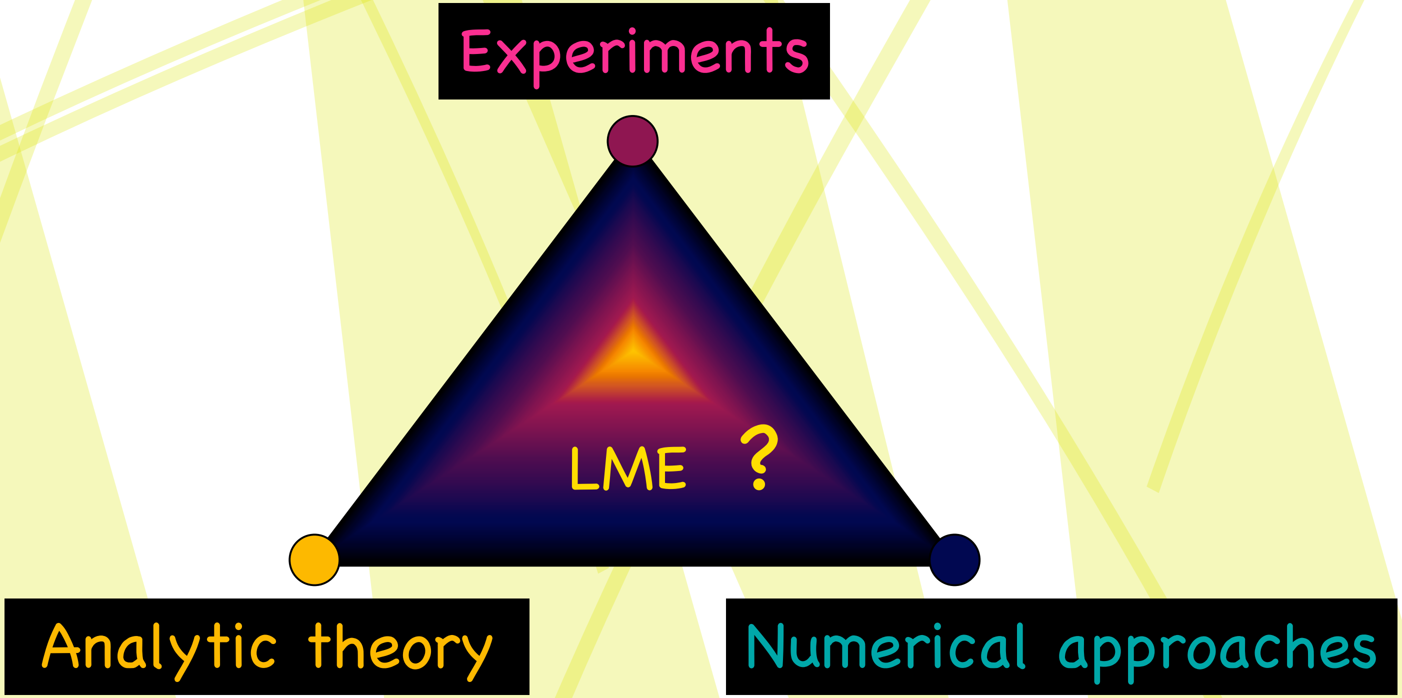
From consensus: prerequisites & empirical criteria of occurrence

- Presence of an external stress
- A pre-existing crack or plasticity (at least limited) & presence of obstacles to dislocation motion e.g. grain boundaries, twins, precipitates
- Adsorption of the active species at the obstacles and at the tip(s) of propagating crack(s)

- Limited mutual solubility of the liquid and the solid
- Little or no tendency of stable high T_m compounds

