ICAF
International Committee
on Aeronautical Fatigue
and Structural Integrity

39th Conference & 32nd Symposium of the International Committee on Aeronautical Fatigue and Structural Integrity

Plantema lecture

Fatigue – a Quantitative Fractography perspective and its uses in Aircraft Structural Integrity

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International Committee
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Plantema lecture

Alternatively:
Where we are and why there are still so many questions -
a look back at what we think we know and what we clearly do not fully understand about fatigue - from a fractography perspective

Professor Simon Barter, 2025

But first, a little about me:

Simon Barter, currently a professor at Royal Melbourne Institute of Technology (RMIT)

40 years service with the Defence Science and Technology Group (previously Aeronautical Research Laboratory), at Fishermen's Bend Melbourne, Australia

- Defect assessment and failure analysis
- NDI investigations
- Aircraft incident and accident investigations
- Full-scale fatigue tests: Mirage III, CT4, Nomad, Macchi trainer, F111, F/A-18A/B/F/G, PC9, C130………
- Aircraft Structural Integrity investigations mainly for fighters
- Researched fatigue crack growth mainly in aluminium alloys, ultra-high strength steels and Ti 6Al 4V.

The difficulties in fatigue prediction

- Even given methods of dealing with the uncertainties and the vast array of crack growth models and data available, crack growth estimates in controlled tests are often not as good as could be hoped, and the prediction of the lives of full-scale tests can disappoint, since fatigue is:
  - Composition sensitive.
  - Microstructure sensitive.
  - Loading sensitive.
  - Scale sensitive.
  - Environment sensitive.

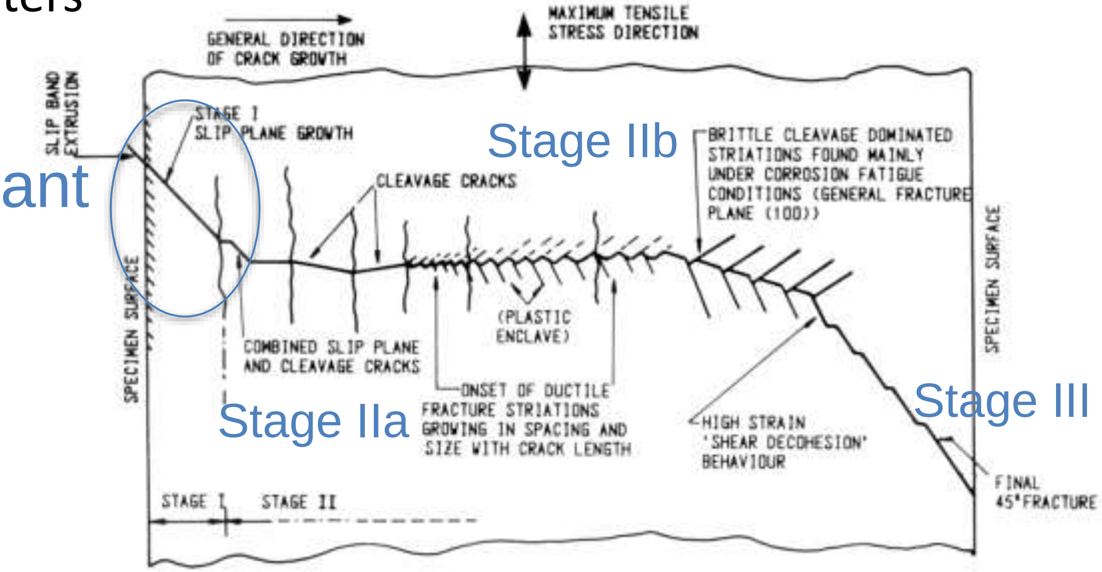
There are a host of new capabilities that can be used to aid fractography

- Improved FE SEMs
- Interferometers
- Atomic force microscopes
- EBSD, better BSE sensors
- Helium Ion microscopes
- Improved optical microscopes, etc.
- A vast suit of software for image manipulation

Enter the further study of fatigue fracture surfaces

Fatigue life predictions and fractography

- Fatigue cracks in aircraft structure often start from small discontinuities (0.01mm)
- At this scale, the cracks are particularly:
    - Material, grain size, loading, grain orientation & environmentally sensitive
- This sensitivity can persist to large sizes, and can re-appear if loads drop at larger crack sizes
- Fractography can help here since it is not restricted to the same limitations as NDI and can give growth information at most scales: from nanometres to meters

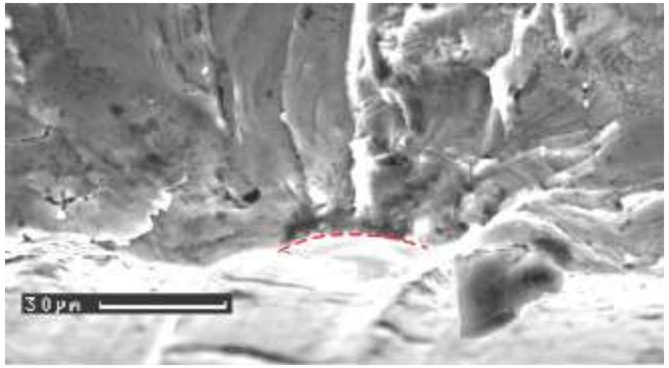


Forsyth's schematic drawing for constant amplitude growth – is it still wildly used to represent of the fatigue cracking process

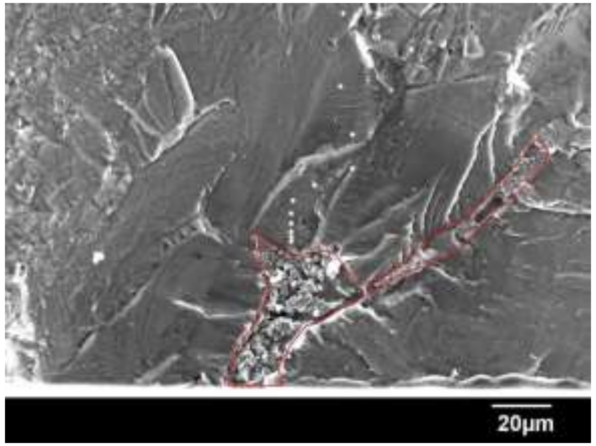
Constant amplitude = CA
Variable amplitude = VA

Discontinuities make Stage I nucleation irrelevant in aircraft parts

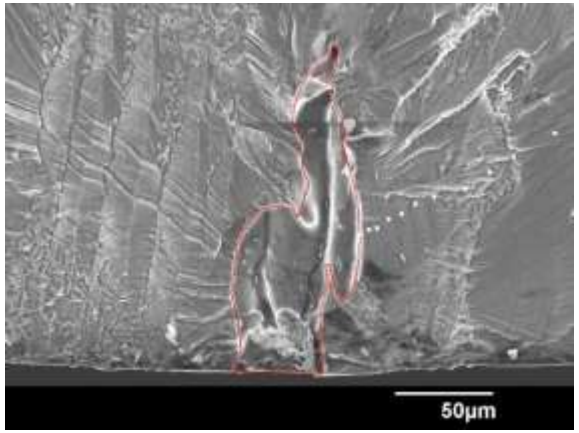
Machining marks



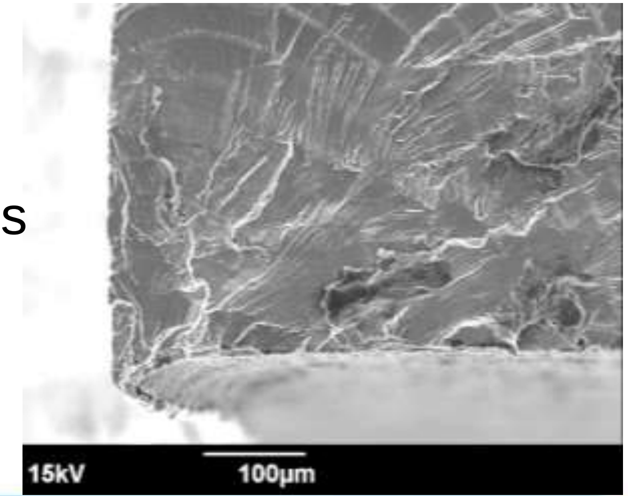
Inclusion clusters



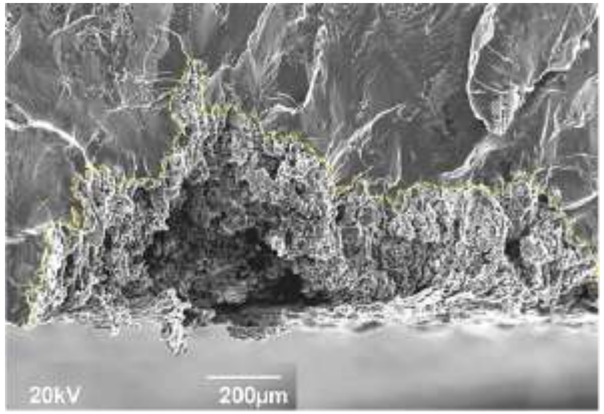
Porosity



Burrs



Corrosion

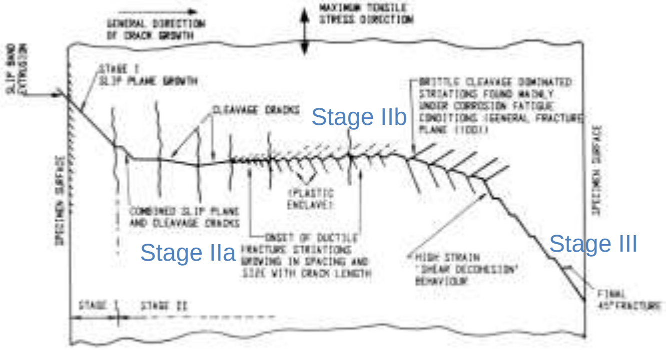


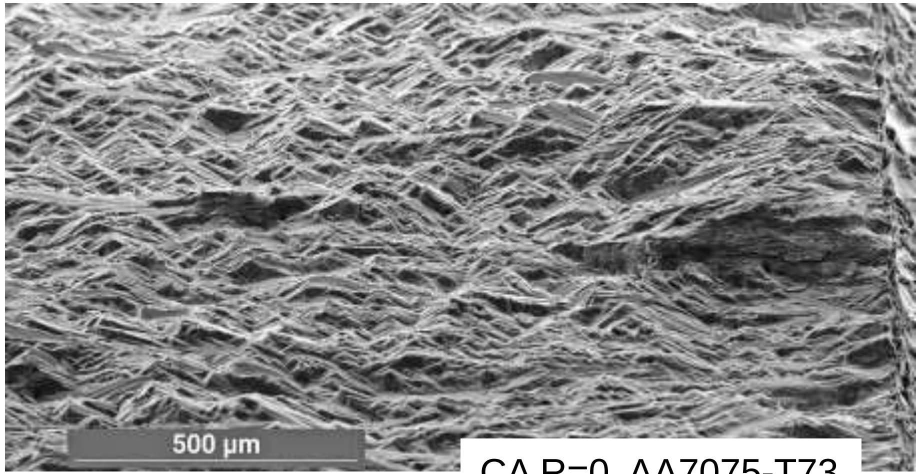
Natural cracks usually nucleate from small discontinuities

- Pits
- Inclusions
- Scratches
- Tears
- Porosity
- Lack of fusion
- Etc.

Stage II Are fatigue cracks flat?

- Fatigue cracks may appear to be flat or reflective on a macro scale, but on a small scale they rough and facetted over most of their life
- CA produces rougher surfaces than VA cracks, but both have high local angular planes
- *Cracking is rarely purely perpendicular to the loading direction*



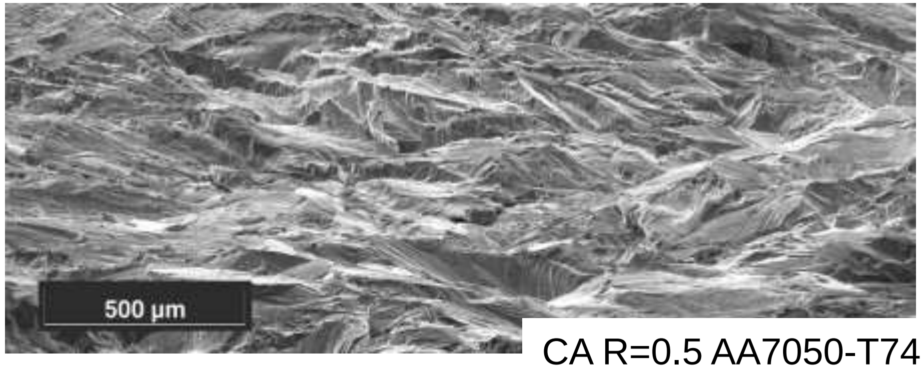


growth

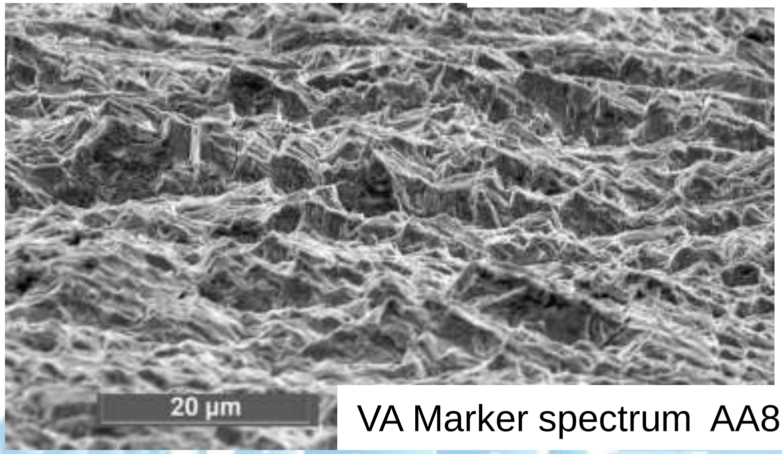
CA R=0 AA7075-T73

Viewed at 70°

Aluminium
Copper
Brass
Steel
Stainless steel all look the same at high angles



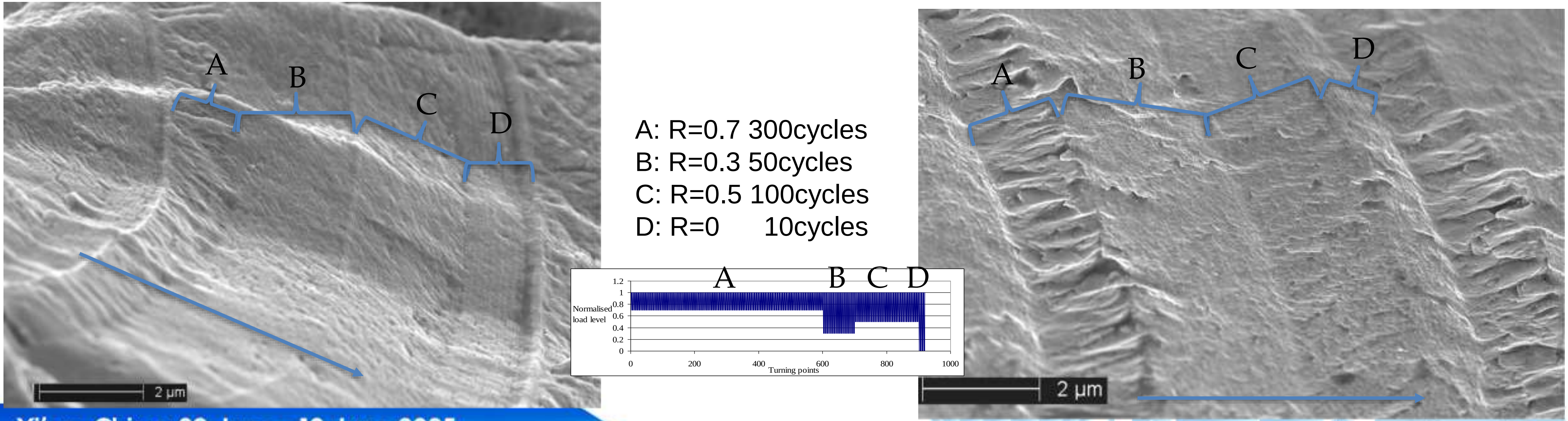
CA R=0.5 AA7050-T7451



VA Marker spectrum AA8090

Why are cracks not flat,?

