

Microstructure-sensitive fatigue crack growth mechanisms in 7XXX-series Al-Zn-Mg-Cu alloys

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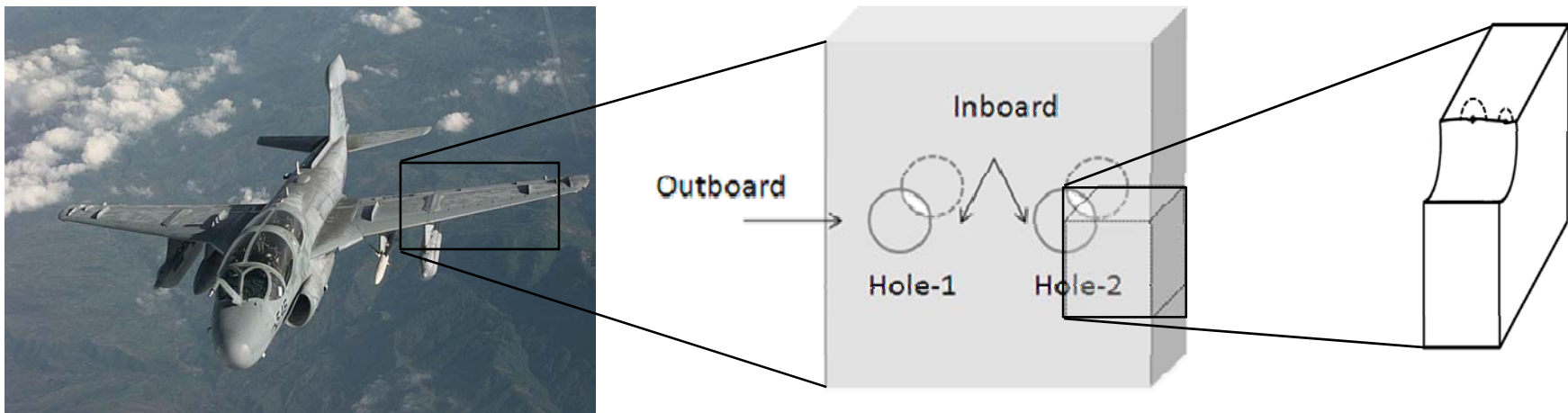


Sponsor: Defense Advanced Research Projects Agency (DARPA)



Motivation

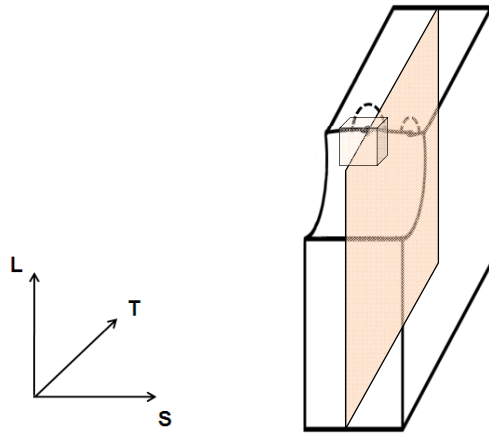
- Simplified models are conservative (costly), impede “readiness”
- **Structural Integrity Prognosis System (SIPS) Program**
(Northrop Grumman Corporation/DARPA)
- Development of physics-based multi-stage fatigue models
 - Need high resolution experimental data.
 - Better understanding of mechanisms of initiation and small-crack growth.



EA-6B Prowler

Overview

- Materials and test conditions



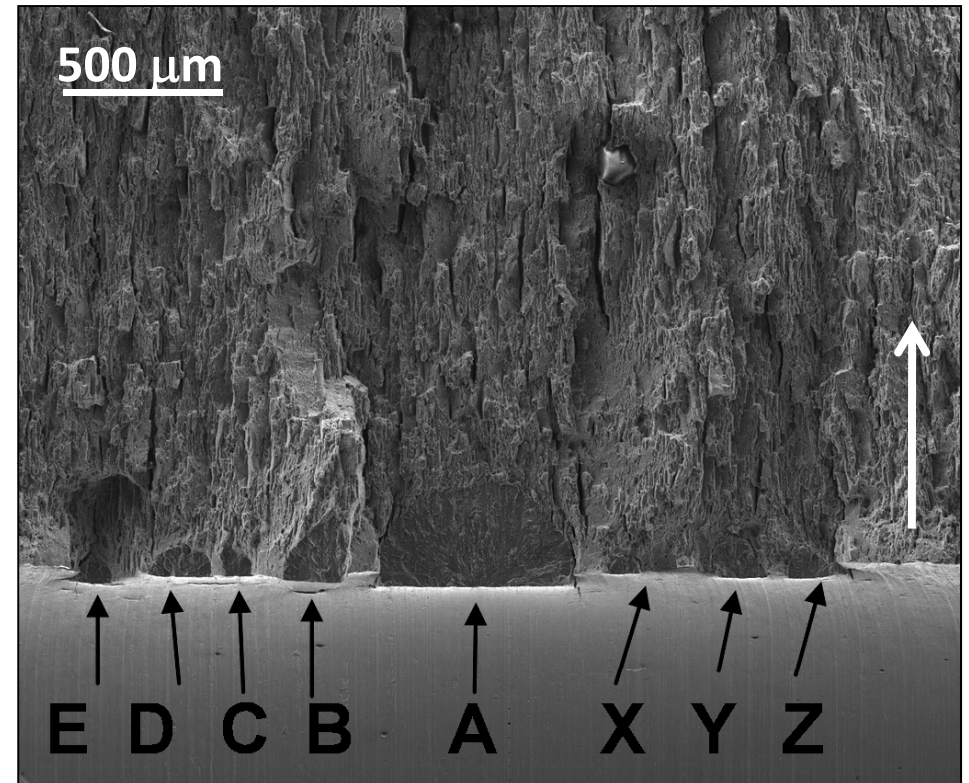
- Results & Conclusions

Part I (Marker-band based analysis)

- Crack initiation sites / fractographic analysis
- Small fatigue crack growth kinetics

Part II (EBSD-based high resolution probe of crystallography & defect structure)

- Fatigue crack surface crystallography near initiation sites
- Microstructure effects on small crack growth



Materials and test conditions

1. Materials

a) Legacy alloy 7075-T651, peak-aged

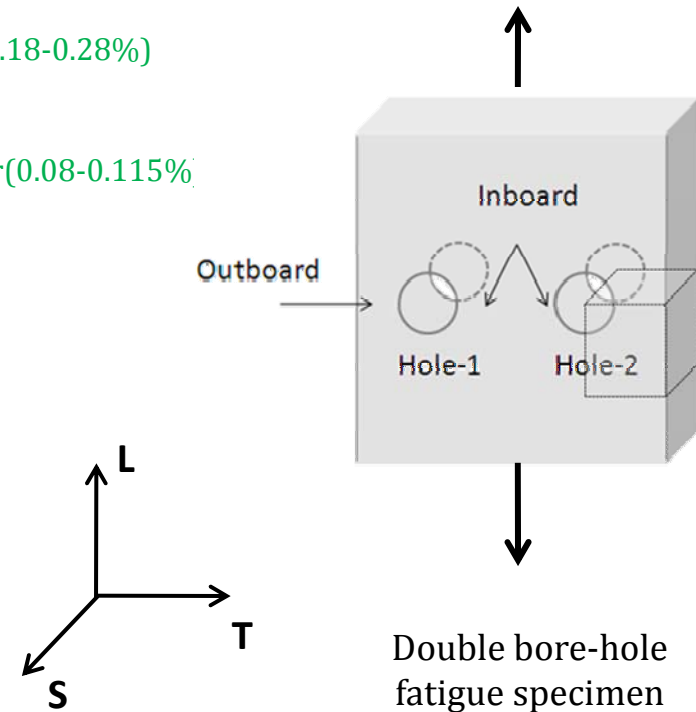
- Zn(5.1-6.1), Cu(1.2-2%), Mg(2.1-2.9%), Si (0.4%), Fe (0.5%), Cr(0.18-0.28%)

b) Modern “cleaner” alloy 7050-T7451, over-aged

- Zn(5.7-6.7), Cu(2-2.6%), Mg(1.9-2.6%), Si (0.12%), Fe (0.15%), Zr(0.08-0.115%)

2. Fatigue test conditions

- Environment
 - a) Ambient moist-air [**warm-humid**]
 - b) -50°C dry N₂ [**cold-dry**]
- Maximum stress: 276 MPa
- Stress ratio (R) : 0.5
- Frequency (Hz) : 5 Hz (warm-humid)
10 Hz (cold-dry)



SIPS program materials were provided by the Alcoa Inc.
Fatigue tests were carried out by the Northrop Grumman Corporation.

Modeling of fatigue crack initiation and early growth

Surface flaws

Scratches, machining marks

Sharp corners

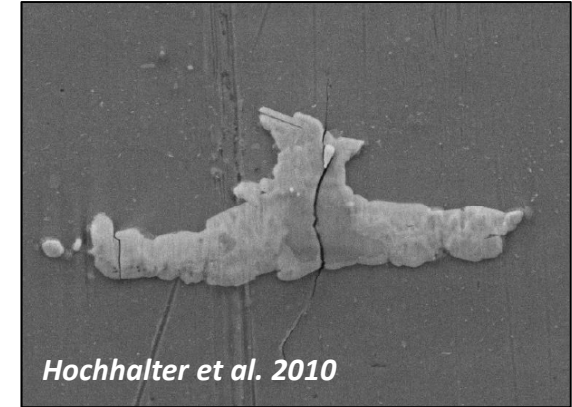
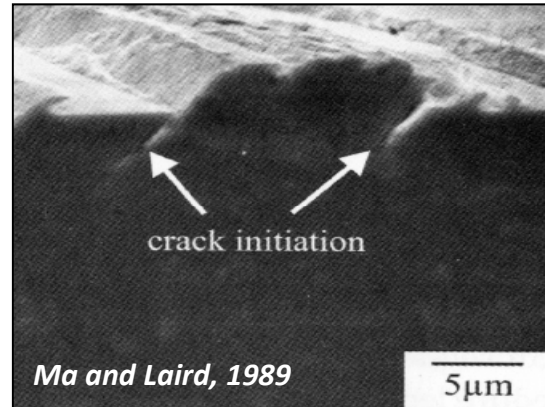
Corrosion pits

Microstructural heterogeneities

Persistent slip bands (PSBs)

Grain boundaries

Second phase particles, inclusions



Grosskreutz, 1967; Bowles and Schijve, 1973;
Kung and Fine, 1979; Lankford *et al.* 1984;
Halliday *et al.* 1999; Hochhalter *et al.* 2010

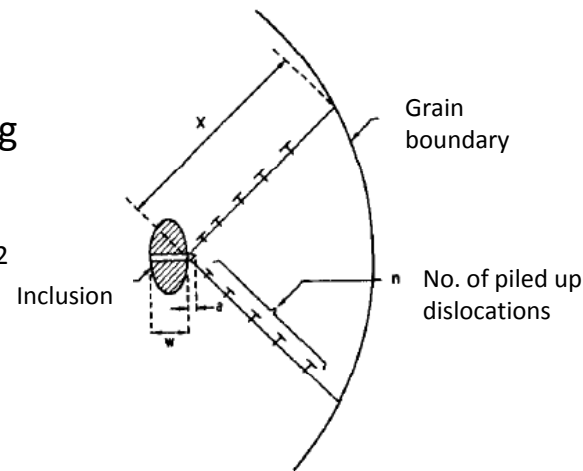
Crack initiation models

- Based upon plastic strain criteria near crack initiating hard particle.

