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Measuring Small Fatigue Crack Growth with the Aid of Marker Bands in Recrystallization Annealed Ti6Al4V

31st ICAF Symposium – Delft, 26th-29th June 2023

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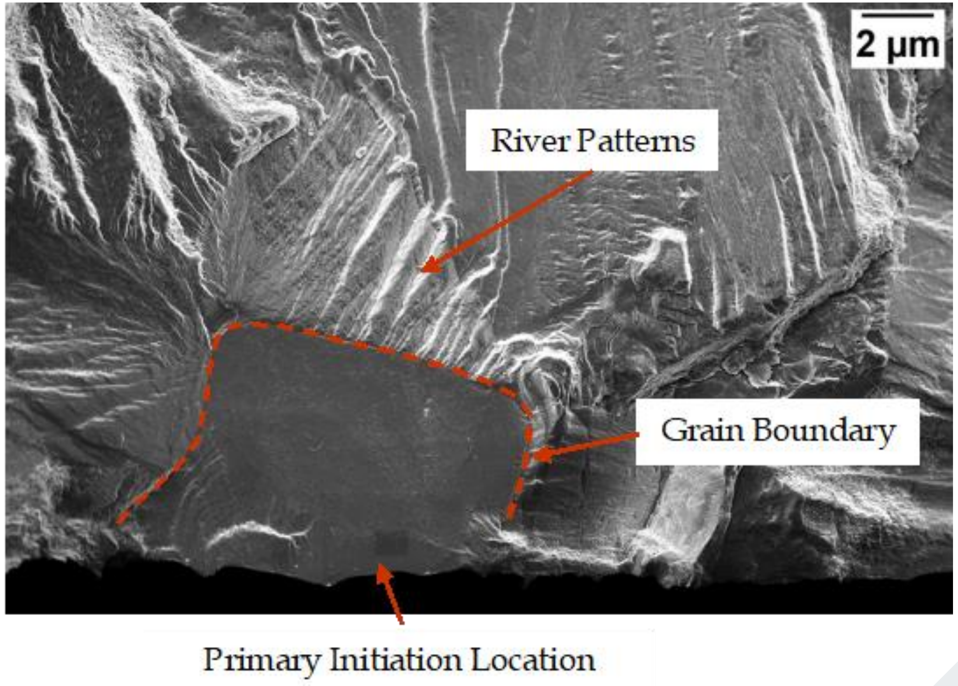
Outline

- Technologies in Transition: what is Quantitative Fractography?
- Challenges / Approach for Marking Ti6Al4V
- Examples from Coupon Testing Program
- Understand Mechanism of Fatigue Growth



Technologies in Transition

Technology supporting Aircraft Structural Integrity (ASI) must continually evolve.

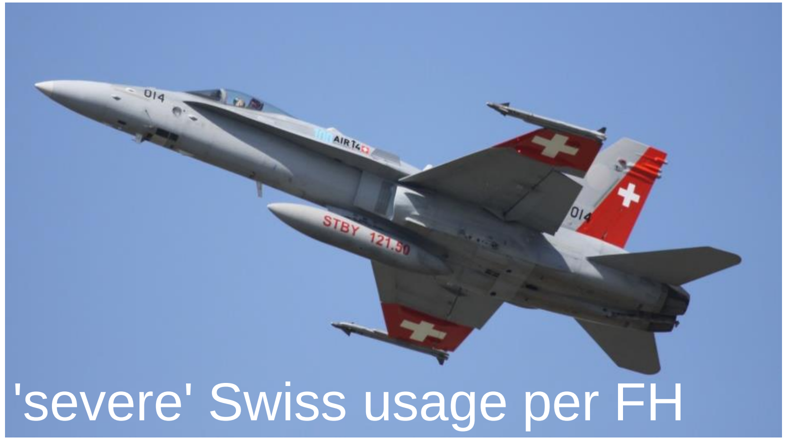
Aircraft themselves are in a technology transition - example is the choice of material for main carry through bulkheads:

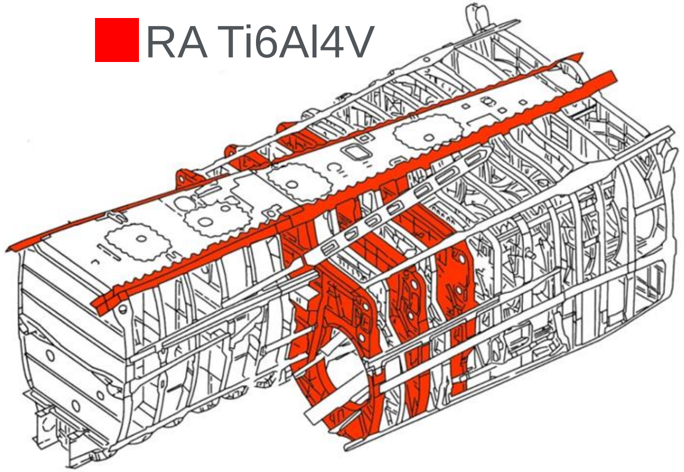
1970's
Aluminum 7050
USN F/A-18 A-D

1990's
RA Ti6Al4V
Swiss F/A-18 C/D

2000's
BA Ti6Al4V
F-35

Swiss F/A-18 C/D:





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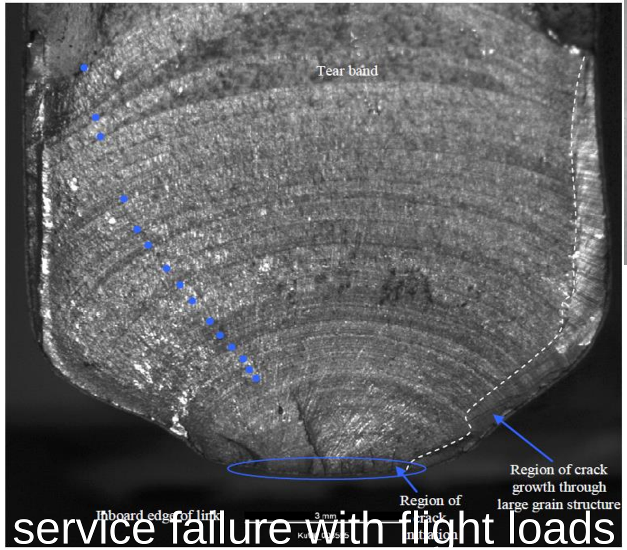
Technologies in Transition: Quantitative Fractography

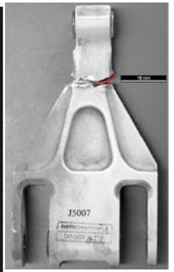
What is Quantitative Fractography (QF) ?

Quantitative Fractography (QF):

- quantifies features of fatigue failures
- correlate them to a material's microstructure, environment and loading history



service failure with flight loads

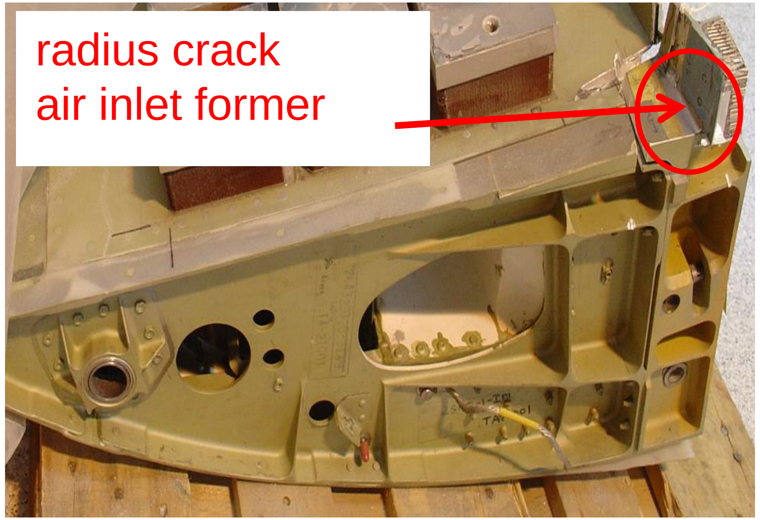


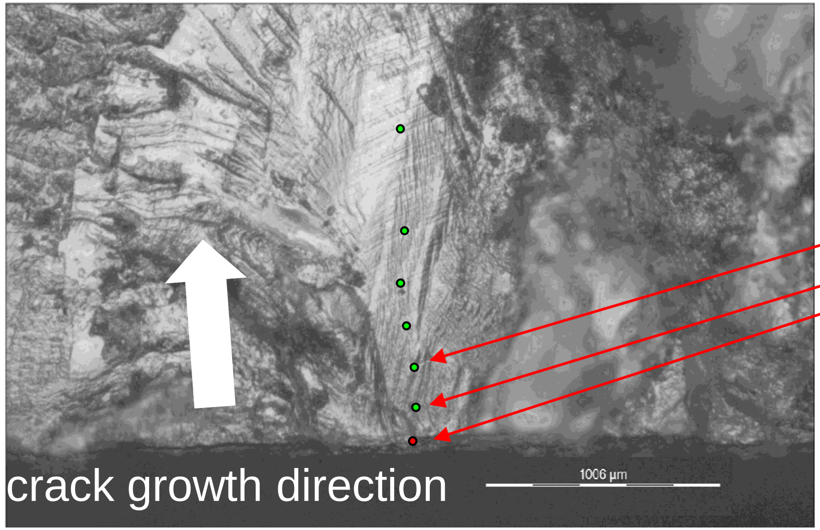
test coupon with marker loads

Technologies in Transition: Quantitative Fractography (QF)

