SAND2006-3079P

Fatigue Behavior in Three LIGA Electrodeposited Ni-based Alloys

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Albuquerque NM and Livermore CA

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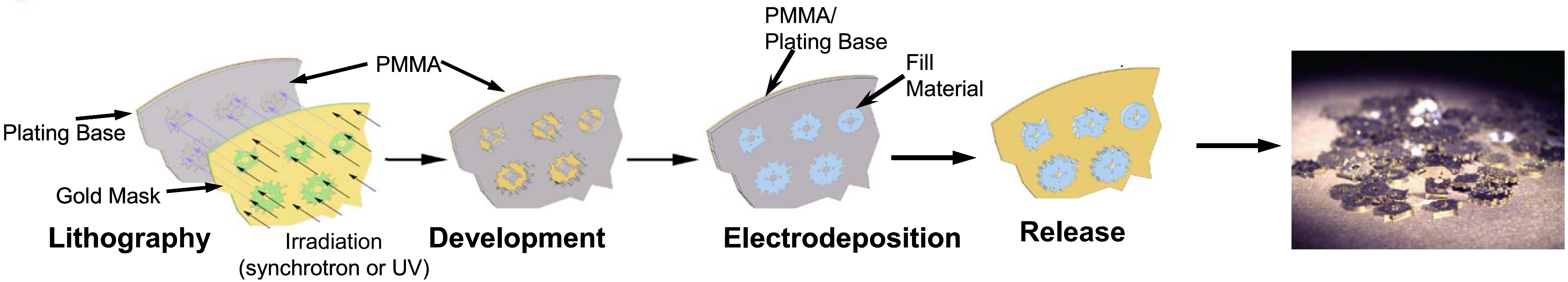
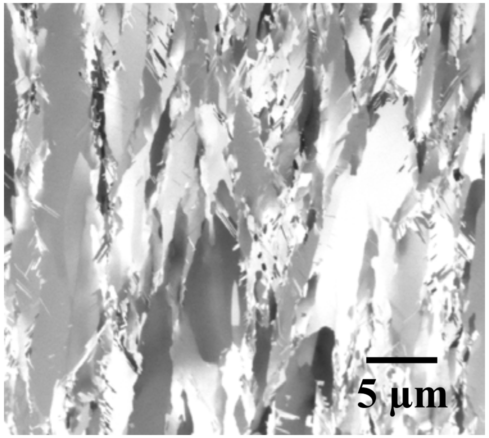
Three Ni-based LIGA MEMS Alloys



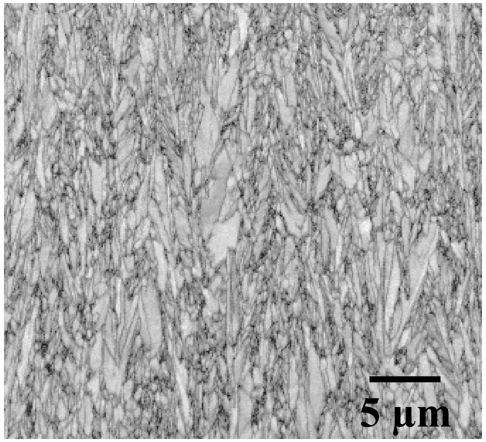
Ni *(sulfamate bath)*



Grain Size ~ 3000 nm

Ultimate Strength ~ 500 MPa

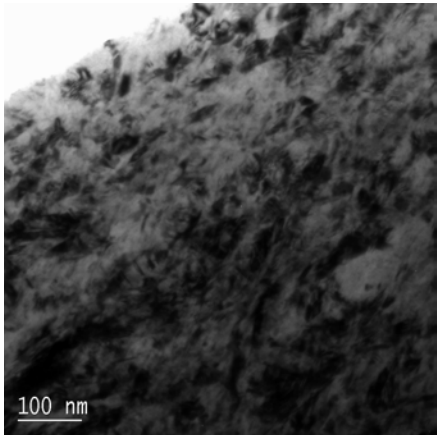
Ni-Mn



Grain Size ~ 100 nm

Ultimate Strength ~ 1500 MPa

Ni-Fe



Grain Size < 50 nm

Ultimate Strength ~ 2000 MPa

Fatigue Testing of Metallic (LIGA) MEMS

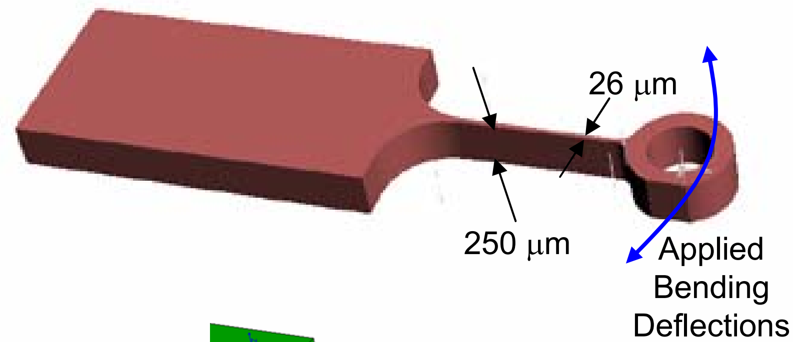
Applied Loads:
~15 mN

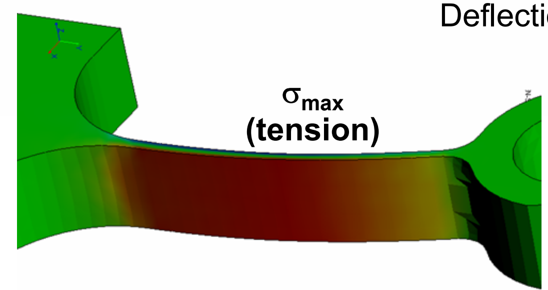
Deflections:
~100 µm

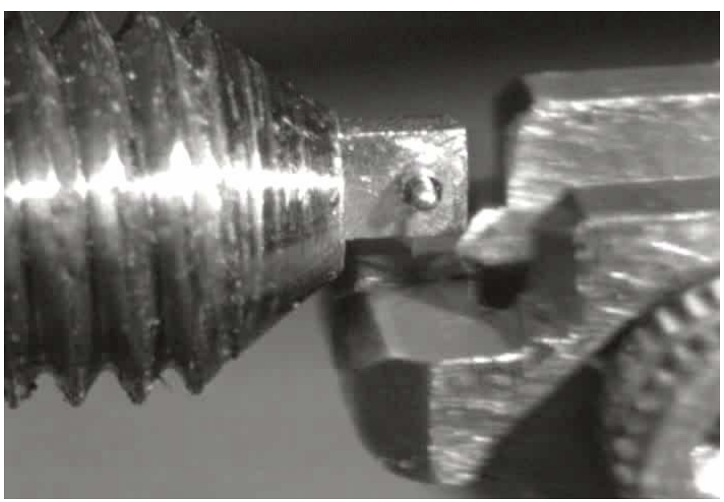
Test Frequency
10-20 Hz

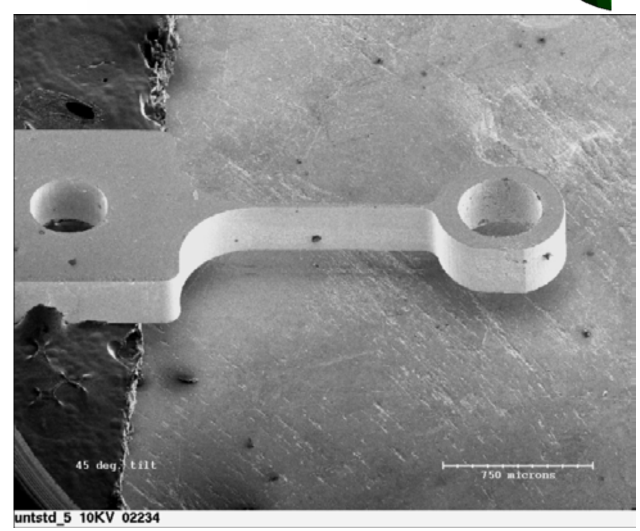
Room Temp.