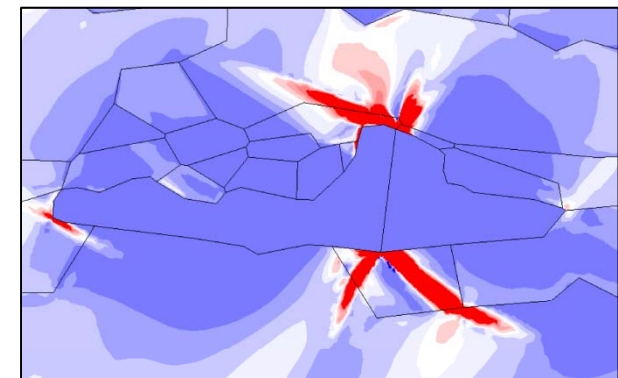
Chang *et al.*, 1979; Tanaka & Mura, 1982
Yi *et al.*, 2003; Xue *et al.*, 2003

- Assume **Stage I** early crack growth mode.

Crack initiation at hard-particle



Chang et al. 1979

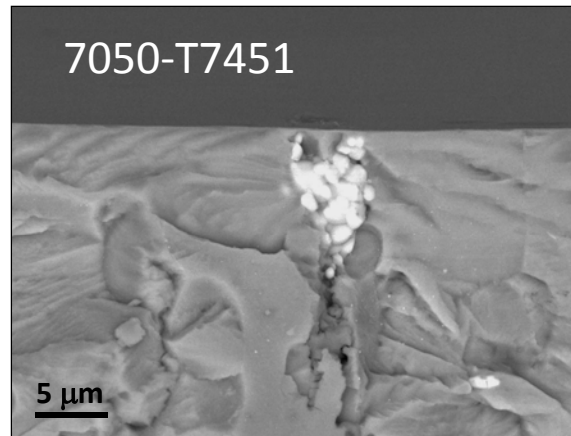
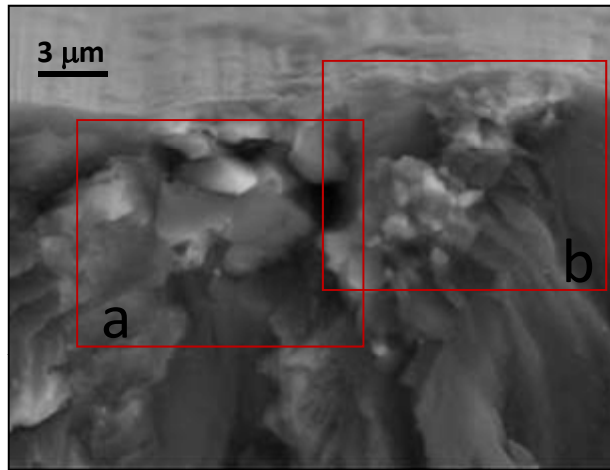
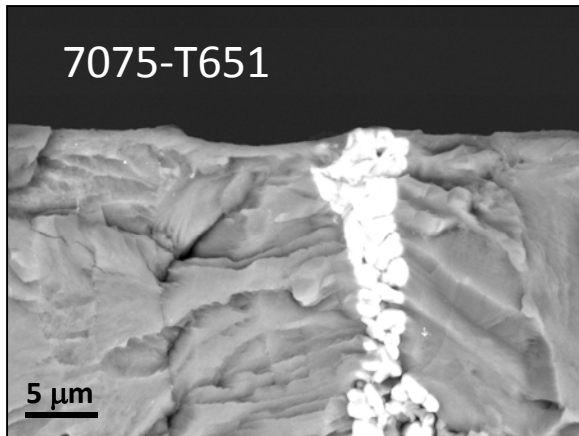
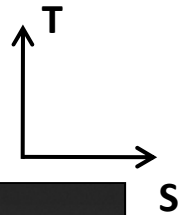


Hochhalter et al. 2010
Crystal plasticity-based finite element (CPFE) modeling

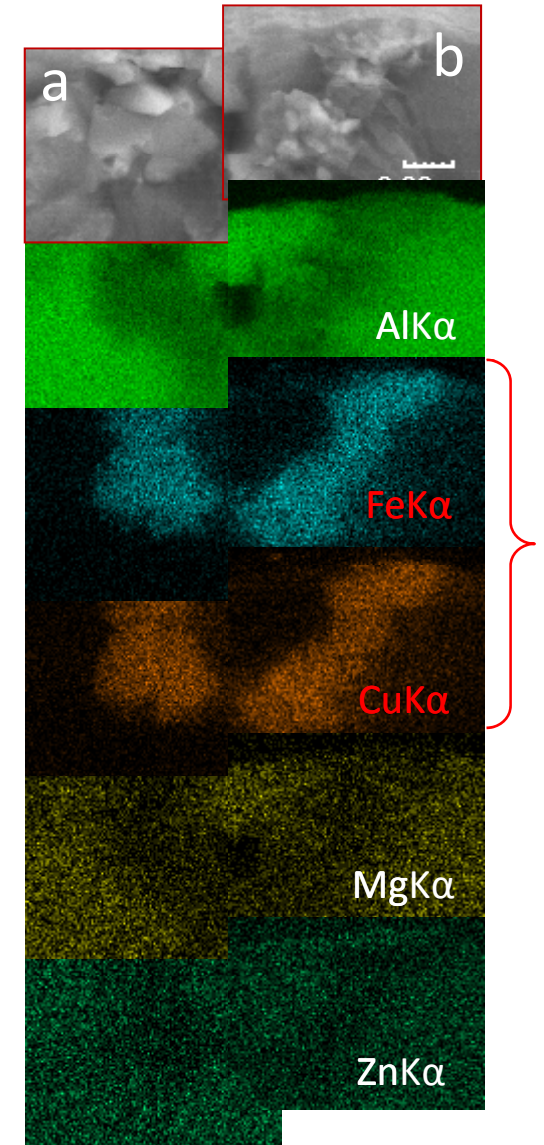
Constituent particles as initiation sites in 7075-T651

Metallurgical crack initiation site for Crack-A (~ 10 μm) in 'as-machined' 7075-T651.

- Constituent particles



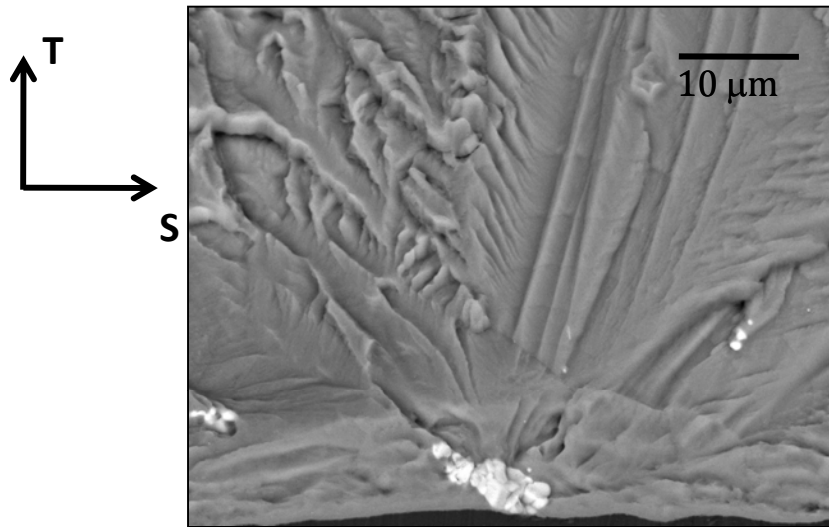
EDS Maps



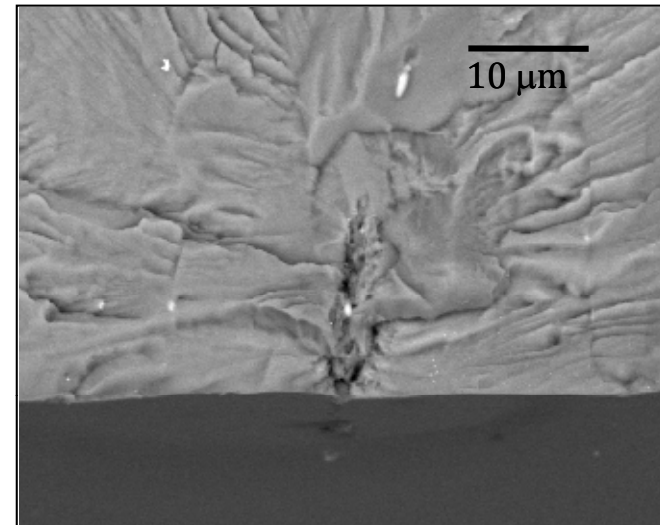
What are typical initiation sites in 7050 ?

