Project 48: Grain Boundary Fracture Analysis in Aluminum 7085

Semi-annual Spring Meeting

April 2022

- Student: Scott Blazanin (ISU)
- Faculty: Dr. Peter Collins (ISU)
- Industrial Mentors: Dr. Matt Krug (AFRL)

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CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

- Student: Scott Blazanin
- Advisor(s): Professor Peter Collins (ISU), Maria Quintana (ISU), Matt Krug (AFRL)

Project Duration
Master's: November 2020 – May 2022

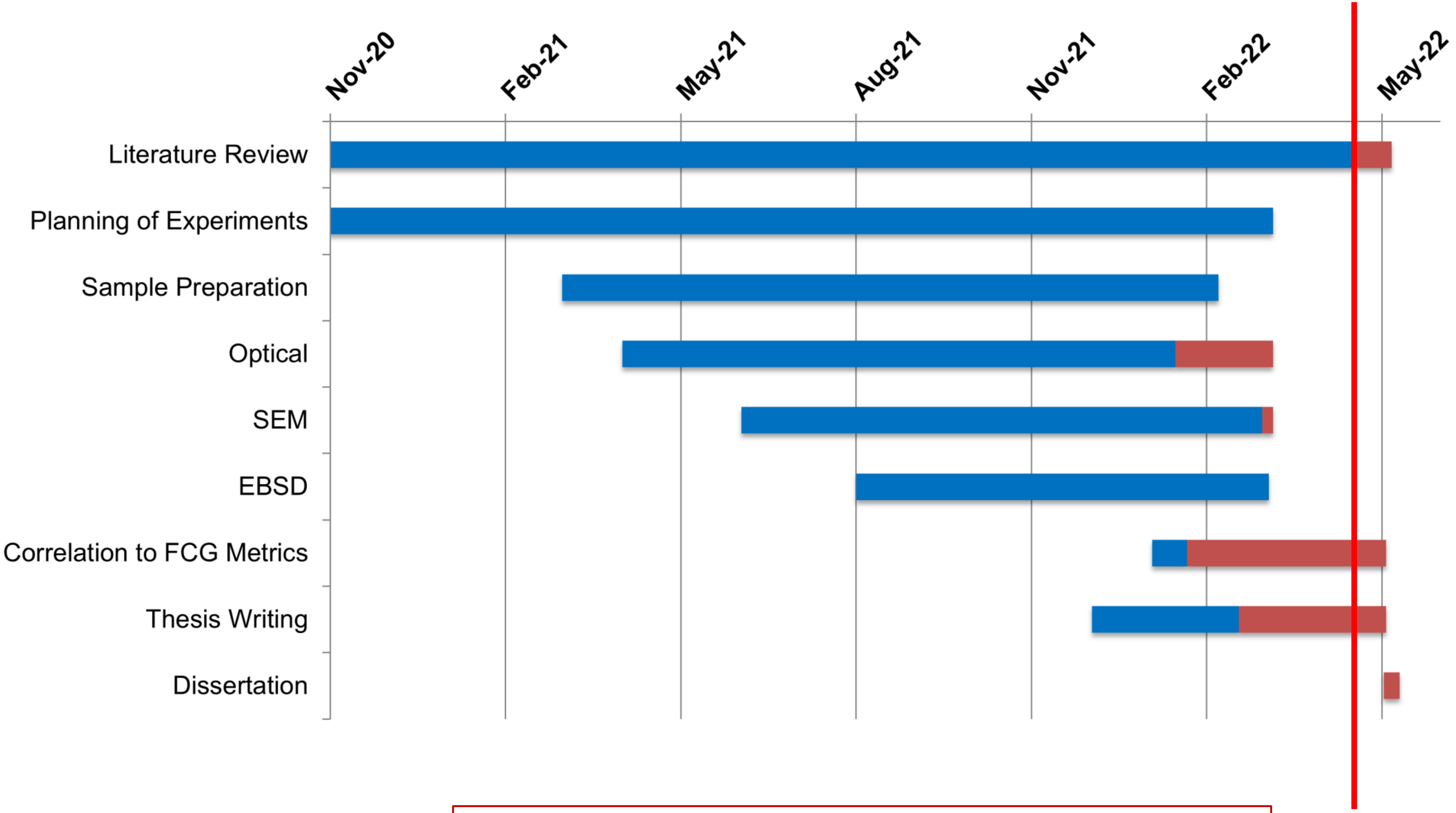
- Problem: Atypical cracking behavior is observed in forged aluminum 7085 plates after fatigue testing. The mechanisms of crack propagation and branching events in this alloy are understudied.
- Objective: Conduct comprehensive metallographic characterization for the analysis of delamination cracking and surrounding microstructure.
- Benefit: Understanding crack behavior in Al 7085 during cyclic loading of this alloy.

Recent Progress
- All sample sections metallographically prepared for optical, EBSD characterization
- Fracture edge mosaics and EBSD maps obtained
- Secondary crack lengths and densities quantified via MIPAR
- EBSD data analysis being completed via MTEX
- Thesis writing in progress for May 9 dissertation

Metrics

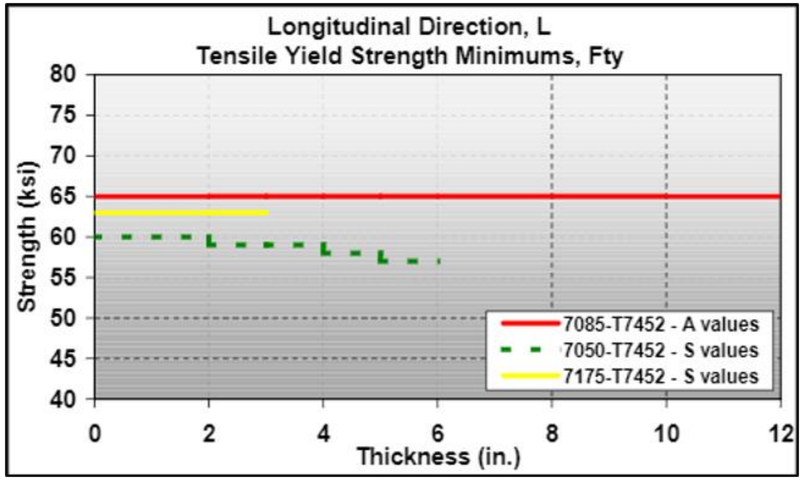
Description	% Complete	Status
1. Literature review	90%	● (green)
2. Sample preparation for optical imaging and EBSD analysis	100%	● (green)
3. Imaging (optical, SEM-BSE) and EBSD area scans	85%	● (green)
4. Microstructural characterization (secondary crack length and density, texture and crystal orientation analysis)	75%	● (green)
5. Relate microstructural features to fatigue crack growth, including macroscale metrics	50%	● (yellow)

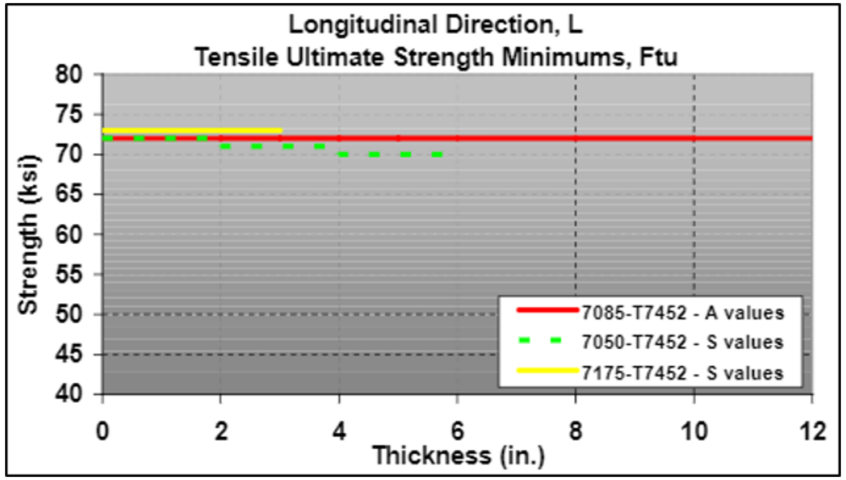
Gantt Chart


Nov-20
Feb-21
May-21
Aug-21
Nov-21
Feb-22
May-22
Literature Review
Planning of Experiments
Sample Preparation
Optical
SEM
EBSD
Correlation to FCG Metrics
Thesis Writing
Dissertation

Relevance of This Work to Industry

- Material-geometry combinations for structural aircraft components have changed
  - Manufacture of unitized components for structural support shows improved performance and reduced weight
- AA7085 (Al 7085)
  - 7-8 Zn, 1.2-1.8 Mg, 1.3-2.0 Cu, 0.08-0.15 Zr, 0.08 Fe, 0.06 Si, balance Al (wt%)
  - Advantageous to other 7xxx series Al alloys
    - Constant YS and UTS (thickness from 0 to 12")
    - Improved fracture toughness and fatigue properties





Burns et al., *International Journal of Fatigue*, 2015. (p 253)
Mueller et al., *ALCOA 7085 Forgings: 7th Generation Structural Solutions*, 2006. (p 12-13)

Project Background

Problem

- Delamination cracking intrinsic to the fracture process in Al 7085 presents design and life prediction challenges
  - Current testing and assessment procedures (ASTM E647-15e1) do not account for the effects of delamination cracking on toughness and strength, nor do they account for the orientation dependence of secondary cracking in AA7085

Objectives

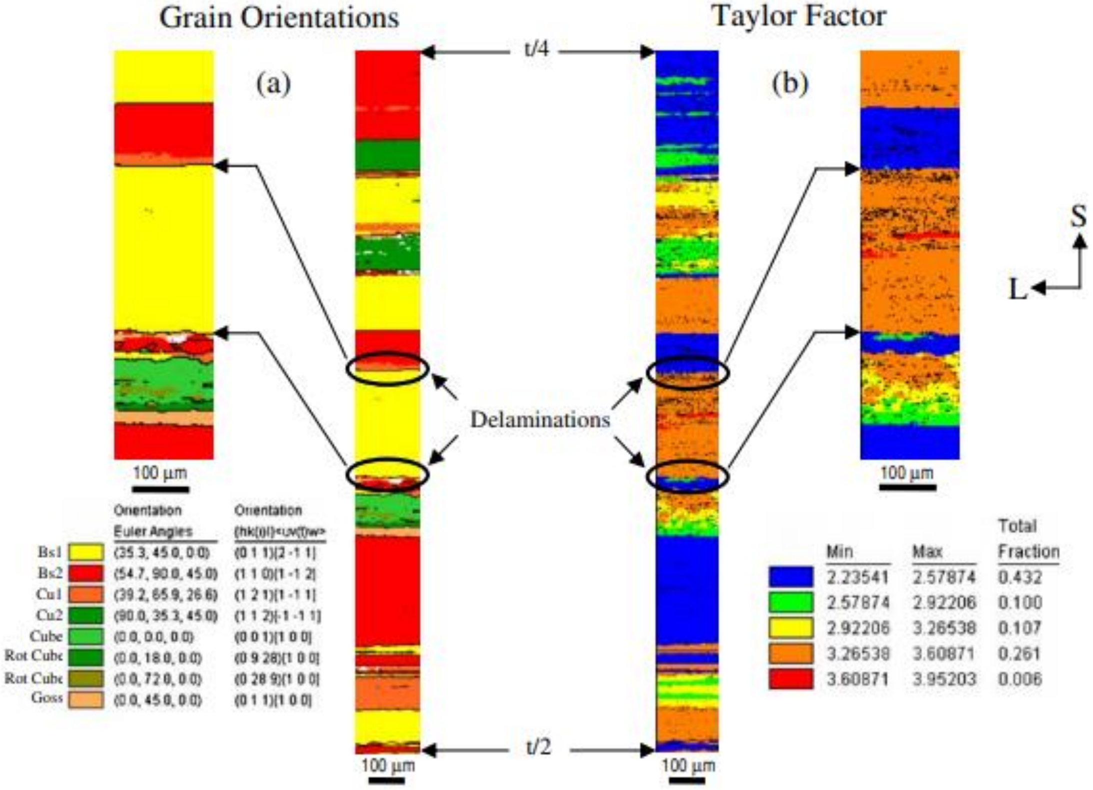
- Develop methods to comprehensively analyze grain effects on crack behavior
  - Understand influence of local crystallographic orientation on crack tip energy
  - Relate loading conditions and crack growth
  - Determine microstructural conditions that promote secondary cracking
- Understand crack branching and grain boundary delamination behavior in Al 7085
  - Provide information for better design decisions and qualification of components using this alloy within the aerospace industry
  - Refine predictions on part life
  - Enable processing modifications for the reduction or elimination of unwanted crack behavior

ASTM E399-20a, 2021.
ASTM E1820-20, 2021.

