# Quantifying Fretting Damage Using a Contact-Evolution Based Modelling Approach

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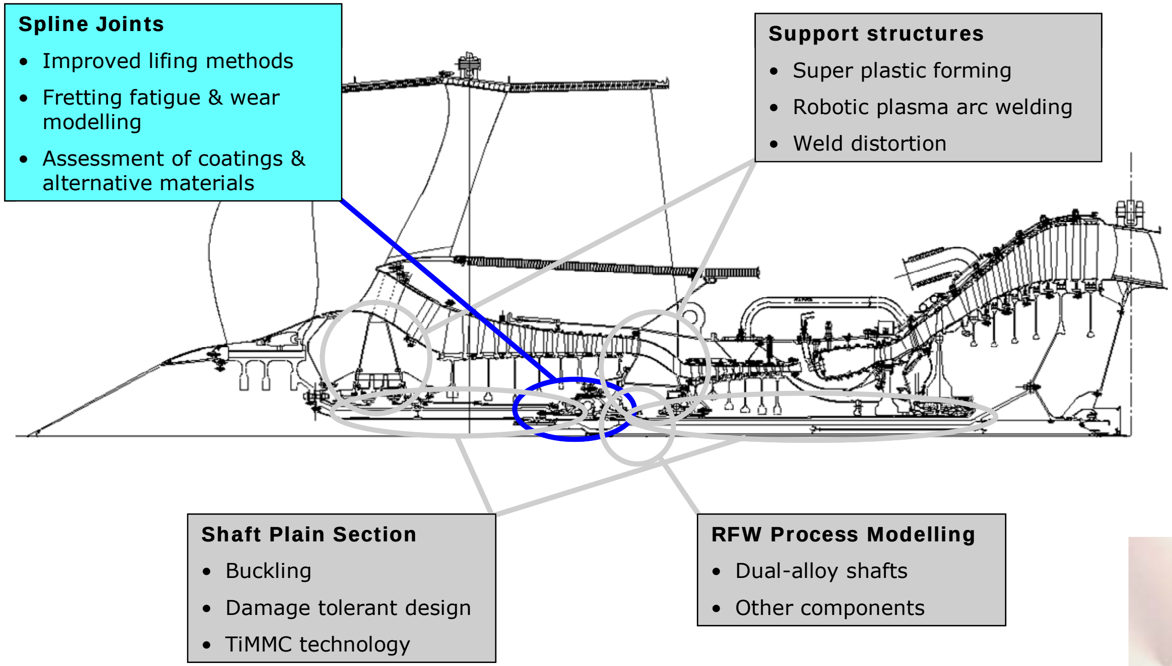
# Nottingham UTC in Gas Turbine Transmission Systems



**Spline Joints**

- Improved lifing methods
- Fretting fatigue & wear modelling
- Assessment of coatings & alternative materials

**Support structures**

- Super plastic forming
- Robotic plasma arc welding
- Weld distortion

**Shaft Plain Section**

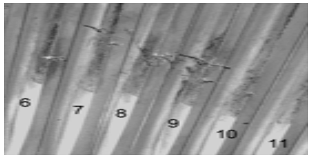
- Buckling
- Damage tolerant design
- TiMMC technology

**RFW Process Modelling**

- Dual-alloy shafts
- Other components

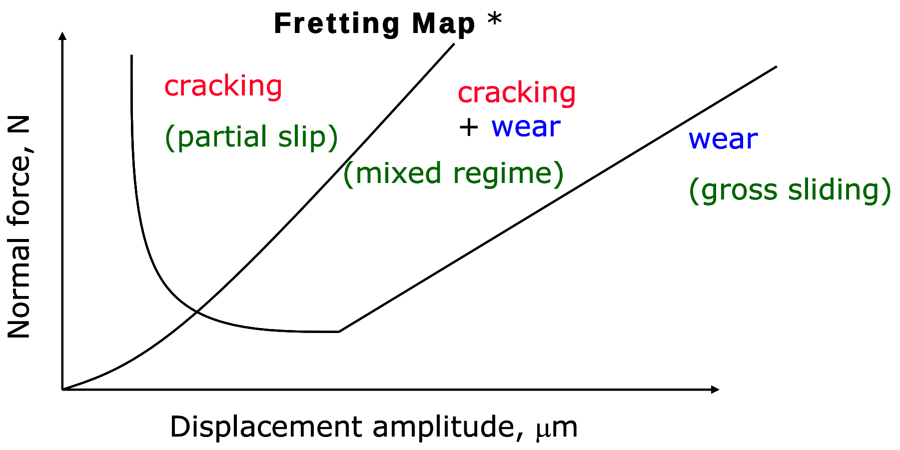
## Study of Spline Couplings

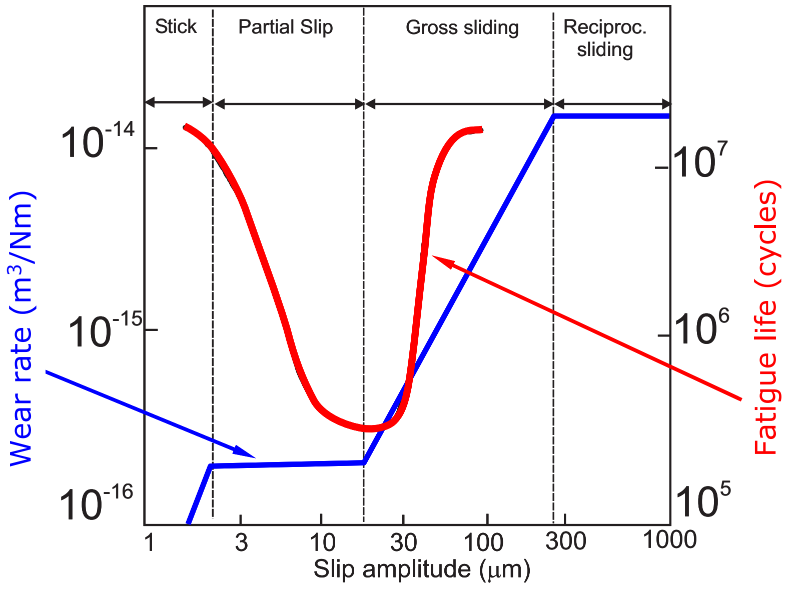
- Experimentally characterise the fretting behaviour of splines using scaled-down spline and/or representative specimens
- Develop lifing methodologies for spline against fretting