- Cracks follow the damage during the tension semi-cycle so are rarely growing directly ahead of the crack tip and perpendicular to the loading
- Changes in R can induce changes in the crack growth path and topography because opening and closing are quite different – the closing semi-cycle does not extend the crack, but collapses the crack tip – more latter.
- Practical outcome: Big R and big ΔK differences can mark surfaces
- There are features here that do not sit well with symmetrical striation models - latter

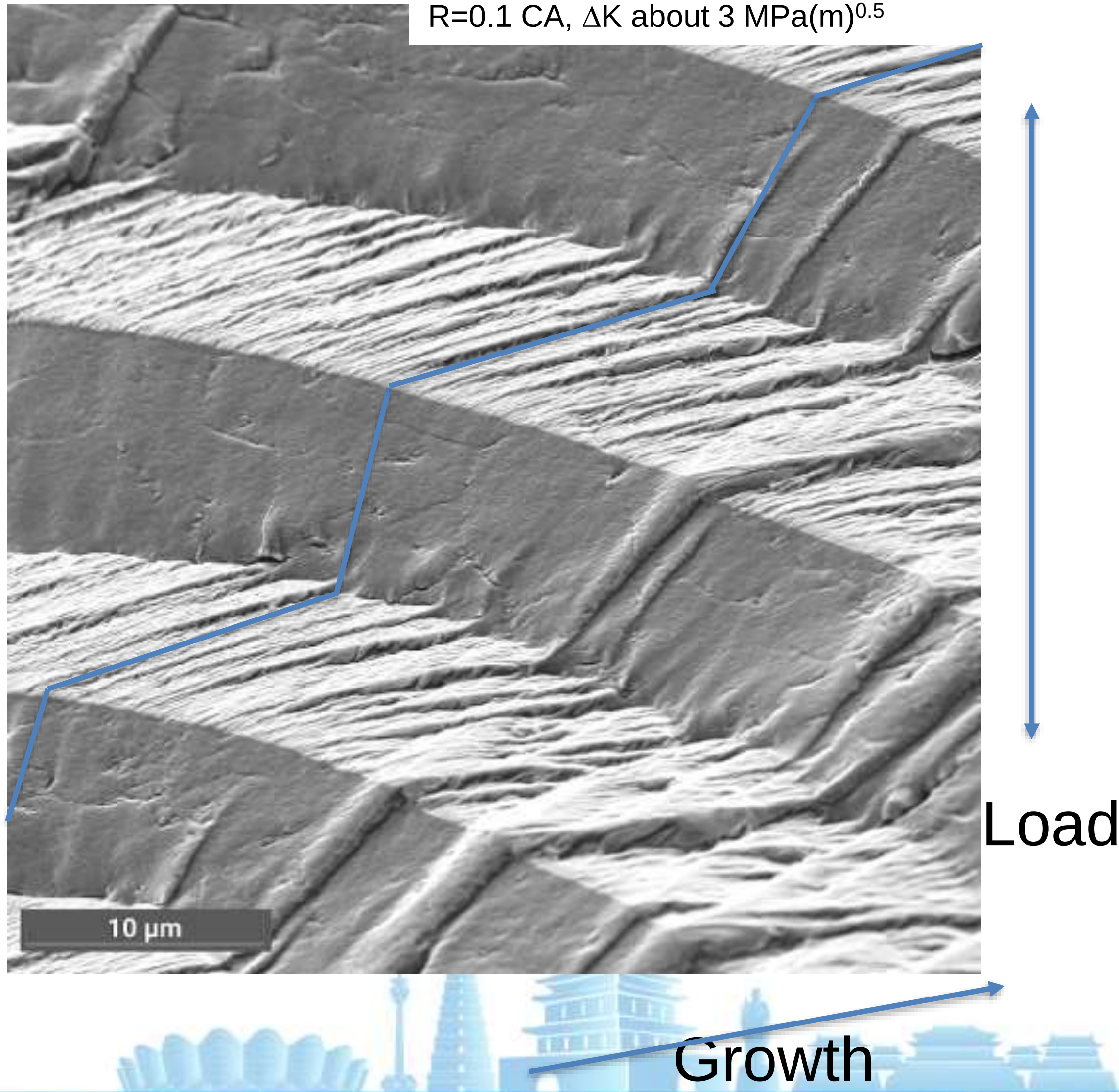


A: R=0.7 300cycles
B: R=0.3 50cycles
C: R=0.5 100cycles
D: R=0 10cycles

Load changes result in path changes

Alternating R=0.1 & 0.8, same K_{max}

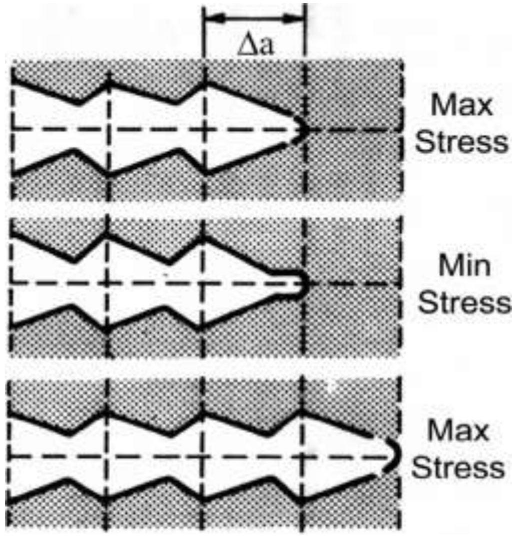
AA7050-T7451 hourglass coupon
R=0.8 and R=0.1 CA bands
R=0.1 CA, ΔK about 3 MPa(m)$^{0.5}$



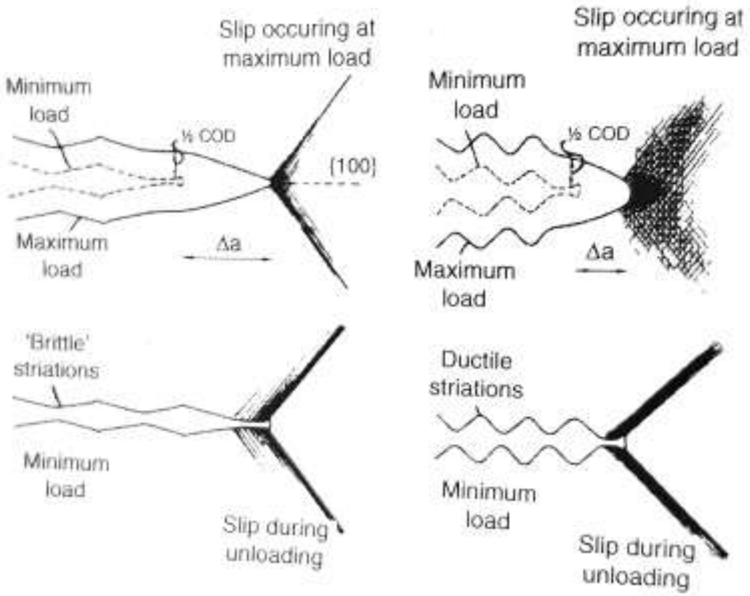
Striations are a key to how cracks grow

- Striations are a features that have attracted much interest
- The models of there formation mainly belong to the Laird/Pelloux/Lynch types:
  - Ductile/brittle plastic blunting and re-sharpening.
- Symmetric surfaces (peak-to-peak) is usually assumed but, asymmetric growth (peak-to-valley) has been proposed but symmetry seems to still be a prime assumption

Pelloux



Lynch

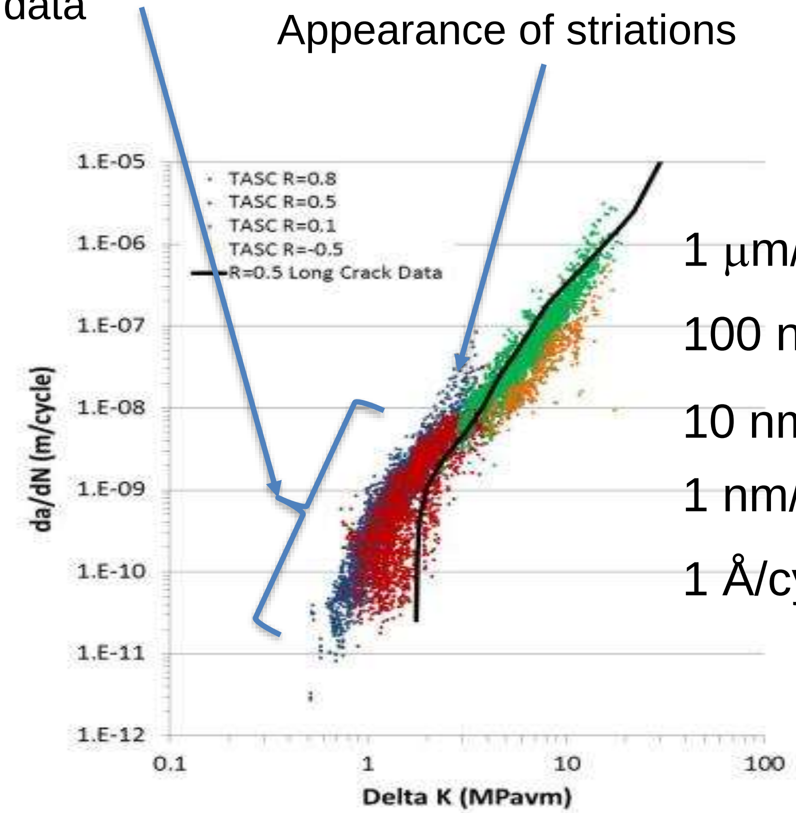


In terms of an da/dN curve?

- The growth of fatigue cracks is often considered to be different for small cracks compared to long cracks.
- Stages I and IIa suggest slip is strongly implicated in crack growth in metals
- Slip produces damage and is most easily activated by shear and the maximum shear is at about 70° to a crack tip or 140° apart.
- In FCC materials if one {111} slip plane is on the shear plane, the other {111} planes will not be on a maximum shear plane
- The result is asymmetry in the damage and the crack path

Bands of cycles can be used to get this data

Appearance of striations



1 μm/cycle

100 nm/cycle

10 nm/cycle

1 nm/cycle

1 Å/cycle

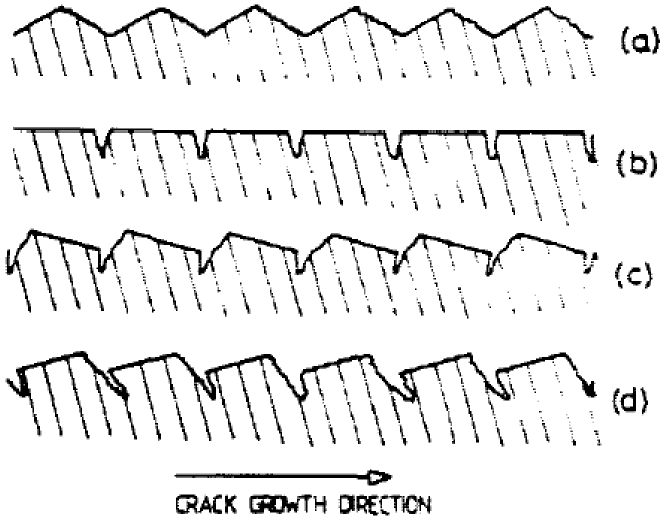
AA7050-T7451

$K = \beta\sigma(\pi a)^{0.5}$ The K concept, as introduced by Irwin, treats the material as a continuum: there is no implied critical K for sub-critical crack extension: it's used with empirical data only

There are several Ks of interest: K (ΔK) the peak K (K_{max}), some modification for 'closure' (ΔK_{eff}), 'threshold' (ΔK_{th}) and the critical K ($\Delta K_{IC \text{ or } c}$). But none of these give a K for crack extension

Nix and Flower found asymmetric striations

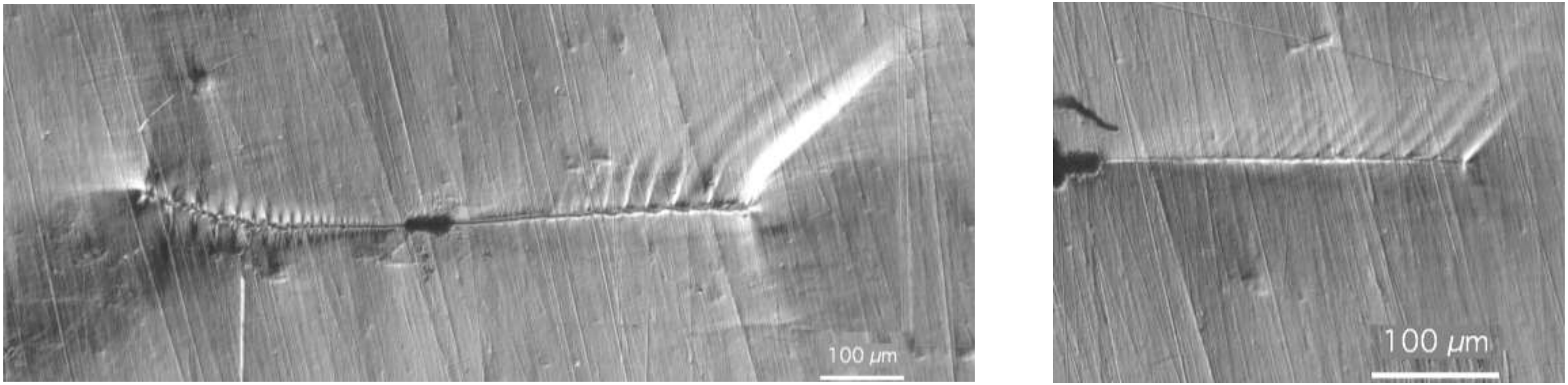
- Nix and Flower proposed several types of striations, but they were not entirely correct
  - “In moist air fracture occurs by cleavage on {110} (unlikely) coupled with plastic deformation during the blunting and closing of the crack”
  - Striation formation was still assumed to be peak-to-peak and valley-to-valley
- Nix and Flower’s striation types ‘a’, ‘b’ & ‘d’ may be observed. In the case of ‘c’ fissures don’t face back towards the origin.
- Fissure are interesting so more on these in a moment



K. J. Nix, H. M. Flower, The Micromechanisms of Fatigue Crack Growth in a Commercial Al-Zn-Mg-Cu Alloy, Acta metall. 30, pp1549-1559, 1982.

Crack tip deformation is not symmetric

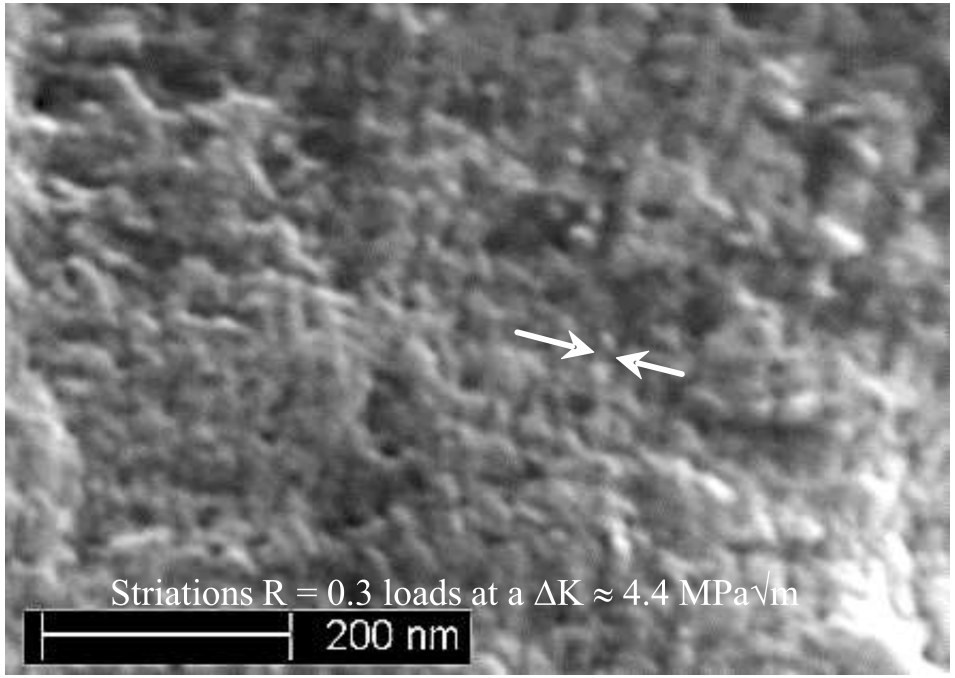
- The damage ahead of the cracking is rarely symmetric and prefers to form on slip planes close to the max shear planes, but can be at surprising angles
- This is a Non-continuum reality and has a big effect locally



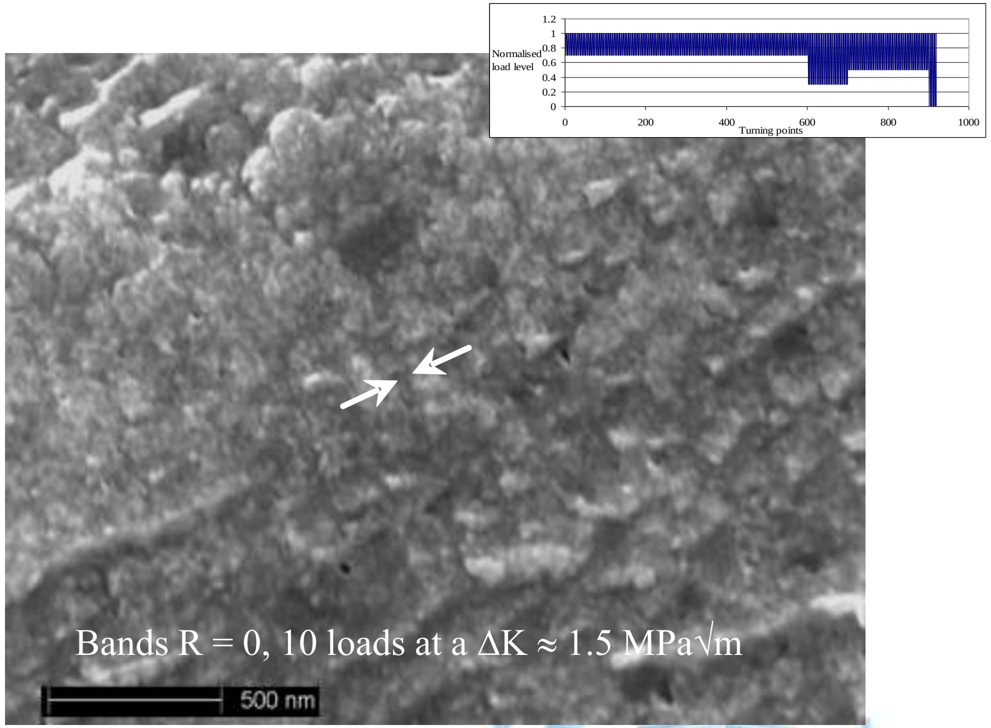
VA with 120% overload, one per WRBM block. Interference contrast images, AA7050 produced

Repeating marks - Striations – one load or many?

