疲劳裂纹启裂源和晶界阻力的定量测量技术

Experimental Techniques for Measurement on Fatigue Crack Initiation Site Density-Strength Distribution and Grain Boundary Resistance to Crack Growth

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Contents

Fatigue Damage Major Cause for Failure

1988, Boeing 737, fuselage blown off in flight, fatigue in fuselage behind front door.

2008, F-15C broken apart in flight, fatigue in a longeron component.

2007, I35W bridge in Minneapolis collapsed, corrosion + fatigue in structure component.

- Fatigue failures cause **capital loss** (**3.1%** of GDP in US in 1998; over **$1 trillion** in 2012)
- **Loss of human lives**
- Many accidents can be **prevented** by accurate prediction of fatigue lives and design of new materials and components

Images from www.google.com

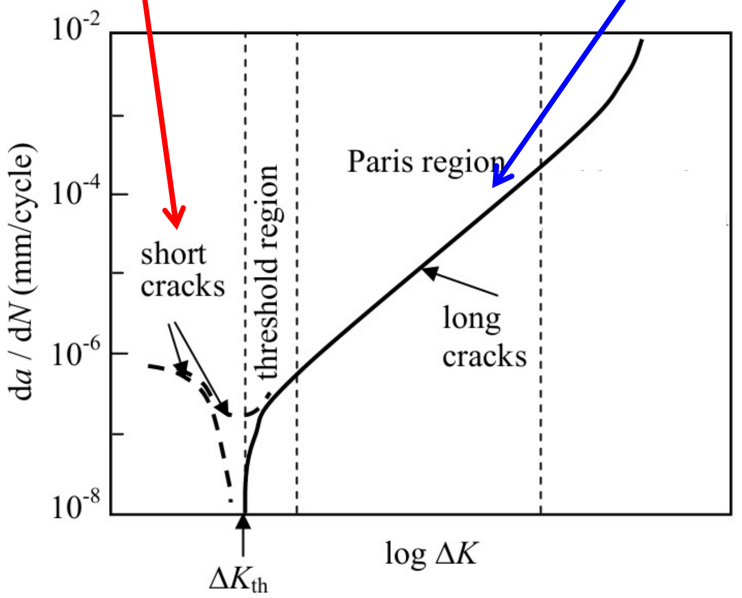
The Process of Fatigue Damage

Cyclic slip → Crack initiation → early crack growth → Long-crack growth → Final failure

早期损伤 Crack initiation period

Crack growth period

- Large fraction (60~90%) of total fatigue life.
- Sensitive to local microstructure; **not** quantitatively understood yet

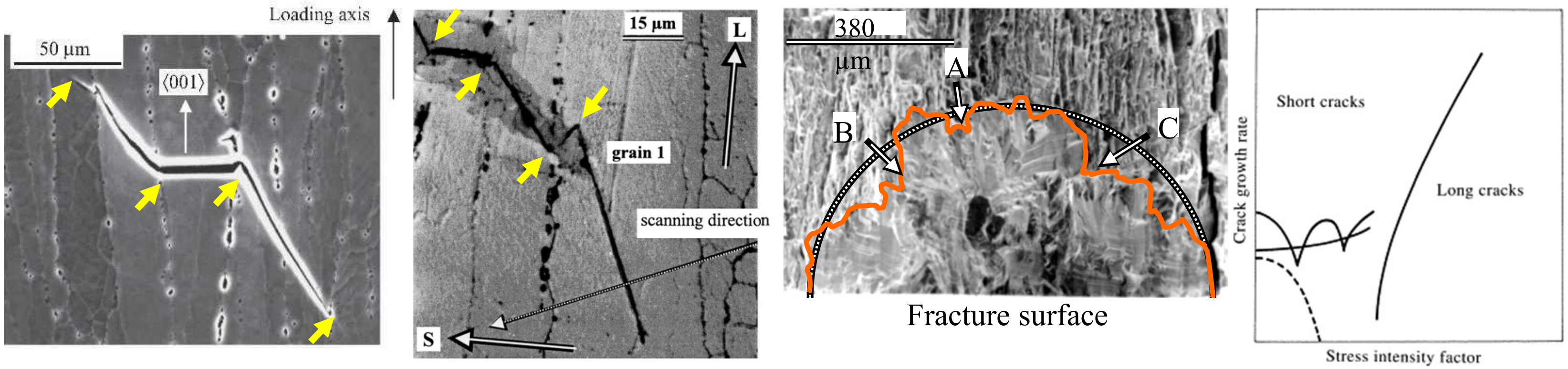


- Small fraction (10~20%) of total fatigue life.
- Quantified by Paris law and its derivatives

Motivation: scientifically significant to quantitatively understand early stage of fatigue crack growth at microstructure scale. **预防断裂：装备关键材料的早期损伤预测非常重要**

Short Fatigue Cracks

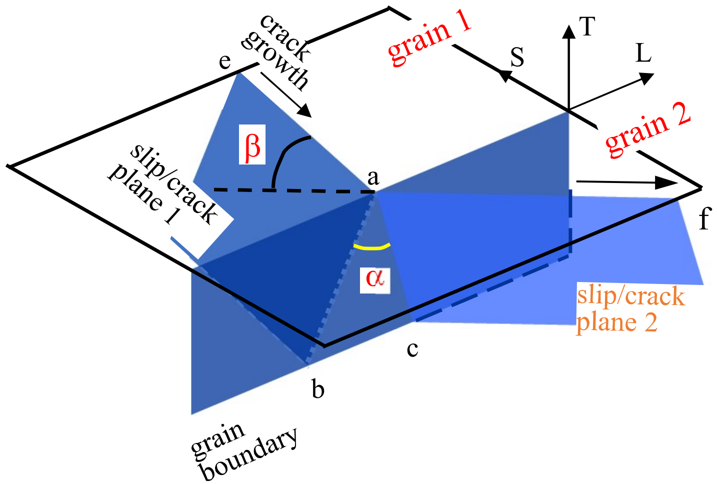
- **Characteristics** of Short Fatigue Crack (SFC) growth behaviors
  - ➢ **Sensitive** to microstructure; behave "abnormally"
  - ➢ **Deflection**, **branching** or even **arrested** at **GBs**, or even inside grains
  - ➢ **Irregular** crack front
  - ➢ **Scattering** growth rate



T. Zhai, Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science, 37A (2006) 3139-3147.
*T. Zhai, A.J. Wilkinson, and J.W. Martin. Acta Materialia, 2000. **48**(20): p. 4917-4927*
K. Obrtlik, J. Polak, M. Hajek, A. Vasek, International Journal of Fatigue, 19 (1997) 471-475.

GBs: **main barrier** to SFC growth → control growth behaviors
晶界是阻碍疲劳裂纹的主要微观结构，定量计算短疲劳裂纹扩展行为，需要知道其阻力的定义与数值？

Zhai's 3-D Crystallographic Model



3-D crystallographic mechanism for crack growth along slip plane 1 in grain 1 onto slip plane 2 in grain 2

$[\mathbf{N}] = [\mathbf{n}] \cdot \mathbf{B}$

With EBSD

$\psi = \arccos([N]\times[S]\cdot[L])$

$\theta = \arccos([N]\times[T]\cdot[L])$

$\alpha = |\psi_1 - \psi_2|$:
twist angle on GB plane

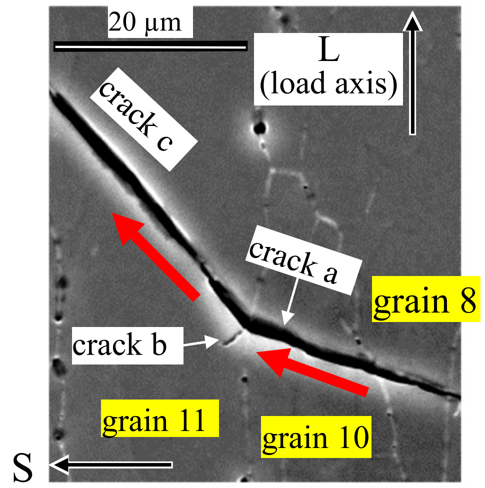
$\beta = |\theta_1 - \theta_2|$:
tilt angle on sample surface

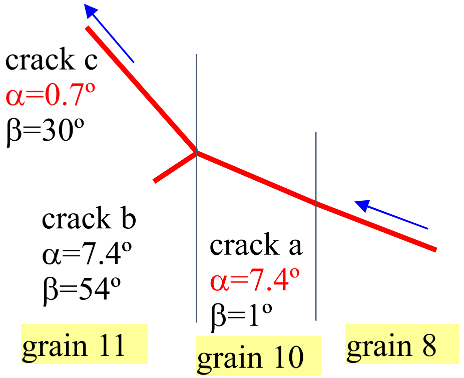
When passing GB, **area *abc* has to be fractured**, **significant resistance** to crack growth.
→ **α has to be minimised.**

Minimum-α criterion: crack twists onto the slip plane.
裂纹穿过晶界的最小旋转角原则！

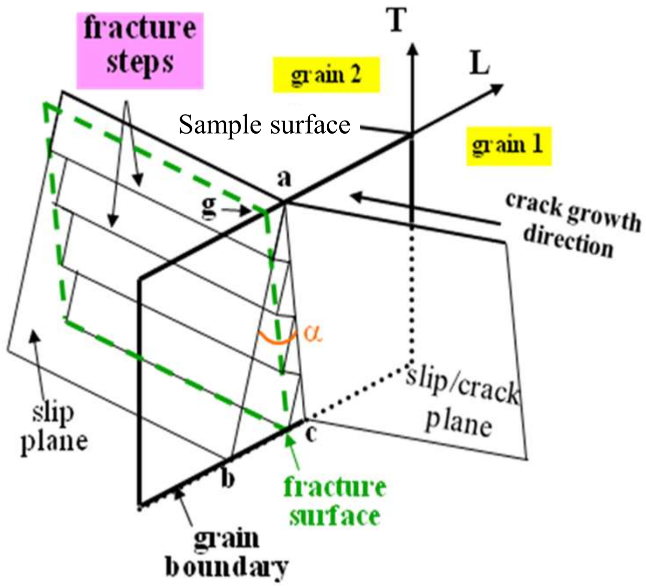
Zhai, T., A.J. Wilkinson, and J.W. Martin. Acta Materialia, 2000. ***48****(20): p. 4917-4927*