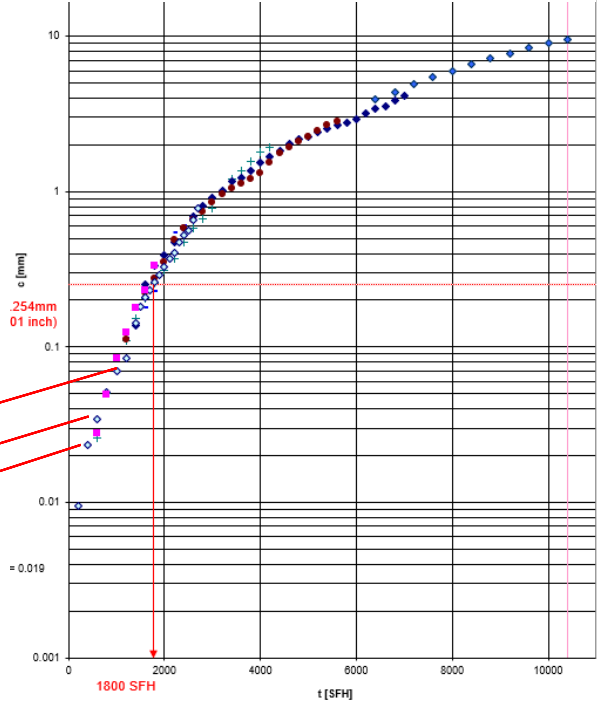
QF is a powerful tool that can be used to:

- determine where and from what a crack grew
- measure crack growth rates





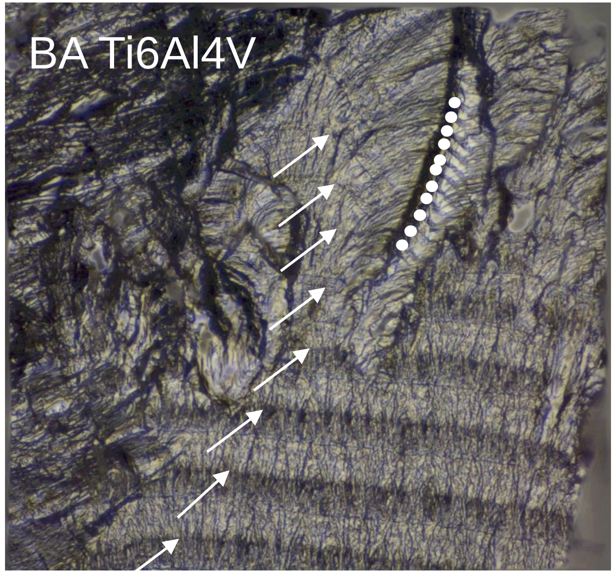
QF-measured crack depth vs flight hours

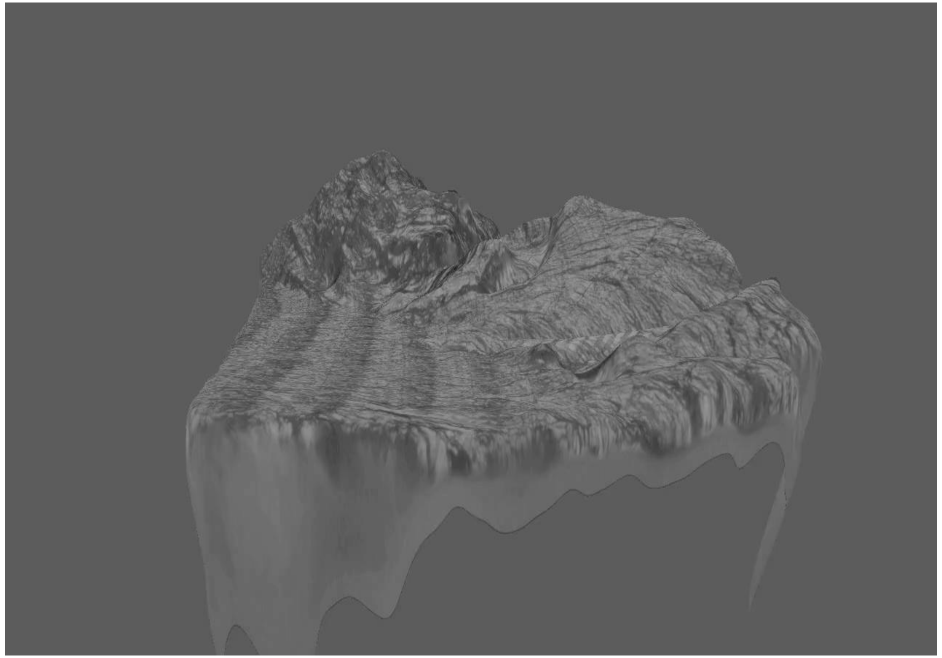


Technologies in Transition: Fractography and QF

Addition / alternative to scanning electron microscopy are realtime, digital optical methods:

- simple, quick, easy to use, instant visualisation





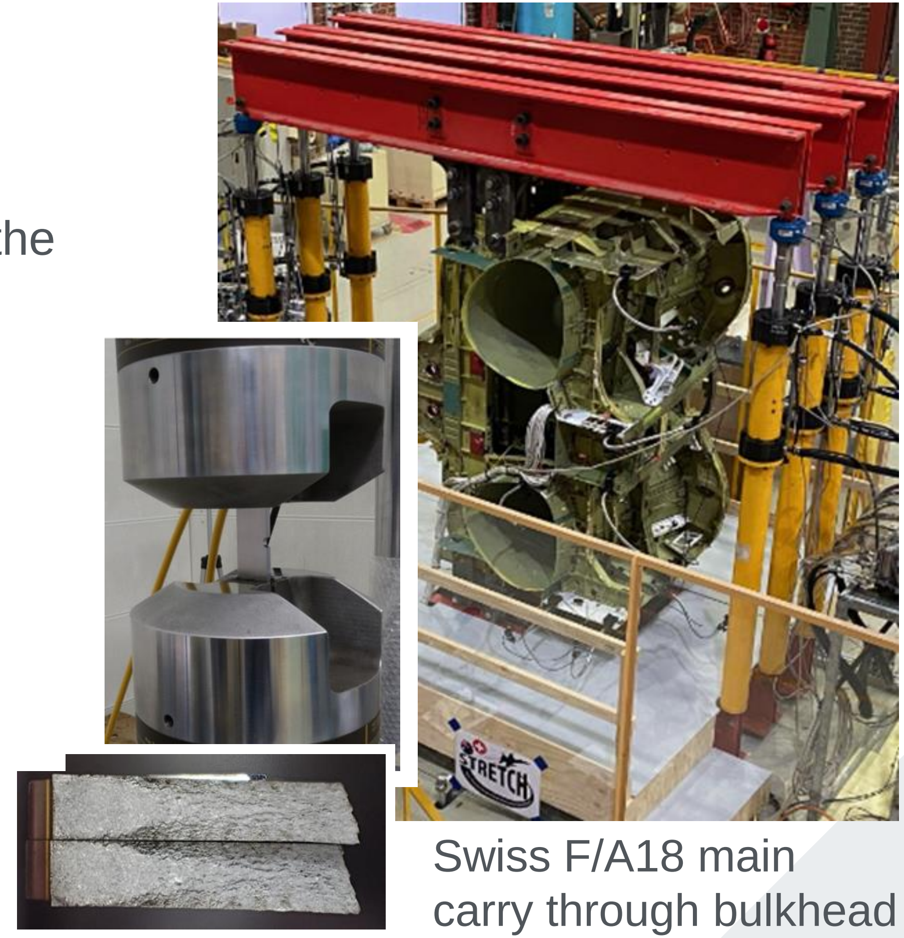
Technologies in Transition: QF for RA Ti6Al4V

Apply QF to support a Swiss F/A-18 center barrel (CB) test:

- develop a *method to mark fatigue growth*
- *measure damage rates* to compare the effects of truncating the CB test spectrum
- understand fatigue damage growth in the 'Swiss unique' bulkheads (forged RA Ti6Al4V)

ICAF Session 13, Wed. 28th June 13:30-15:10

Swiss Titanium Research Experiments on the Classic Hornet (STRETCH)



