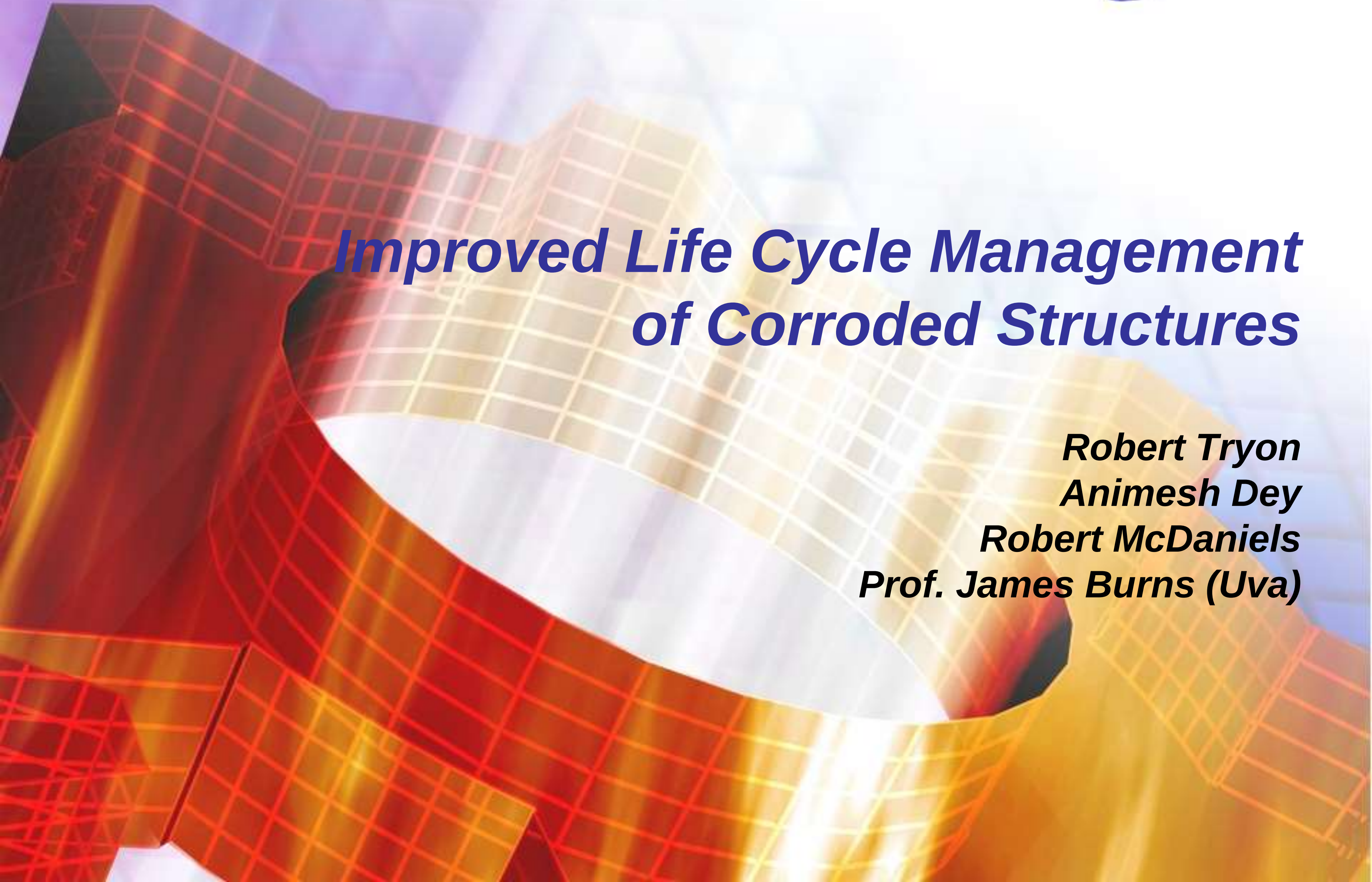

Improved Life Cycle Management of Corroded Structures

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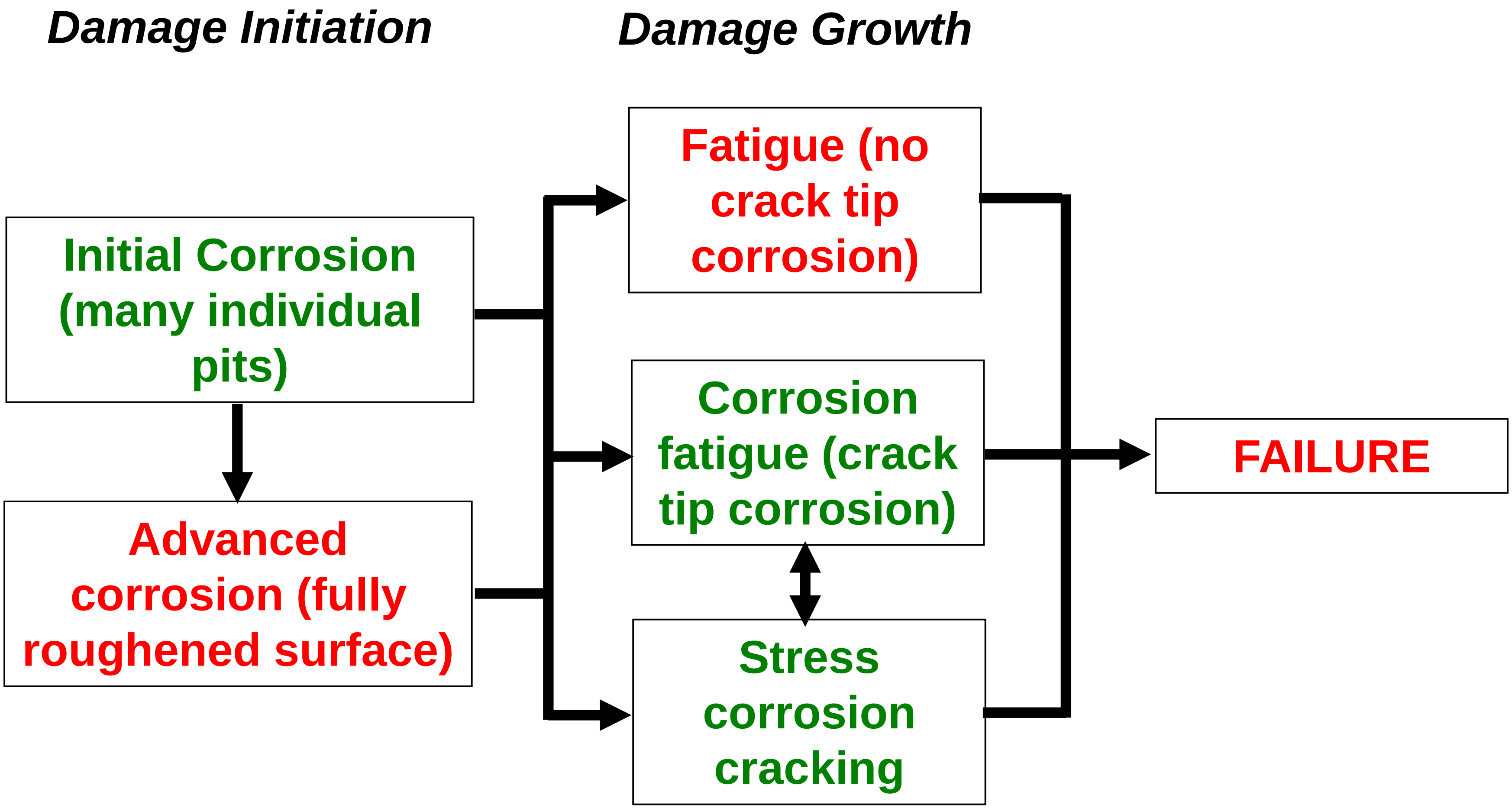
Discussion Topics