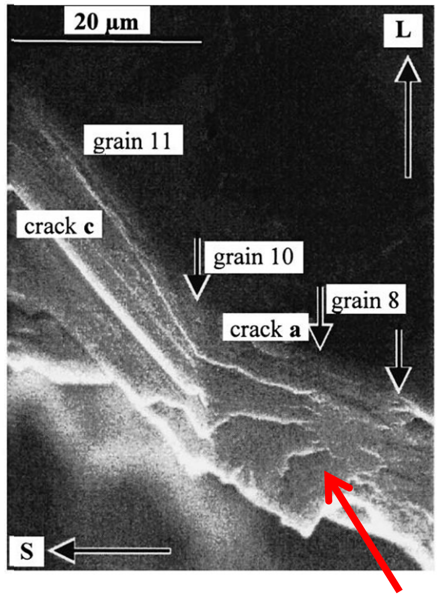
Experimental Evidence





minimum α angle





fracture steps

fracture surface

formation of fracture steps due to crack twist

__W. Wen__ T. Zhai, Philosophical Magazine, 91 (2011) 3557-3577.
T. Zhai, A.J. Wilkinson, and J.W. Martin. Acta Materialia, 2000. 48(20): p. 4917-4927
T. Zhai, X.P. Jiang, J.X. Li, M.D. Garratt, G.H. Bray, International Journal of Fatigue, 27 (2005) 1202-1209

Growth across Grain Boundaries: A Crystallographic Model

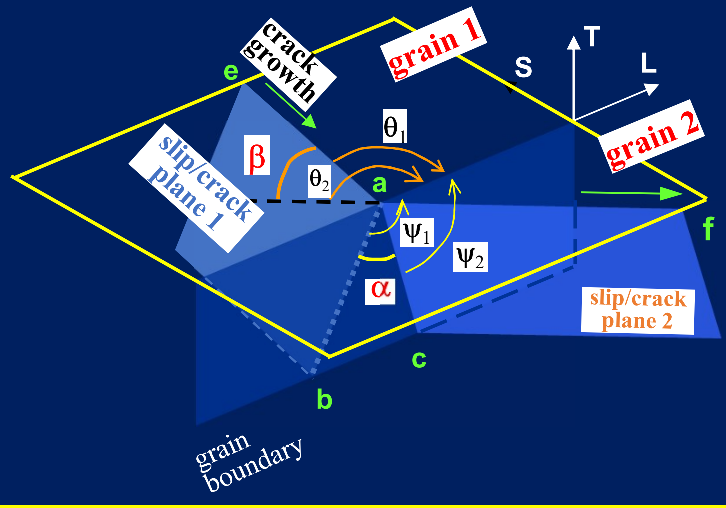
- **α and β angles**: the main factors controlling short fatigue crack growth across a grain boundary

  $\alpha = |\psi_1 - \psi_2|$

  twist angle of the crack plane on grain boundary plane

  $\beta = |\theta_1 - \theta_2|$, $0° \le \beta, \alpha, \psi_1, \psi_2, \theta_1, \theta_2 \le 180°$

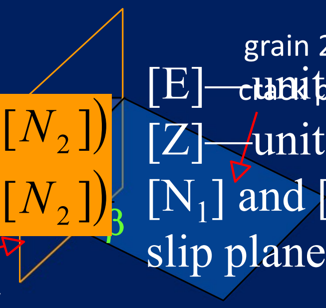
  tilt angle of crack deflection at grain boundary



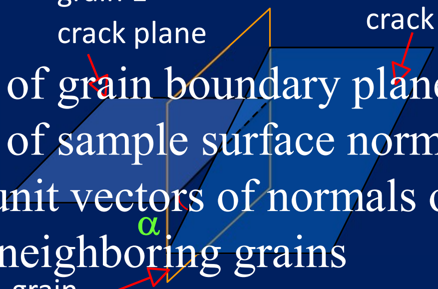
α and β have to be minimised for a crack to pass through a grain boundary

Two components of crack

$$\alpha = \arccos([E]\times[N_1]\bullet[E]\times[N_2])$$
$$\beta = \arccos([Z]\times[N_1]\bullet[Z]\times[N_2])$$

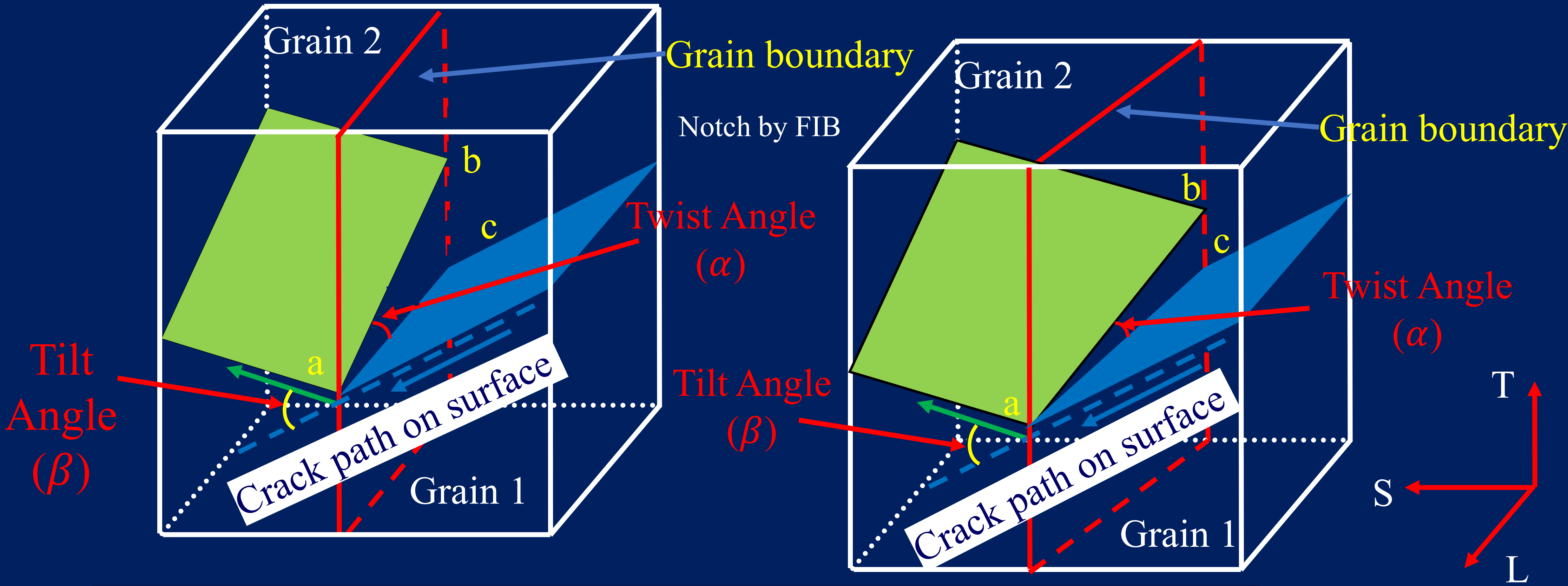


[E]—unit vector of grain boundary plane normal
[Z]—unit vector of sample surface normal
[N$_1$] and [N$_2$]—unit vectors of normals of the two favored slip plane in the neighboring grains



T. Zhai, A.J. Wilkinson, J.W. Martin, Acta Materialia, Vol.48, pp. 4917, (2000).

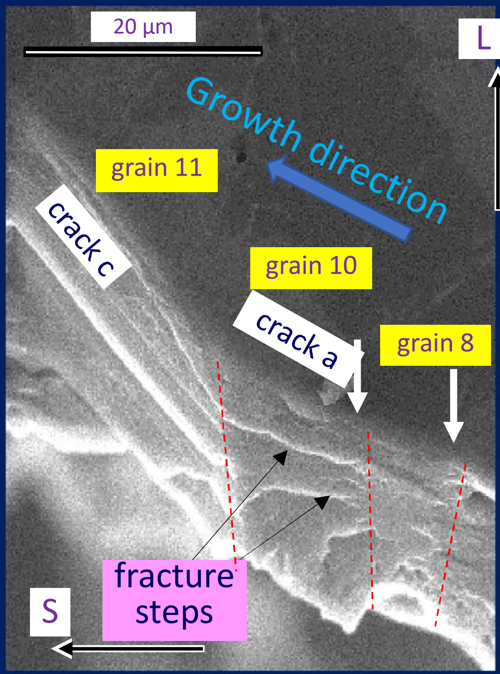
Microstructural 3-D Effect on Fatigue Crack Nucleation: Grain Boundaries

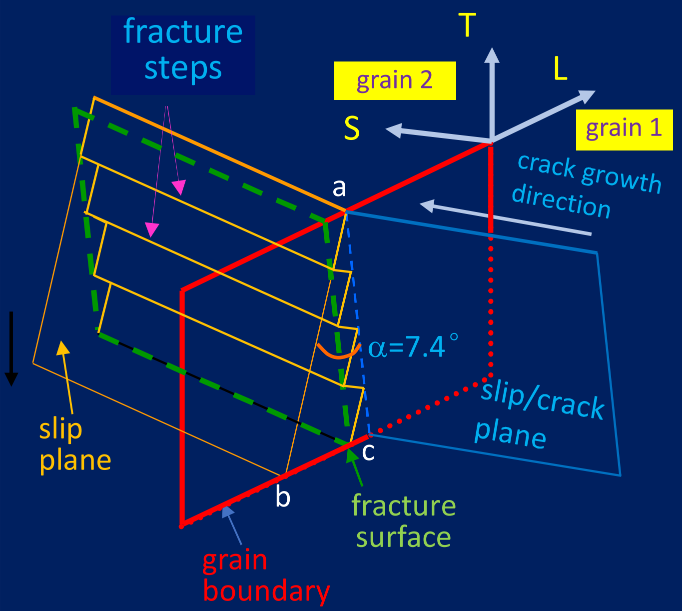


Controlling Parameter: the Minimum Twist Angle

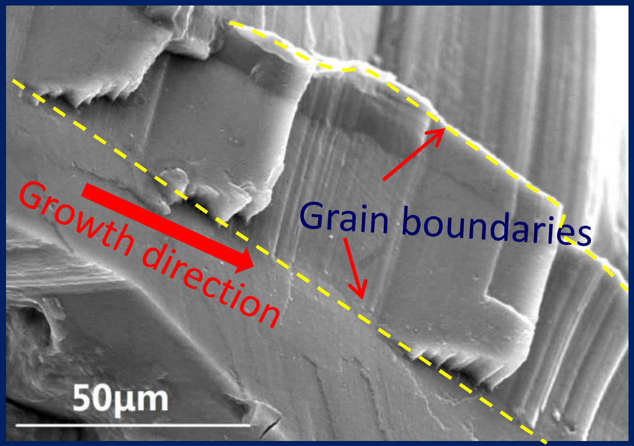
The twist angle is affected by grain orientation and GB orientation