Swiss F/A18 main carry through bulkhead test at DSTG

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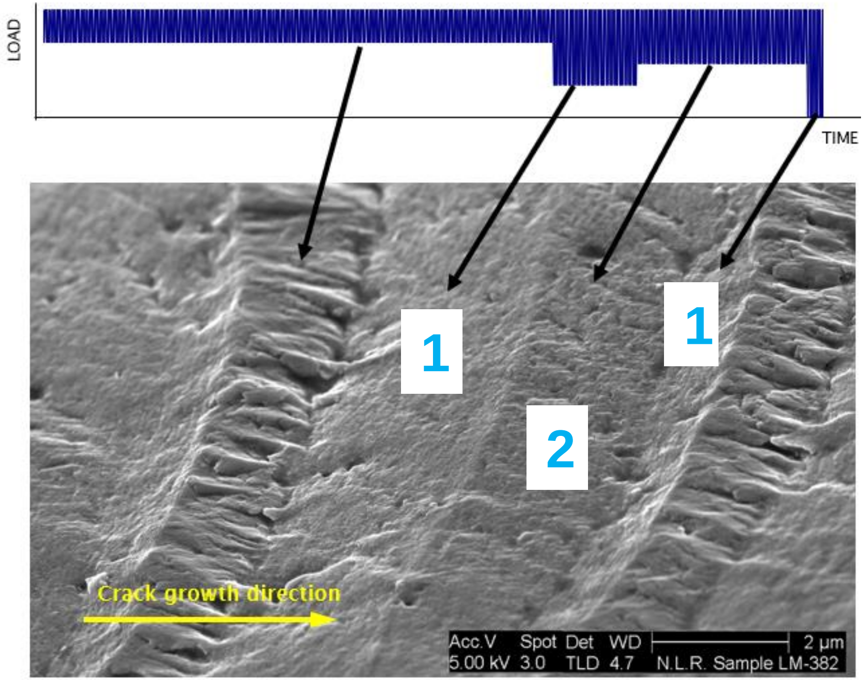
How does one mark a fracture surface?

Loading blocks with different R-ratio:



Altering the loading can change the crack growth path / topography.

Good markers can be created by creating *changes to the crack path and fracture surface topography*.

Influenced by:

- microstructure, available deformation systems (slip)
- loading history, crack tip stress distribution, environment

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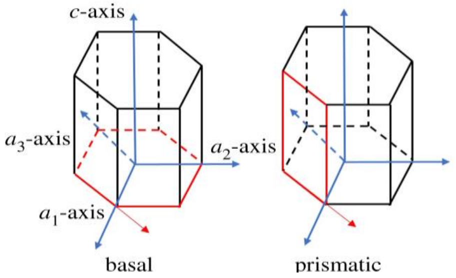
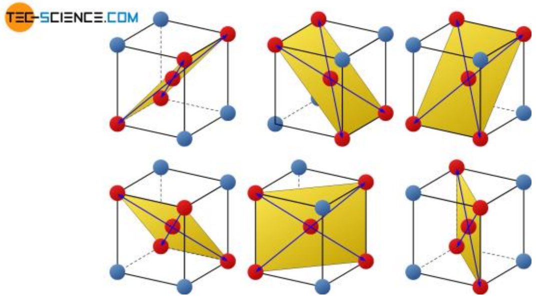
Microstructures of Ti6Al4V: BA, RA and AM

Two main phases produce multiple microstructures - alpha (α) phase and beta (β) phase

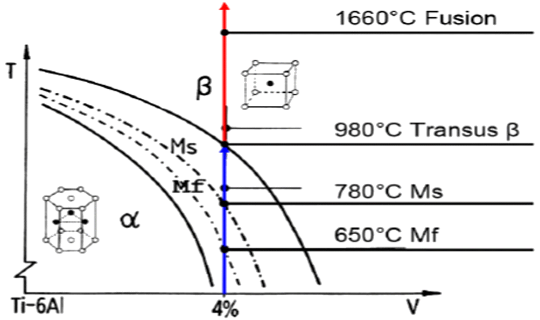
α: HCP – 3 close packed primary slip systems on basal plane



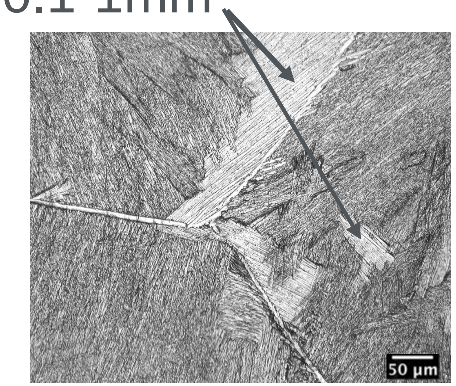
β: BCC – more slip systems (48) but none close packed



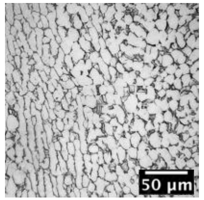
Heat-treatment dictates the microstructure:



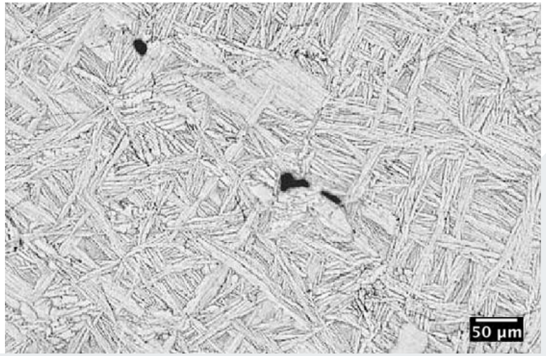
BA: α lath packets = 0.1-1mm



RA: α = 0.01mm



Additive Manufacturing: α = 0.01mm



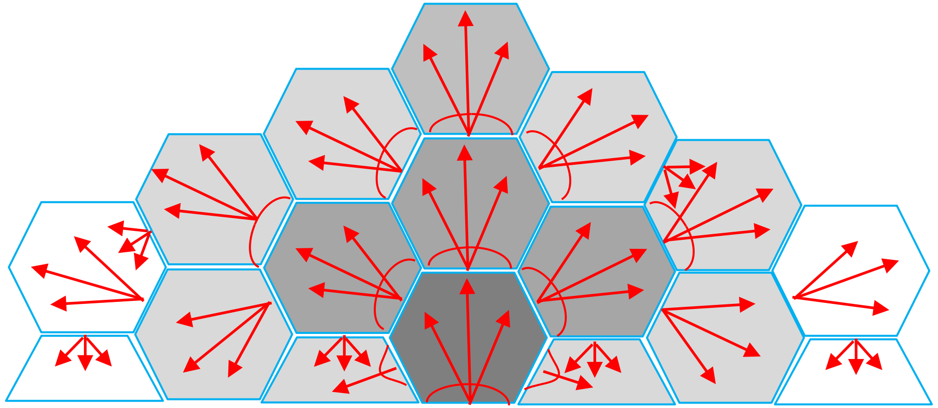
BA: beta annealed, RA: recrystallization annealed, AM: additive manufacturing

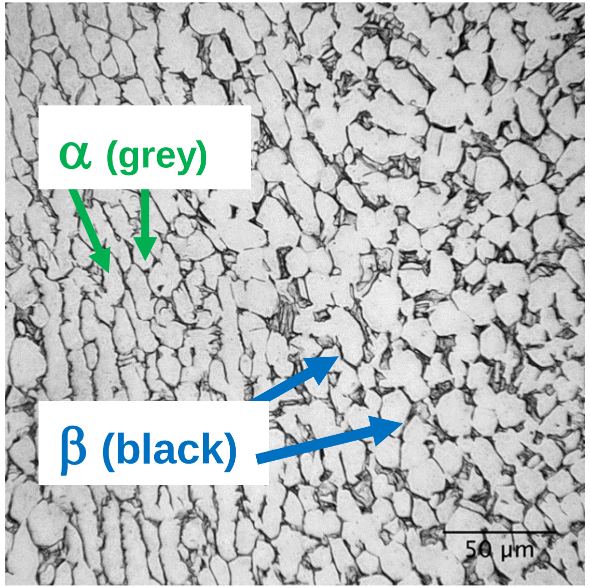
Marking Ti6Al4V: RA

Microstructure in RA *causes micro-surface roughness in small cracks*:

- crack growth on basal plane of the α phase
- α planes are *mis-oriented to one another, and to the β*
- small grain size results in *many changes to the crack path*

➢ RA and AM have *good resistance to small cracks* (crossing many grains)
➢ less resistance to long cracks (plastic zone covers many grains)





equiaxed alpha (grey areas)
beta phase (dark areas)

