SAND2013-3213P

Nanocrystalline alloys: Impervious to Fatigue Failure?

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April 19th , 2013

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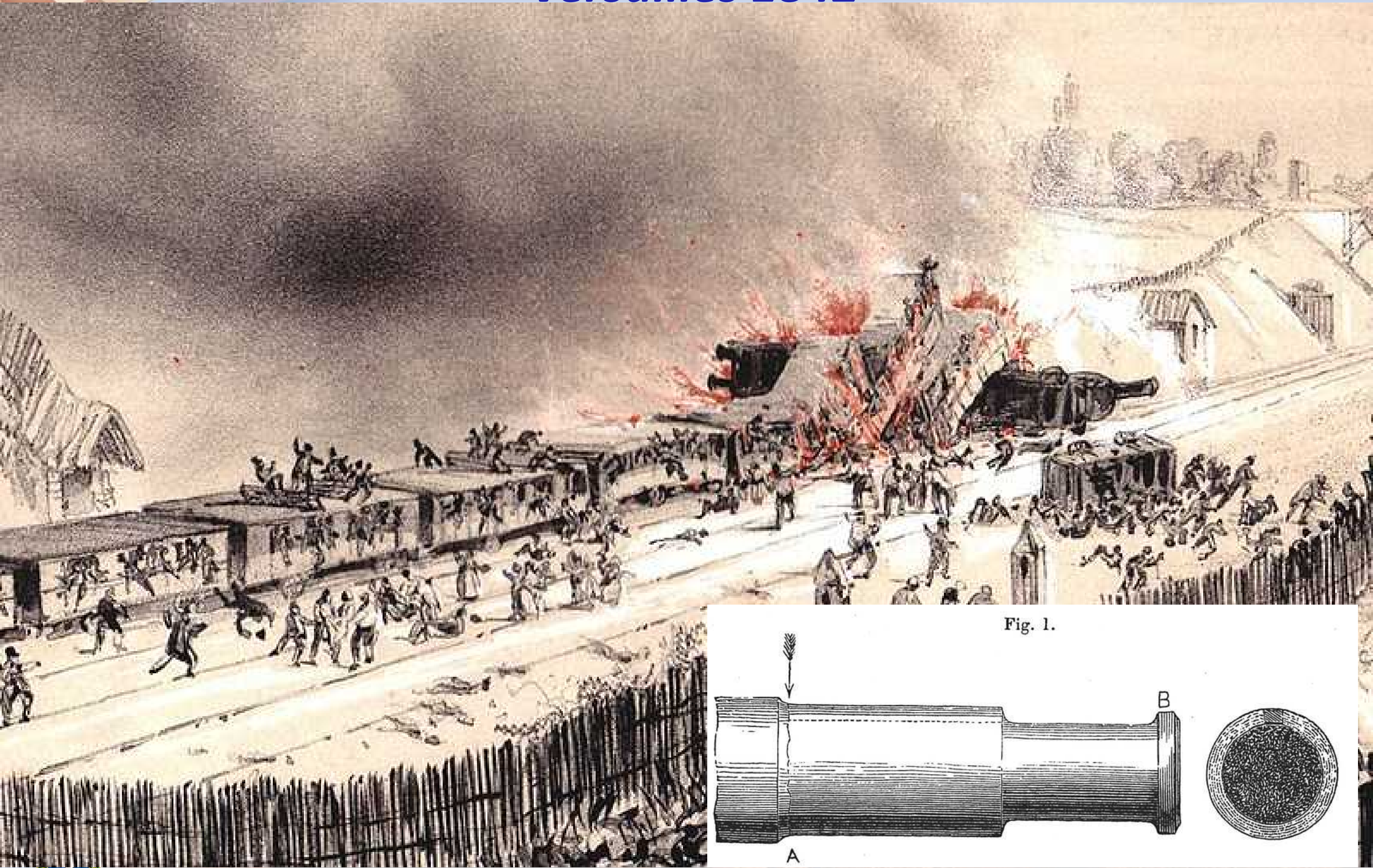
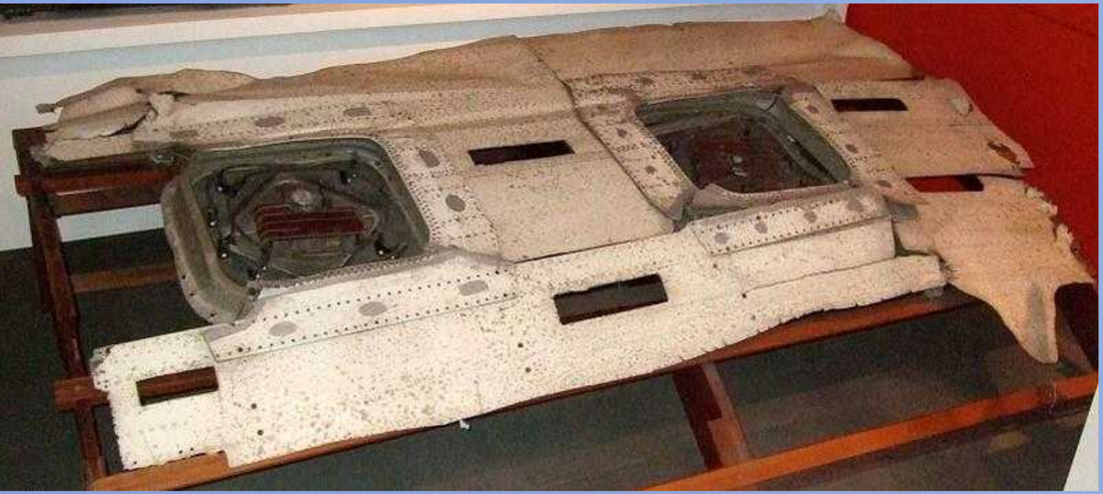
Versailles 1842



by Joseph Glynn, 1843

De Havilland Comet, 1953-4



Aloha Airlines, 1988

4-28-1988 After 89,090 flight cycles on a 737-200, metal fatigue lets the top go in flight.

The New York Times

Pentagon Orders F-35 Jets Grounded

Michael Spooneybarger/Reuters

An inspection found a crack in a turbine blade in the engine of one of the planes.

By CHRISTOPHER DREW
Published: February 22, 2013

The Pentagon said on Friday that it had grounded all of its stealthy new F-35 fighter jets after an inspection found a crack in a turbine blade in the engine of one of the planes.

The Pentagon office that runs the program said the crack in the turbine blade was discovered on Tuesday in a routine inspection. The crack occurred on a test plane at Edwards Air Force Base in California. The blade is being shipped to a plant in Connecticut, where the engine manufacturer, Pratt & Whitney, will inspect it and look for the problem's cause.

Background Concepts: What is fatigue?

"…Changes in properties which can occur in a metallic material due to the repeated application of stresses or strains, although usually this term applies specially to those changes which lead to cracking or failure…"

General Principles for Fatigue Testing of Metals, International Organization for Standardization, Geneva, 1964.

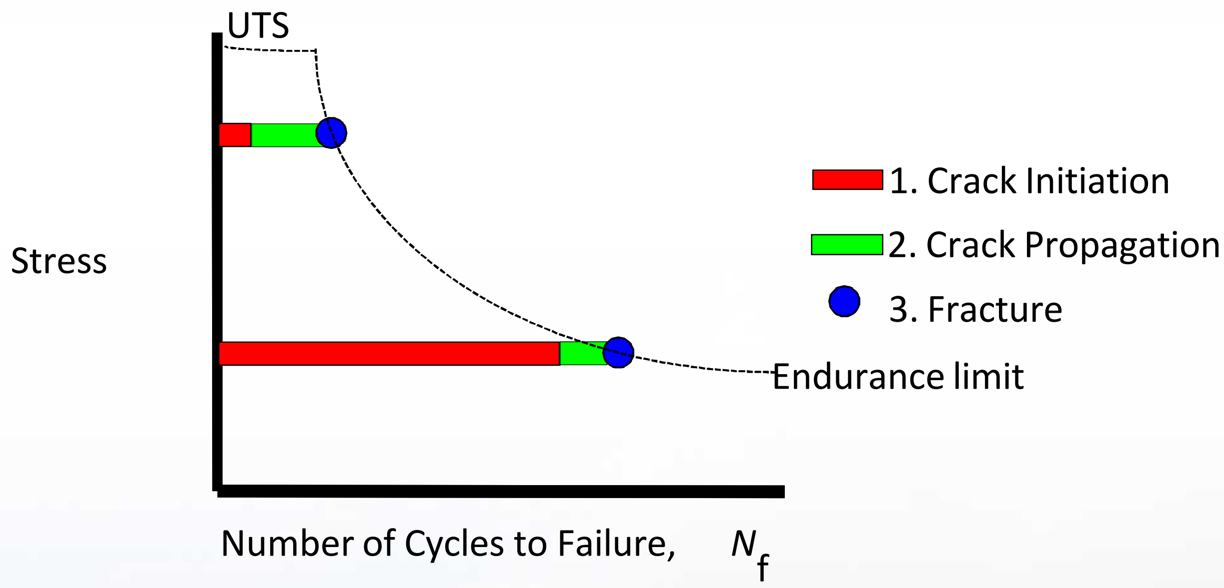
Fracture and Fatigue cost U.S. economy an estimated $119 billion.

The Economics Effects of Fracture in the U.S., U.S. Dept. of Commerce, 1982.

70-90% of all structural fractures result from cyclic damage accumulation (fatigue).

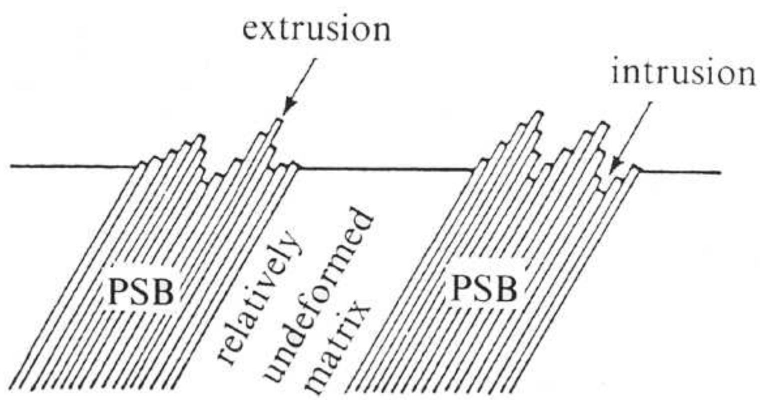
Fatigue occurs in metals, polymers, ceramics, and composites, although the mechanisms can differ between classes.

Background Concepts: Fatigue Life

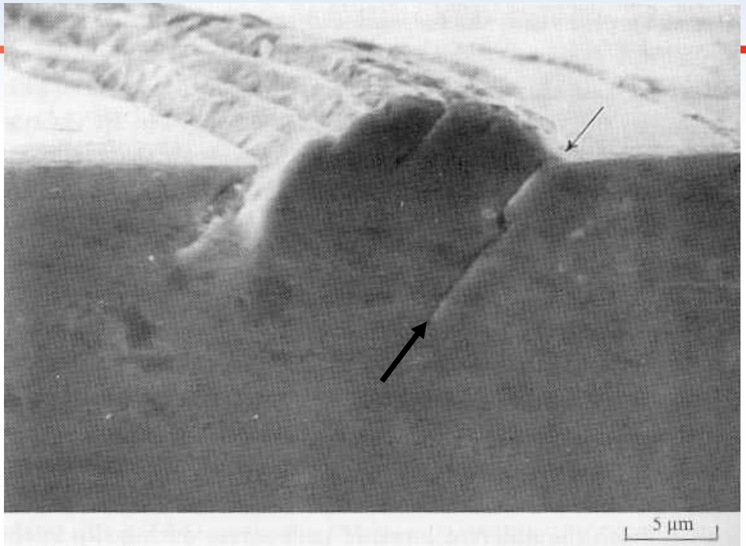


The S-N approach was originally described by Wöhler, 1860; Basquin 1910

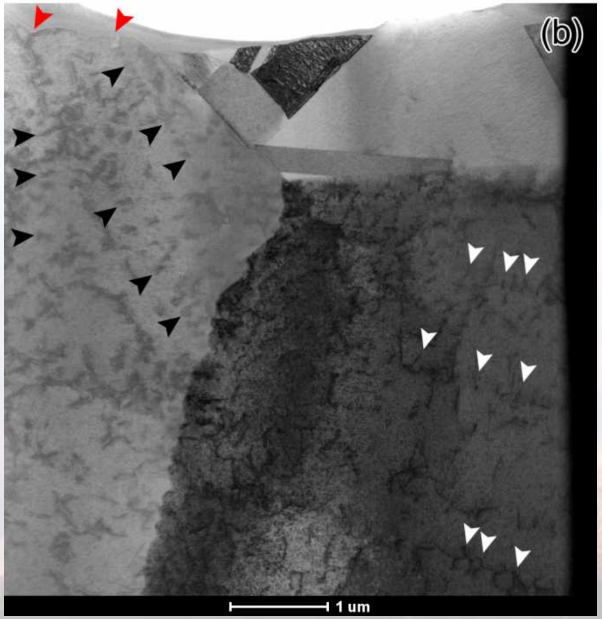
In the absence of pre-existing defects, fatigue crack nucleation occurs by a persistent slip band process