Groundwork from Literature

According to foundational work on delamination cracking in aluminum alloys:

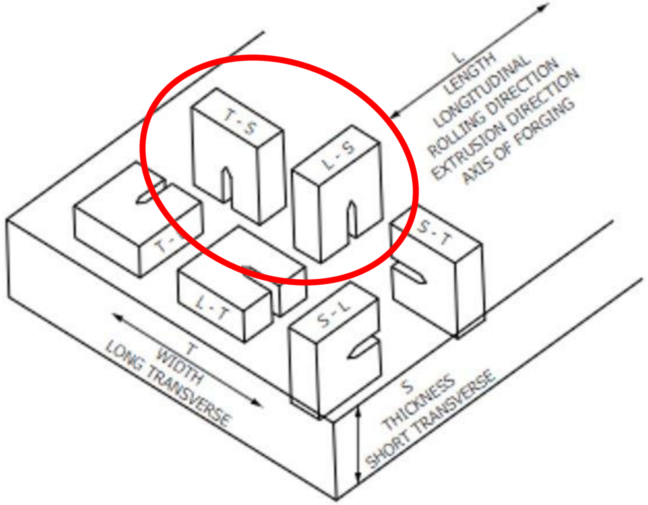
- Grain anisotropy leads to increased delamination cracking along elongated grain boundaries (Sohn et al.)
- Grain boundaries in Al-Li alloys show simulated elevated mean stress on grain boundaries (Messner, Beaudoin et al.)
- Delamination in Al-Li alloys typically initiates between soft and stiff grain pairs and may be characterized by a difference in Taylor factors (Messner et al., Tayon et al.)
- Delamination cracking increases apparent fracture toughness via deflection and shielding of the primary crack (Rao and Ritchie)

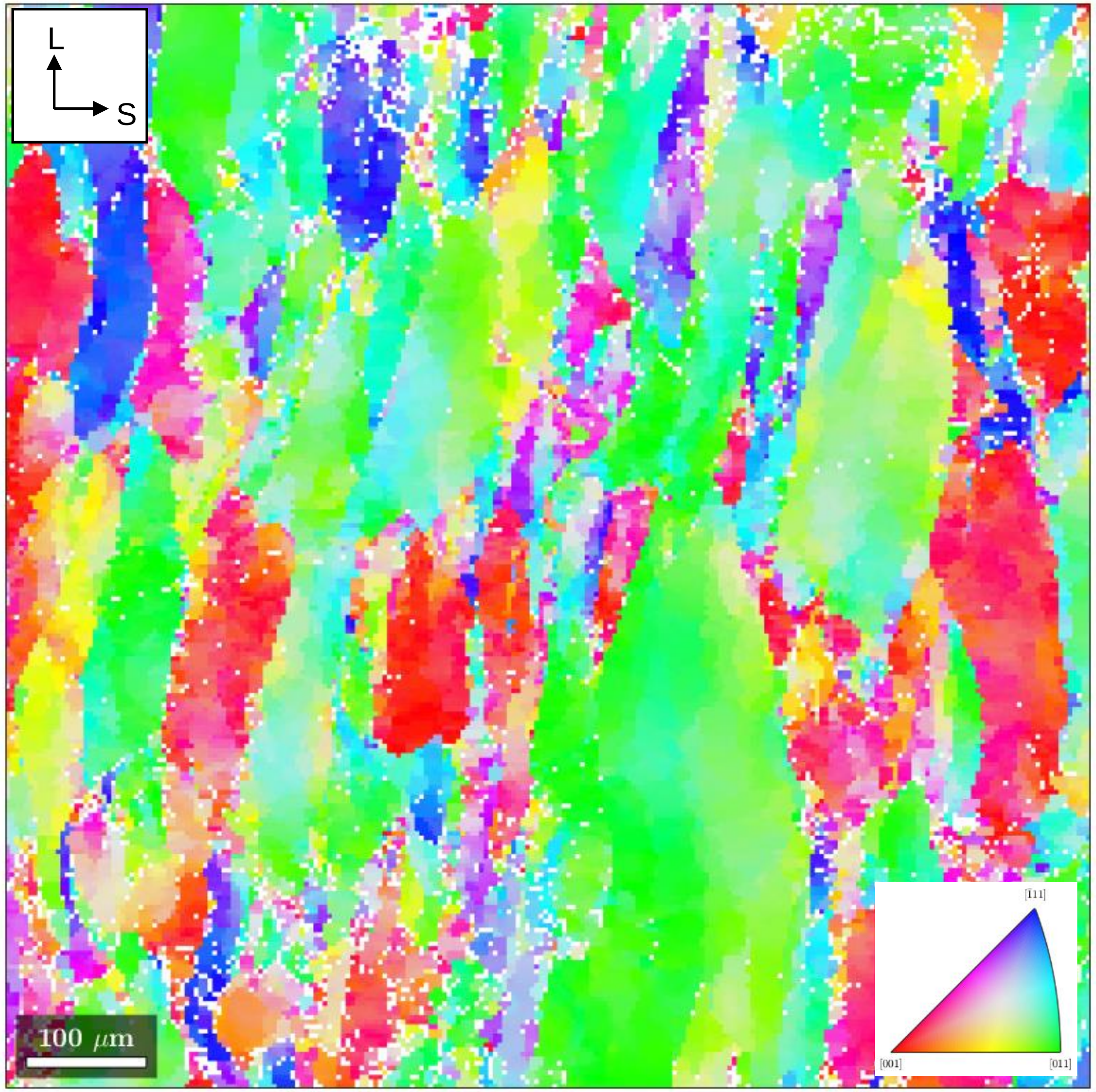


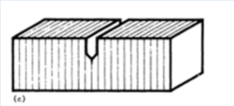
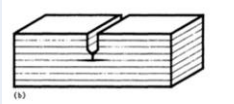
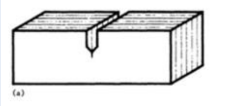
Tayon et al., *Experimental Mechanics*, 2008.

Grain Anisotropy of AA7085

- Forging process causes elongated, flat grains
- Anisotropic grain structure leads to anisotropic mechanical properties



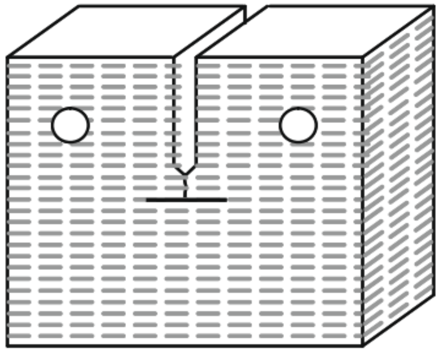


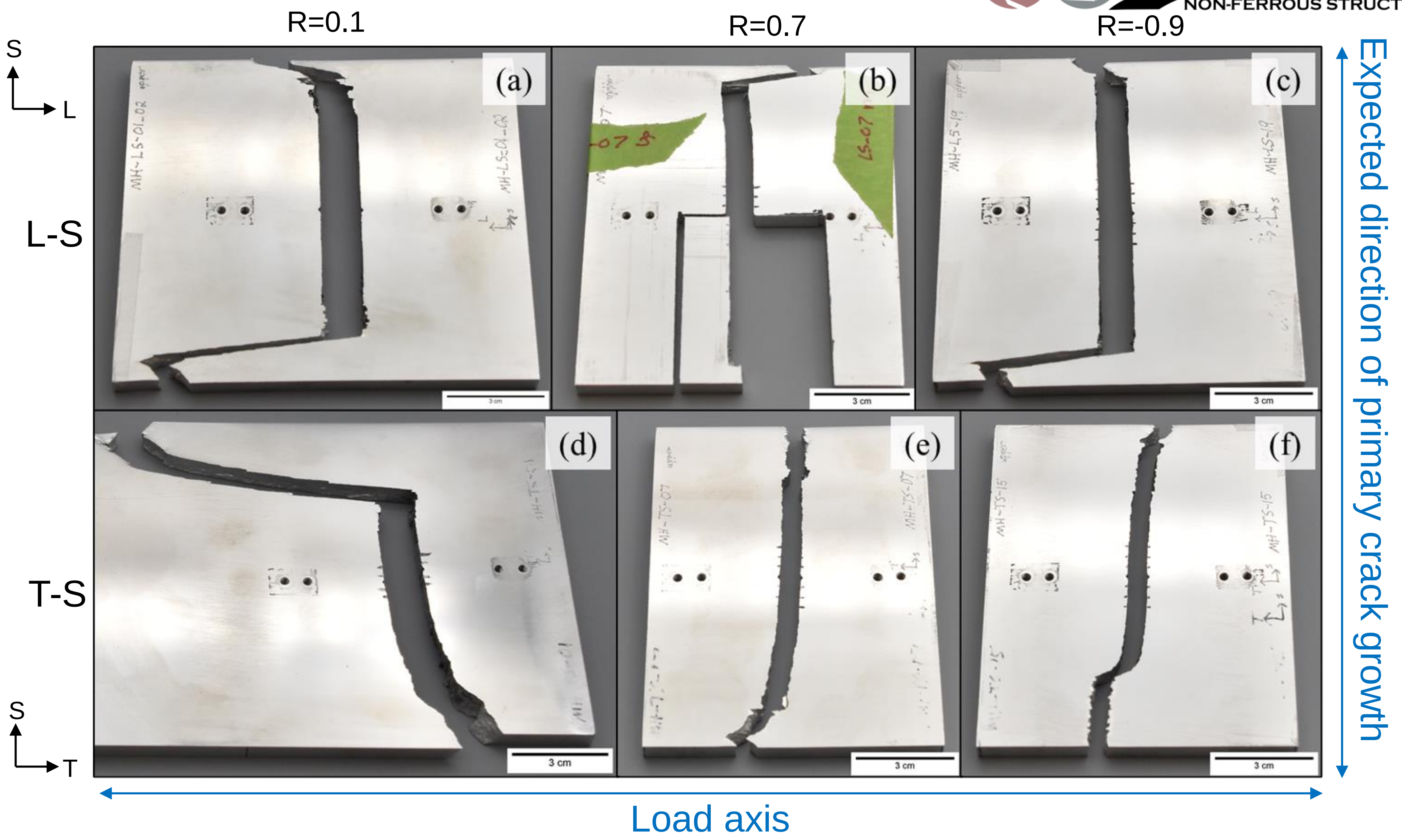
Condition	Orientation	Diagram
Crack splitting delamination	S-L, S-T	
Crack arrester delamination	T-S, L-S	
Crack divider delamination	L-T, T-L	

Neely, *Thesis*, 2015.
Rao et al., *Materials Science and Technology*, 1989.
ASTM E399-20a, 2021.

