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Fatigue Stress Concentration and Notch Sensitivity in Nanocrystalline Metals

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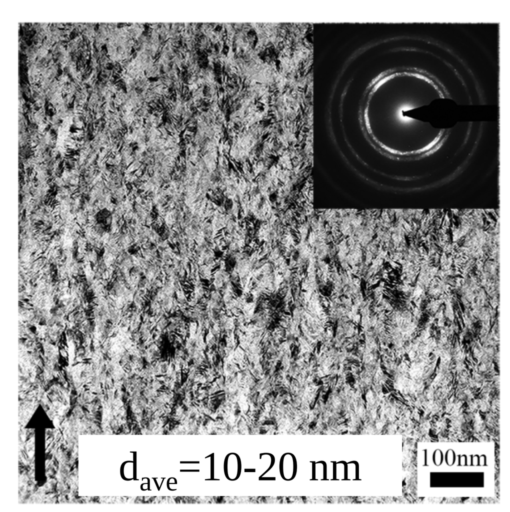
Introduction

Nanocrystalline metals have shown the potential for ultrahigh fatigue resistance, which has been mostly attributed to the suppression of dislocation-based deformation mechanisms and the promotion of grain boundary related mechanisms. The unique deformation behavior of nanocrystalline metals may also lead to distinct material responses in the presence of traditional stress concentrators, e.g. notches, and thus classical stress concentration theory may not be sufficient. For these materials to be predictable and reliable in their future applications, it is critical to understand the stress concentration effects of notches and other geometric discontinuities on their fatigue properties, especially since these metals can be particularly susceptible to processing related flaws (e.g. pores, inclusions, and surface roughness).

Material Synthesis

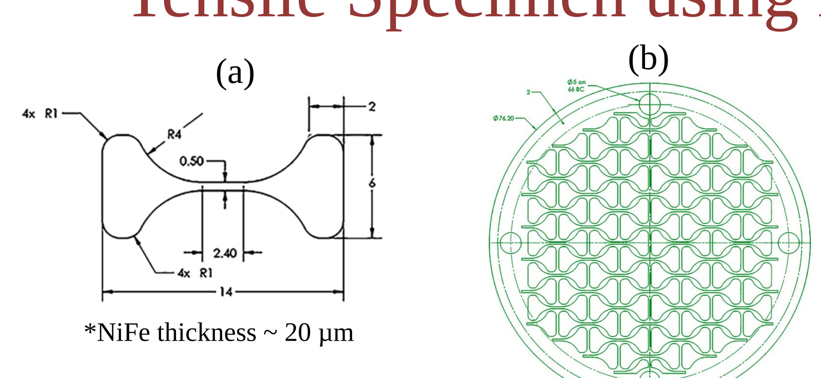
Electrodeposited Nanocrystalline NiFe

- Nanocrystalline NiFe produced by pulsed electrodeposition
  - 1 sec "on cycle", 3 sec "off cycle"
  - Stir-bar agitation
  - 30°C, 4.8pH
  - Si with 100nm Cu substrate
- 20 μm thick NiFe coating
- Nominal composition ~ Ni-40wt%Fe
- Average grain size ~10-20 nm