Constituent particles as initiation sites in 7050-T7451

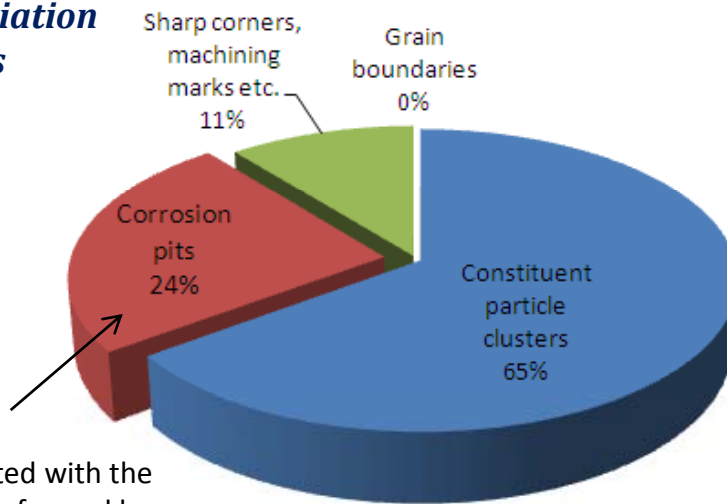
As-machined



Electropolished

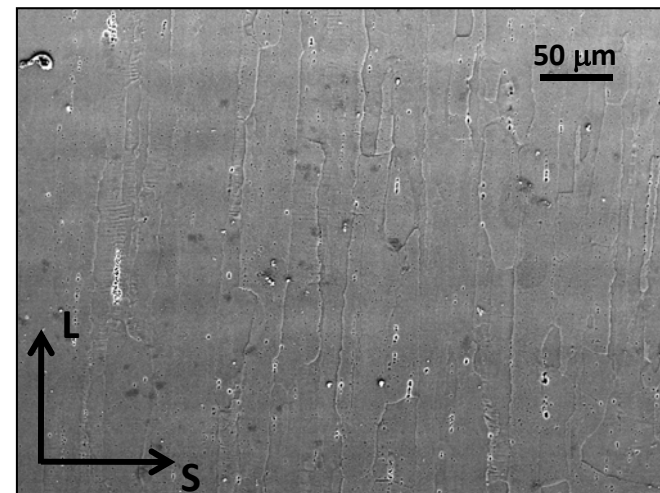


Crack initiation sites



Sites associated with the corrosion pits formed by electropolishing

Absence of grain boundary cracking



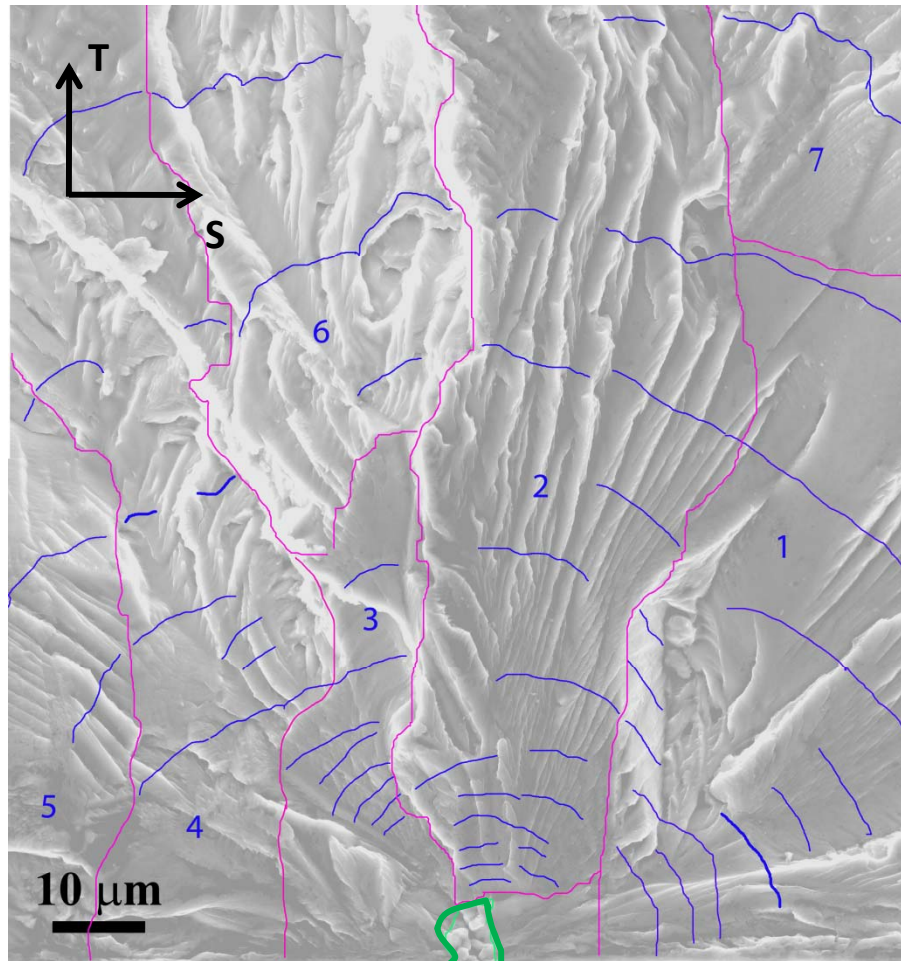
Constituents particles as initiation sites within either environment

Crack initiation sites were combined from both alloys and parsed according to the environment in which they were cracked.

	Warm-humid (total 28 sites)	Cold-dry (total 9 sites)
Constituent particles	22 (79%)	6 (67%)
Suggestive of particle initiation	4 (14%)	-
Unidentified	-	2 (22%)
Misc (corner crack etc.)	2 (7%)	1 (11%)

>75% of initiation sites are associated with constituent particles within both alloys and environments.

Marker band analysis on fatigue crack surface

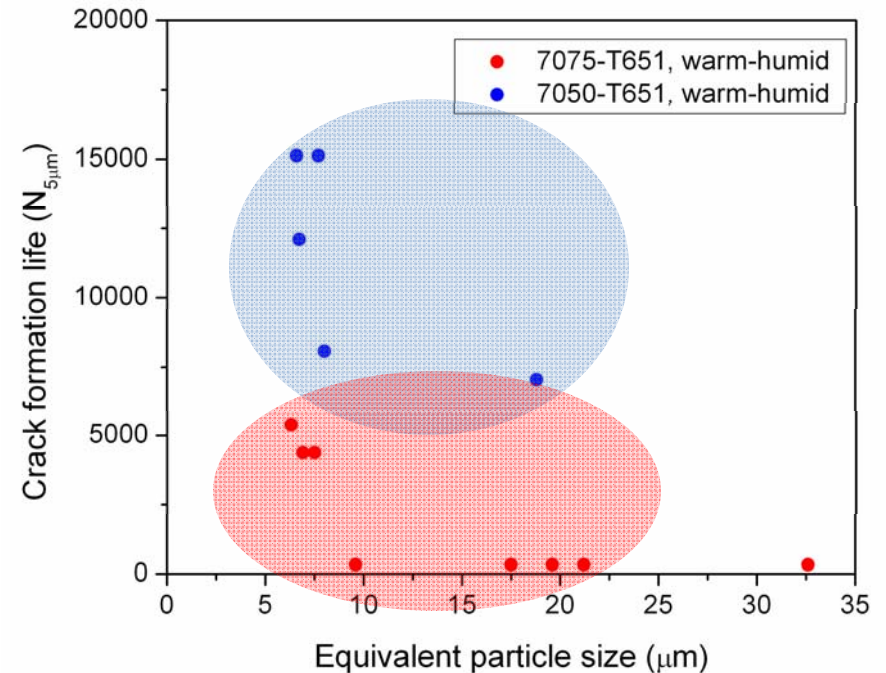


Grain boundaries – magenta

Constituent particle – green

Marker bands* – blue

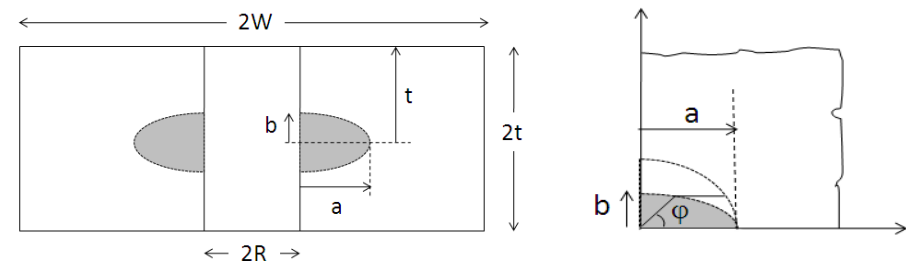
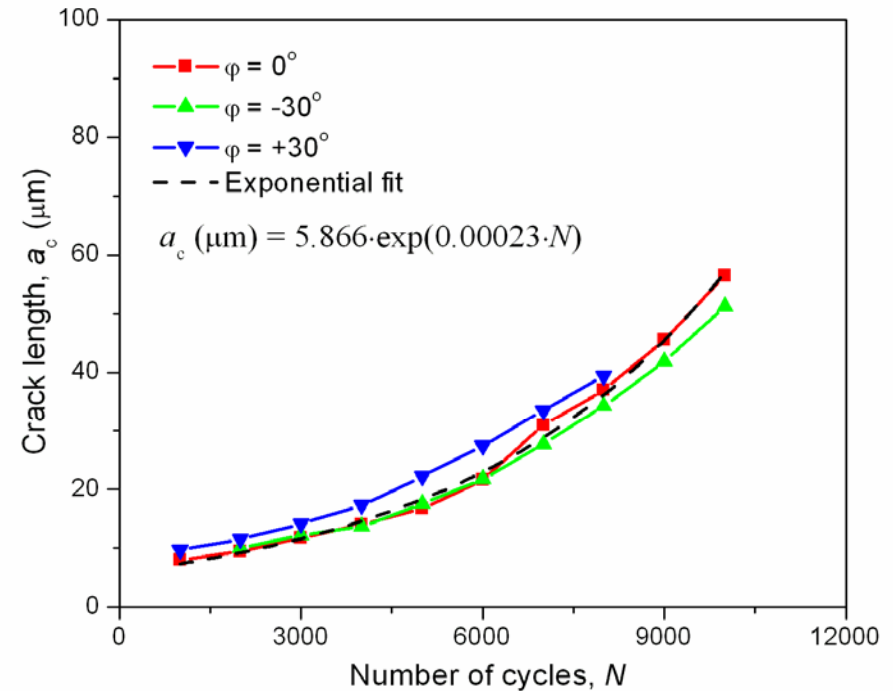
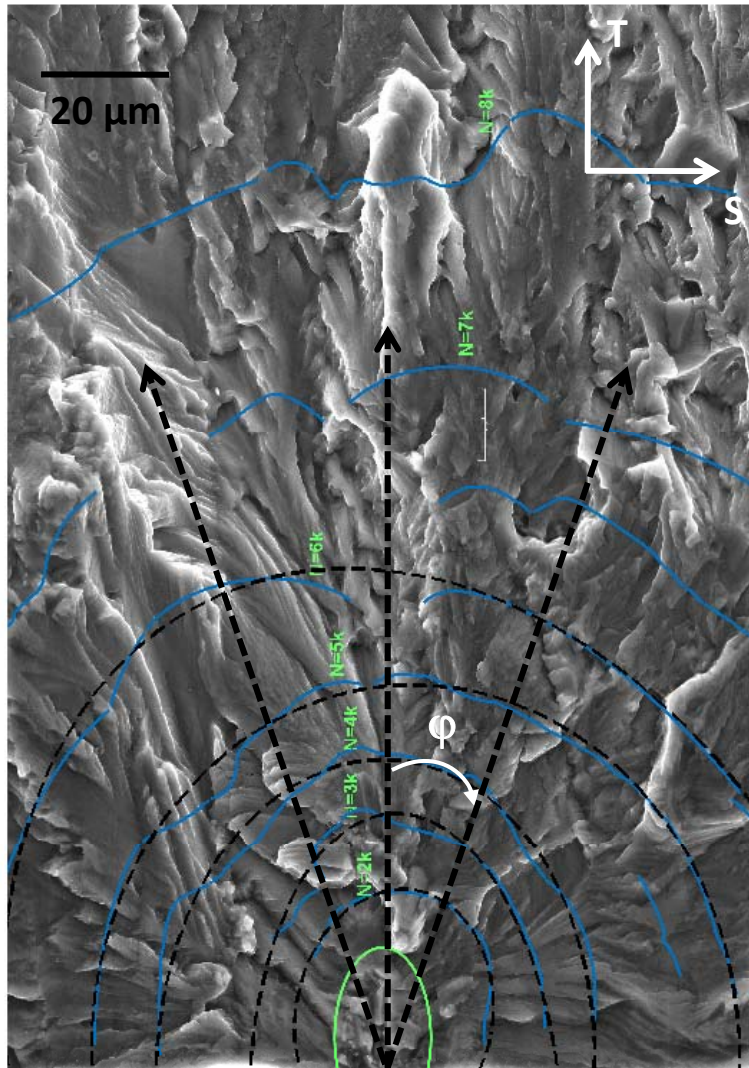
*produced by the Sunder loading spectrum



- “Formation” includes incubation, nucleation and growth of crack to a finite size ($\sim 5 \mu m$).
- Equivalent particle diameter was measured on T-S plane (particle dimension in L direction is unknown.)
- A large scatter in crack formation lives $\rightarrow$ variety of crack initiating particle sizes and shapes.

Modern “cleaner” alloy 7050-T7451 is more resistant to fatigue cracking.