Lab Air

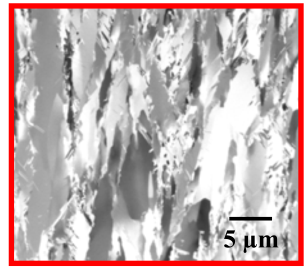




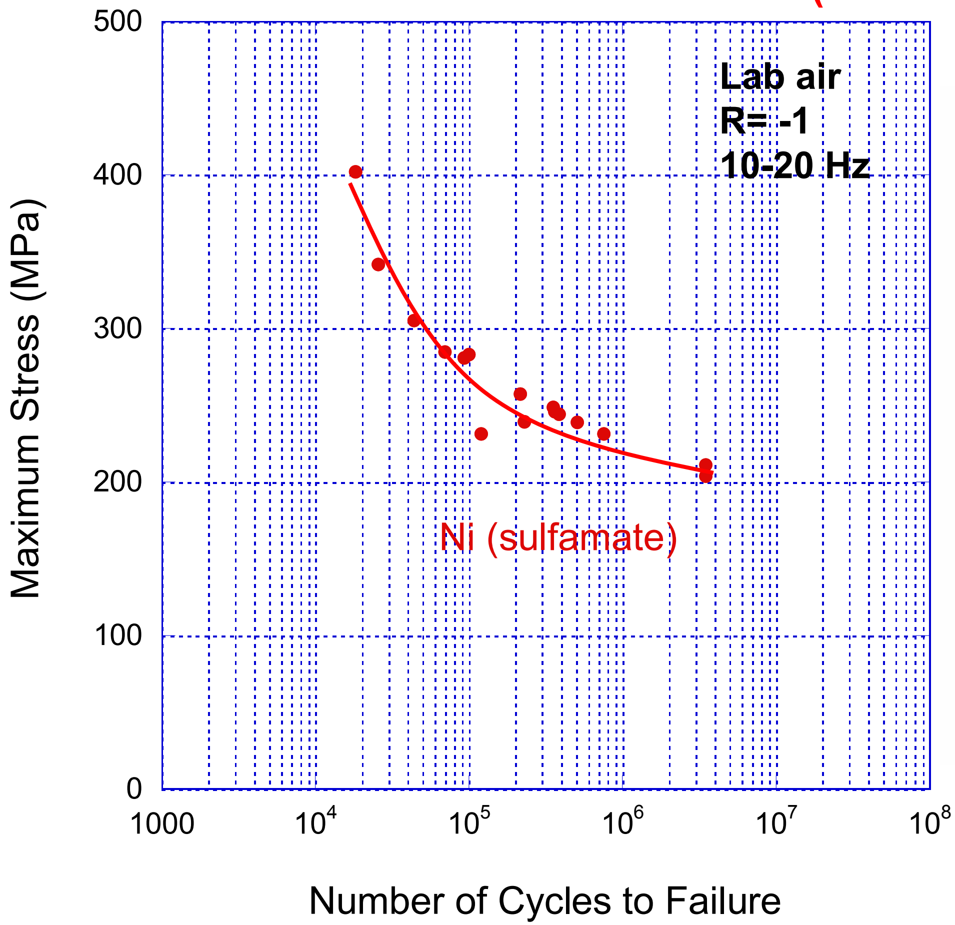




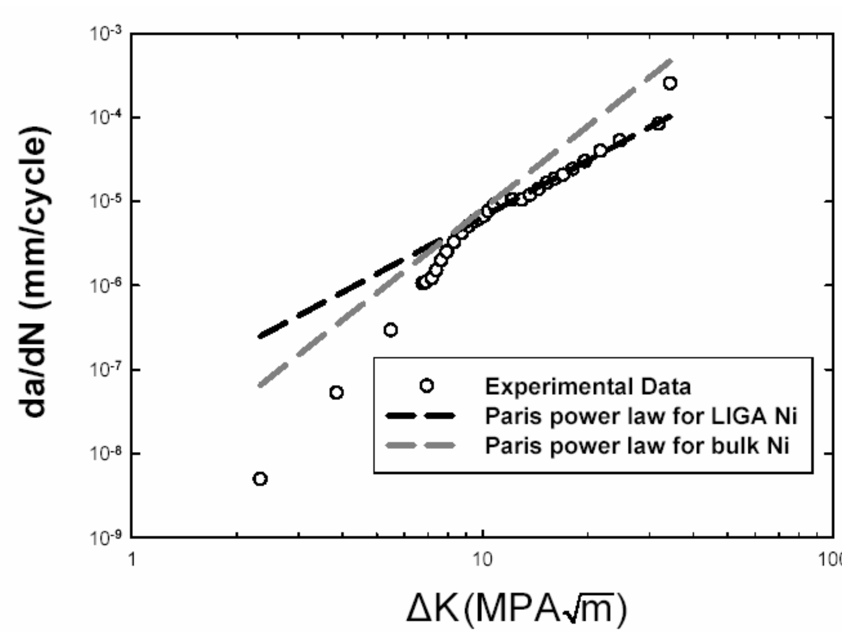
High Cycle S-N Results On LIGA Ni



Ni (sulfamate)

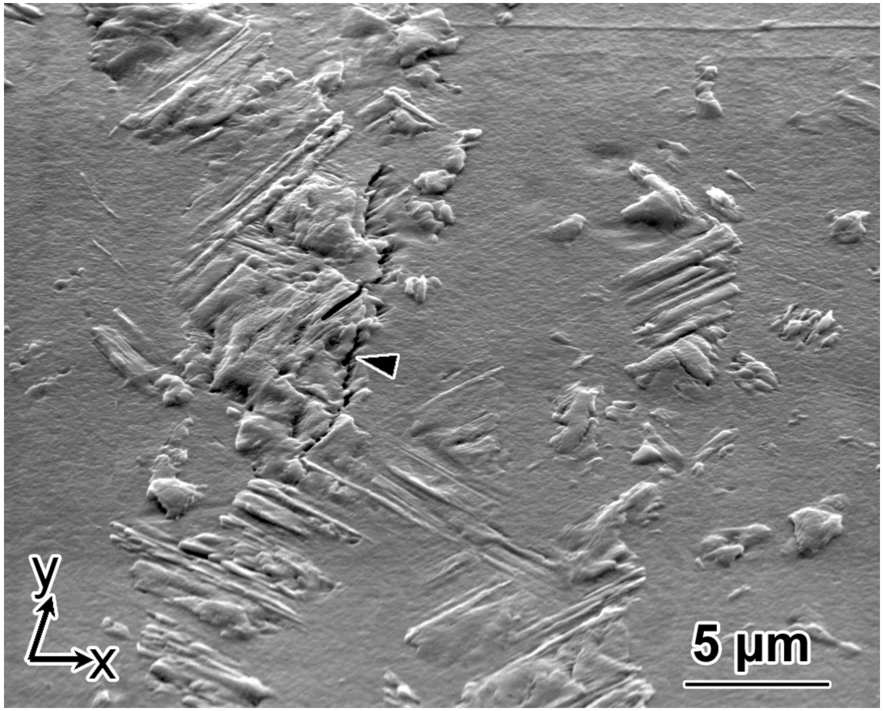


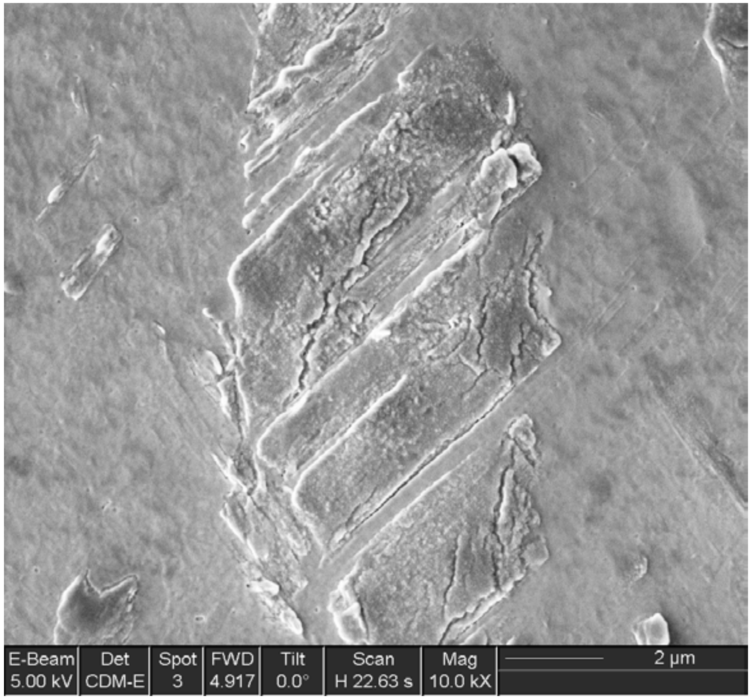
B.L. Boyce, J.R. Michael, and P.G. Kotula, *Acta Mater.*, 2004



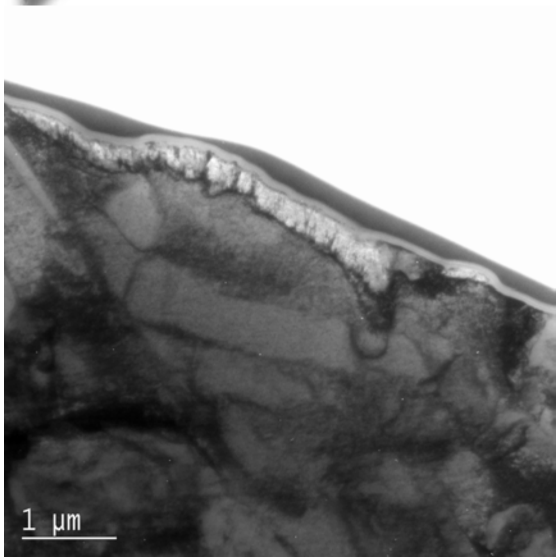
Y. Yang, S. Allameh, J. Lou, B. Imasogie, B.L. Boyce and W.O. Soboyejo, Metall. Trans. A., In Review

Cracks Are Found in Persistent Slip Bands On the Surface

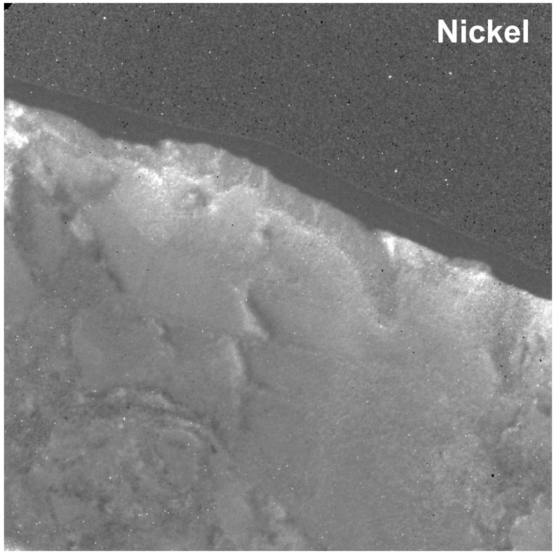




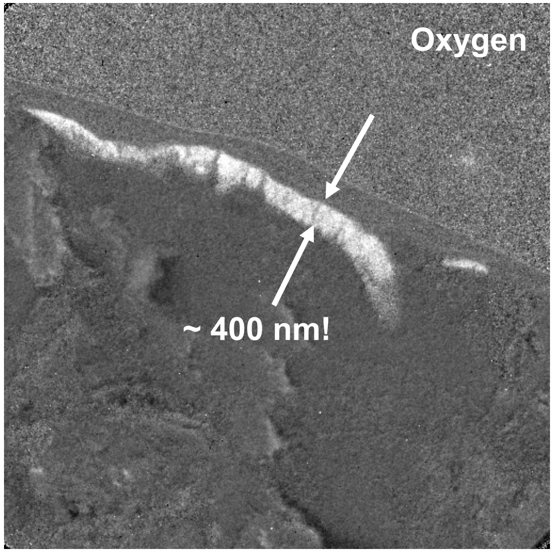
These Surface Layers Are Covered in A Thick Oxide!