- Davidson and Lankford (1992) reported minimum striation spacings of about 0.1μm – this is wrong.
- ‘Striations’ can be seen on AA7050/Ti6Al4V surfaces at about 2 x 10^{-8} m/cycle or smaller.
- ‘Bands’ of cycles are also visible at about 2 x 10^{-8} m/band – this can give much lower growth rates for da/dN v ΔK data (via measuring these progression marks)



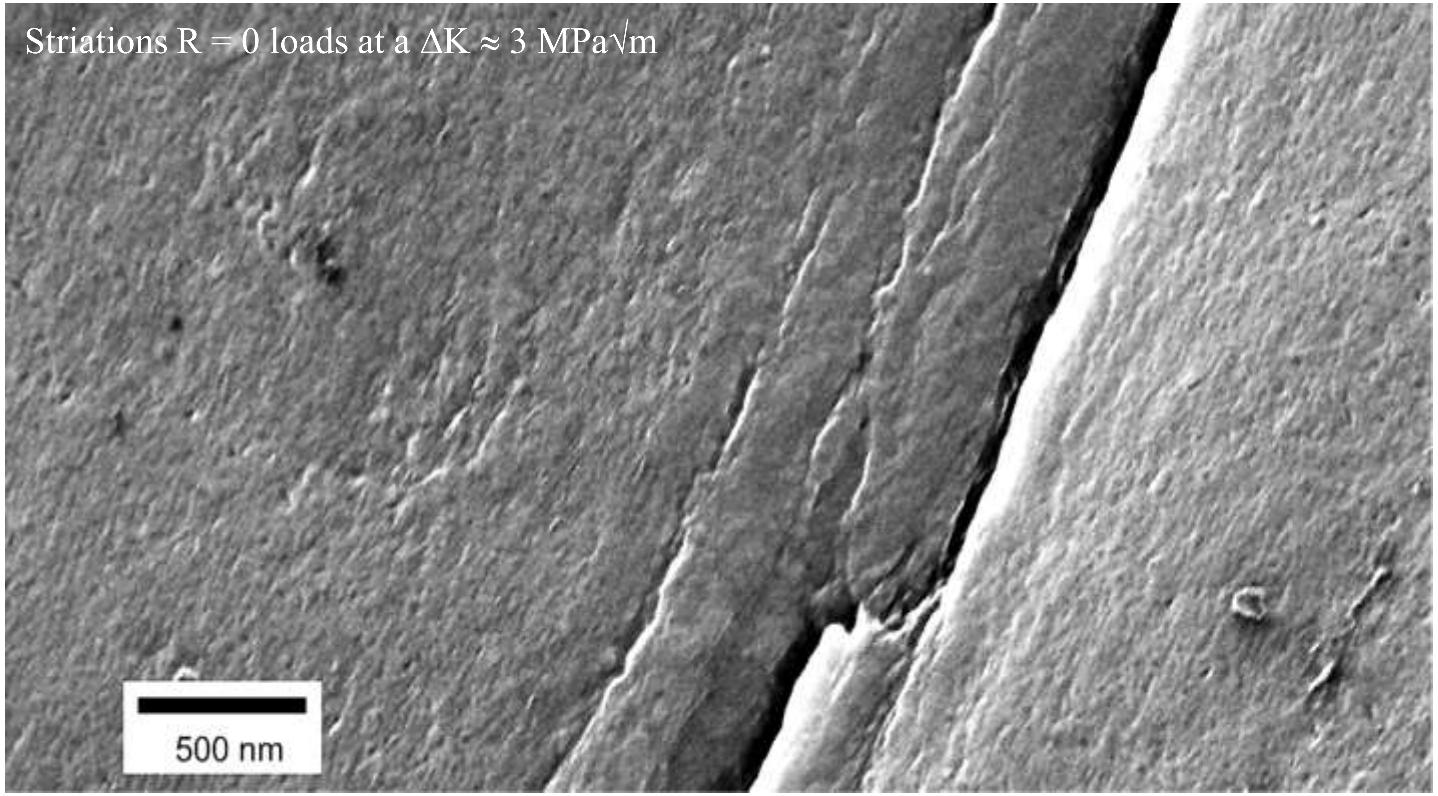
Striations R = 0.3 loads at a ΔK ≈ 4.4 MPa√m

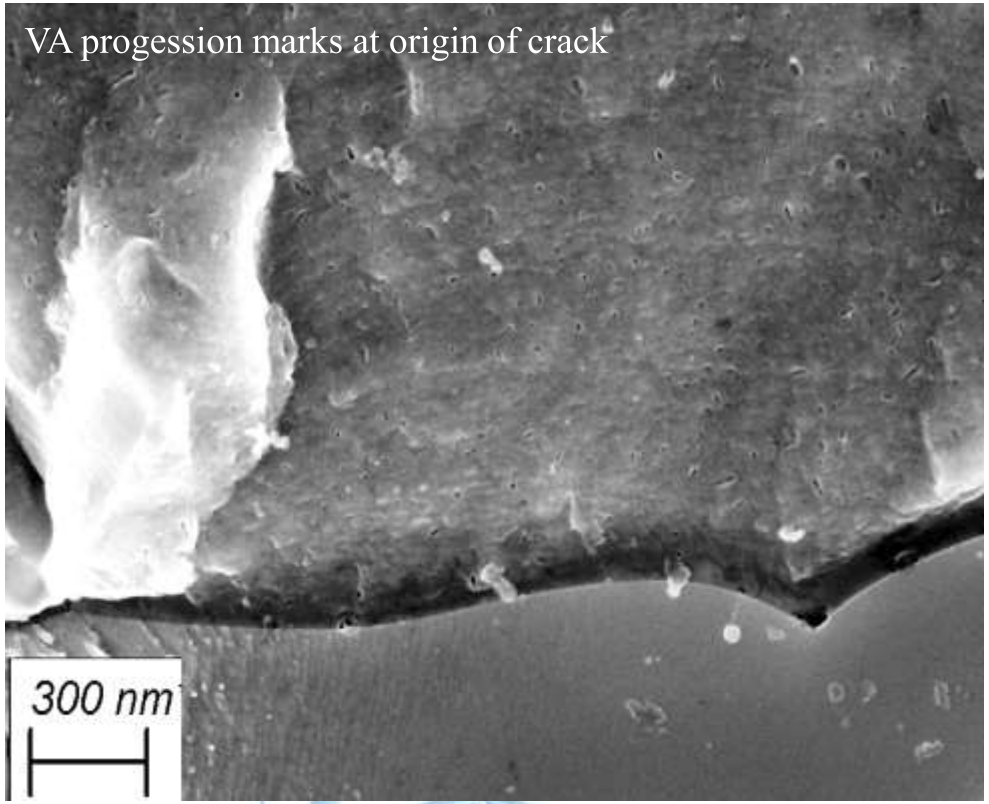


Bands R = 0, 10 loads at a ΔK ≈ 1.5 MPa√m

Striations – one load or many?

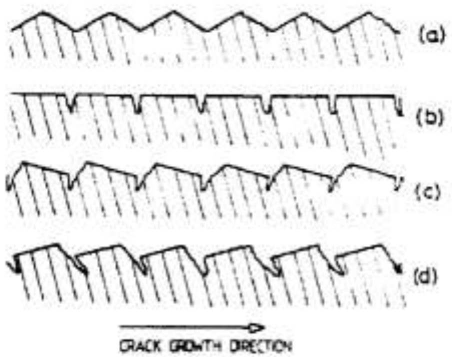
- And at low ΔKs VA bands can also be seen

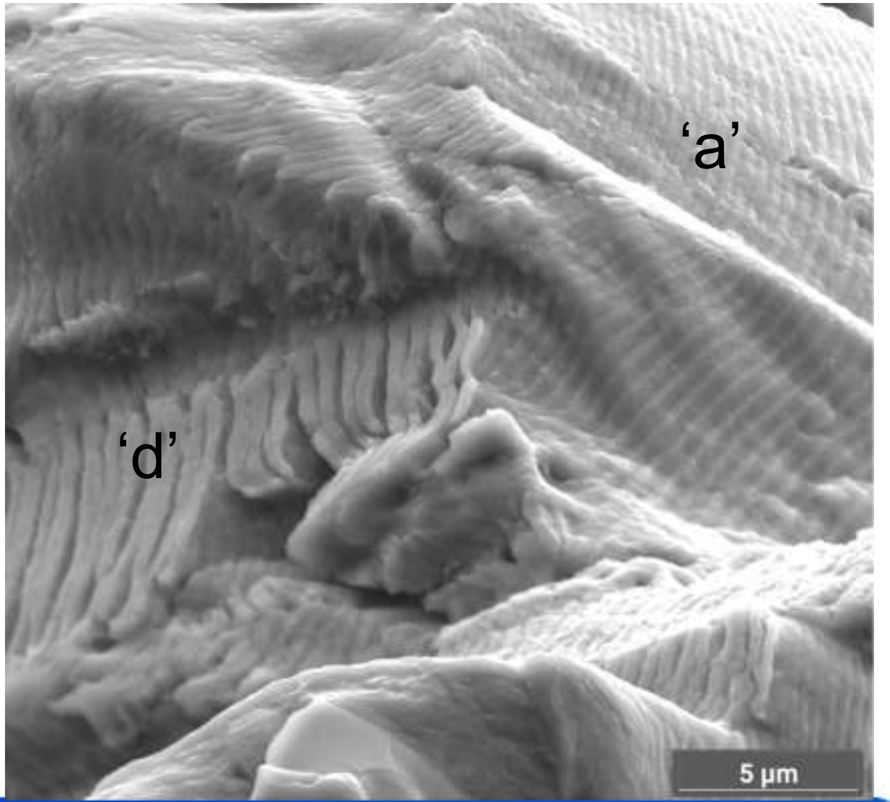

Striations R = 0 loads at a ΔK ≈ 3 MPa√m

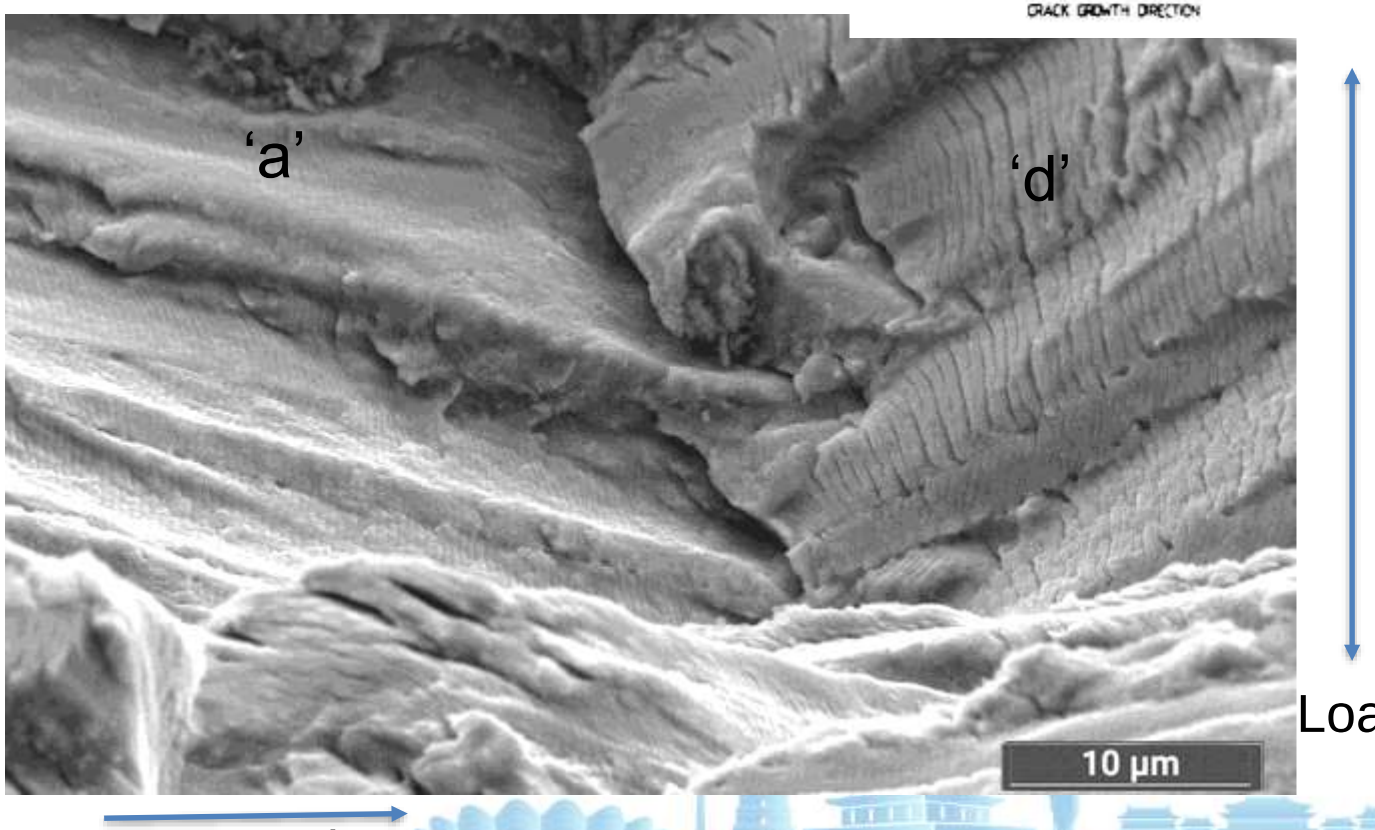

VA progession marks at origin of crack

Striations are not symmetric

- While striations can look symmetric, they are not.
- Here these appear like Nix and Flower’s type ‘a’ (ridge) and type ‘d’ striations
- The fissures of the ‘d’ are not present after every loading cycle
- The crack switches between these as it changes path