- **Issues and Objectives**
- **Corrosion Cracking Software**
- **Modelling the Corroded Surface**
- **Applying Small Flaw Fracture Mechanics**
- **Example Results**

Program Objective

- Issue:
  - Corrosion causes stress corrosion cracking and corrosion fatigue resulting in wasteful repair or removal from service.
  - Current corrosion damage analysis methods provide expensive, yet only rough estimates of corrosion degradation.
- Objective:
  - Develop analysis methods addressing the multi-disciplinary, multi-scale corrosion damage problem that integrates multiple mechanisms for accurate simulation of the damage state and better prediction of failure risk.
  - Use probabilistic method to account for the large variability that exists in the material and loading conditions that drive corrosion cracking.
  - Predict remaining useful life of aircraft structure by modeling the evolution of the damage state of the structure in response to corrosion as well as fatigue and/or sustained load.

Overview of Corrosion Damage Software



Damage Initiation

Damage Growth

Initial Corrosion (many individual pits)

Advanced corrosion (fully roughened surface)

Fatigue (no crack tip corrosion)

Corrosion fatigue (crack tip corrosion)

Stress corrosion cracking

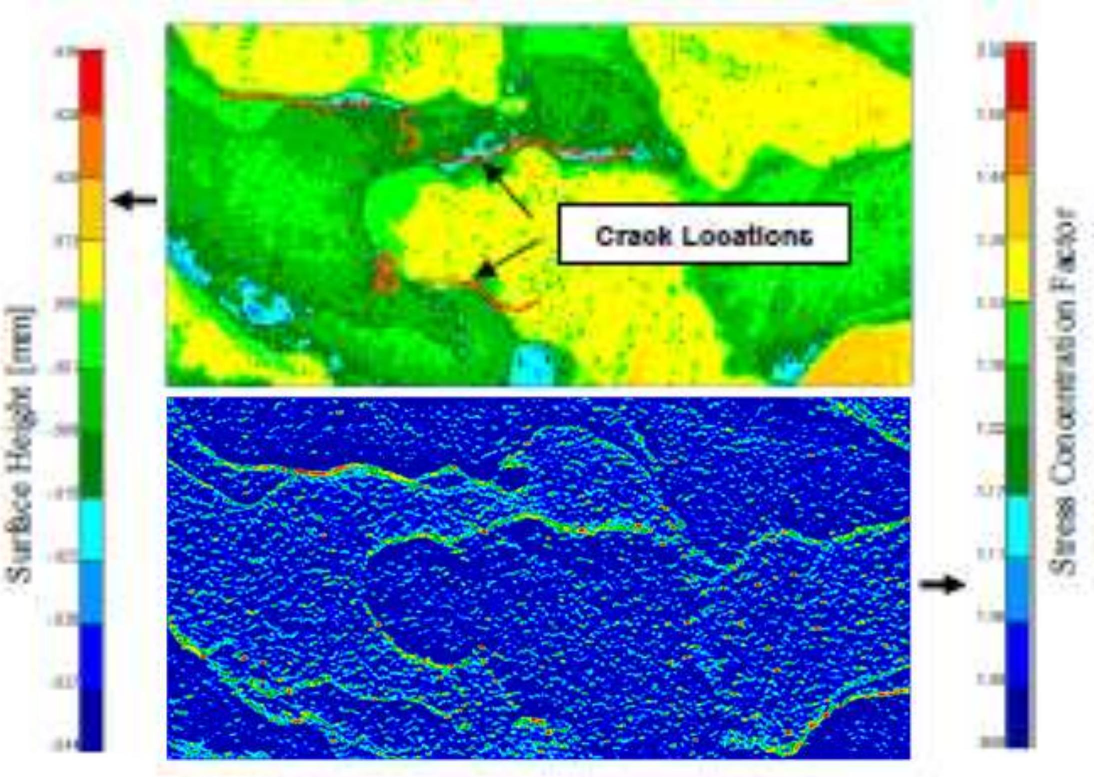
FAILURE

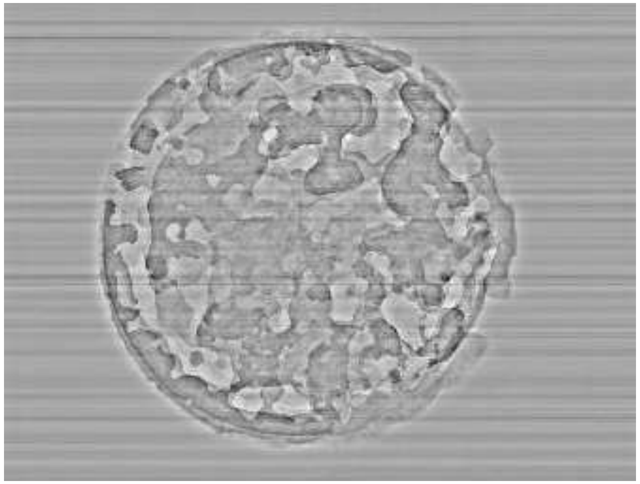
Model Microstructural Features of Corrosion

- Electro chemical attack culminates in stress risers at the surface geometry
  - Stress riser nucleate fatigue cracks
- Micro geometry is analyzed for stress with structural mechanics
- Probabilistic structural analysis methods is used to superimpose stresses at different microstructure size scales
- Small flaw fracture mechanics is used to model damage progression

Earlier models of surface roughness

- Rusk et al. used *Kt* to model corroded AF1410 steel surface
- Found cracks initiated at locations of high *Kt*



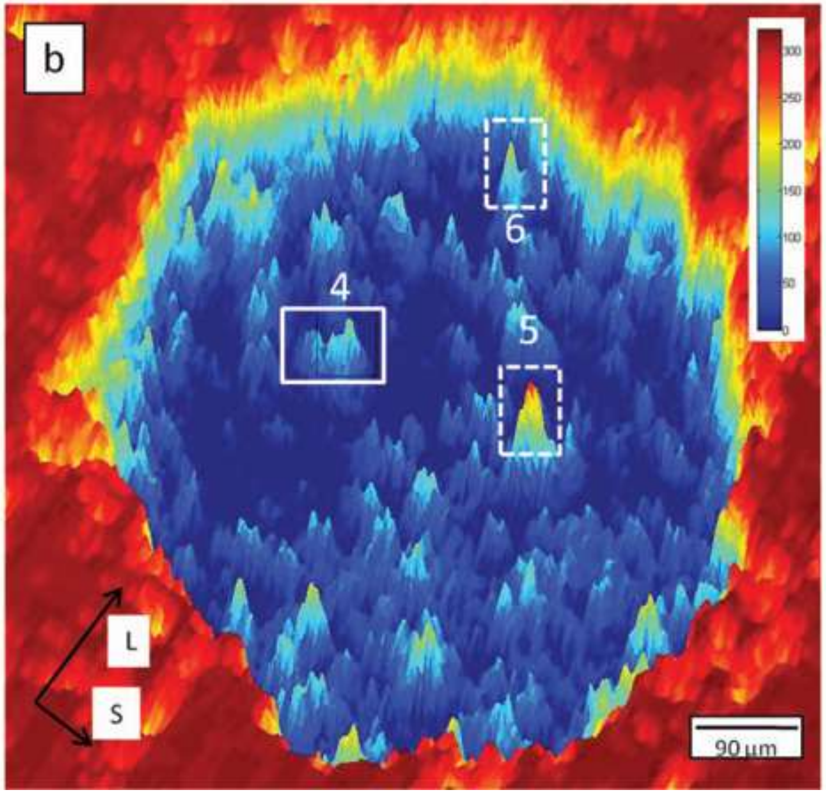


Rusk, D. T., Hoppe, W., Braisted, W., Powar, N., Report NO: NAWCADPAX/TR-2008/60.