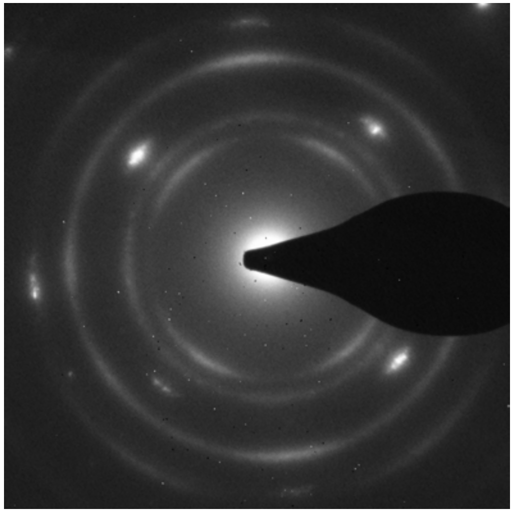
Bright Field Image



White intensity scales with intensity of nickel peaks in EELS spectra



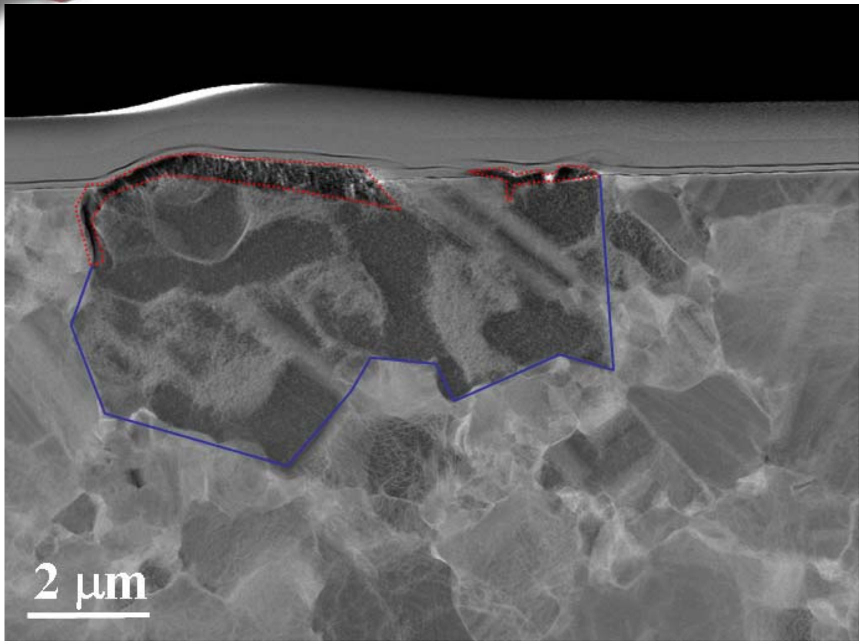
White intensity scales with intensity of oxygen peaks in EELS spectra

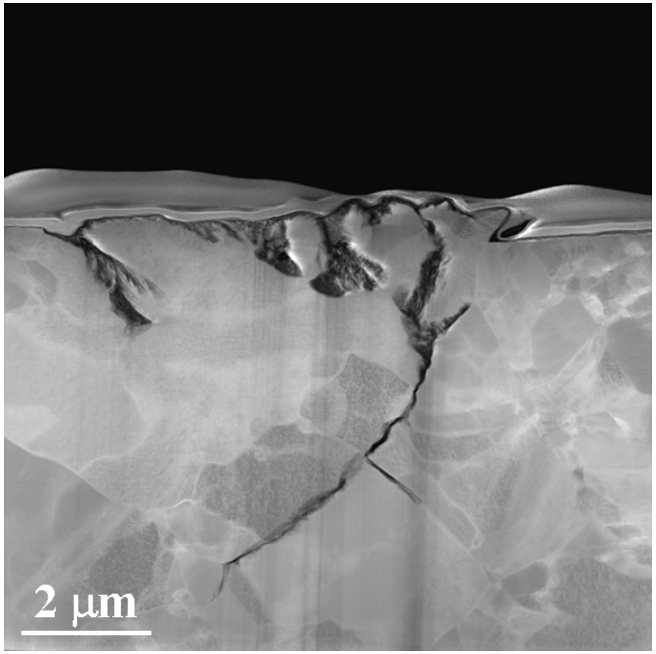


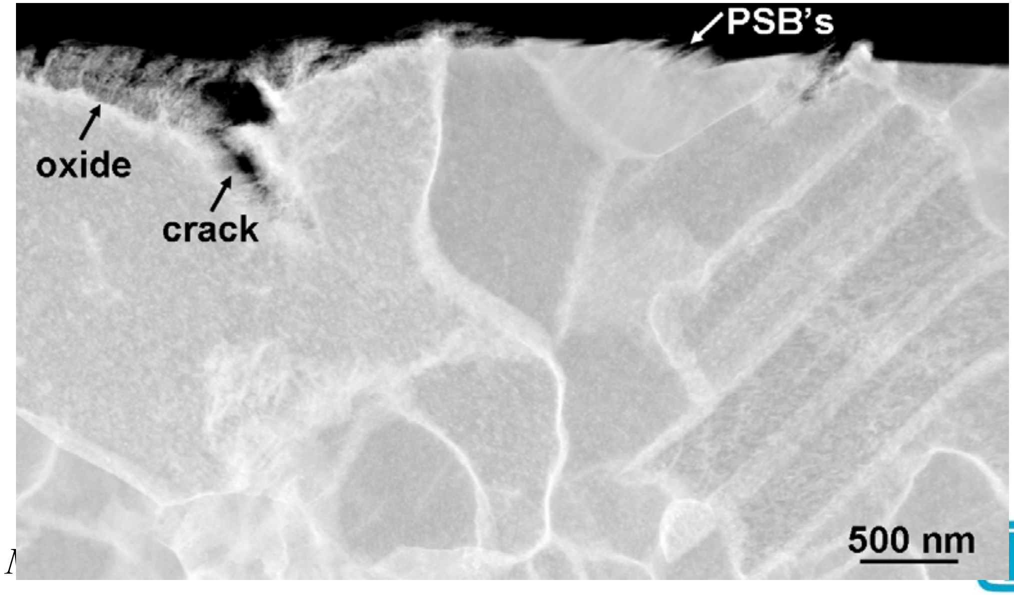
Selected Area Diffraction

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

Cross-sectional TEM of PSBs and Oxide Microcracks

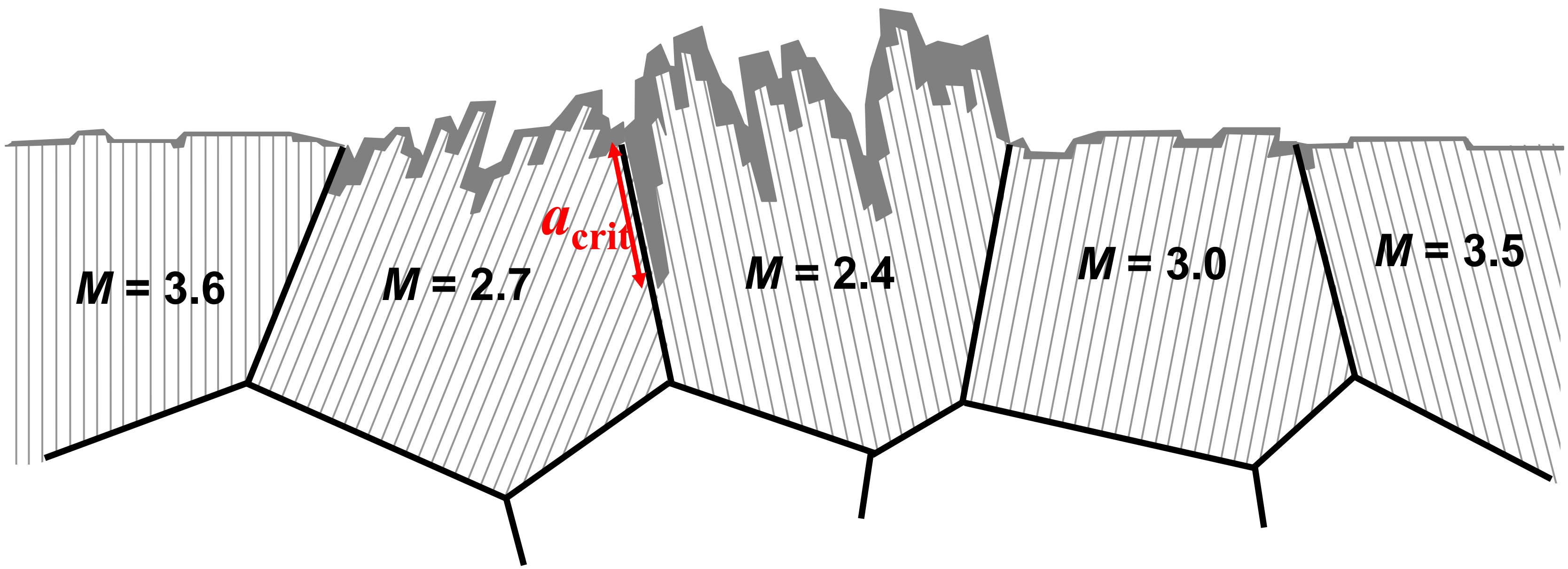




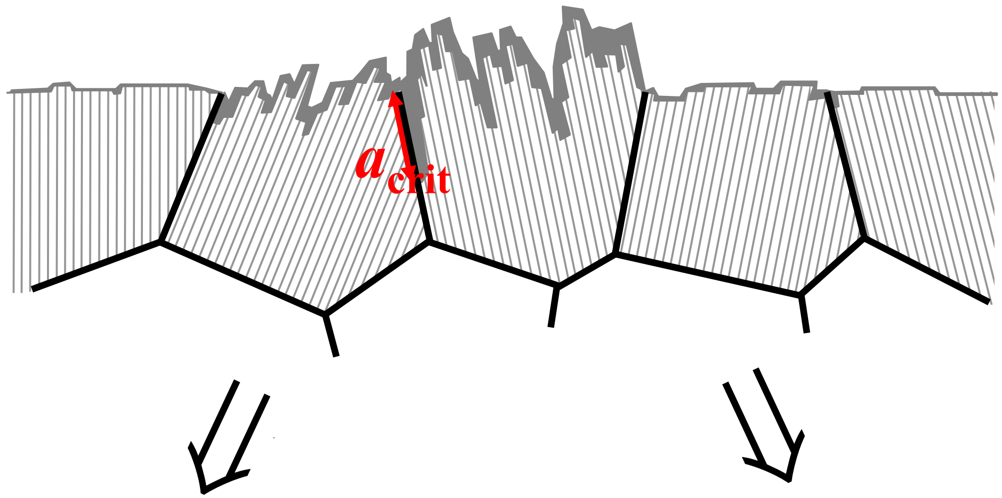


INITIATION: A Transition from Oxide Growth to Fatigue Crack Propagation

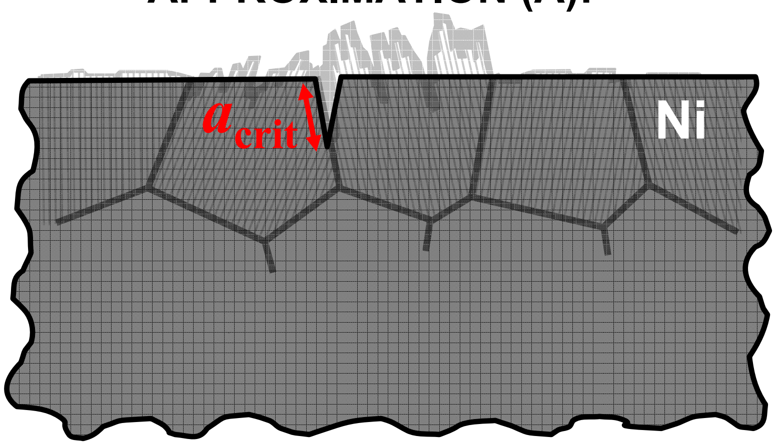
Hypothesis: The fatigue cycles serve to cyclically rupture the repassivated film. Once an oxide of sufficient thickness is grown, the imbedded flaws are large enough to exceed the fatigue threshold, allowing a crack to propagate into the matrix