Sample Set Overview

Crack arrester delamination
(L-S, T-S)

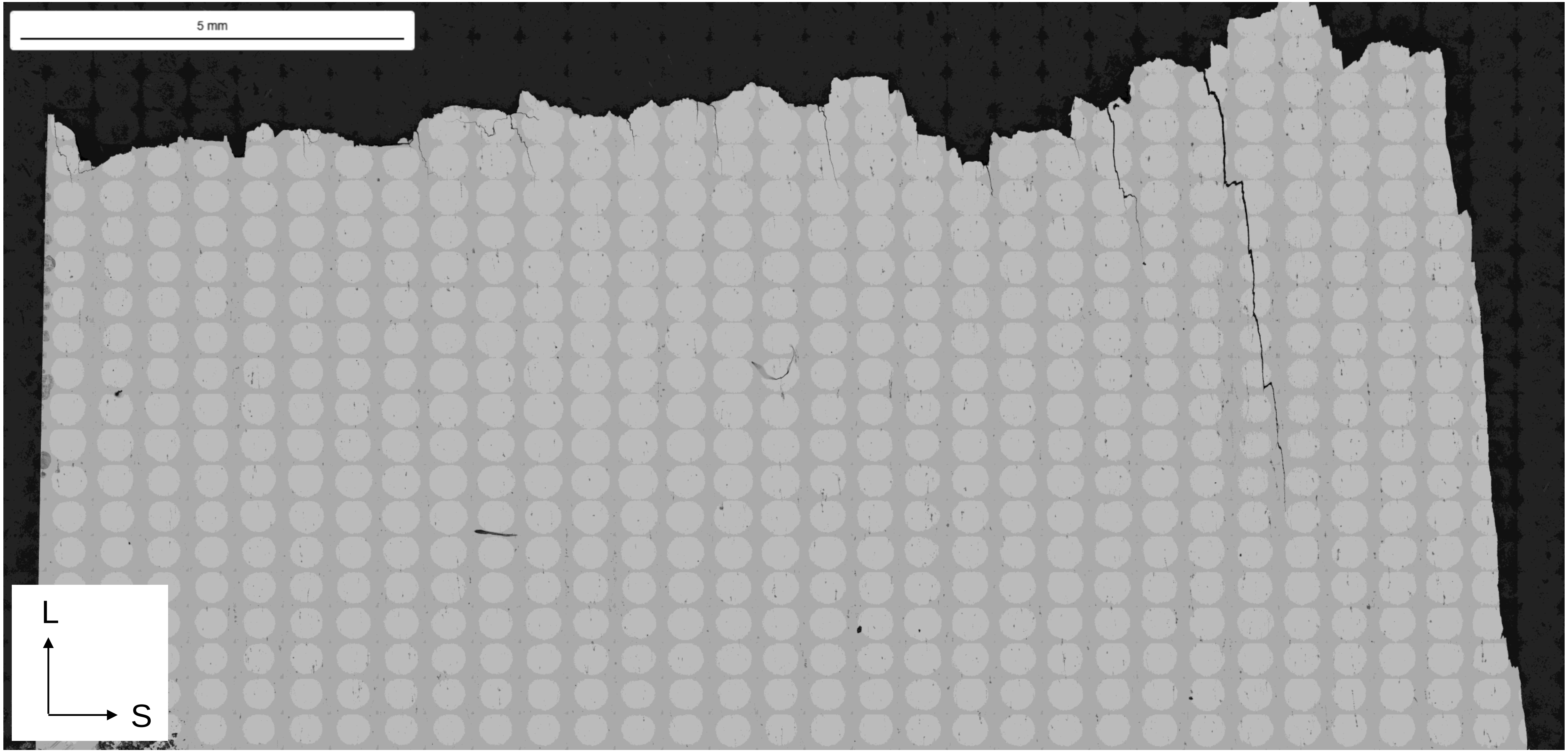




Crack turning is present on both macro- and microscopic length scales.

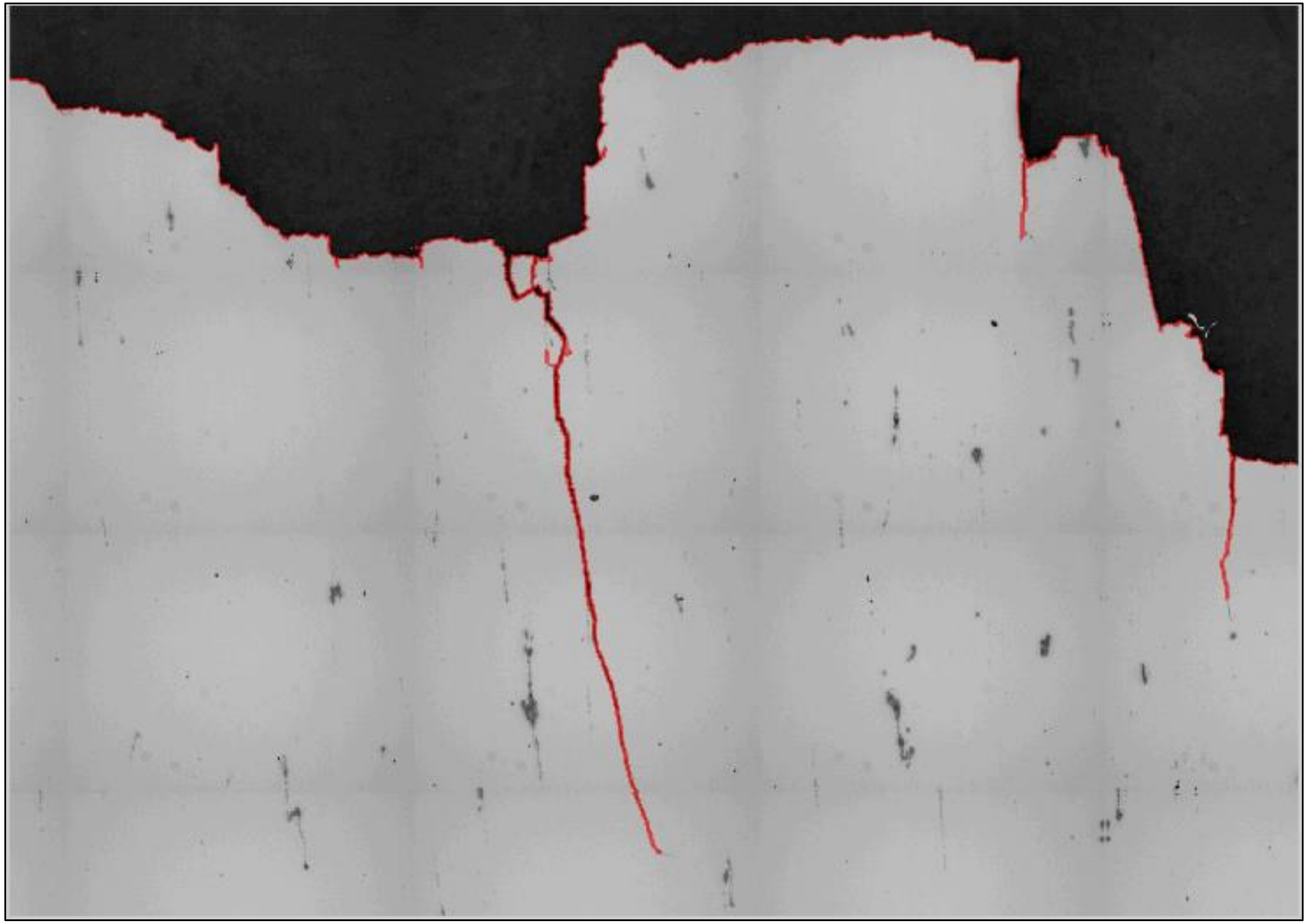
Kalyanam et al., *Engineering Fracture Mechanics*, 2009.

Optical Mosaic Showing Secondary Cracks



MIPAR for Secondary Crack Quantification

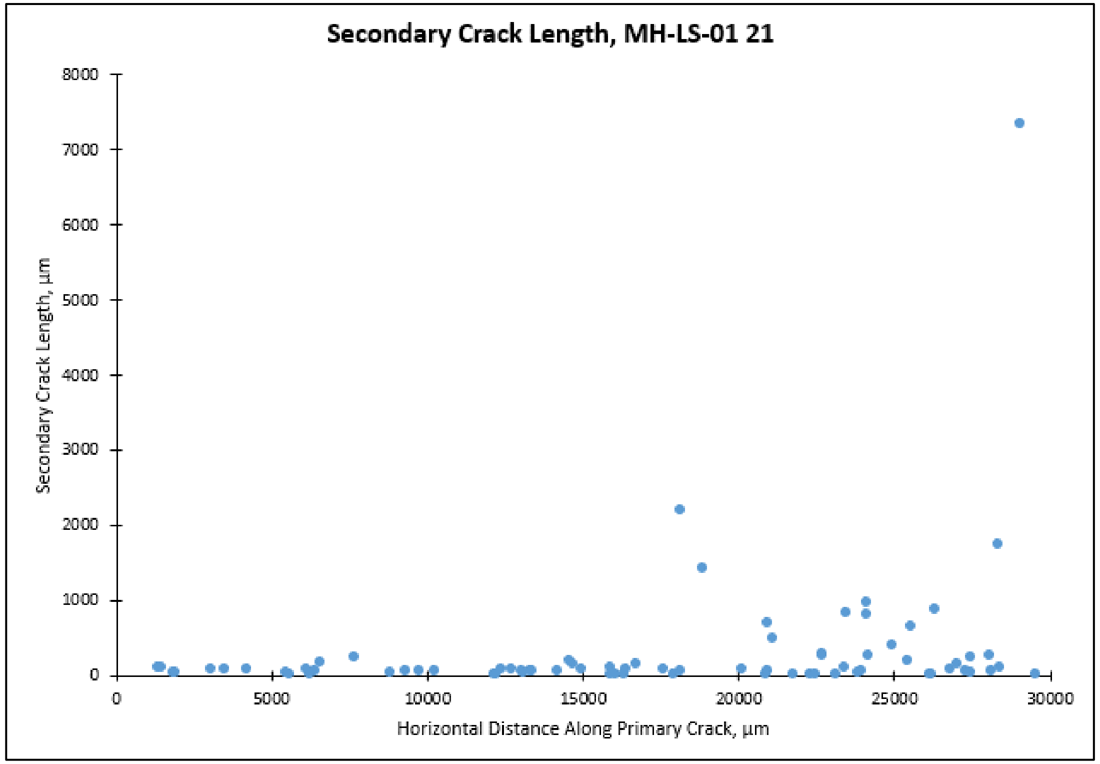
- Crack edges can be segmented out of the image using pixel value differences
- Primary crack edge and individual secondary cracks can be isolated and measured
- Quantifications made:
  - True primary crack length
  - Primary crack length between secondary cracks
  - Number of secondary cracks
  - Length of secondary cracks