Representative TEM micrograph of the electrodeposited NC NiFe

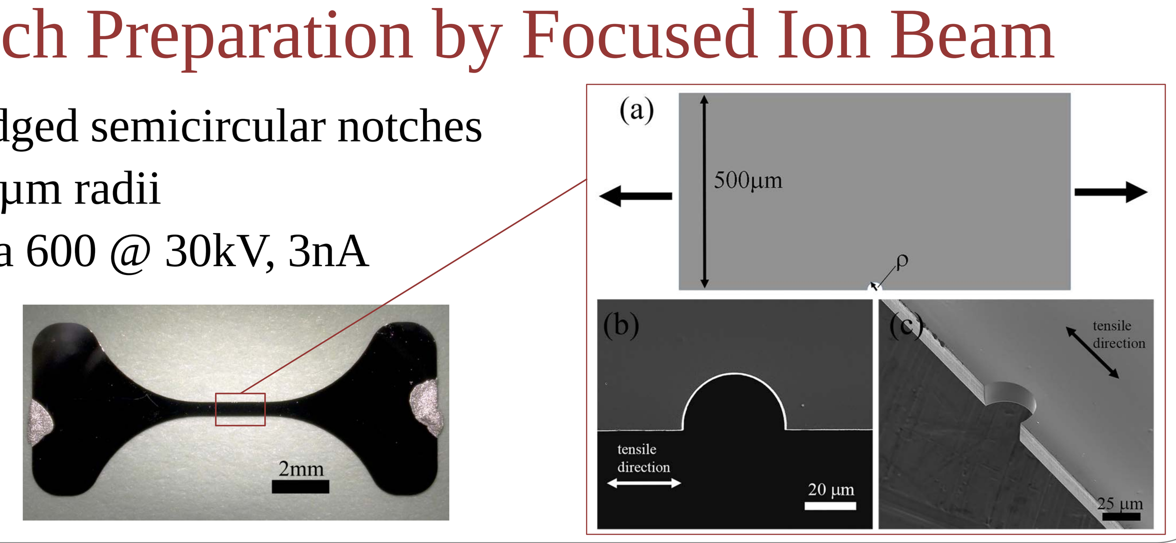
Tensile Specimen using Photoresist Mold



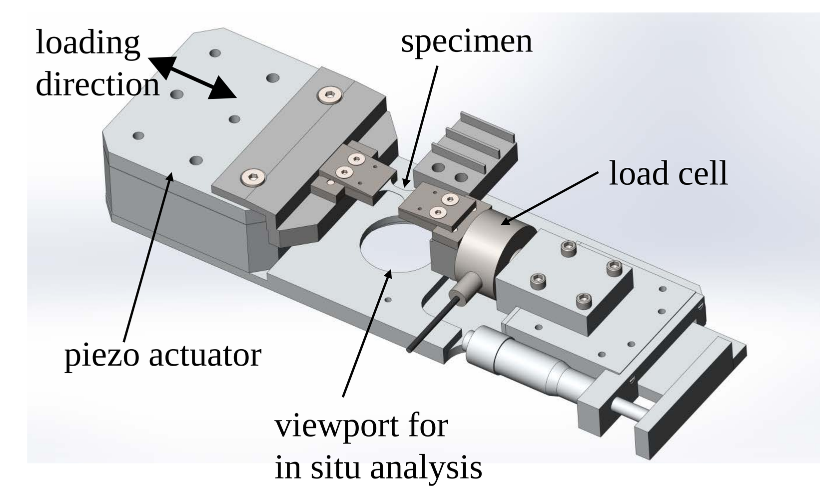
(a) dimensioned (mm) drawing of the tensile specimens defined by the photoresist mold. (b) drawing of the masked wafer (actual size). Wafer was Si with a 100 nm thick Cu coating.