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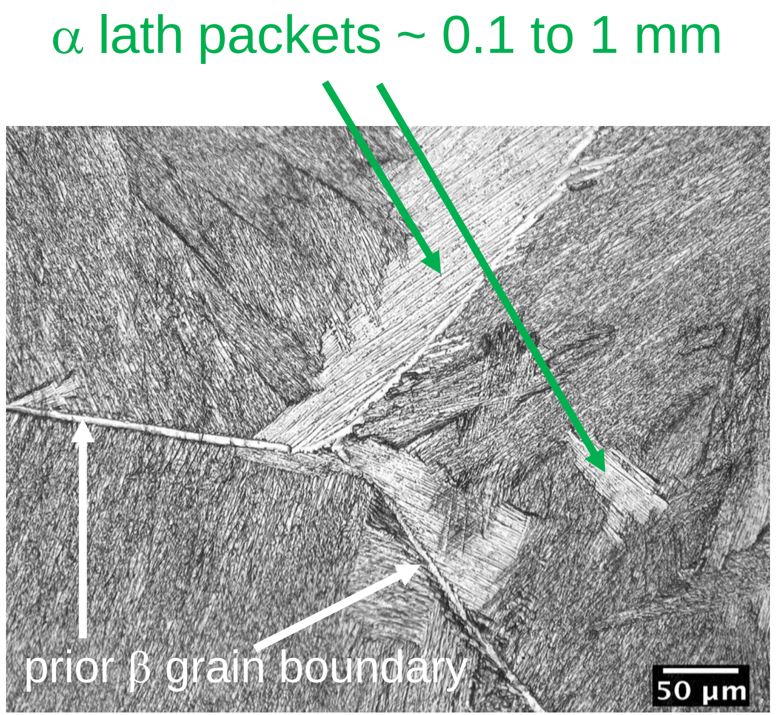
Marking Ti6Al4V: BA

BA has *macro-surface roughness* due to:

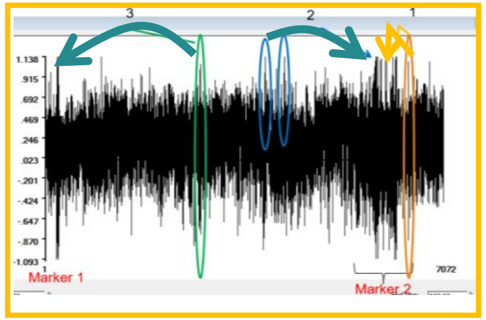
- *'large'* packets of aligned alpha
- longer flattish growth planes ~ packet size

➢ BA has less resistance to small cracks (crossing few grains)
➢ *good resistance to long cracks* (crossing many grains)



BA Ti6Al4V

Methods of Producing Marker Bands

1


Methods to add markers

1 Loads reordering

2 Over-loads

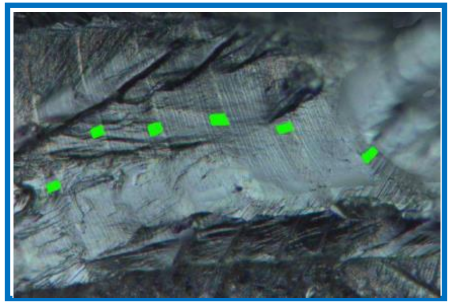
3 Under-loads

4 CA loads

5 Bar-coded CA bands

2
higher than Pmax

3 *increase ΔK, or to offset retardation*

4


CA = constant amplitude

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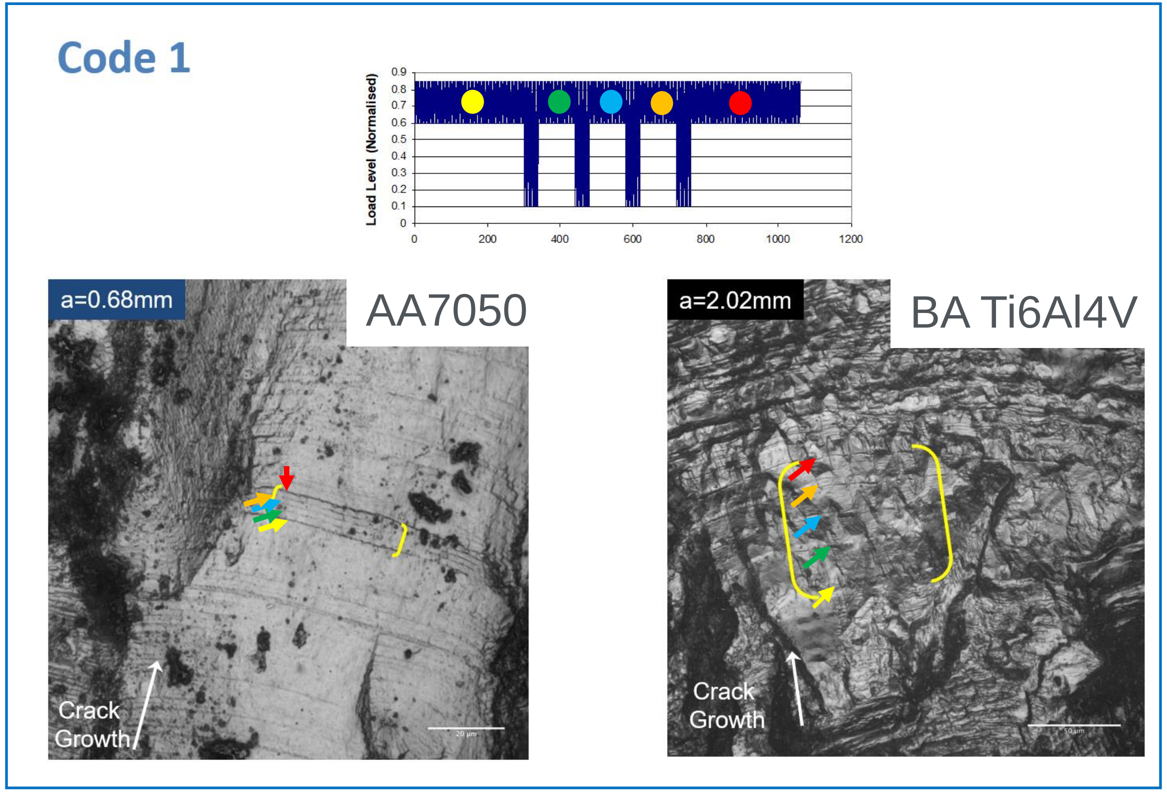
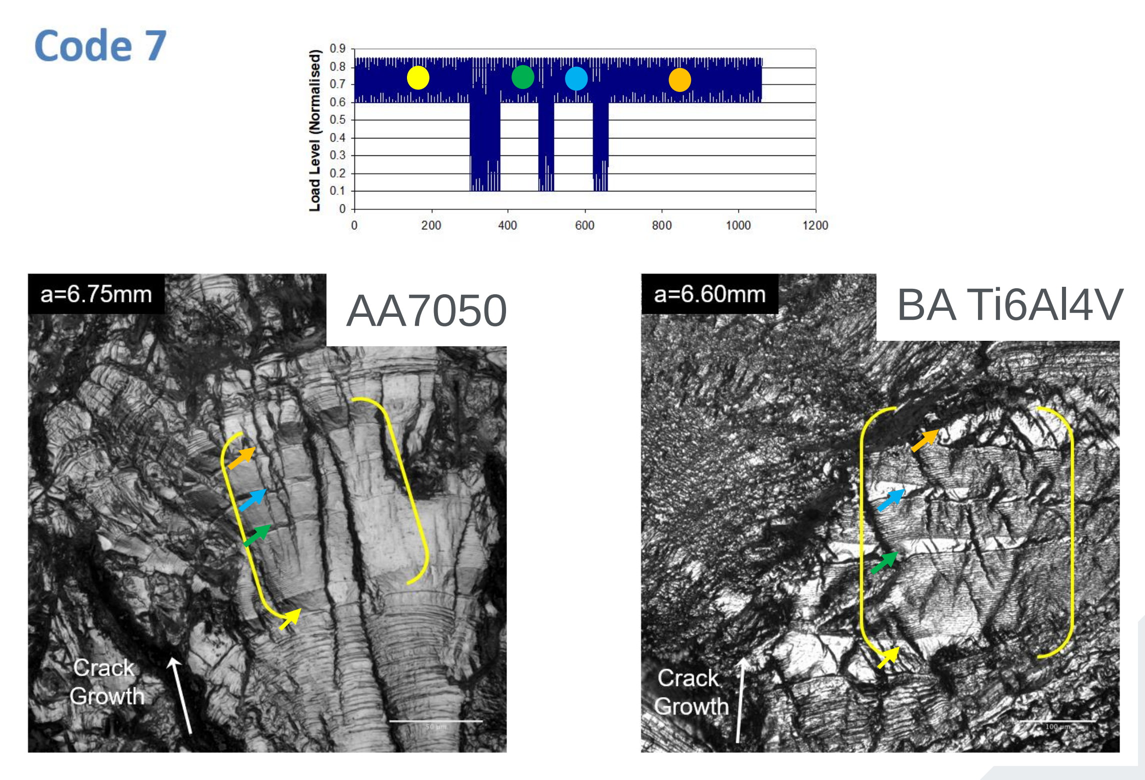
Constant Amplitude Bar-Coded Markers