**Spline fretting failure**

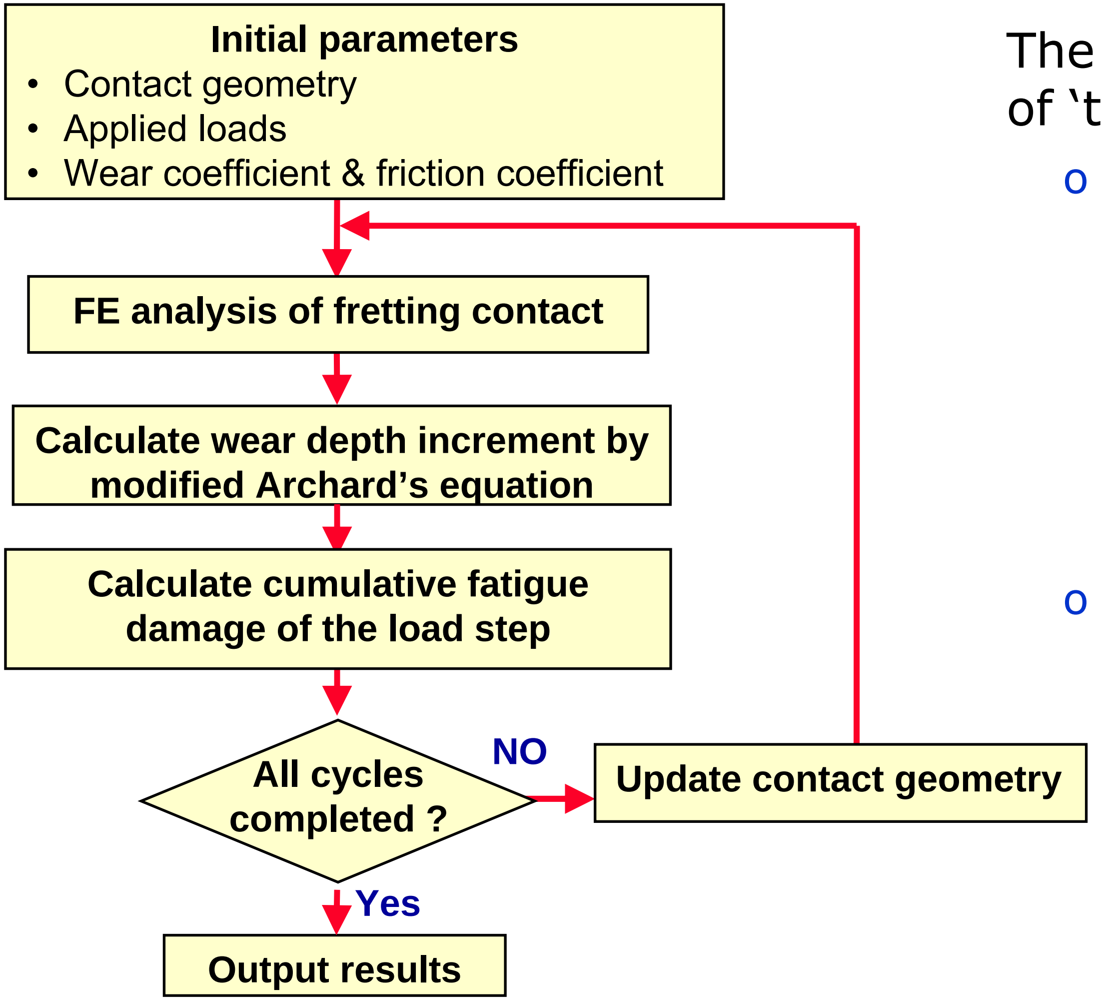
# Contact-evolution based lifing methodology





- An approach that considers transient interaction between wear and fatigue under fretting, especially the effect of wear on fatigue life.
- Contact-evolution based lifing approach comprises:
  - A finite element wear simulation tool to determine the evolution of contact geometry.
  - Damage Accumulation approach for crack nucleation.
- Ongoing EPSEC project in collaboration with Oxford (total grant ~0.6 Millions)

# Modelling Framework



**Initial parameters**

- Contact geometry
- Applied loads
- Wear coefficient & friction coefficient

**FE analysis of fretting contact**

**Calculate wear depth increment by modified Archard's equation**

**Calculate cumulative fatigue damage of the load step**

**All cycles completed ?**

**NO**

**Update contact geometry**

**Yes**

**Output results**

The approach integrates a number of ‘tools’.

- Fretting wear tool is central, which predicts the extent of wear damage and the concomitant change of contact geometry

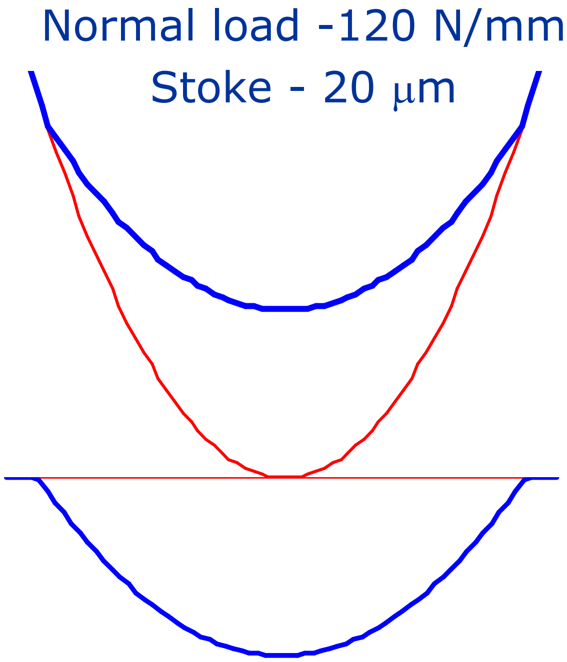
Archard’s Wear equation:

$$dh_i(x,t) = k_i \times p(x,t) \times ds(x,t)$$

- For each wear step n, accumulated fatigue damage is calculated by fatigue parameter Smith-Woston-Topper; thus, total accumulated damage is given by

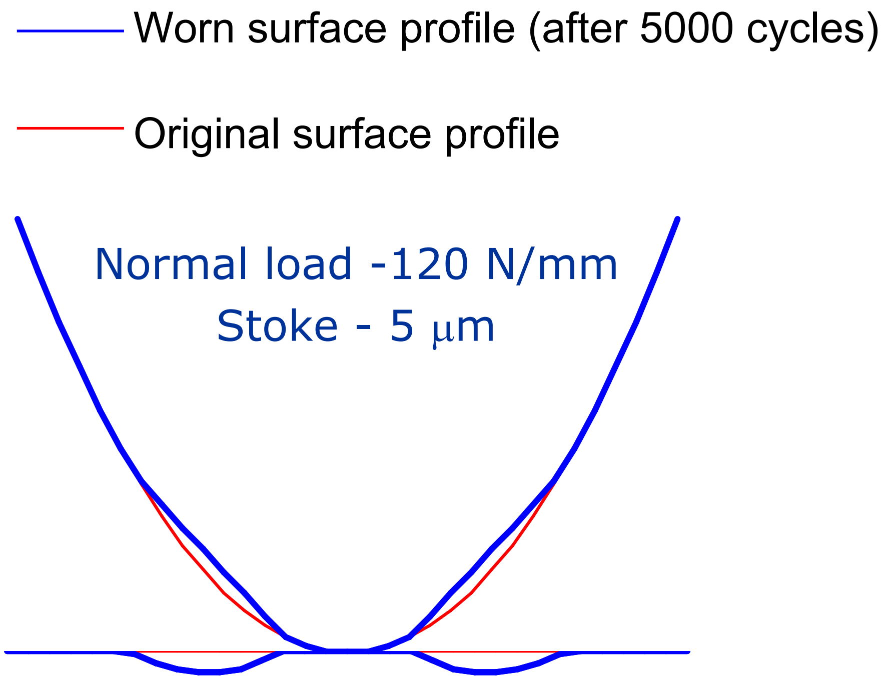
$$\varpi = \sum_{n=1}^{n=\frac{N_T}{\Delta N}} \frac{1}{N_{i,n}}$$