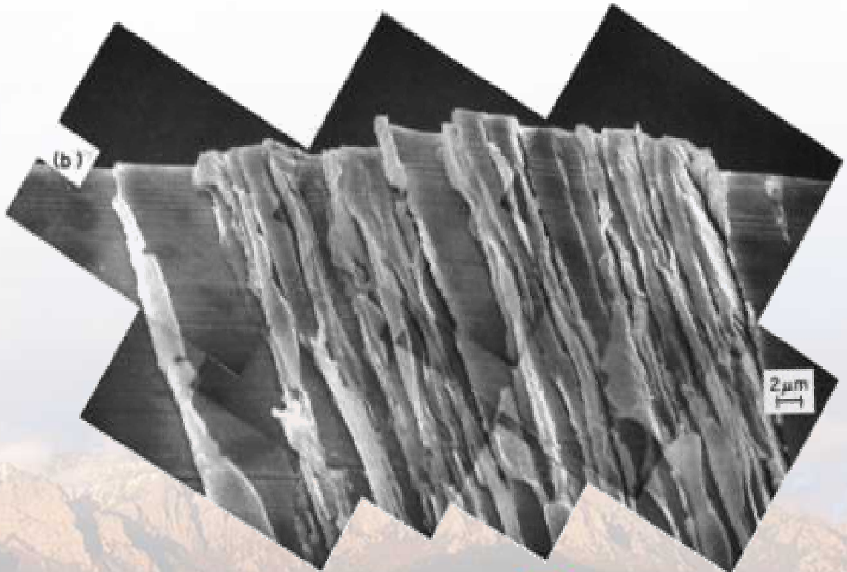
S. Suresh, Fatigue of Materials



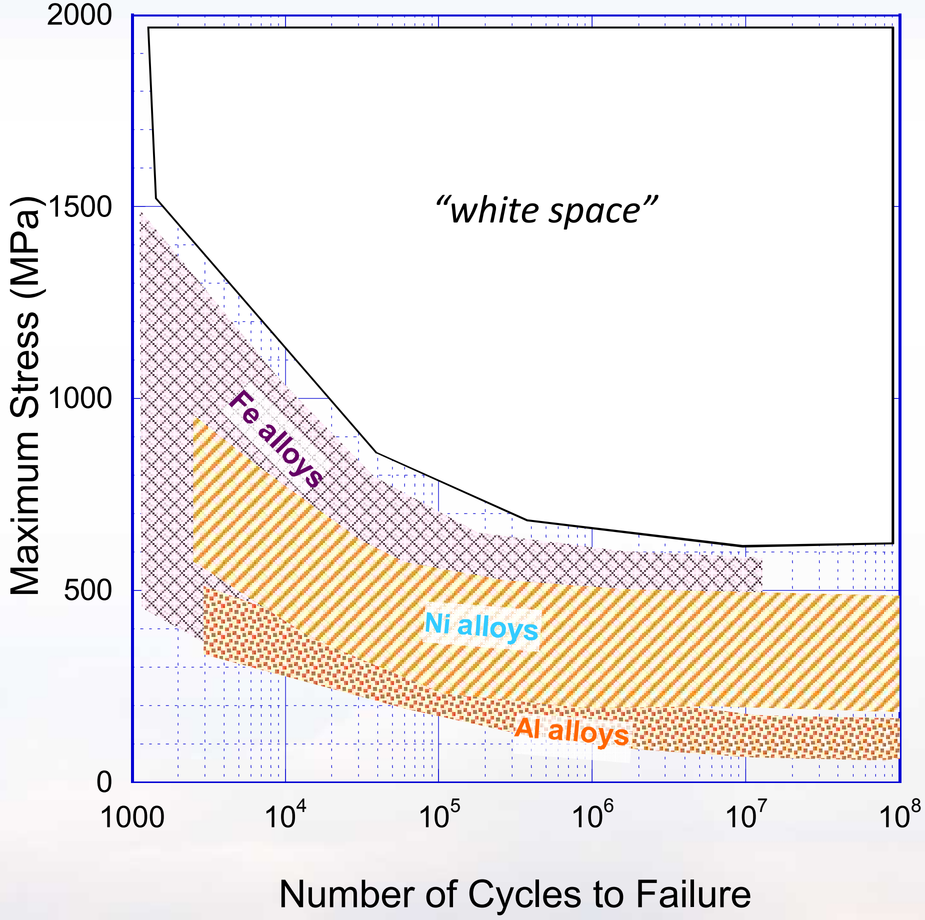
Ma and Laird, 1989



Boyce & Padilla, Metall. Mater. Trans. A, 2011

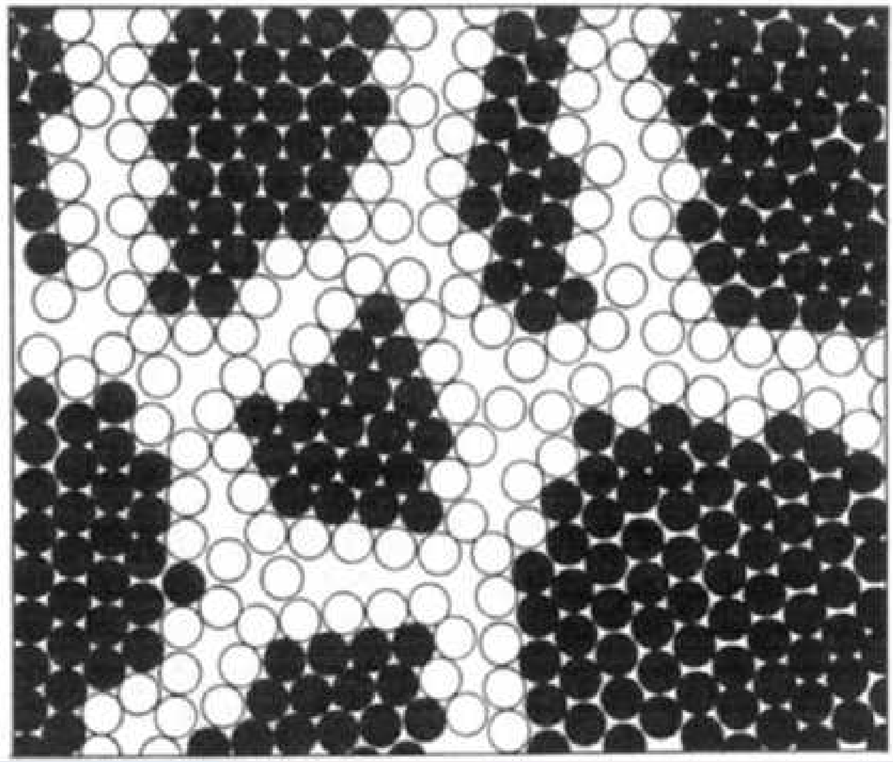


Fatigue Life in Engineering Alloys



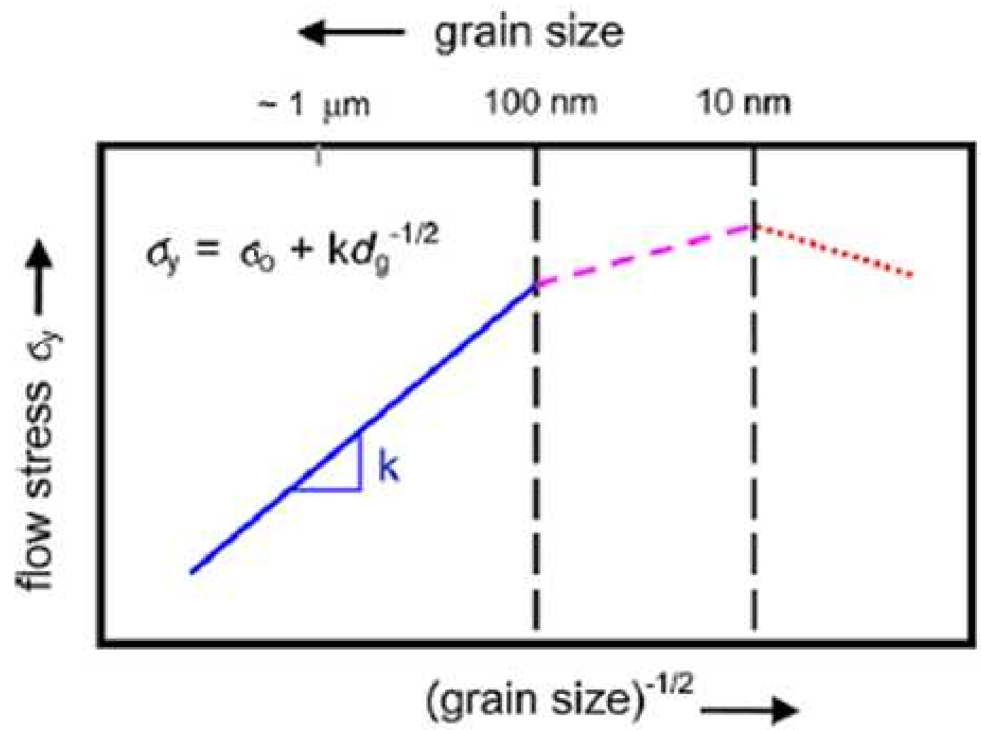
Nanocrystalline metals possess excellent strength

1989
Gleiter
Nanocrystalline Materials



>2000 citations

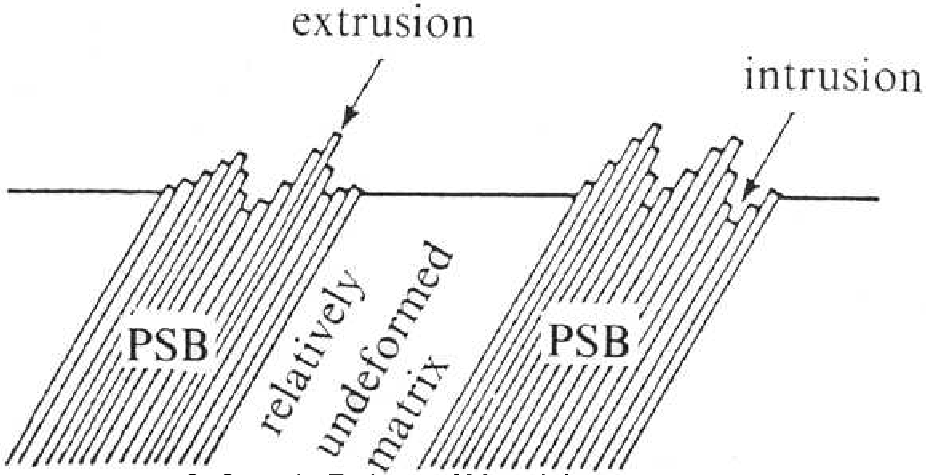
2003
Kumar, VanSwygenhoven Suresh
Hall-Petch Breakdown



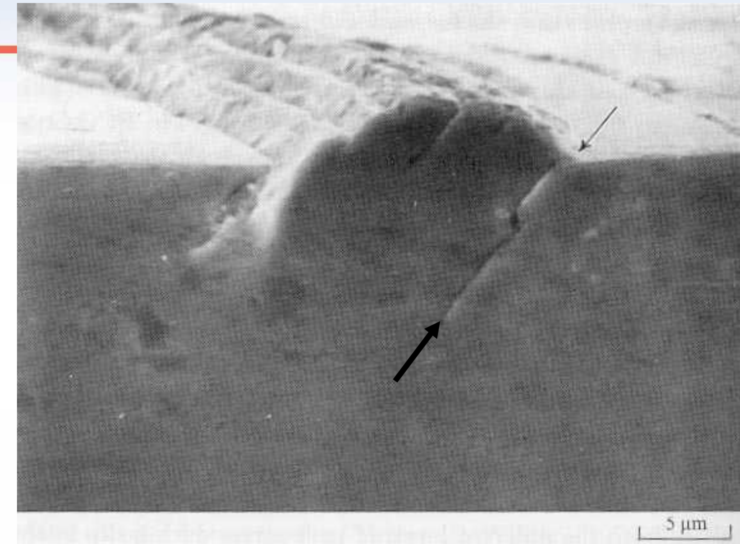
>400 citations

…what about their fatigue resistance???

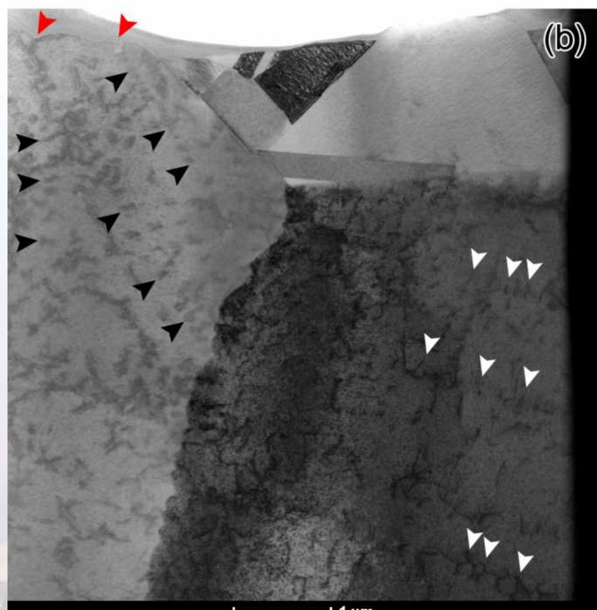
Hypothesis: the small grain size of nanocrystalline *metals suppresses persistent slip crack initiation processes*



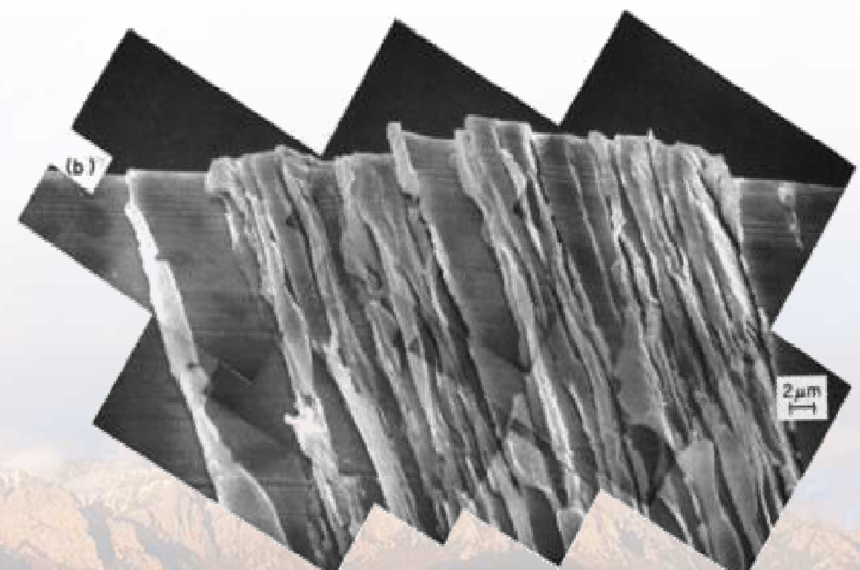
S. Suresh, Fatigue of Materials



Ma and Laird, 1989



Boyce & Padilla, Metall. Mater. Trans. A, 2011



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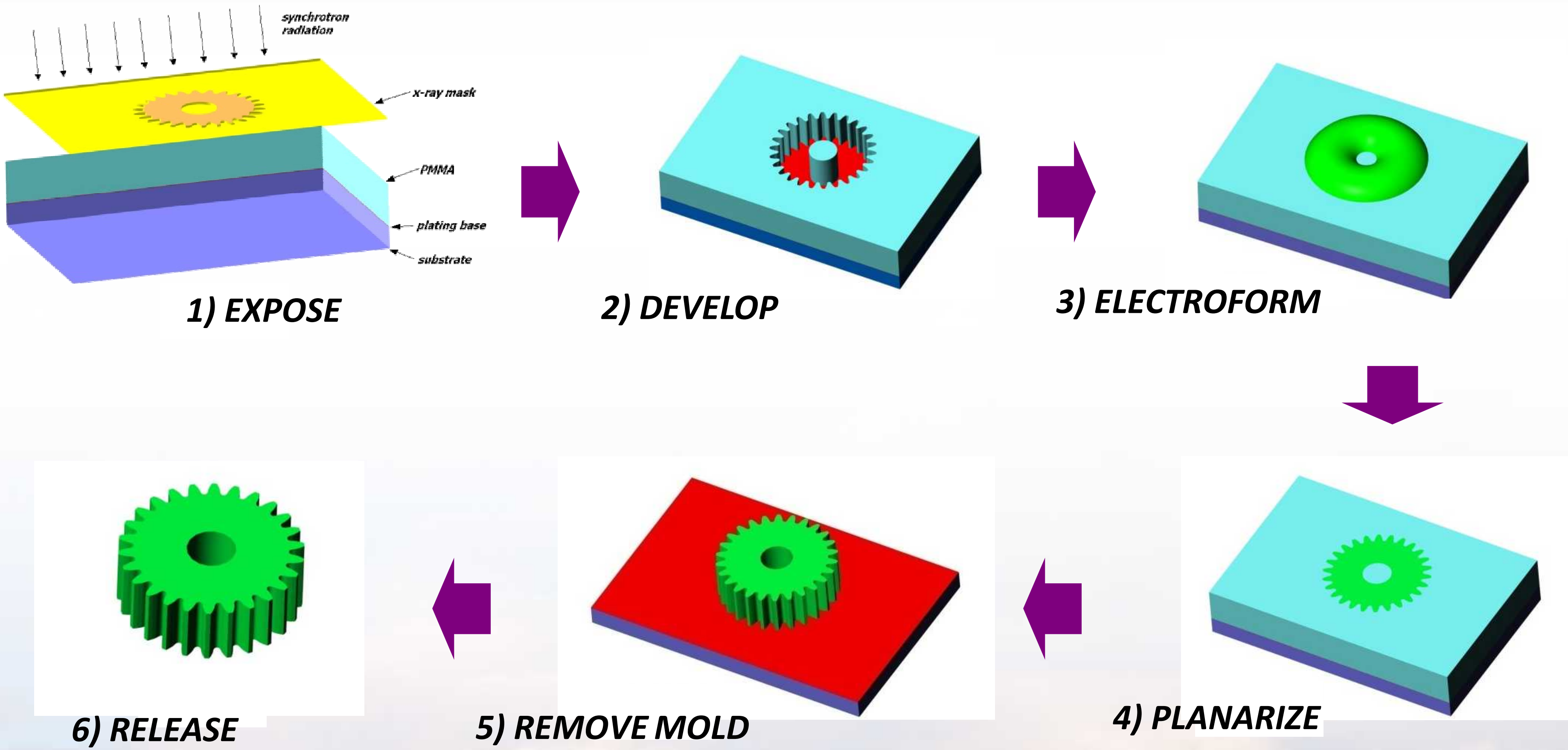
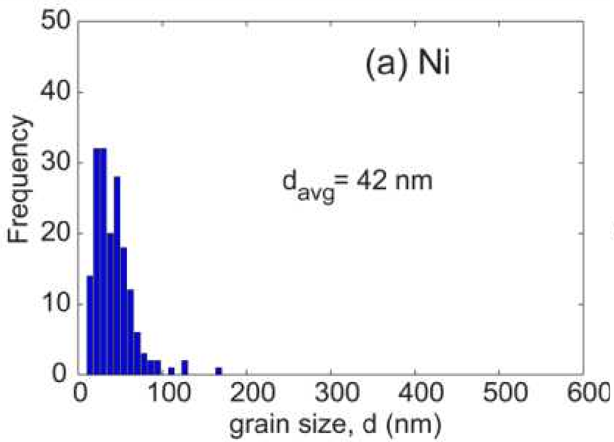
The Direct LIGA Process for Metallic Microdevices