Resistance due to Crack Plane Twist





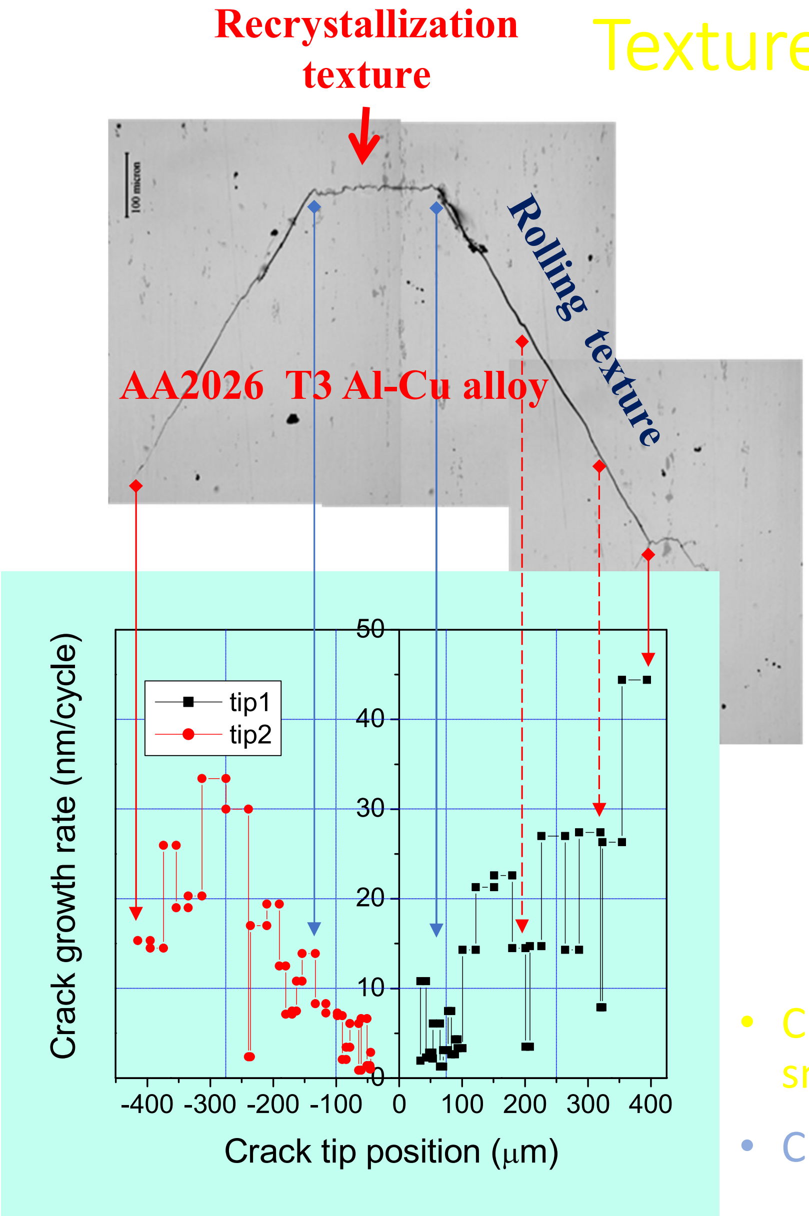
Fracture steps formed to accommodate crack plane twist

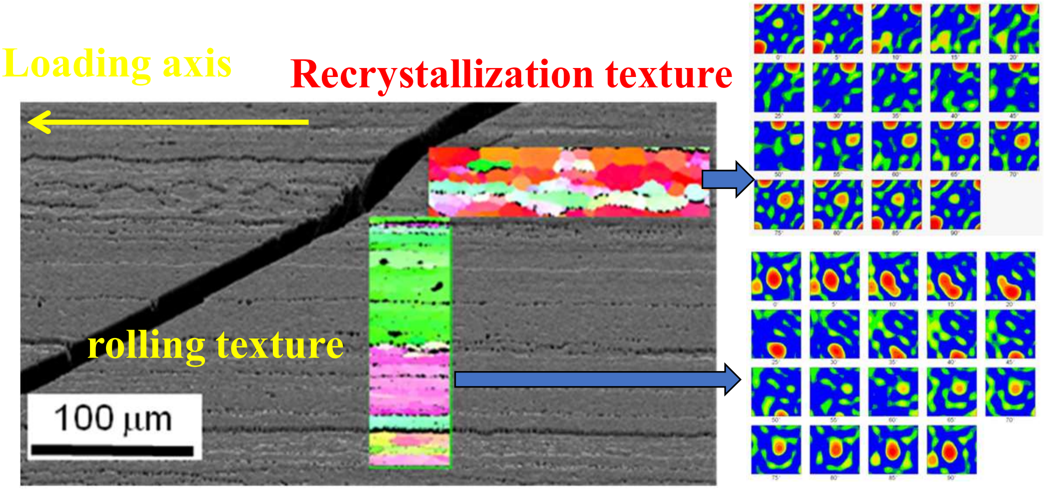


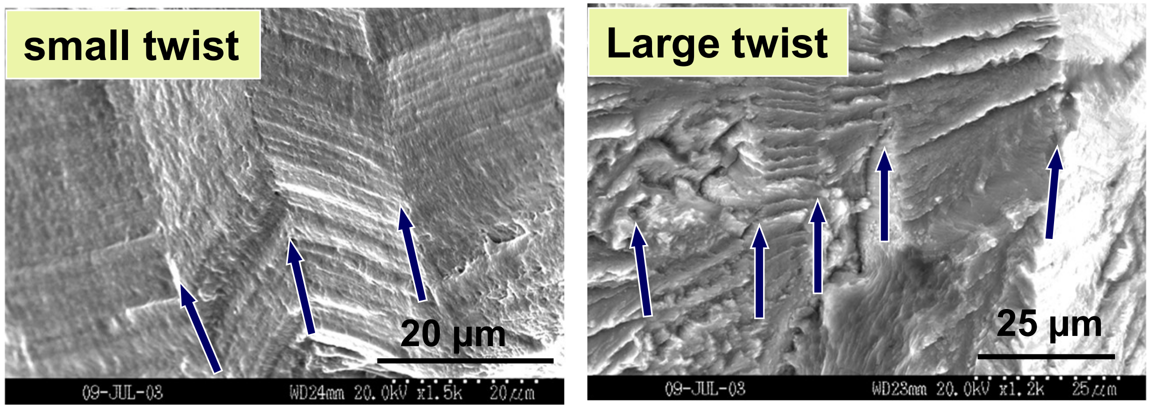
Larger twist ⇒larger fracture steps ⇒ higher resistance

This crystallographic model can explain the observed anomalous growth behaviors of short fatigue cracks

Texture Effect on long Crack Growth Behaviors

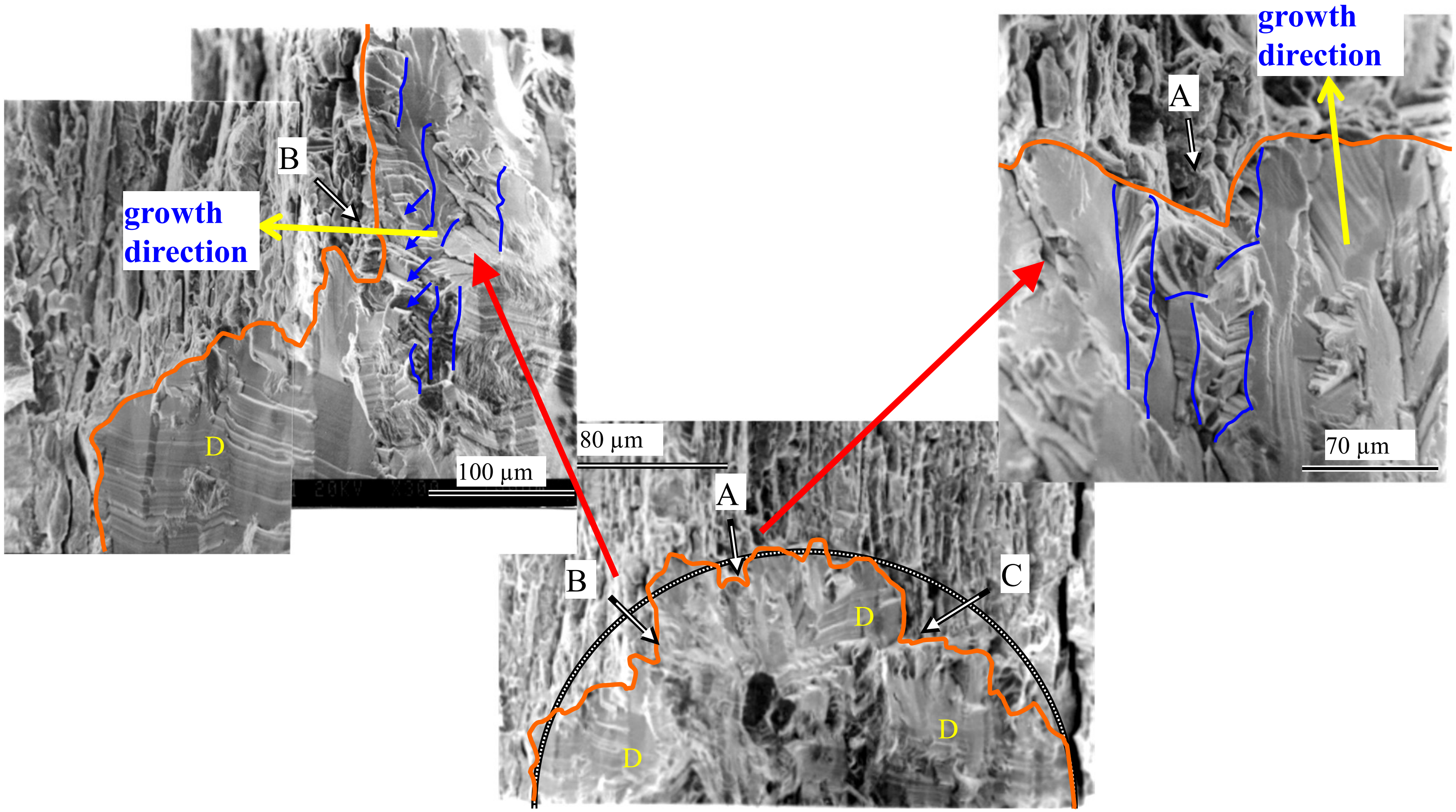






- Crack growth faster (30°) in rolling texture region due to predominant small-twist deflection;
- Crack growth slower due to large twist deflection in recrystallized region