Examples with aluminum and BA Ti6Al4V:





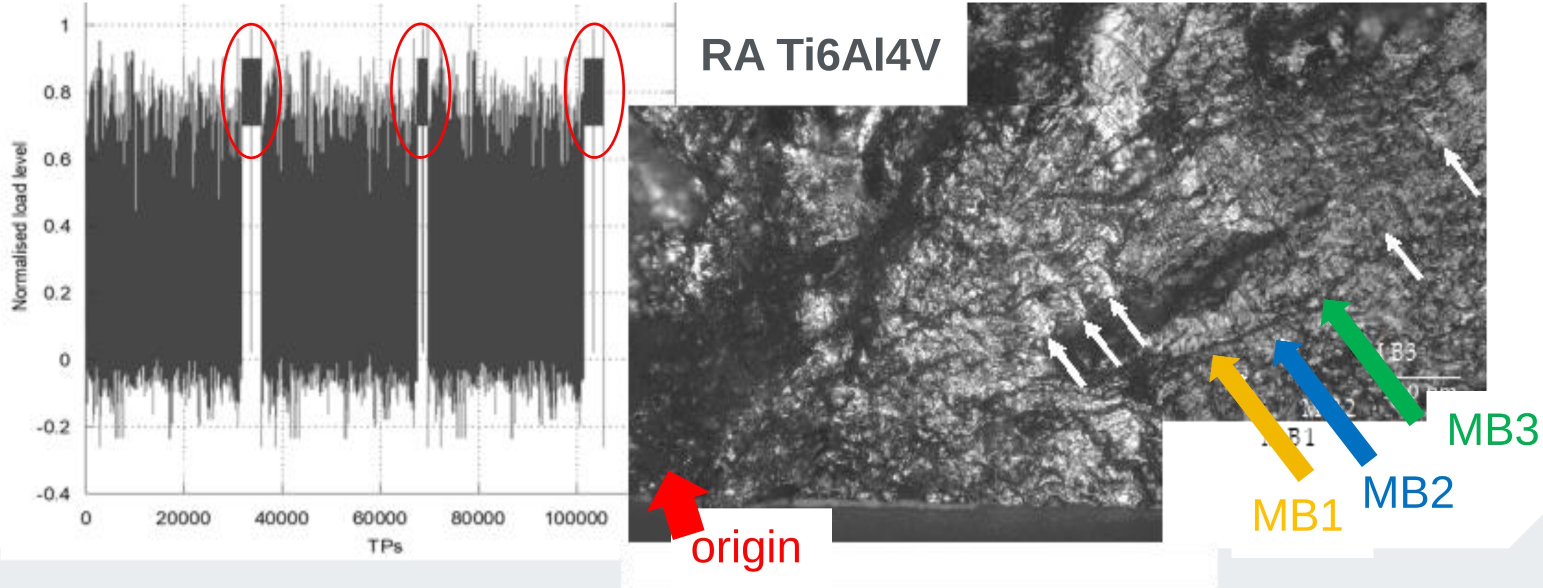
Marking Scheme Approach: RA Ti6Al4V

RA Ti6Al4V:

- adopt a bar-code of high R / low R / high R that will be 'simple' yet 'unique'

Goal: < 10% growth/block

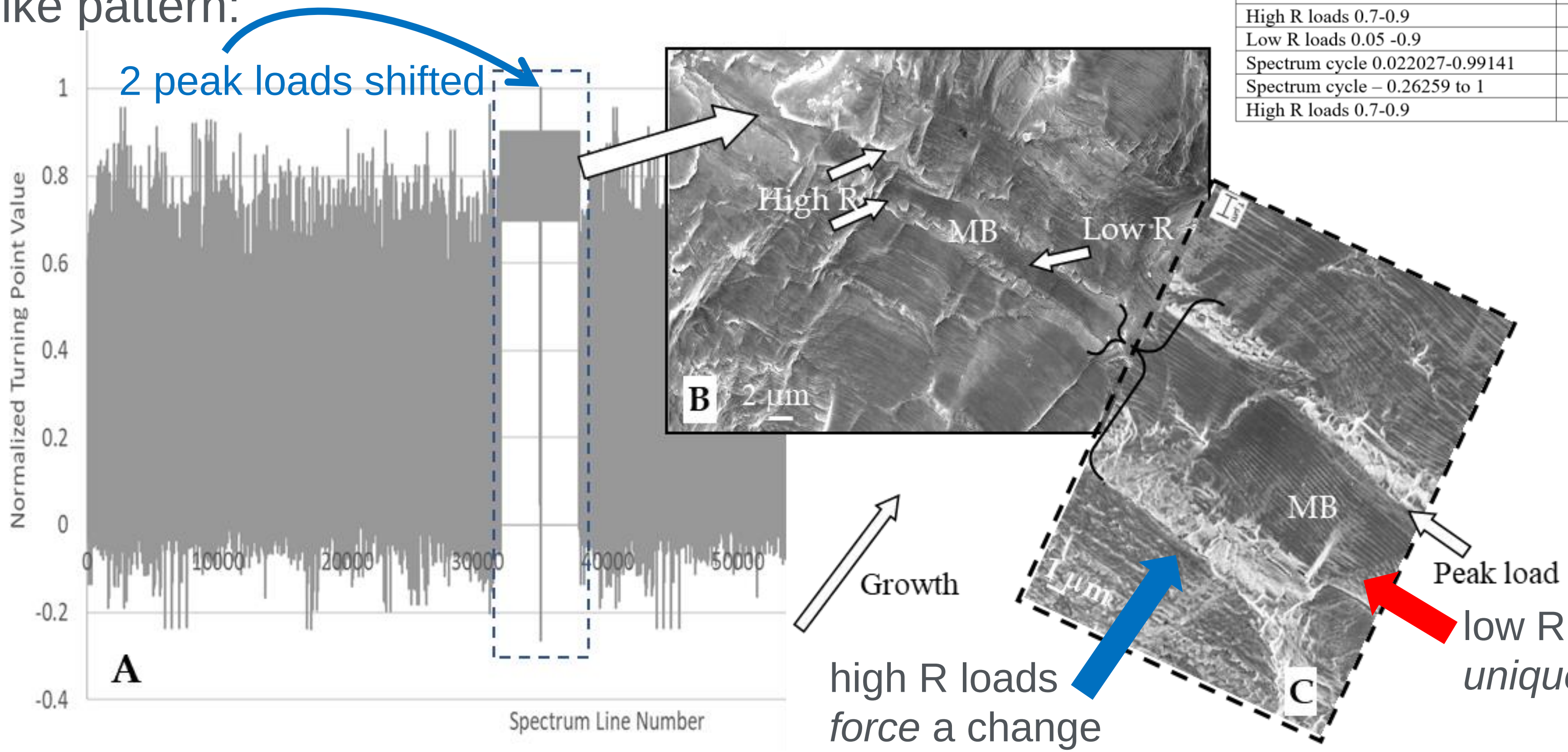
Pre-trials: 3 marker types



Marking Scheme Approach: RA Ti6Al4V

'*Tram-track*' like pattern:

	MB1	MB2
High R loads 0.7-0.9	1500	1500
Low R loads 0.05 -0.9	20	15
Spectrum cycle 0.022027-0.99141	1	1
Spectrum cycle – 0.26259 to 1	1	1
High R loads 0.7-0.9	1500	1500



high R loads *force* a change in crack path

low R loads provide a *unique* pattern

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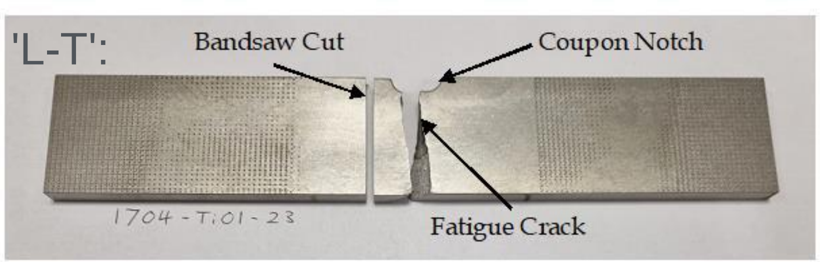
Coupon Testing

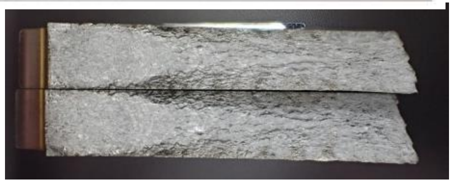
Markers evaluated in a coupon test program:

- high Kt coupons, RA TiAl4V forged plate coupons
- untruncated / truncated spectrum