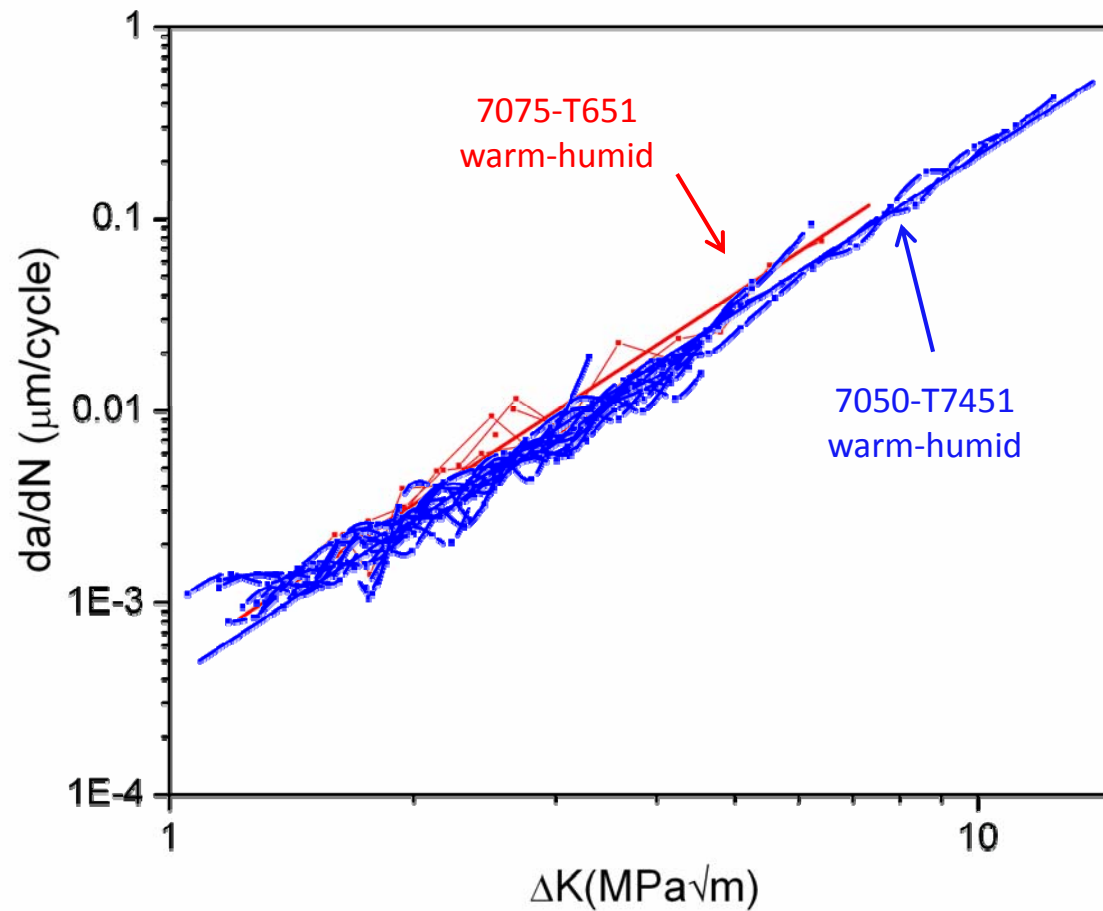
Crack growth kinetics within early growth regime



$$\Delta K = \Delta \sigma \sqrt{\frac{\pi a}{Q}} F_{sn} \left(\frac{b}{a}, \frac{b}{t}, \frac{R_h}{t}, \frac{R_h}{W}, \frac{a}{W}, \phi \right)$$

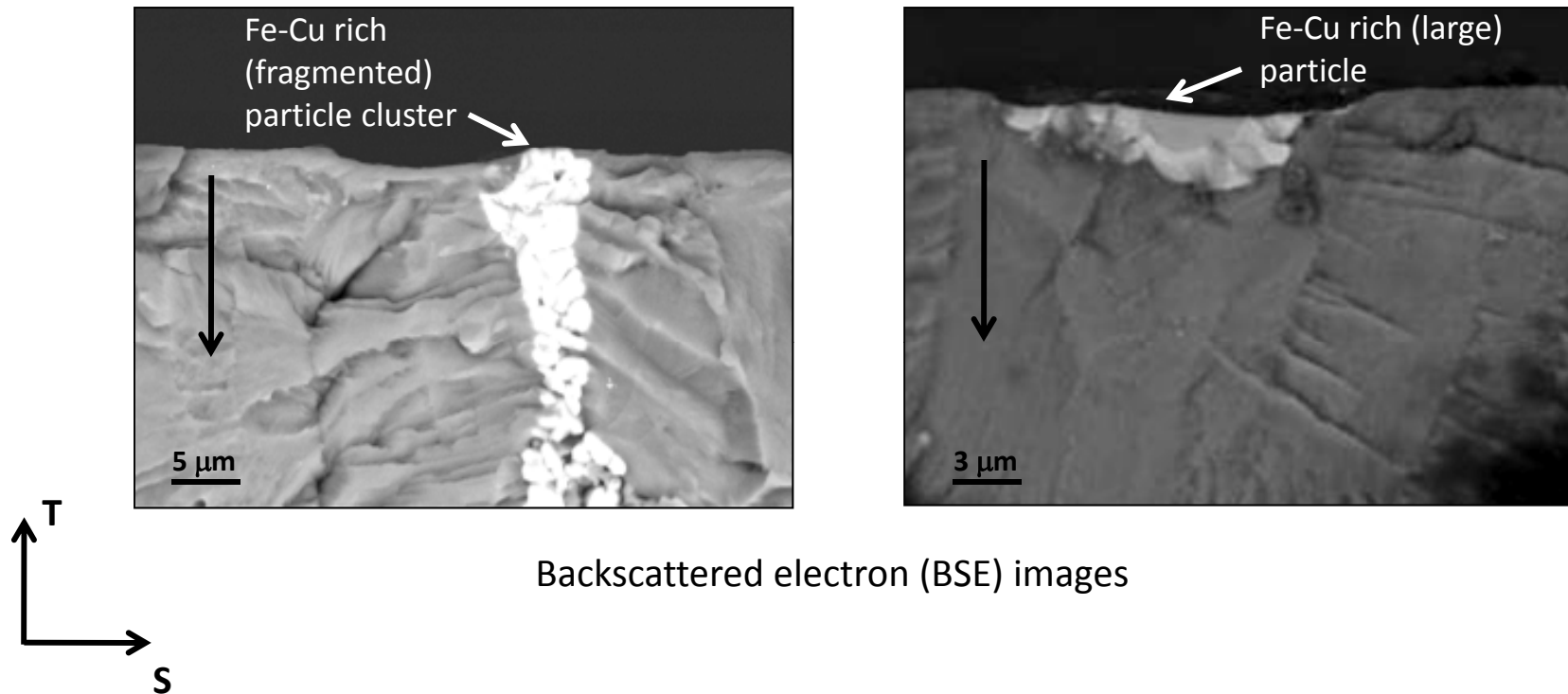
Newman (1992)

Small fatigue crack growth rates are not distinct



	c	m
7075-T651, warm-humid	$4.4 \cdot 10^{-4} \pm 0.2 \cdot 10^{-4}$	2.81 ± 0.025
7050-T7451, warm-humid	$4.2 \cdot 10^{-4} \pm 0.2 \cdot 10^{-4}$	2.70 ± 0.022

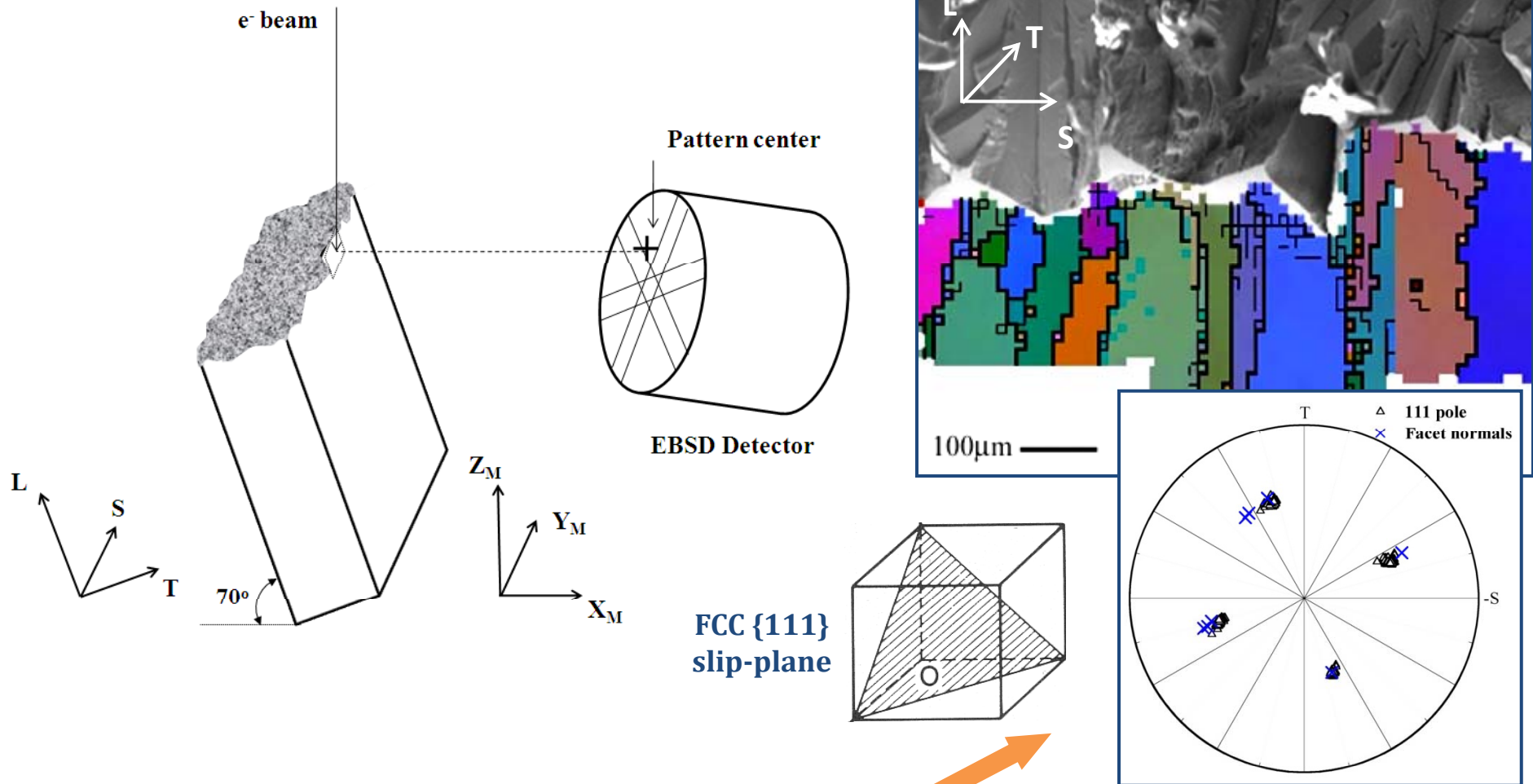
Crack facet crystallography near initiation sites



- Typical crack facets near Fe-Cu rich constituent particle(s).
- Facet appearance may vary with crack initiating particle's morphology.