Two Bounding Solutions for "PSB Oxide Initiation"

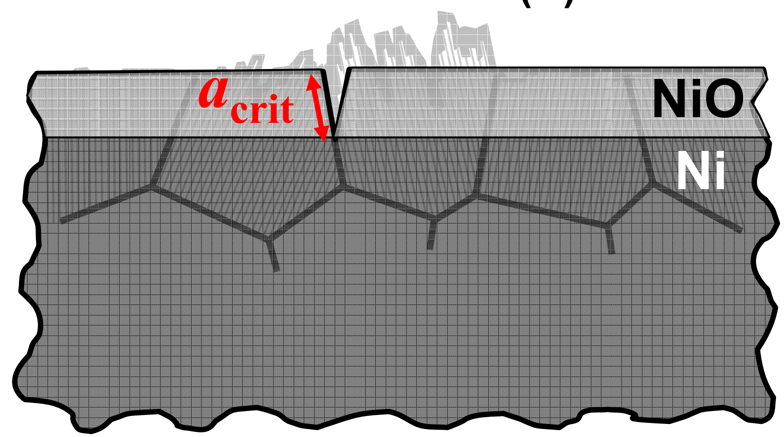


APPROXIMATION (A):



A crack in a homogeneous monolith

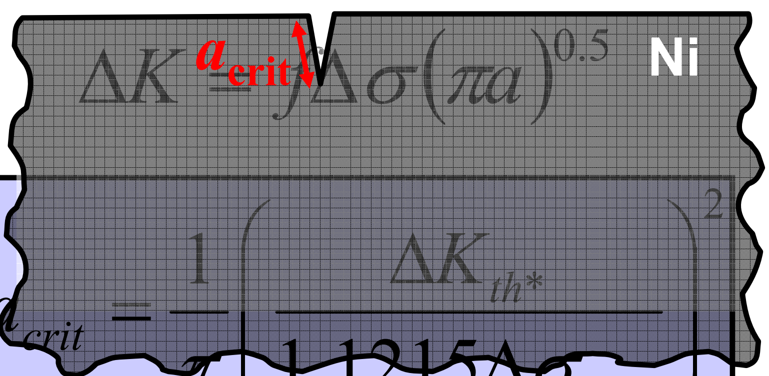
APPROXIMATION (B):



A fully-cracked film penetrating into the substrate

Two Bounding Solutions for "PSB Oxide Initiation"

APPROXIMATION (A):

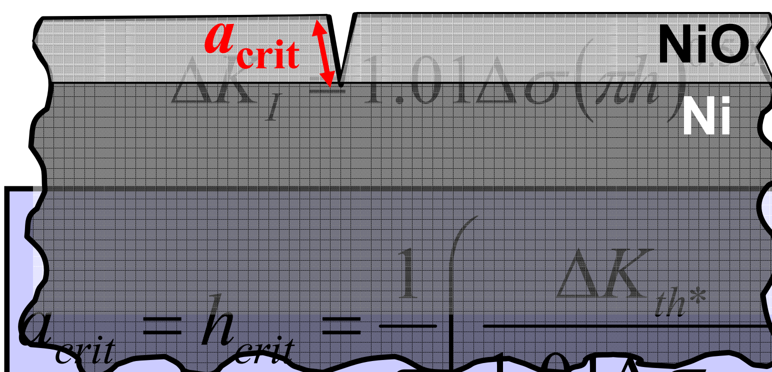


$$\Delta K = f\Delta\sigma(\pi a)^{0.5}$$

$$a_{crit} = \frac{1}{\pi}\left(\frac{\Delta K_{th*}}{1.1215\Delta\sigma_{app}}\right)^{2}$$

A crack in a homogeneous monolith

APPROXIMATION (B):



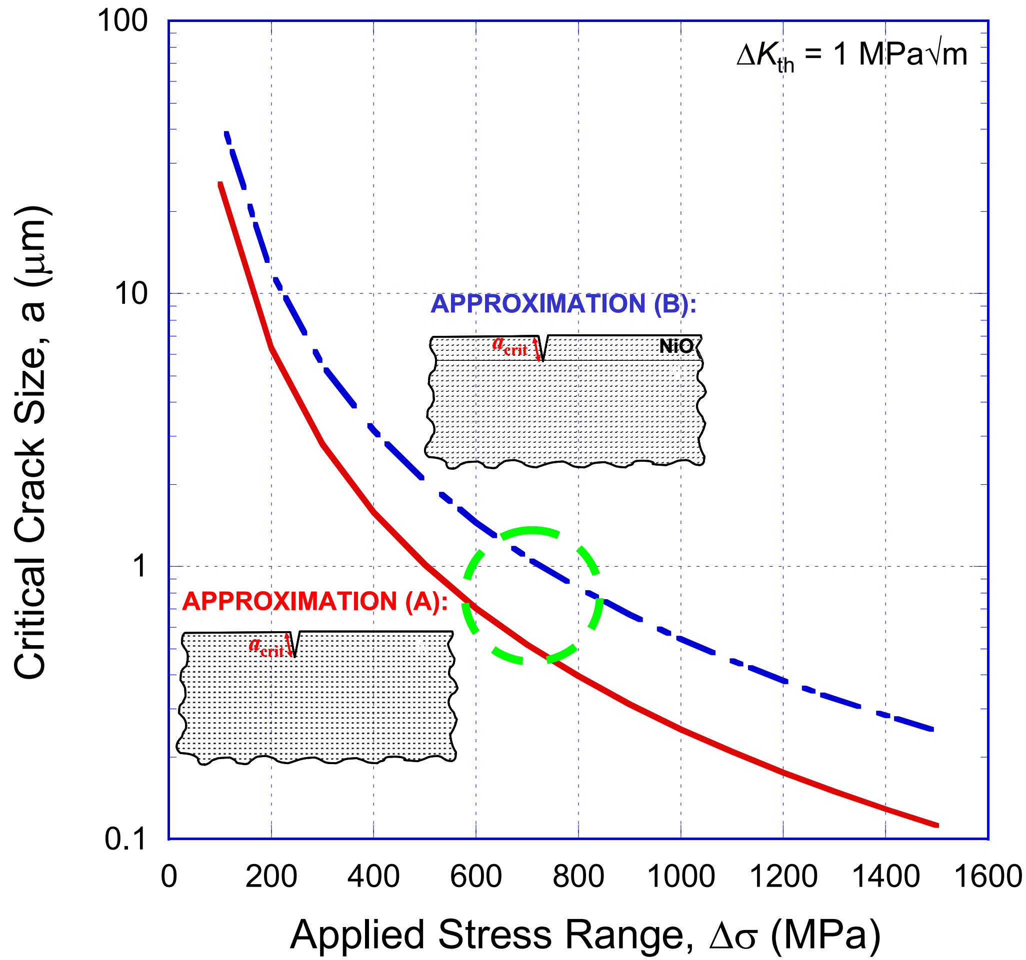
$$\Delta K_I = 1.01\Delta\sigma(\pi h)$$

$$a_{crit} = h_{crit} = \frac{1}{\pi}\left(\frac{\Delta K_{th*}}{1.01\Delta\sigma_{app}}\right)^{1.92}$$

A fully-cracked film penetrating into the substrate

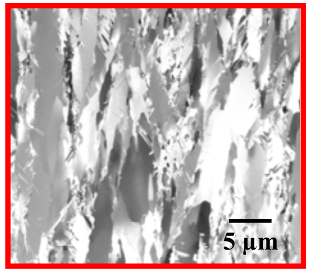
Ye, Suo, and Evans; Hutchinson and Suo (1992); Bleuth (1991)

Critical Oxide Thickness Depends on Applied Stress

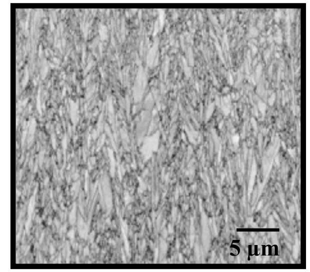


These estimates predict a critical oxide thickness in the vicinity of 600-1200 nm, depending on the applied stress levels.