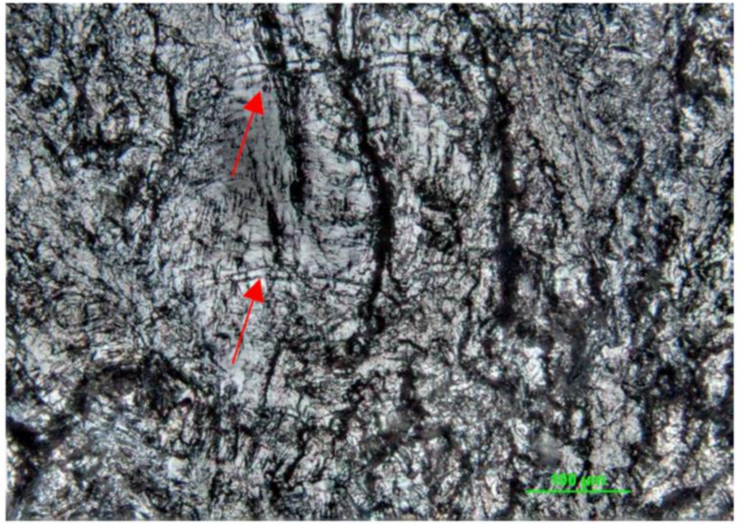
Results:

- markers provide an effective means of capturing small to large growth
- the effects of truncation were negligible

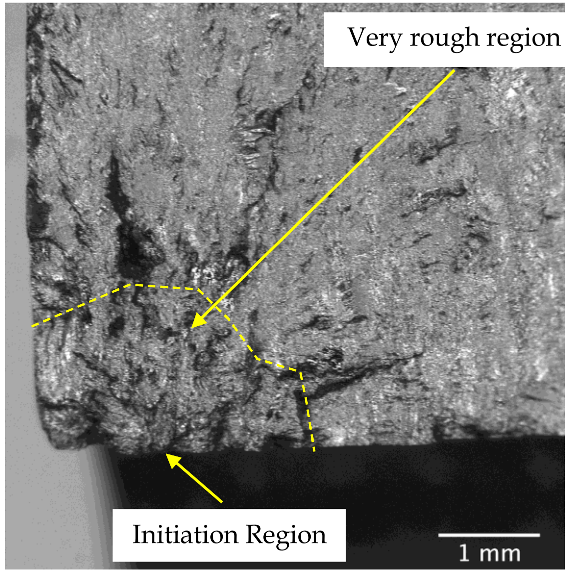


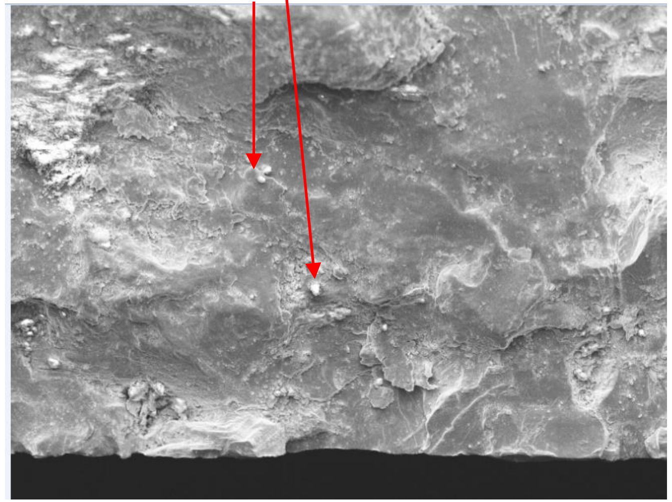


~ 0.5 mm optical:

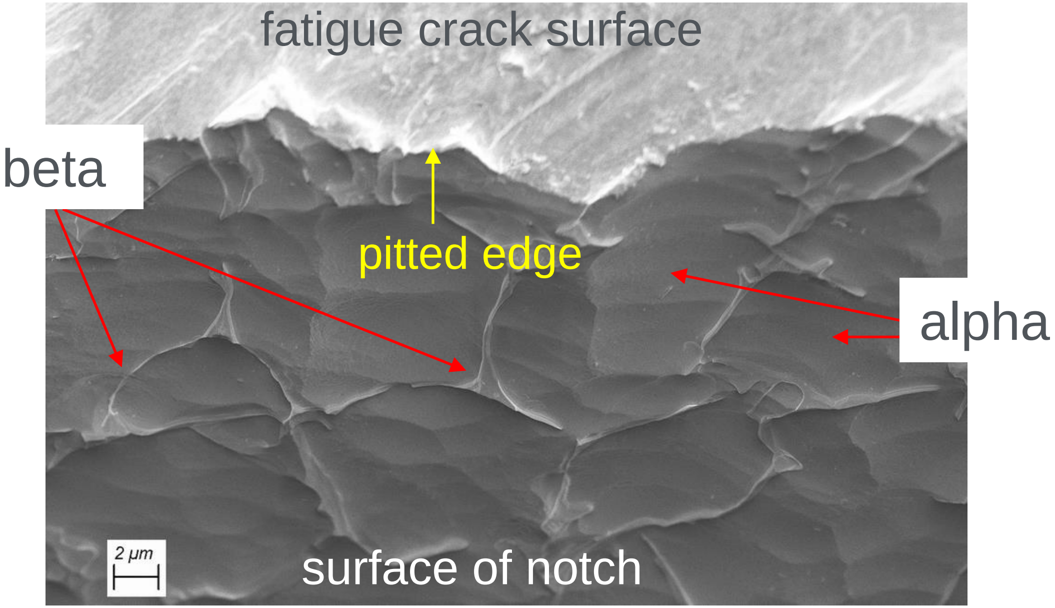


Fracture Surface near the Origin





- origin is very ‘clean’ with no inclusions, no porosity



Etching:

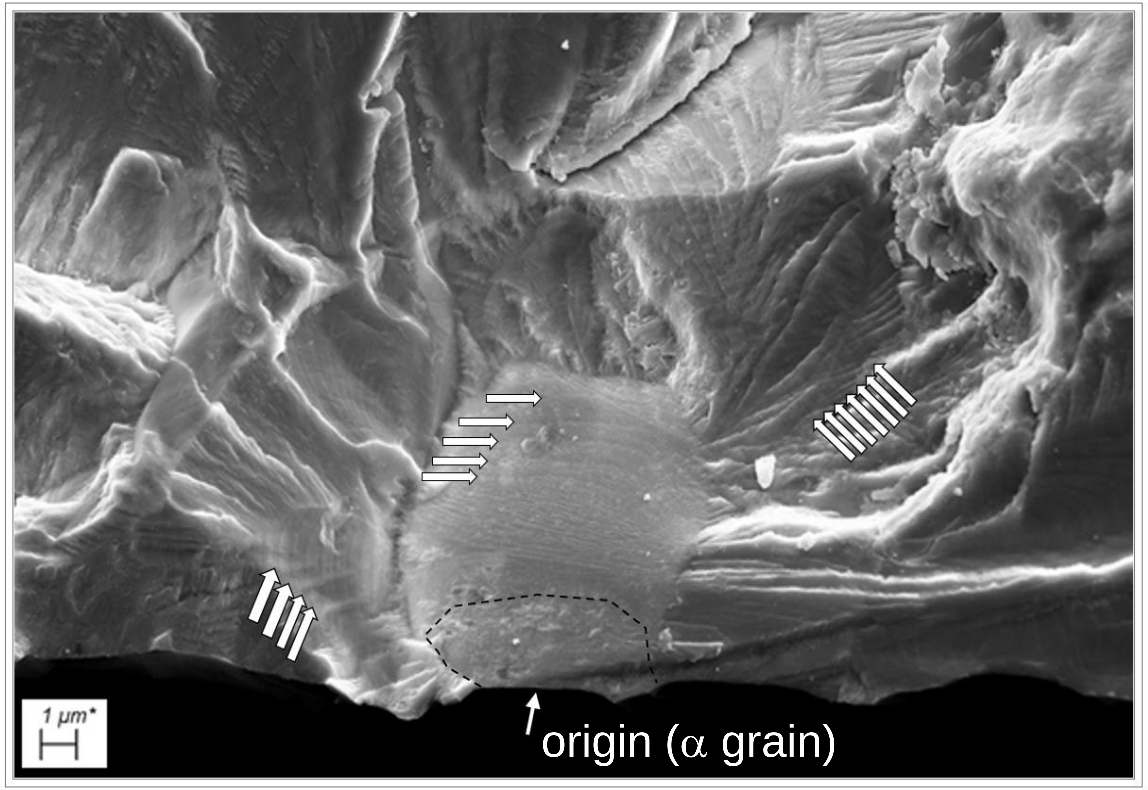
- no β grain boundary (GB) attack, so no GB discontinuities
- depressions are broad and shallow and not very 'crack-like' (circa 1-2 microns deep)