Stress: Various size scale

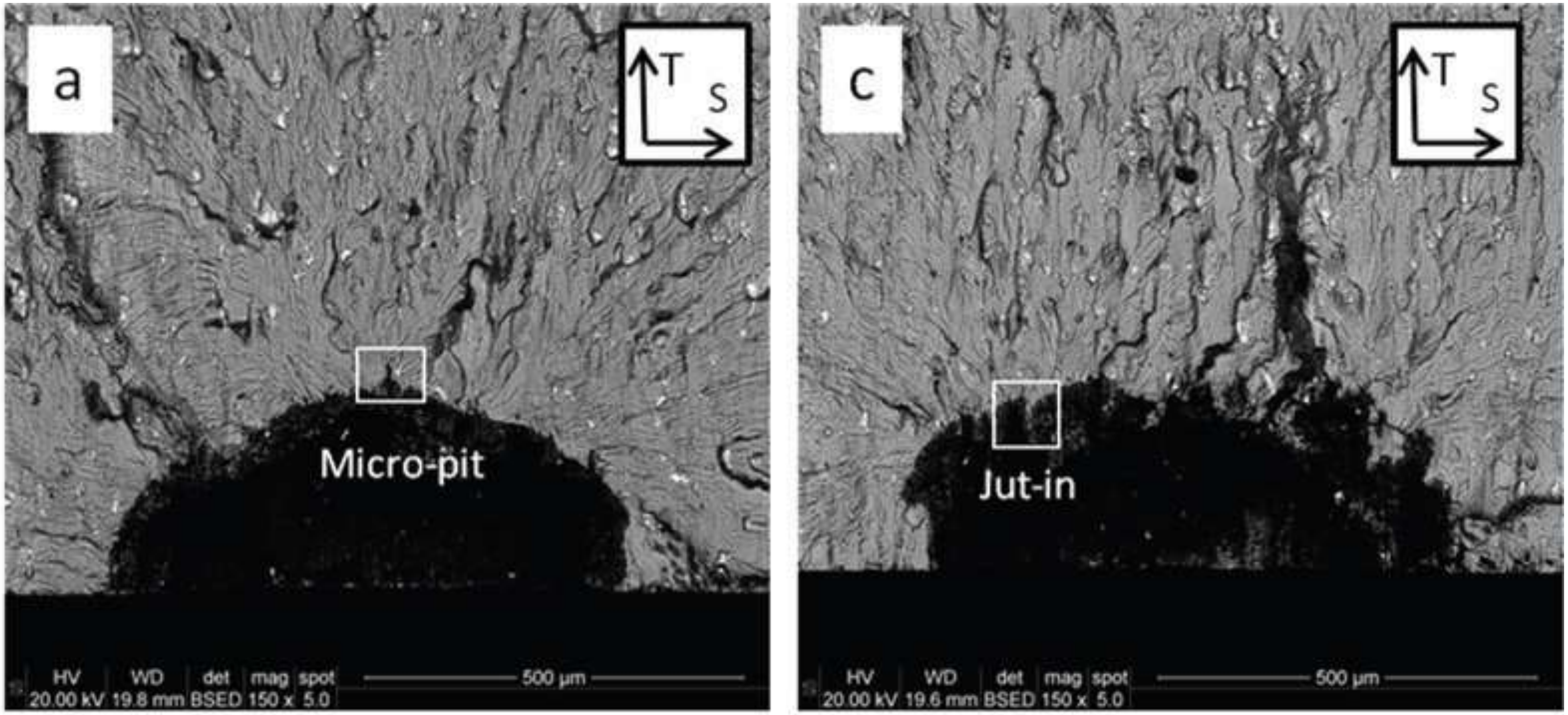
- Stress analysis uses superposition to determine stress as a spatially distributed random field
  - – K_t caused by macro pits
  - – K_t caused by micro geometric features
  - – K_t caused by material inclusion

AA 7XXX corroded surface



J. T. Burns, J. M. Larsen and R. P. Gangloff, (2011) Fatigue Fract Engng Mater Struct 34, 745–773.

Geometry: Various size scales

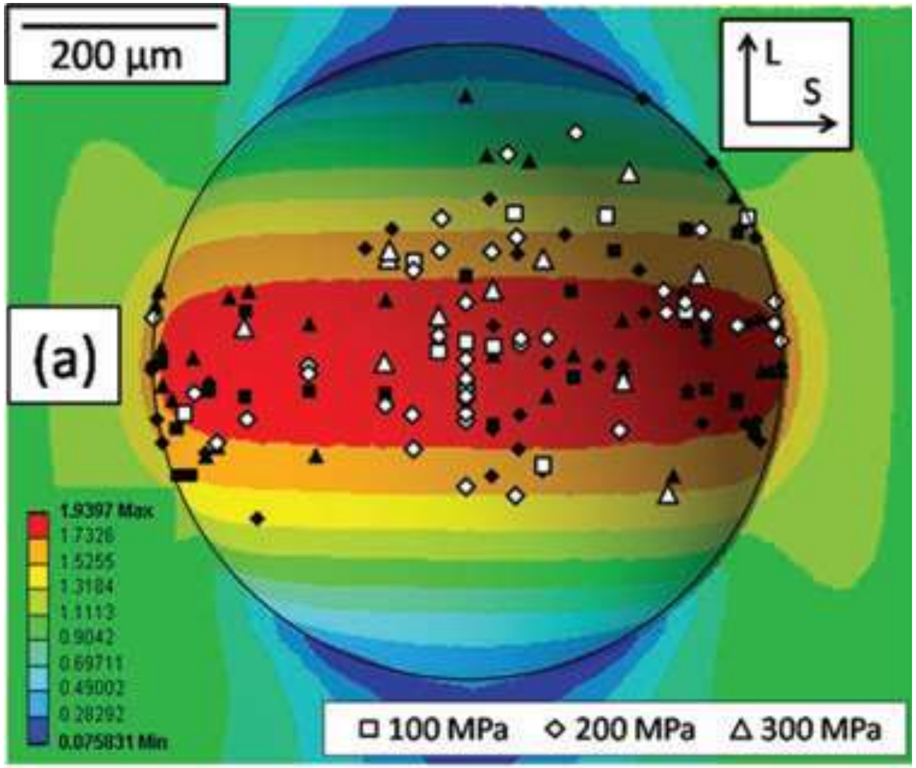


- Micro-pits and jut-ins – 10 µm diameter
- Inclusion 25 µm diameter

Burns (2011)