Crack Front Pinned by Large Twist

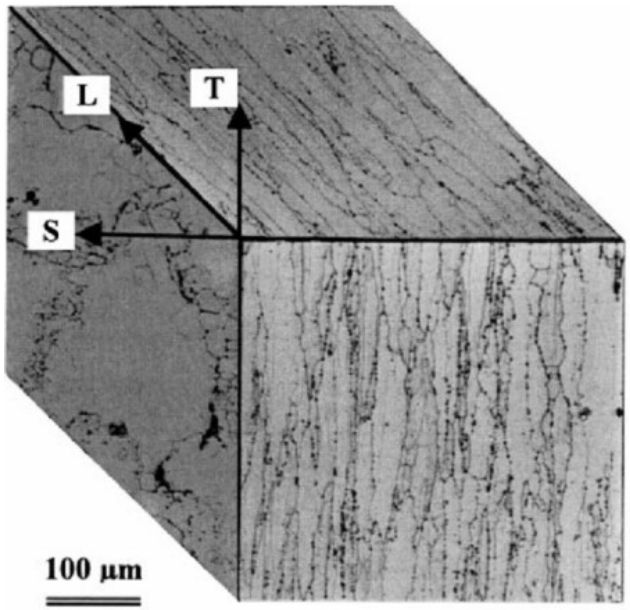


Crack front pinned by crack plane twist

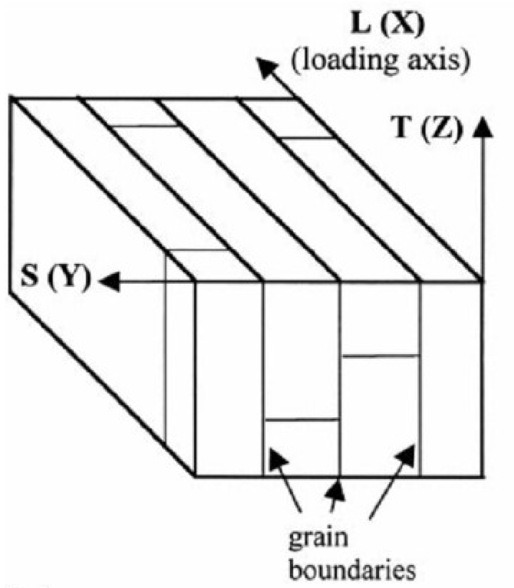
Zhai, T., A.J. Wilkinson, and J.W. Martin. Acta Materialia, 2000. **48**(20): p. 4917-4927

SFC Growth in Rolled Al-Li Alloy 8090

- Hot cross-rolled, pancake shaped grains → major GBs vertical to L-S and T-S surfaces



Grain size: 217 µm ×176 µm × 26 µm

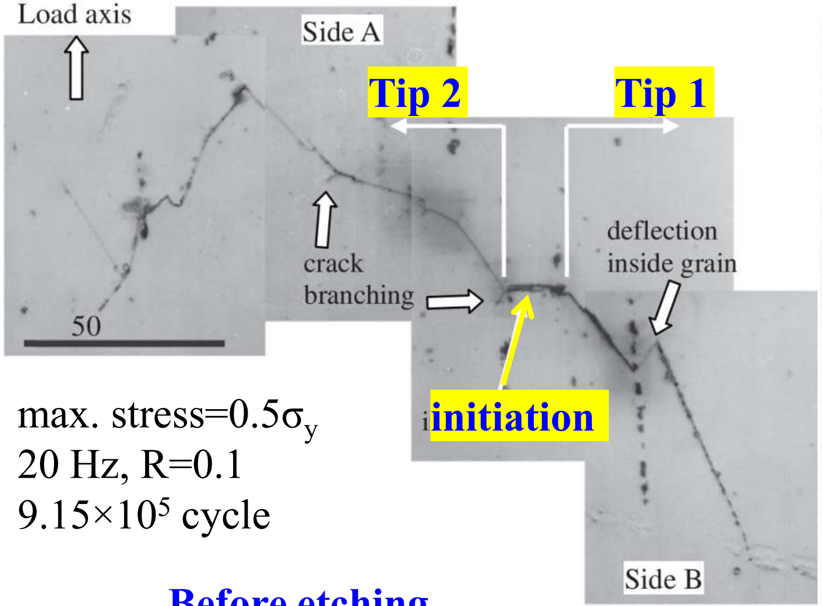


Simplified grain structure

- L-S sample, fatigued on four-point bend rig, max. stress=$0.5\sigma_y$, 20 Hz, R=0.1

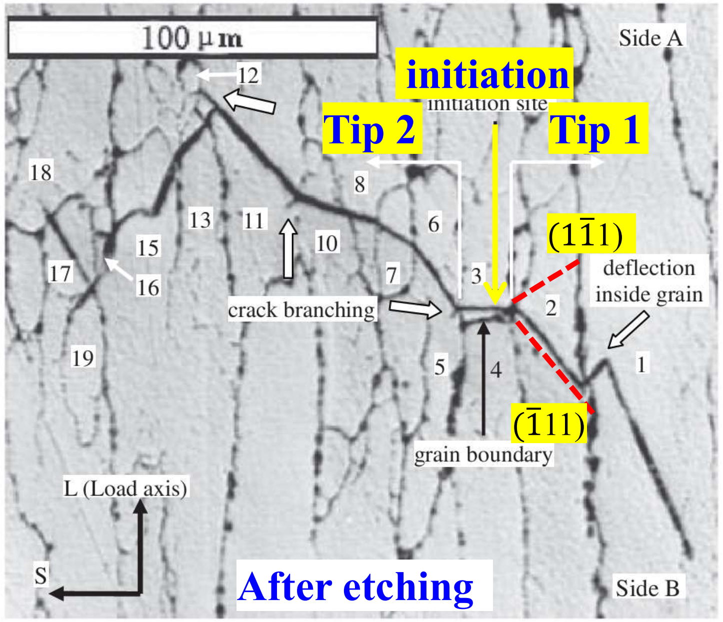
Zhai, T., A.J. Wilkinson, and J.W. Martin. Acta Materialia, 2000. **48**(20): p. 4917-4927