Notch Preparation by Focused Ion Beam

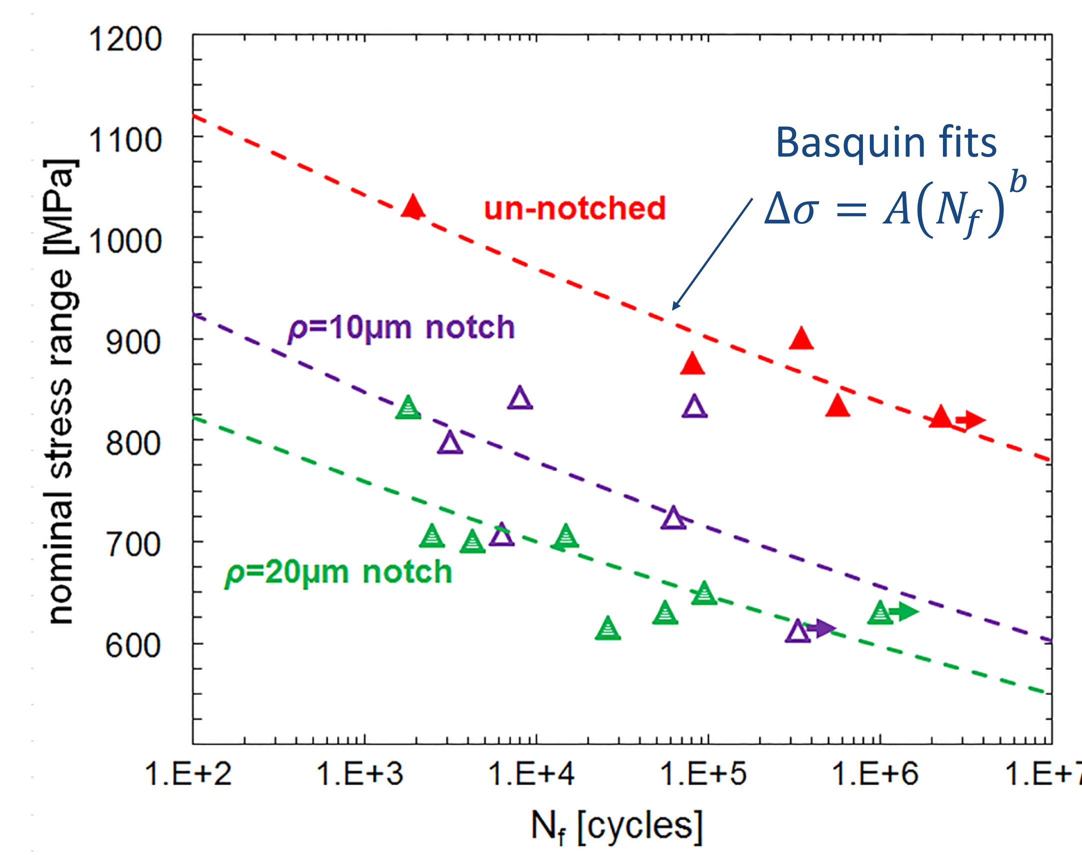
- Single-edged semicircular notches
- 10 or 20 μm radii
- FEI Nova 600 @ 30kV, 3nA



Fatigue Testing



- Custom built piezo actuated *in situ* fatigue tester for thin foil testing
- Fatigue conditions:
  - Constant-force
  - Sinusoidal loading
  - 4-6 Hz