# Fretting Wear Modelling



Contact width increase markedly from Hertz prediction

Gross slip case

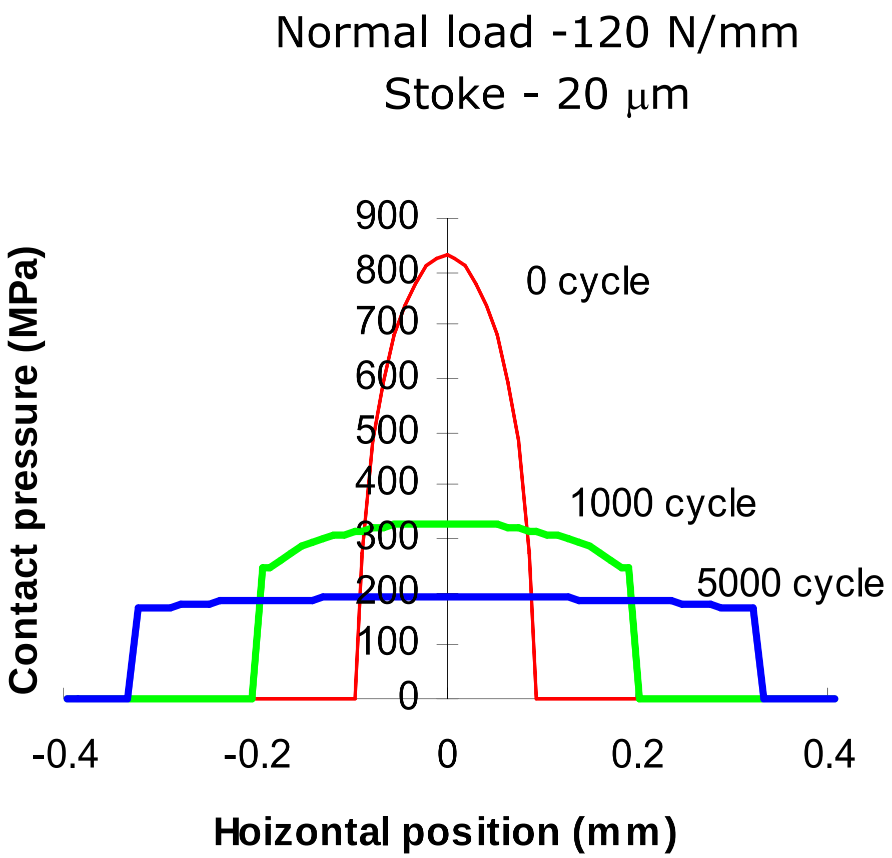


Little change of contact size, wear occurring at slip zone

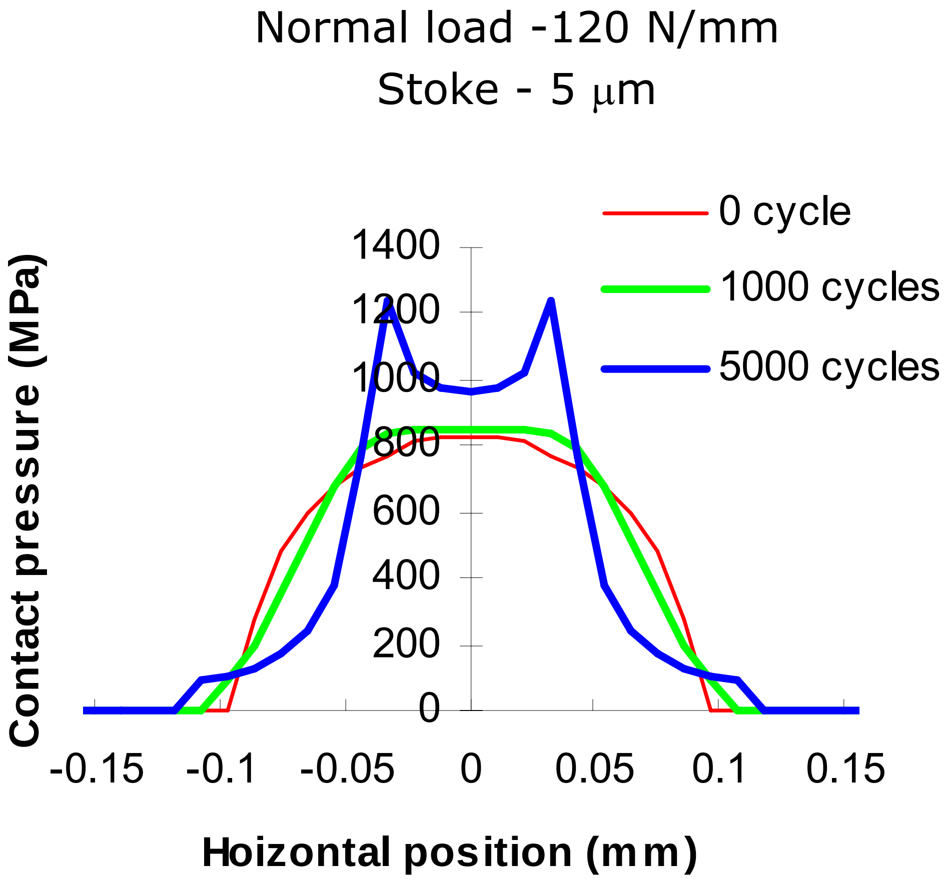
Partial slip case

**(Ding et al, *Int J of Fatigue*, 2004)**

# Fretting Wear Modelling



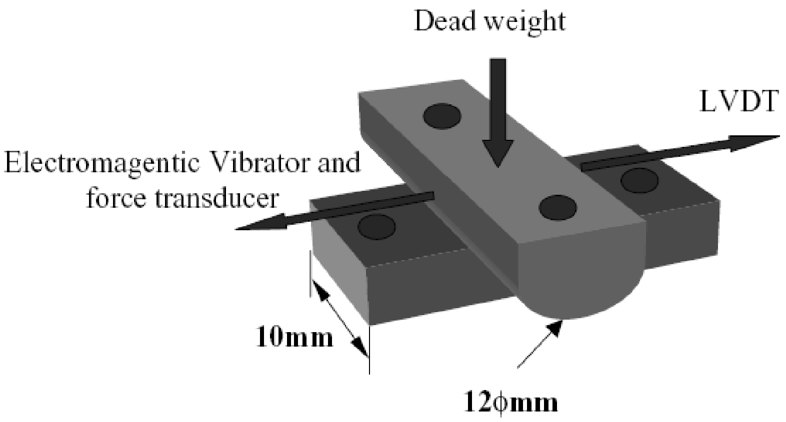
Gross slip case

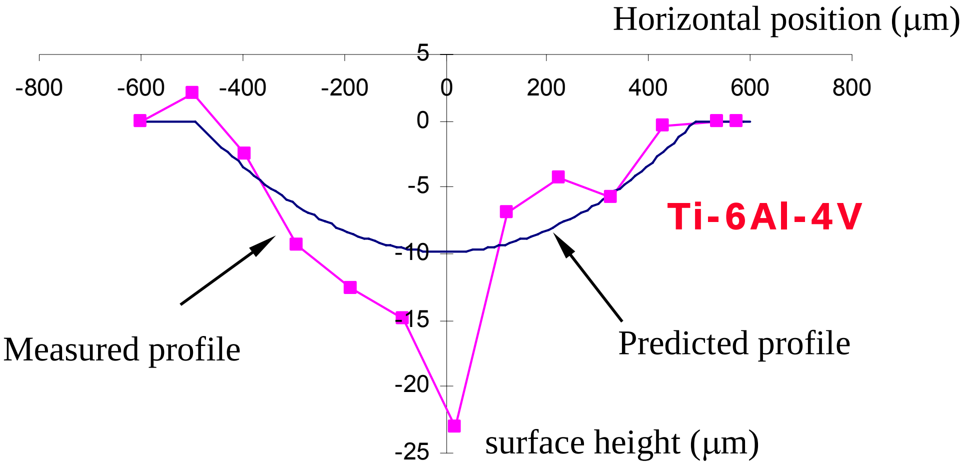


Partial slip case