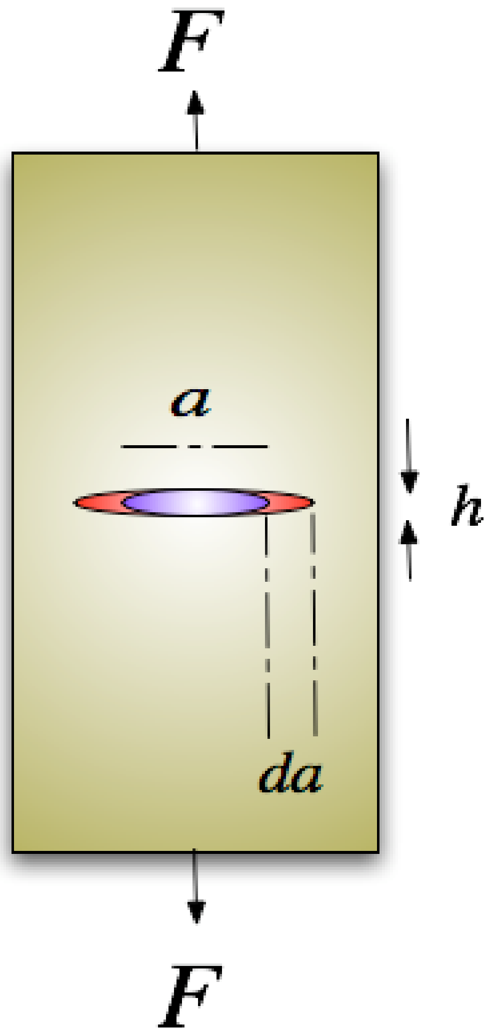
However factors determining which liquid metal will embrittle which solid metal still remain unclear !

Is modeling understanding ?



An heuristic approach (sometimes a random walk)

Modeling LME & Crack propagation: Elasticity



$$dU = \pi a da \frac{\sigma^2}{E}$$

$$G = \frac{dU}{da} = \pi a \frac{\sigma^2}{E} \qquad G_c = 2\gamma_s$$

$$\sigma_c = \sqrt{\frac{2\gamma_s E}{\pi a}} \qquad (Griffith - 1921)$$

Adsorption of the liquid at the crack tip decreases γ_s and thus σ_c

LME & Crack propagation: ....adding plasticity

Griffith's model is elastic (Orowan, Stoloff & Johnson, …)

$$\sigma_c = \sqrt{\frac{2\gamma_{eff}E}{\pi a}} \qquad (Orowan - 1950)$$

But…

$$\gamma_{eff} = \gamma_p + \gamma_s \quad (Al : \gamma_p \approx 4200\gamma_s, \text{ Kargol } et\ al., 1977)$$

However…

$$\gamma_{eff} = A\gamma_s, \qquad A \approx \sigma_0 / \sigma_y \approx 100 \ \ for\ steel \quad (Gilman, 1960)$$

Small changes in γ_s large influence on γ_{eff}

“Thermodynamic” model: Successes & limitations

• Cu/Pb-melt	*Eborall et al. (1956)*
• Al bicrystals/HgGa solution	*Kargoll et al. (1977)*
• Al 6061/inclusions Bi, Cd, Pb	*Roth et al. (1980, 1982)*

