Enhancing irradiation tolerance of steels via nanostructuring by innovative manufacturing techniques

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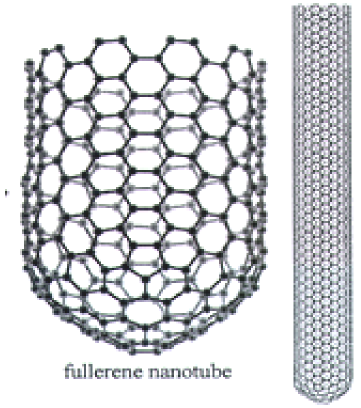
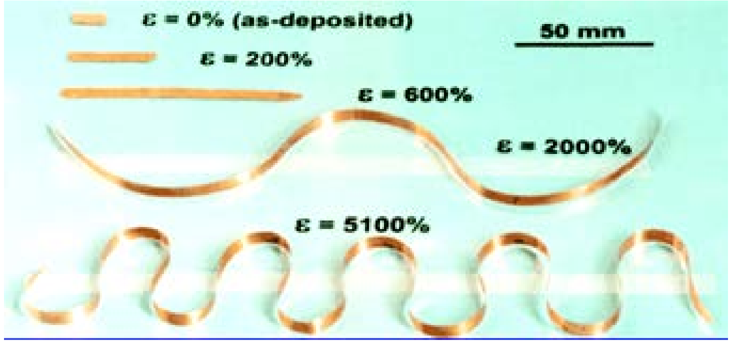
Why We Need to Go into NANO

Carbon Nanotubes



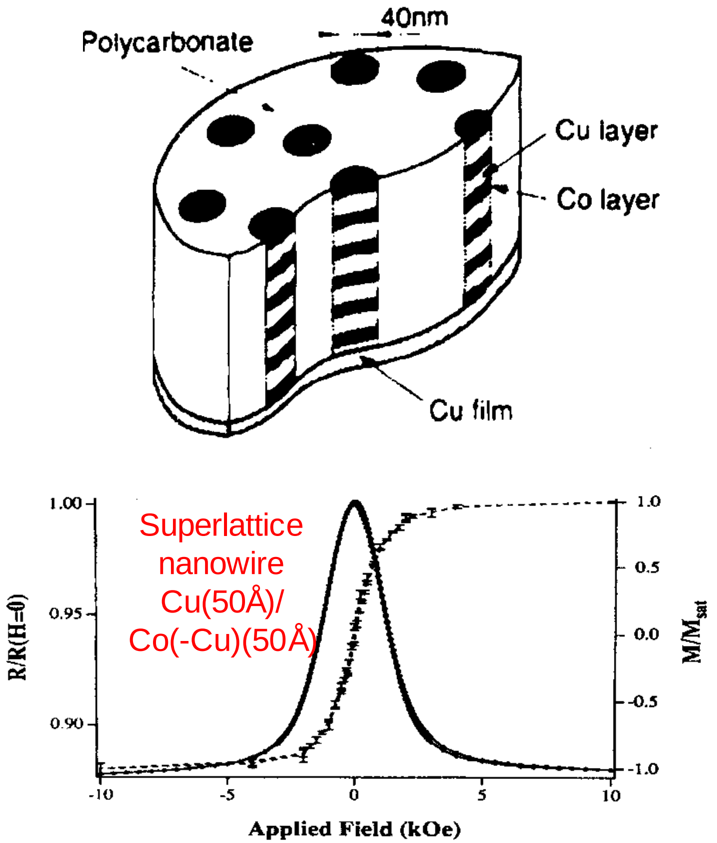
Conductive fine probe
with a few nm diameter

Superextensibility of nc-Cu at room T



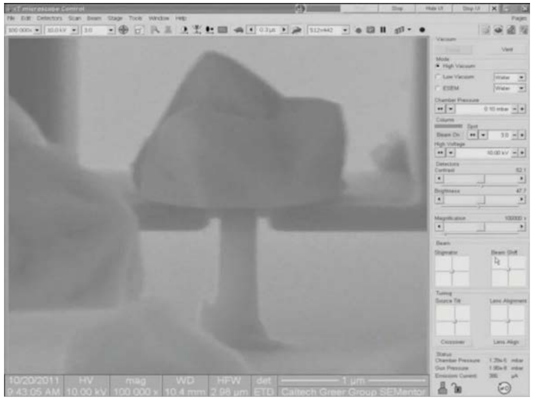
Lu et al. Science (2000)