Fracture Surface near the Origin

Repeating growth blocks are visible in the α grains (starting at ~6 microns, growth of ~0.5 µm)

Initial growth:

- *is fast* within the first α grain due to *favourable initial orientation*
- crosses a grain boundary and re-orients the path
- has a 'facet-like' appearance (similar to cleavage), but clearly shows evidence of block repeats.
- 'facets' are often at high angles (max τ planes)



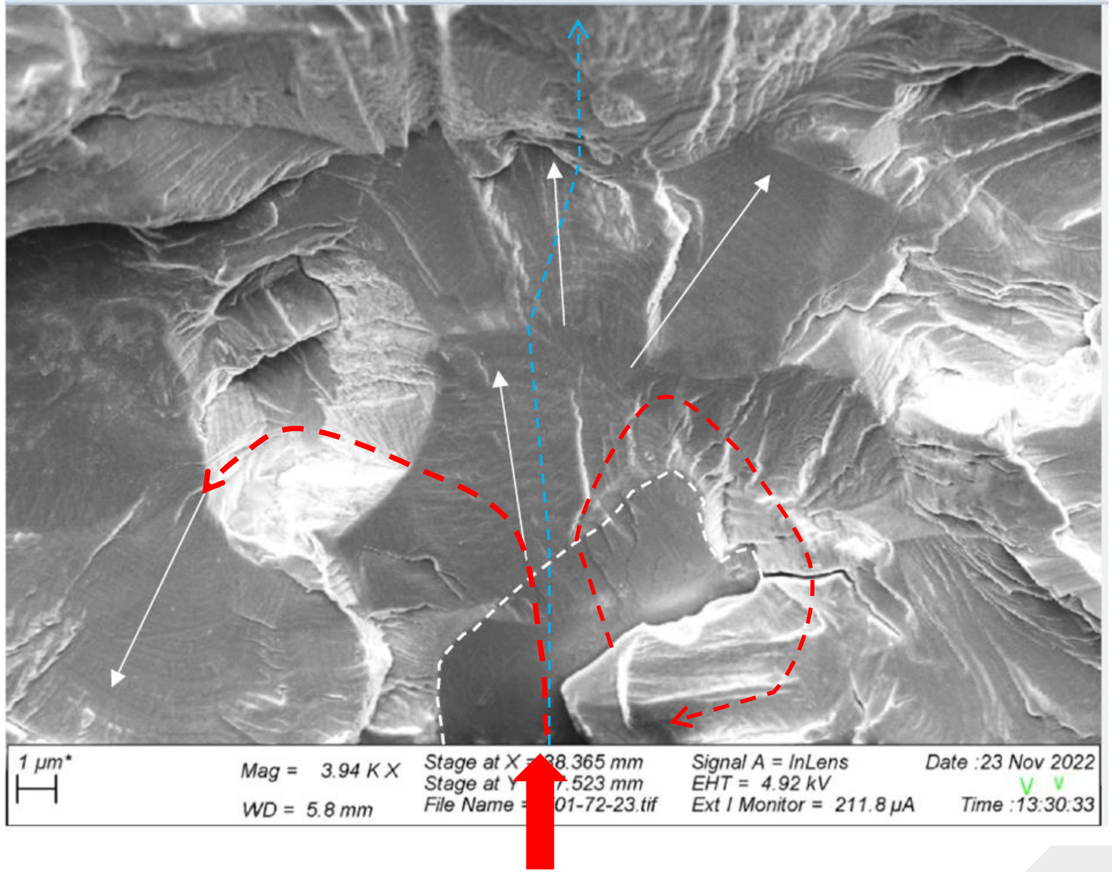
white arrows indicate block repeats

Faceted Growth Affects Fatigue Behaviour

Markers suggest fatigue growth mechanism:

- *growth is by mode I tensile crack opening and not by mode II shear or cleavage*
- *growth direction may change dramatically from grain to grain*, even growing backwards
- *local fatigue growth rate* is influenced by grain boundaries and β causing *forced path changes*

➢ Advantageous for fatigue resistance of small cracks



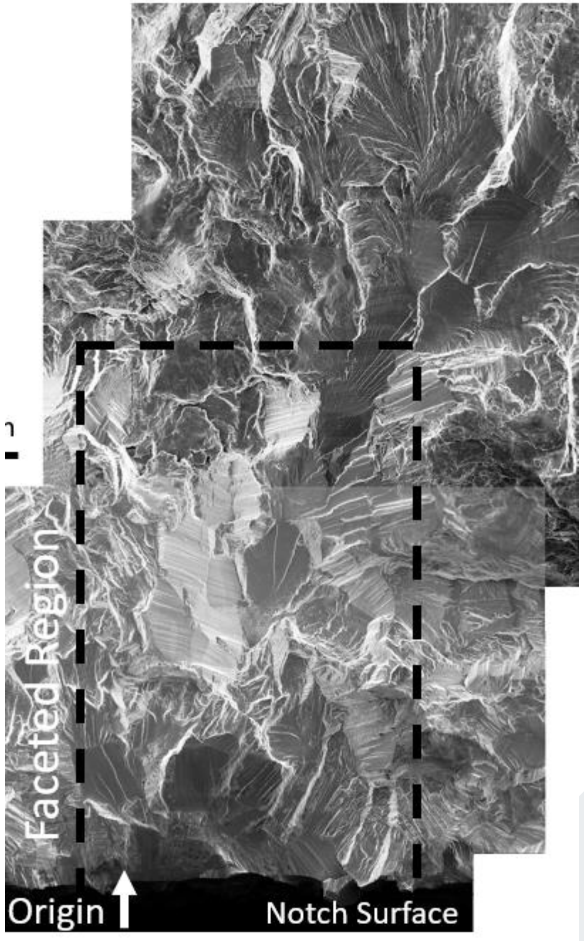
originating alpha grain

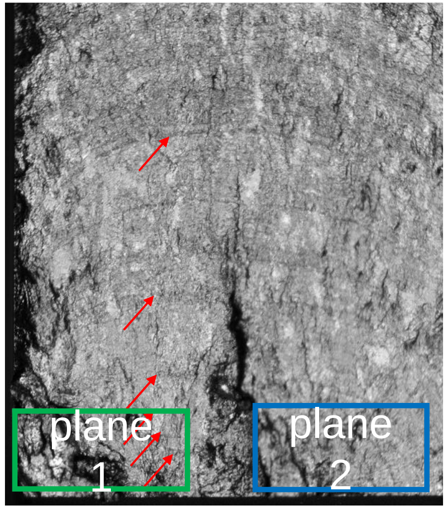
Faceted Growth Affects Fatigue Behaviour

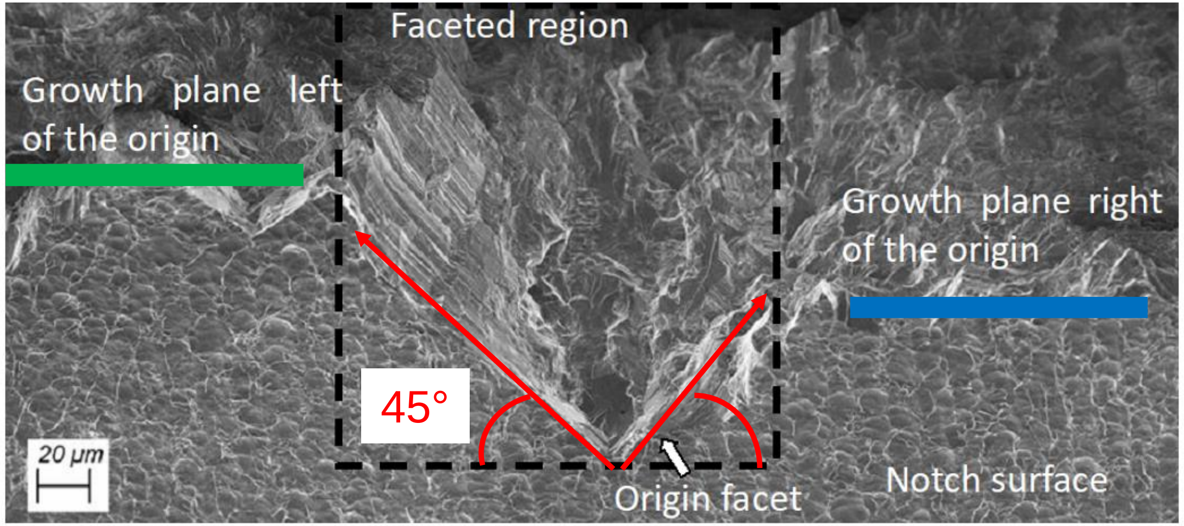
Additional roughness further *away from the origin* is caused by:

- faceted surfaces are at high angles
- crack follows a steep path
- the average growth planes are often on separate levels