Stress: Surface Roughness Macro Pit

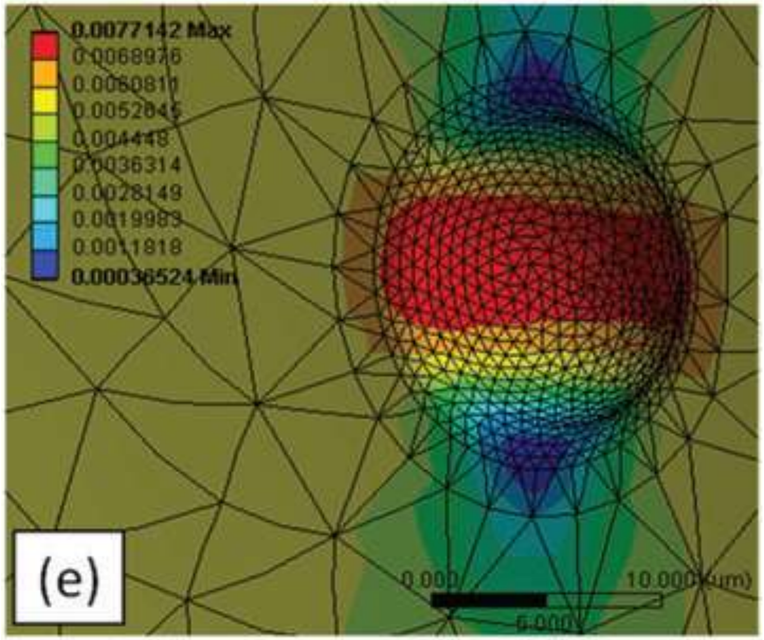
- Spherical Kt = 1.94
- S elongation Kt = 2.23
- L elongation Kt = 1.95

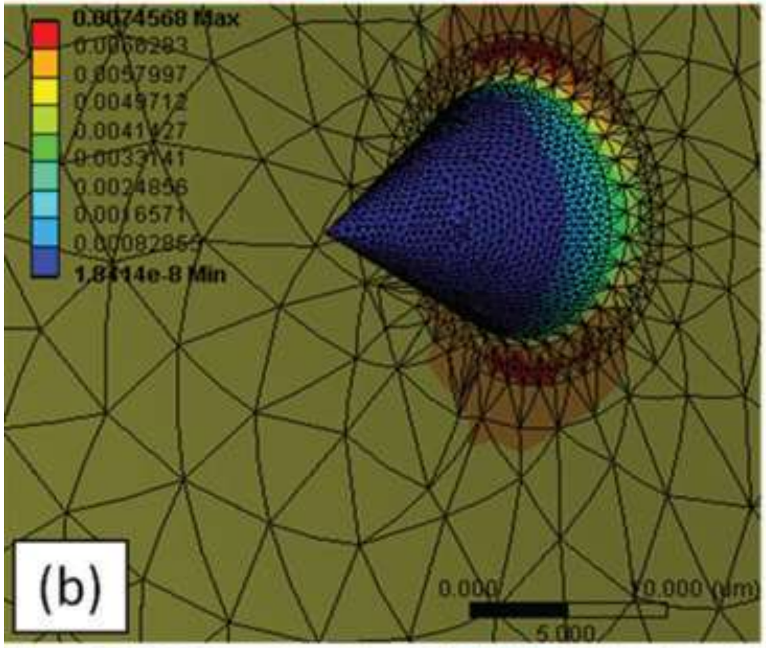


K_t of the pit

J. T. Burns, J. M. Larsen and R. P. Gangloff, (2012) International Journal of Fatigue 42 104–121.

Stress: Surface Roughness Micro Features



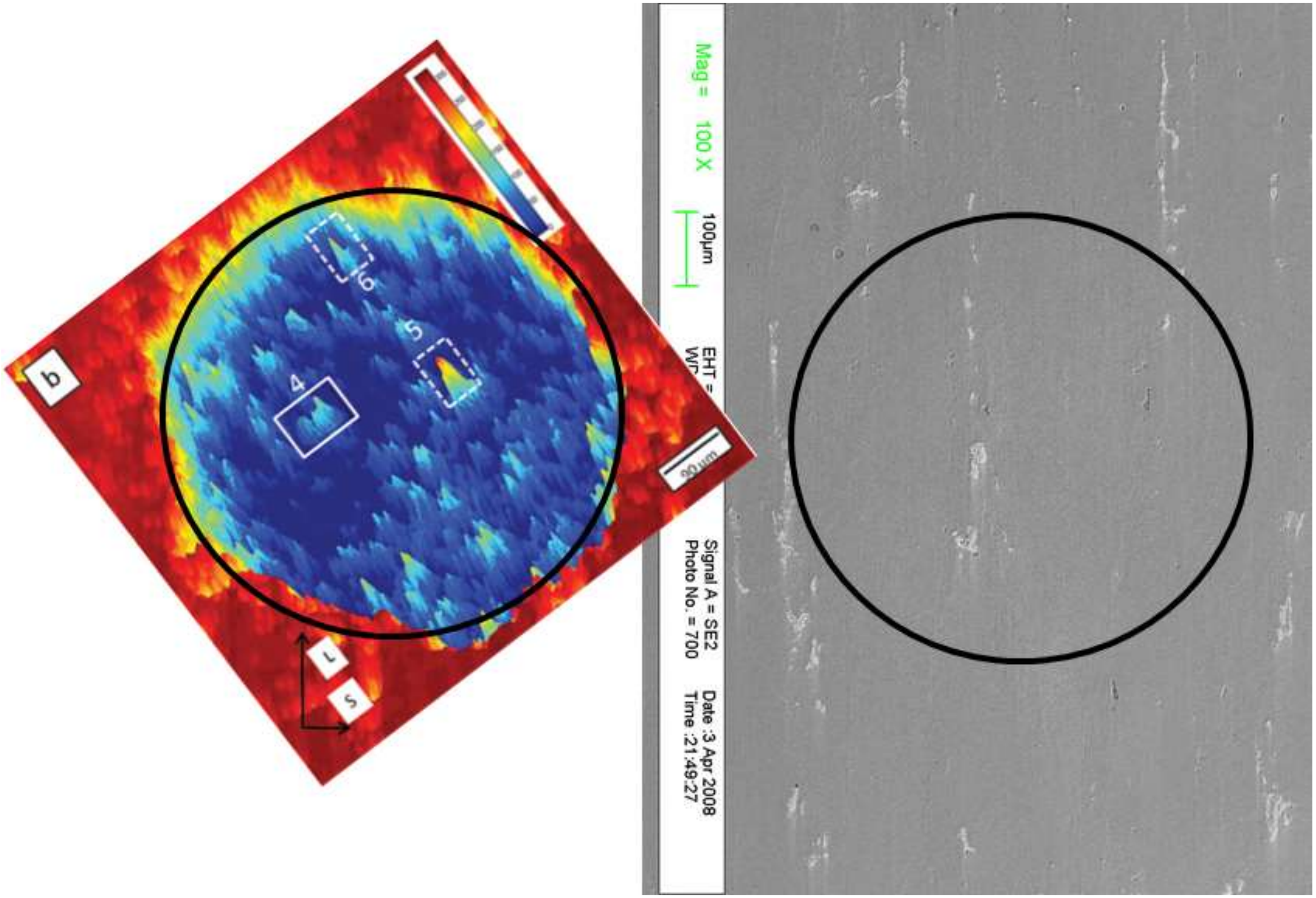


Micro pits Kt range from 3.83 – 4.48

Micro Jut–in Kt range from 3.65 – 4.26

Burns (2011)