Giant Magnetoresistance (GMR)

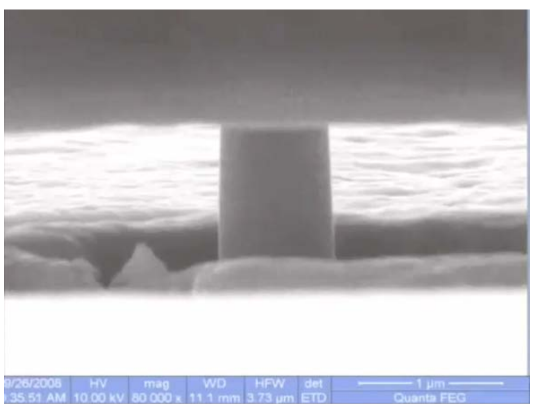


Schwarzacher, et al,
IEEE Trans. Magnetics (1996)

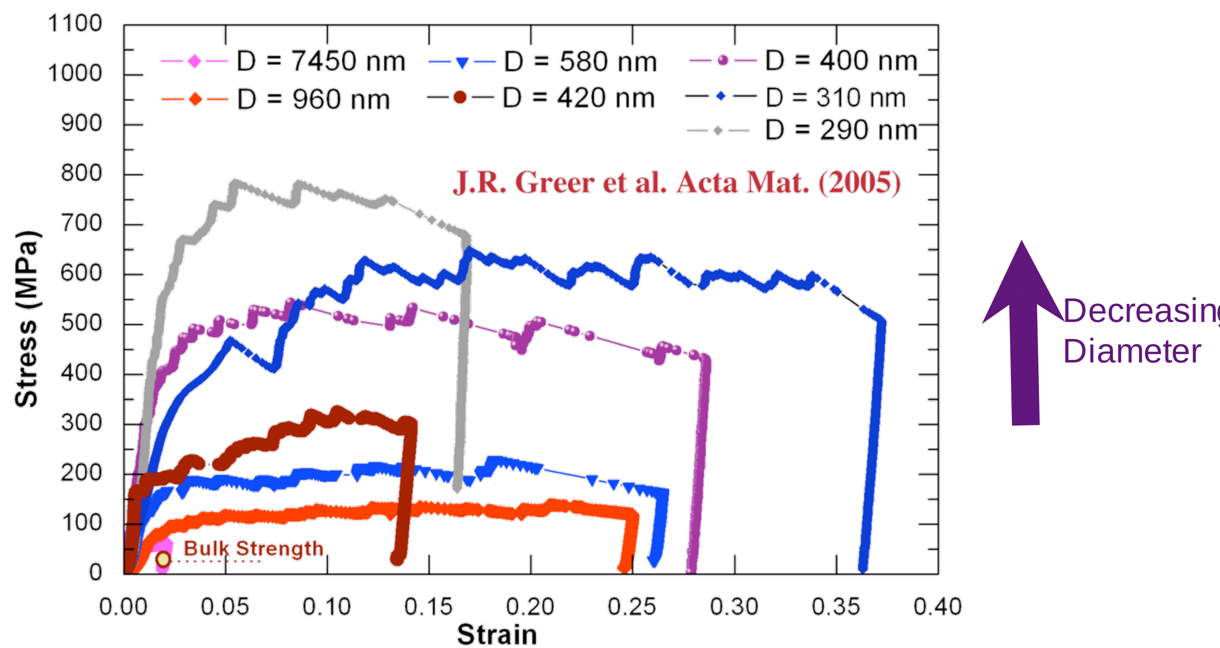
Why We Need to Go into NANO



1 micron



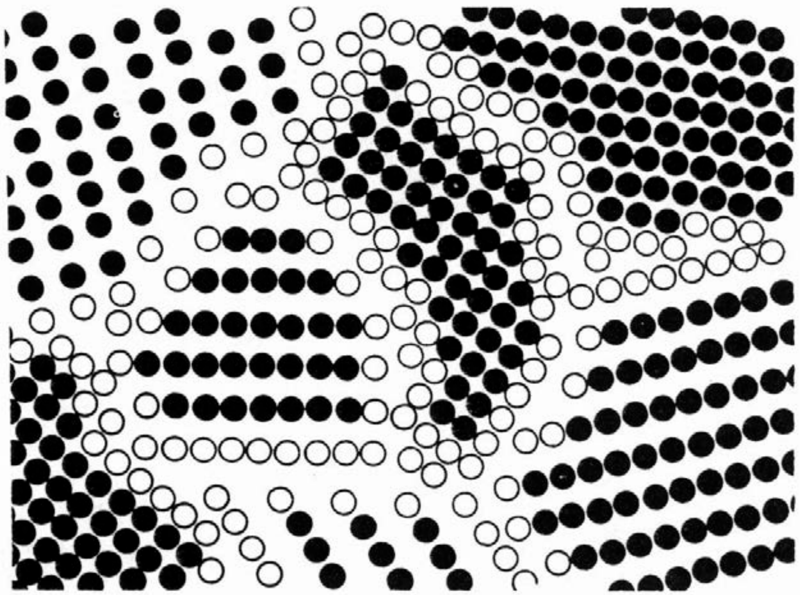
1 micron



Single-crystalline metals