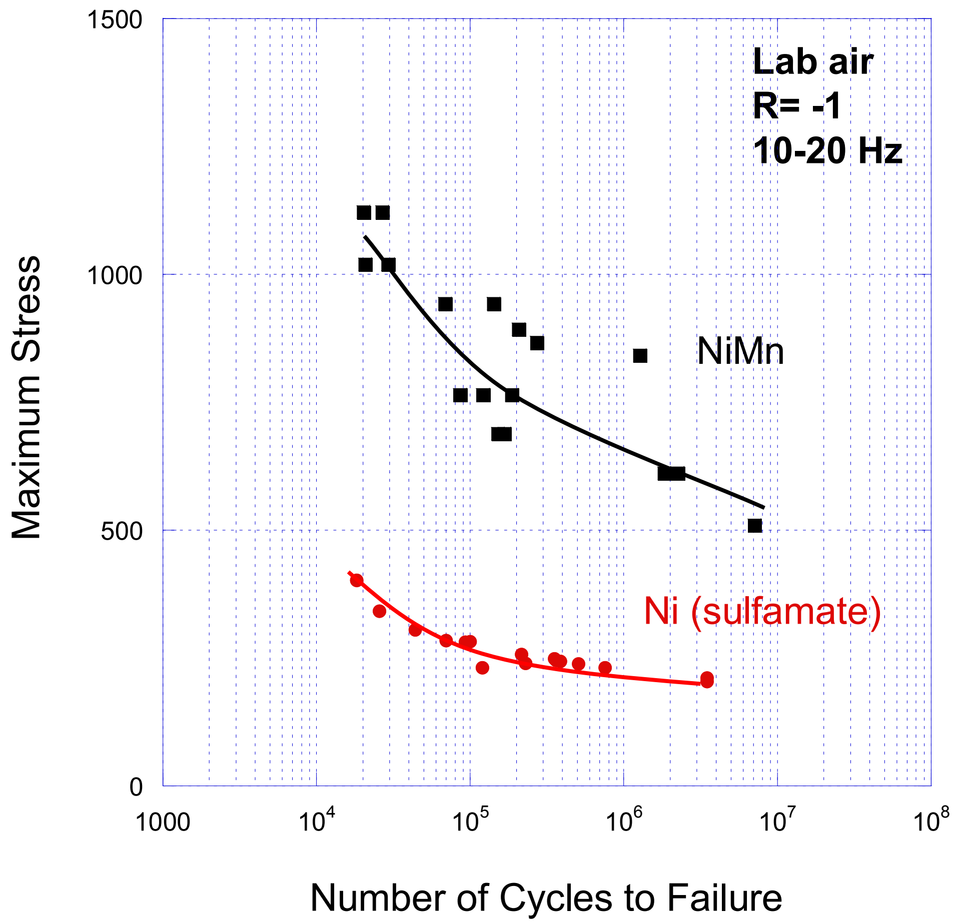
Fatigue Behavior: Two Ni Alloys



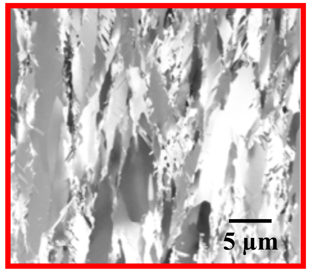
Ni



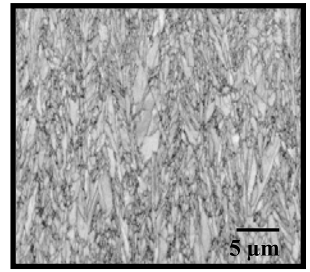
NiMn



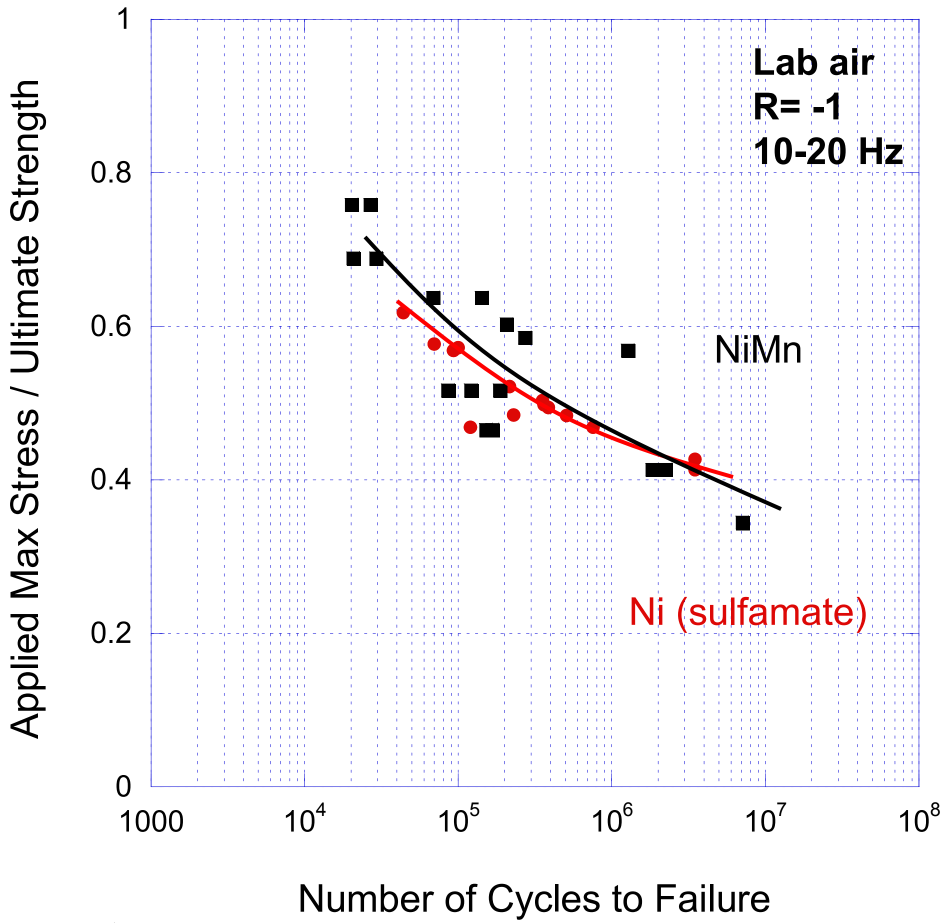
Fatigue: Normalized S-N Results



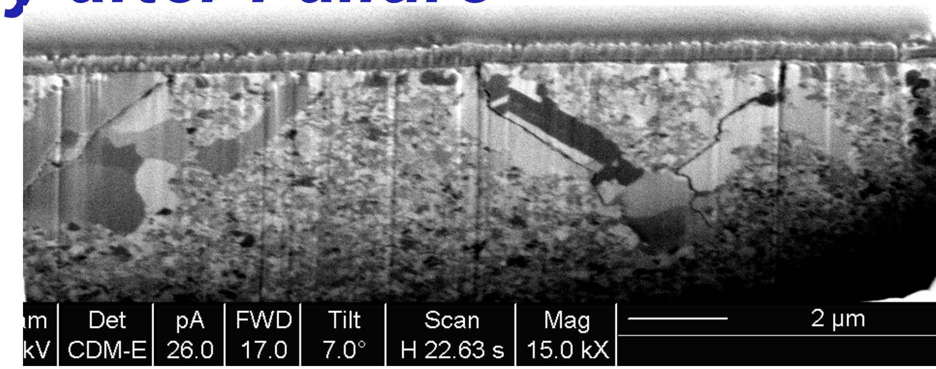
Ni



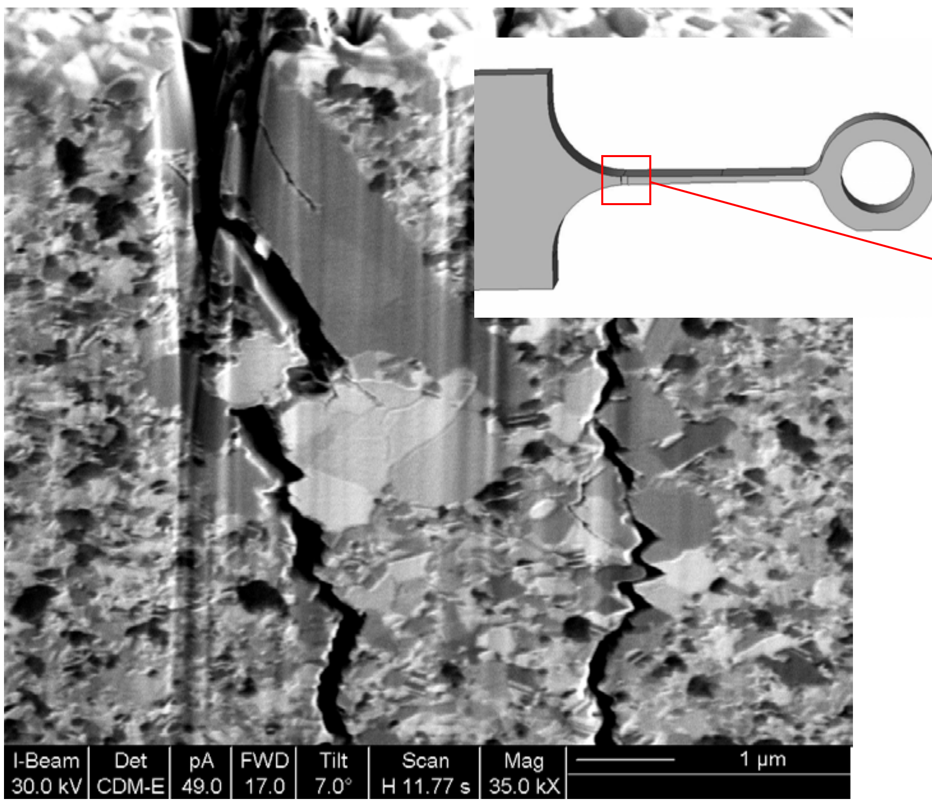
NiMn

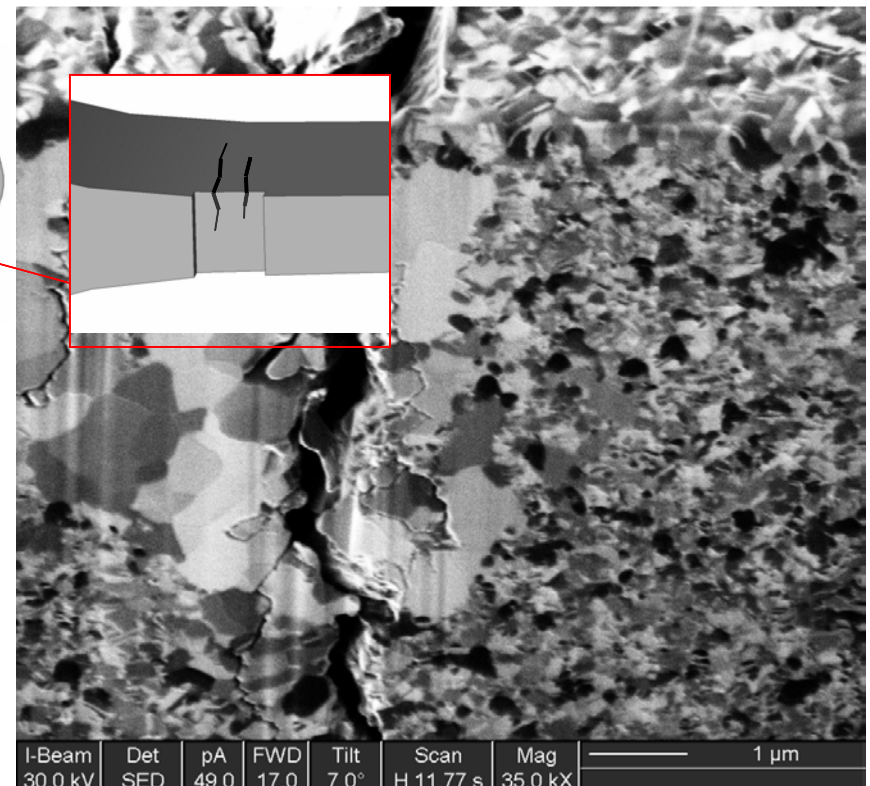


Fractography after Failure



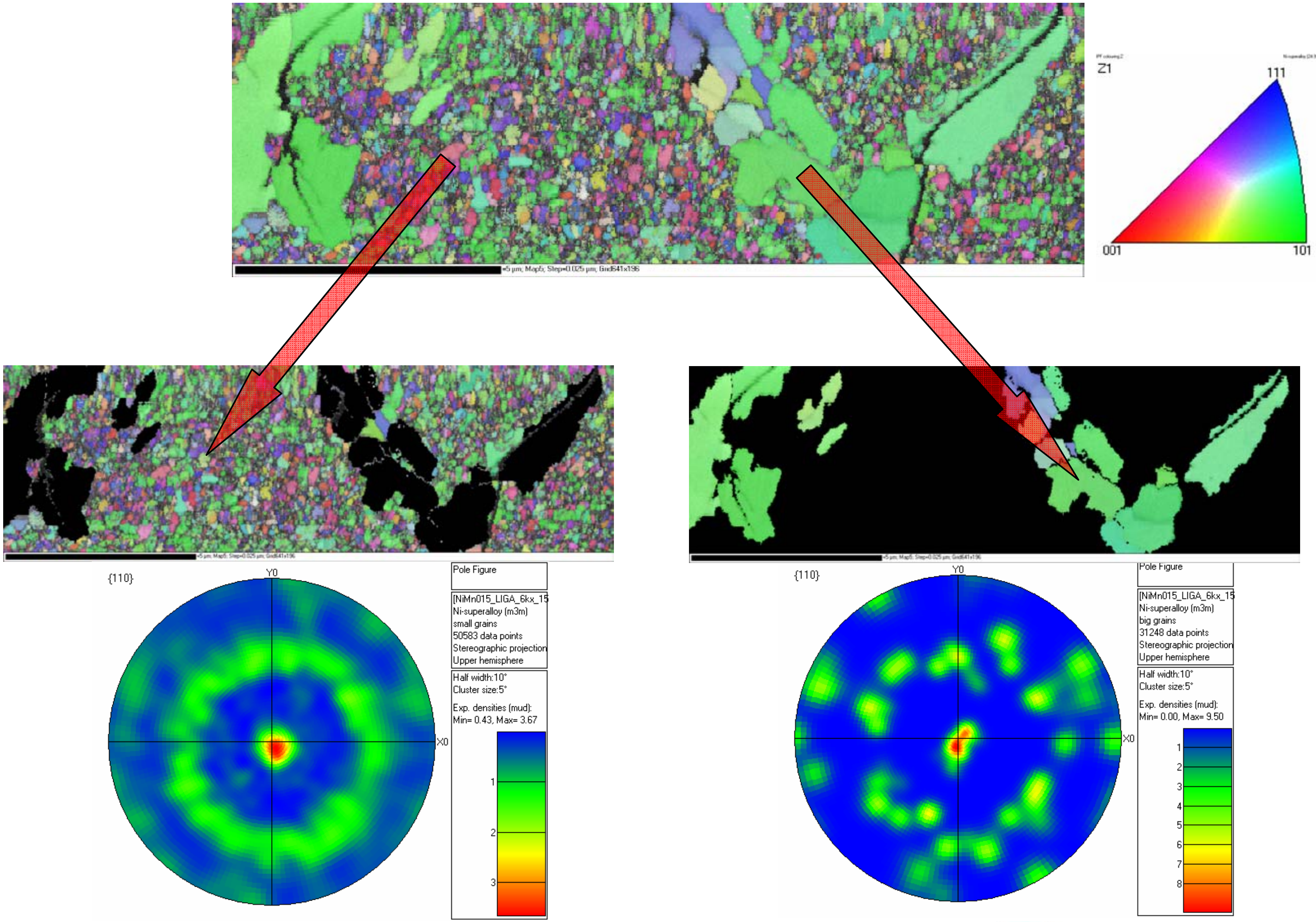
Subsurface microstructure revealed by FIB excavation and Ion Channeling Contrast Imaging





σ_{max} = 688 MPa; N_f = 166,997 cycles

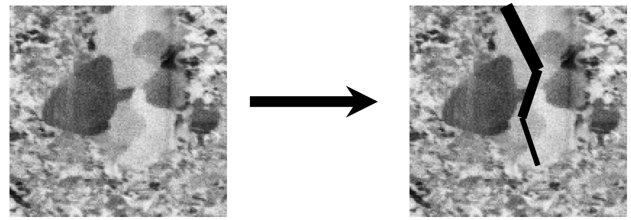
Large Grains Retain (110) Deposition Texture



Three Scenarios for Coarsening+Initiation

1

Deposition causes coarse grains.
Initiation prefers coarse regions.

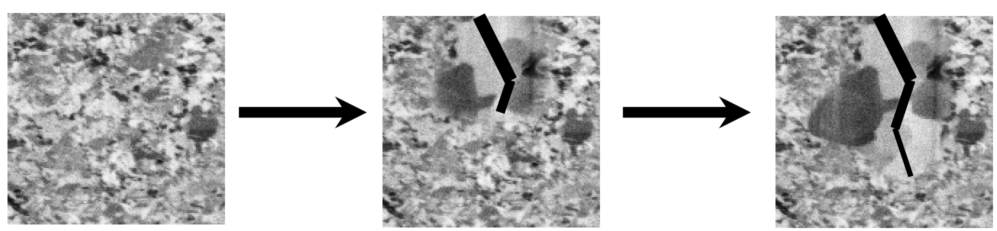


2

Fatigue stresses cause coarse grains.