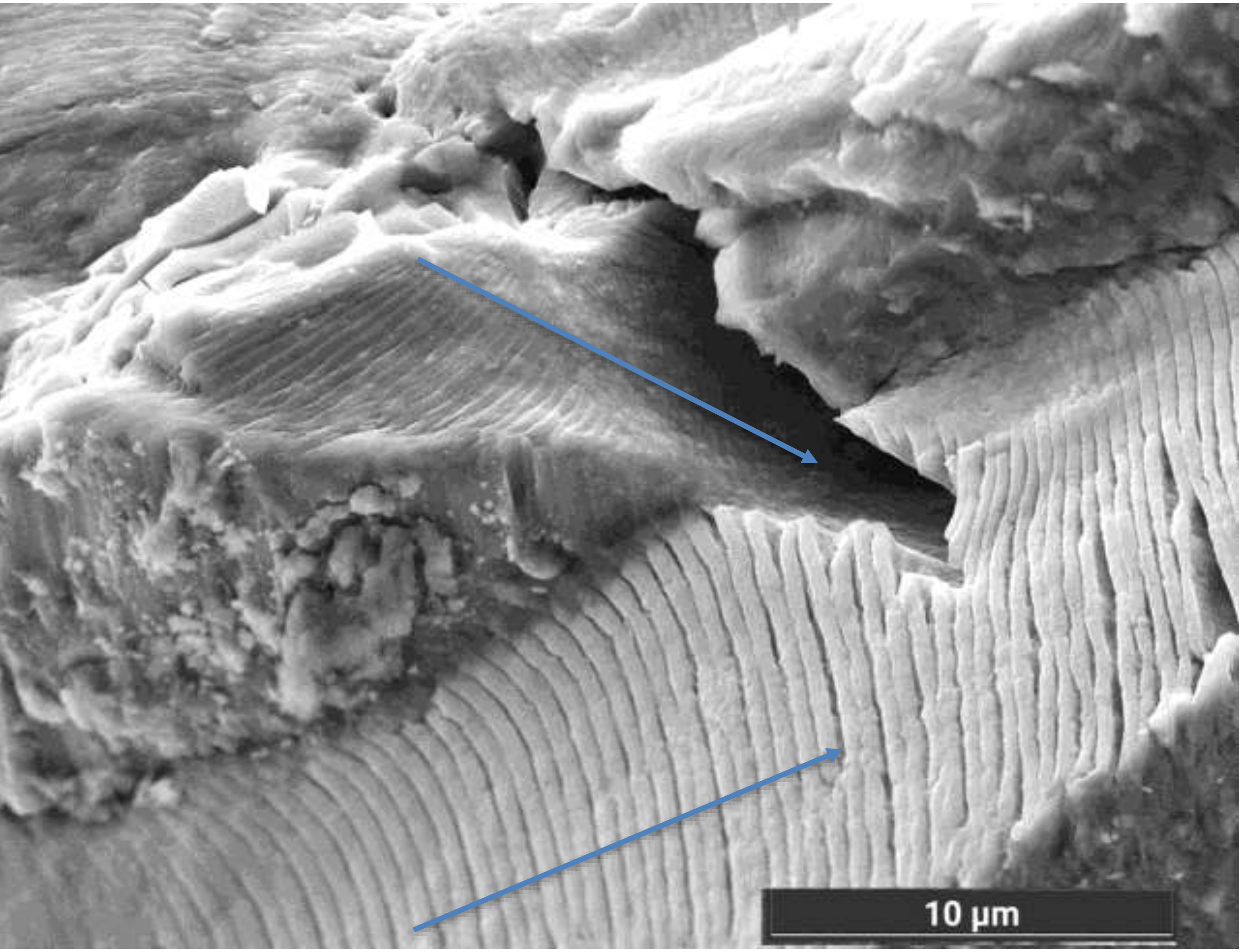


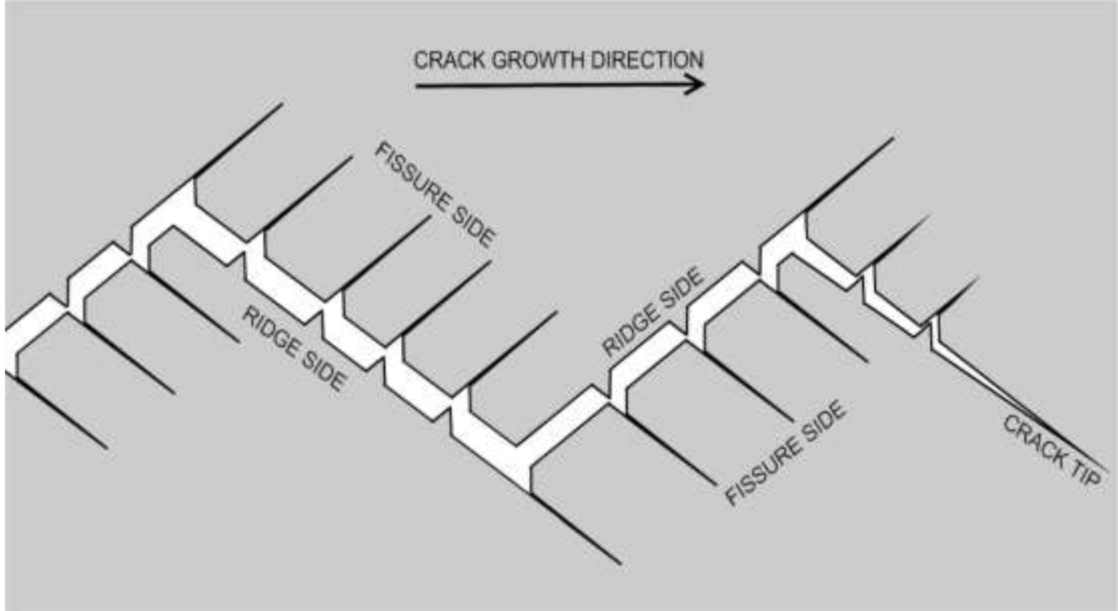


R=0 AA7075-T73 viewed at 70º

Fissures allow cracks to grow on many paths

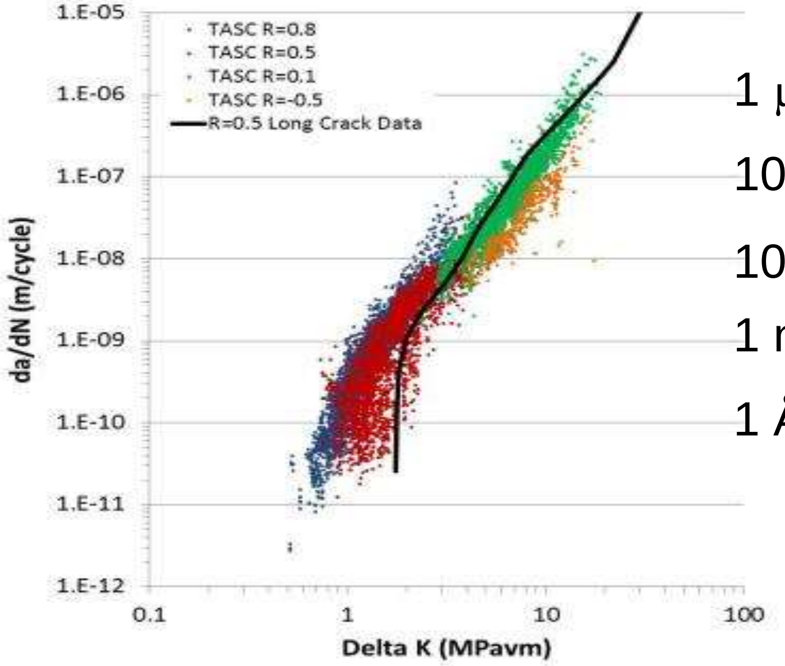
- Fissures form on the faces facing the origin and point towards the crack tip and ridge striations form on the other side
- For CA fissures form at some, then several and finally all loads at higher ΔKs
- The fissures are alternative crack paths





Growth variation be high

- Growth can vary by large amounts from location to location
- Practically the case for growth driven by low loads and when preferred growth planes are at high angles to each other



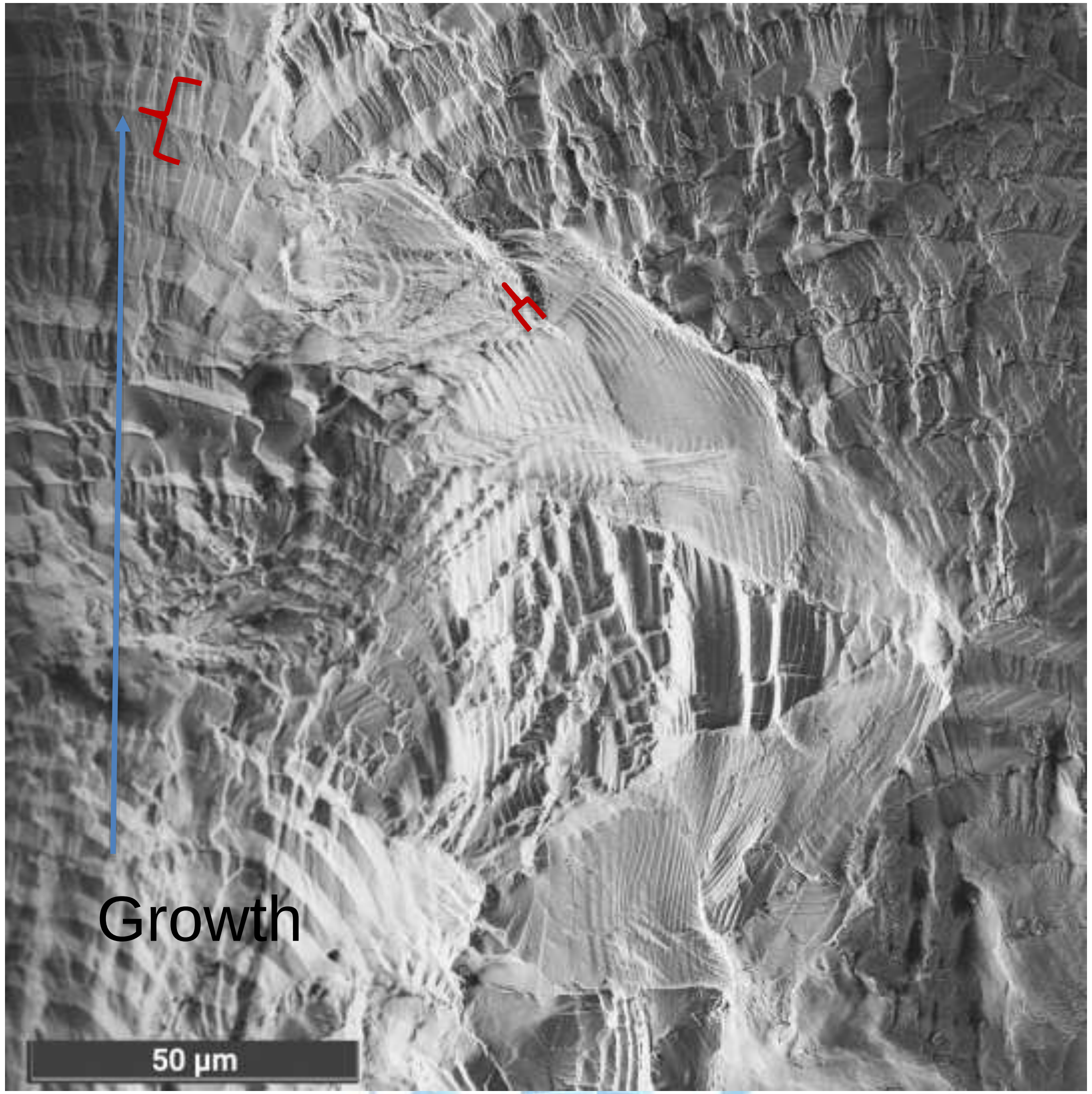
1 µm/cycle

100 nm/cycle

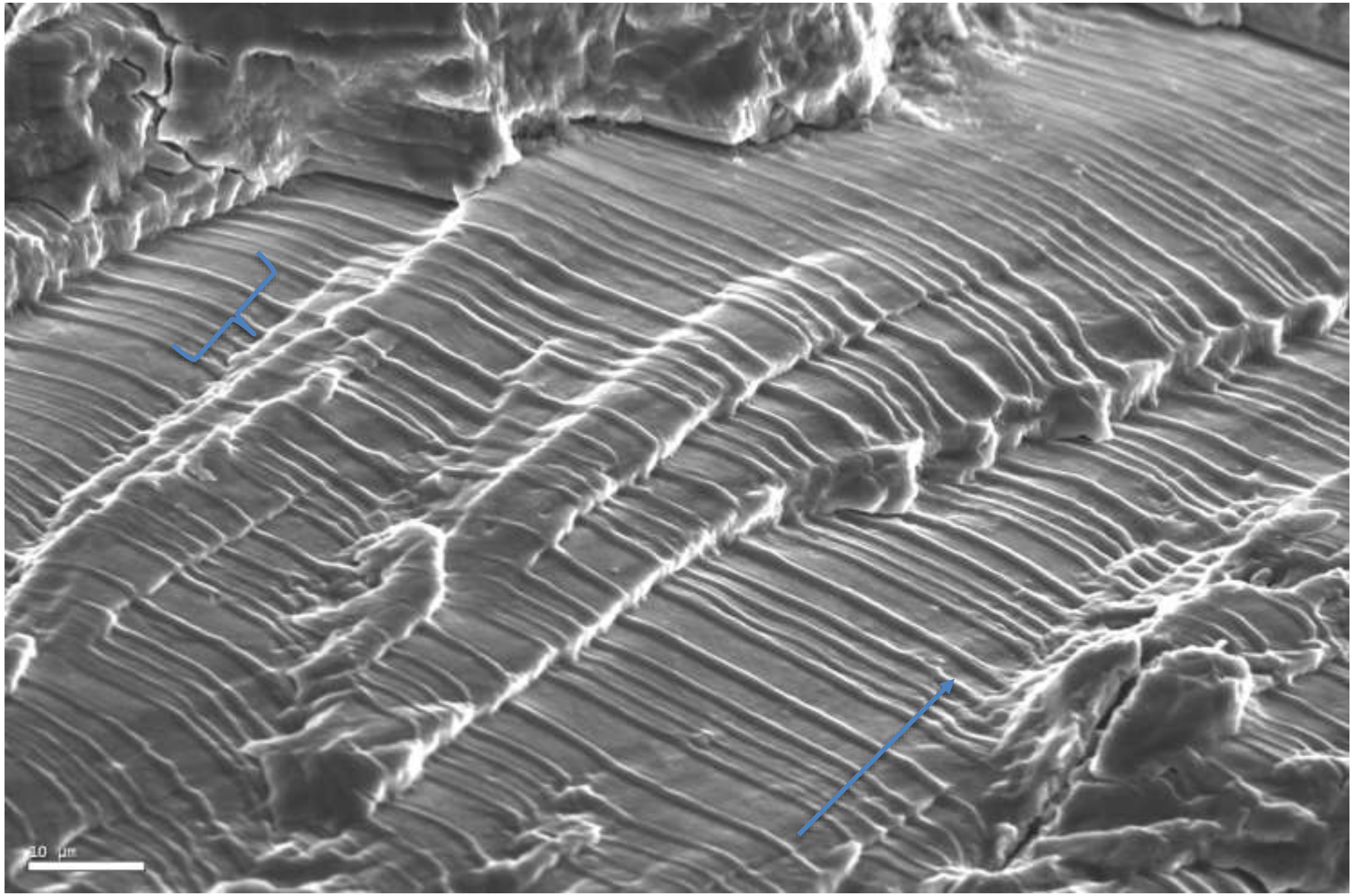
10 nm/cycle

1 nm/cycle

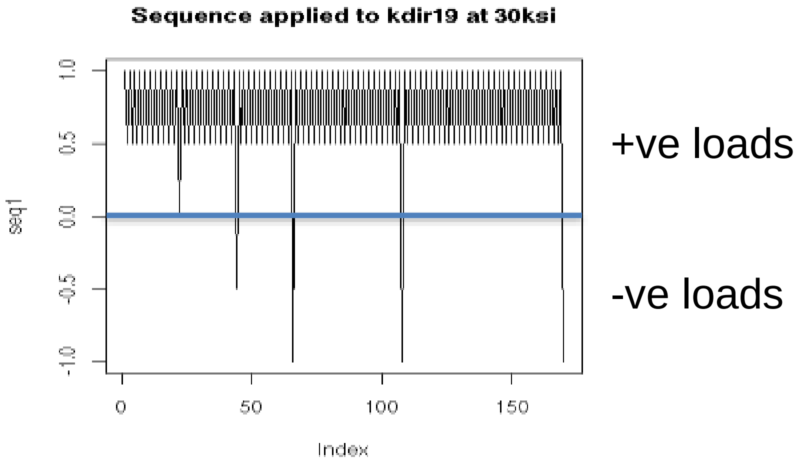
1 Å/cycle



Negative loads matter



- Here the ridges formed associated with underloads are different
- If loads less than 0 have no effect, then all these underloads should look the same – they do not!
- Underloads are important and accelerate growth* while cracks are small