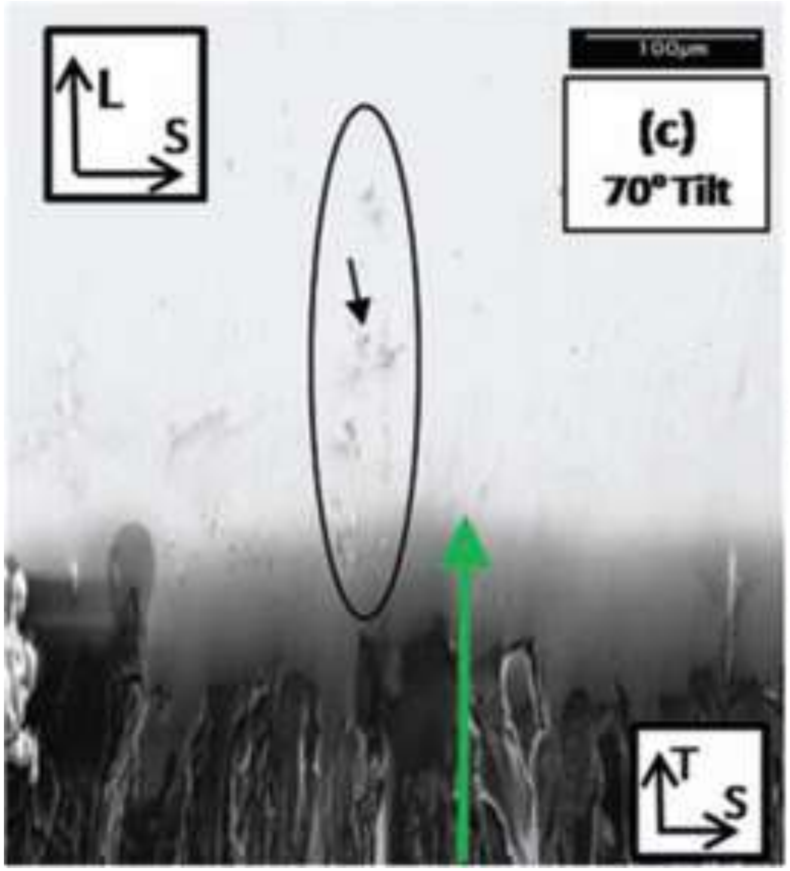
Influence of Inclusions



Burns (2011)

Material Microstructure Influence

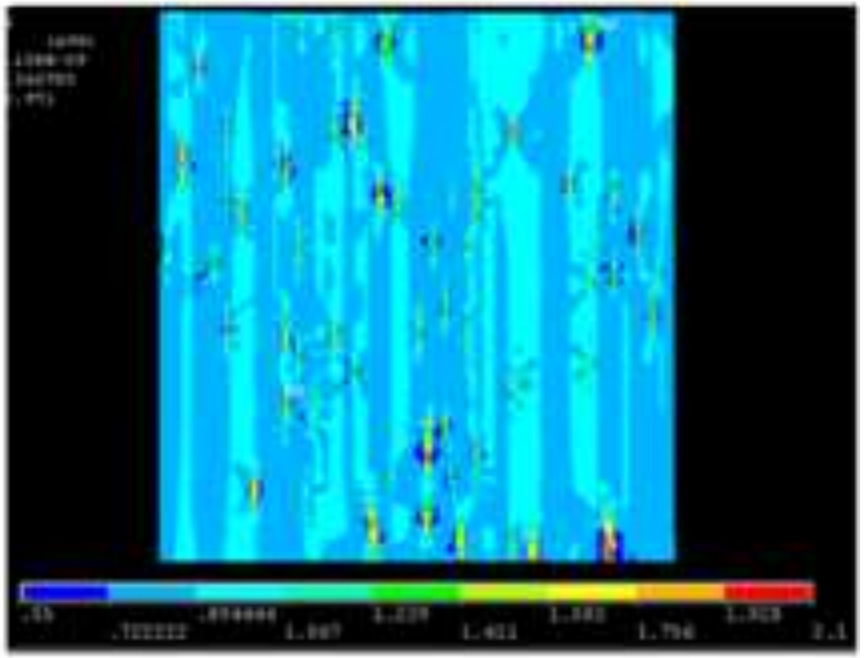
- Crack tend to form at material inclusions
  - 70° tilted SEM images of the intersection of the fracture plane (T-S) and polished (L-S) planes
  - Green arrows shows crack initiation location
  - Circled region is a stringer of inclusion particles



Burns (2011)

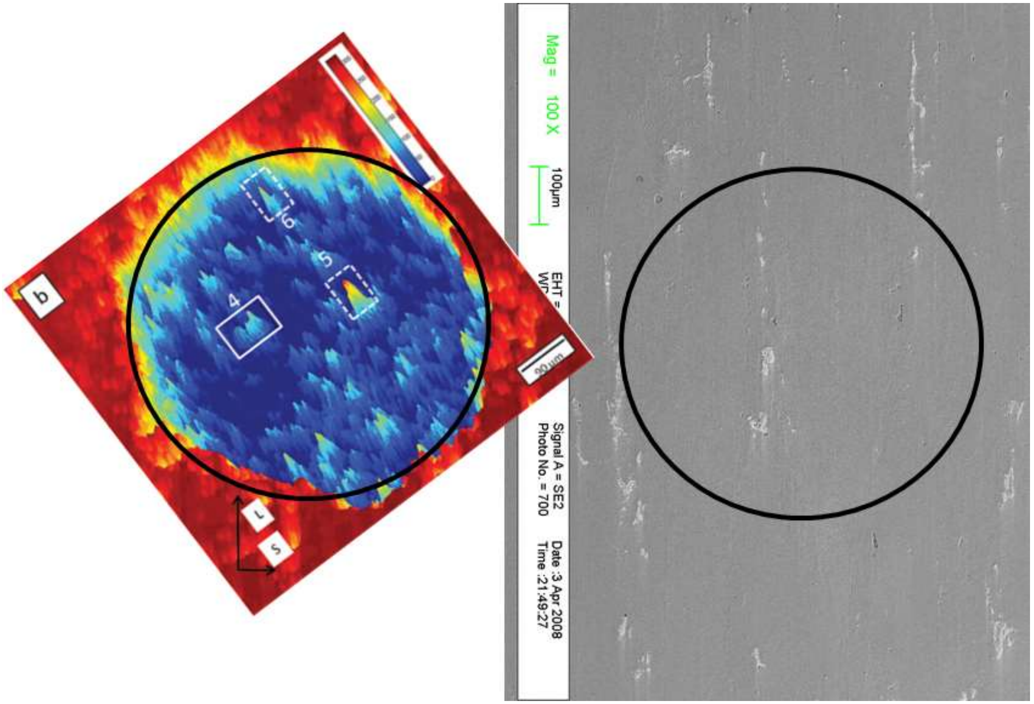
Stress: Material Microstructure

- K_t of the inclusion (~ 2)
- Variation caused by the grain anisotropy (±0.24)