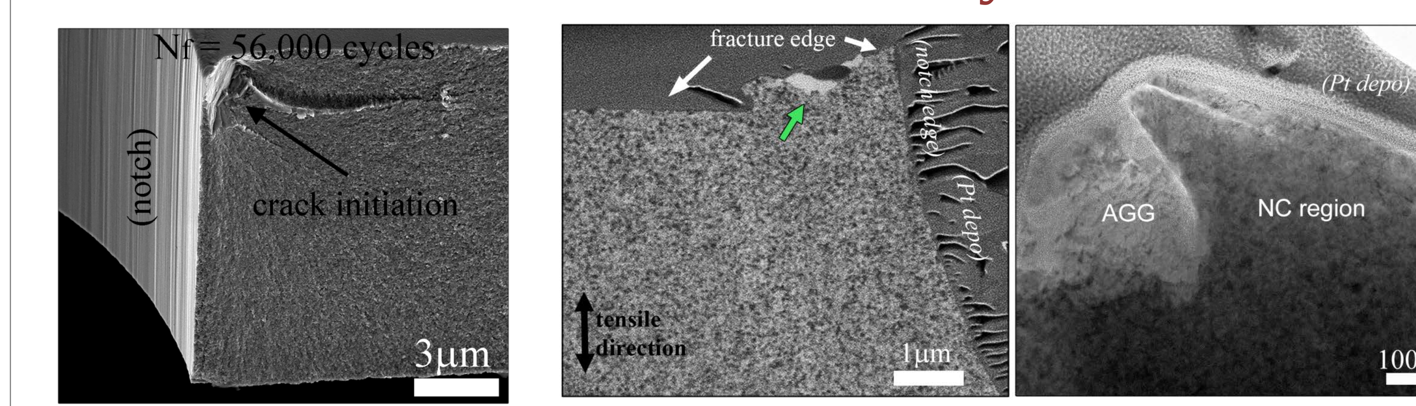
$$q = \frac{(K_f - 1)}{(K_t - 1)}$$

Summary of the key results showing the fatigue strength exponent (Basquin exponent), *b*, and the Basquin coefficient, *A*, the approximated endurance limit, $\Delta\sigma_{lim}$, fatigue stress concentration factor, K_f, and notch sensitivity factor, *q*.

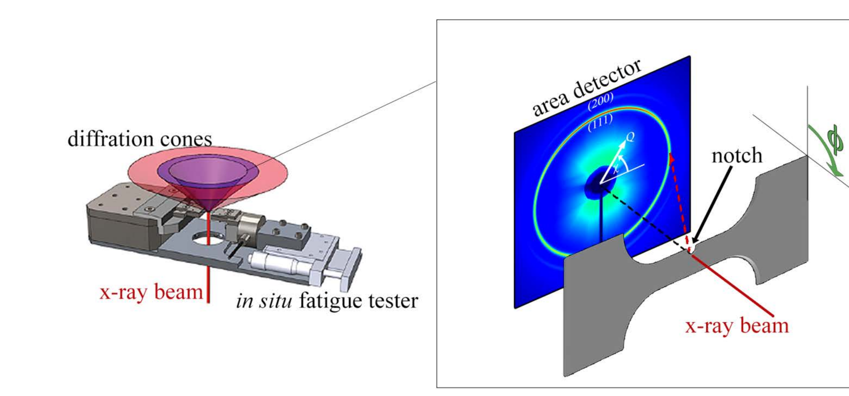
ρ (μm)	b	A (MPa)	RMS (MPa)	$\Delta\sigma_{lim}$ (MPa)	K_t	K_f	K_f/K_t	q
none	-0.0315	1295	23	838	n/a	n/a	n/a	n/a
20	-0.0349	966	44	596	2.73	1.41	0.52	0.24
10	-0.0373	1097	70	655	2.89	1.28	0.44	0.15