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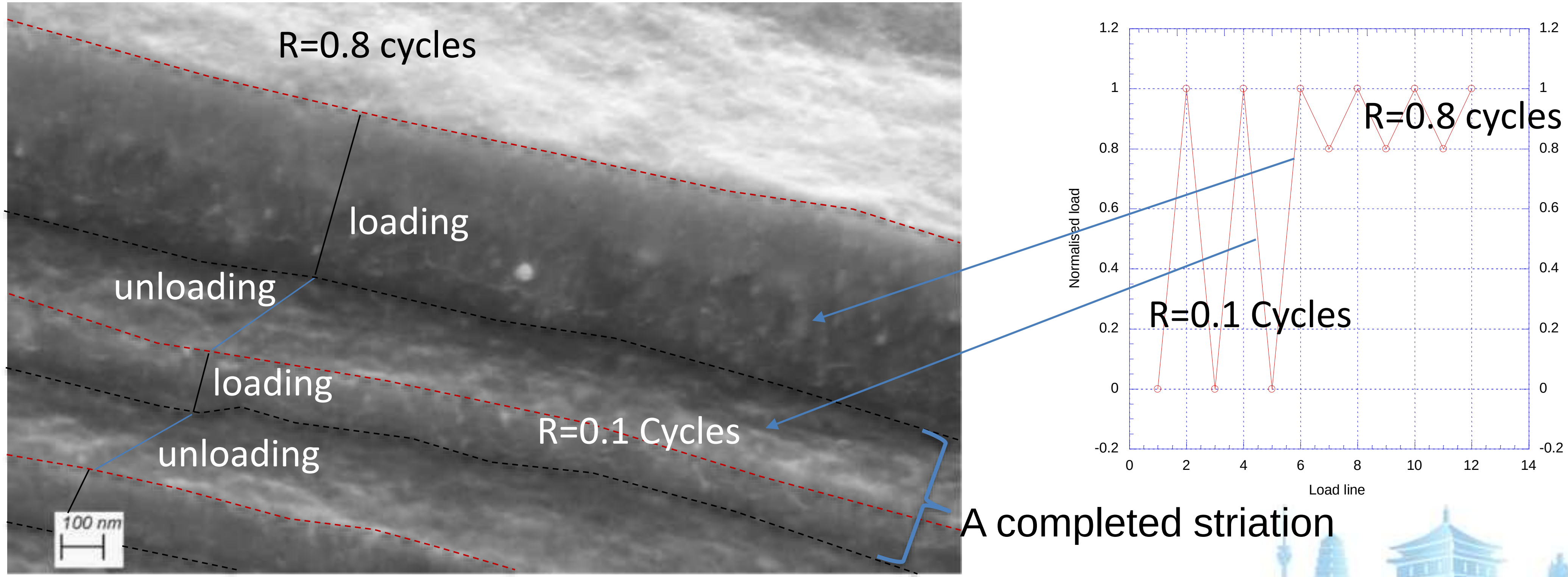
*Field, I., Kandare, E., Dixon, B., Tian, J., Barter, S. Effect of underloads in small fatigue crack growth. *International Journal of Fatigue*, *157*, 2022, p.106706.

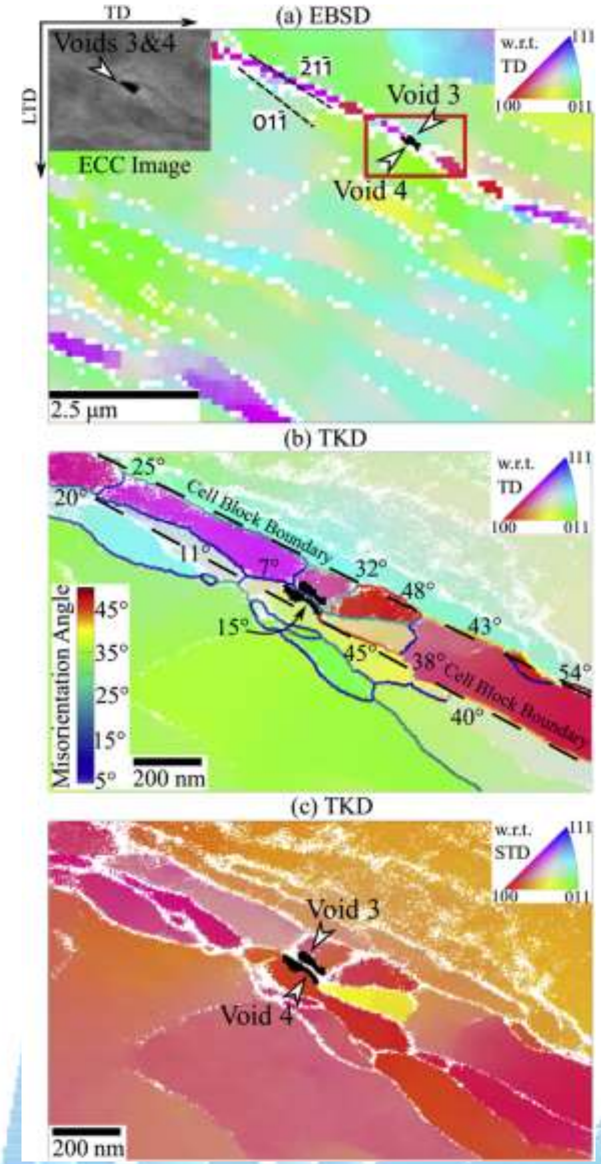
Striation growth

- The tension part and the compression part of a cycle are the same in magnitude but their effect is different



How may the crack advance?

- Crack advance during the tensile semi-cycle, probably along damaged planes
- These planes may form voids, but at what?
- Voids normally form at precipitates in aluminium alloys
    - At non-coherent precipitates that are large enough > say tens to hundreds of nanometres
- But Noell et al. showed that voids form at dislocation cell block boundaries rather than grain boundaries or inclusions.
    - So, fatigue cracks grow by following dislocation cell block boundaries
    - These are usually orientated in the primary slip planes (for FCC <111>)
    - It is hypothesized that vacancy condensation is the primary mechanism for void nucleation, with the environment helping – mono-atomic H
- The liking up these voids could produce the ‘rough’ parting surface of a striation

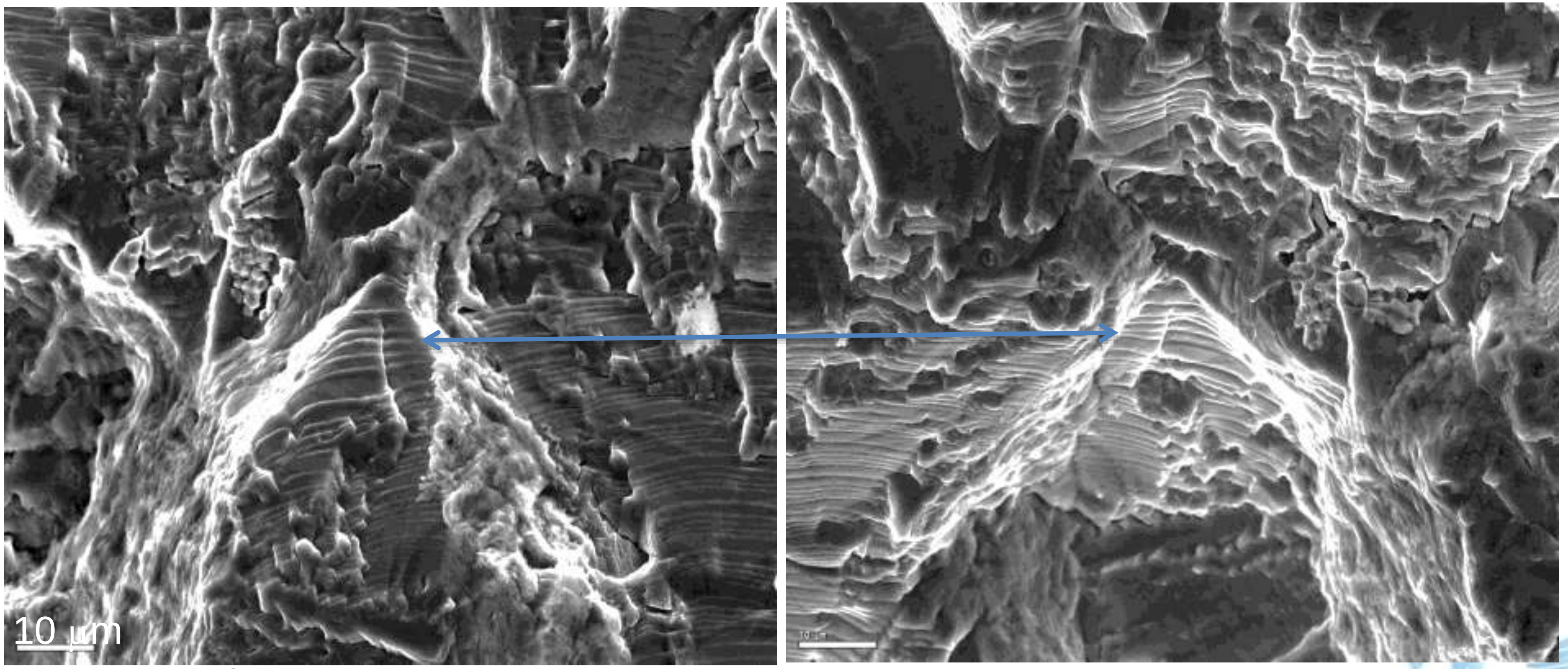


EBSD data for BCC Tantalum, showing the microstructure around two incipient voids.
(a) orientation map constructed using TKD data from this microstructure, plotted with respect to the (b) TD and (c) STD. Misorientation angles across deformation-induced boundaries are coloured according the misorientation angle and there average angles are labelled. The average angle across the boundary separating the voids is 15° (Found to be mostly larger than 10°). P Noell, J Carroll, K Hattar, B Clark, B Boyce. “Do voids nucleate at grain boundaries during ductile rupture?” Acta Materialia, 137 (2017) pp103-114.

Electron Channelling Contrast (ECC)
Long Transverse Direction (LTD)
Face Centre Cubic (FCC)
Transmission Kikuchi Diffraction (TKD)
Transverse Direction (TD)
Body Centre Cubic (BCC)
Electron Backscatter Diffraction (EBSD)
Short Transverse Direction (STD)

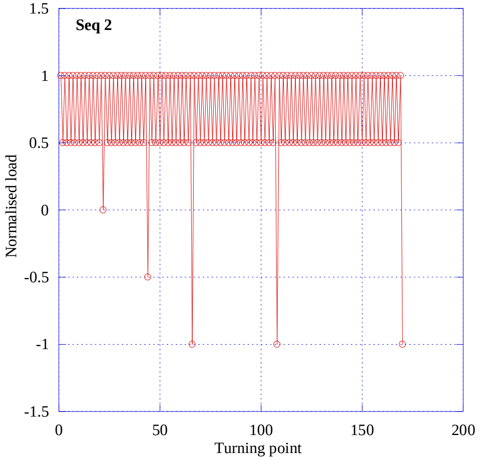
Cracks grow asymmetrically

- With cracks having two different sides, the asymmetry is evident as: lumps/ridges on one side and matching depressions/fissures on the other.



KDIR19

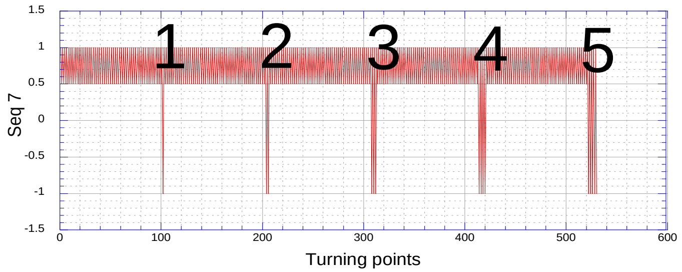
Depressions/Fissures and Ridges

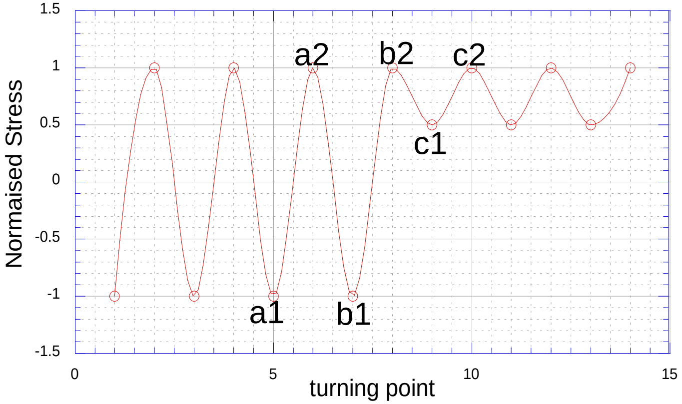


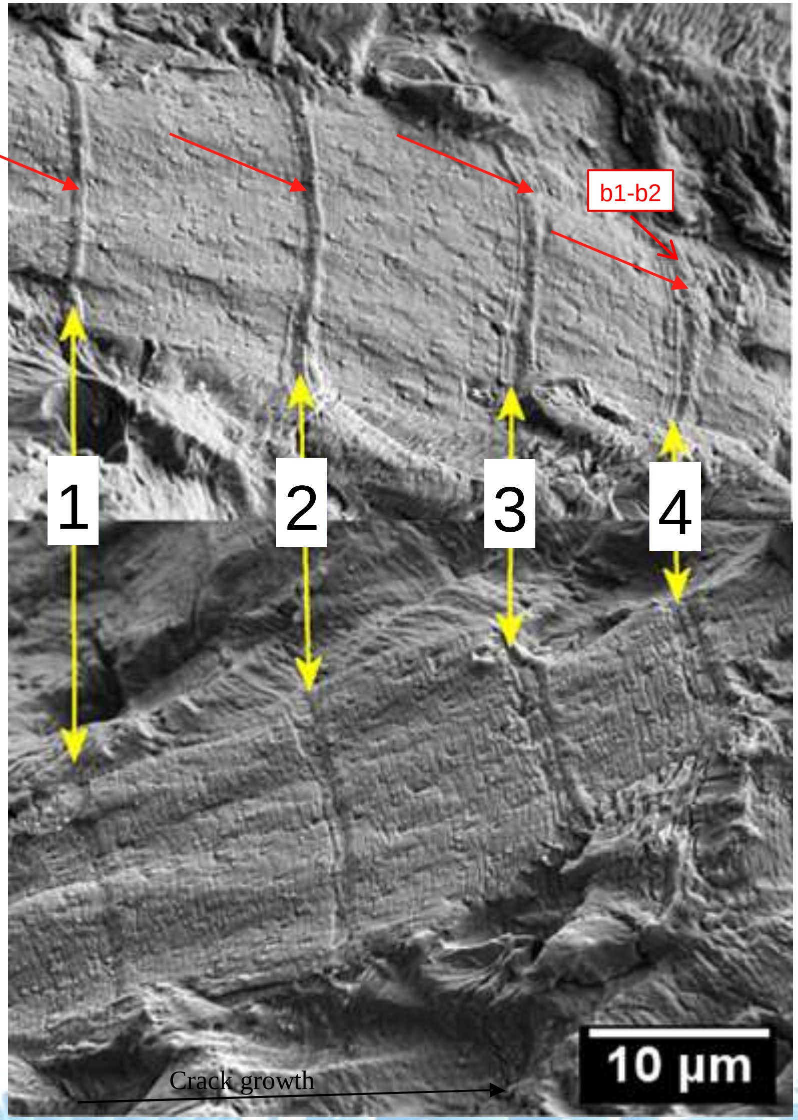
Growth

Cracks are asymmetric in many if on all metals

- This is not restricted to AA7XXX alloys
- AA2024-T3, with similar features.