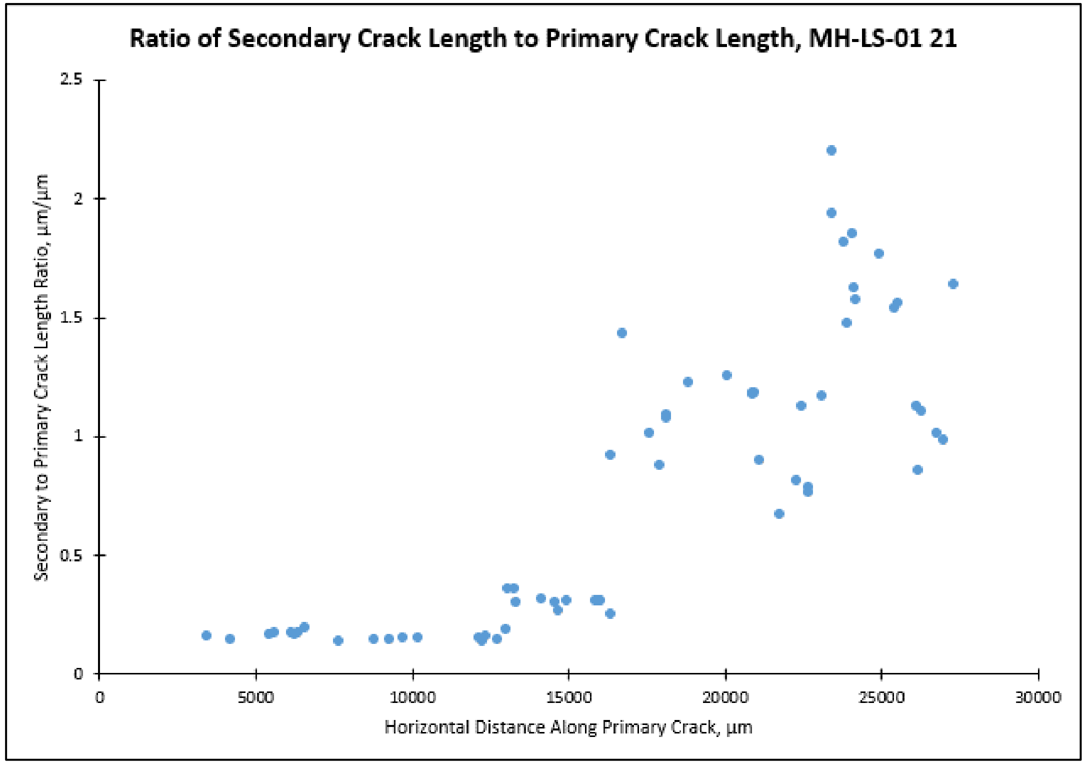


Secondary Crack Length and "Density"

- Across full fracture edge, secondary crack length and rate of occurrence increase
- $Secondary: Primary = \frac{(\sum_{i=1}^{i=n} L_{s,i})}{X_n - X_1}$

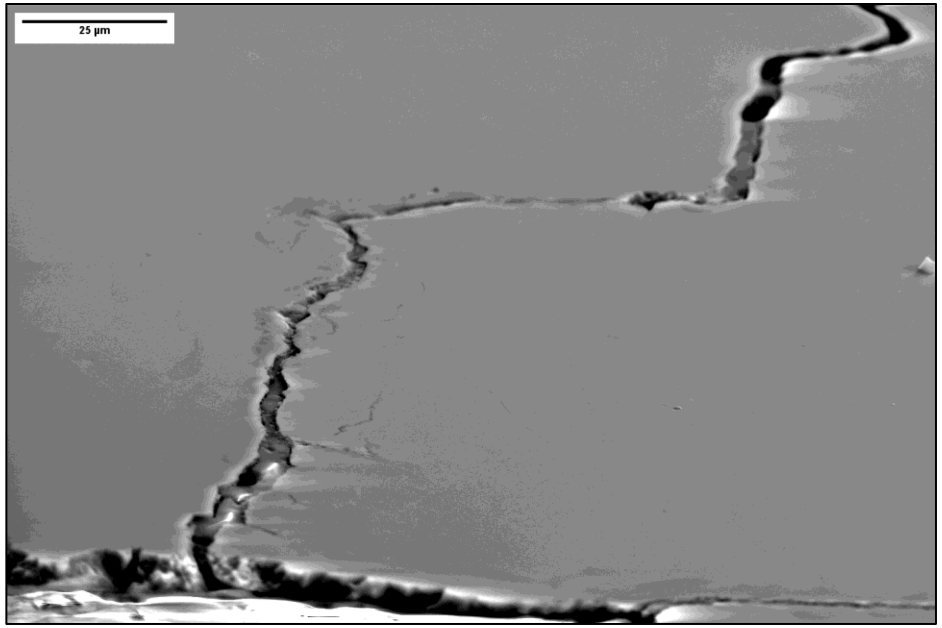
  L_s = secondary crack length, X = x-coordinate of secondary crack initiation point

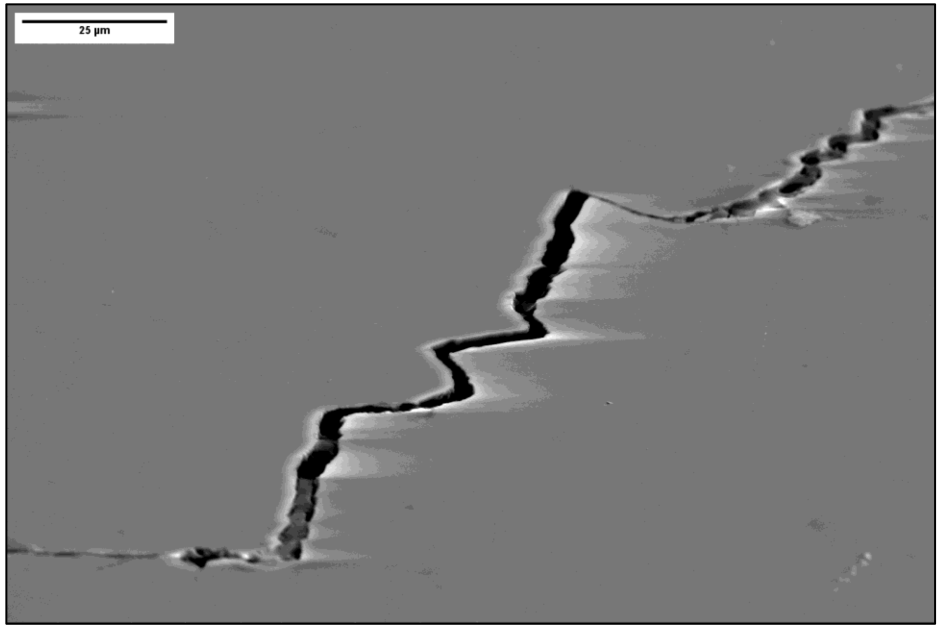


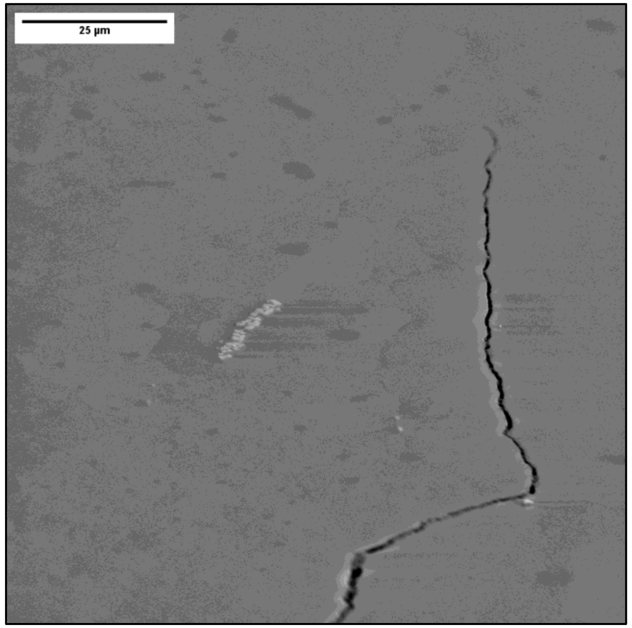


EBSD Analyses

- Regions of interest:
  - Secondary crack initiations
  - Secondary crack redirections
  - Secondary crack terminations