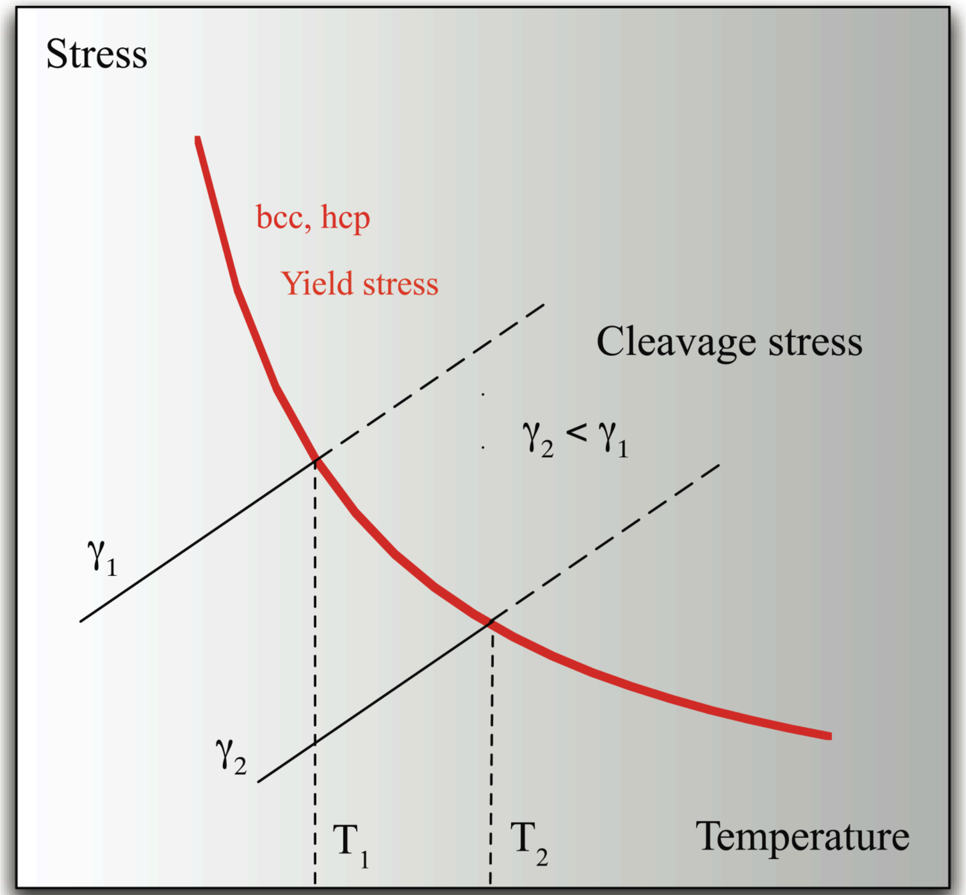
BUT …

- No mechanisms
- No microscopic description of the SL interface
- No kinetics
- No understanding of plasticity at the crack tip

LME & Cracks & DuctileBrittleTransitionTemp

System	γ_s (J/m^2)
Al	1.0
Al-Pb	0.344
Al-Cd	0.298
Al-Bi	0.288

Old & Trevena (1979)

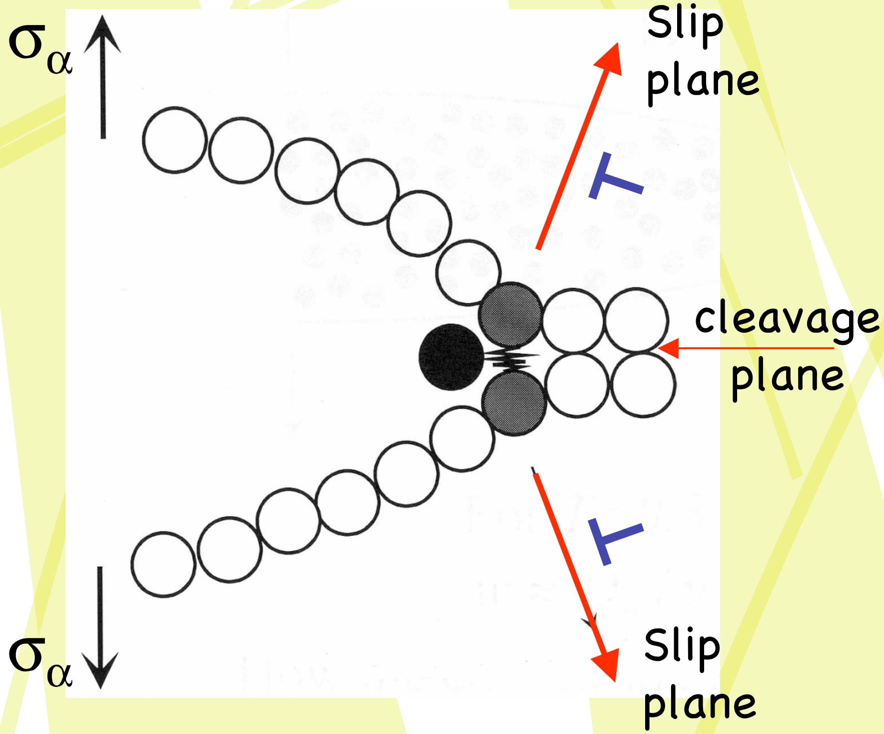


Limitations of this approach

- Lack of surface energy data (ab-initio ?)
- Physical parameters influencing LME do not appear in the model (e.g. microstructure)
- No insight into the mechanisms (atomistic scale)