Three Nanocrystalline Ni-Based Alloys

Ni

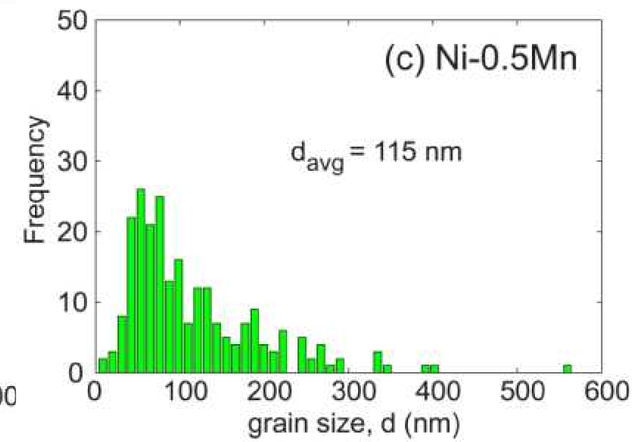


impurities

Yield ~ 1200 MPa

<200> + <111> very weak texture

Ni-0.5Mn

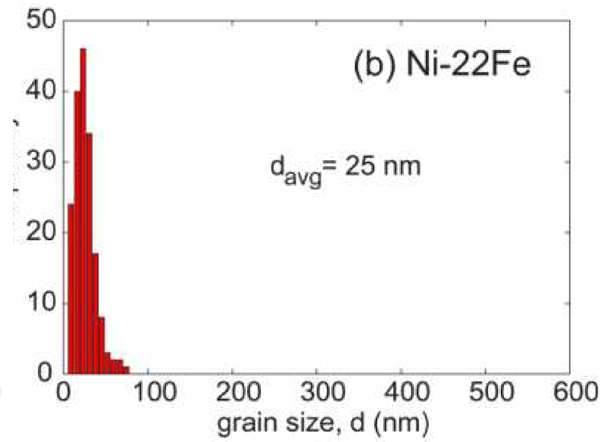


nanoprecipitates

Yield ~ 1200 MPa

<220> texture

Ni-22Fe

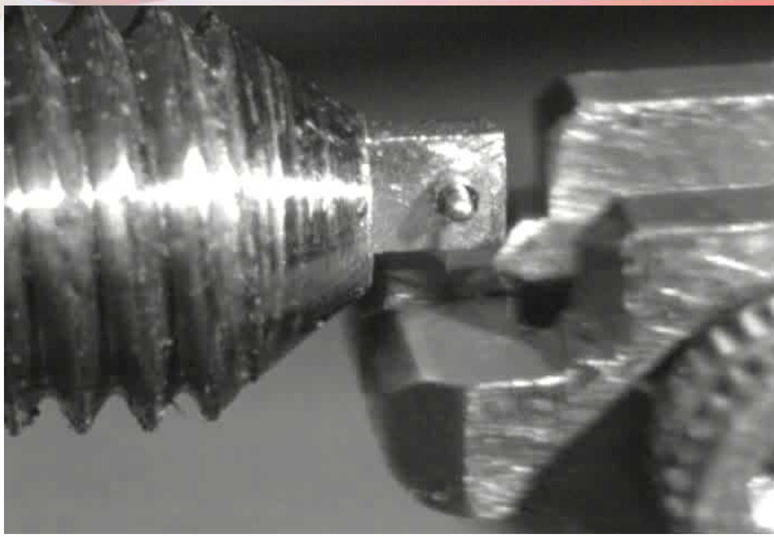


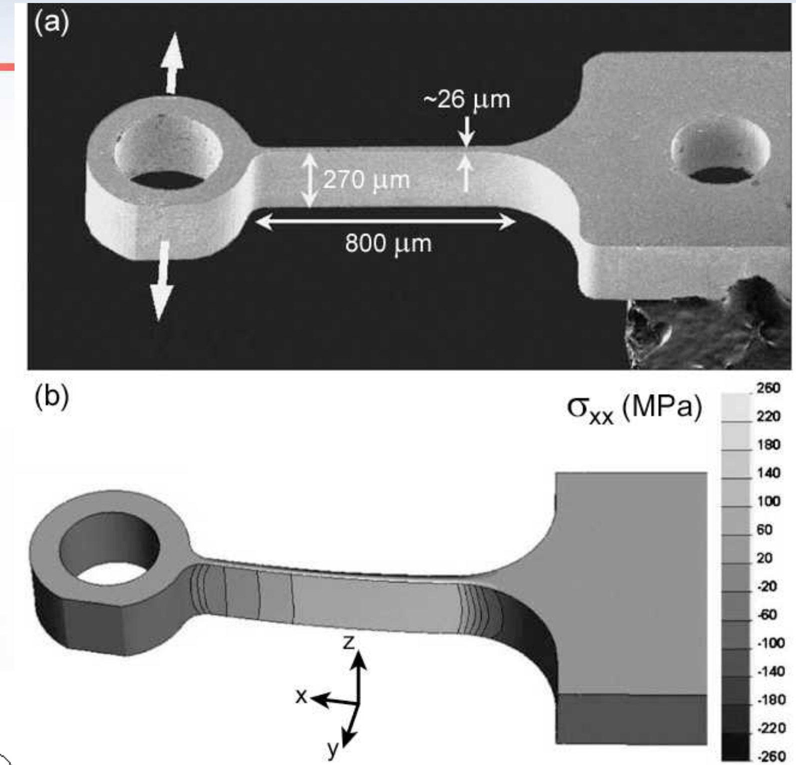
high solute content

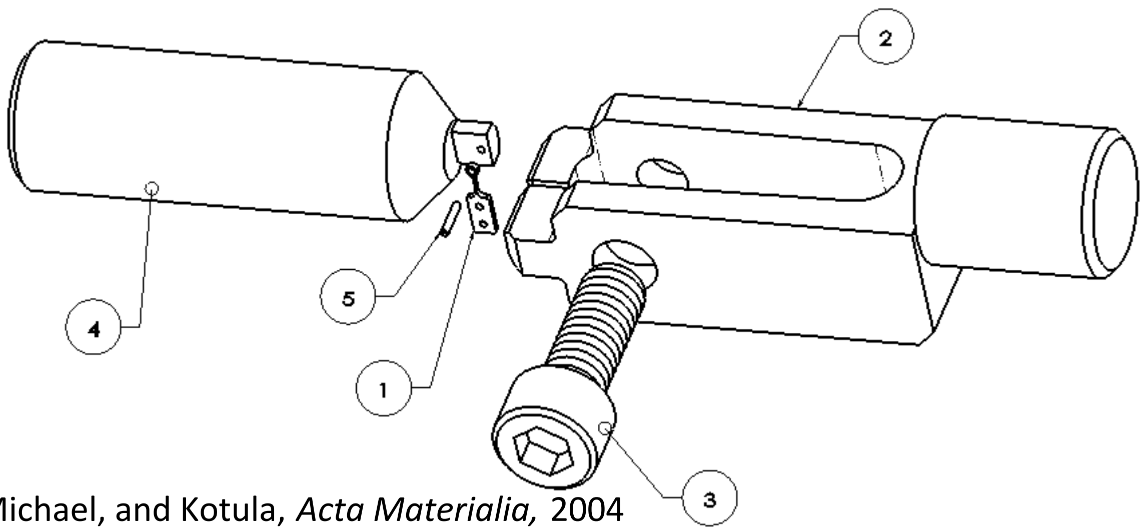
Yield ~ 1400 MPa

<200> + <111> texture

LIGA Fatigue Testing

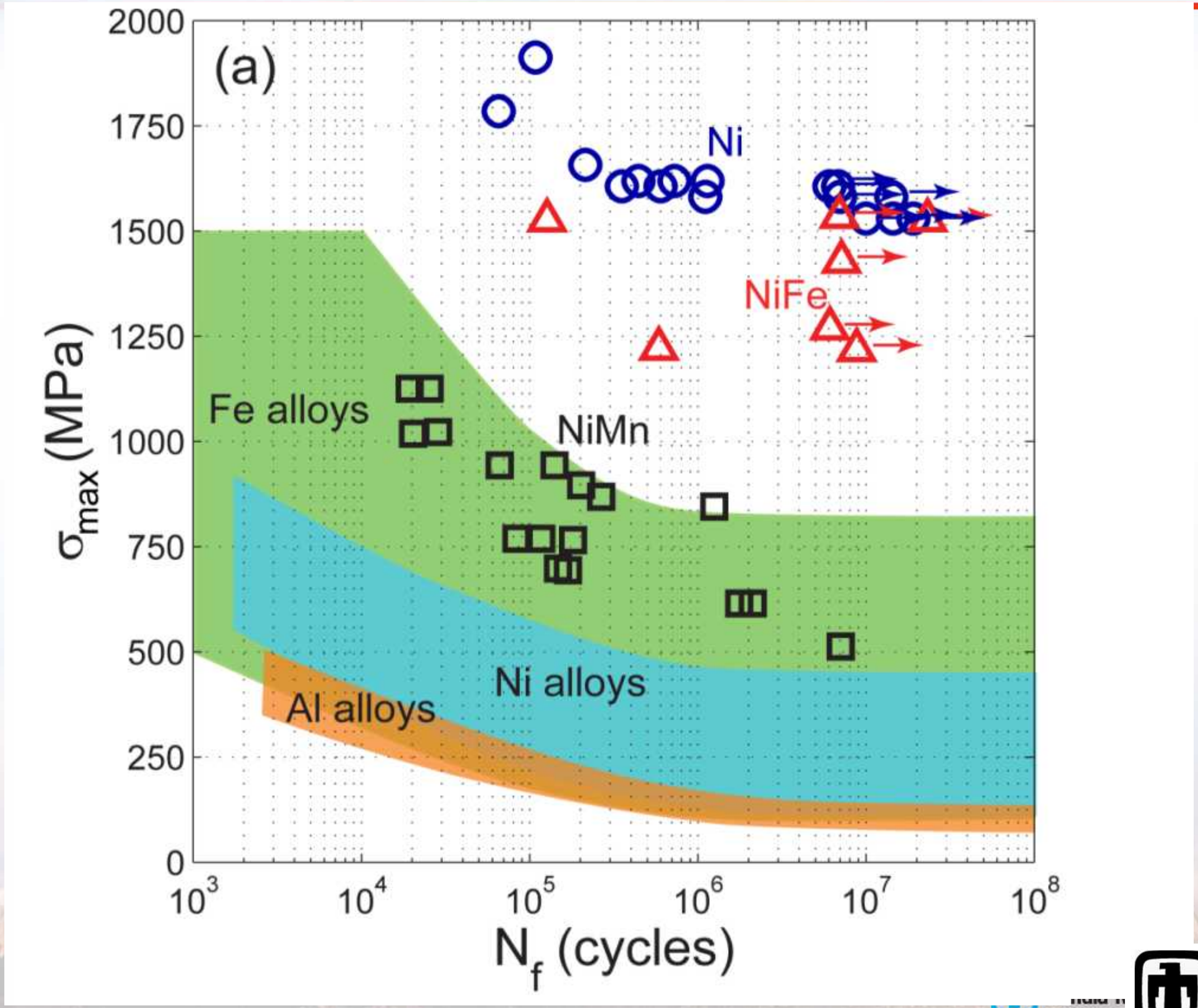






Boyce, Michael, and Kotula, *Acta Materialia,* 2004

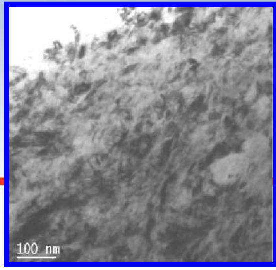
Fatigue Lifetime Results

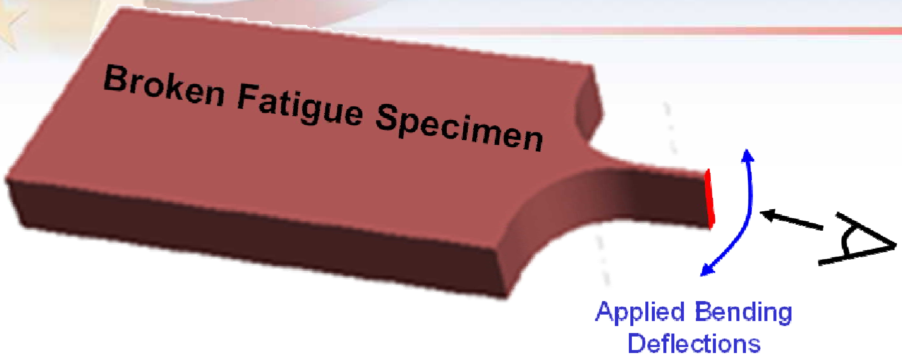


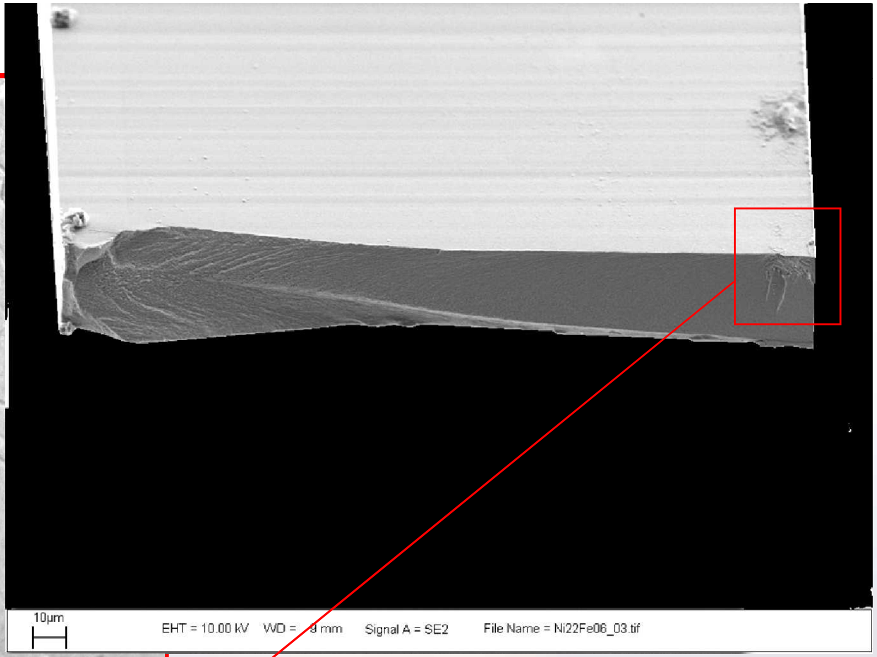
Boyce and Padilla, *Metall. And Mater. Trans. A,* 2011

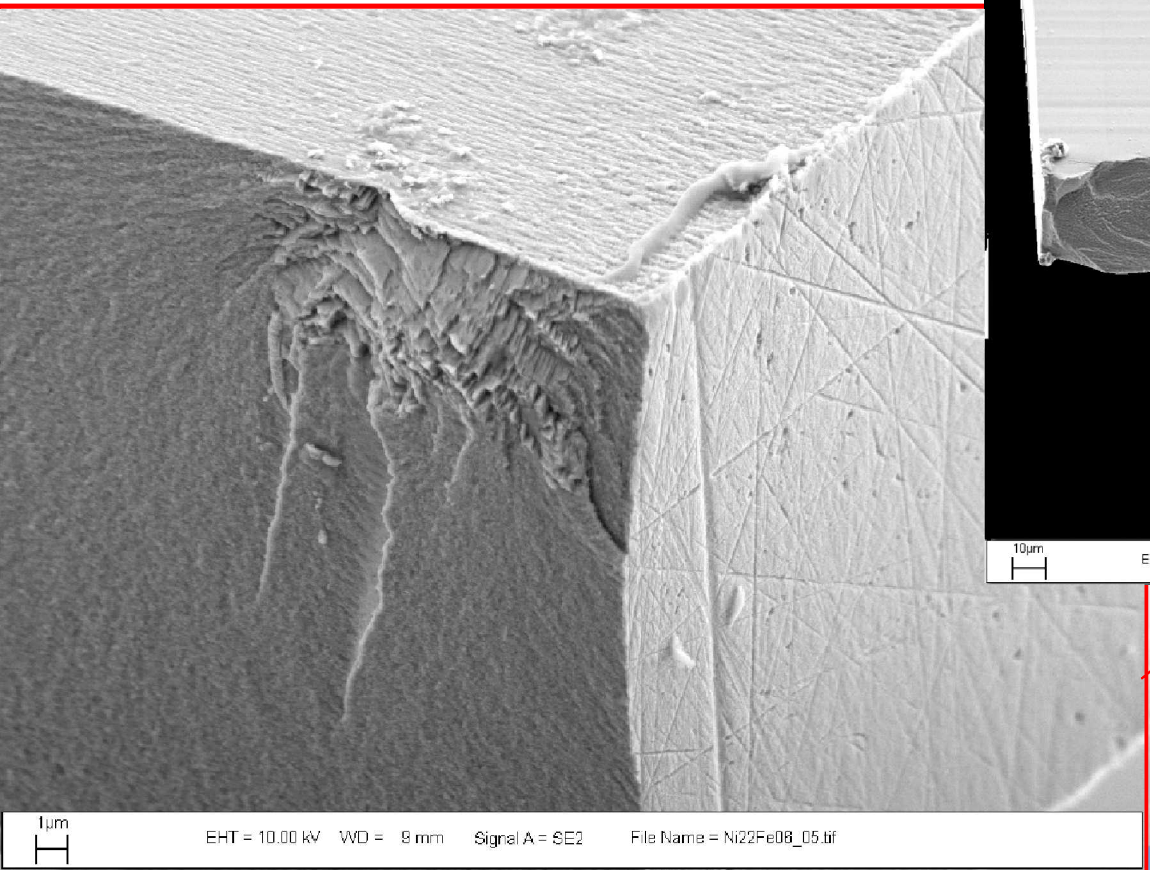
Unusual Initiation Zone In Nanocrystalline Ni-Fe Alloy