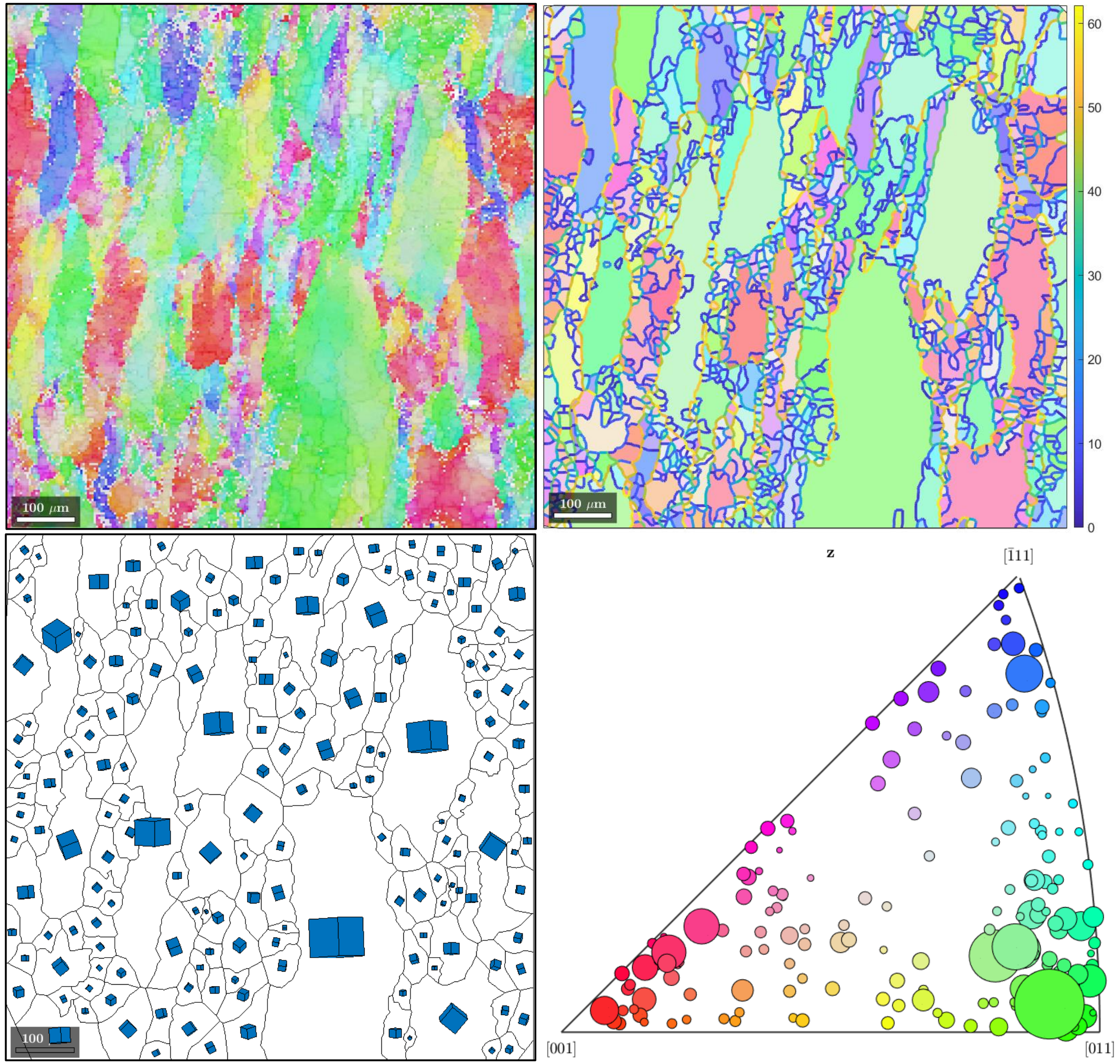




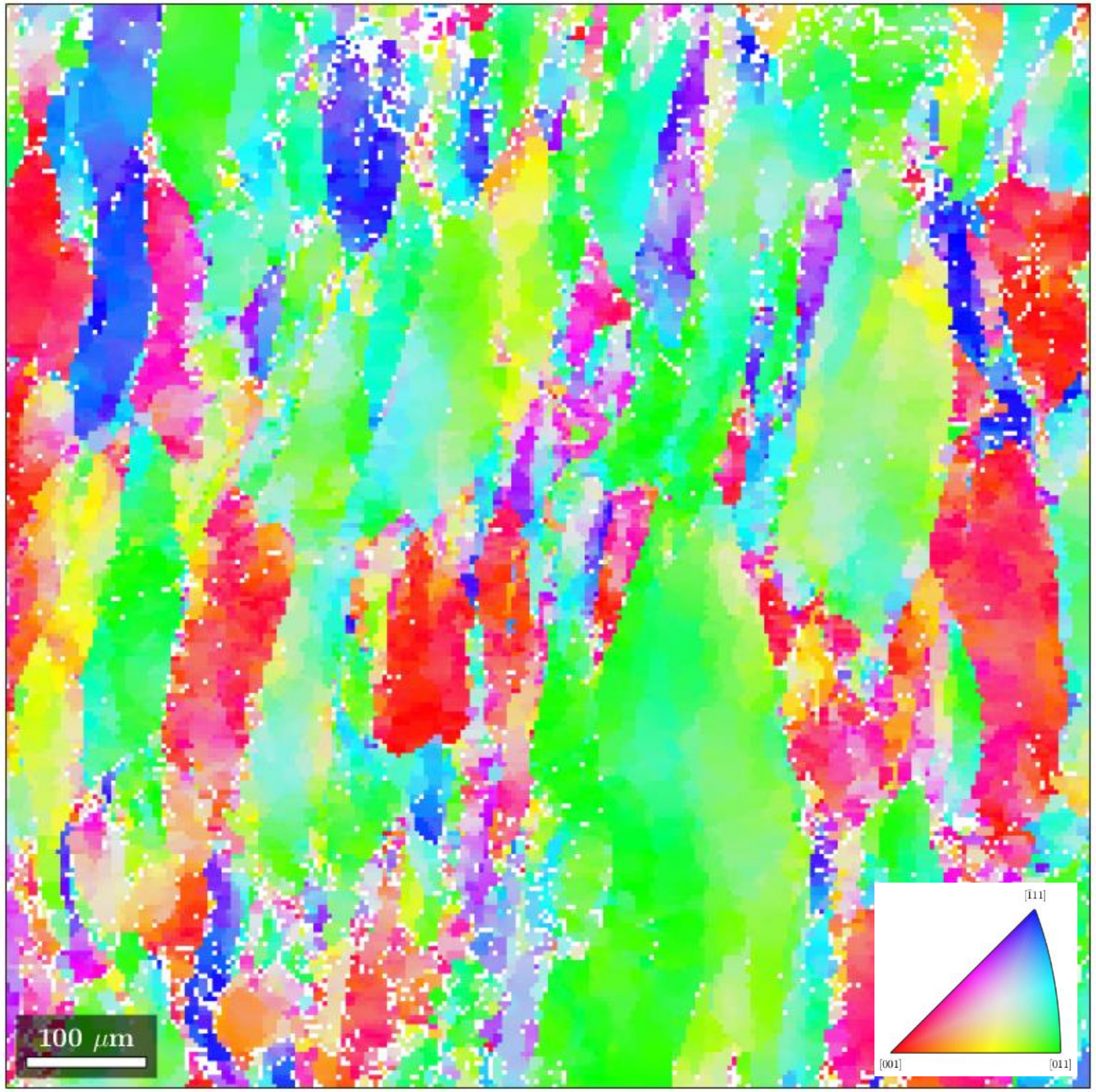


MTEX Script for Rapid EBSD Data Analysis

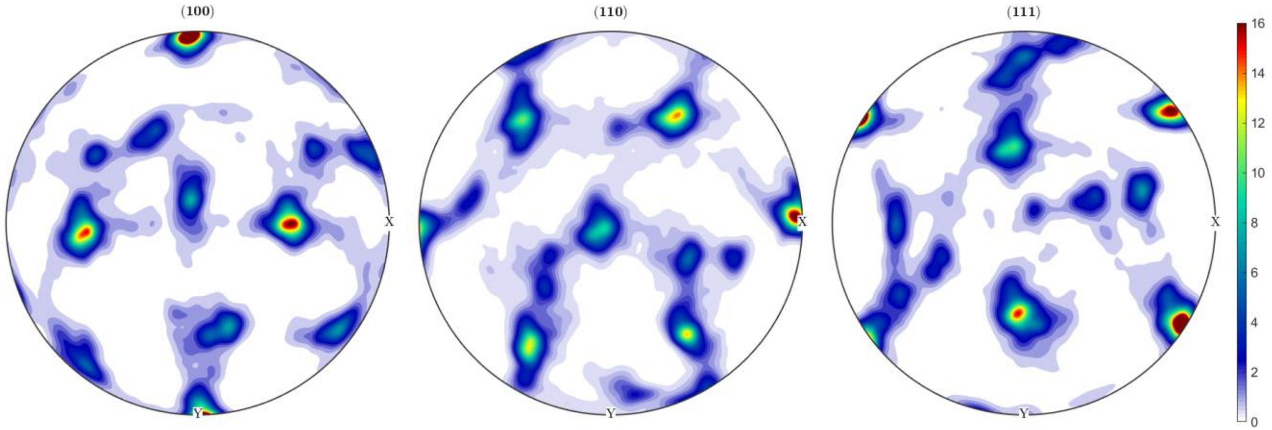
- MTEX MATLAB toolbox used for all EBSD data analysis
- Script developed to take raw EBSD datasets and output:
  - IPF-X, -Y, -Z maps with color IPF key
  - Band contrast maps
  - Segmented grain orientation maps
  - Grain boundary misorientation maps and misorientation distribution
  - Distribution of poles in IPF
  - Visualization of crystals overlaid onto segmented grain maps
  - Pole figures in (100), (110), (111) directions
  - Kernel average misorientation maps
  - Schmid factor maps



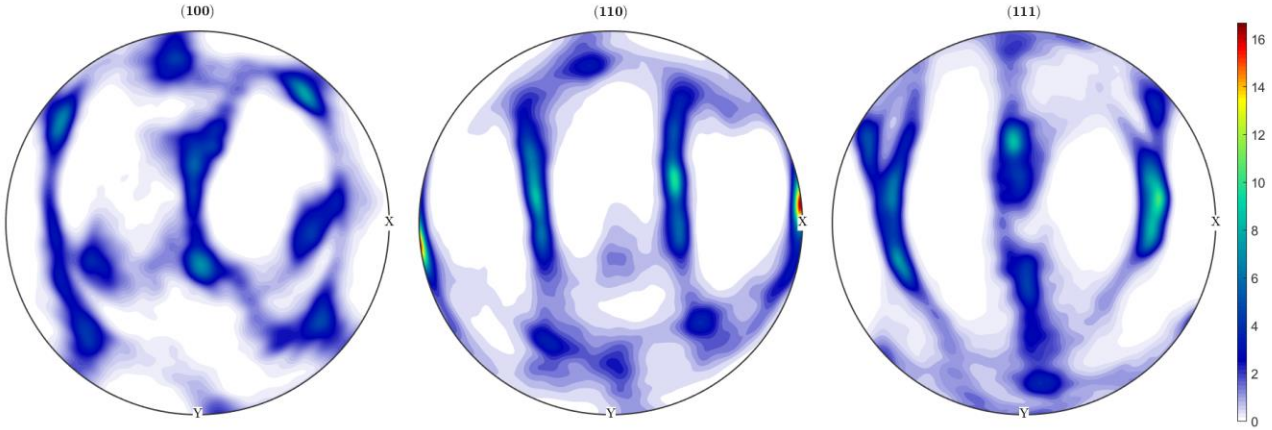
Pole Figures Showing Texture of L-S and T-S samples