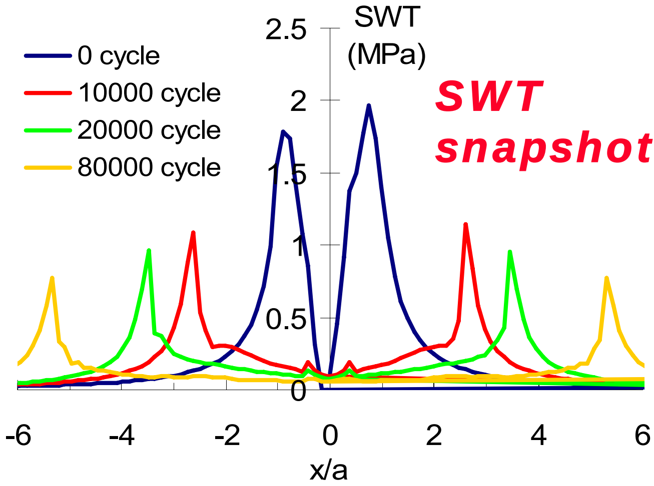
## Evolution of contact pressure

# Contact-evolution based prediction of crack nucleation (I) gross sliding

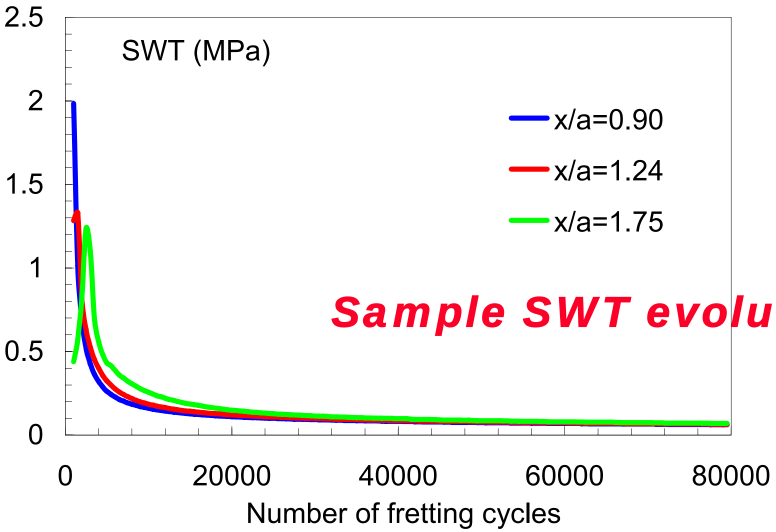




Ti-6Al-4V

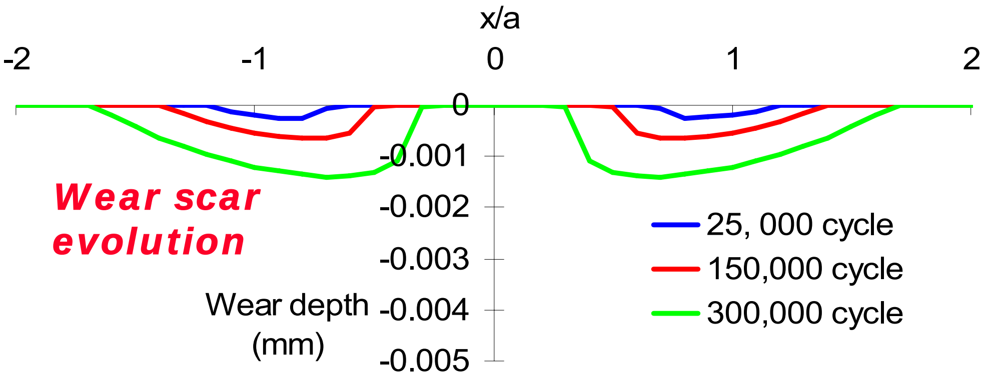


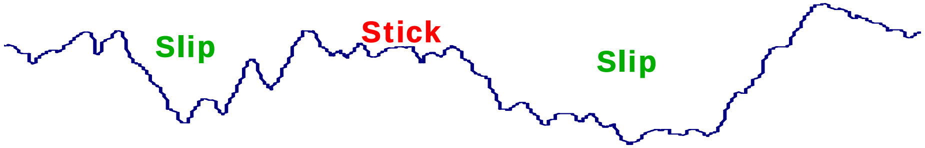
*SWT snapshots*

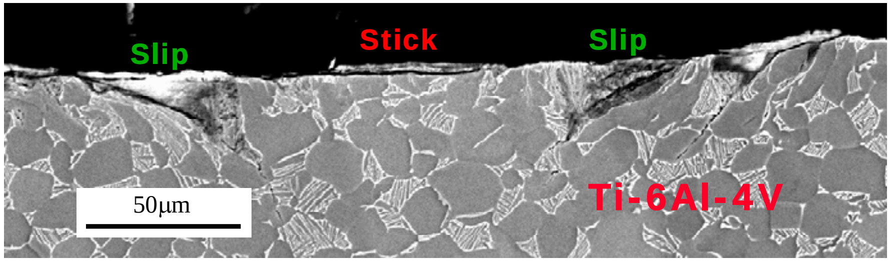


*Sample SWT evolutions*

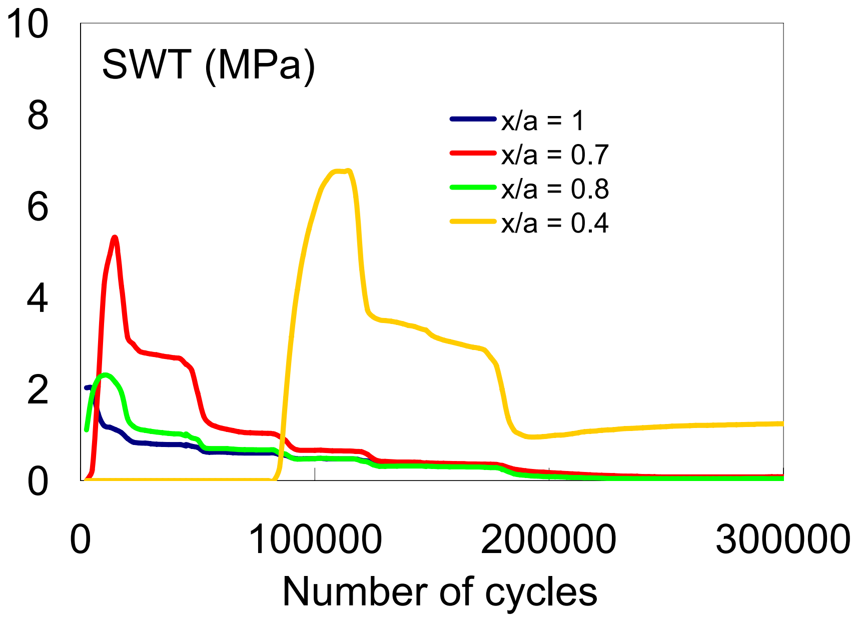
# Contact-evolution based prediction of crack nucleation (II) partial slip