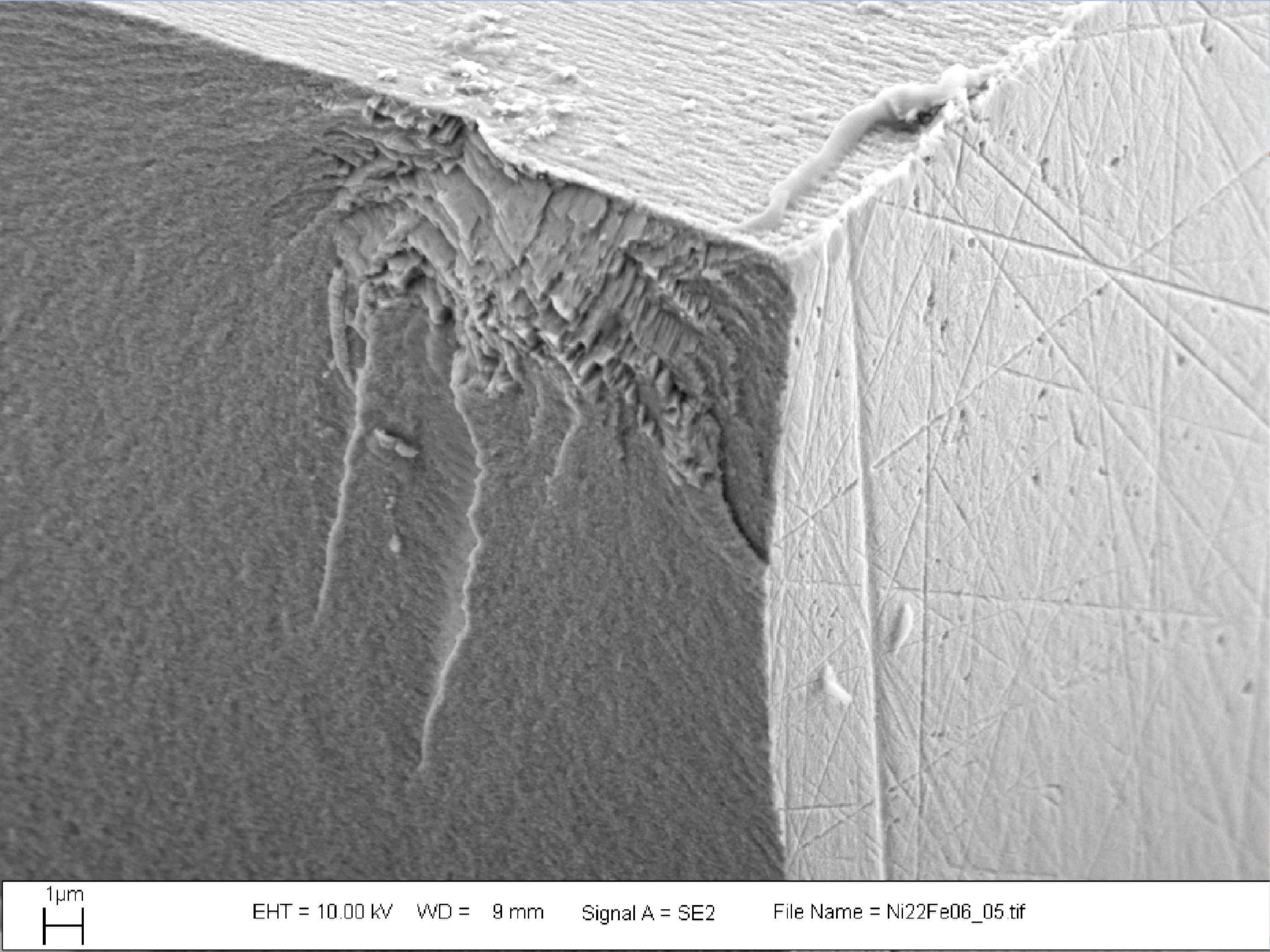
NiFe



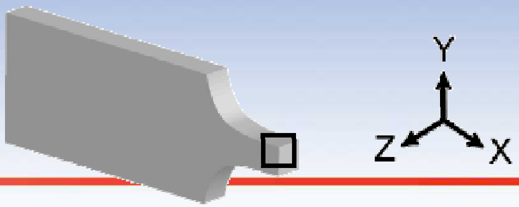


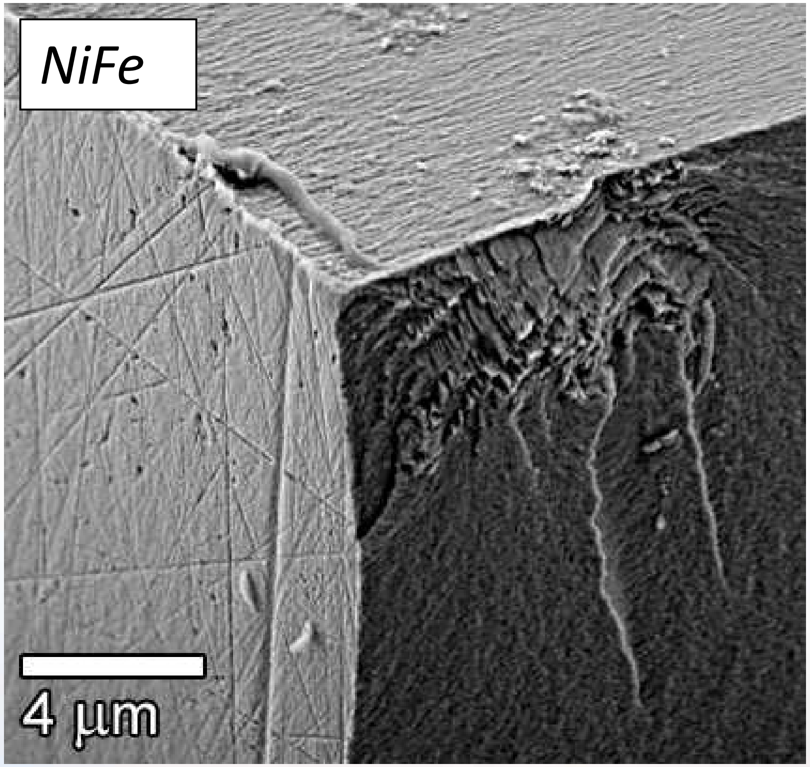


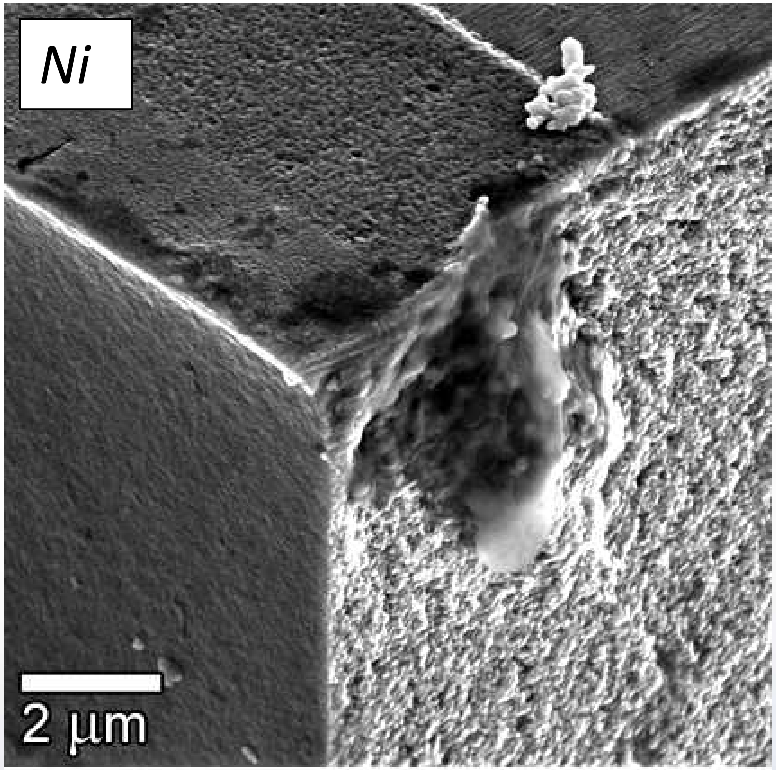



1µm
EHT = 10.00 kV
WD = 9 mm
Signal A = SE2
File Name = Ni22Fe06_05.tif

Typical Fracture Surface (SEM)



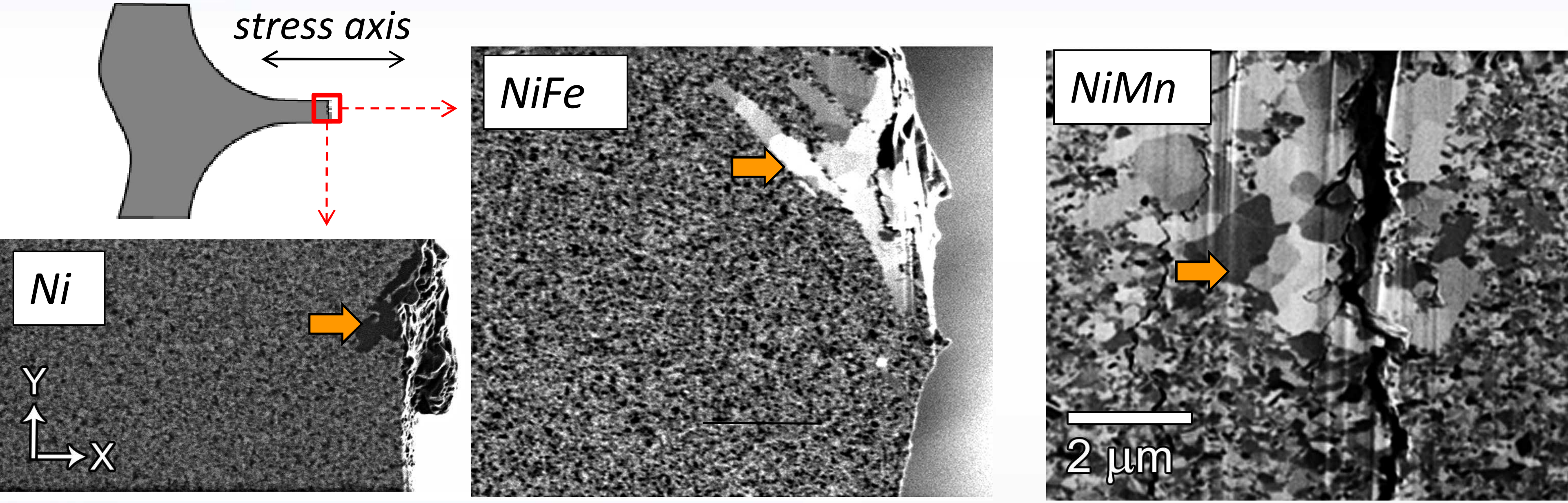




- **Initiation zone marked by large blocky features**
- **Propagation zone morphology follows NC microstructure**

Boyce and Padilla, *Metall. And Mater. Trans. A*, 2011

Microstructural Analysis (FIB)

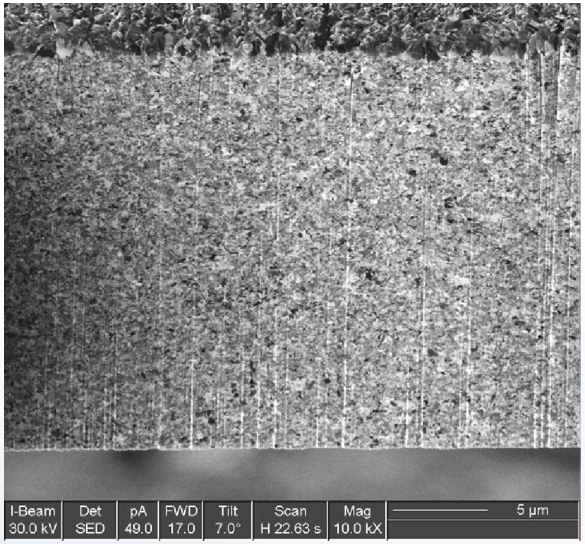


- **Fatigue-induced coarsened zone *at room temperature!***
- **Coarsened zone only forms locally (abnormal grain growth) in regions of maximum stress, prior to crack initiation**
- **No coarse grains found in as-deposited samples**
- **No coarse grains found in monotonically stressed samples**

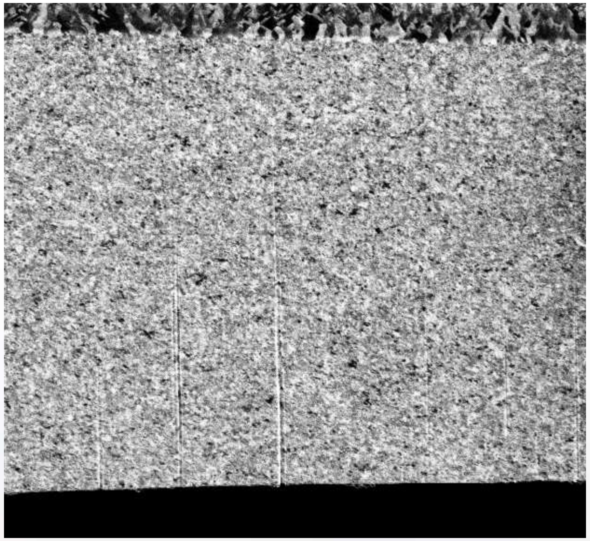
Boyce and Padilla, *Metall. And Mater. Trans. A*, 2011