Subsequent initiation prefers coarse regions.

3

Cracks initiate first.
Crack tip stress fields cause coarsening.



Three Scenarios for Coarsening+Initiation

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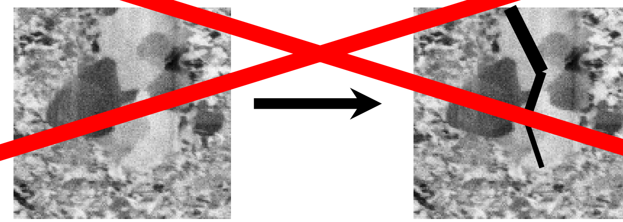
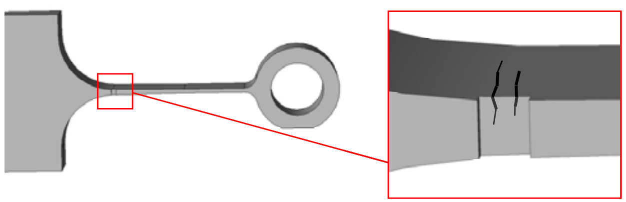
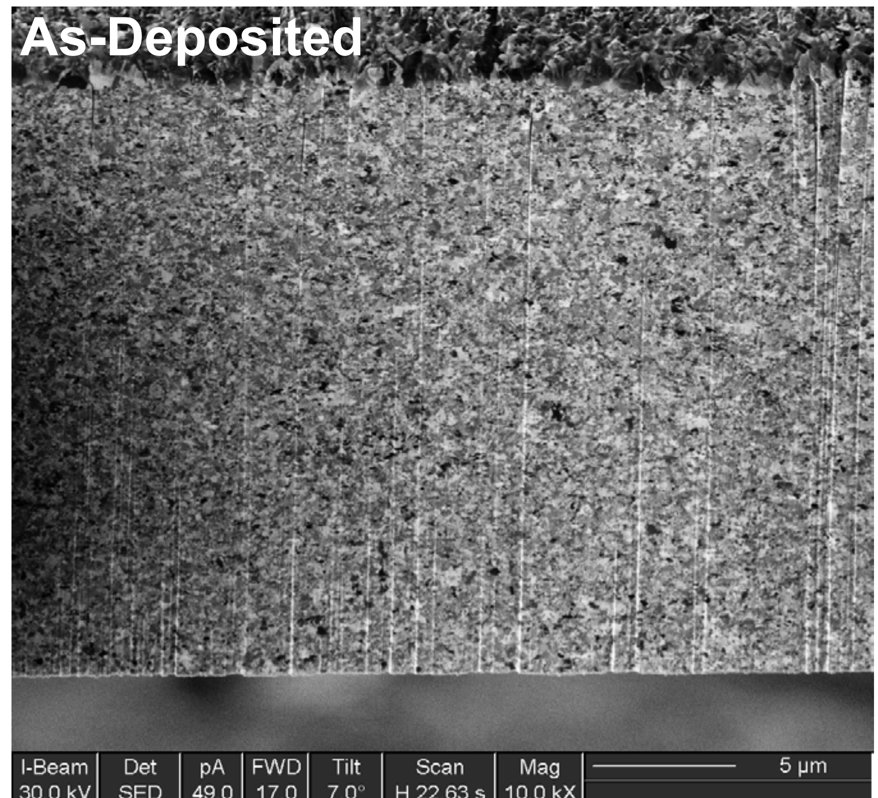
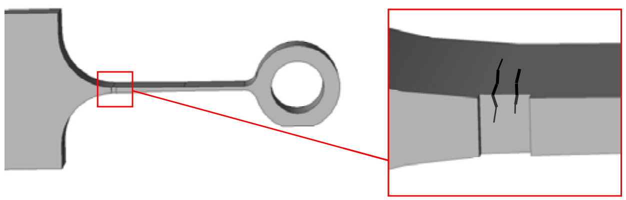
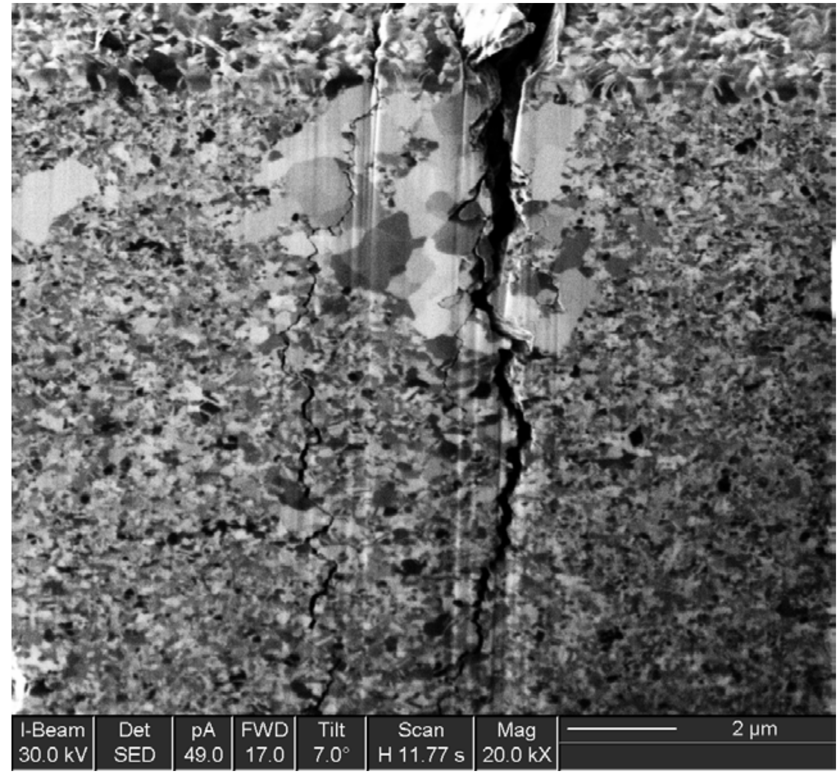






Three Scenarios for Coarsening+Initiation

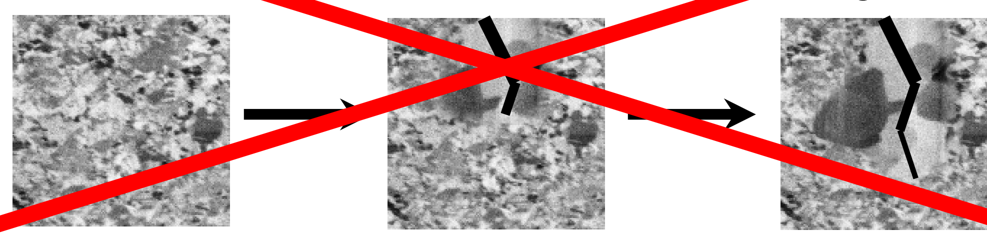




3

~~Cracks initiate first.~~

~~Crack tip stress fields cause coarsening.~~



Three Scenarios for Coarsening+Initiation

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Deposition causes coarse grains.
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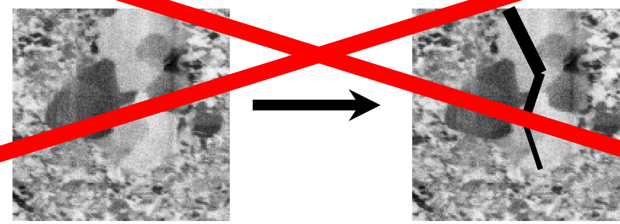

2

Fatigue stresses cause coarse grains.
Subsequent initiation prefers coarse regions.