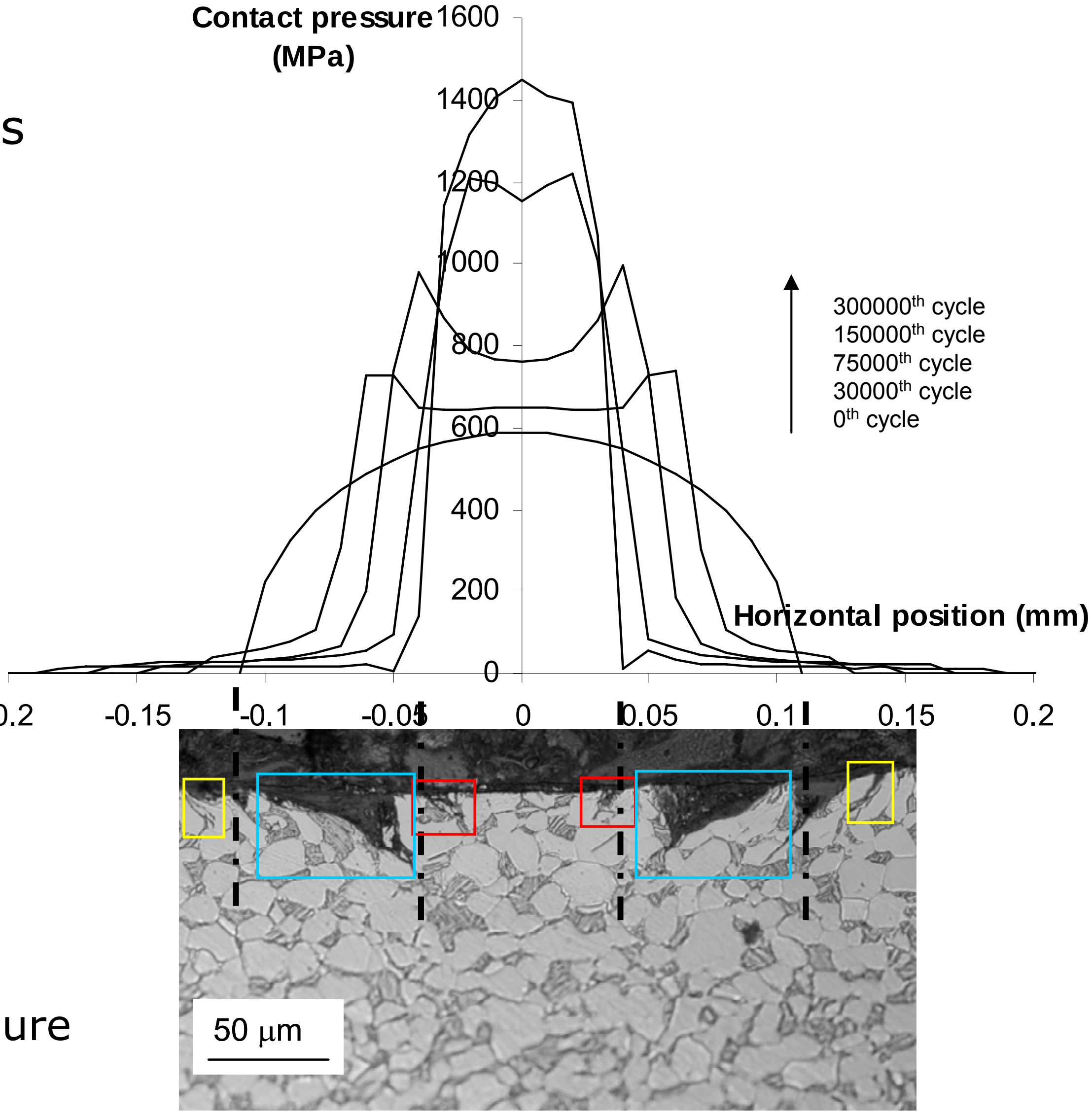


**Sample SWT evolutions**

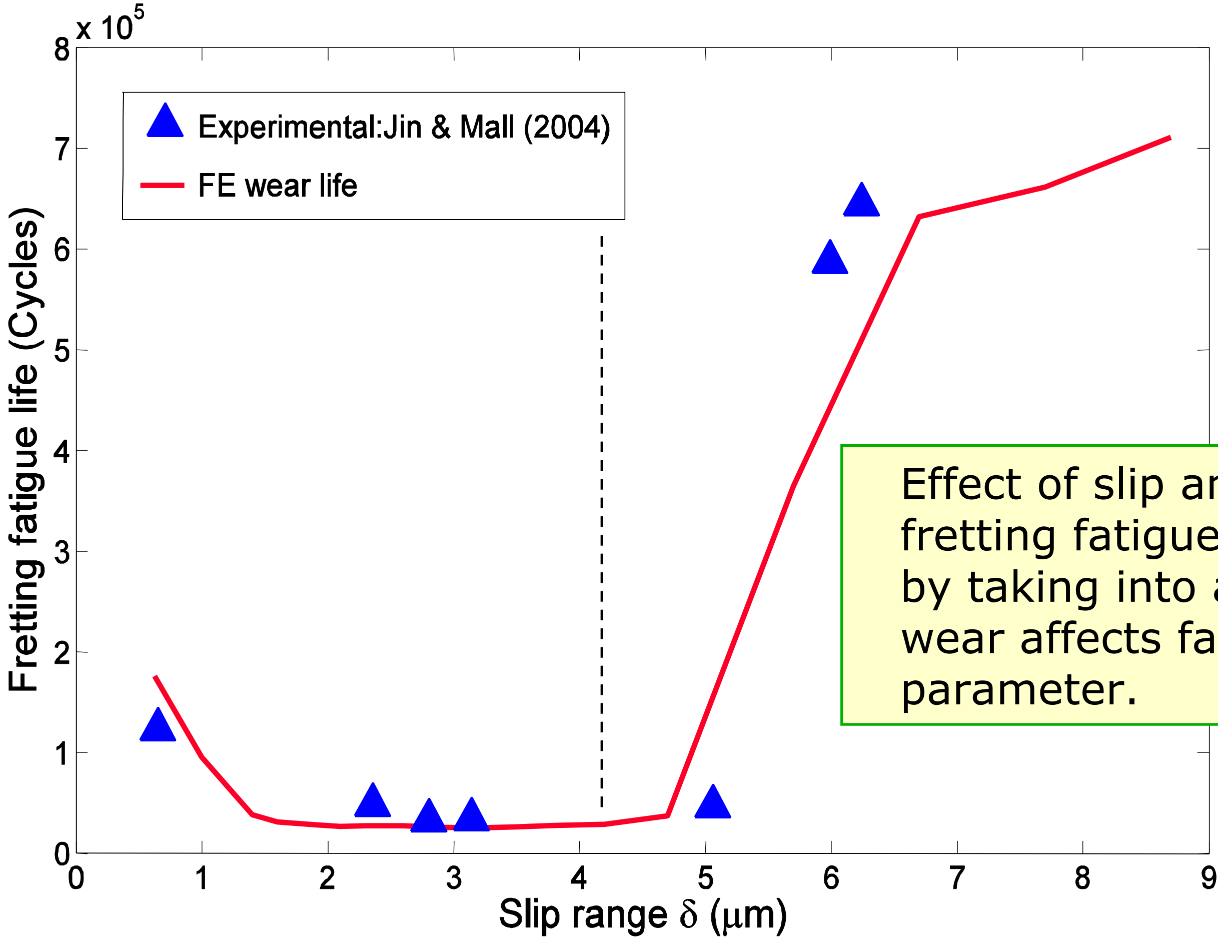


# Contact-evolution based prediction of crack nucleation (II) partial slip

- Complex pressure evolution predicted due to plasticity effects
- Multiple cracking locations
  - $x \approx \pm 0.11$ mm (light blue)
  - $x \approx \pm 0.04$ mm (red)
  - $x \approx \pm 0.13$ mm (yellow)
- $x \approx \pm 0.13$ mm
  - Initial Hertzian contact edge
  - early cycles, low COF: gross sliding ($N < 3$k)