Crack Initiation & Growth



max. stress=0.5σ_y
20 Hz, R=0.1
9.15×10^5 cycle

Before etching

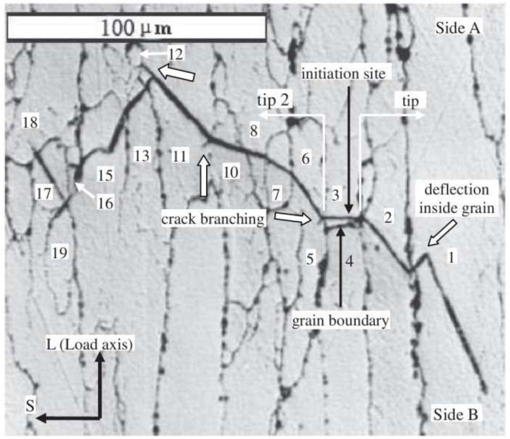


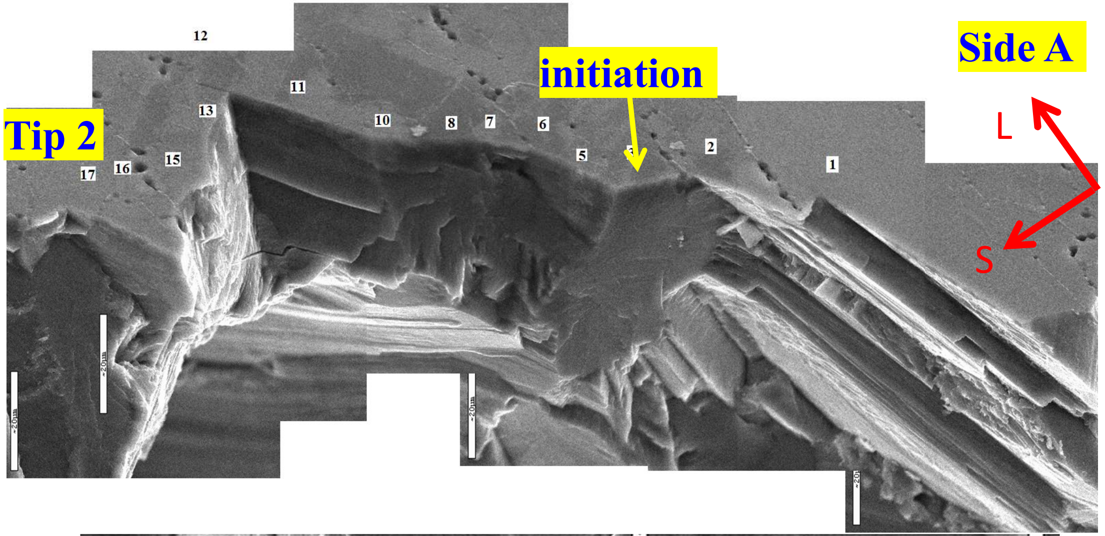
After etching

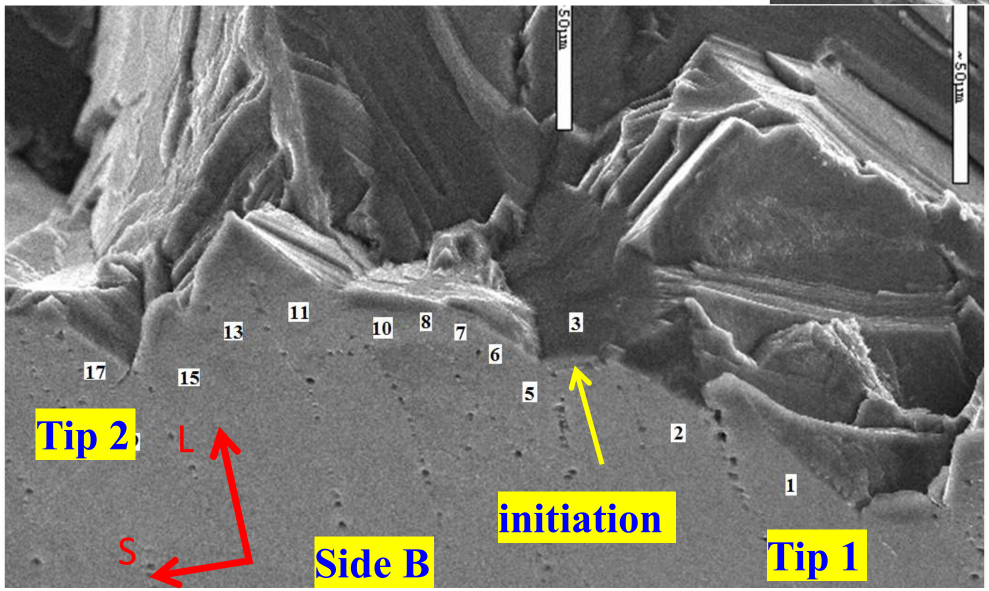
- Crack initiated // (001) plane, vertical to loading axis, due to the trace element of Na and K
- Crack propagated crystallographically through over **13 grains**
- Assume GBs ⊥ surface: crack twisted onto a **minimum-α** crack plane at all GBs, except at GB3/2. **why?**

W. Wen, T. Zhai, Philosophical Magazine, 91 (2011) 3557-3577.
Zhai, T., A.J. Wilkinson, and J.W. Martin. Acta Materialia, 2000. **48**(20): p. 4917-4927

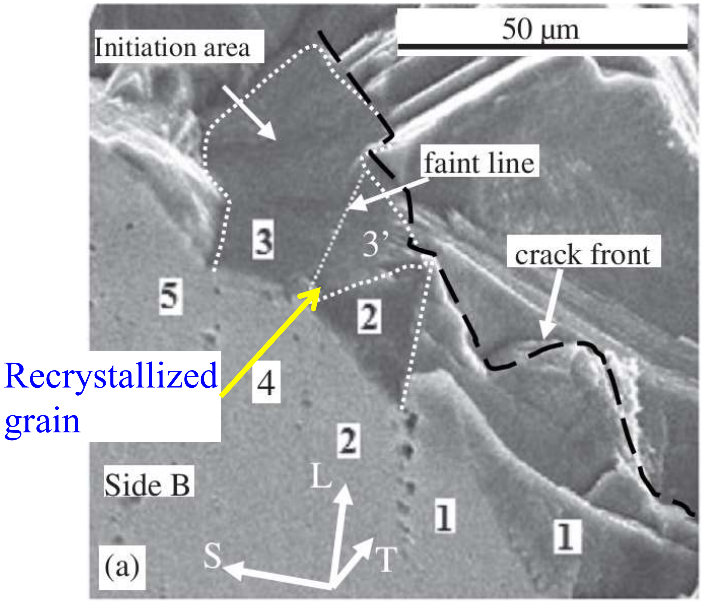
Mating Fracture Surfaces

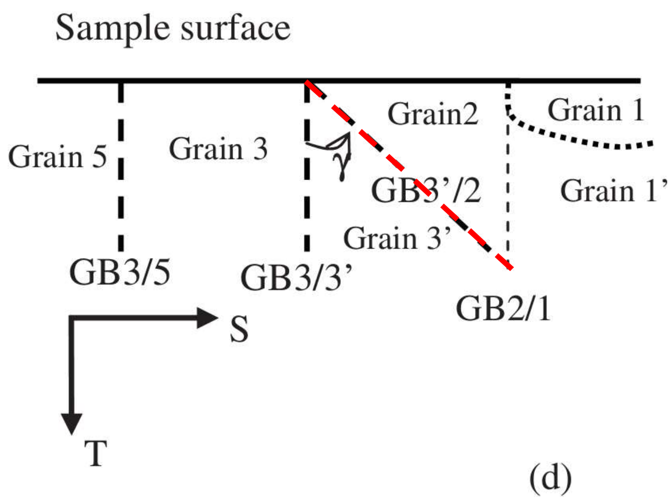






Fracture Surface & GB Tilting





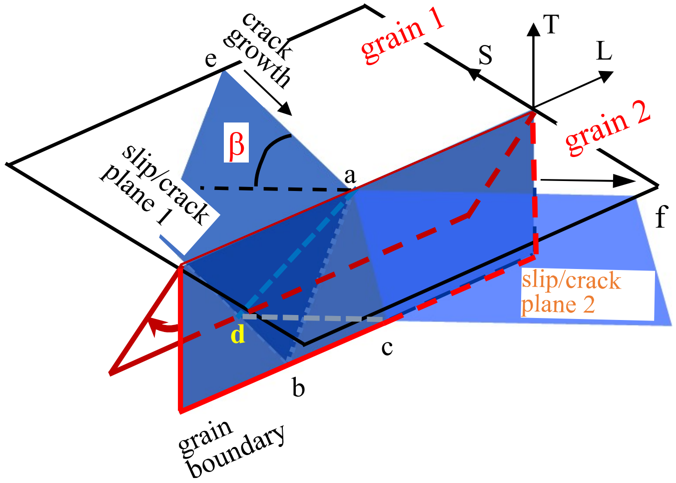
- Hot rolled→20% recrystallized small grains→ cube or Goss orientation, {100}⊥load axis, preferred sites for crack nucleation

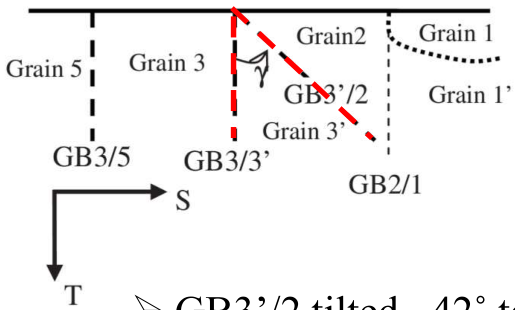
- Minimal crack deflection at GB3/3'→grain 3' had either a {111} or {001} almost parallel to the crack plane

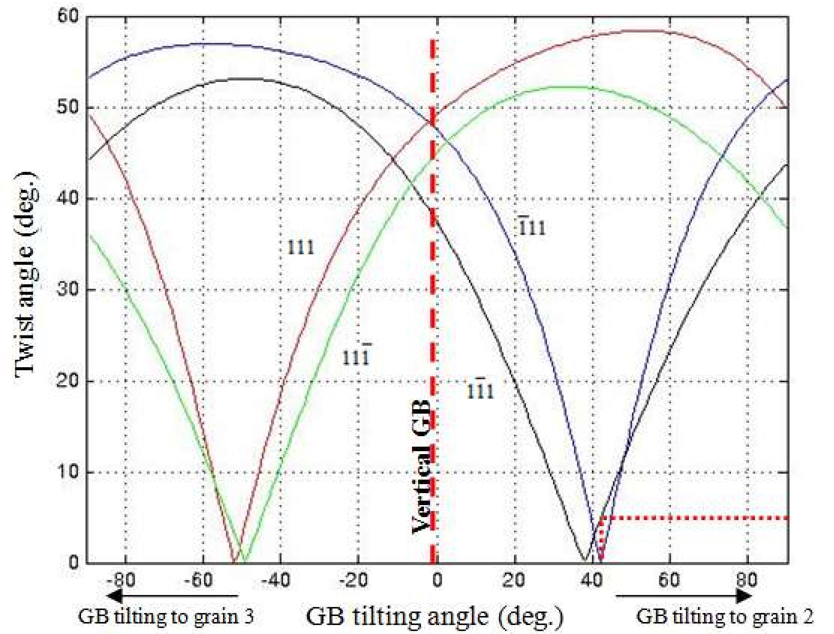
- Grain 3 & 3' together are crack initiation site, the crack plane vertical to load axis

W. Wen, T. Zhai, Philosophical Magazine, 91 (2011) 3557-3577.

Effect of GBs Plane Tilting







plot of twist angles of four slip planes in grain 2 vs. GB tilting angle

- ➢ GB3'/2 tilted ~42˚ towards to grain 2
- ➢ Reduced α of $(\bar{1}11)$ to 0, α of $(1\bar{1}1)$ is 5˚. → Grew onto $(\bar{1}11)$
- ➢ GB tilting affects α & GB resistance
- ➢ Confirmed at other GBs.

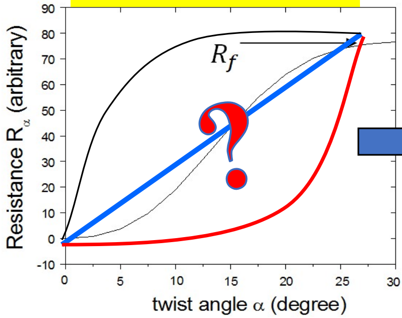
W. Wen, T. Zhai, Philosophical Magazine, 91 (2011) 3557-3577.

Overview of Quantitative Crack-growth Model

What we know now:

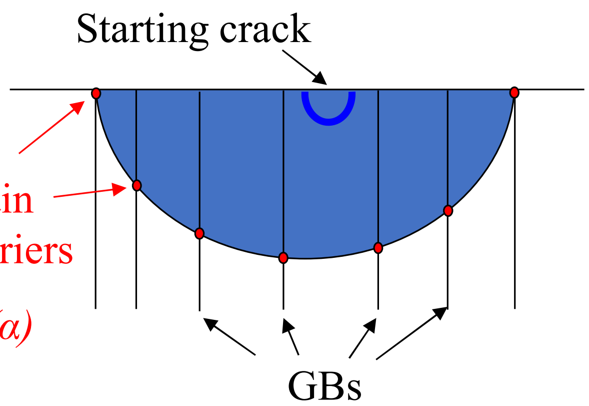
- Main resistance: GB
- α↑ → GB-resistance↑ **(qualitatively)**
- GB titling effect on α (quantitatively)

$R_i = f(\alpha)$



Main barriers

$R_i(\alpha)$



Along crack front:
Effective driving force = nominal driving force - resistance

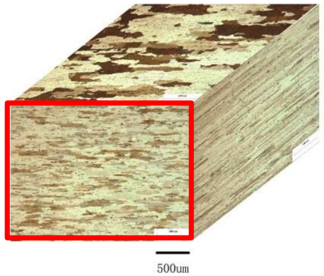
Advancement of each point along crack front

Growth rate **along the whole crack front**.