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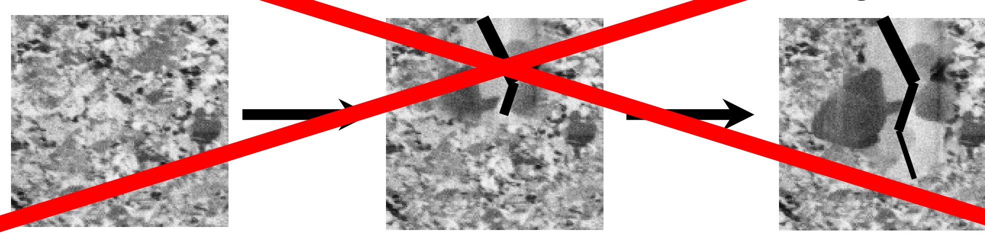
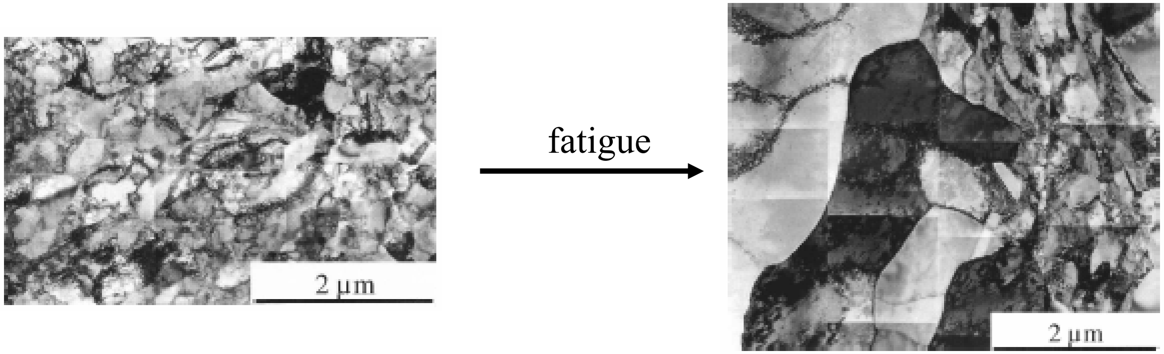
Crack tip stress fields cause coarsening.



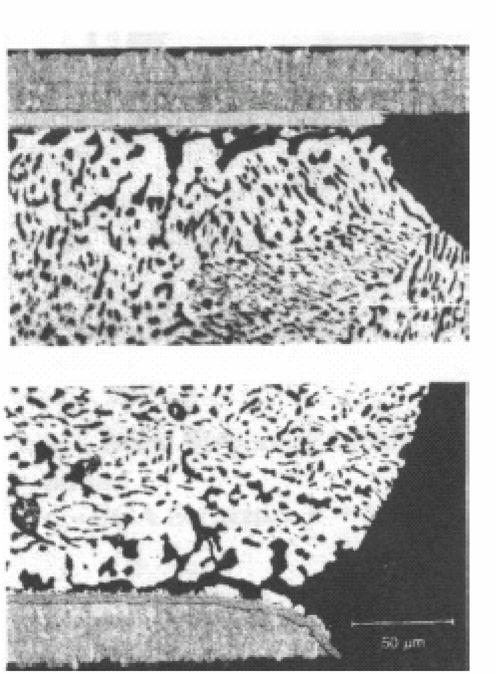
Other Examples of Mechanical Coarsening

High Cycle Fatigue of UltraFine Grained Copper (99.99%)



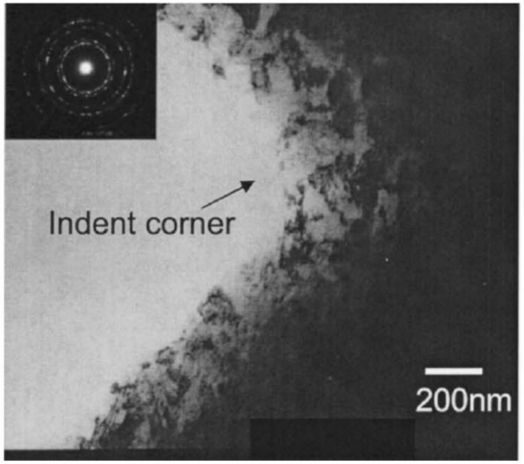
Höppel, Zhou, Mughrabi, and Valiev, 2002

Thermomechanical Fatigue of Solder Alloys



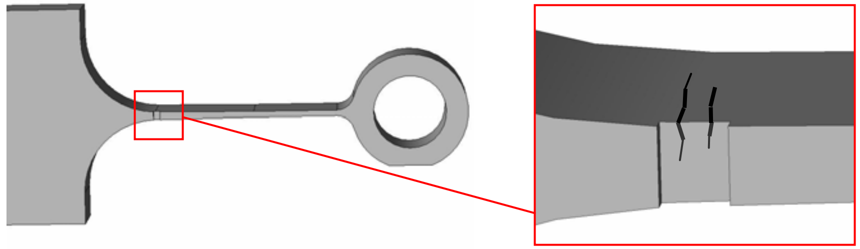
Muller and Dreyer, Int J Solids Struct, 2000

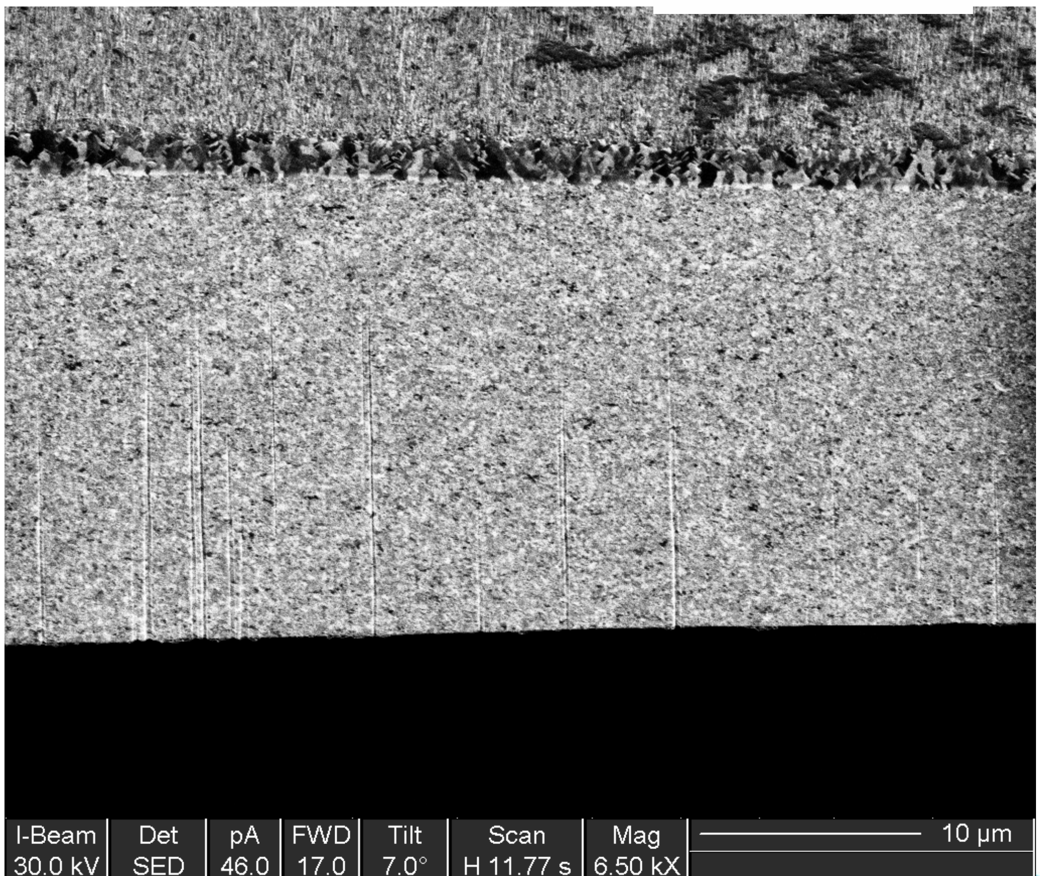
Monotonic Indentation of Nanocrystalline Copper (99.999%)



Zhang, Weertman, and Eastman, 2003

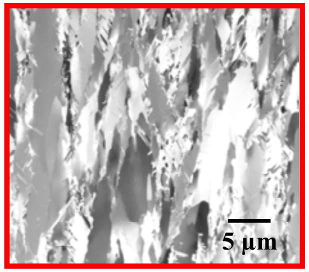
After a Single Fatigue Cycle, No Coarsening Is Found