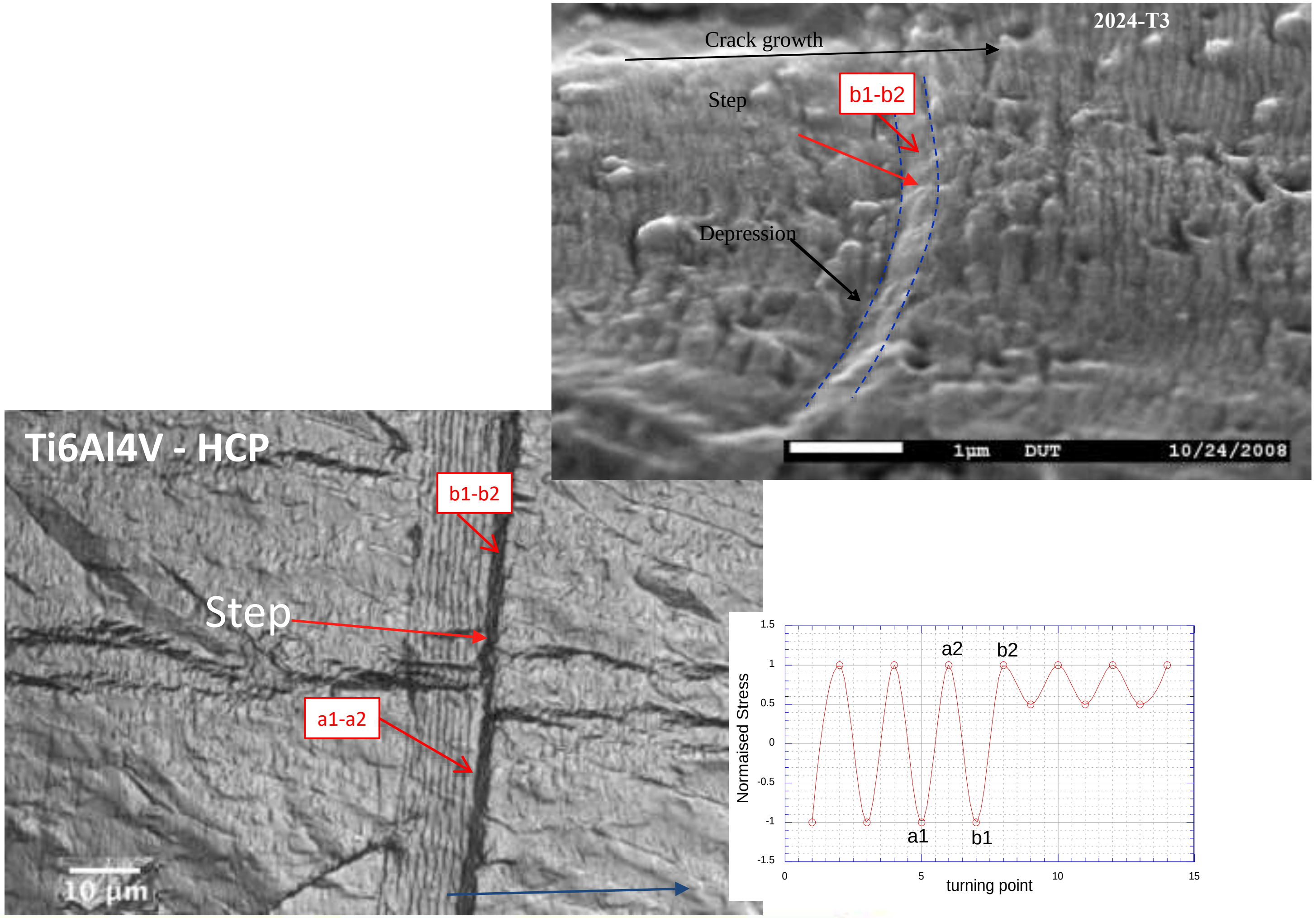




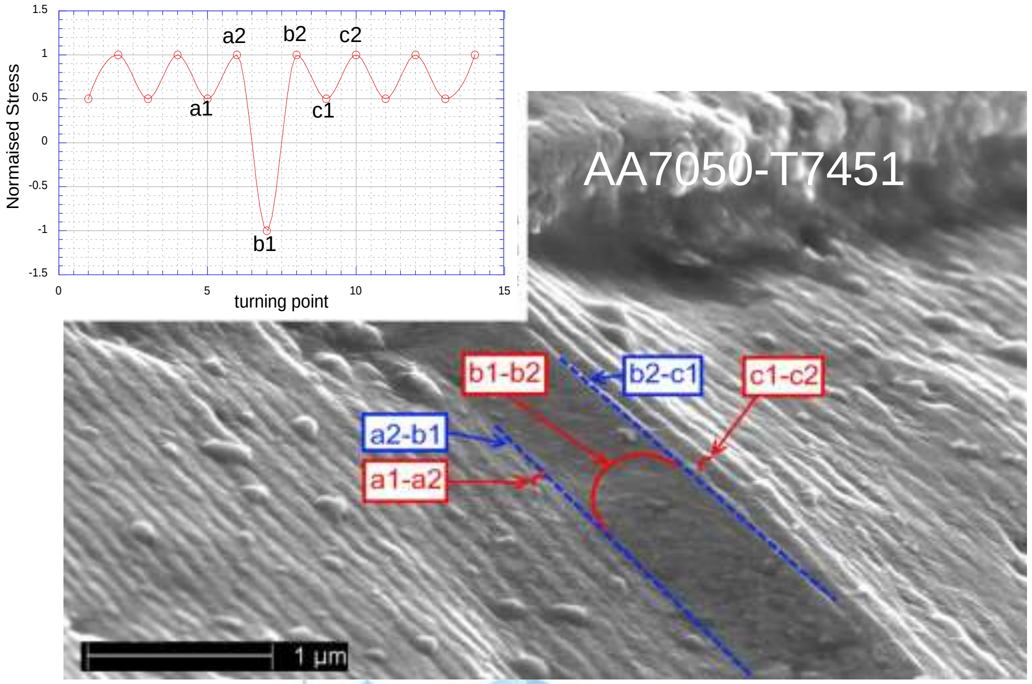


Krkoska, M., Barter, S.A., Alderliesten, R.C., White, P., Benedictus. R. Fatigue crack paths in AA2024-T3 when loaded with constant amplitude and simple underload spectra, Engineering Fracture Mechanics, V77, 11, 2010. pp1857-1865, https://doi.org/10.1016/j.engfracmech.2010.03.030

Similar features are found with other metals



- Fissures, ridges/steps, path changes etc.

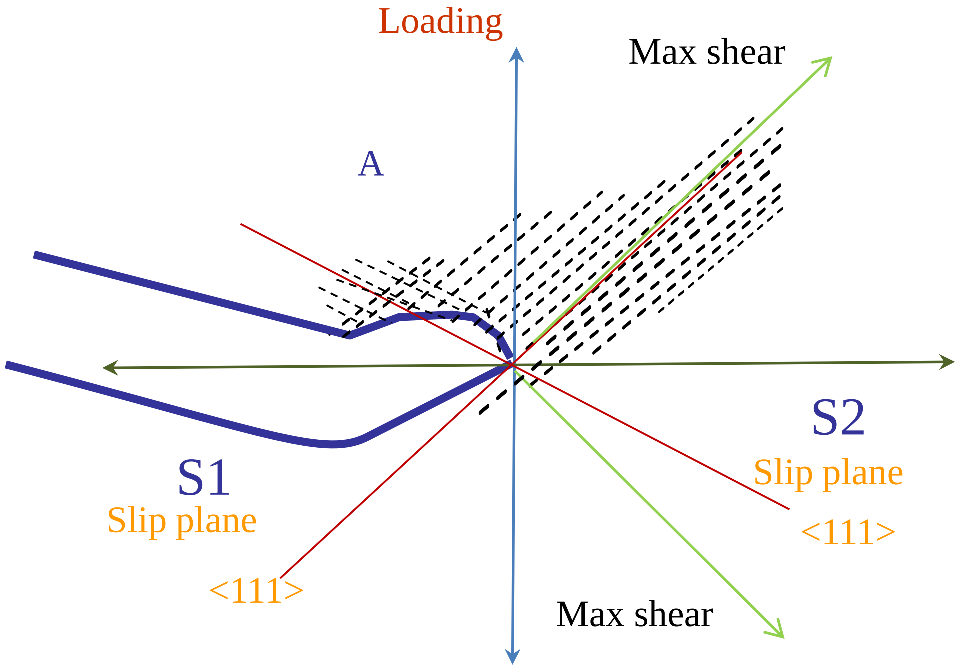


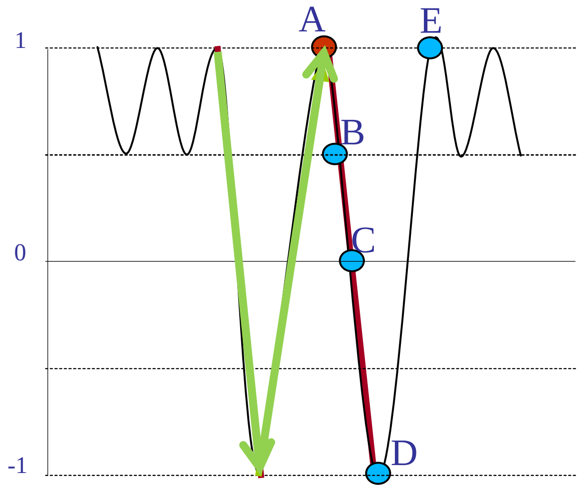
A crack path model

- The following model is illustrated with growth in the mid ΔKs, but is equally applicable to rates where striations are not very visible, since the same effects occur with bands of growth
  - Crack planes are generally locally tilted to the loading axis since shear is the source of the damage.
  - Striations and therefor cracks are locally asymmetric - symmetric cracking is the exception.
  - Microstructural orientation to the shear planes is important.
  - Dislocation structures formed ahead of the crack are the source of growth.
  - Crack tip collapse occurs on unlading
- The following is much simplified since crystal plasticity is complex, and importantly, the response of the material is different between crack extension and collapse.

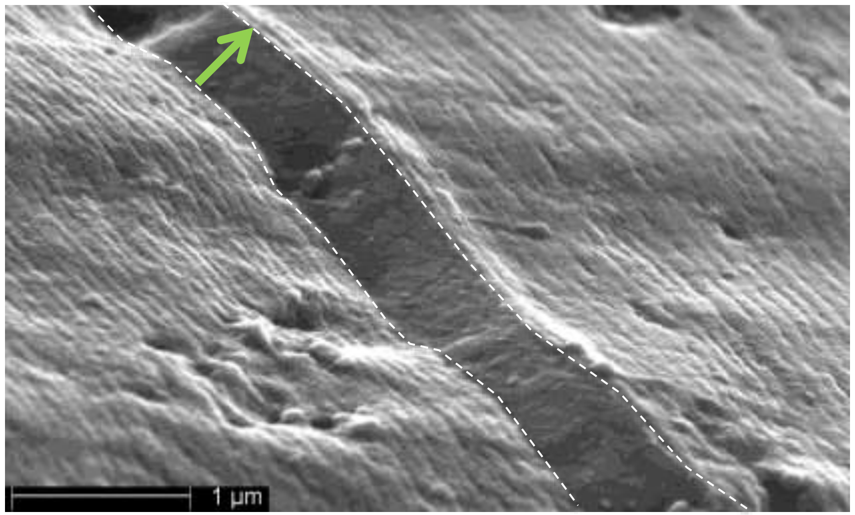
Ductile striation growth – tension semi-cycle

- On upload the material parts by decohesion assisted by environment (H) and pre-existing slip damage in a confined slip band that produces a flattish plane of growth close to the most convenient primary slip plane.
- Decohesion – peeling - during the tensile semi-cycle forms the front face of a ridge



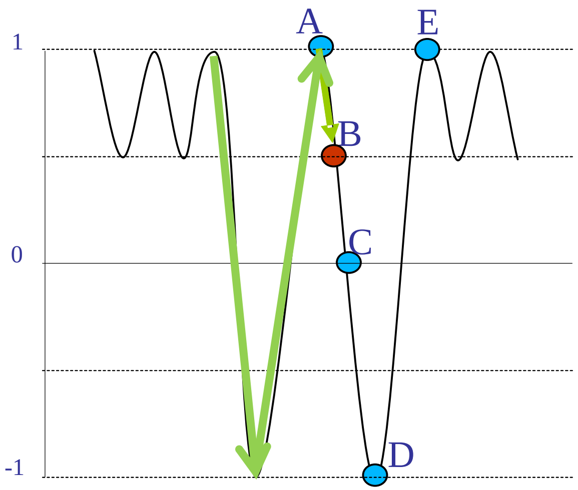


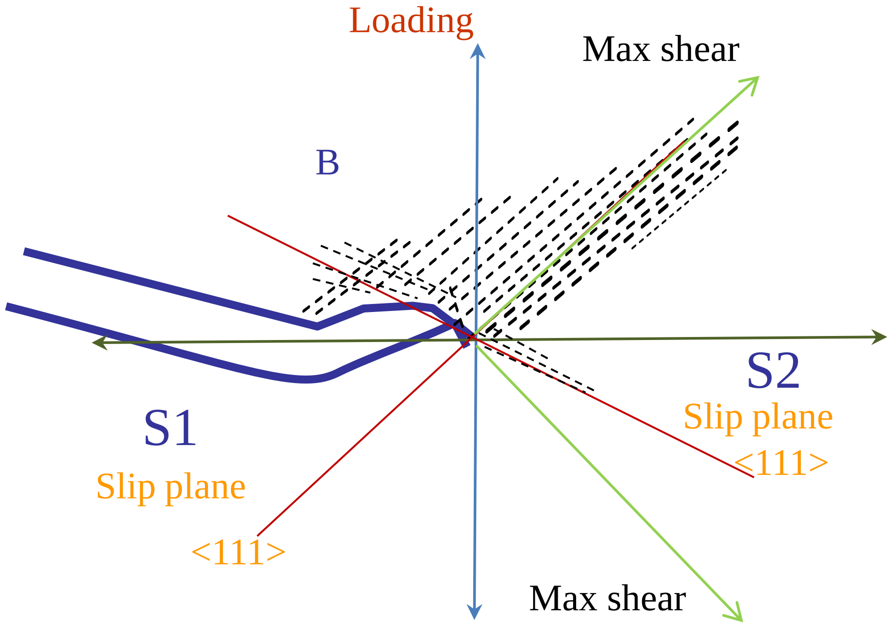
A



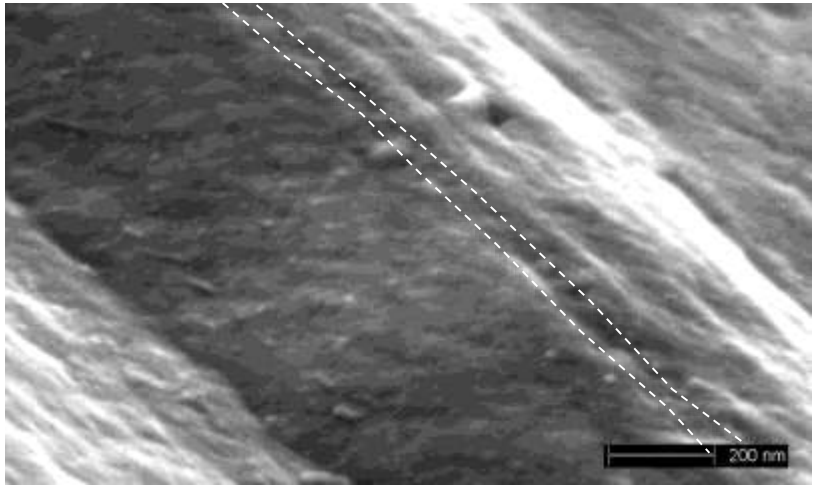
Tip collapse (A-B)

- As the load decreases, the tip of the crack collapses with the extent of the collapse governed by the slip state/damage state at the crack tip.
- There is tangled slip on the upper side which resists further deformation.
- There is no slip on the lower side so critical shear stress lower than upper side and collapse tends to follow the lower side.