Grain growth is induced by fatigue

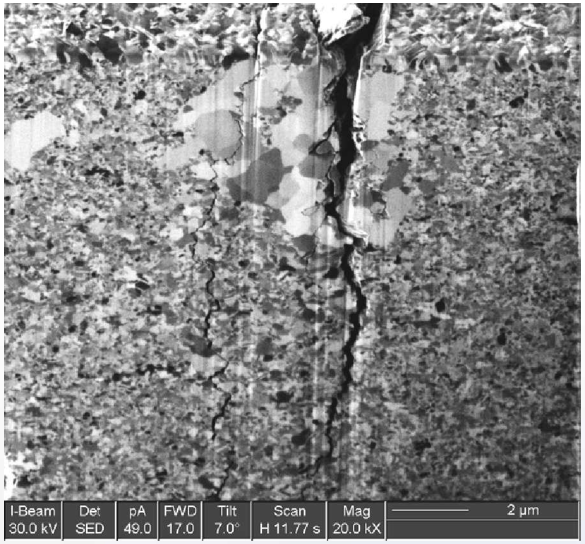
As-Deposited



After 1 Cycle



After ~100,000 Cycles



Boyce and Padilla, *Metall. And Mater. Trans. A*, 2011

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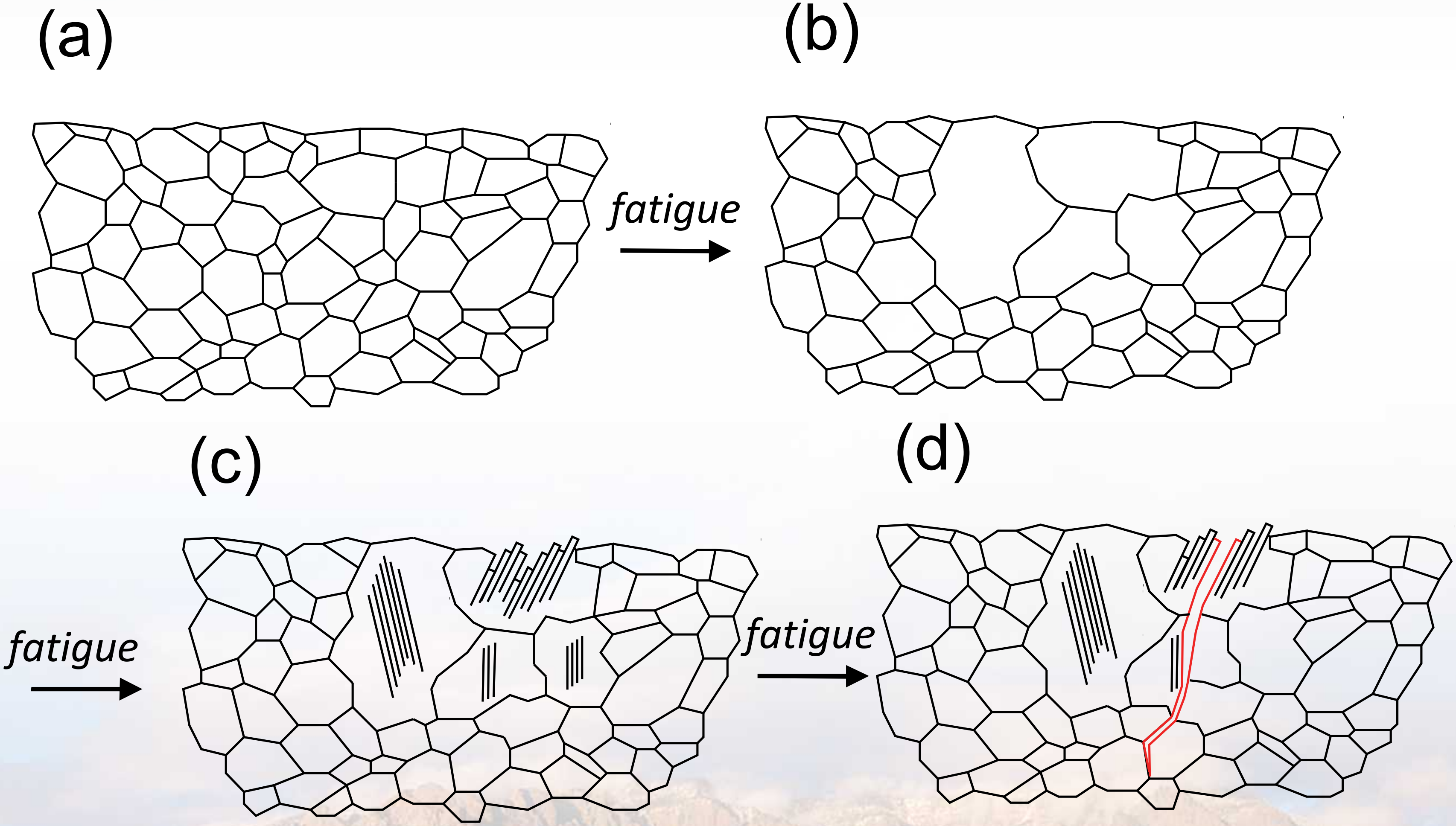
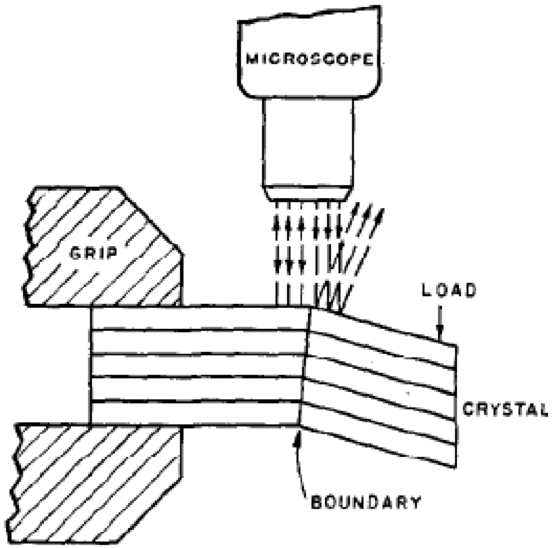
New Fatigue Process in Nanocrystalline Ni Alloys

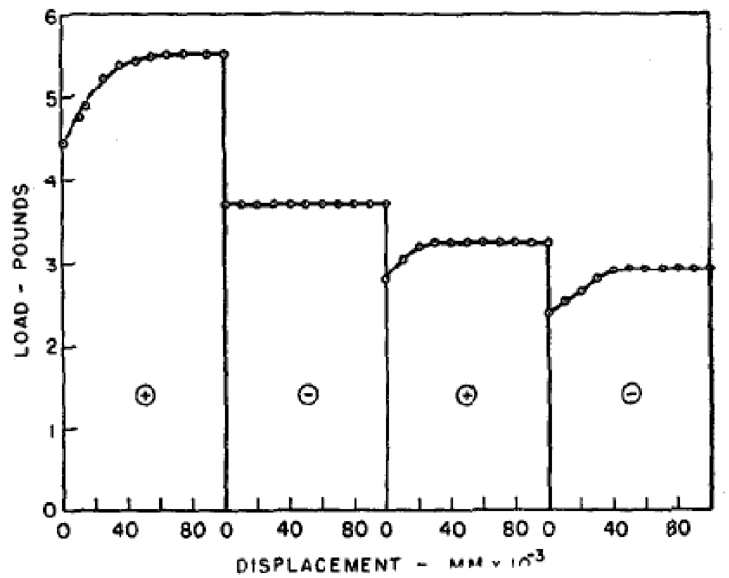


Boyce and Padilla, *Metall. And Mater. Trans. A*, 2011

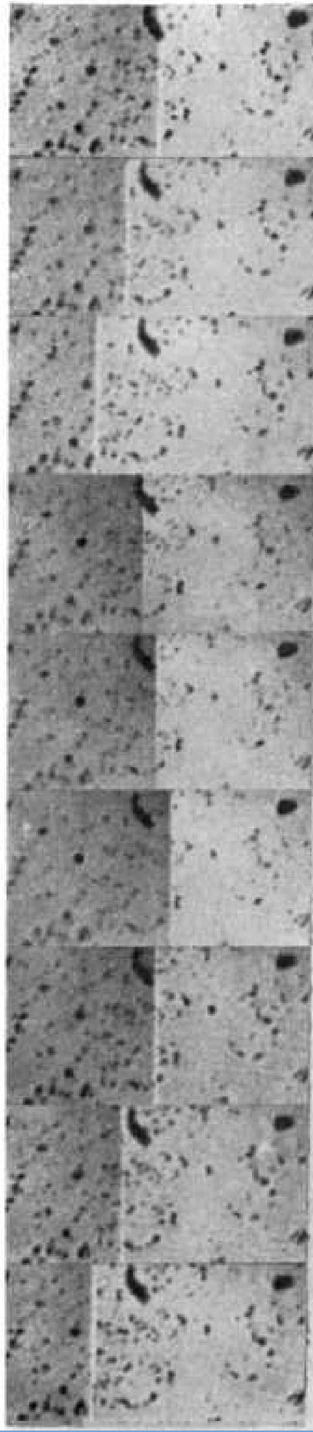
Mechanically-Induced Grain Boundary Motion

2° LAGB in 99.99% Zinc





Li, Edwards, Washburn, and Parker, Acta Metall., 1953

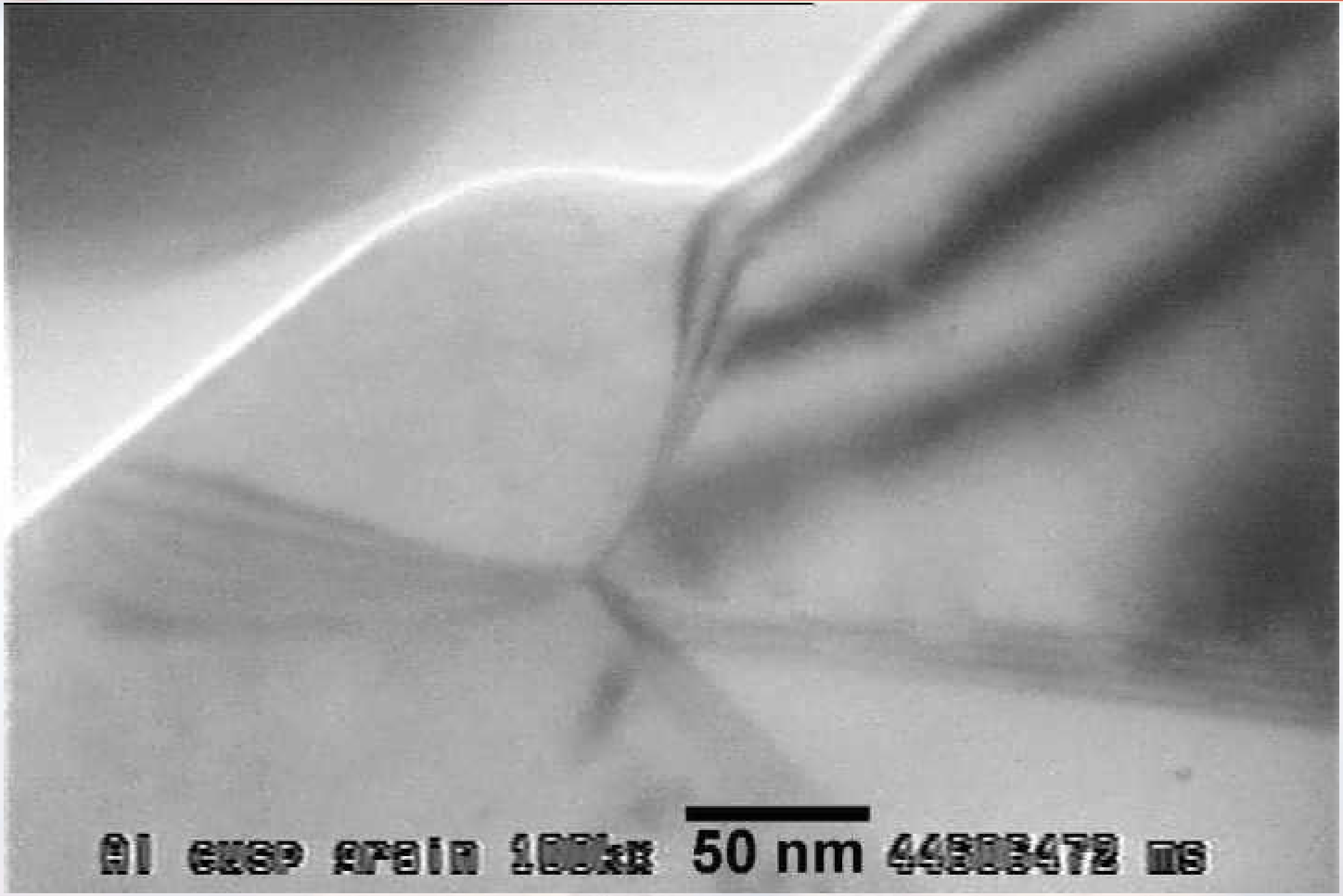


Recent Theoretical Models for Elastic Stress or Strain-Driven Grain Growth:

Cahn and Taylor, Acta Materialia, 52, 2004

Gutkin and Ovid'ko, Applied Physics Letters 85, 2005

Can Stress Really Move Grain Boundaries?



A. Minor, et al, National Center for Electron Microscopy, Lawrence Berkeley National Laboratory

Summary so far: Fatigue of Nanocrystalline Ni alloys

Three nanocrystalline Ni alloys exhibit exceptional fatigue resistance, apparently due to the suppression of traditional dislocation-mediated crack initiation processes.

Only when nanocrystalline Ni is driven to undergo grain-growth does fatigue-crack initation ensue.

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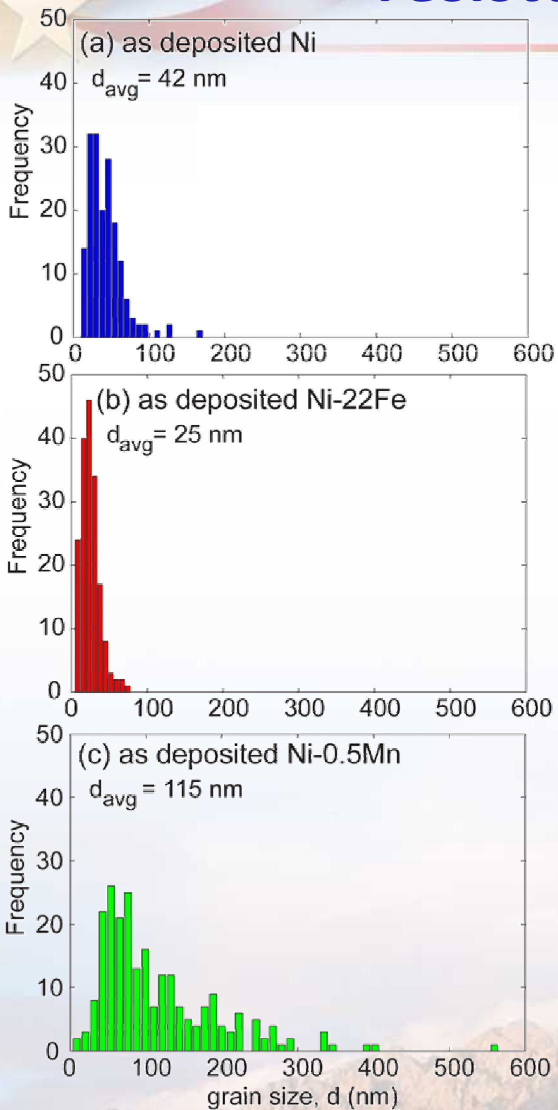
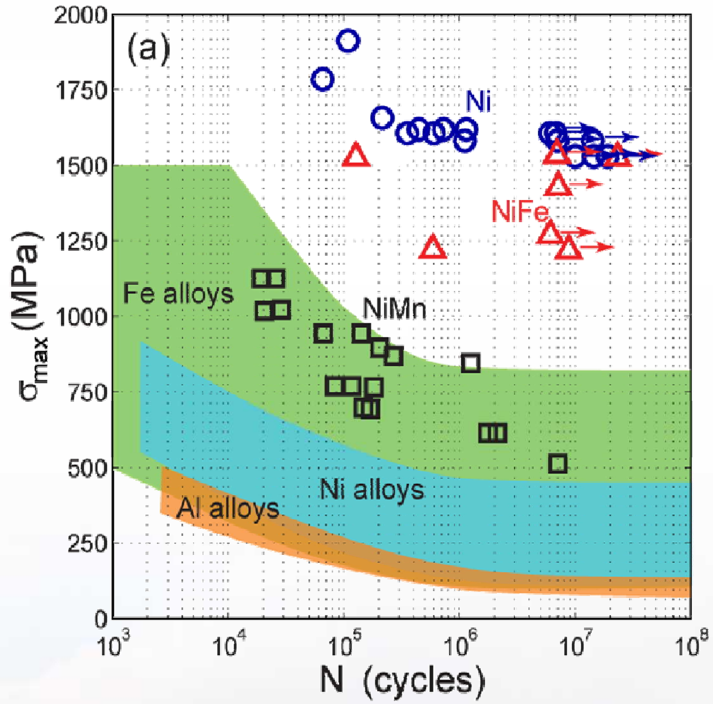
A Question Left Unanswered… How does fatigue resistance scale with grain size?



Fully-reversed bending, R=-1



Boyce & Padilla, Metall. Mater. Trans. A, 2011

While ultrafine grained Ni-0.5Mn only exhibited modest improvement in S-N fatigue performance, nanocrystalline Ni and Ni-Fe both showed dramatic improvement in fatigue performance. Why such a large difference? How does fatigue performance scale with grain size and strength?