Consensus: reduction in γ_s is necessary but not sufficient

AIRC Adsorption Induced Reduction in Cohesion



- Bond breaking $\sigma_m = \sqrt{\dfrac{\gamma_s E}{x_0}}$
- Crack length 2a
  Stress at the tip $\sigma = 2\sigma_a \sqrt{\dfrac{a}{\rho}}$
- $\rho = x_0$ $\longrightarrow$ $\sigma_{prop} = \sqrt{\dfrac{\gamma_s E}{4a}}$

$$\sigma_{prop(blunted)} = \sqrt{\frac{E\gamma_{fracture}}{4a}} = \sqrt{\frac{E\gamma_s \xi}{4a}}$$

AIRC: the atoms of the liquid (black) reduce/increase the bond strength

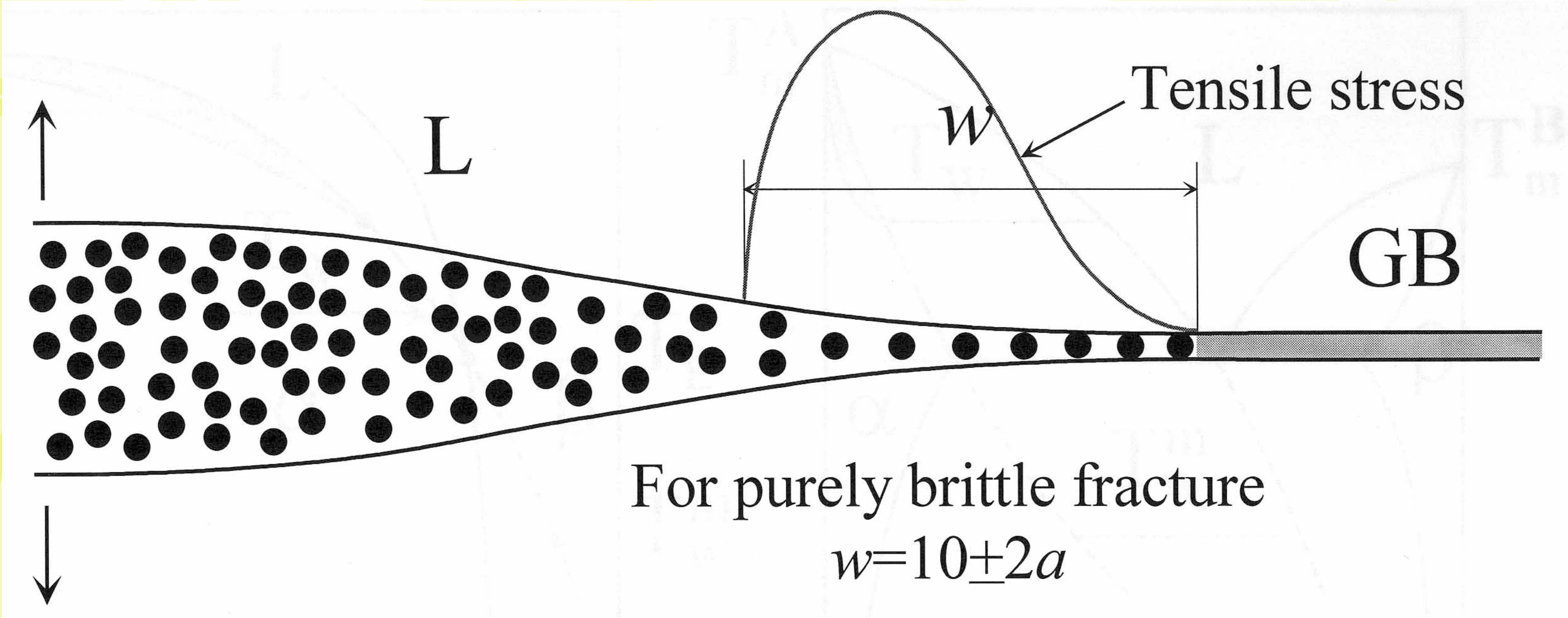
AIRC: present situation

- AIRC is widely accepted
- Consistent with several experimental findings (Zn-Hg, Zn-Ga, hydrogen, …)
- Explains impurity action

BUT …

- Hardening is absent
- Enhanced plasticity at the crack tip and HT LME are not explained
- Transport mechanisms are not considered
- No realistic prediction of the crack velocity

AIRC variants & improvements

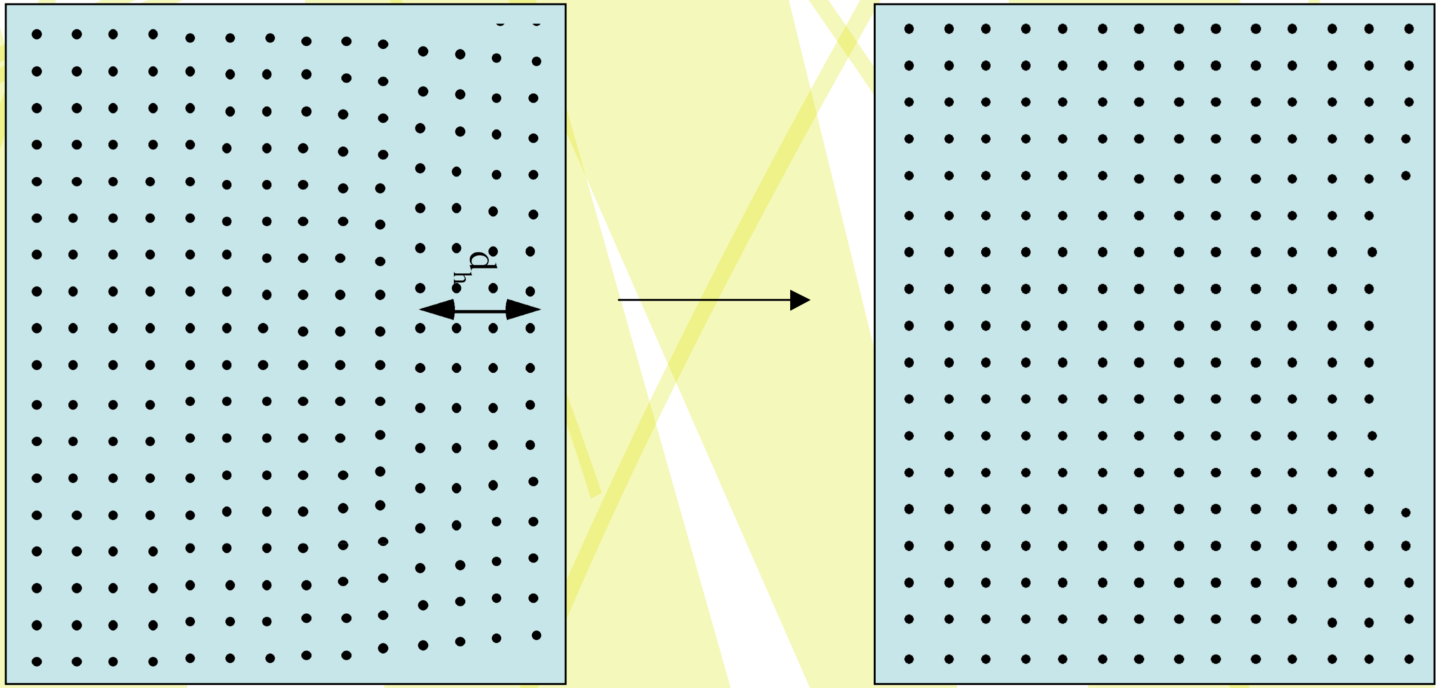


Wetting effects

Rabkin et al, (19..)