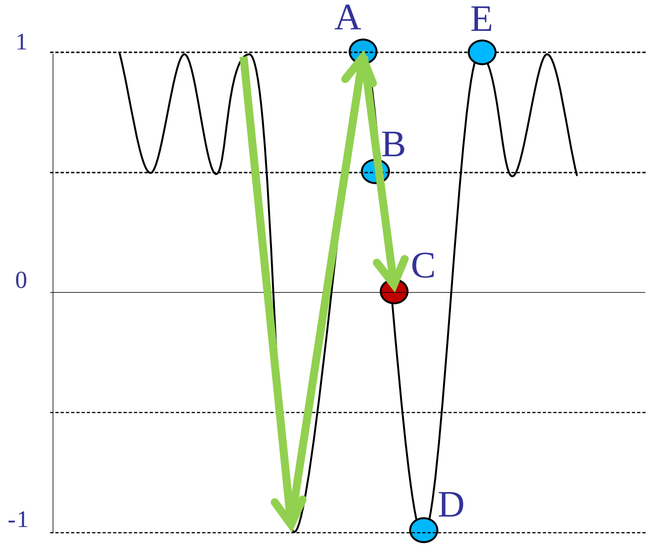


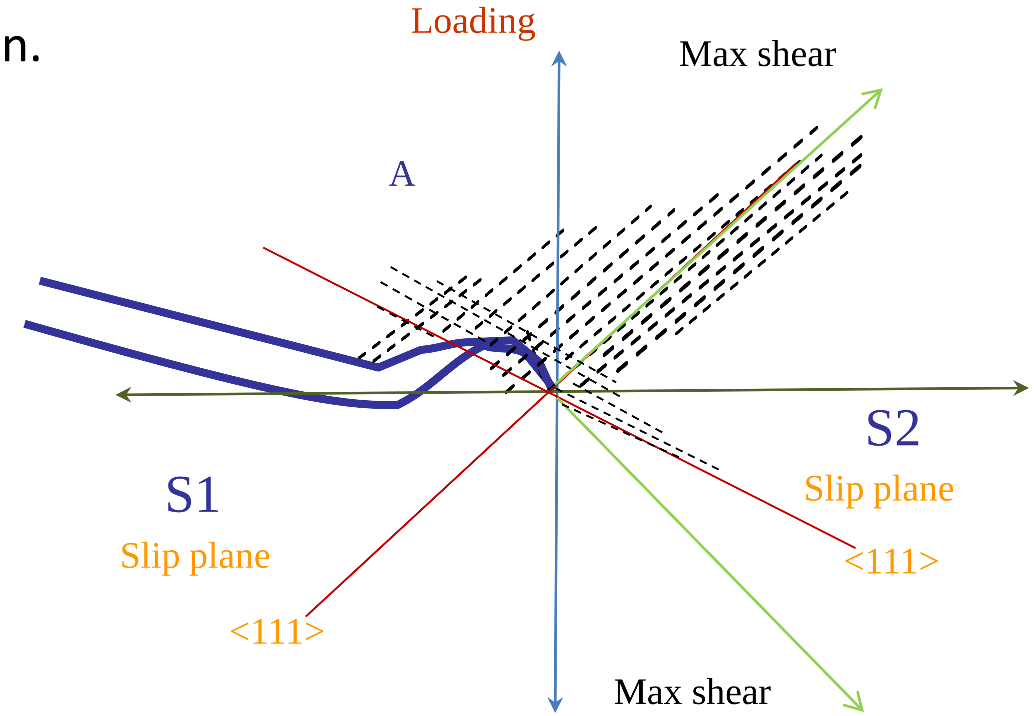
A-B



Tip collapse continues (A-C)

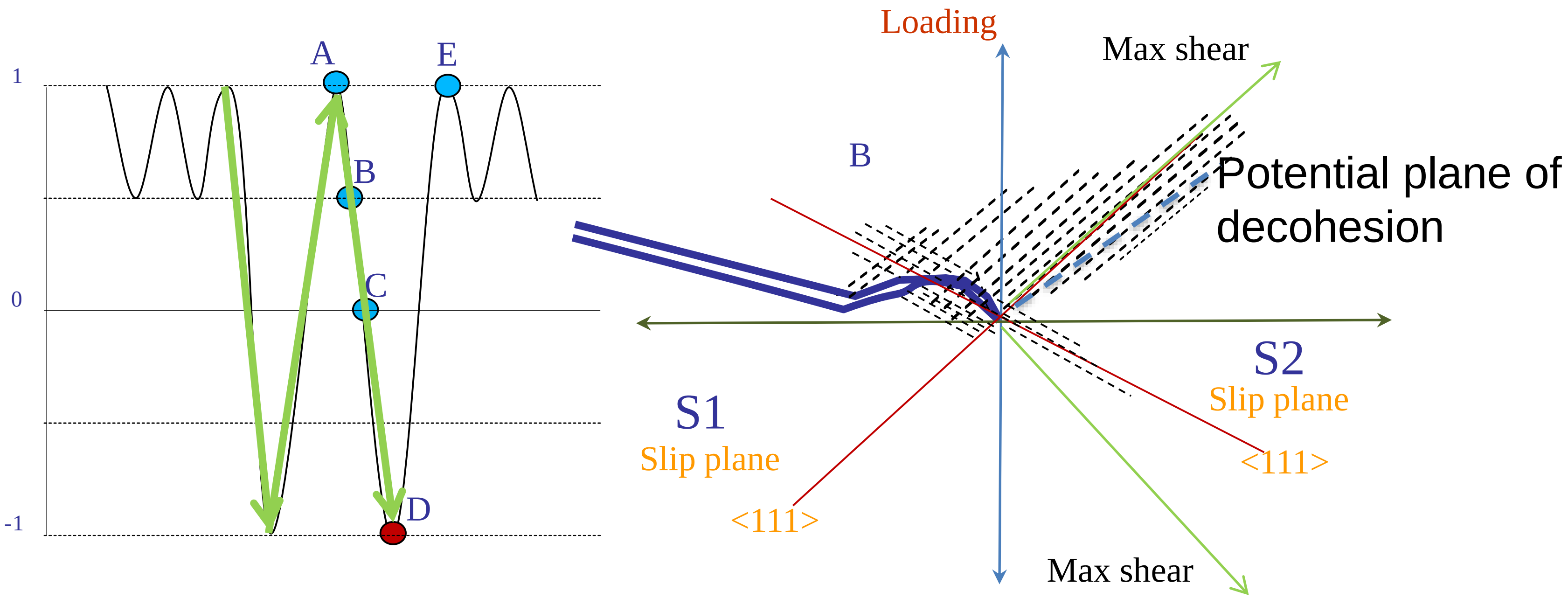
- As the load decreases further, the tip of the crack collapses faster.
- The extent of the collapse is governed by the slip state at the crack tip.
- Upper side continues to resist deformation.
- New slip forming on the lower side aids deformation.



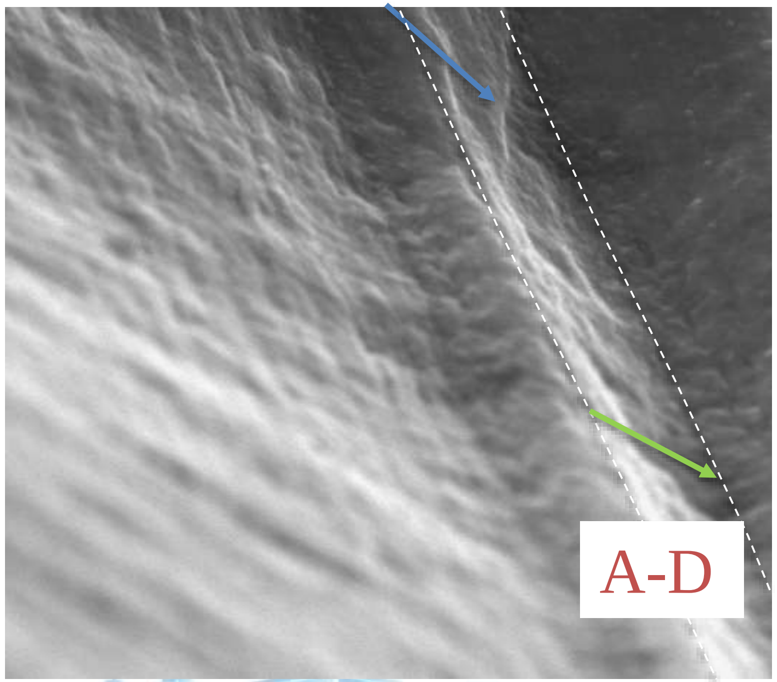


Striation completed by tip collapse (A-D)

- Trailing face of the striation consists of the original extension surface while the leading flank of the striation consists of a deformed surface with slip traces evident.
- The average plane of the completed striation is near a <100> or <110> planes but this is governed by extent of collapse and has been report to be near either.

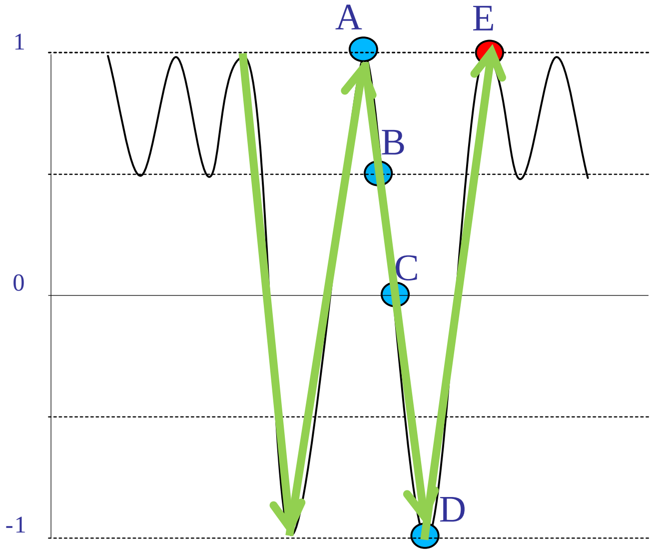


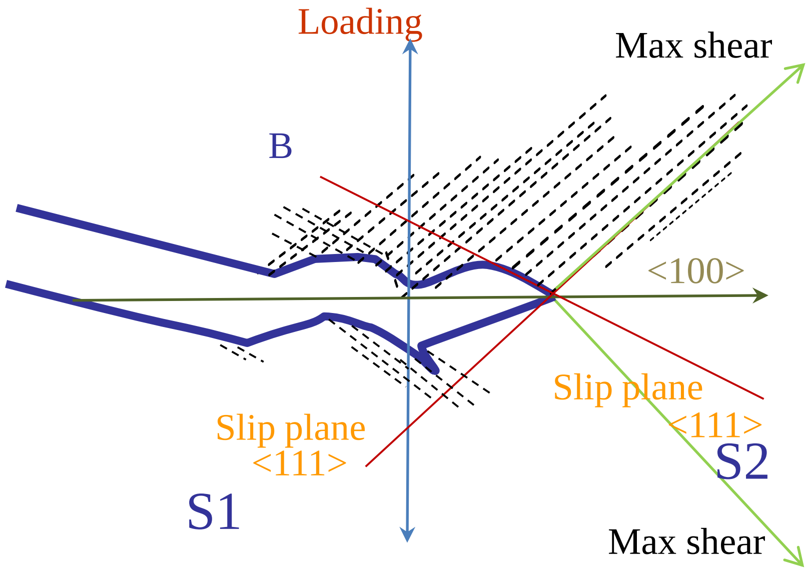
Collapsed part of striation

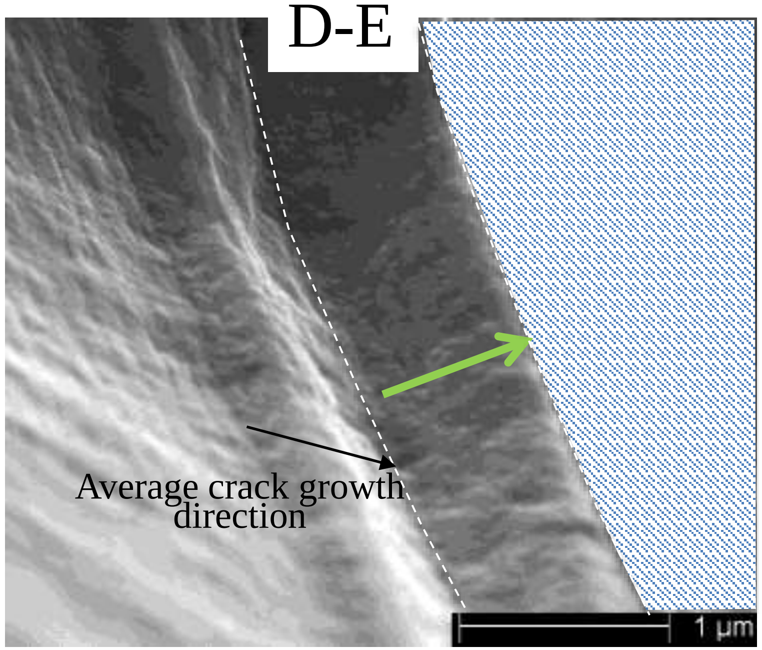


Crack branching (D-E)

- Crack extends initially by decohesion in damage ahead on or near either the upper or lower <111> slip planes.
- Slip occurs on S2 in the upper face as it deforms, resulting in dislocation tangling.
- Again, the lower face has little deformation ahead of the crack but can grow its fissure forward if there is sufficient damage on this plane.