Smaller is Stronger

Concept of bulk nanostructured materials

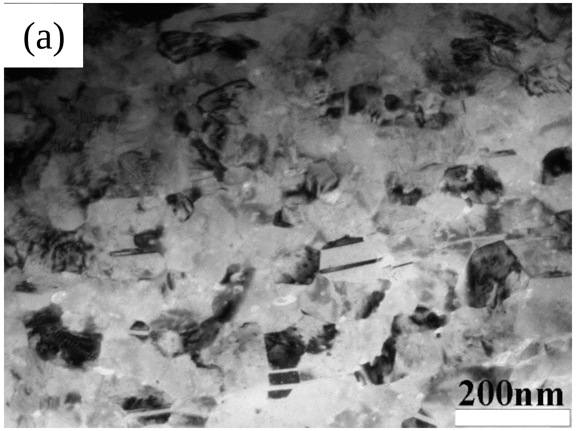


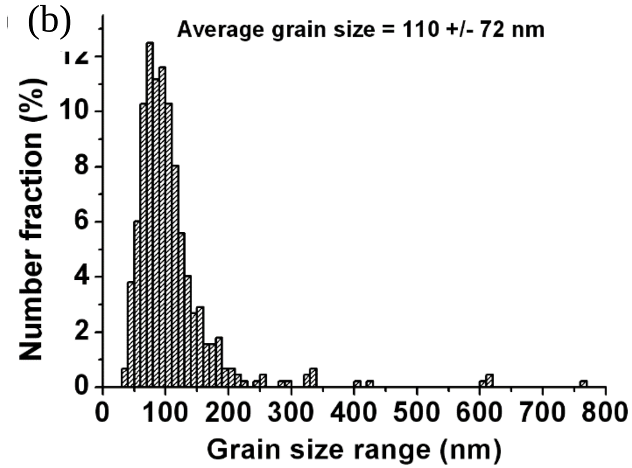
Single or multiple-phase polycrystals with structural features (grain, subgrain, dislocation cell, twin, etc.) smaller than 100 nm