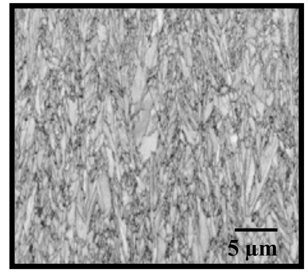


$\sigma_{max} = 867$ MPa

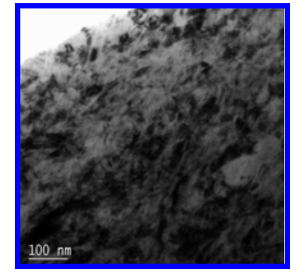
Fatigue Comparison: All 3 Alloys



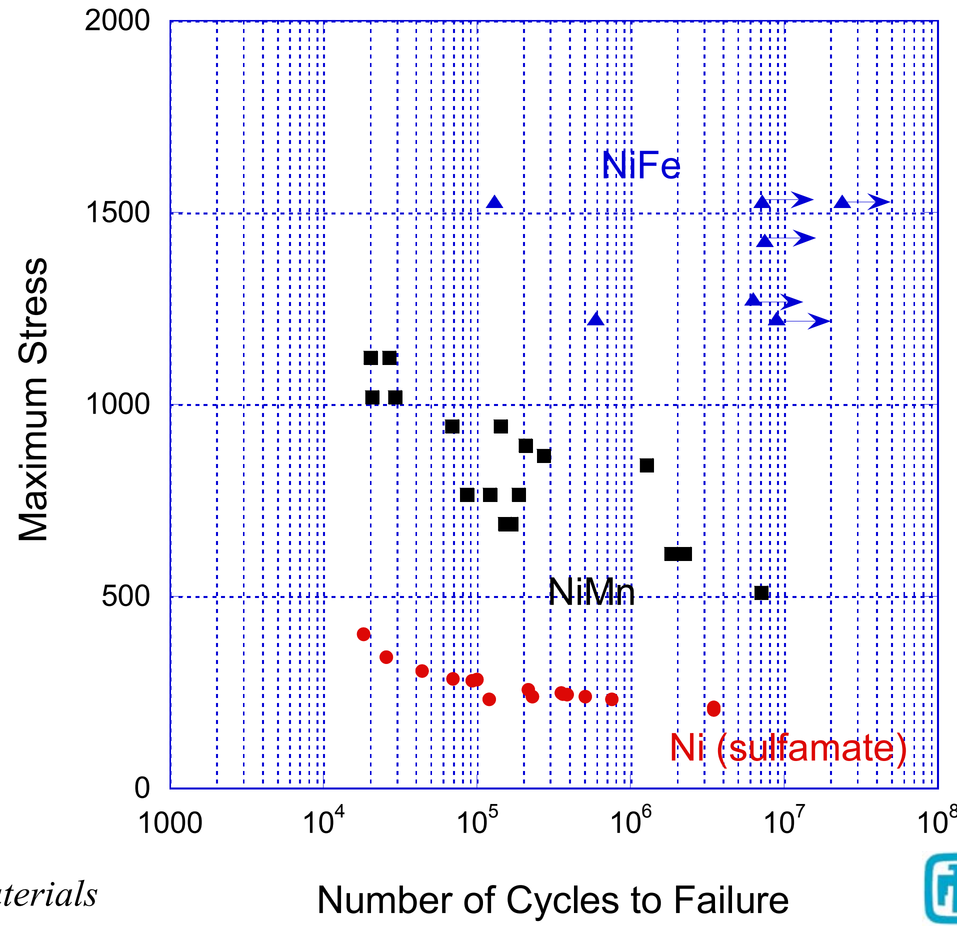
Ni



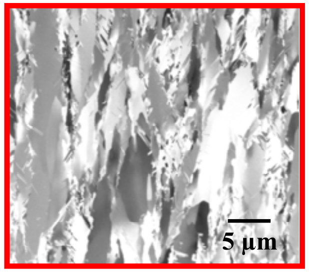
NiMn



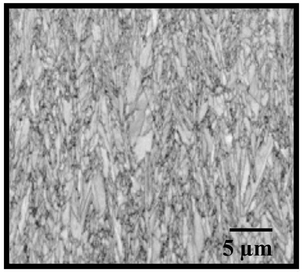
NiFe



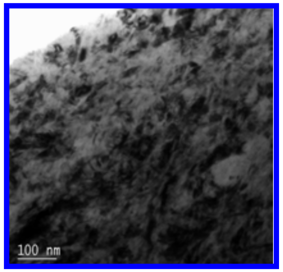
Fatigue Comparison: All 3 Alloys



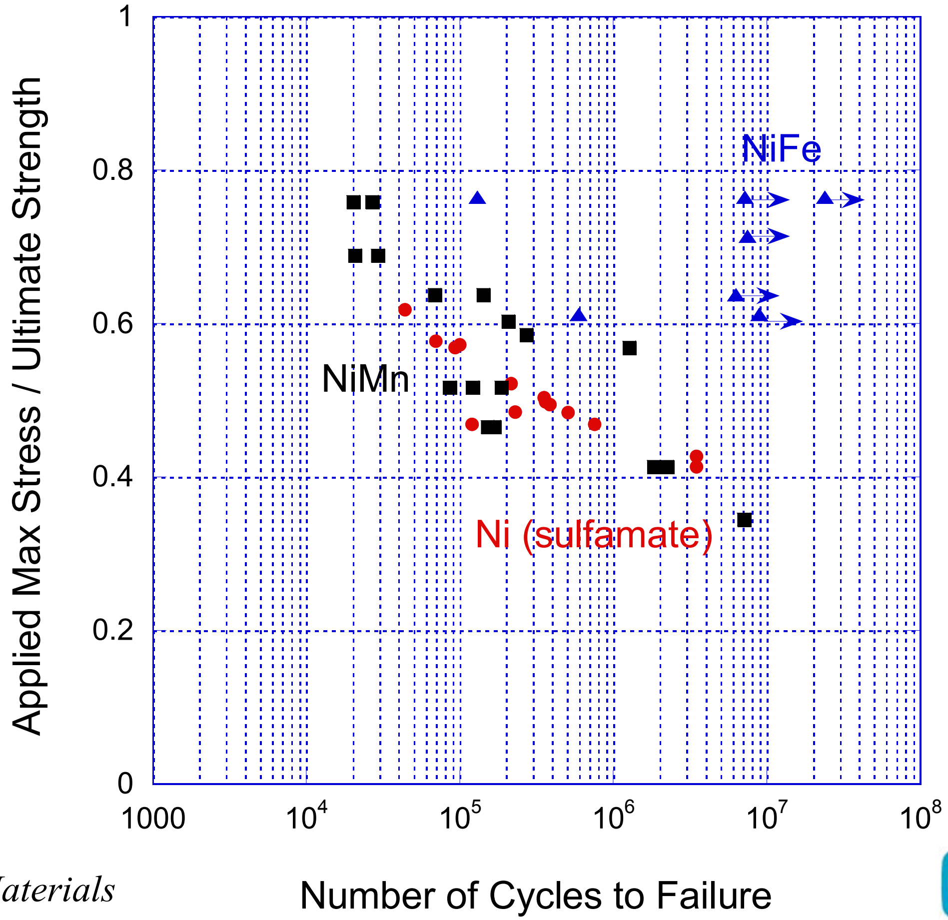
Ni



NiMn



NiFe



Summary: Fatigue Behavior in Three LIGA Electrodeposited Ni-based Alloys

Alloy

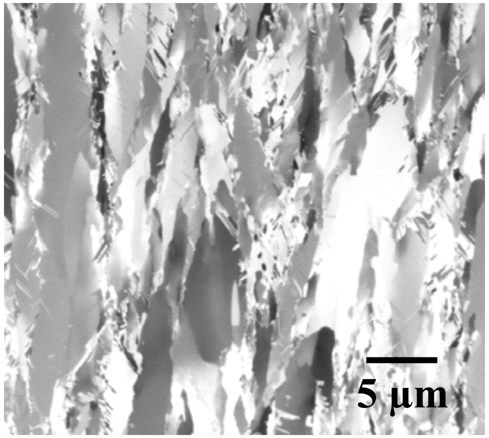
Ni (sulfamate bath)

Ni-Mn

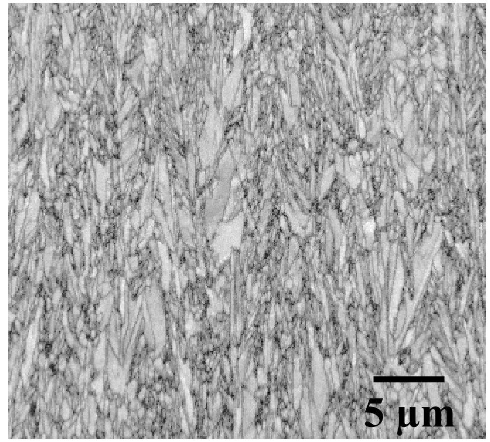
Ni-Fe

Microstructure

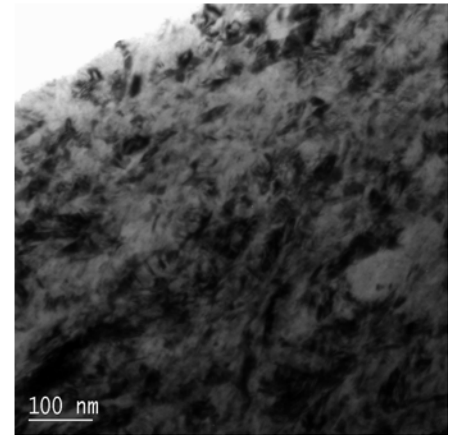
Ni — Grain Size ~ 3000 nm



Ni-Mn — Grain Size ~ 100 nm



Ni-Fe — Grain Size < 50 nm



Fatigue Limit

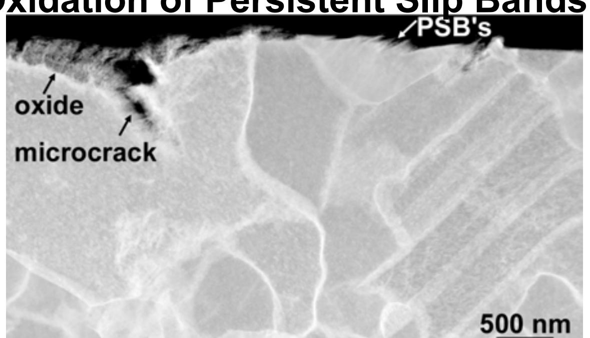
Ni: "Normal S-N Behavior": $\sigma_{fat} / \sigma_{uts} = 0.35$

Ni-Mn: "Normal S-N Behavior": $\sigma_{fat} / \sigma_{uts} = 0.35$

Ni-Fe: "Enhanced S-N Behavior": $\sigma_{fat} / \sigma_{uts} >> 0.35$

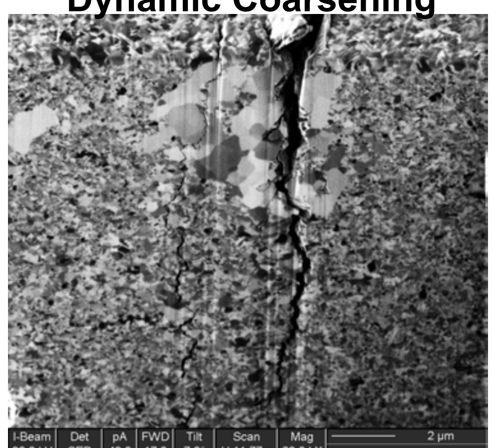
Initiation

Oxidation of Persistent Slip Bands



(Boyce, Michael and Kotula, Acta Mater., 2004)

Dynamic Coarsening



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