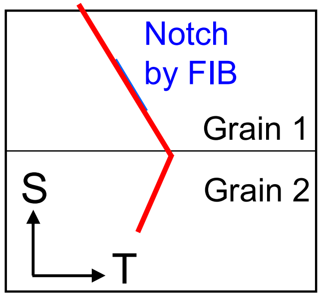
Quantify crack growth **in 3-D**, not just on surface.

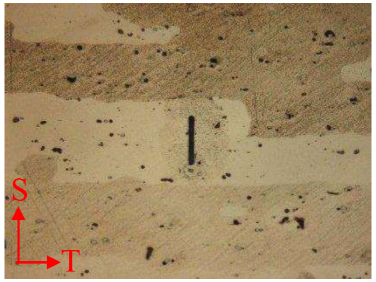
Experimental Design of Quantification: *R vs. α*

Material:
AA2024-T351 sheet
grain size ~361×97×37 μm^3
Test T-S plane, avoid GB tilting

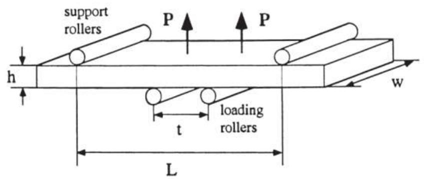


Make micro-notches before GBs in selected grains using focus ion beam (FIB)

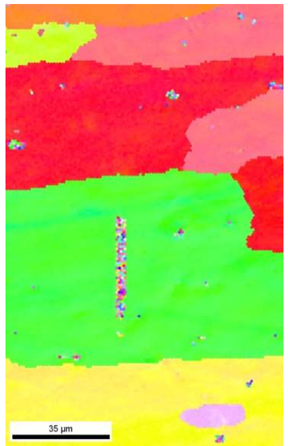




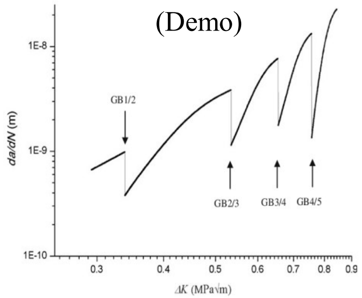
- 4-ponit bend fatigue
- $\sigma_{max} = 0.85 \sim 1.05\sigma_y$



- Monitor crack growth
- Crystal orientation (EBSD)



- growth rate da/dN
- Extract *R* at GBs



- Identify crack plane
- Calculate α at GBs

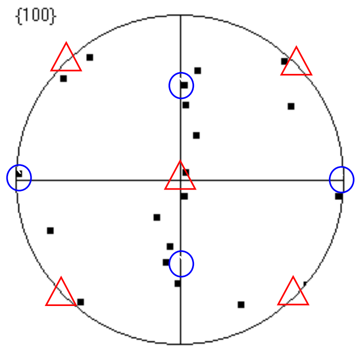
(EBSD + FIB)

Quantify *R* ~ *α*

W. Wen, A. Ngan, T. Zhai, Acta Mater., to be submitted.

Orientation of Crack-initiation Grains

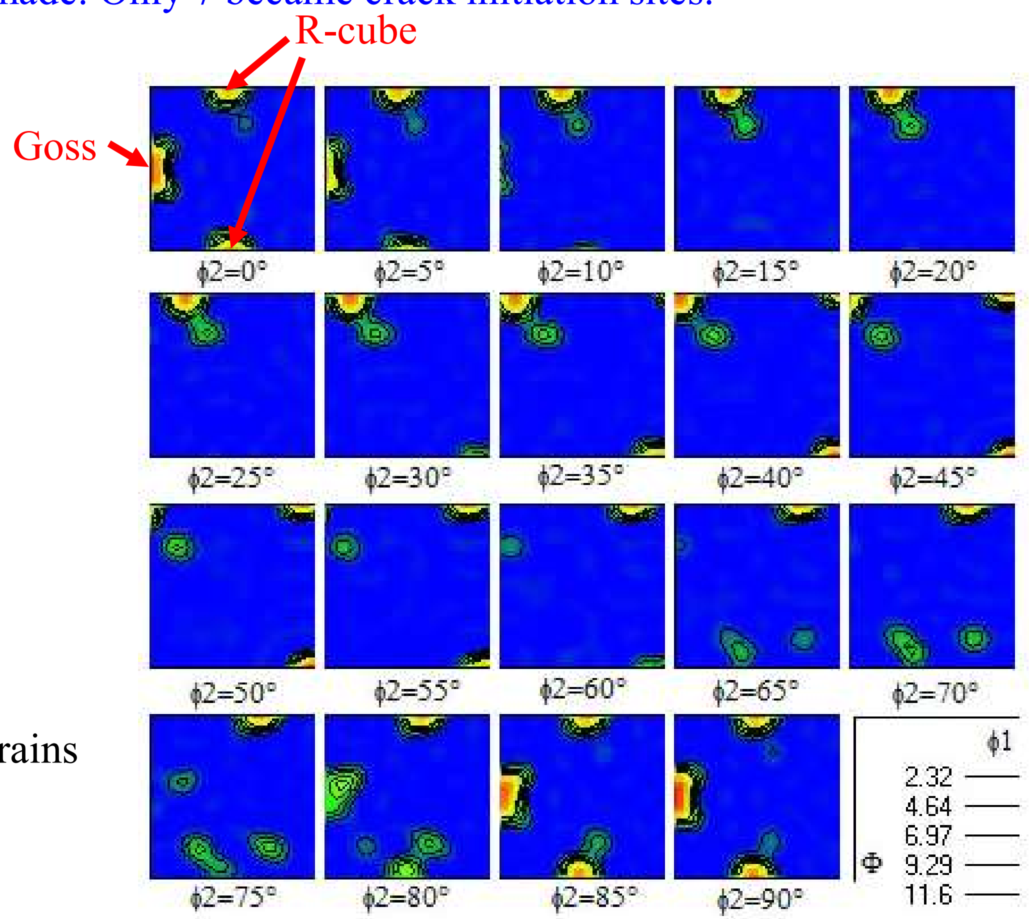
- 68 micro-notches were made. Only 7 became crack initiation sites.



△ Ideal Goss

○ Ideal R-cube

Pole figure of crack-initiation grains



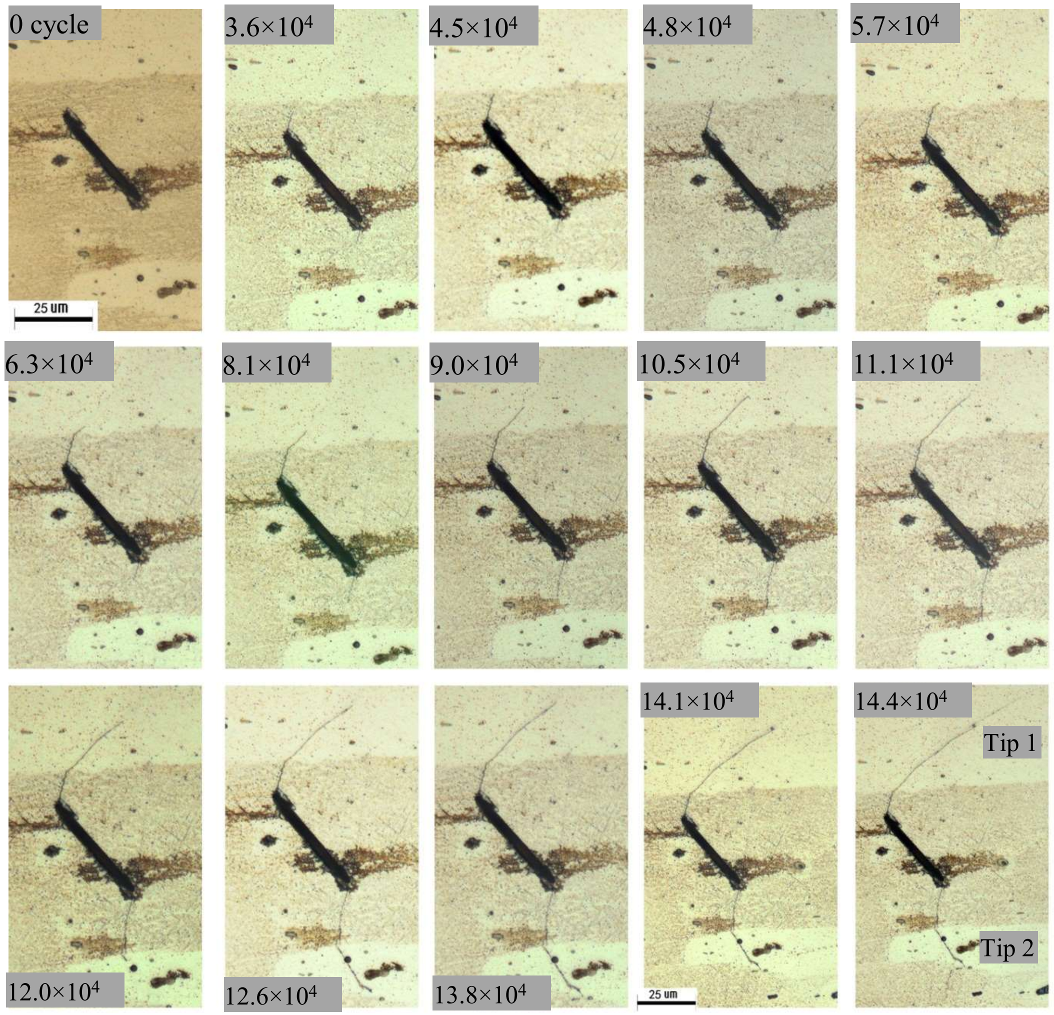
ODF of crack-initiation grains

- **Crack-initiation grains were either Goss or R-cube orientated.**
- **Soft—high Schmid factor**

W. Wen, A. Ngan, T. Zhai, Acta Mater., to be submitted.

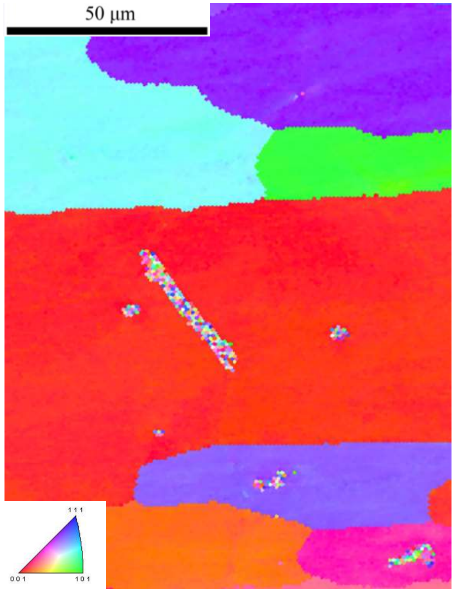
Monitoring Short Fatigue Crack Growth

- Cracks propagated crystallographically through up to 5-8 GBs (150~250 μm long).