SEM-based EBSD/stereology

Experimental set-up

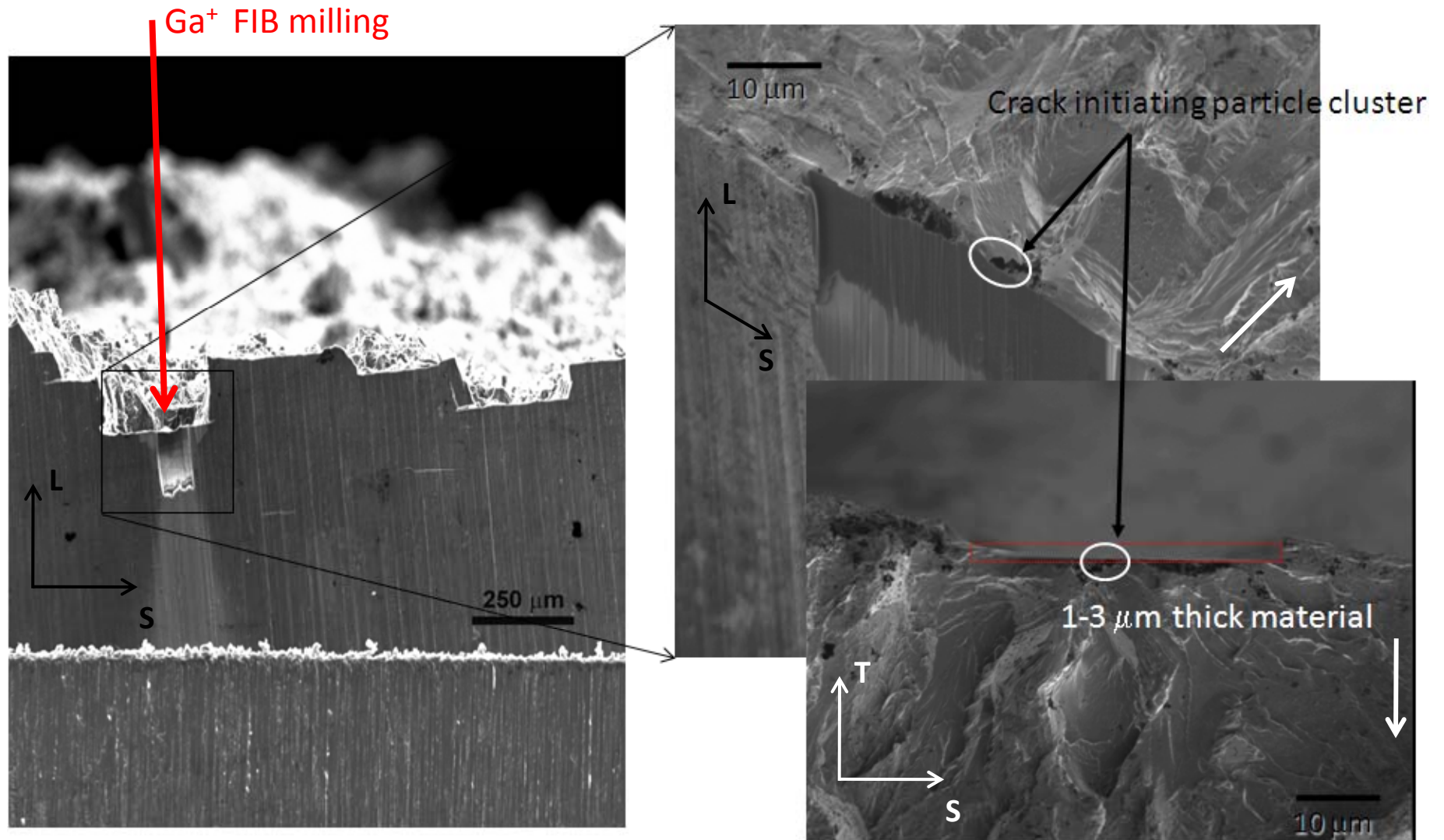


Faceted cracking path in Al-Li alloy fatigue cracked in ultra high vacuum environment.

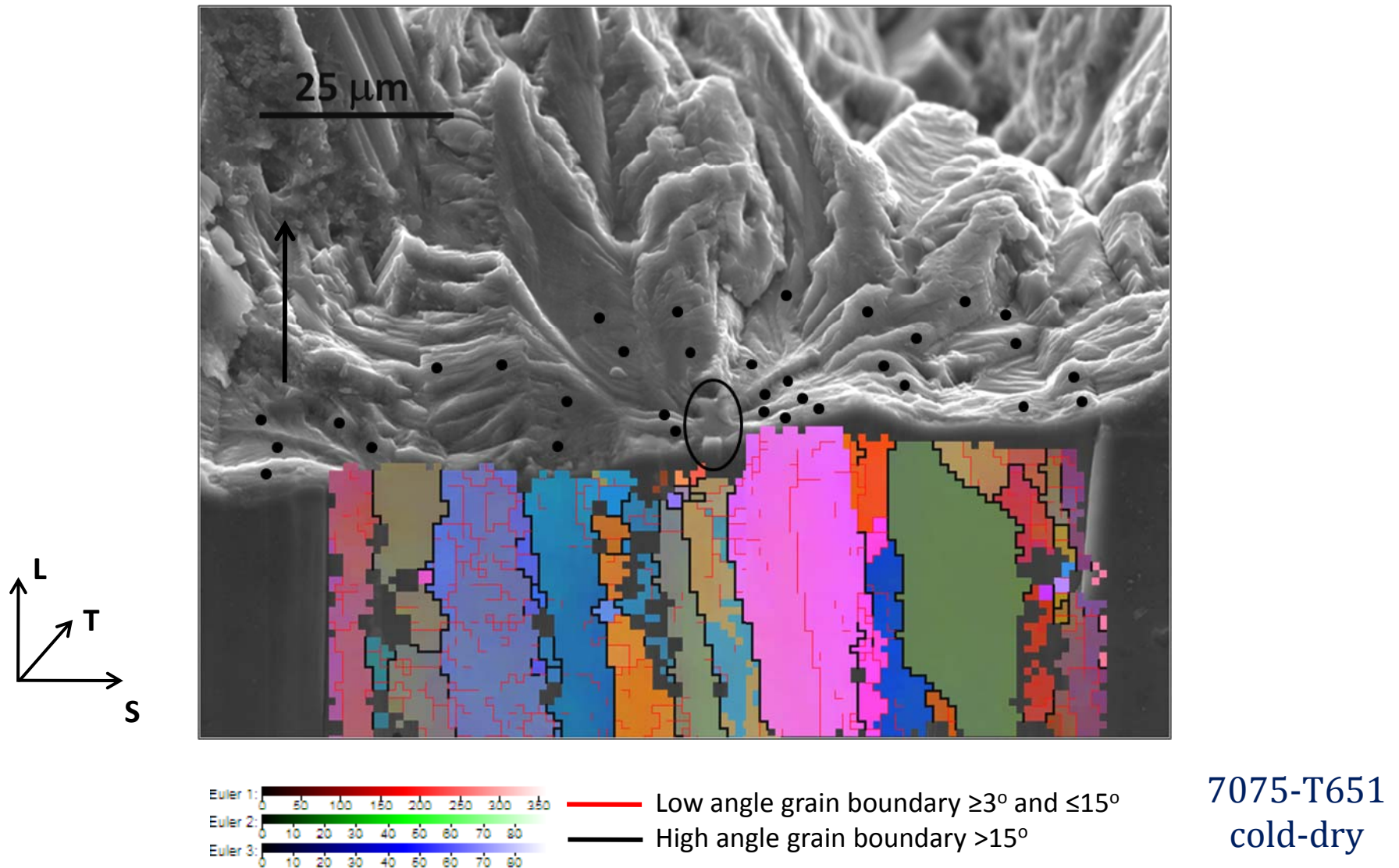
Ro, Agnew, Gangloff, Scripta Mater, 2004

Ro, Agnew, Gangloff, Metall Mater Trans A, 2007 & 2008

Focused ion beam surface preparation for EBSD mapping



Crack facet crystallography near initiation site

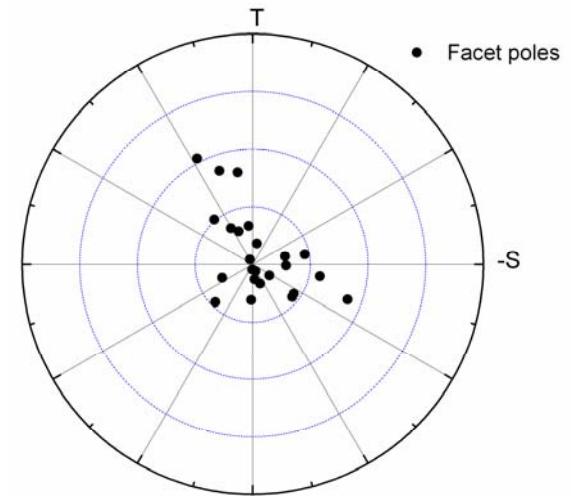
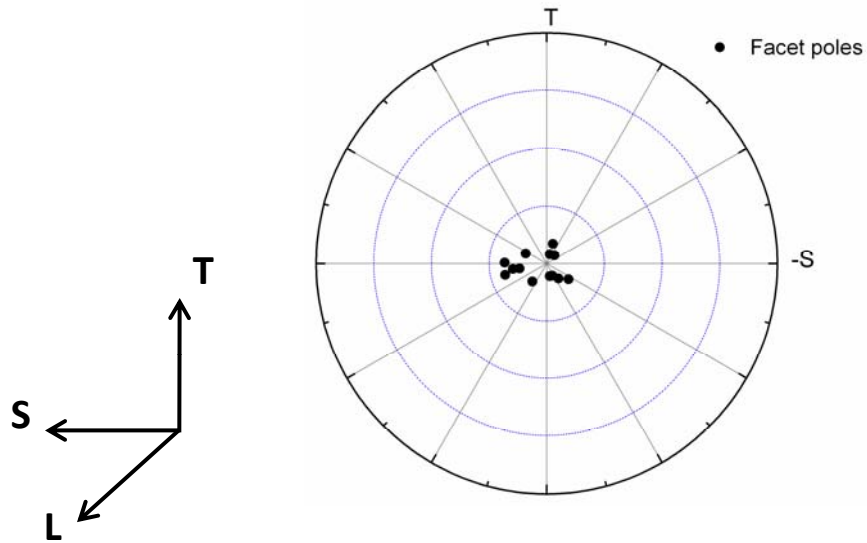


Multiple facets within region (1-50 μm) of crack initiation site measured.