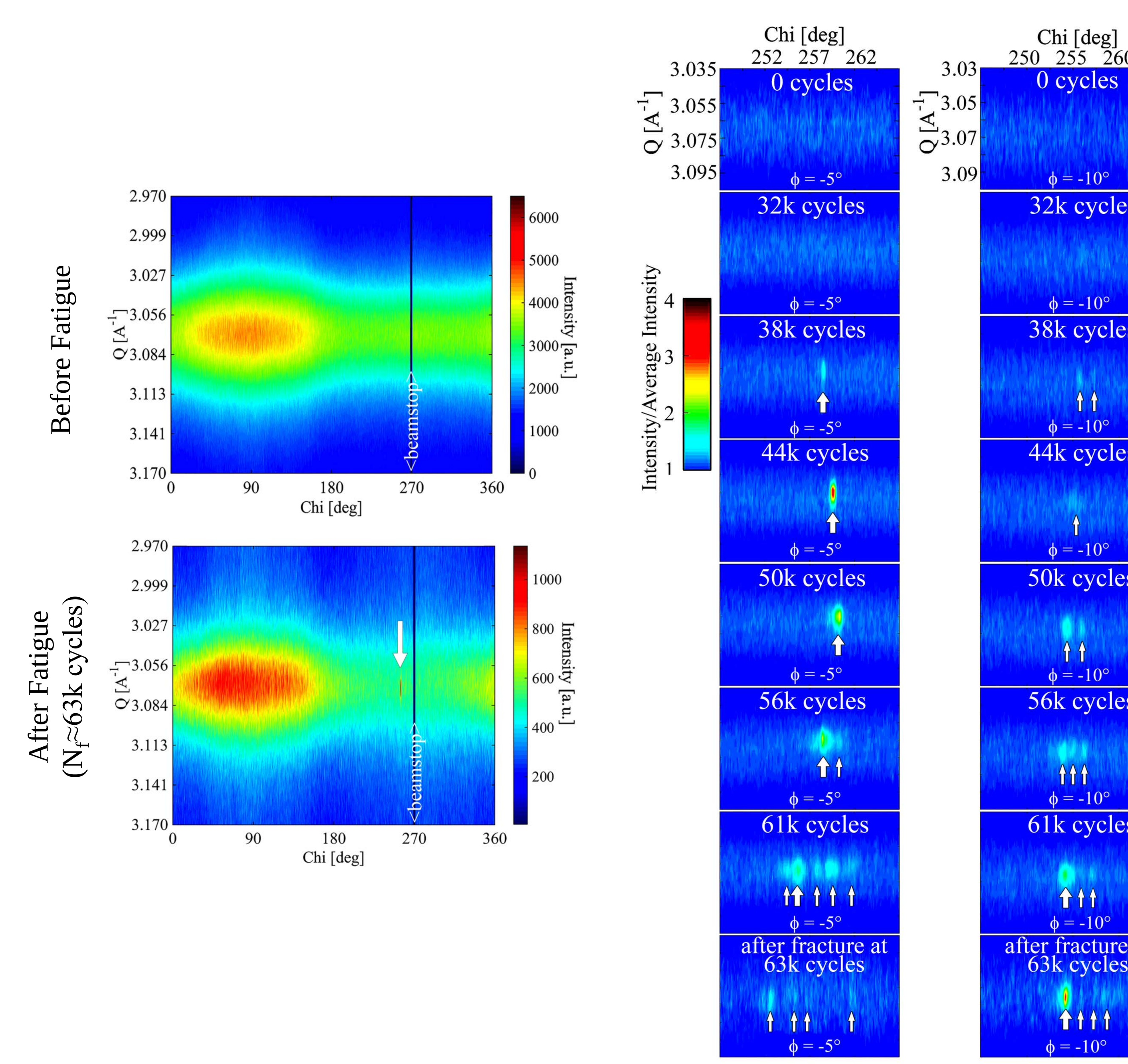
Microstructural Analysis under Notches

Post-Fracture Analysis



In Situ XRD detection of AGG





Summary

The fatigue stress concentration, notch sensitivity, and crack initiation in nanocrystalline NiFe with an average grain size of 10-20 nm was investigated by performing tension-tension fatigue to failure on specimens containing 10 and 20 μm radii FIB-milled notches. The Wöhler S-N curves revealed dramatic reductions in the fatigue resistance of the notched specimens, corresponding to notch sensitivity factors of 0.15-0.24, much larger than might be expected from their coarse-grained counterparts. Post-fracture microstructural analysis and *in situ* synchrotron x-ray diffraction revealed fatigue-driven abnormal grain growth (AGG) as the predominant precursor for crack initiation and subsequent catastrophic failure. We hypothesize that the stress concentrations from the notches led the early promotion of AGG in the notched specimens, thus leading to the high notch sensitivity in the material. Therefore, devising means to suppress the onset of AGG in these materials will be paramount to delaying fatigue crack initiation, thus dramatically reducing the fatigue stress concentration effects and improving the notch sensitivity of nanocrystalline metals.

U.S. DEPARTMENT OF ENERGY | Office of Science

NNSA National Nuclear Security Administration

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