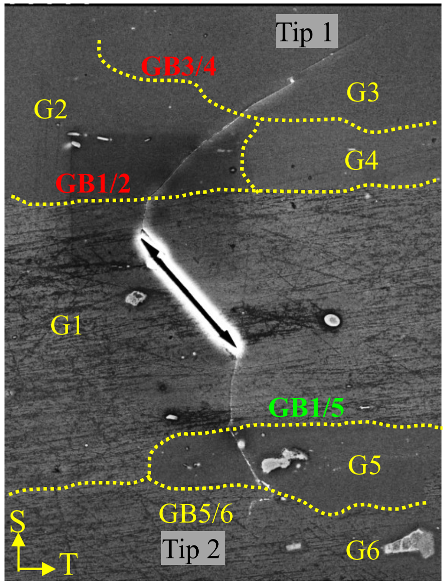


W. Wen, Pei Ca, A. Ngan, T. Zhai, *Materials Science and Engineering A*, 666, pp. 288-296.

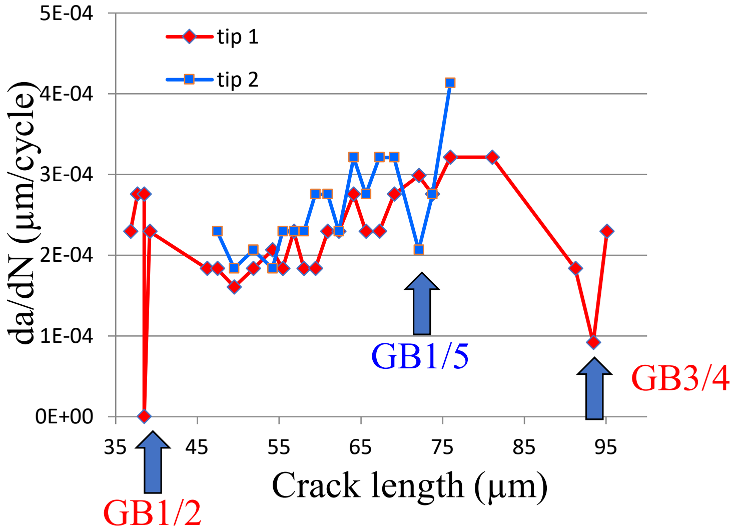
Identify GBs and Growth Rate on Surface



EBSD: IPF-L axis



SEM: GBs highlighted

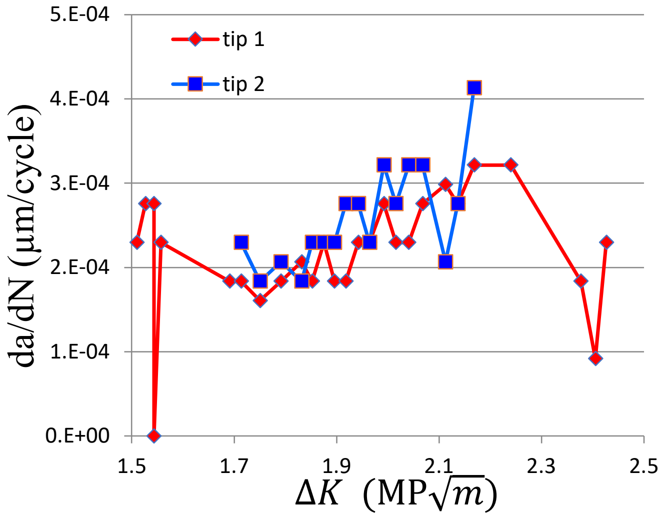


Stress intensity factor range (nominal driving force)

$$\Delta K = 2\Delta\sigma\sqrt{a/\pi}$$

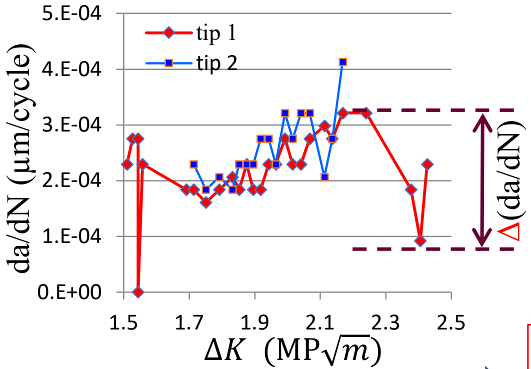
$\Delta\sigma$: stress amplitude

a: half of the crack length



W. Wen, A. Ngan, T. Zhai, Acta Mater., to be submitted.

R vs. α裂纹面旋转角



$$\left(\frac{da}{dN}\right) = C \cdot \Delta K^{m}$$ (not considering GB resistance)

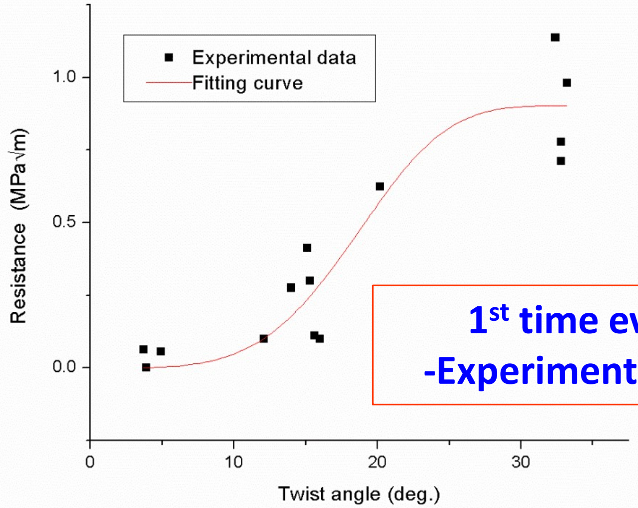
$$\left(\frac{da}{dN}\right)' = C \cdot (\Delta K - R)^{m}$$ (considering GB resistance)

$$\Delta\frac{da}{dN} = \frac{da}{dN} - \left(\frac{da}{dN}\right)'$$

$$R = \Delta K - \left(\Delta K^{m} - \Delta\frac{da}{dN}/C\right)^{1/m}$$

C=1.89E-7 mm/cycle , m=2.73, obtained by fitting growth rate curve of long crack in 2024-T351

(C. Blochwitz and R. Richter: Eng. Mater. Struct., 1999, vol. 267, pp. 120–29.)



1st time ever in the world
-Experimental Quantification !

R~α defined by a two-parameter Weibull function.

$$R(\alpha) = 0.9\,\{1 - \exp[-(\alpha/20.1)^{4.2}]\}$$

W. Wen, Pei Ca, A. Ngan, T. Zhai, *Materials Science and Engineering A*, 666, pp. 288-296.

材料的疲劳裂纹源密度和强度分布

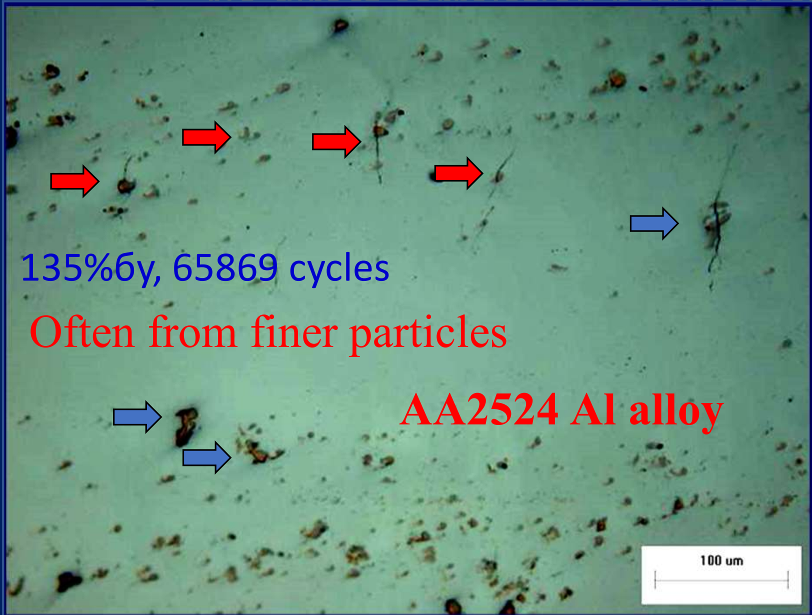
- **疲劳裂纹源密度和强度分布-有效的疲劳性能**
  - 高周疲劳性能（应用）：高铁、大飞机等
    - 裂纹萌生寿命90%-99%全寿命
    - 裂纹源密度越低，抗疲劳性能越好
  - 材料质量控制重要参数（材料制造）
- **需要研究工作**
  - 实验测量?
  - 定量模拟?
  - 各向异性、与微观组织结构关系?