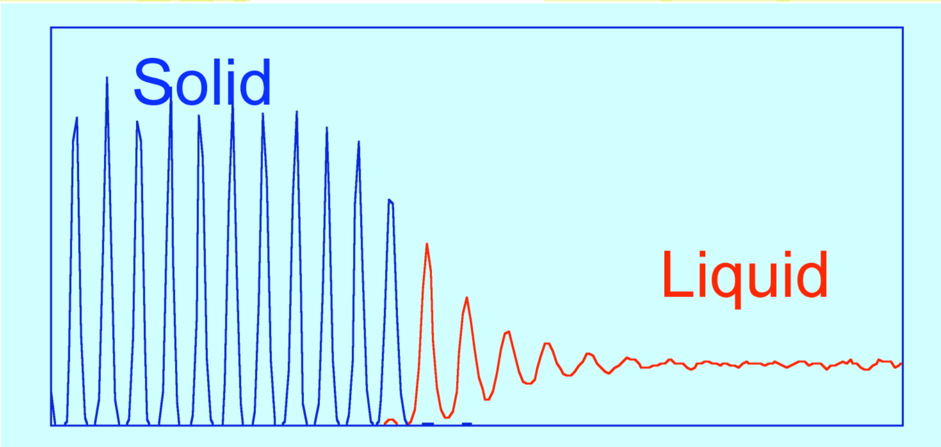
Modeling PIN: nano-cracks

Geysermans et al. (2003)