Near mode I crack facet normal vectors

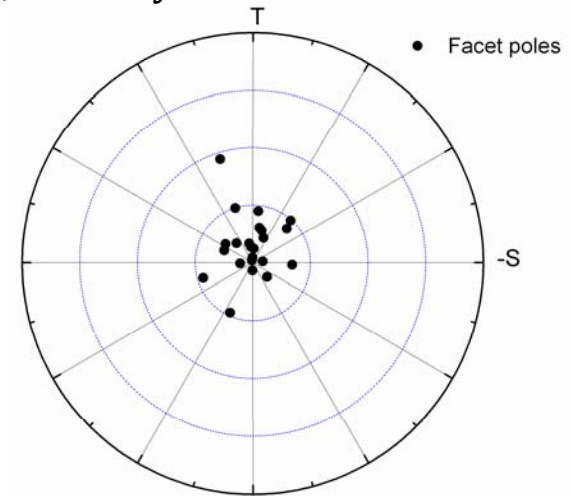
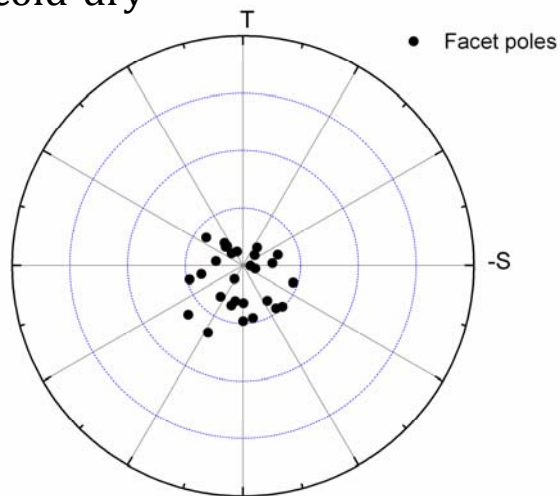
7075-T651, warm-humid

7050-T7451, warm-humid

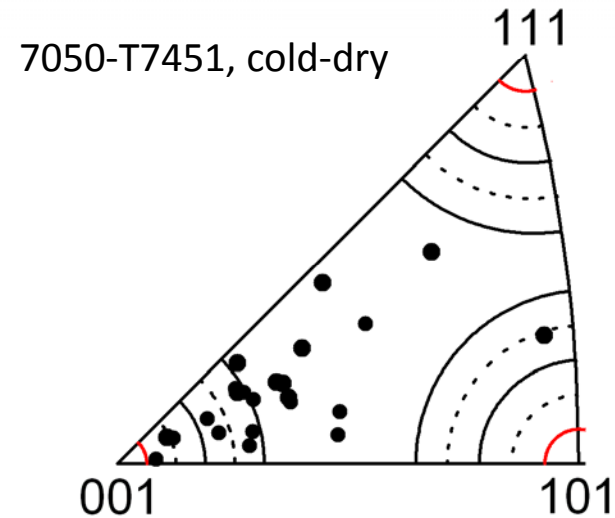
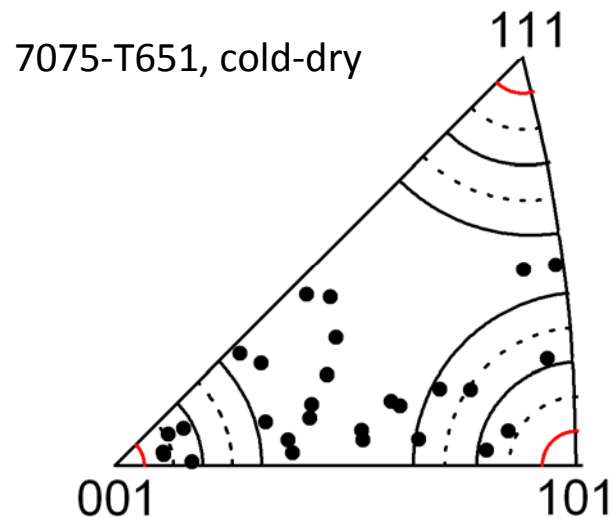
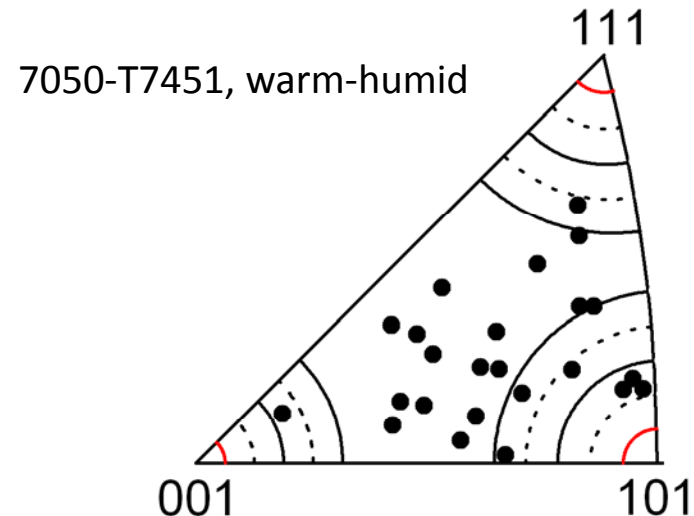
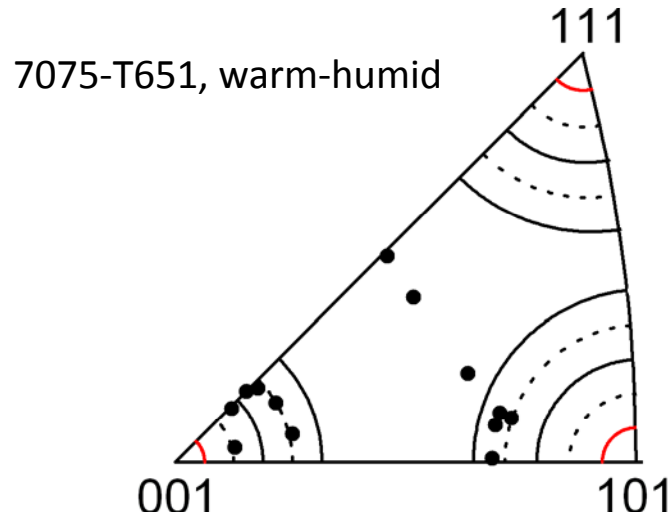


7075-T651, cold-dry

7050-T7451, cold-dry

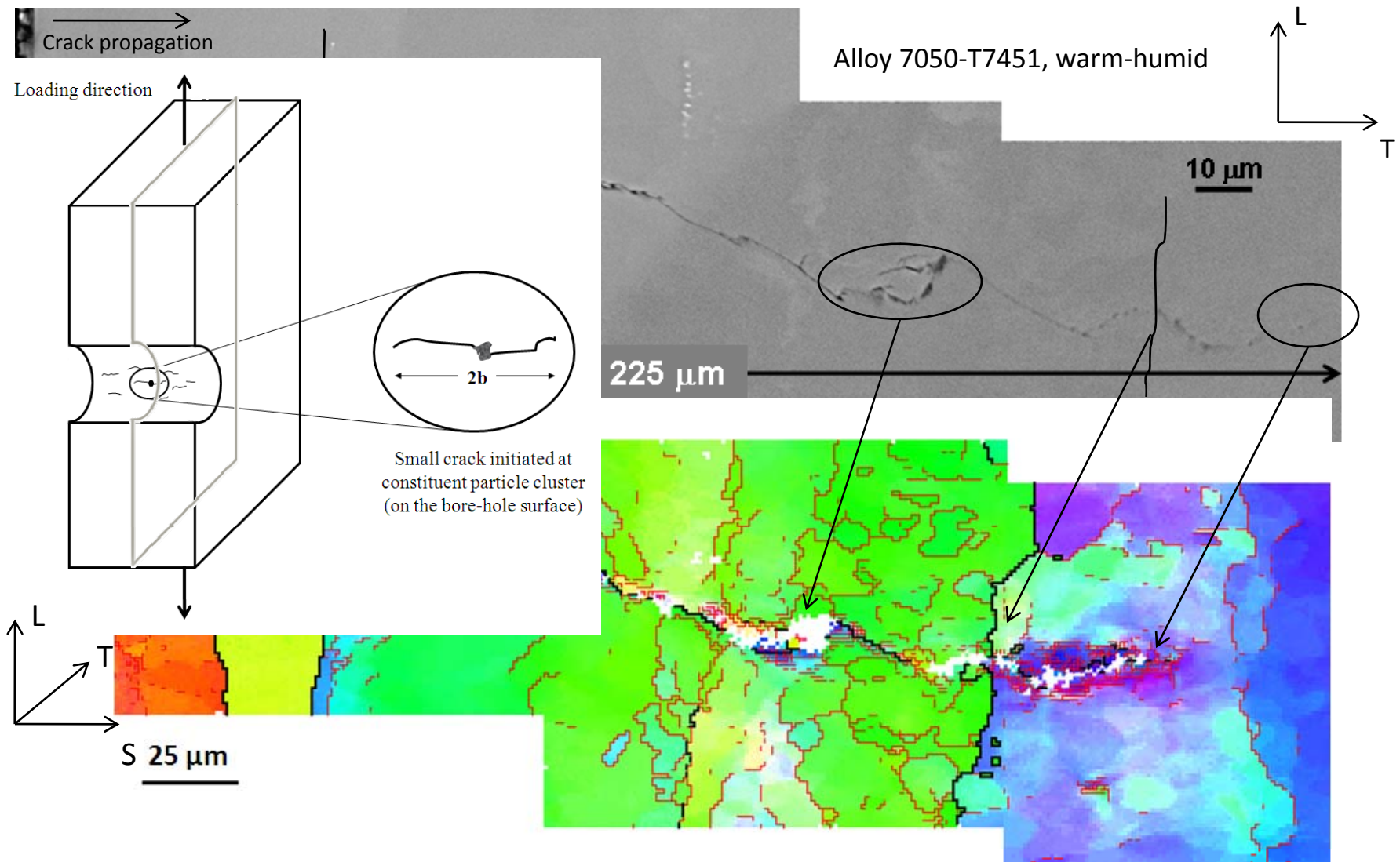


Absence of slip-band cracking near constituents



Emerging models must capture the absence of slip plane cracking in 7XXX alloys.

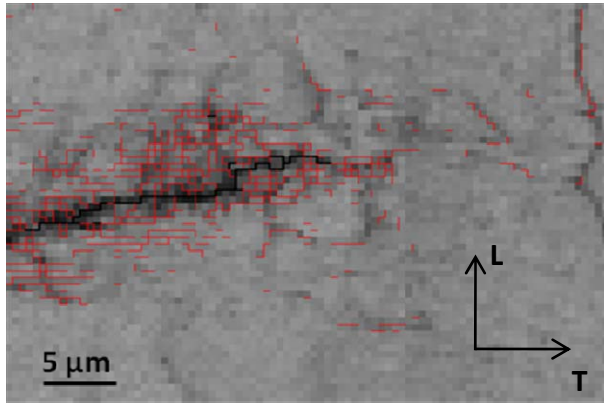
EBSD orientation mapping along small fatigue crack



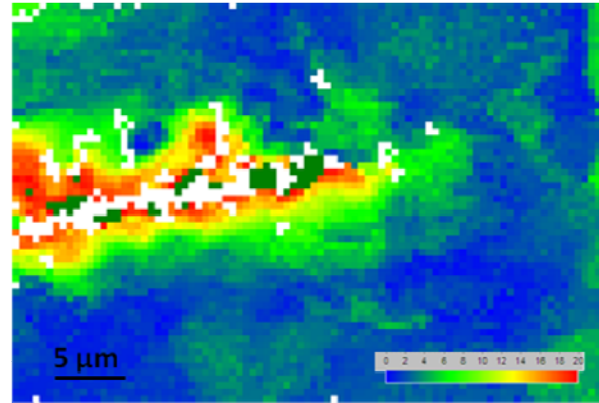
- IPF map illustrates grain structure and transgranular crack propagation path.
- Low-angle boundaries reveal unrecrystallized nature of the alloy.