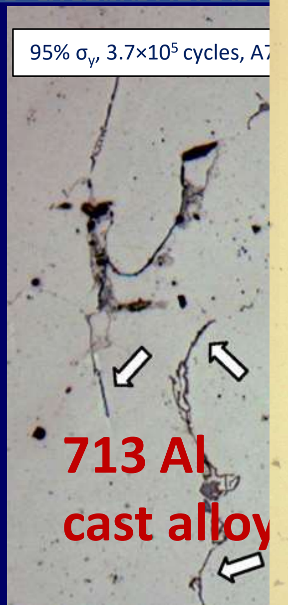
Multi-site Fatigue Crack Nucleation in Al alloys

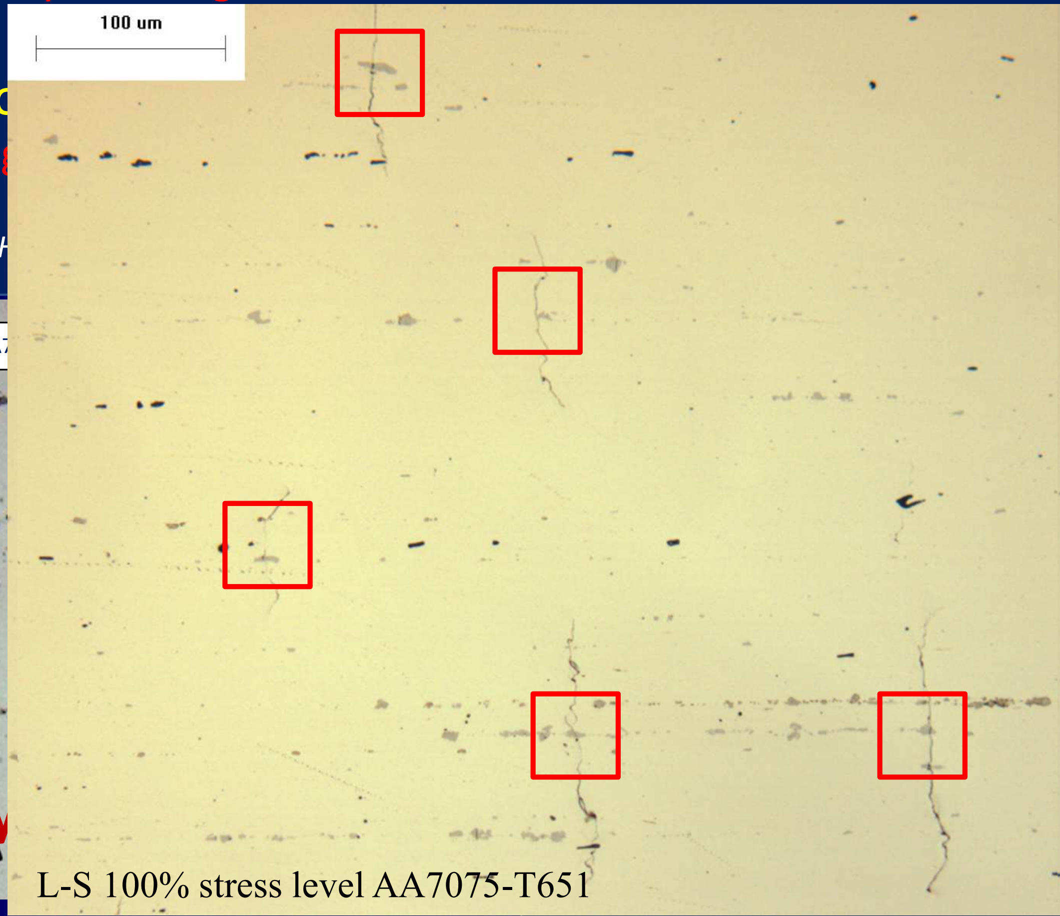
- Microstructural heterogeneities: inclusions, pores, particles, grain/phase boundaries, etc.
- Multi-site nucleation ➡ Crack initiation site density & strength distribution?
- Most become non-propagating ➡ reason?
- Coarser particles/pores unnecessarily initiatio
  - Crack initiation sites identified using FEA assuming typically elastic-plastic

J.E. Bozek, D.G. H

- No direct correlation between size distribution





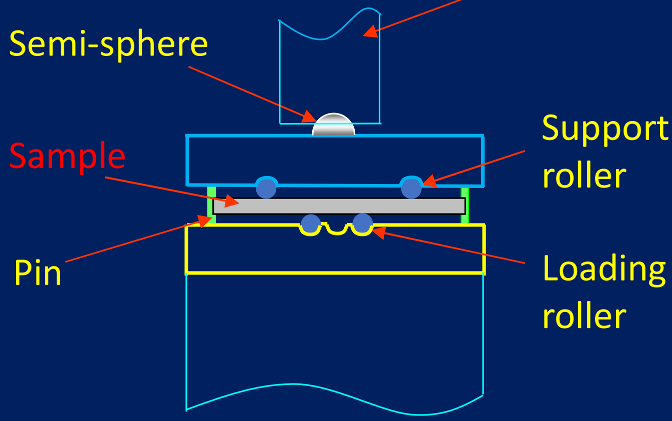


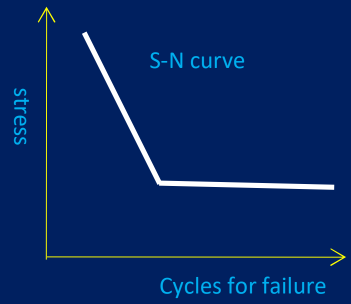
An Experimental Method to Characterize Fatigue Weaklinks

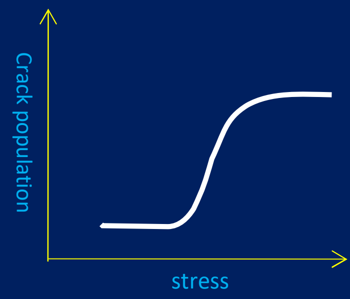
- Important fatigue properties
  - Fatigue crack initiation: 60%-99% total life
  - Useful in design for optimum microstructure, quality control and evaluation of materials properties
- Desirable to quantify FWLs
  - Experimental characterization
  - Theoretical modeling

- Four point bend fatigue testing, Load controlled, R=0.1, f=20 Hz, room temperature
- Maximum stress varies to measure the life
- Sample surface well polished
- Crack population measured at each stress

Self-aligning four point bend rig







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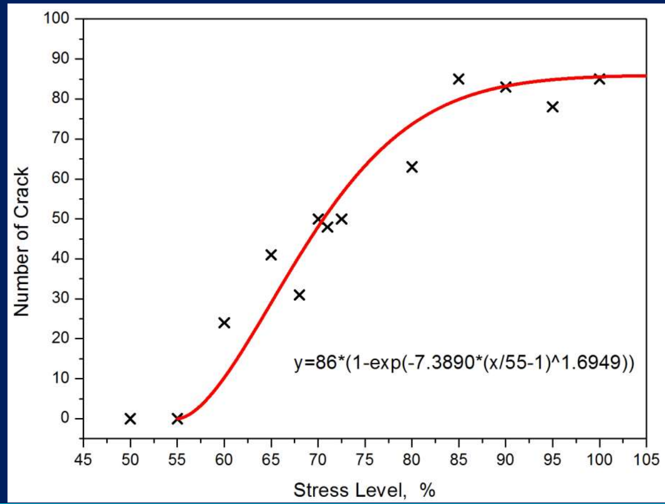
Weibull Function of Fatigue Weakest-links

- Crack number vs. stress curve can be described by 3-parameter Weibull function,

$$N = N_0\left(1 - \exp\left[-k\left(\frac{\sigma - \sigma_0}{\sigma_0}\right)^m\right]\right)$$

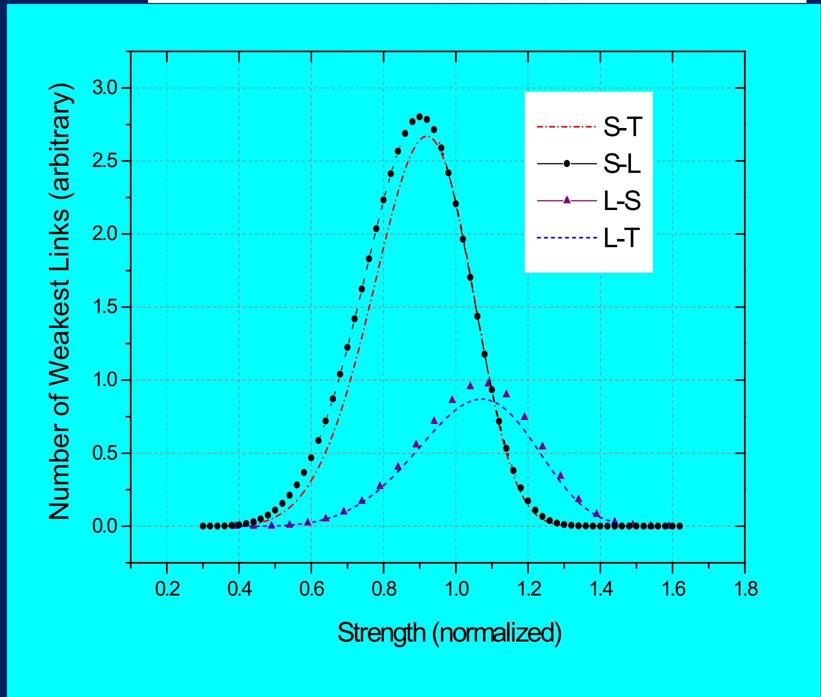
  - N_0: the number of cracks in the surface area of 10×6 μm^2 at the stress level close to the ultimate tensile strength (σ_s), i.e., FWL number density (N_0/(10×6 μm^2)).
  - k: constant, m: Weibull modulus,
  - σ_0: fatigue limit



Strength Distribution of Fatigue Weakest-links

$$n = CN_0\left(\frac{km}{\sigma_0}\right)\left(\frac{\sigma - \sigma_0}{\sigma_0}\right)^{m-1}\exp\left[-k\left(\frac{\sigma - \sigma_0}{\sigma_0}\right)^m\right]$$

Fatigue weakest link density and strength distribution are materials properties



Summary

- The resistance against crack growth at GBs can be quantified experimentally, which has paved a way for computing short crack growth behaviors.
- In an over-aged AA7050 Al alloy, the resistance against crack growth across grain boundaries is as high as 4-5 times as along GBs.
- The density and strength distribution of crack initiation sites can be quantified experimentally, which are important fatigue properties of a material. 裂纹源密度和其强度分布-材料的重要疲劳性能，实验方法应该制定国家标准，确定中国在关键过程材料应用的话语权！
- The effects of moisture and the anisotropy of crack site density can be quantitatively studied.