- $x \approx \pm 0.04$ mm
  - ~ initial stick-slip boundaries
  - late cycles ($N \approx 150$k-300k)
- $x \approx \pm 0.11$ mm
  - intermediate cycles (3k $< N <$ 150k)
  - due to flat indenter type pressure peaks



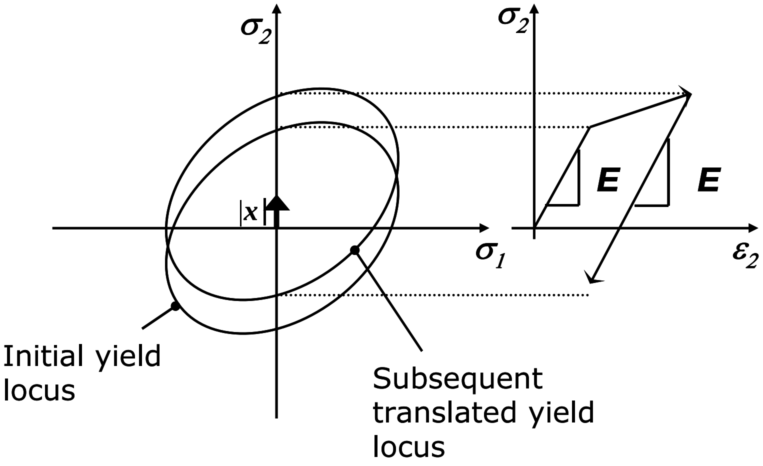
# Effect of slip amplitude on fretting fatigue



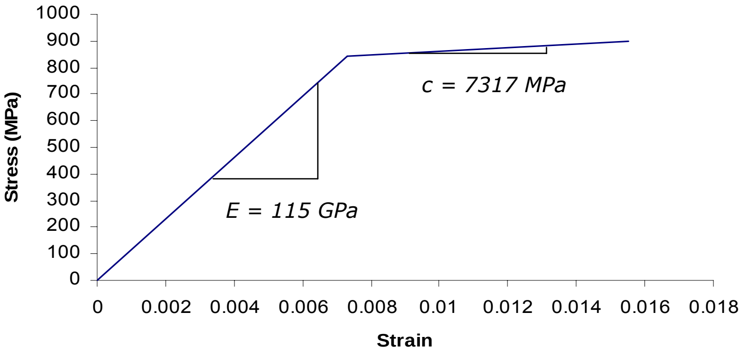
Effect of slip amplitude on fretting fatigue is captured by taking into account how wear affects fatigue damage parameter.