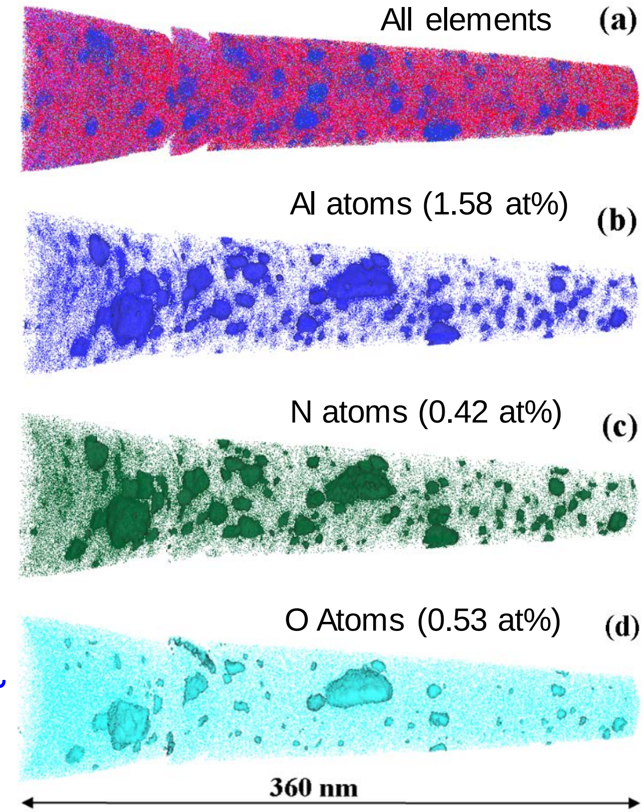
- D=5 nm, fraction of GBs=50%
- D=100 nm~1 μm, ultrafine grained materials; D=1~10μm, fine grained materials; D>10 μm, coarse grained conventional materials

H. Gleiter, in Proceedings of the second Risϕ International Symposium on Metallurgy and Materials Science,1981, Denmark: Risϕ National Laboratory, Roskilde

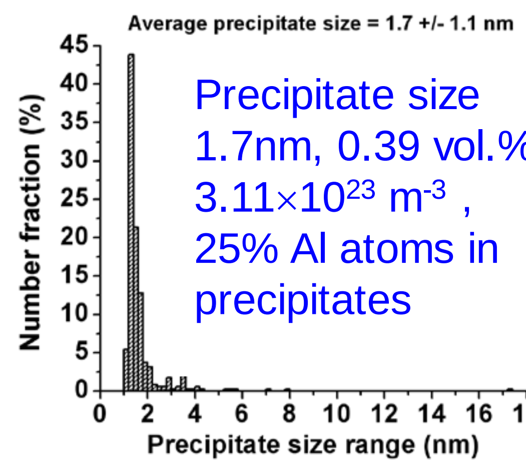
High-strength bulk nanostructured brass







Alloy composition	Stacking fault energy (mJ/m^2)	Processing condition	Yield strength (MPa)
CuZn30	7	Liquid nitrogen temperature dynamic plastic deformation	717
CuZn30	7	HPT + cold rolling	690
CuZn30	7	HPT	~ 962 (1/3 microhardness)
CuZn30	7	Cryomilling + room temperature milling	877
Cu-12.1 at % Al – 4.1% at% Zn	7	Cryomilling + room temperature milling	1067
Cu–16 at.% Al	6	ECAP	740
Cu–16 at.% Al	6	HPT	820
Cu–11 at.% Zn	33	ECAP	~ 500