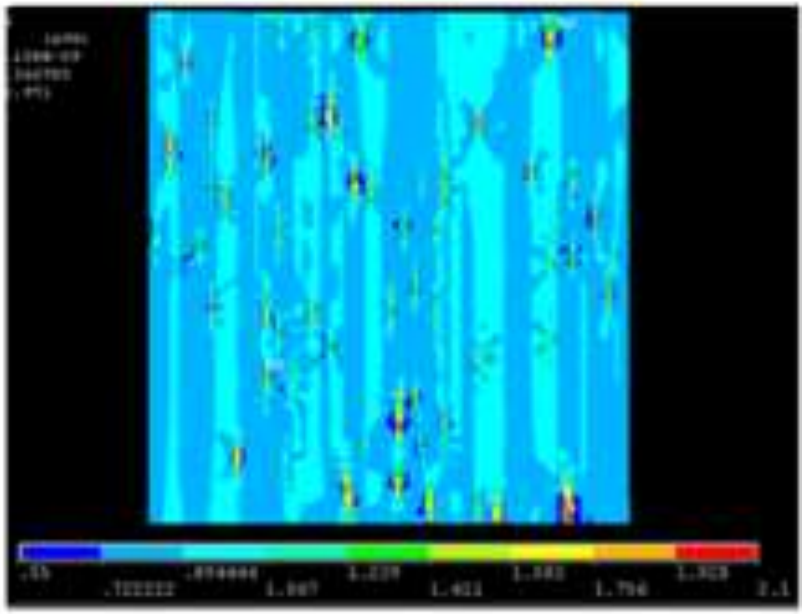
Stress Superposition

- Material microstructural inclusions are the limiting factor
- Model surface as a spatial distribution of inclusions
- Each inclusion has a Kt of ~2 multiplied by a random distribution of surface roughness Kt

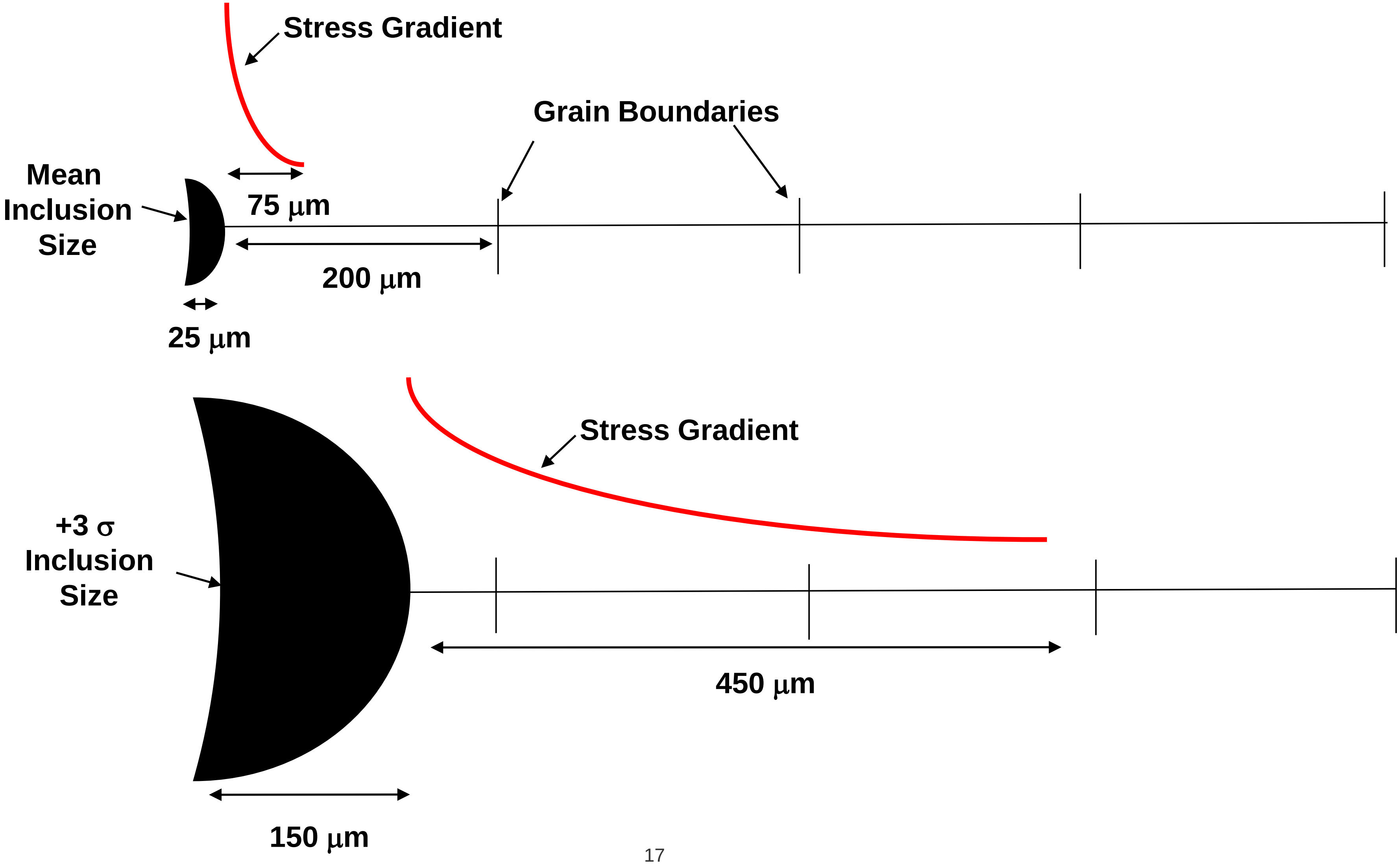


Stress Superposition

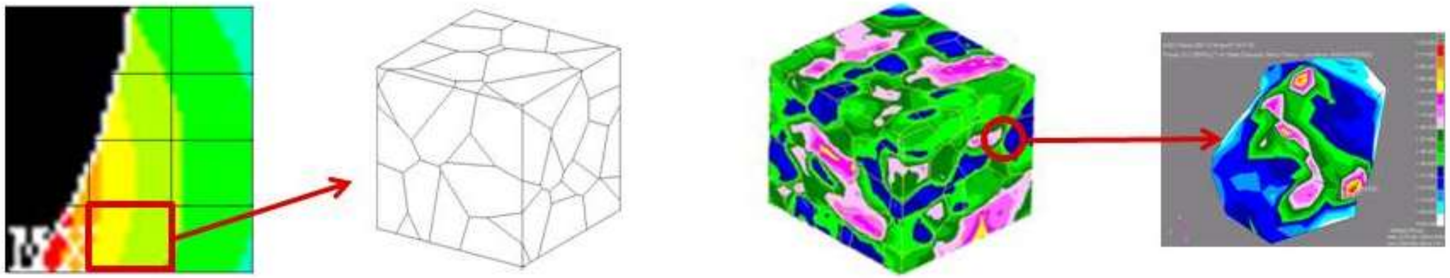
- Example
  - Assume fully roughened surface (no macro pit)
  - Each material inclusion has a Kt of ~2 multiplied by a random distribution of surface roughness micro feature (Kt of 1 to 4.5)
  - Kt at inclusions is a uniform random distribution between 2 and 9