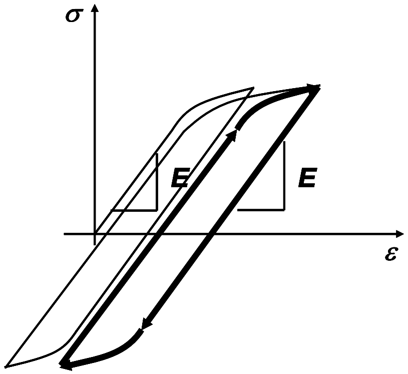
Prediction vs. tests (Madge et al, 2007)

# Cyclic Plasticity in Fretting

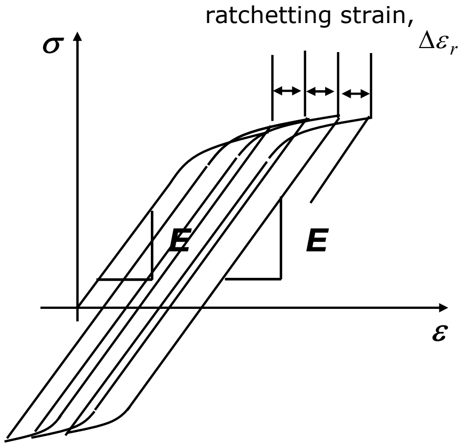


- Prager linear kinematic hardening
- Material: Ti-6Al-4V ($\alpha + \beta$)
- Coefficient of friction – 0.9





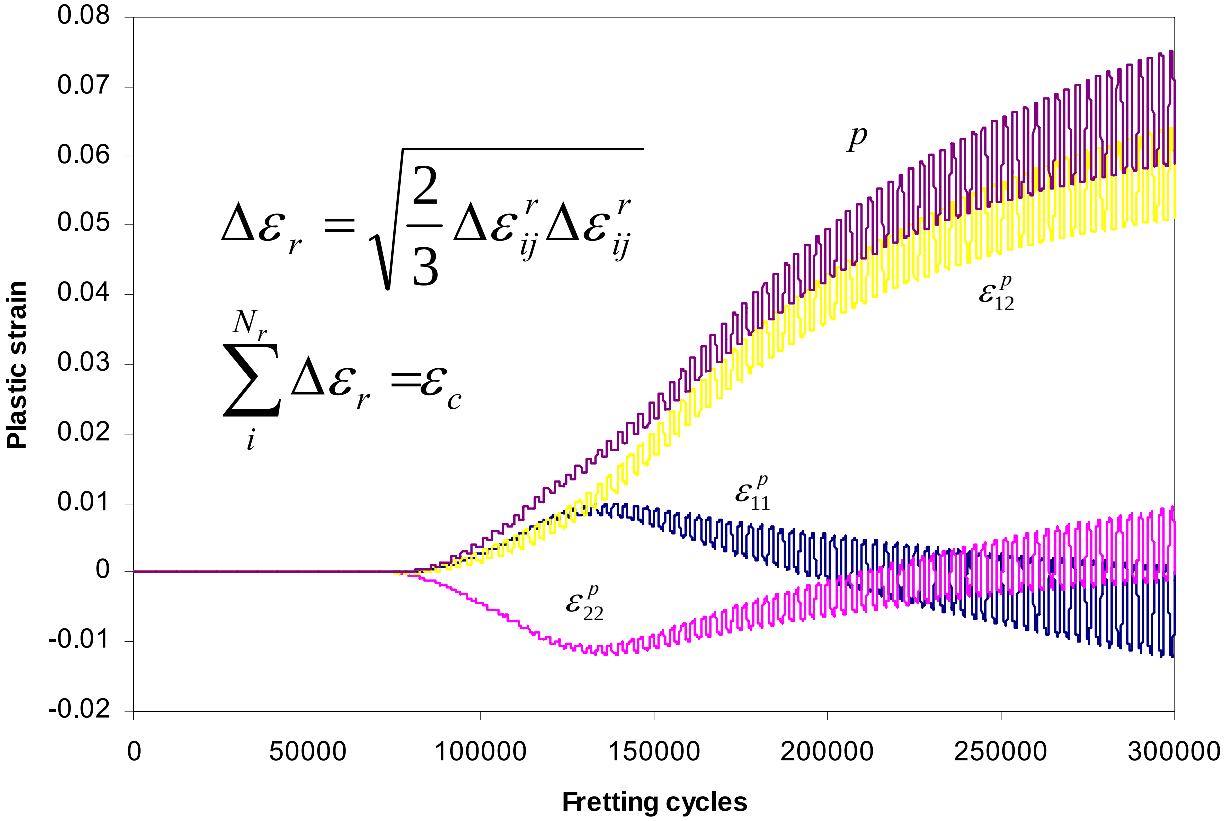
Plastic shakedown
steady reversed cyclic plastic strains



Ratchetting
plastic strain magnitude increases continually with load cycling

# Cyclic Plasticity in Partial Slip

- Nominal Hertzian geometry ➔ elastic
- Wear simulation with plasticity ➔ ratchetting phenomenon
- Possibility of damage/cracking due to ductility exhaustion



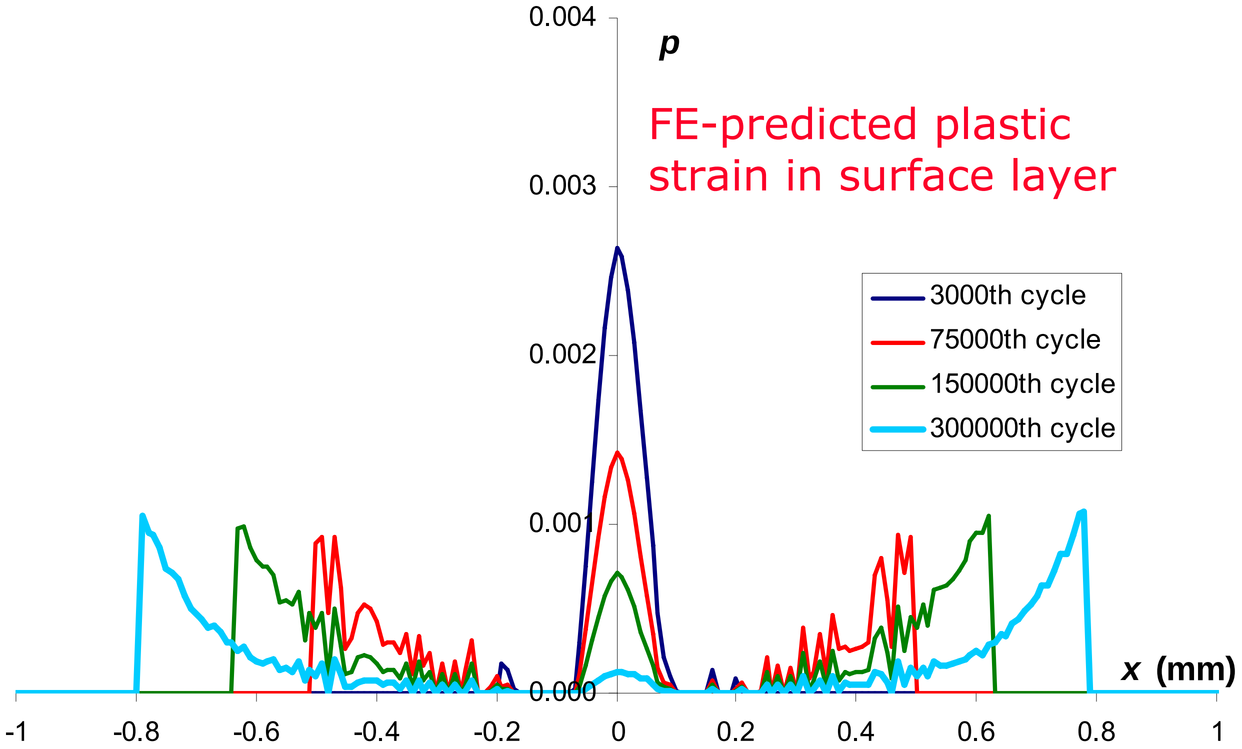
$$\Delta\varepsilon_r = \sqrt{\frac{2}{3}\Delta\varepsilon_{ij}^{r}\Delta\varepsilon_{ij}^{r}}$$