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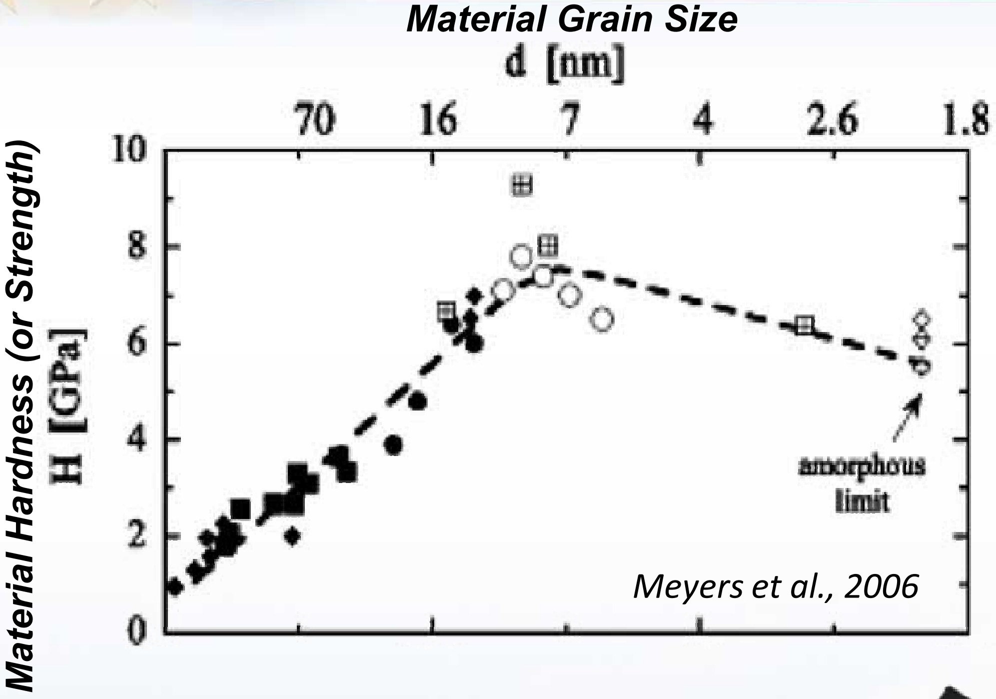
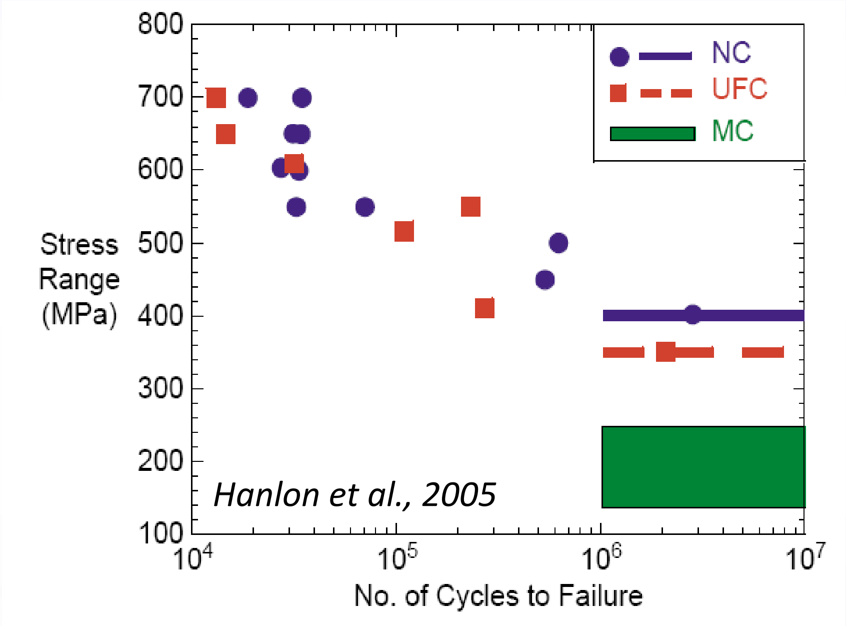
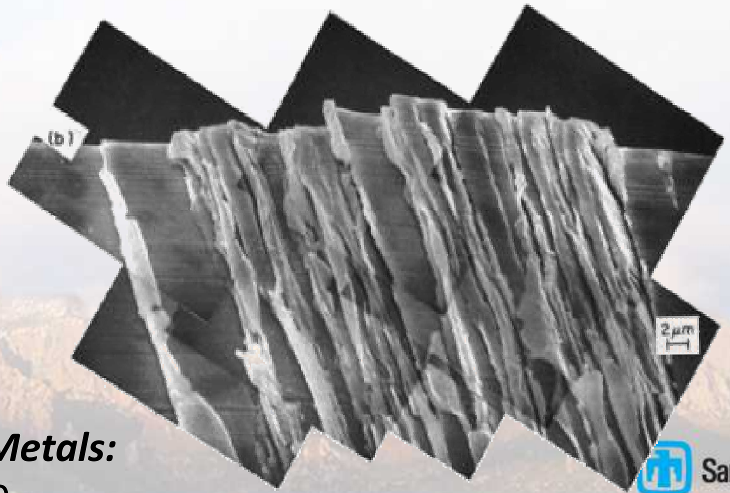
Can we systematically vary grain size in a single alloy to see a fatigue-equivalent of Hall-Petch Breakdown?

Hall-Petch Grain Size Effects







Ma and Laird, 1989

At what length scale do conventional fatigue processes (i.e. persistent slip) begin to break down?

Review of Fatigue Behavior in Nanocrystalline Metals:
Padilla and Boyce, *Experimental Mechanics*, 2010

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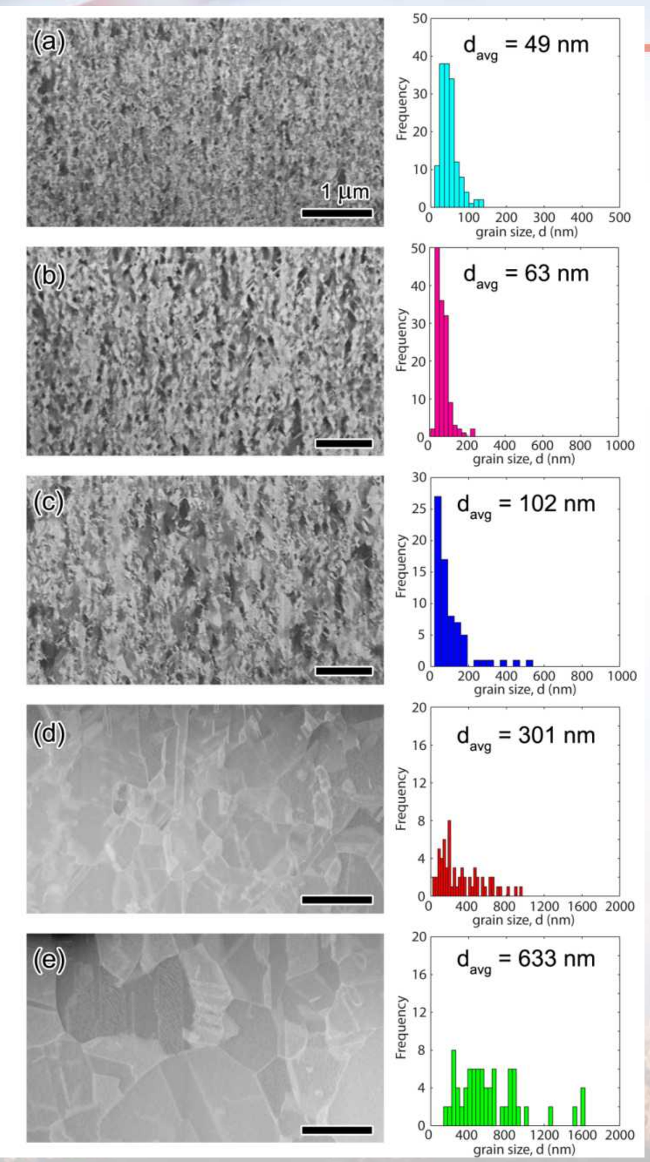
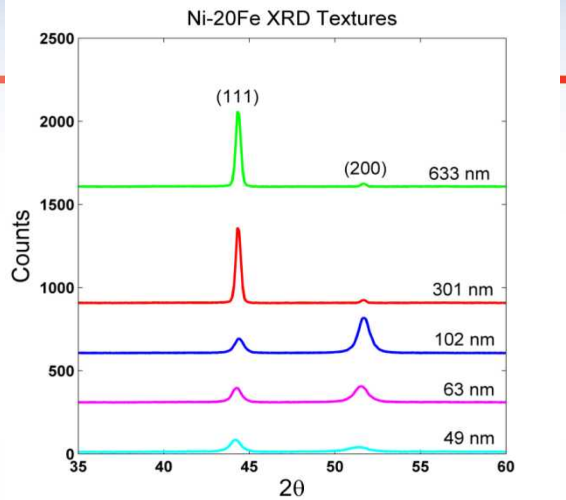
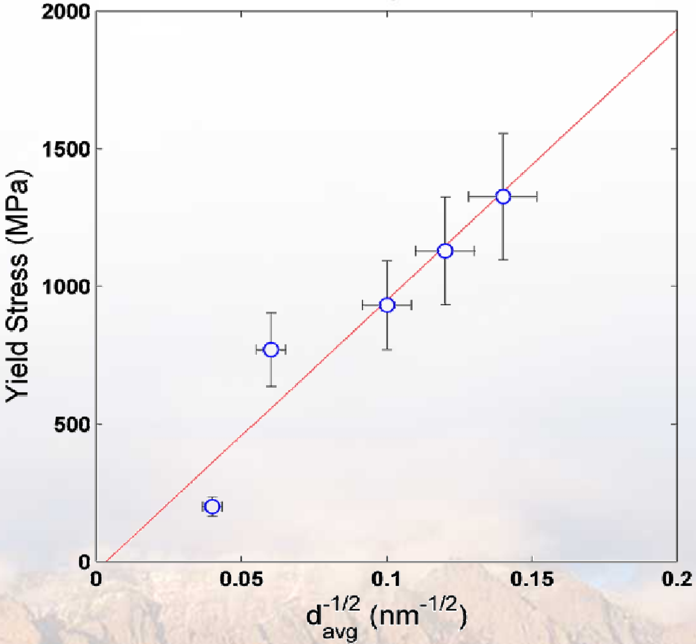
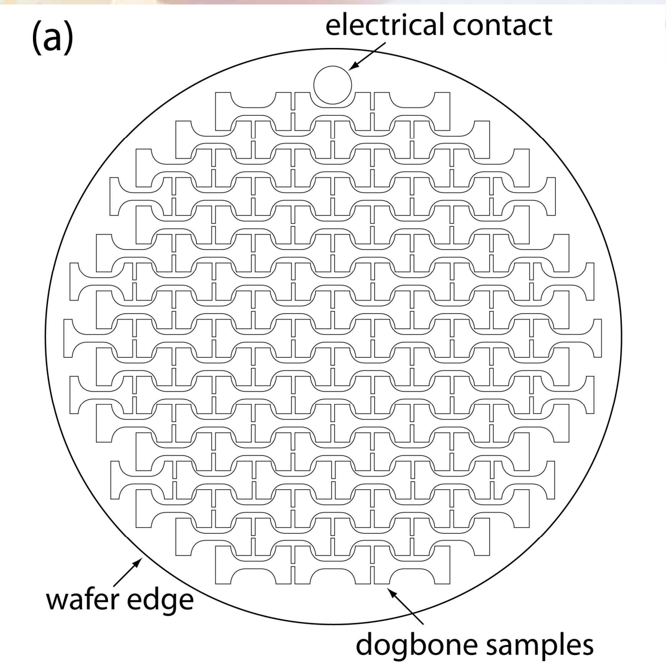
One alloy (Ni-10Fe) produced with 5 Grain Sizes

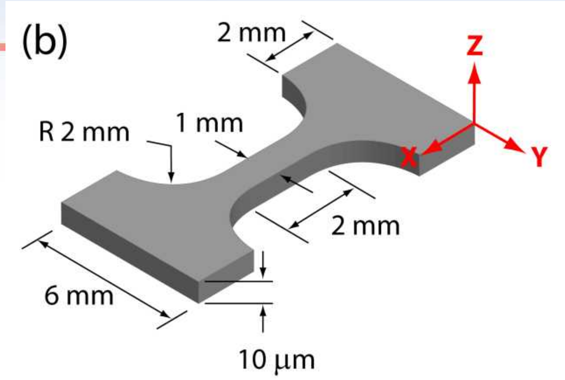




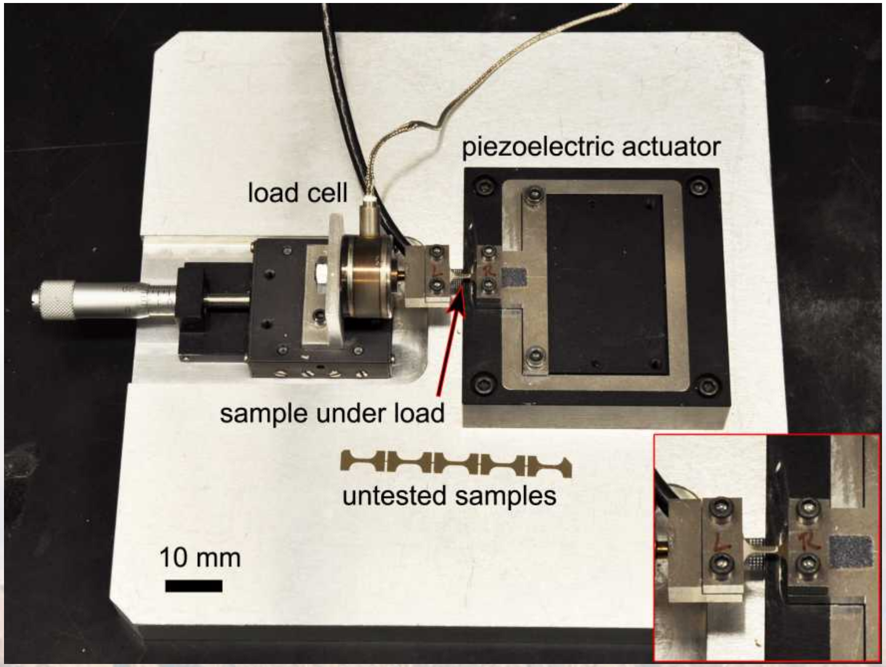


Thin film fatigue of electrodeposited Ni-Fe (permalloy)