L-S Orientation

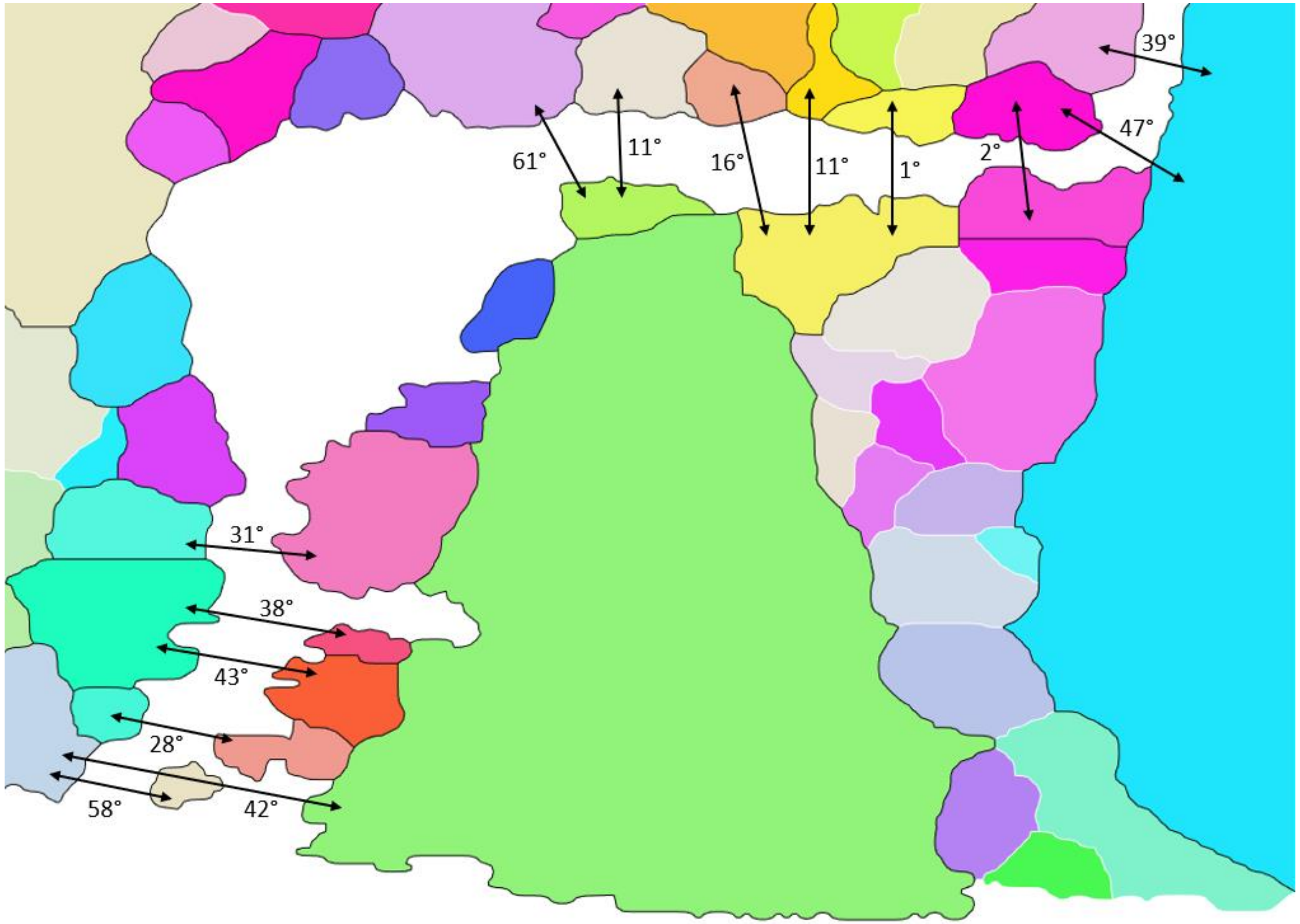


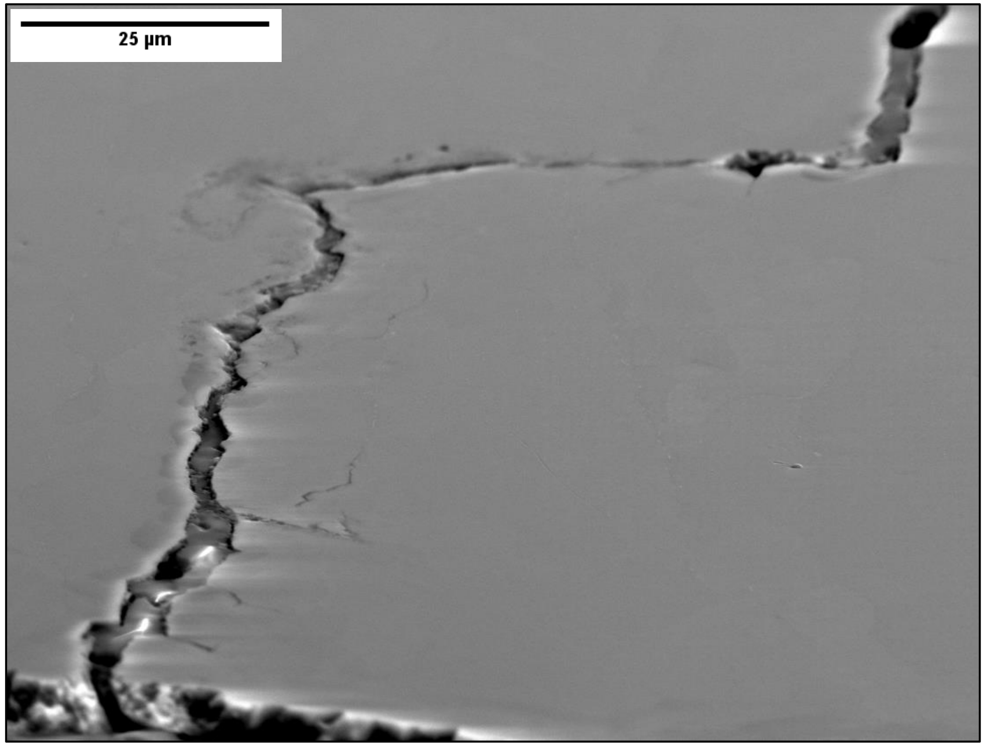
T-S Orientation*



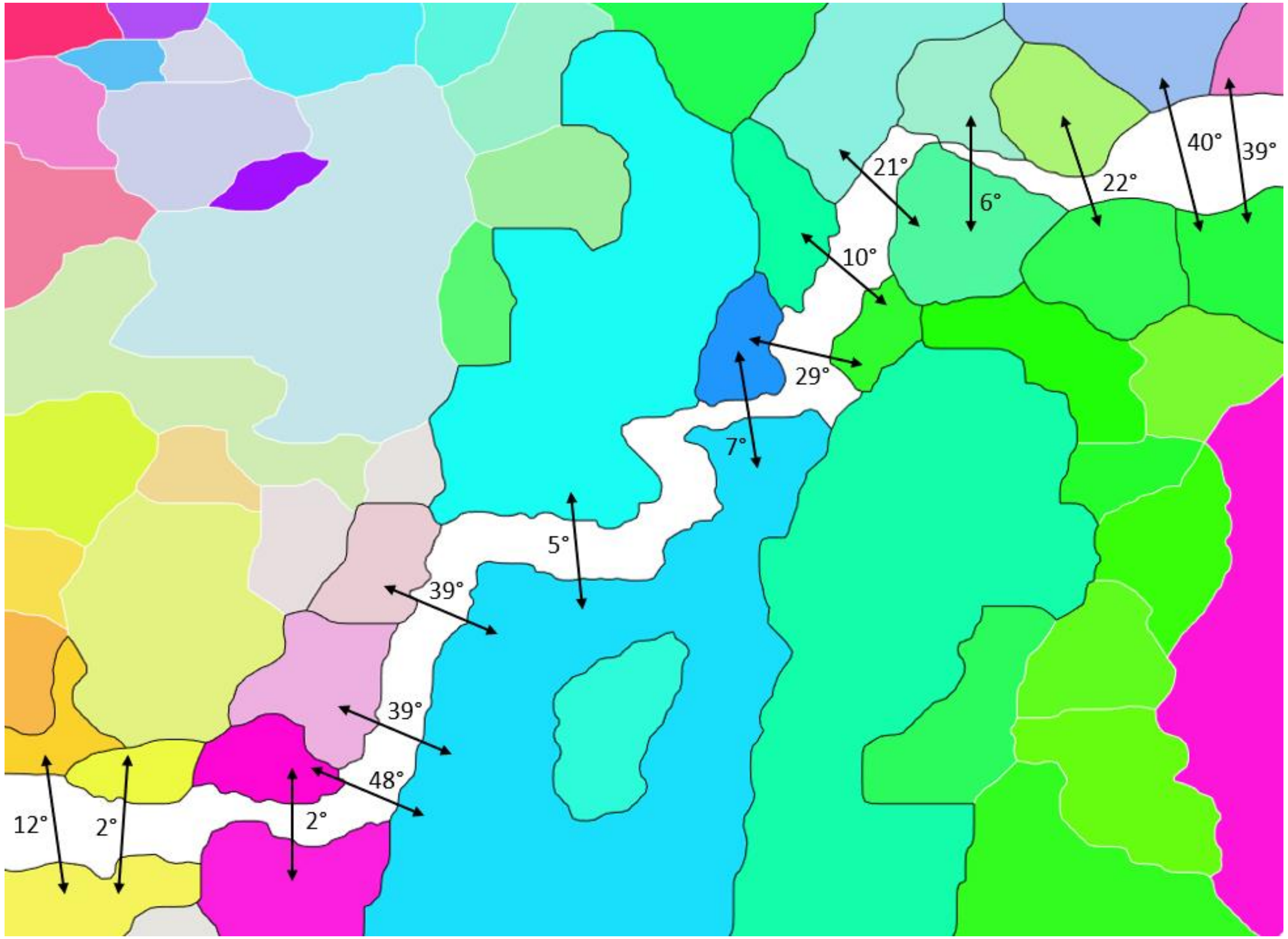
*data taken from large area scan along fracture edge