➢ Result: *further increase of retardation* until crack merges

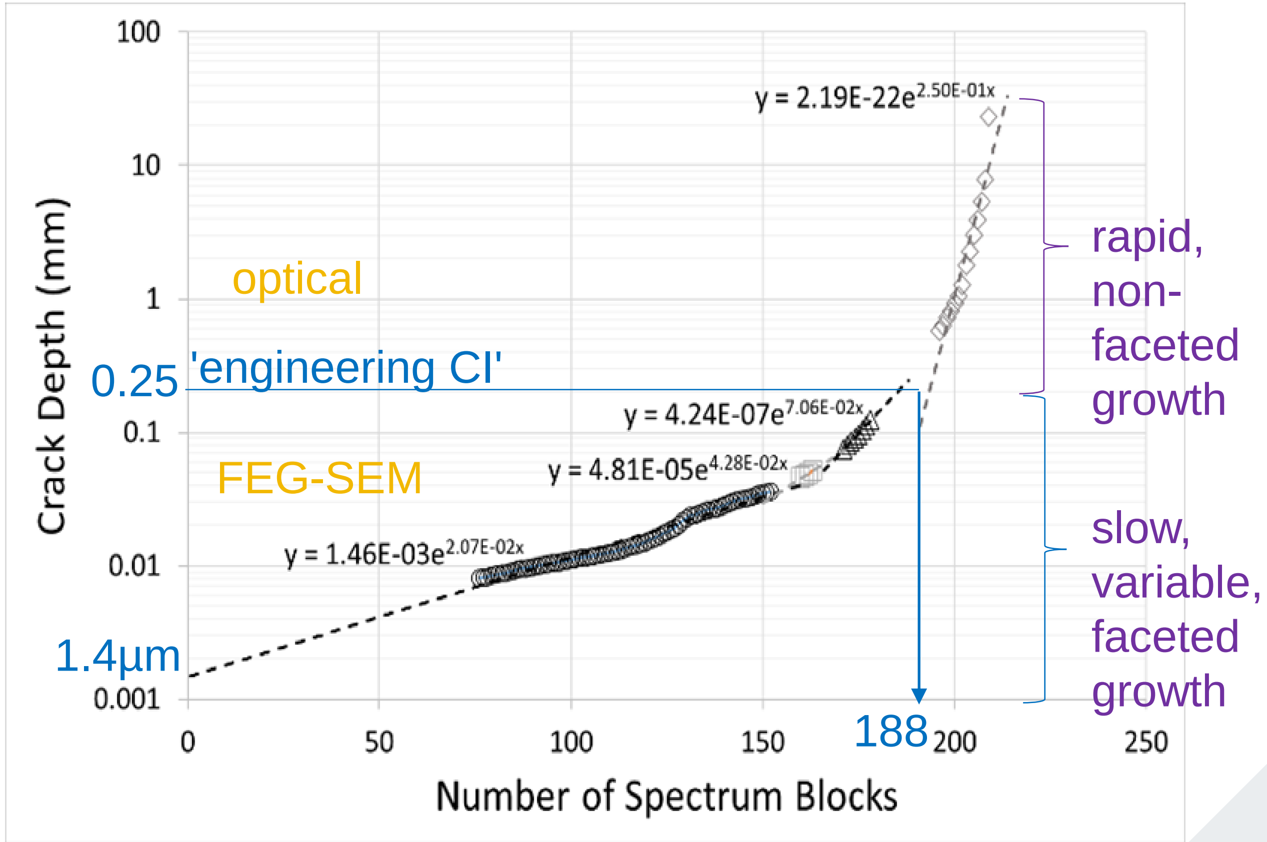






Crack Growth Measurements

- generate 'complete' growth curves
- growth rate per grain is measurable
- early growth rates are a function of grain orientations and local crack paths
- beyond ~0.25 mm -> rapid growth, single growth plane (no faceting)



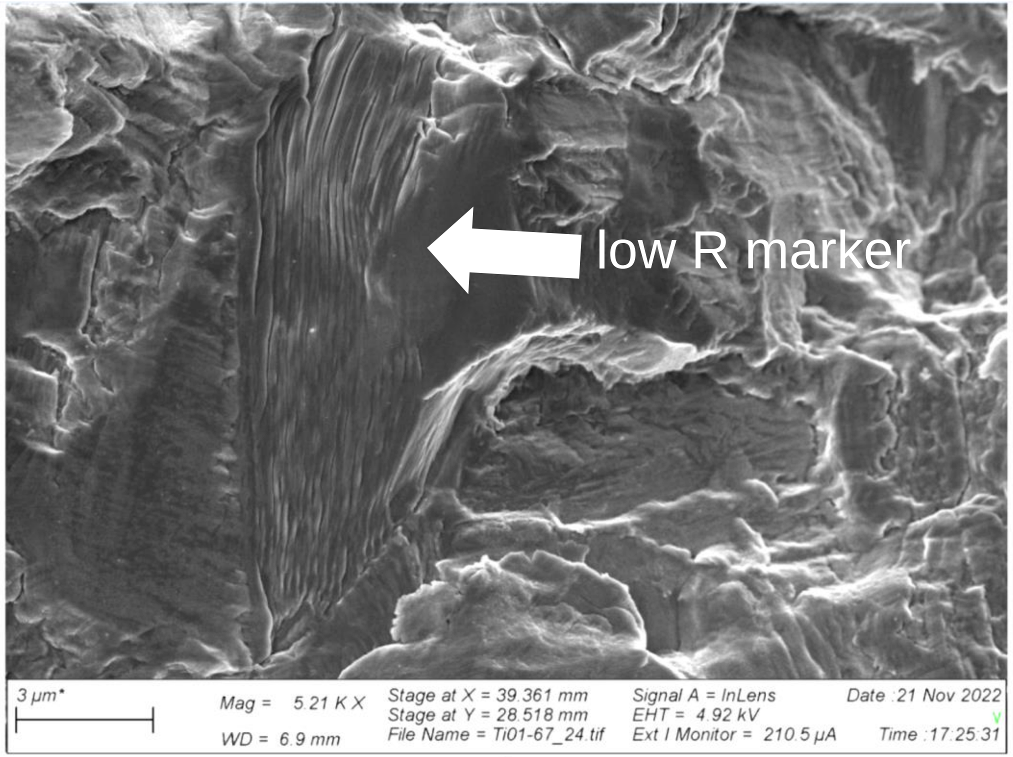
Conclusions

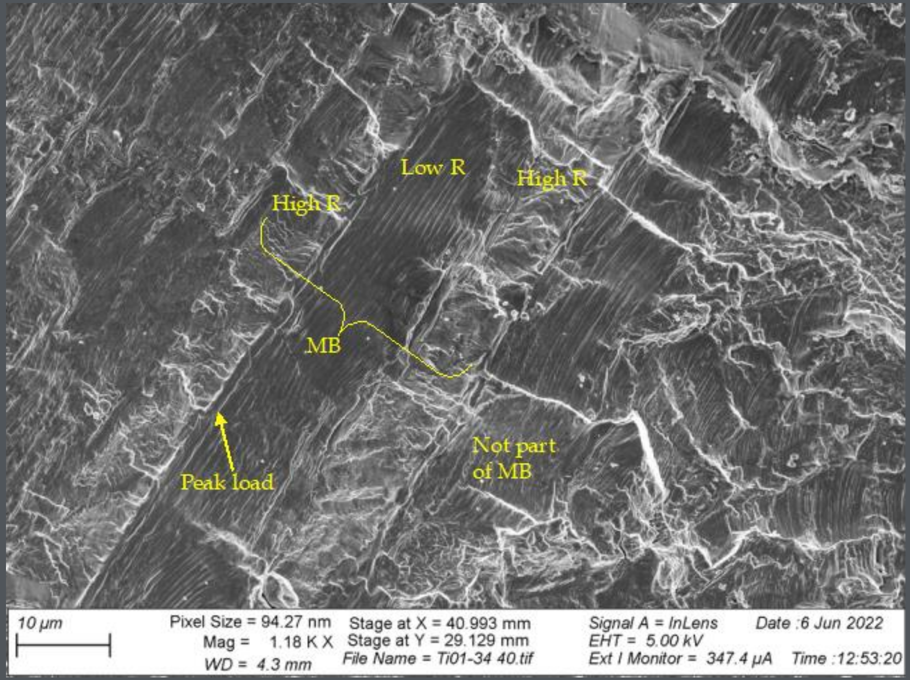
Marking tips:

- 'simple but unique' markers
- naturally occurring max/min loads
- two marker variations

This technique allows us to:

- ➢ measure the growth within single α grains, where the rate and direction is highly variable
- ➢ determine an overall growth curve
- ➢ visualize and explain the excellent fatigue resistance of this alloy





Acknowledgements

The authors would like to gratefully acknowledge the financial support of the Swiss Federal Office for Defence Procurement (armasuisse).

Thank you for your attention.