Microstructural Crack Nucleation



Computational Model of Corrosion Fatigue



Initial Element

Superimpose Natural Substructure

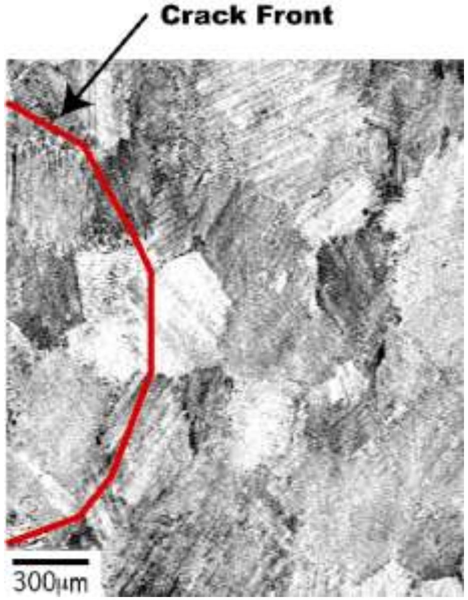
Map FEA Stress to Substructure

Translate Microstress to each Grain

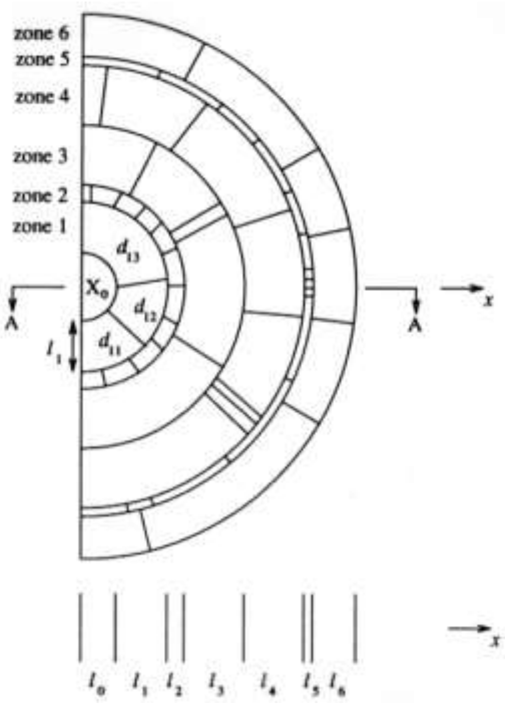
- Integrates structural FEA model stress information with the microstructure model.
  - A key feature of this approach is to separate the global FE model from the microstructural damage model.
  - This allows complex parts with a pre-existing FEA model to be analyzed efficiently
- Outcome: point-by-point description of the part with information necessary to apply the microscale corrosion fatigue damage model.
- Builds on VEXTEC's NNR SBA program with Navy

Small Flaw Fracture Mechanics

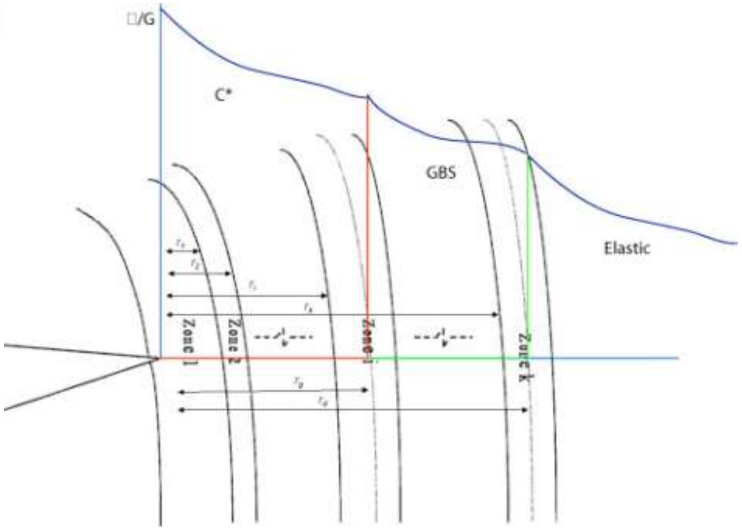
Top view of real crack



Top view of idealized crack



Side view of idealized crack



Computational Model of SFFM

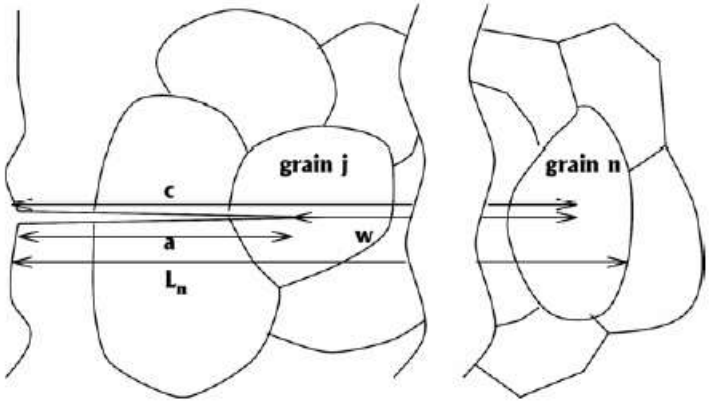
- Fatigue crack growth

$$\frac{da}{dN} = C'\Delta\phi_t$$

- Microstructurally small crack

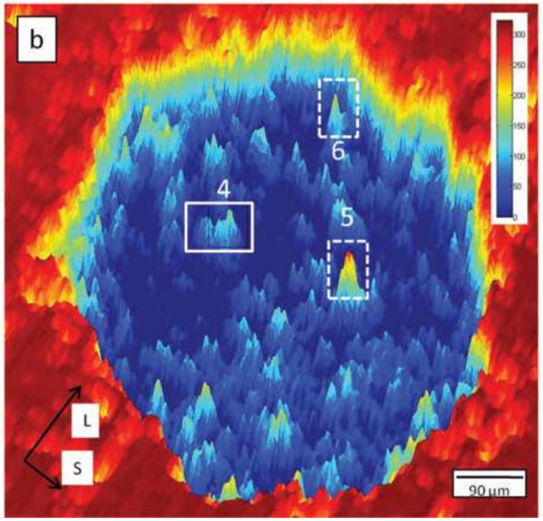
$$\phi_t = \frac{2k_j a}{\pi^2 A}\ln\frac{c}{a} + \sum_{i=j+1}^{n}\frac{\left(\tau_{i-1}-k_{i-1}\right)-\left(\tau_i-k_i\right)}{\pi^2 A}g\left(a;c,L_{i-1}\right)$$