$$\sum_{i}^{N_r}\Delta\varepsilon_r = \varepsilon_c$$

**Predicted wear-induced evolution of plastic strains at final stick-slip interface**

# Cyclic Plasticity in Gross Sliding

- Gross sliding: shear-dominant plasticity
- g.s. plasticity take a W-shape
- Wearing away of plasticity ➔ reduction in equivalent plastic strain



FE-predicted plastic strain in surface layer

# Conclusions and Future Challenges

- Contact-evolution based fretting lifing methodology provides
  - an integrated solution for fretting wear and fatigue prediction.
  - a convincing explanation about the effects of slip amplitude on fretting fatigue
- Future challenges:
  - Incorporate near-surface effects into fretting fatigue prediction, such as asperity, oxidation, plasticity and debris accumulation. How important are they for fretting crack nucleation?
  - Fretting contact mechanics under micro or nano scales.

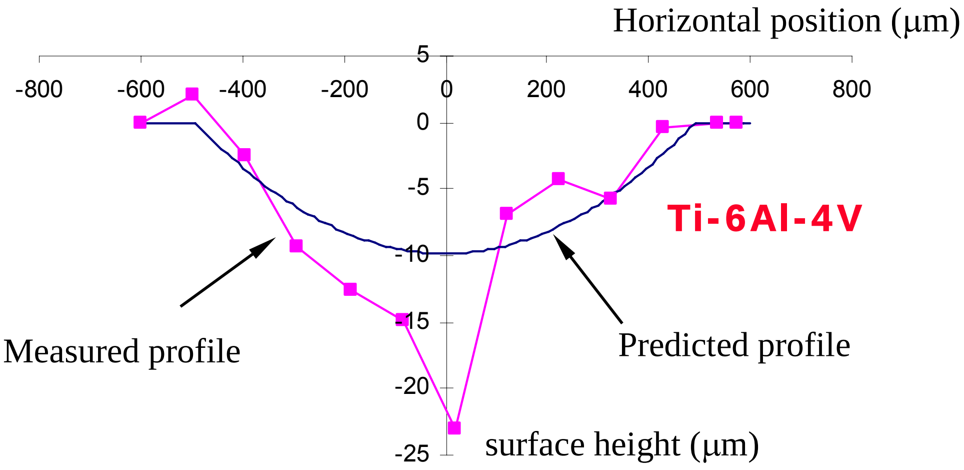
# Contact-evolution based prediction of crack nucleation (I) gross sliding

Crack nucleation defined to occur at material point *i* when accumulated damage $\varpi$ reaches value of 1, where $\varpi$ is defined as :

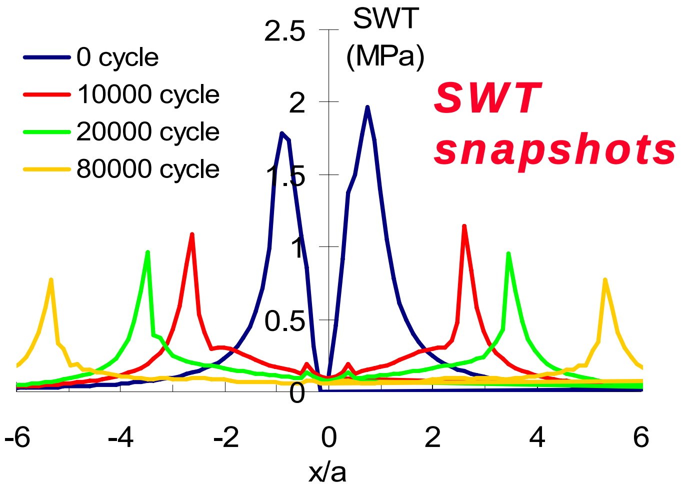
$$\varpi = \sum_{n=1}^{n=\frac{N_T}{\Delta N}} \frac{\Delta N}{N_{i,n}}$$

Each $N_{i,n}$ is calculated based on a critical-plane fatigue damage parameter Smith-Watson-Topper (SWT).

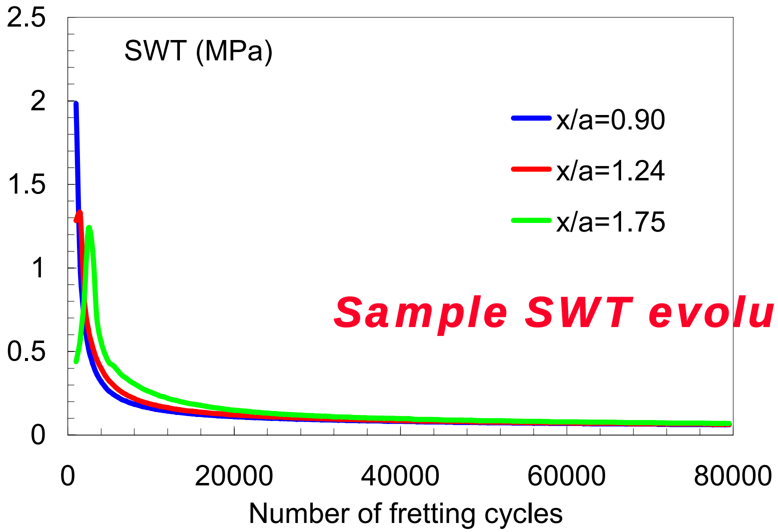
$$(\sigma_{\max}\Delta\varepsilon_a)_{i,n} = \frac{(\sigma_f')^2}{E}(2N_{i,n})^{2b} + \sigma_f'\varepsilon_f'(2N_{i,n})^{b+c}$$



**Ti-6Al-4V**



***SWT snapshots***



***Sample SWT evolutions***