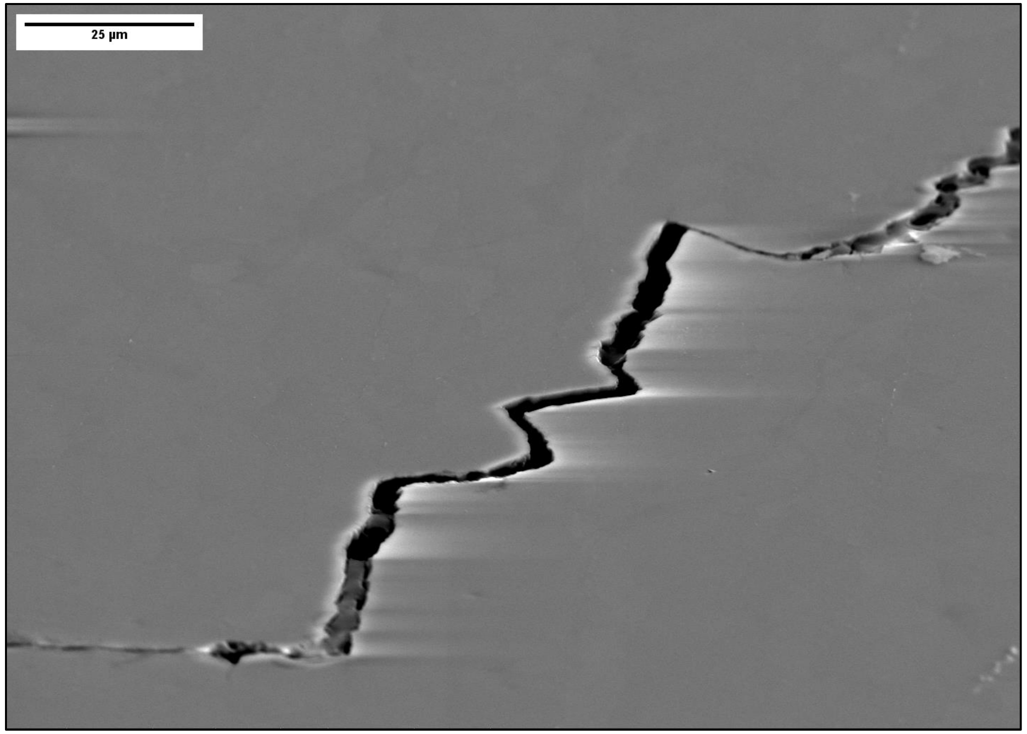
Secondary Crack Initiation



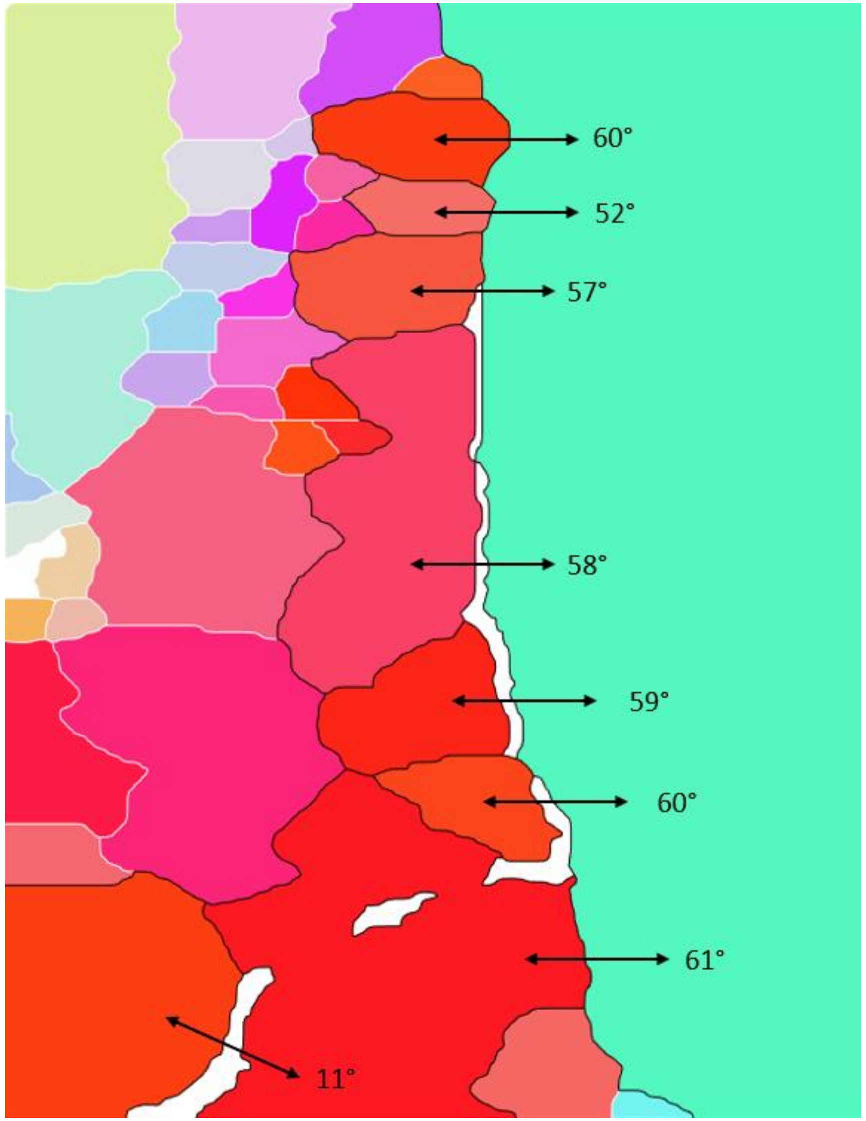


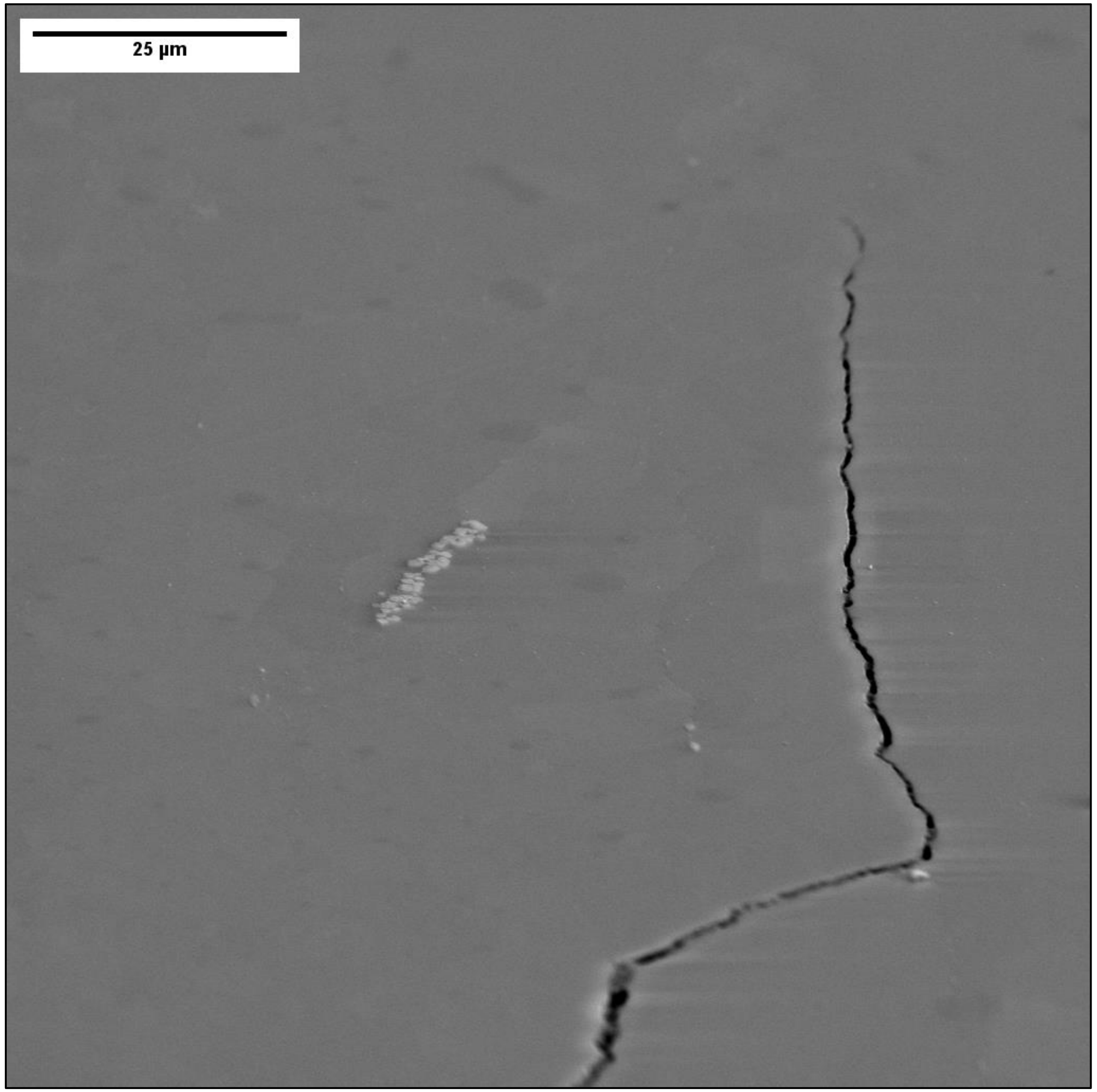
Secondary Crack Redirection





Secondary Crack Termination

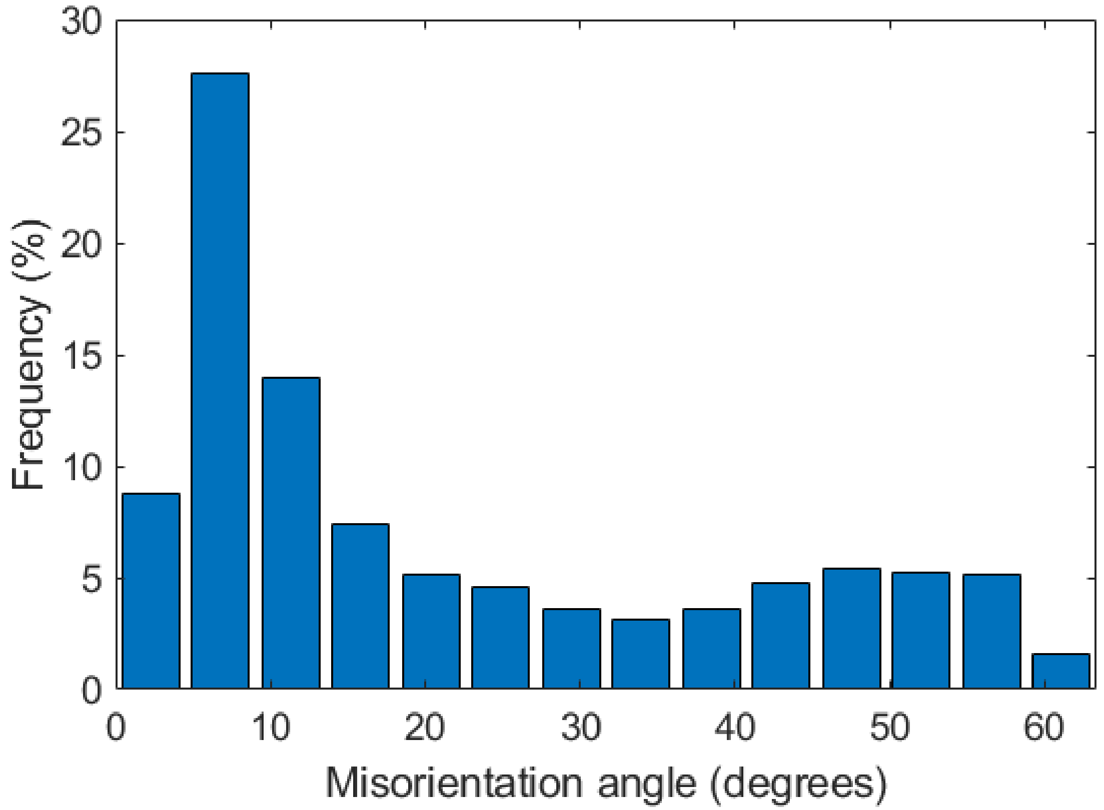




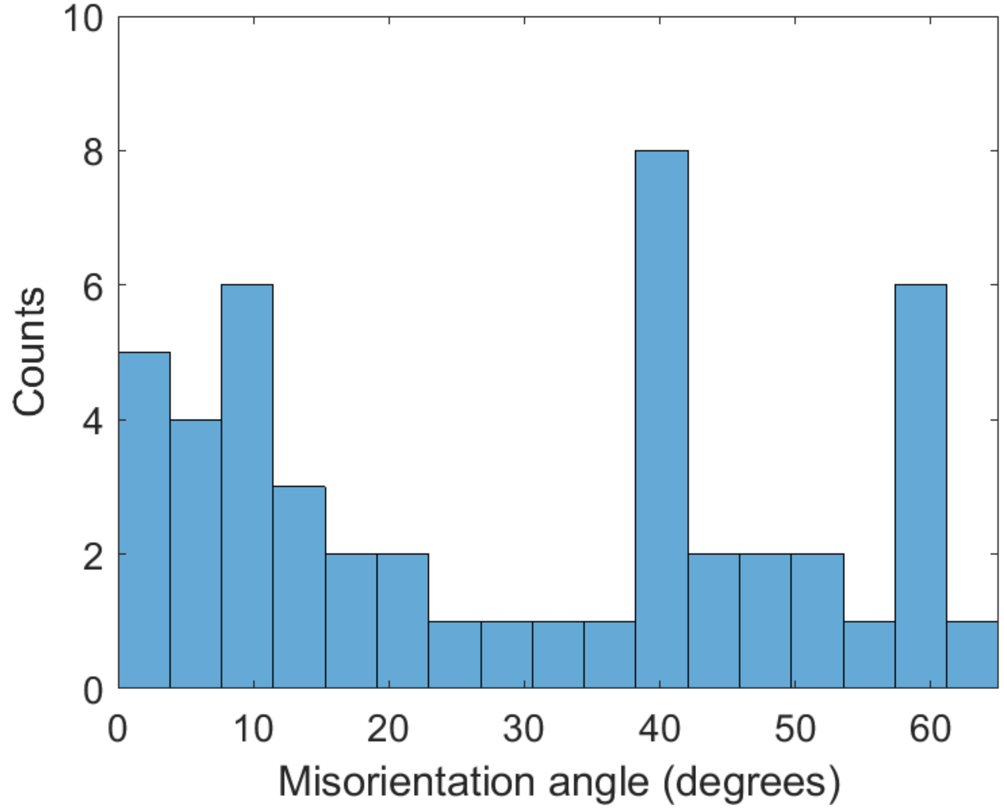
Center Proprietary – Terms of CANFSA Membership Agreement Apply