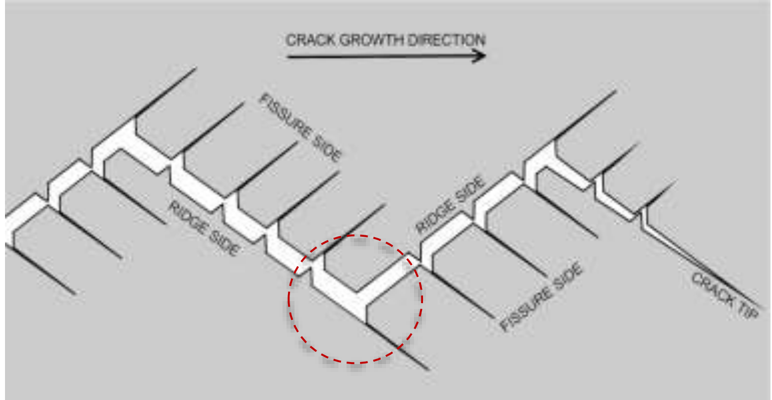


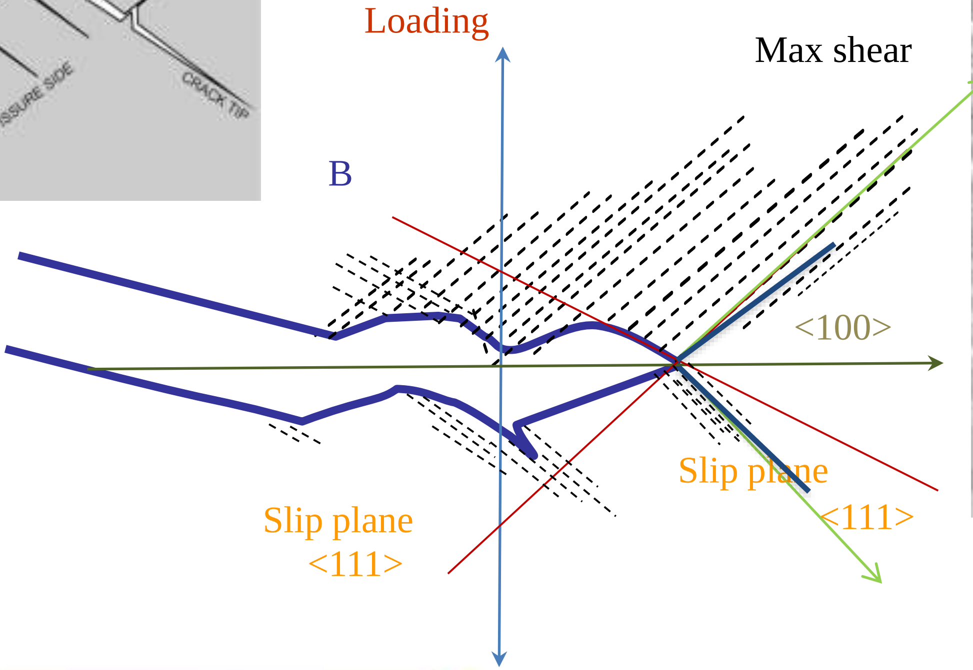


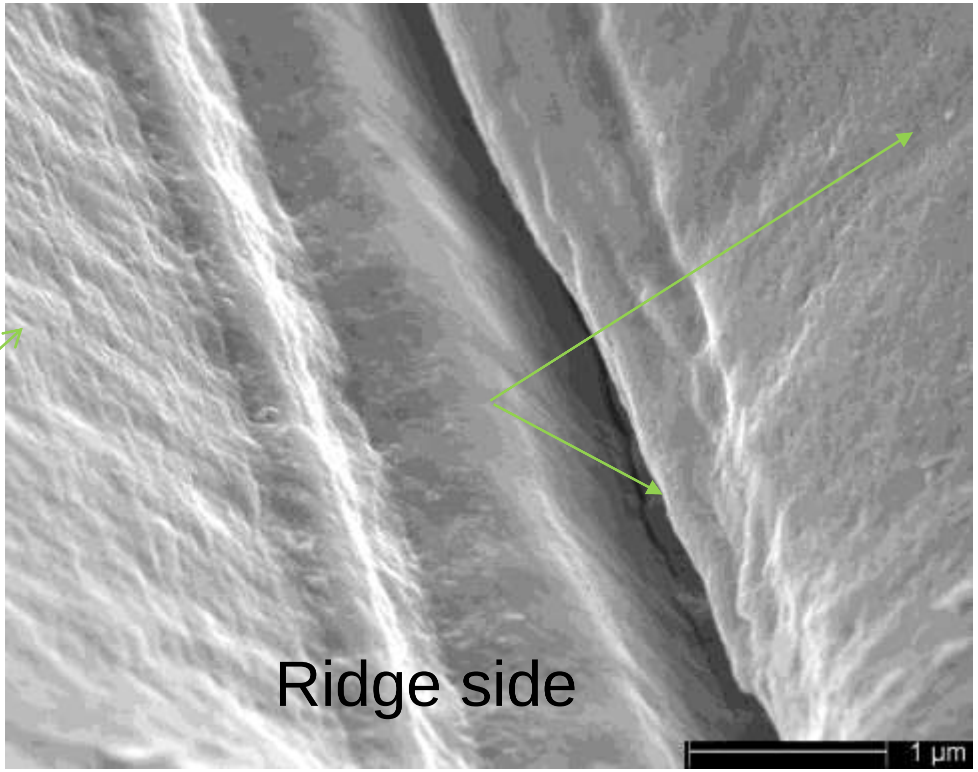


Crack branching changes paths

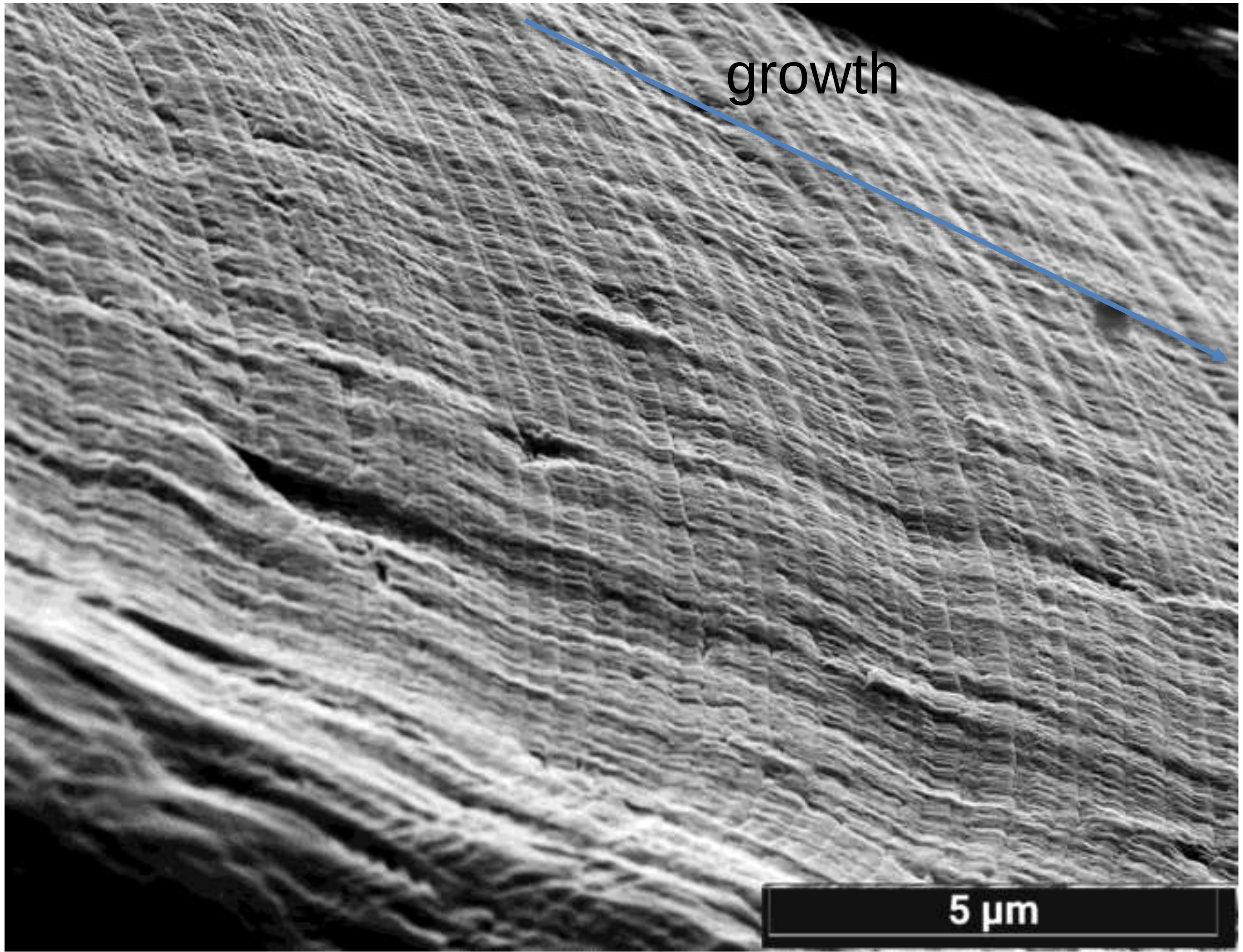
- After each big change in loading, a choice of crack paths may become available, so VA can allow more efficient fatigue crack growth through crack branching







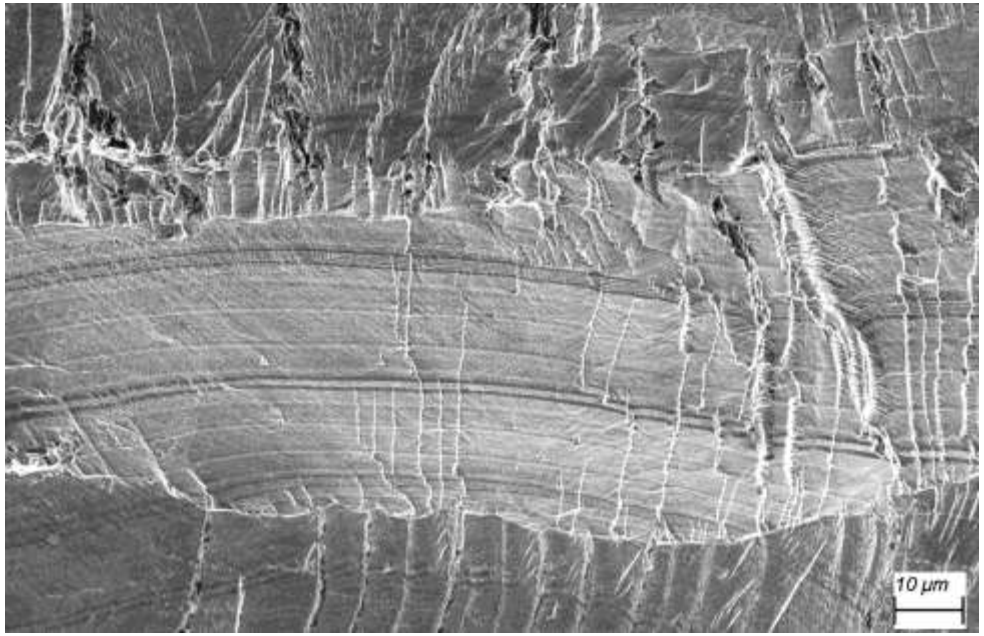
VA path



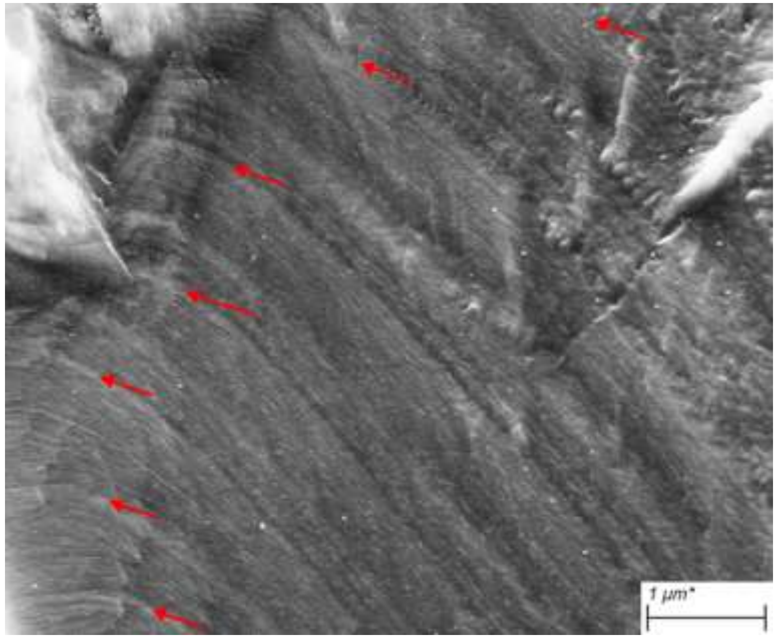
- The result is that for VA the path is constantly changing
- This allows a more efficient crack path

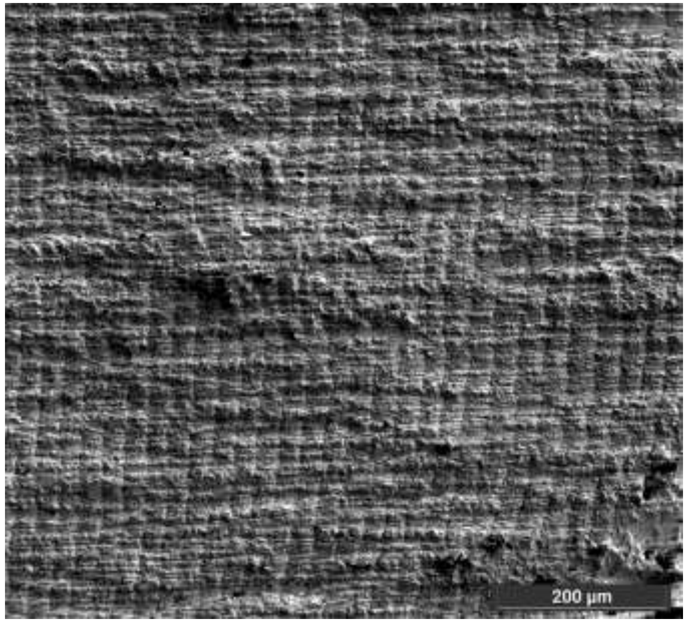
Practical outcome: Load changes can be used to mark fractures

AA7050 high R low R MBs



MBs RA Ti6Al4V high R low R





AA8090 high R low R & VA MBs

Summary

- Striations and paths changes are dependent on crack tip peak K_{max} and ΔK and the effects of unloading.
  - Load order, partial semi-cycles and unloading/compression help steer cracks.
- The damage ahead of the crack tip is very important and dictates the extent of growth and the direction of the growth.
  - environment
- The slip system and load orientation are import, and grain-to-grain orientations are also important

So what?

- Understanding the causes of crack path changes allows us to use them for studying crack growth
- We can design marker bands for quantitative fractography
- We can measure bands of CA to produce crack growth rates for small realistic cracks
- We can start to understand why different materials respond to fatigue as they do
- We can predict how a material may respond to fatigue cycling to improve material design
- We can produce better predictions of fatigue life

So what? Quantitative fractography for fatigue tests and service investigations offer real advantage

- Marker Bands (MBs) – making QF easier, more reliable, faster = CG curve
- Crack growth data – enhances knowledge and life assessments
- ASI benefits – reduces risks maintains capability

Understand crack growth from
Nucleation to failure

- RAAF F/A-18A/B program: $400m saved through removal of major modification of the centre fuselage; life extension and NDI reduction for the empennage and outer wing.
- Swiss F/A-18 program: $77m saved through NDI reduction
- RAAF P3C program: refined lifing and life extension
- RAAF Hawk 124 program: refined lifing and demonstration of repairs
- RAAF F111 program: refined lifing and demonstration of repairs
- RAAF Macchi recovery program

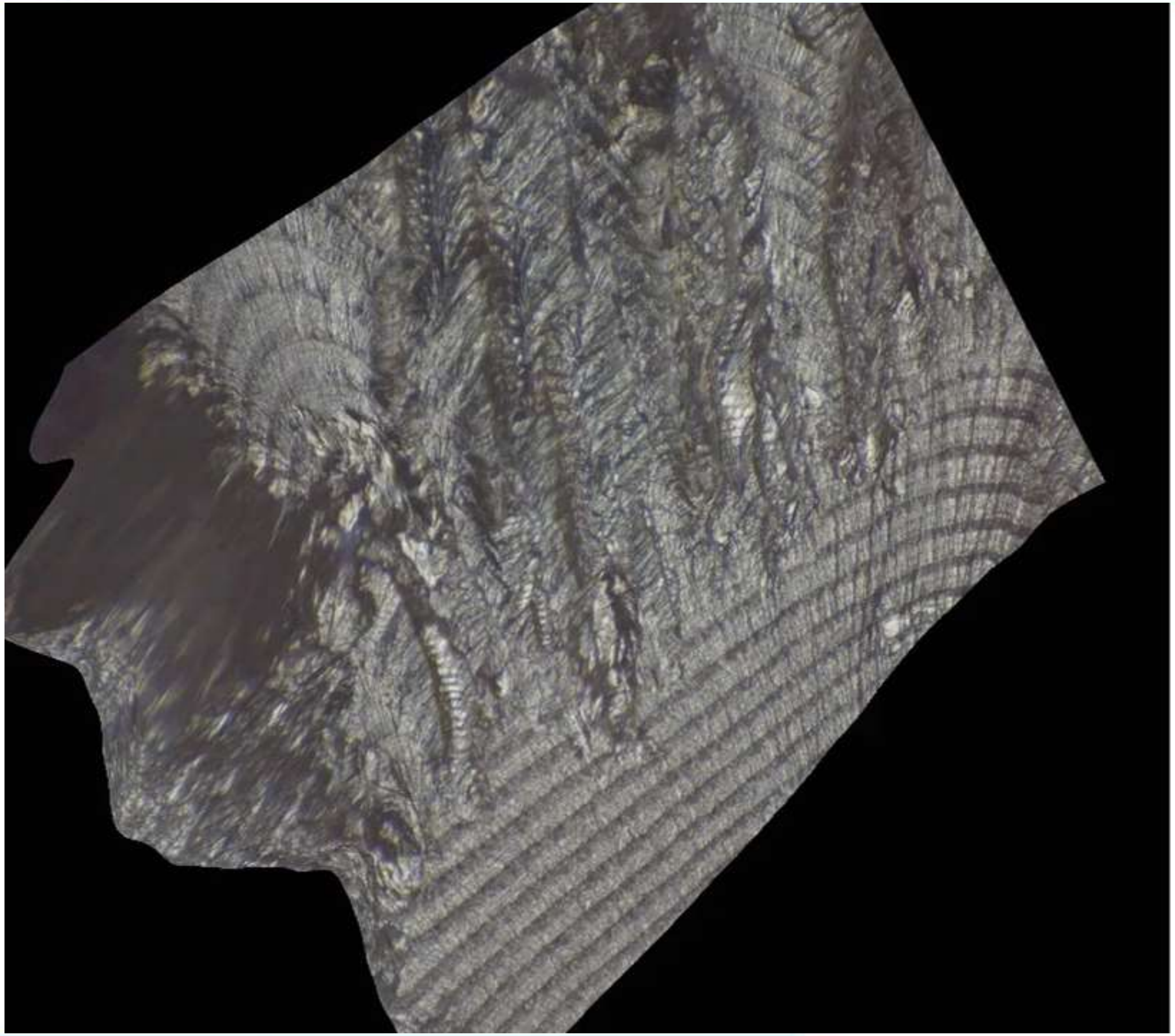
Extend life limits; Reduce/eliminate inspections; Improve repairs/re-designs

Full-scale fatigue tests and fractography

- Post test detailed quantitative fractography is a valuable tool that has been proven to be capable of extracting more information from full-scale tests
- Examples in the Australian context: Hawk 124, F/A-18 empennage tests

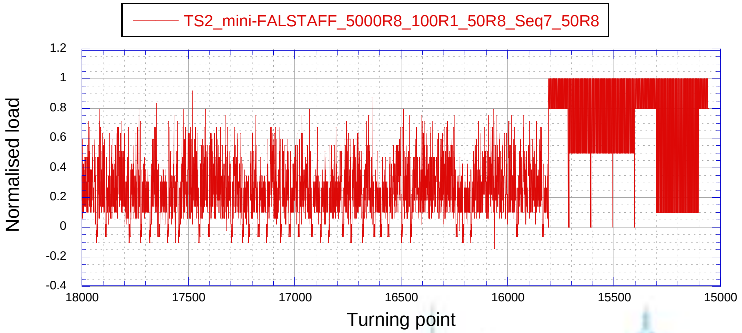
Conclusions

- Fractography has been available as a tool to understand fatigue since the original observations of Zapffe in 1944
- It has been out of favour for some time but is once again finding uses in the assessment of the aircraft structures and new materials
- Simple spectra and new and improved instruments have allowed a better understanding of the process and this better understanding gives some control over:
  - crack paths through the application of certain loading sequences
- We can see that short crack growth is not that much different to long crack growth.
- The average crack growth direction is not necessarily a defined crystallographic plane since it is the product of the growth and collapse in two semi-cycles.
- The effect of the crystallography of a metal on crack growth can be locally stronger than the crack tip K



BA Ti-6Al-4V

Questions?



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