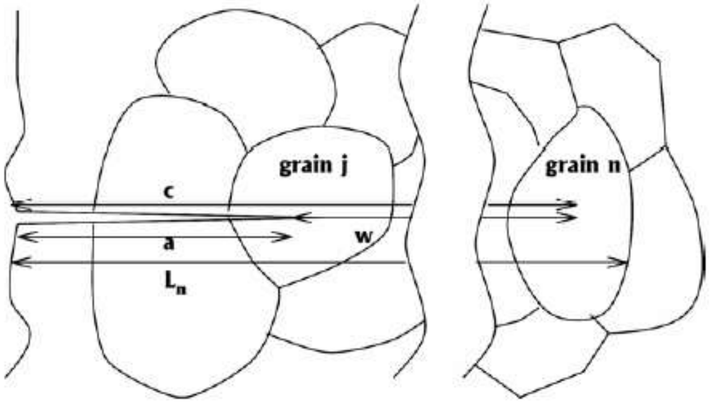
- Fracture mechanics approach



Model Corrosion Fatigue

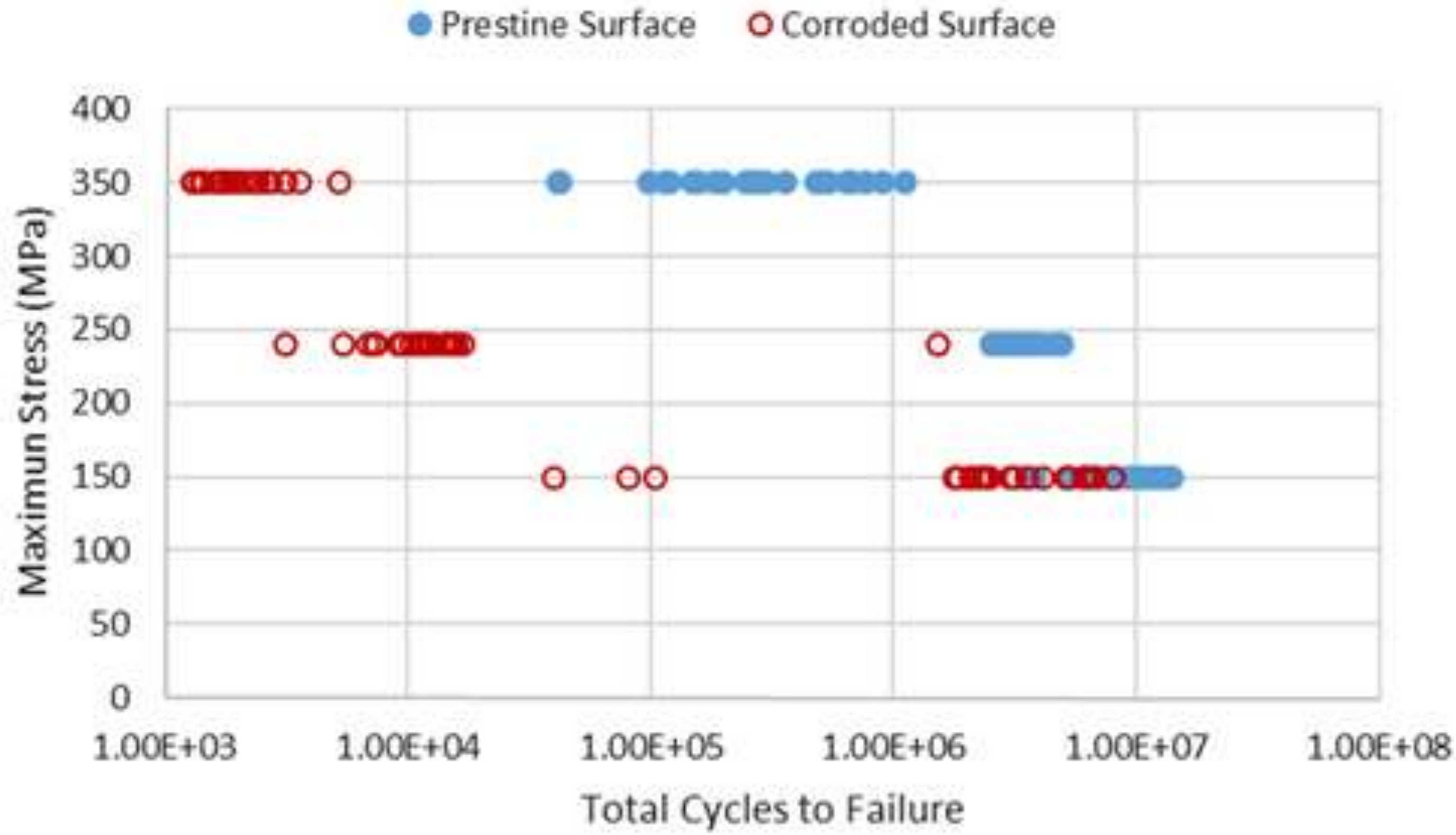
- Probabilistic multi-site fatigue
  - Crack nucleation at 2-D statistical distribution of inclusions with roughened surface
  - Crack growth through 3-D random field of microstructure



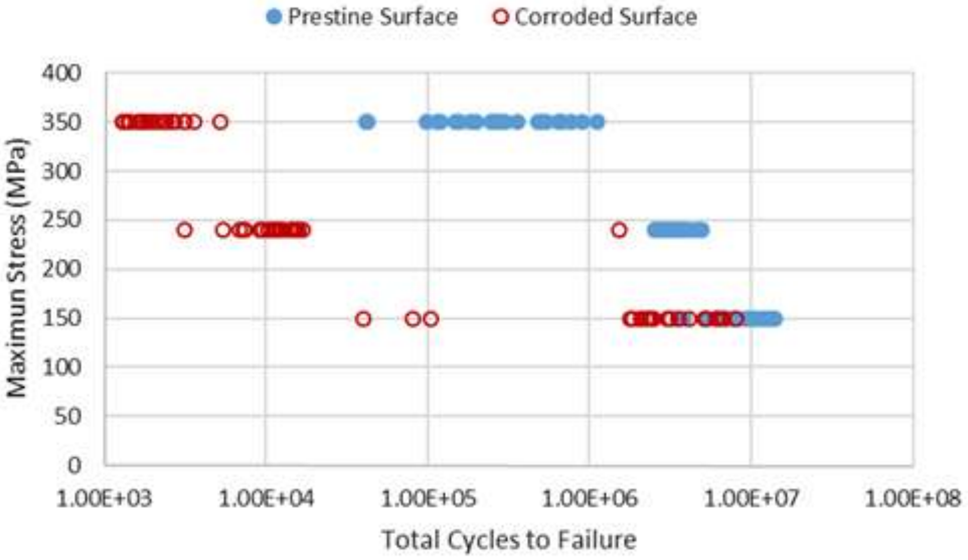


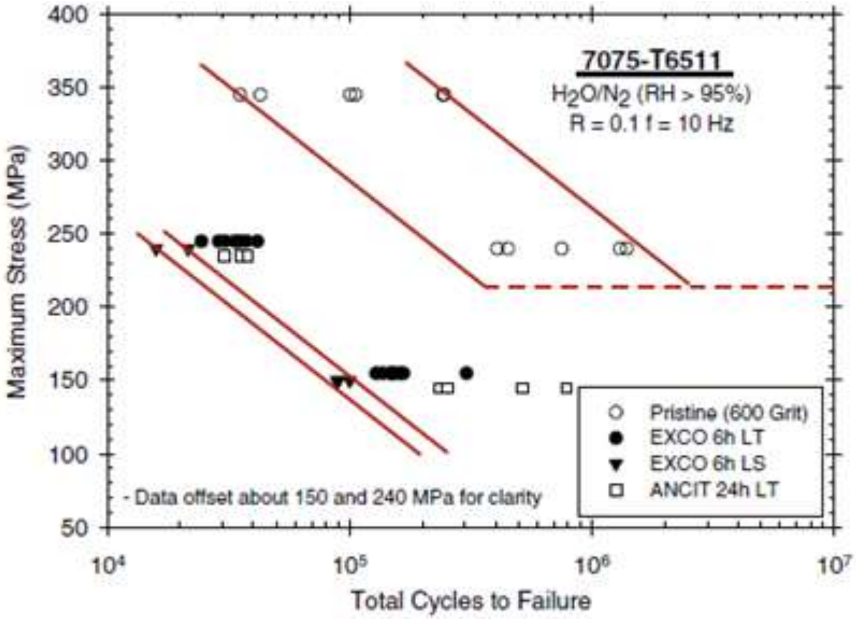
Simulation Output

Predictions for 7075-T651



Qualitative Comparison





Predictions for 7075-T651

Test data for 7075-T6511

Burns (2011)

Questions and Next Steps