Distributions of GB Misorientation Angles

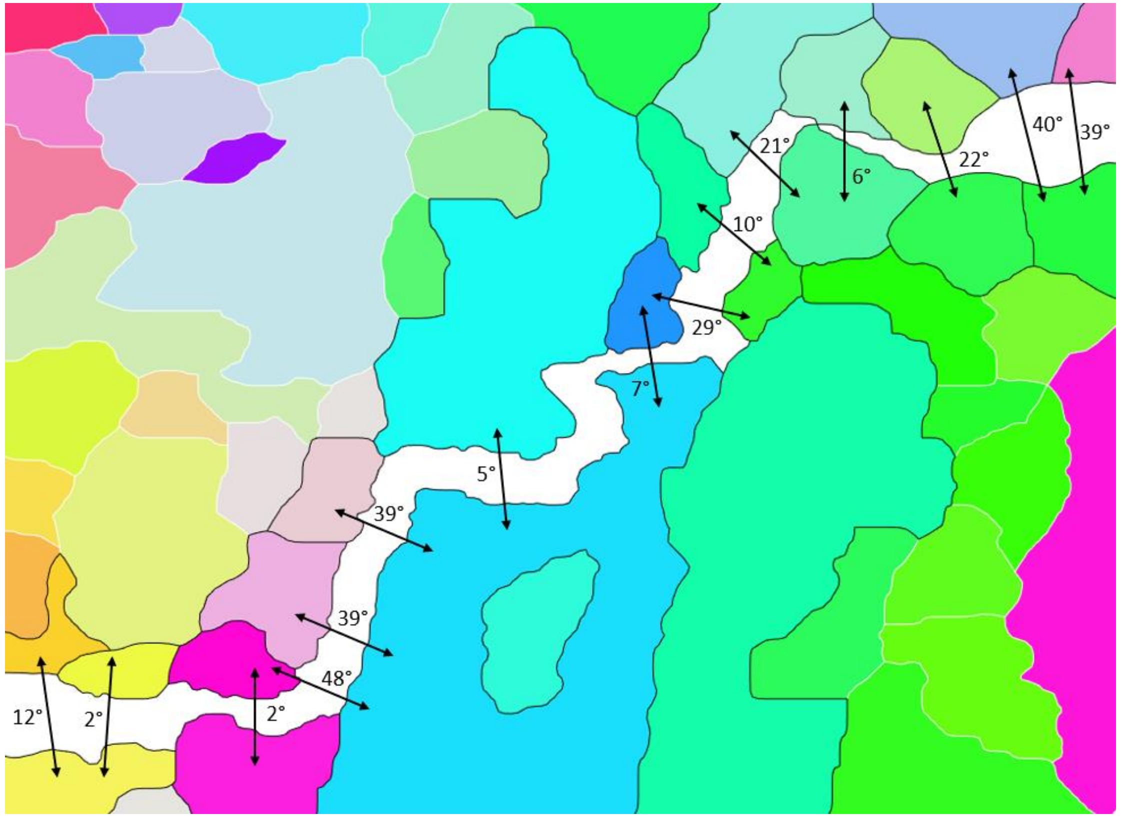
Grain Misorientation Angles in Bulk

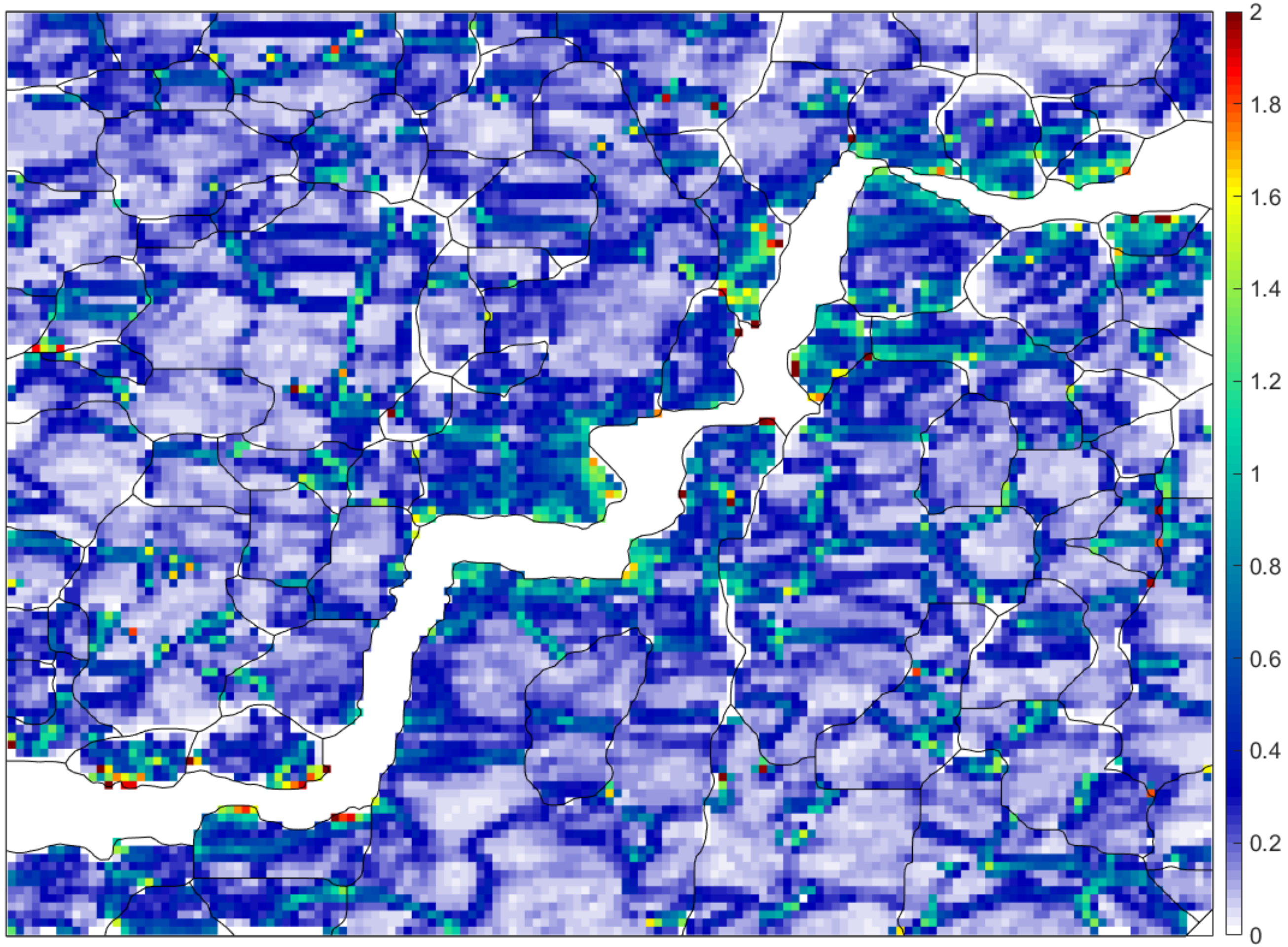


Grain Misorientation Angles at Secondary Crack Edges

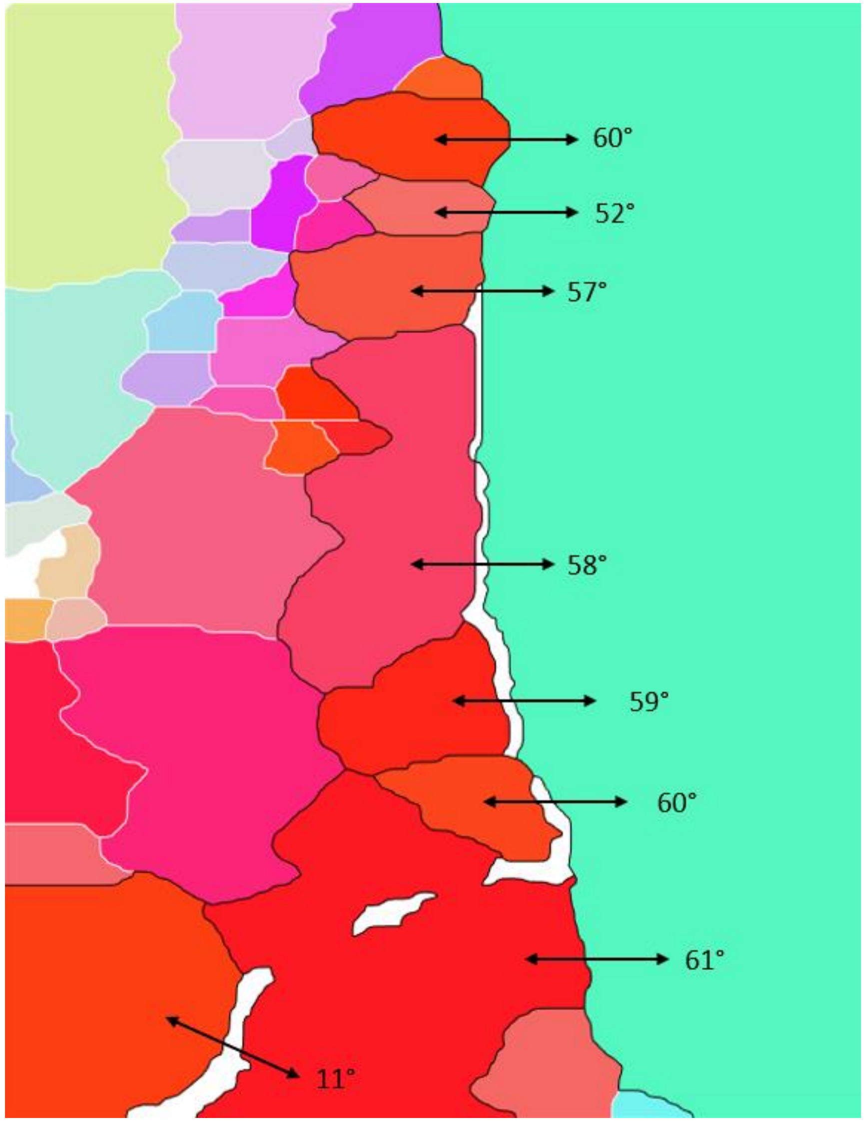


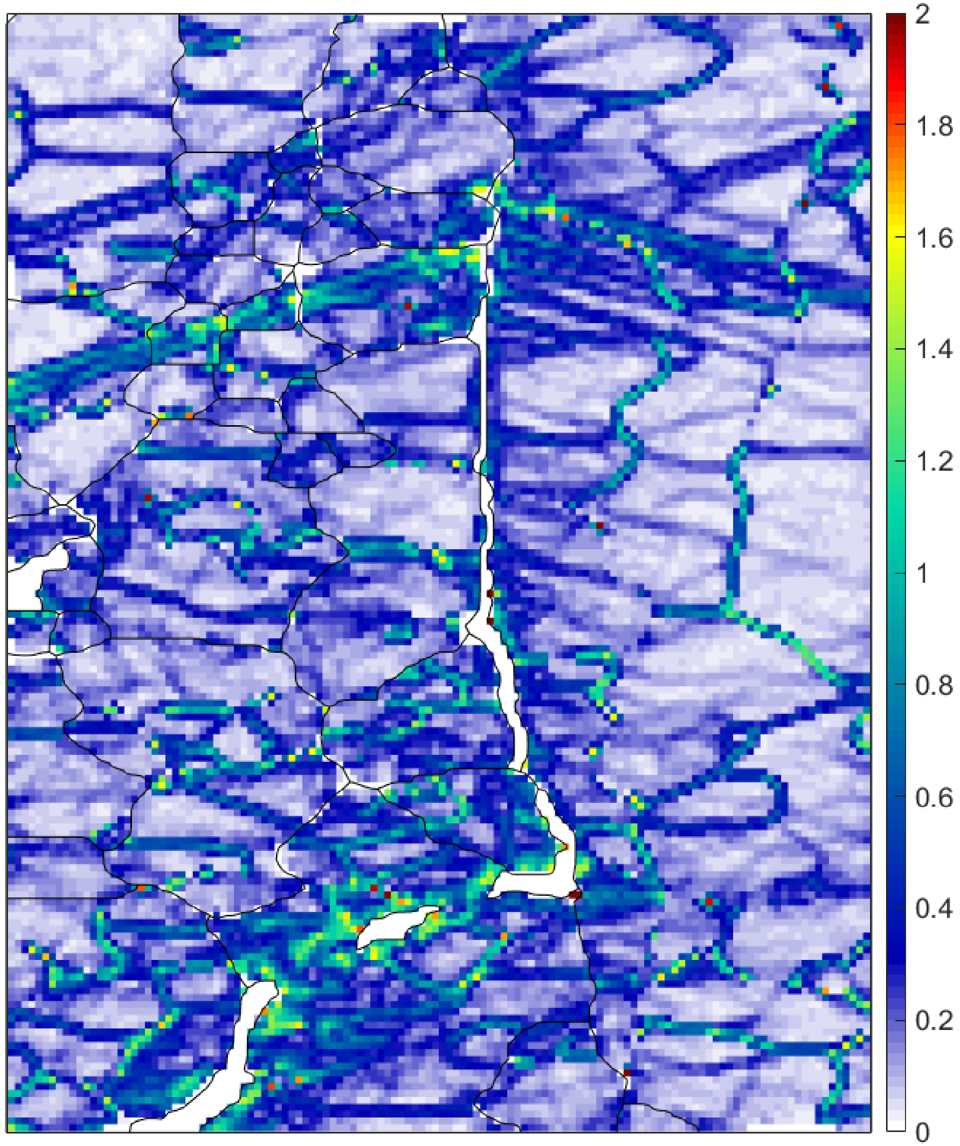
Kernel Average Misorientation





Kernel Average Misorientation





Conclusions

- Secondary crack quantification shows an increase in secondary crack number and length as the primary crack progresses
  - Linking this increase to an increasing ΔK is of interest
- Local grain misorientation is a good predictor for secondary crack nucleation and growth
  - Grain boundary misorientations over 30 degrees show increased delamination crack occurrences
- Delamination fracture along high-angle grain boundaries behaves like brittle fracture
  - KAM shows little stored strain energy in grains bounding high-angle GB cracks

Remaining deliverables:

- Finalized data analyses
- Thesis document
- Dissertation

Thank you!

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References

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