Dislocation sub-structure at a small fatigue crack tip

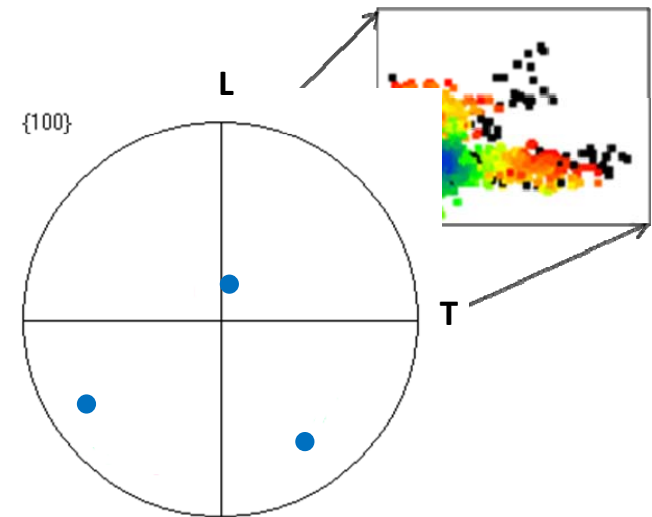
EBSD band contrast map



Least misorientation map



Stereographic Projection Pole-figure

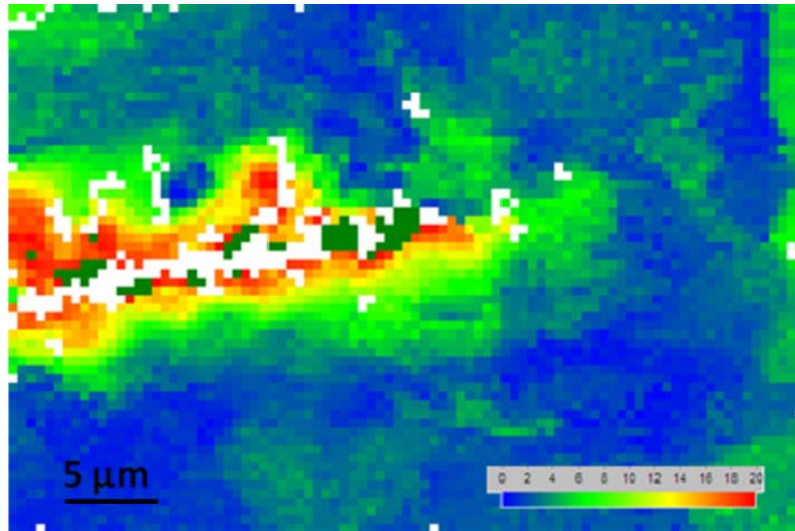


- Misorientation map illustrates the presence of highly misoriented regions in the vicinity of the crack-wake.
- Crystal orientations plotted on {100} pole-figure reveal lattice rotations in the crack-wake region.

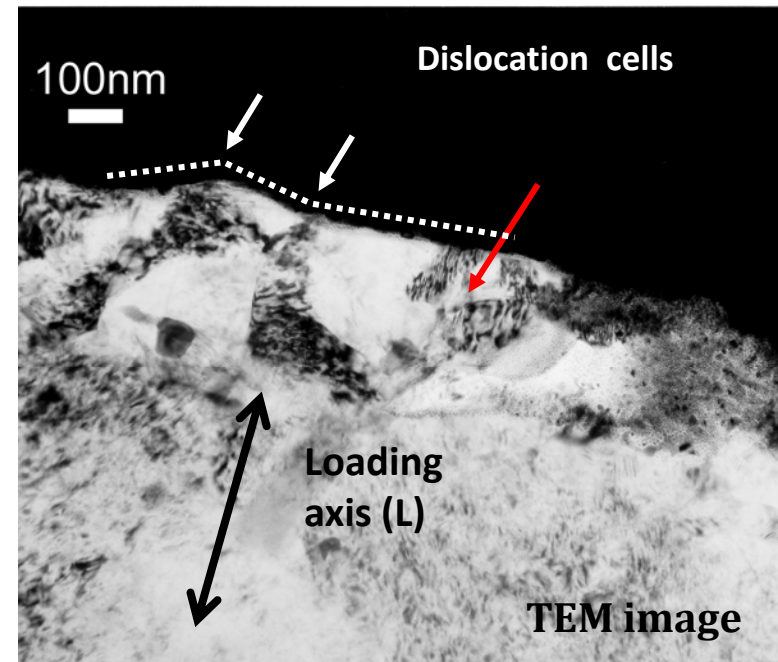
EBSD observations provide evidence that crack-tip cyclic plastic strain accumulation develops its own dislocation sub-structure as crack propagates.

Formation of dislocation substructure near a crack tip

Least misorientation map



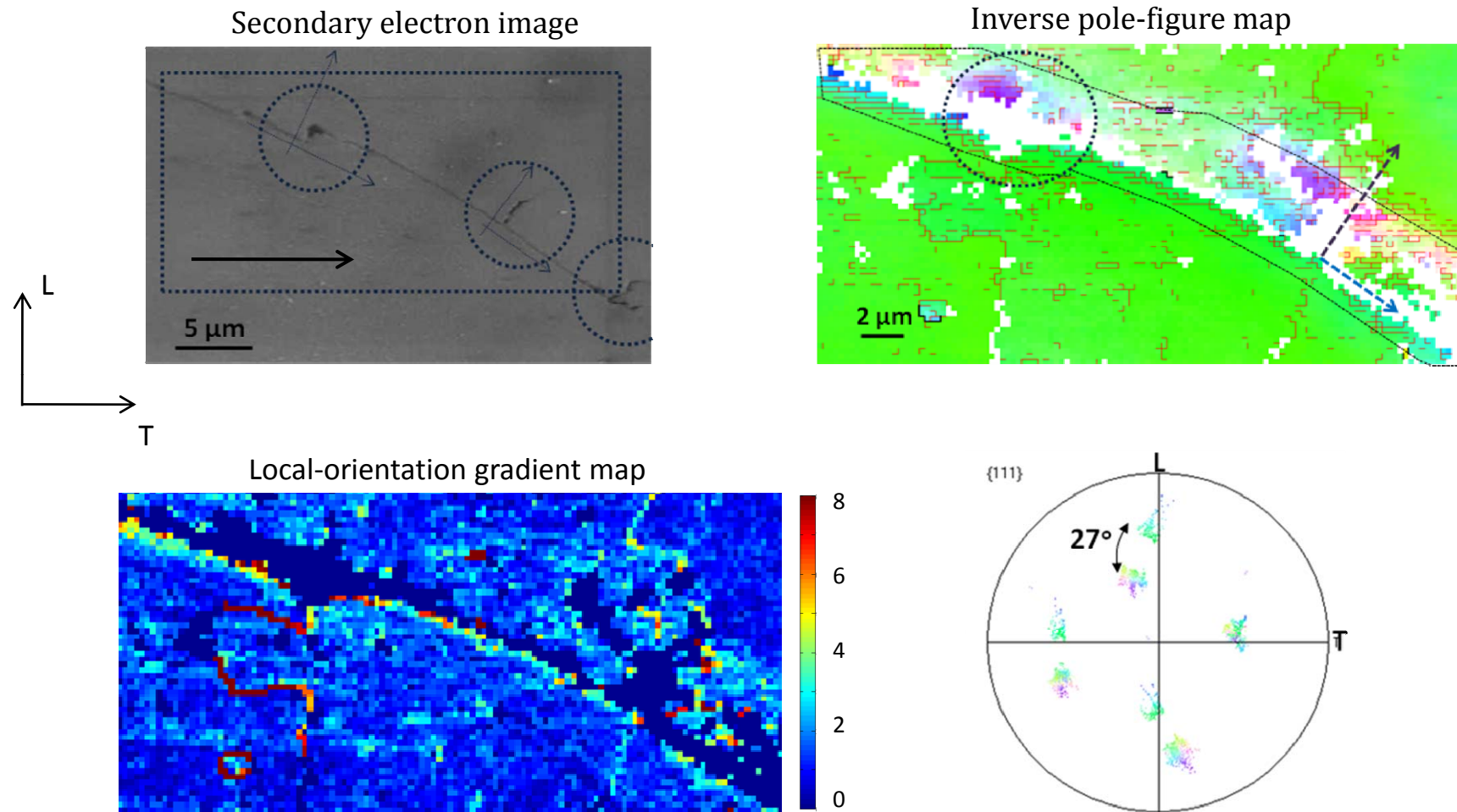
- EBSD (microscale) provides complementary information to TEM (nanoscale).
- Indirect observation of dislocation substructure (highly misoriented region) near a crack tip/wake.



Layers of dislocation cells were observed in Al-Cu-Mg alloy (C433-T351) tested within moist-air environment.

Ro, Agnew and Gangloff, 2008

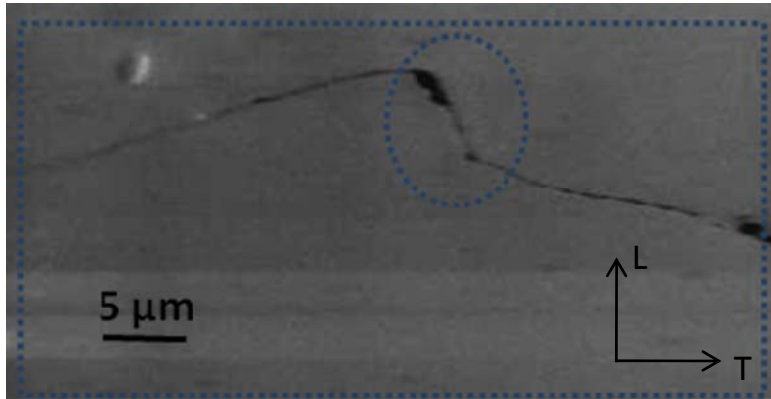
Crack branching and deflection at low-angle boundaries



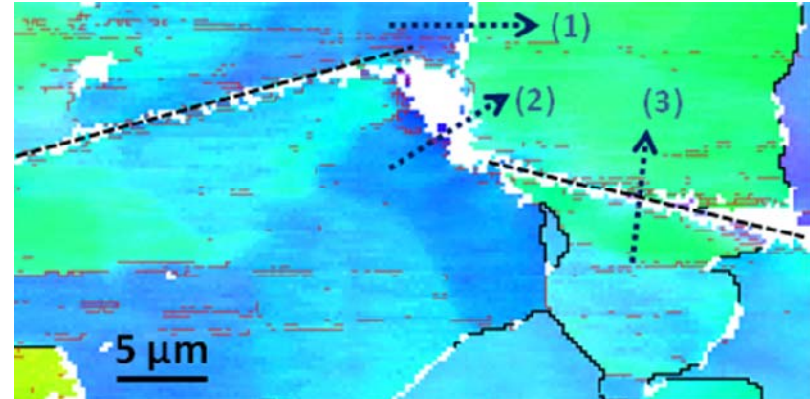
- Crack deflection and branching occurred at low-angle grain boundaries.
- Extensive sub-grain structure within the scanned area is also detectable.
- Significant population of dislocations at the crack surface → large orientation spread.