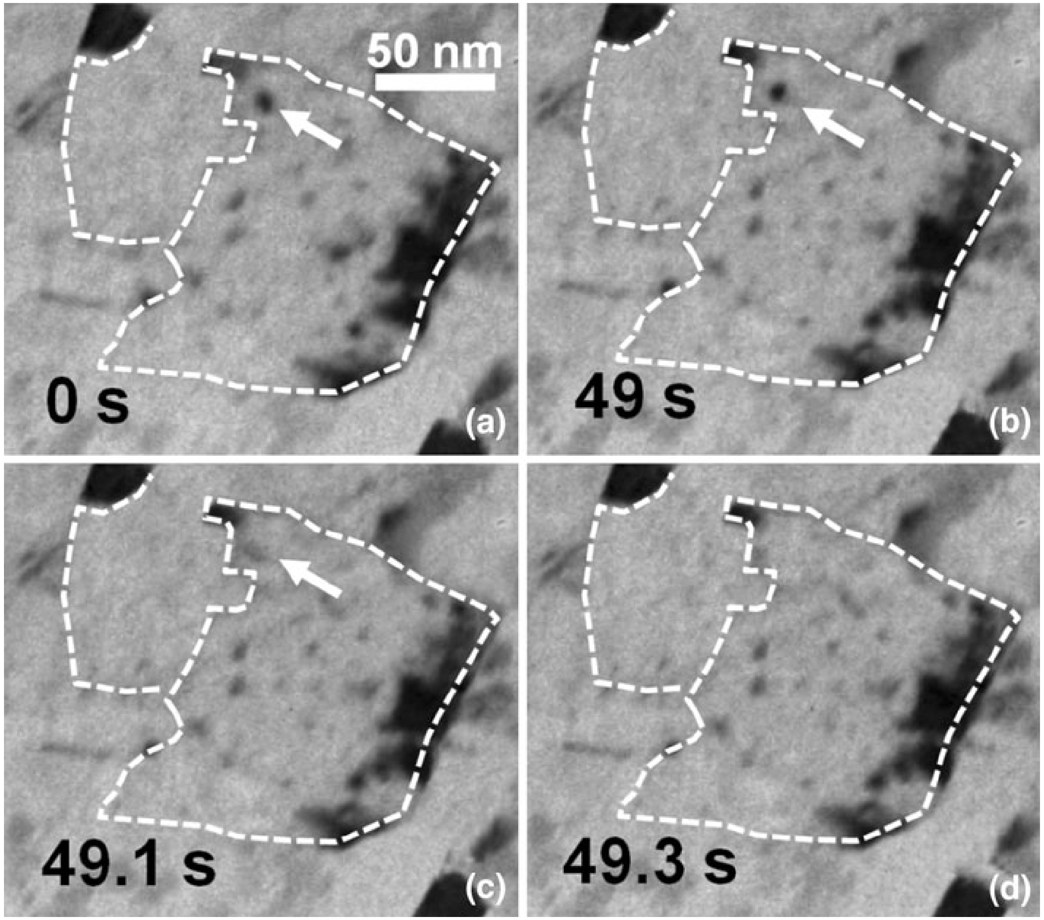


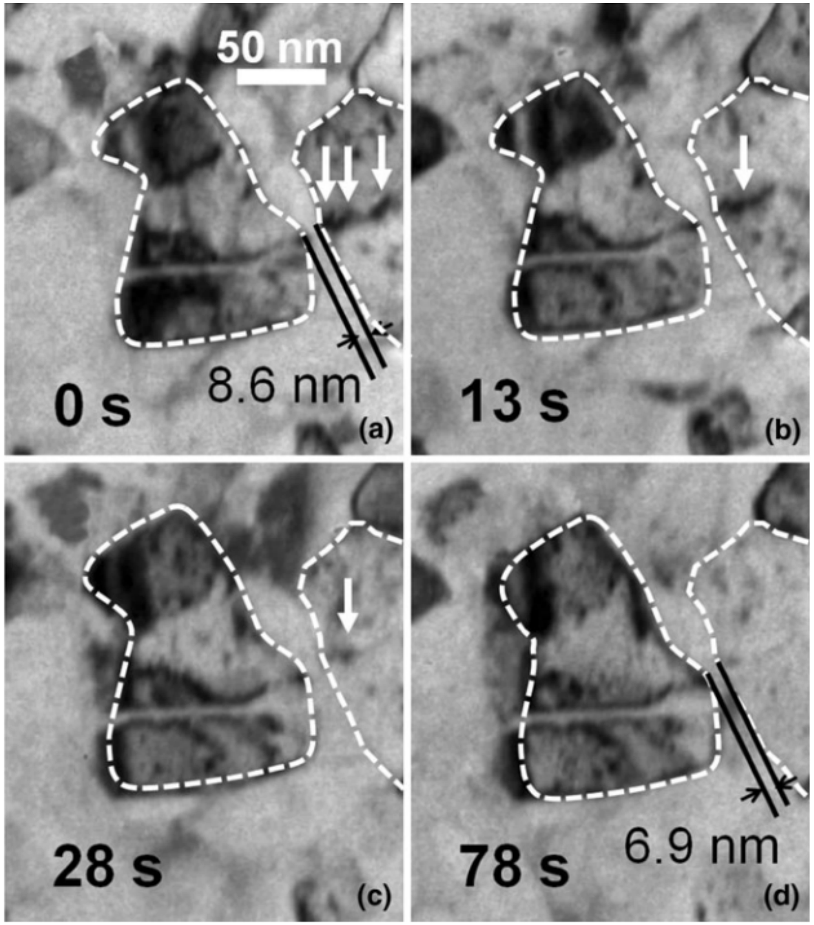
Precipitate size 1.7nm, 0.39 vol.%, 3.11×10^{23} m^{-3} , 25% Al atoms in precipitates