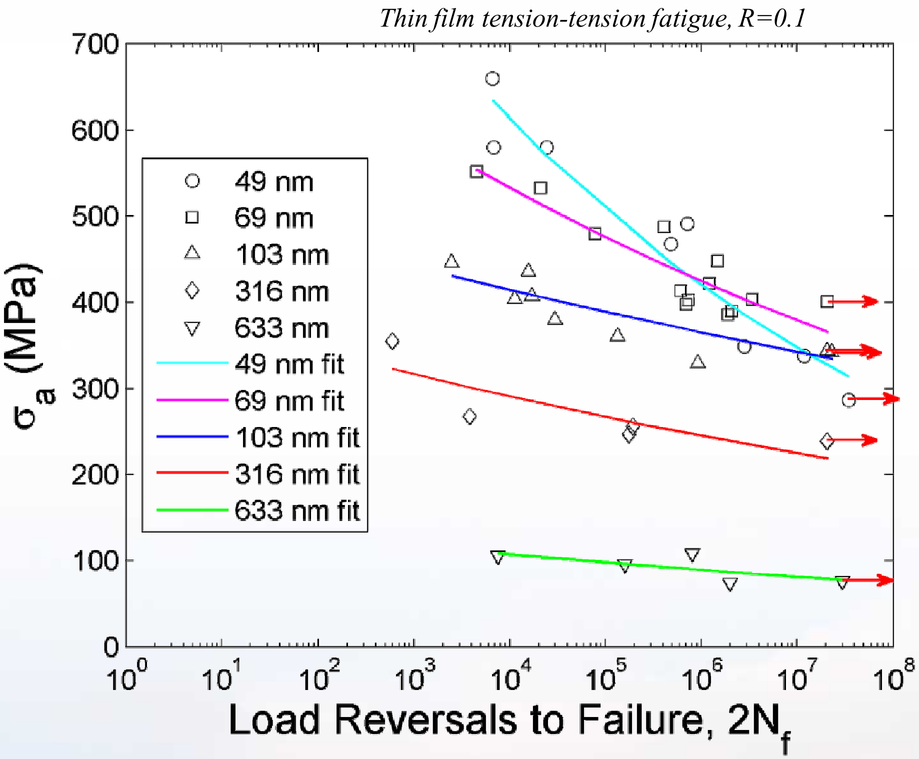


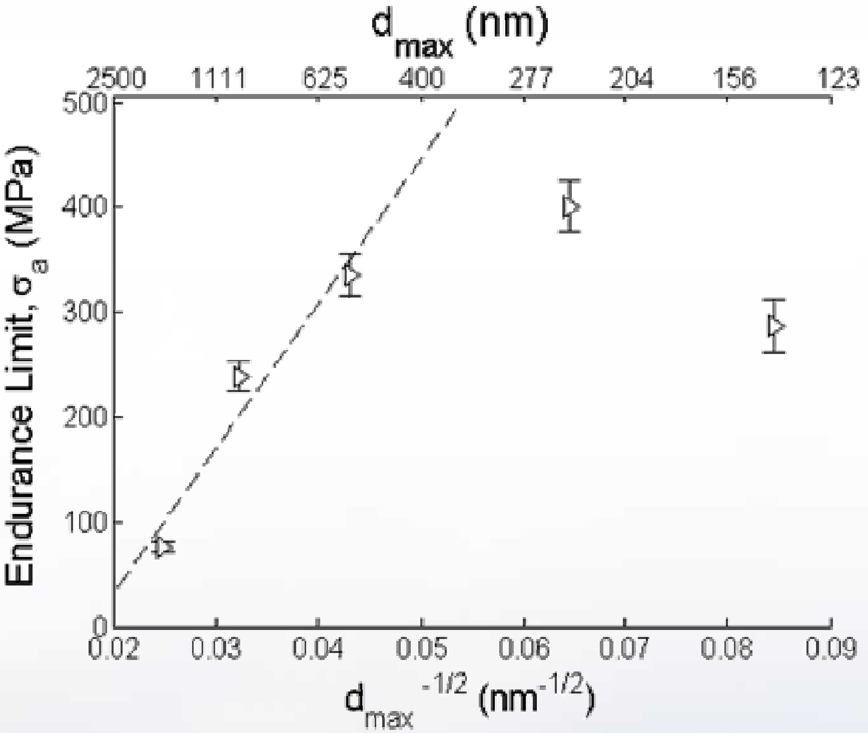


Thin film tension-tension fatigue, R=0.1

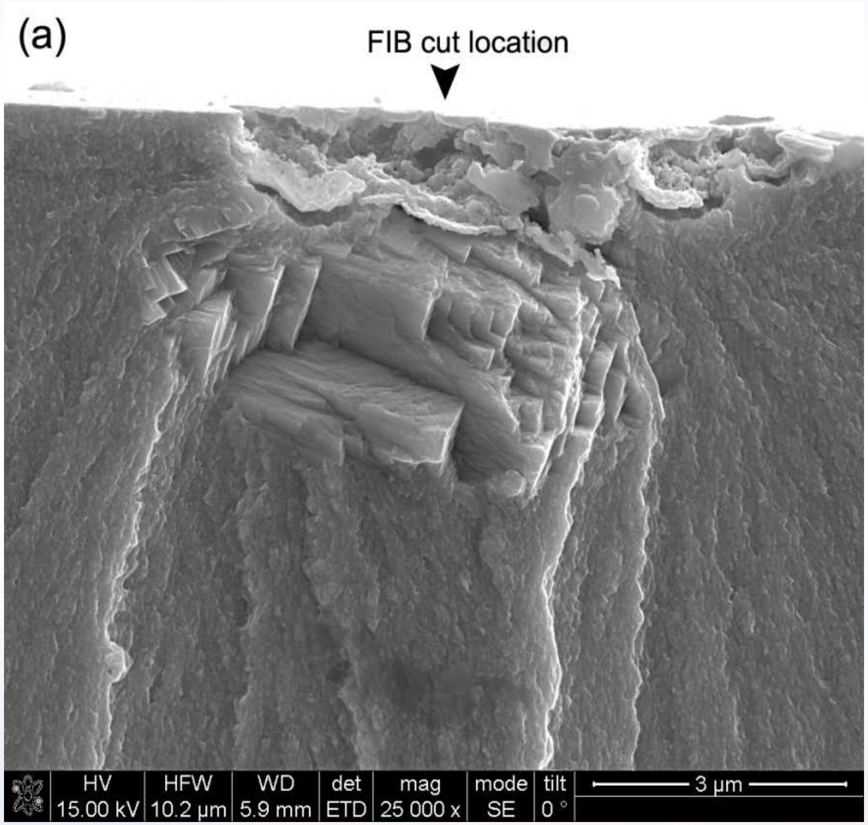


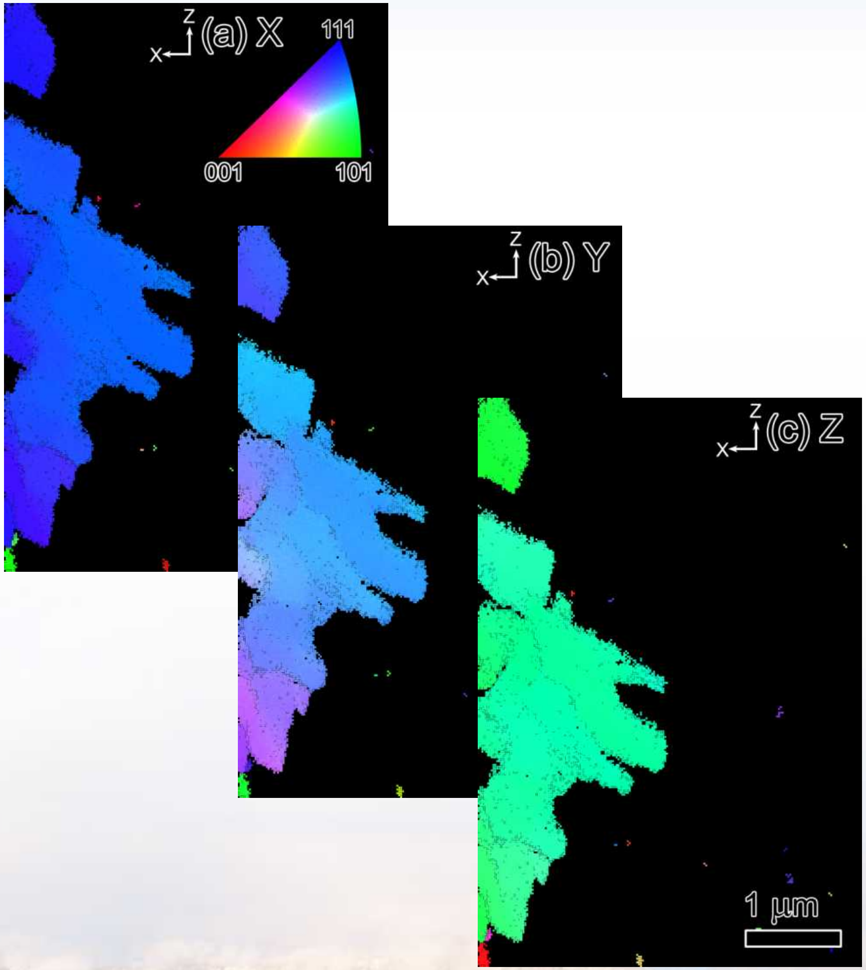
Endurance limit plateaus at average grain size ~70 nm!
(max grain size ~400 nm)





Same morphology of highly textured, fatigue-coarsened grains form in samples with grain sizes of 100 nm or less.

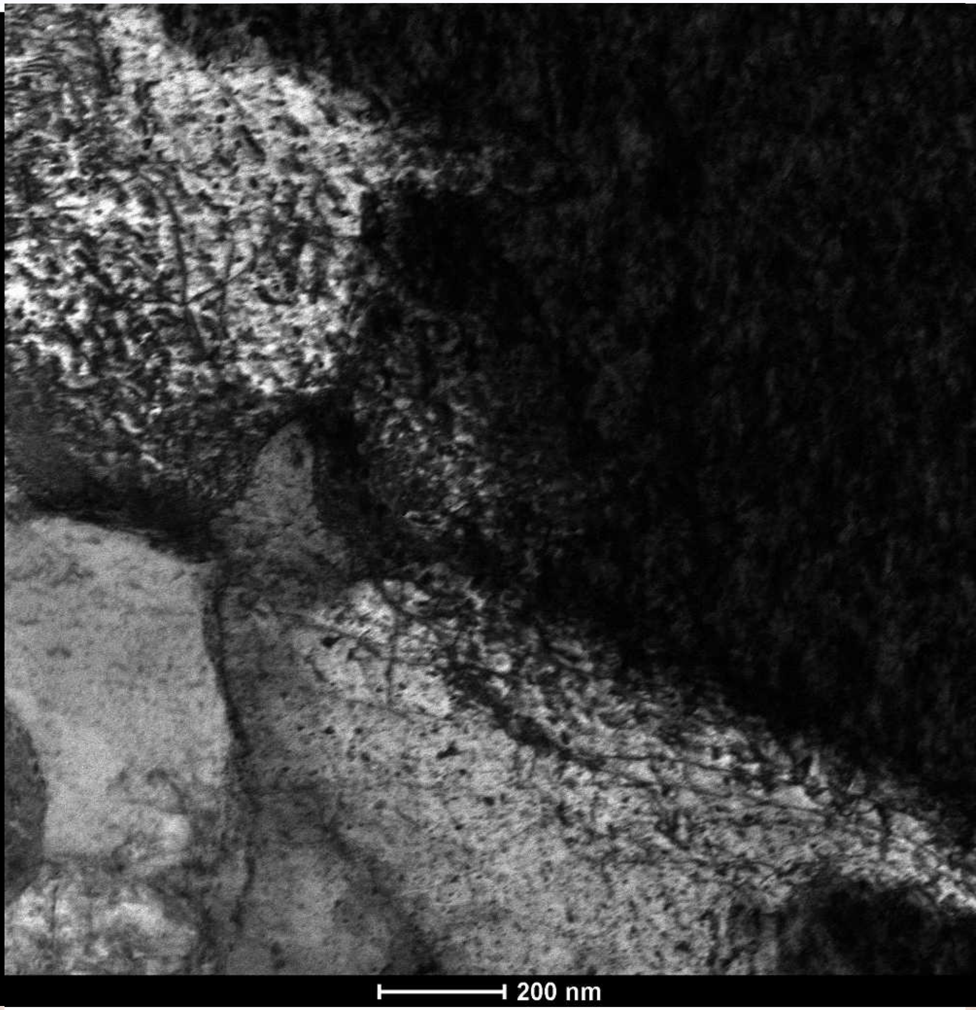




Persistent slip ladders are apparent in coarse grained metals, but have not yet been found in fatigue-coarsened grains

Coarse Grained Ni-Fe
Produced by annealing @ 650°C/1hr

Nanocrystalline Ni-Fe

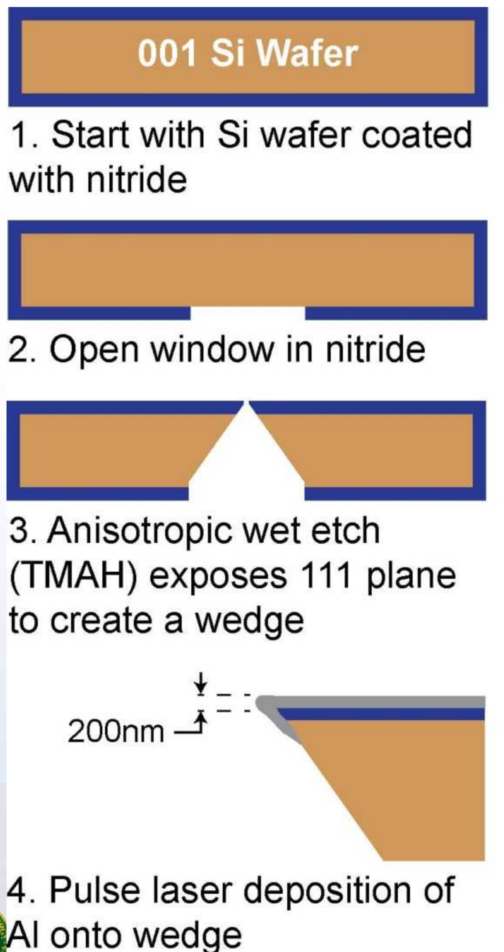


Boyce & Padilla, Metall. Mater. Trans. A, 2011

Can we observe the fatigue-driven grain evolution directly?

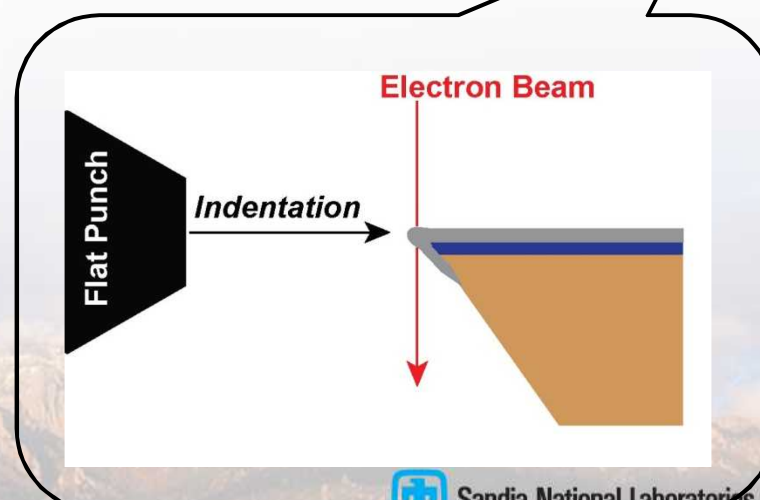
Quantitative In-situ TEM fatigue of electron-transparent nanocrystalline films

Sample Fabrication

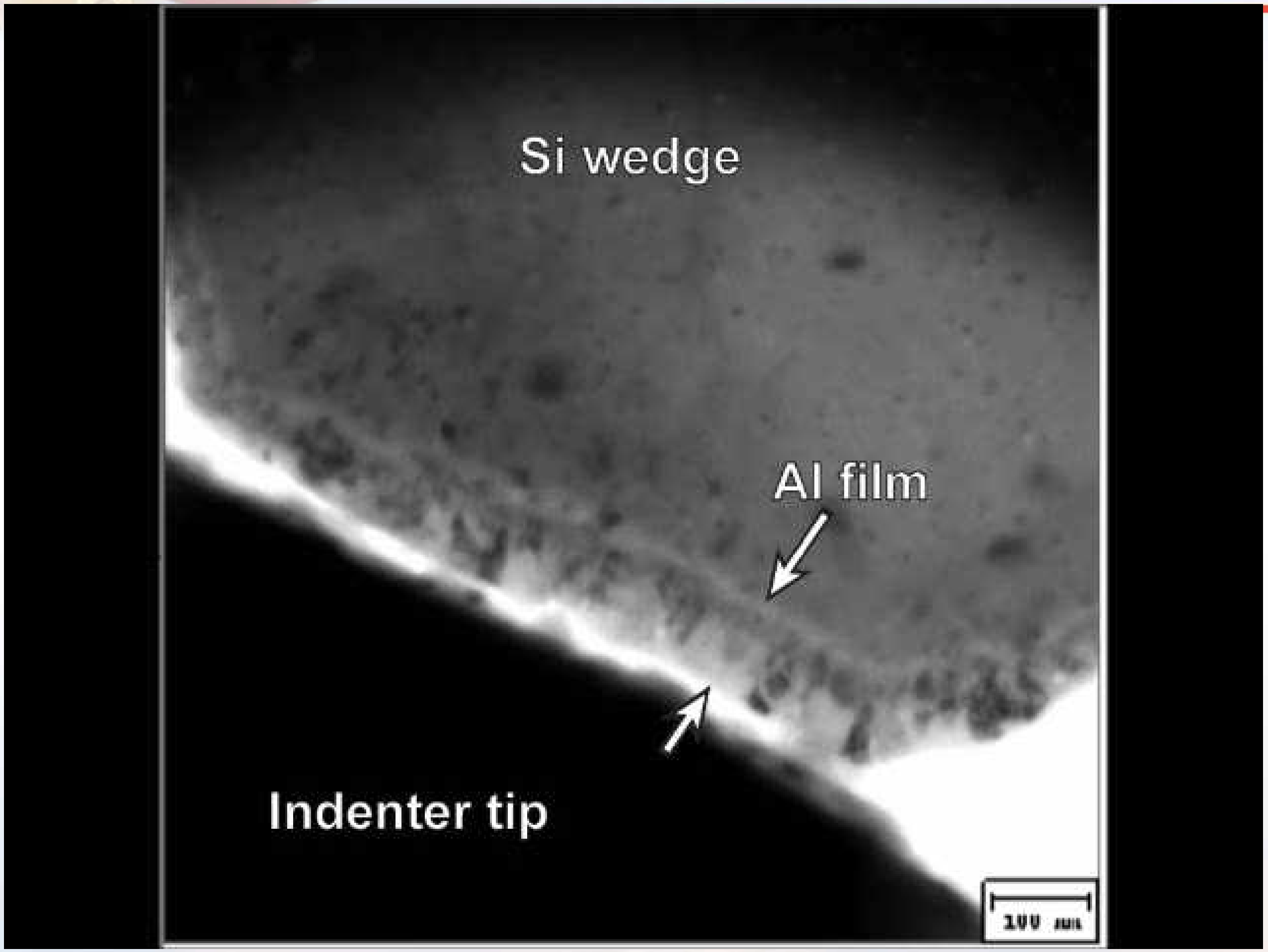


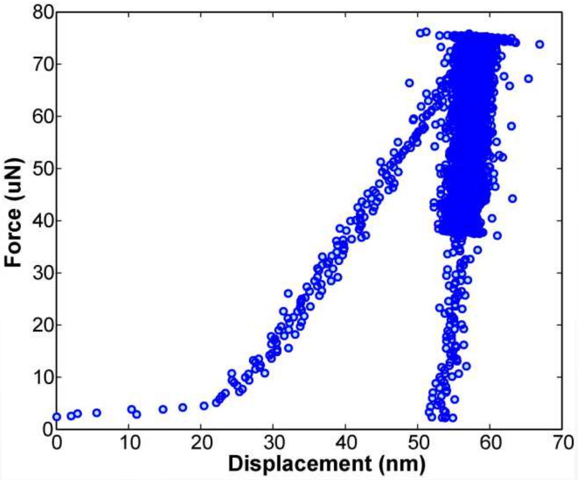
In situ TEM fatigue

- *Microscope: JEOL JEM 2100 LaB_6 TEM*
- *Holder: Hysitron PI-95 PicoIndenter with a 1µm flat tip punch*