Crack deflection at low-angle grain boundary

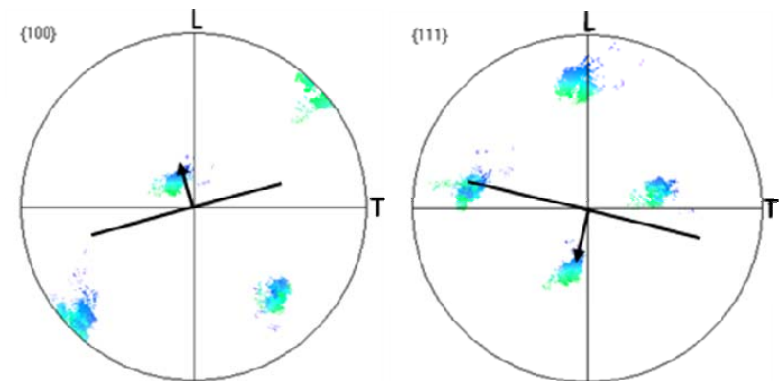
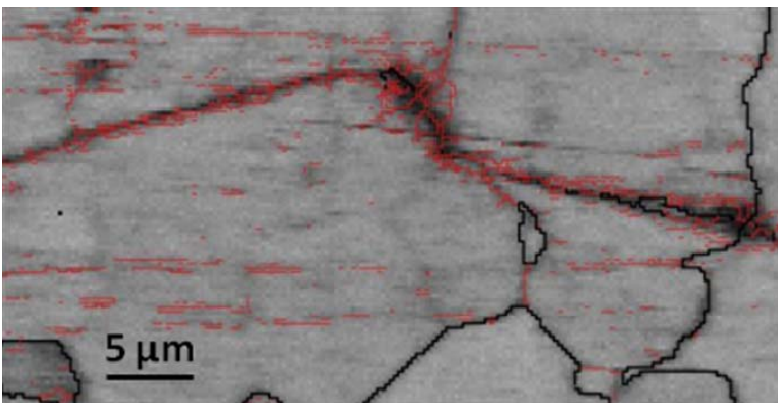
Secondary electron image



Inverse pole-figure map



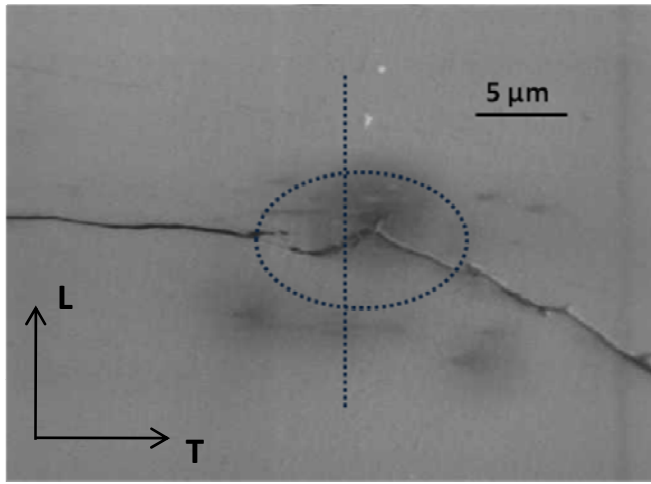
EBSD band contrast map



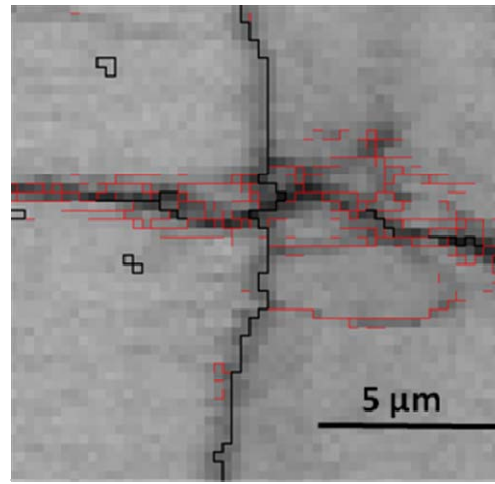
- Crack is deflected at low-angle grain boundary ($\sim 14^\circ$).
- Crack initially traversed for a short distance along the low-angle boundary ($\sim 9^\circ$) followed by transgranular cracking in a neighboring grain.

Crack branching and deflection at low-angle boundary

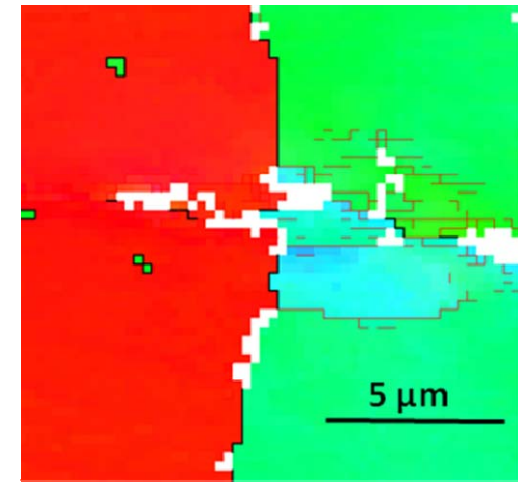
Secondary electron image



EBSD band contrast map

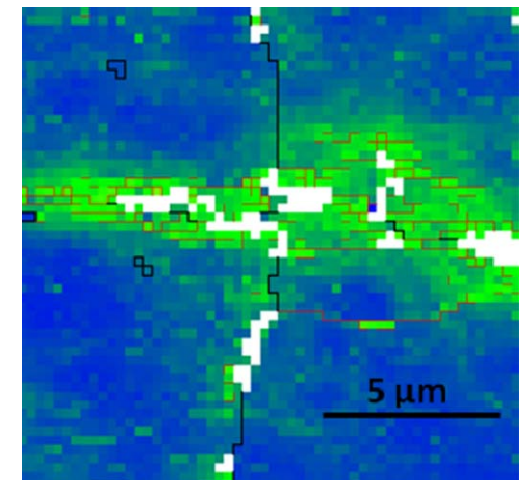


Inverse pole-figure map

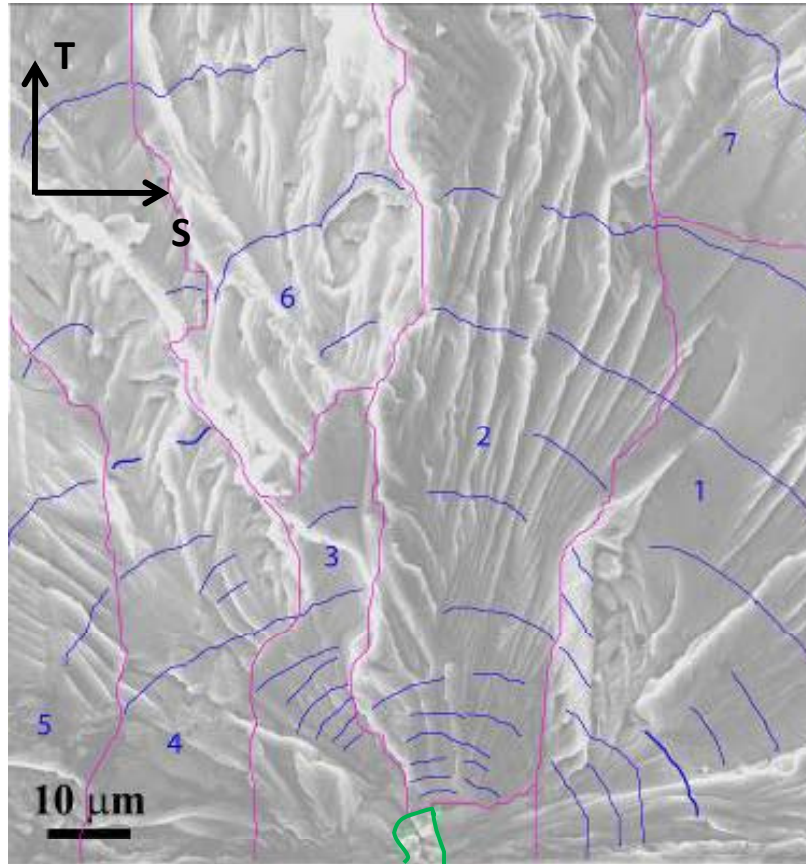


- Crack continues to propagate in a transgranular fashion until it encounters a sub-grain boundary.
- Main crack propagates inter-subgranularly along a low-angle sub-grain boundary.
- Note the sudden change in plastic damage distribution across the high-angle grain boundary.

Least misorientation map



Erratic behavior of microstructurally small cracks

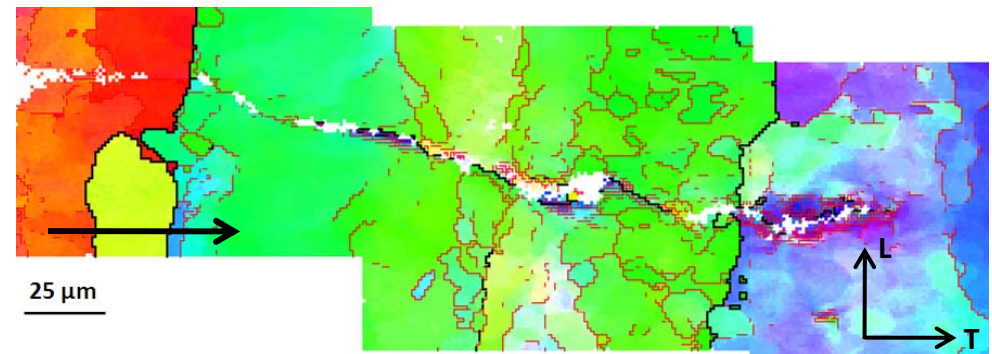
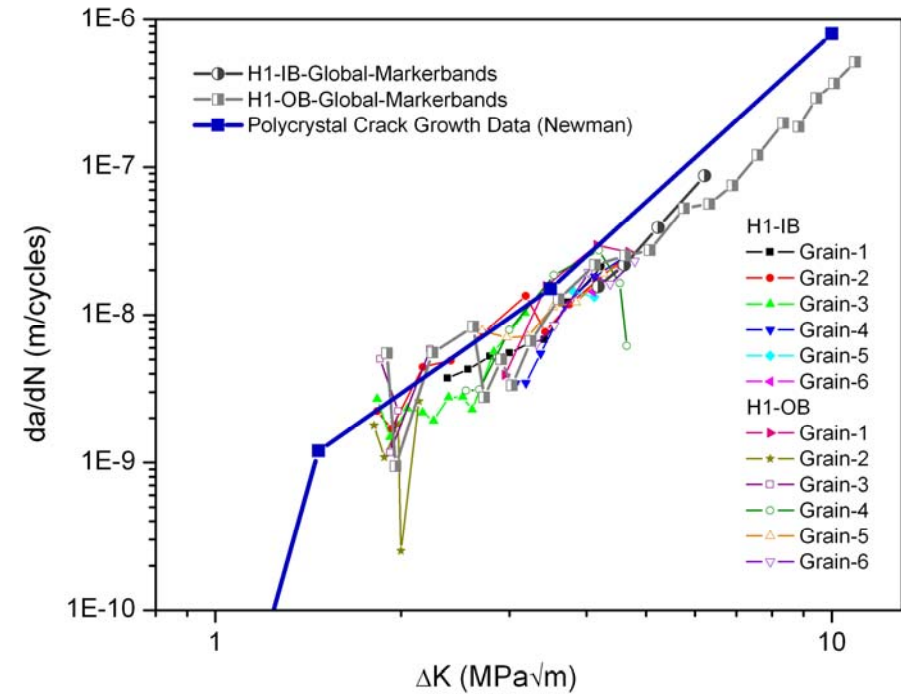


Grain boundaries – magenta

Constituent particle – green

Marker bands* – blue

*produced by the Sunder loading spectrum



Grain-level da/dN vs. estimated ΔK data (along with grain orientation information) provide resource for comparisons with crystal plasticity-based finite element model predictions.

Summary

- Fe-Cu rich constituent particle clusters are the dominant fatigue crack initiation sites.
- The modern cleaner alloy 7050 is more resistant to fatigue cracking.
- The overall crack growth response was not distinct between two alloys.
- No stage I cracking observed: Fatigue crack facets close to initiation sites span the entire lower portion of the irreducible stereographic triangle.
- Multi-stage fatigue models should include initiation and growth criteria sensitive to resolved normal stresses, rather than commonly invoked critical accumulated plastic shear strain on {111} slip planes.
- Crack propagation was mostly transgranular, with periodic crack deflection and branching at low and high angle grain boundaries.
- Growing cracks interact with dislocation sub-structure even if there are no pre-existing sub-grains. This supports the hypothesis that the crack path is defined by the defect structure with trapped environmental H ahead of a crack tip.
- Crack propagation through the underlying sub-structure (pre-existing or formed) and interaction with low-angle (sub-grain) boundaries result in local fluctuations in small crack growth rates.