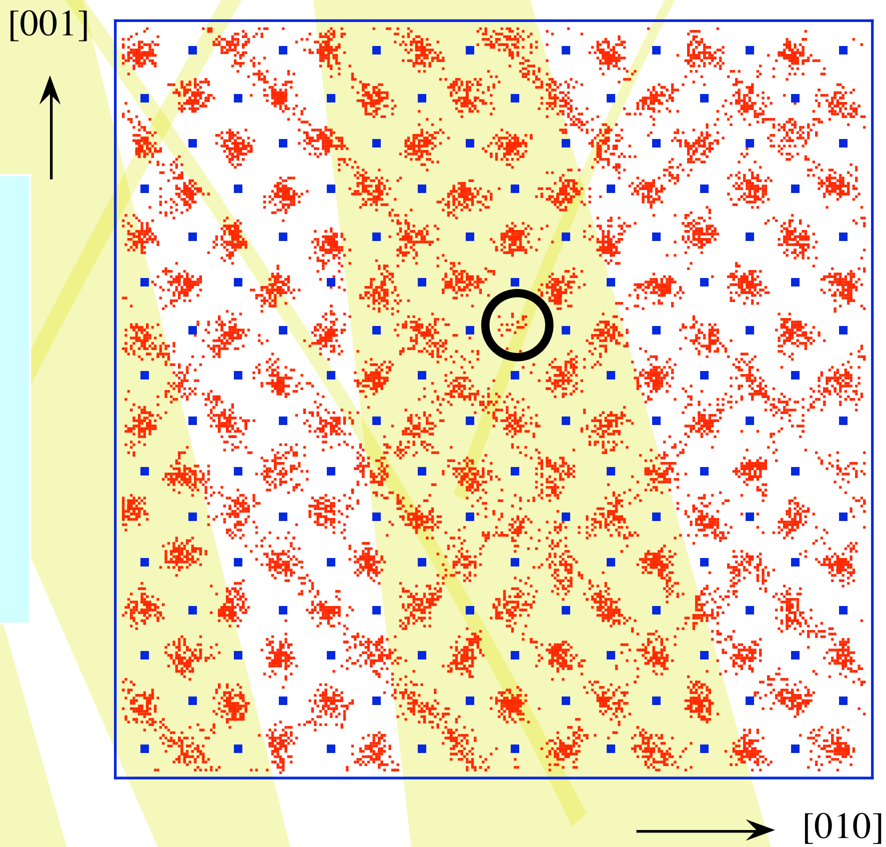


$$d_h \leq \frac{\mu b^4}{4\sqrt{2}\pi(1-\nu)E_v^f} \qquad (Friedel,\ 1964)$$

Modeling: Crystal-Liquid interface



$$\tilde{\rho}(x) = \left\langle \sum_i \delta\left(x - x_i\right) \right\rangle$$



Geysermans et al. (2005)

Conclusive remarks

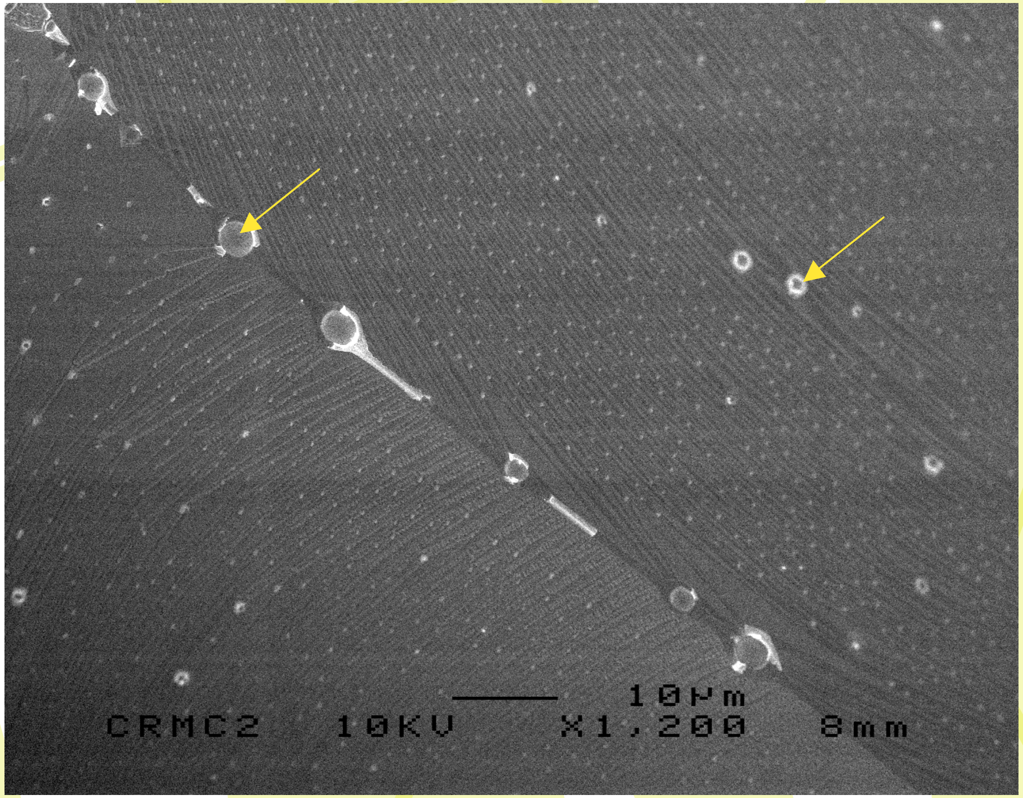
- LME can affect several structural materials and be a major cause of damage

- Understanding of LME is still limited
- No general agreement exists about mechanisms
- There is lack of atomic scale description
- No predictions can be made i.e. which liquid metal embrittles which solid metal

- Research on LME could result in decisive advances in the physics & chemistry of interfaces

Origins of Illustrations

1. http://www.tech.plym.ac.uk/sme/Interactive_Resources/tutorials/FailureAnalysis/Fractography/Fractography_Resource4.htm


10μm
CRMC2 10KV X1,200 8mm