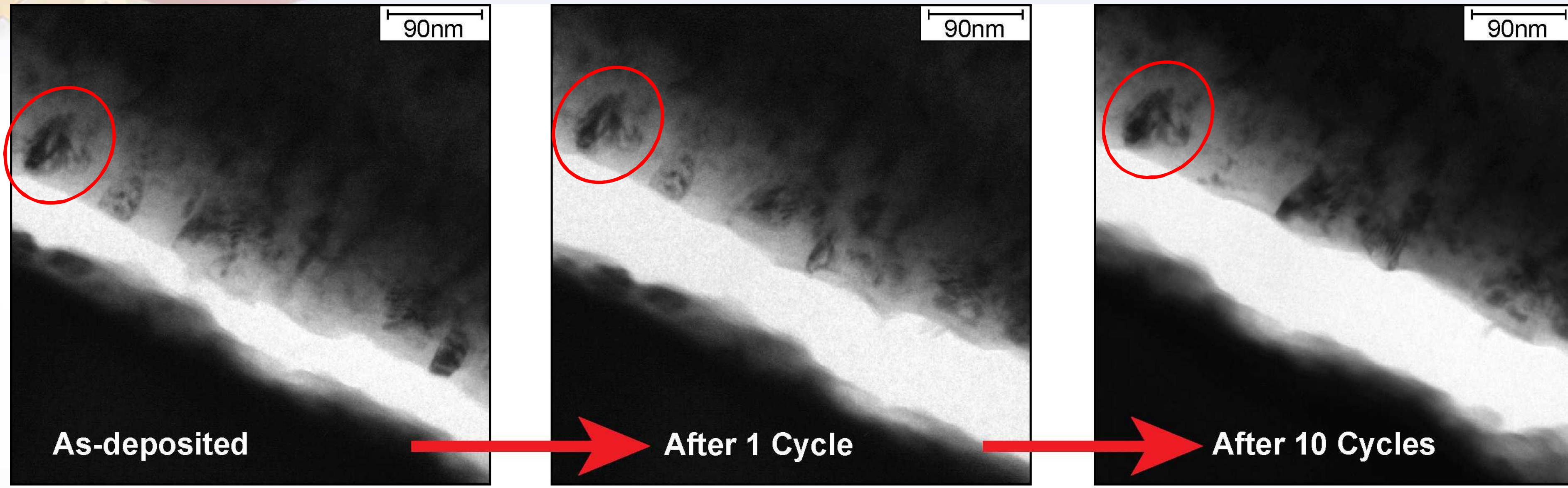


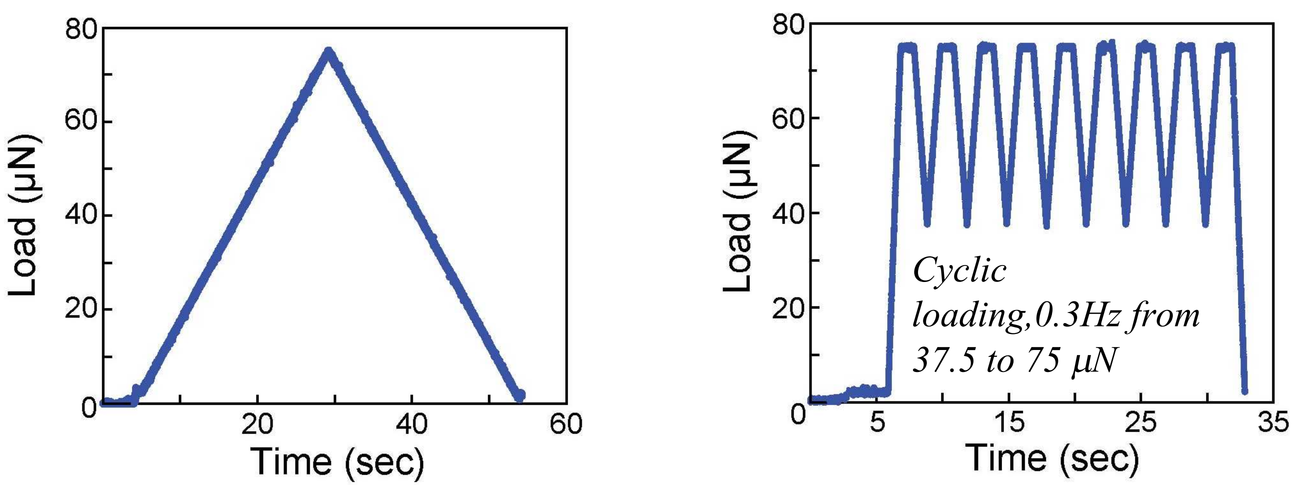
In Situ TEM Indentation





Some regions show no evolution



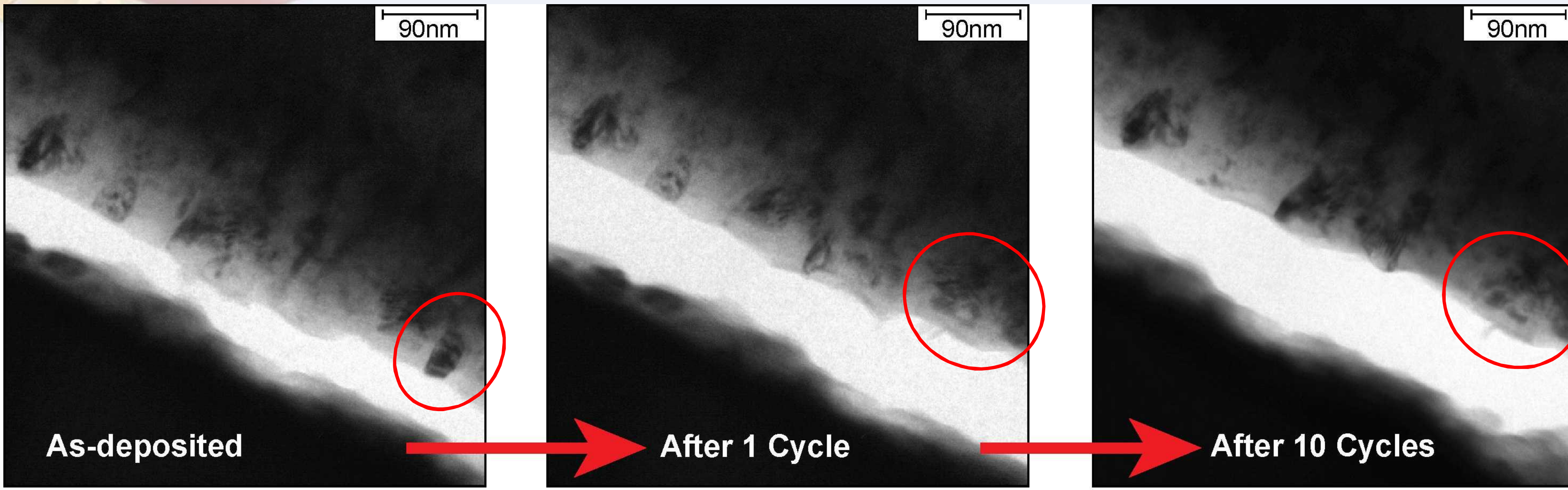


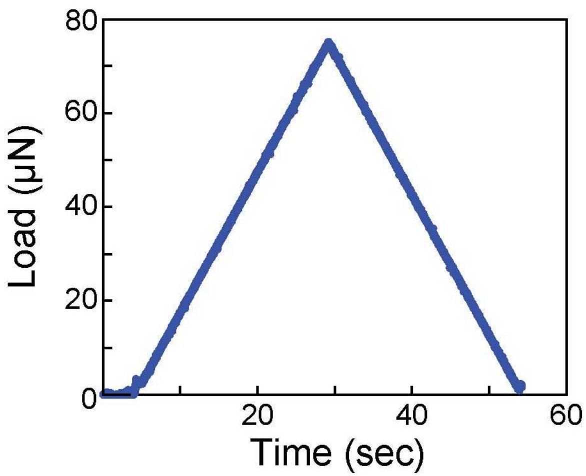
Peak load of 75 μN

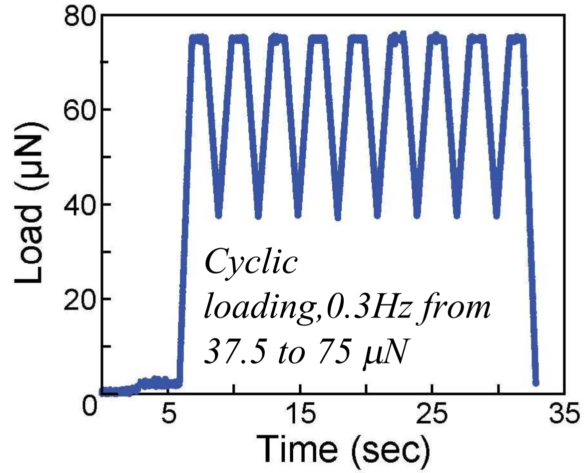
375 MPa nominal contact stress

Sandia National Laboratories

Some regions evolve during the 1st cycle

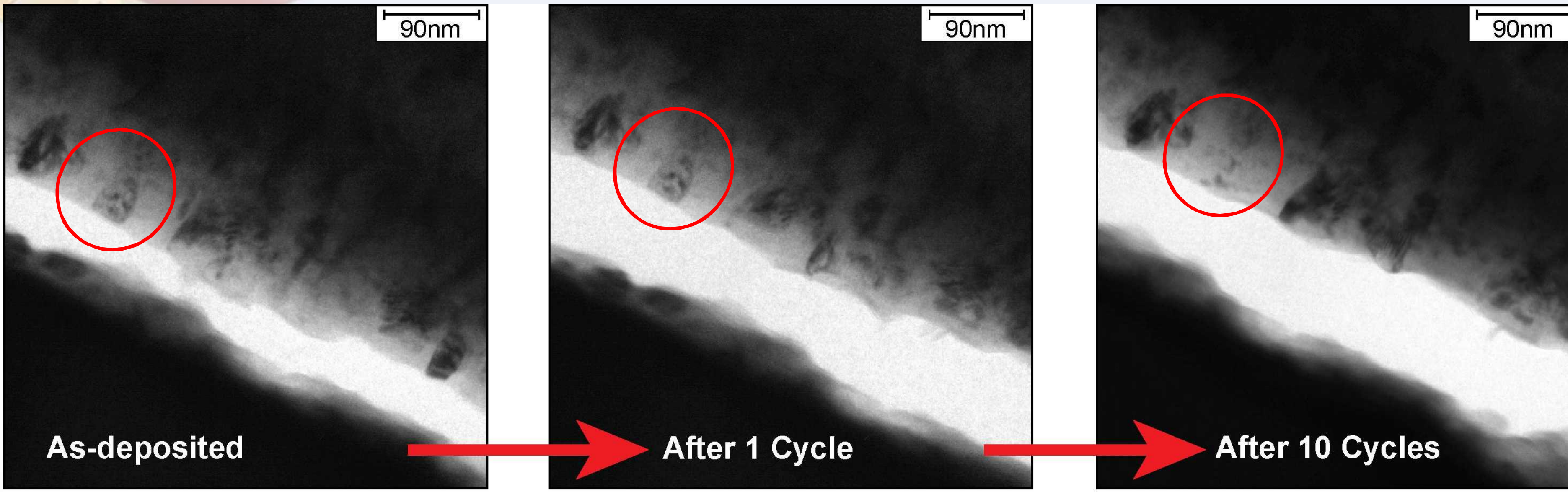


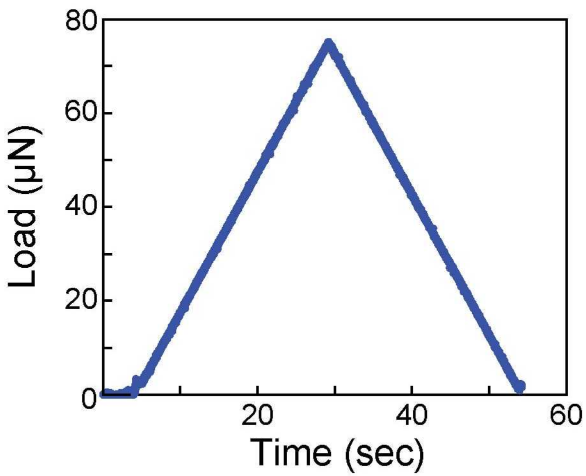


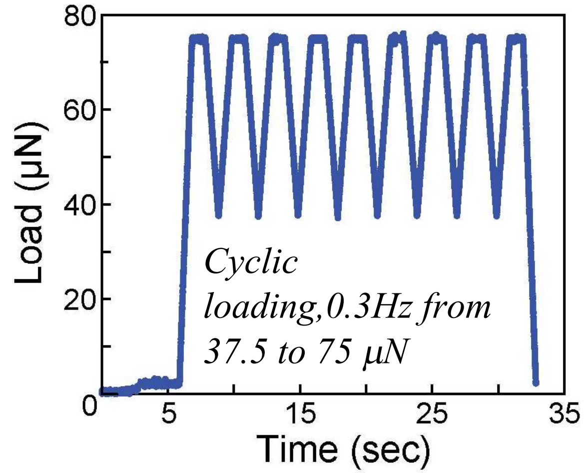


375 MPa nominal contact stress

Some regions evolve during subsequent cycles

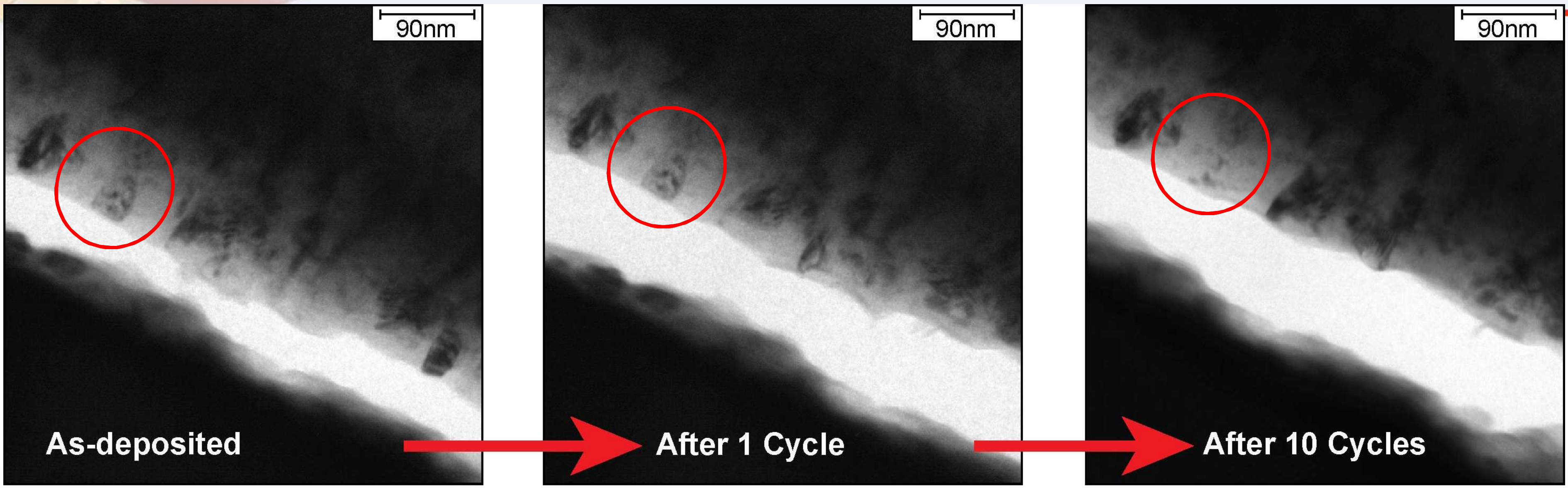






375 MPa nominal contact stress

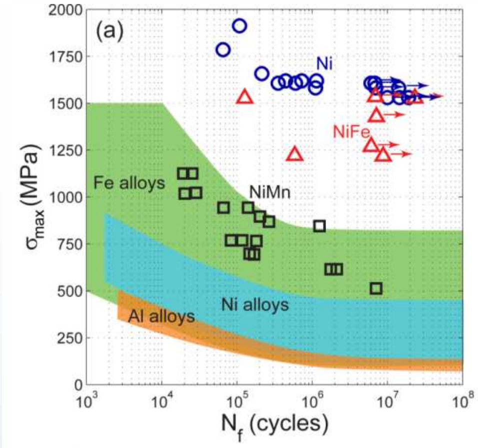
Implications of this Observation

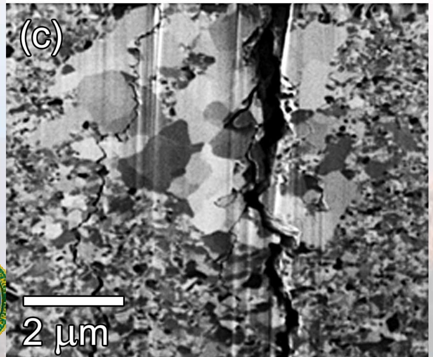


1. *The first direct imaging observation of grain evolution under cyclic loading*
2. *Grain boundaries are perpendicular to loading axis, suggesting the possibility That the boundary migration mechanism may not be shear driven*
3. *This grain evolution is not dynamic recrystallization.*

Recap…

4-28-1988 After 89,090 flight cycles on a 737-200, metal fatigue lets the top go in flight.





Fatigue is a failure process which continues to challenge structural metals.

Nanocrystalline metals offer outstanding strength, and enhanced fatigue resistance

Nanocrystalline grains grow under fatigue loading and these larger grains cause crack initiation, limiting fatigue enhancement.