Wen HM, Lavernia EJ, Scripta Mater 67 (2012) 245

Wen HM, Lavernia EJ, et al, Acta Mater 61 (2013) 2769

GBs as sinks for irradiation defects

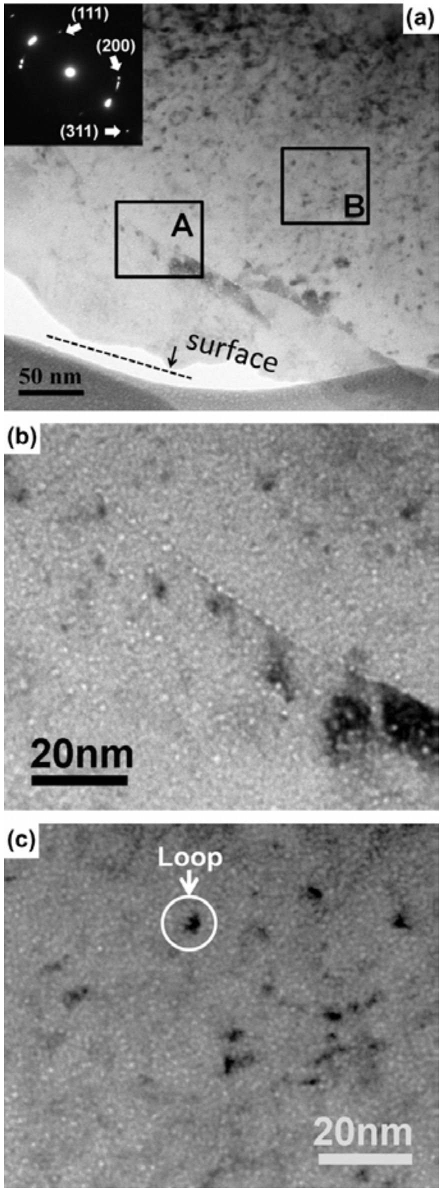


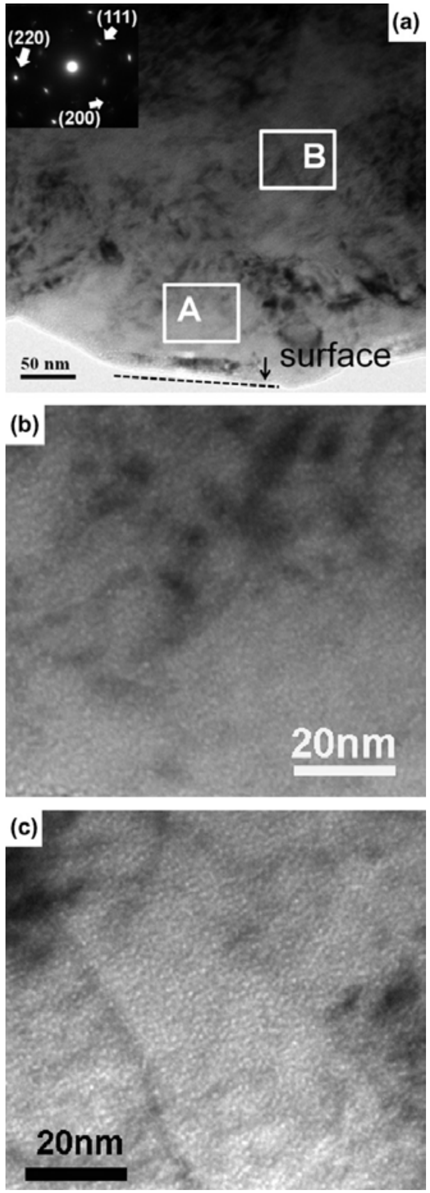


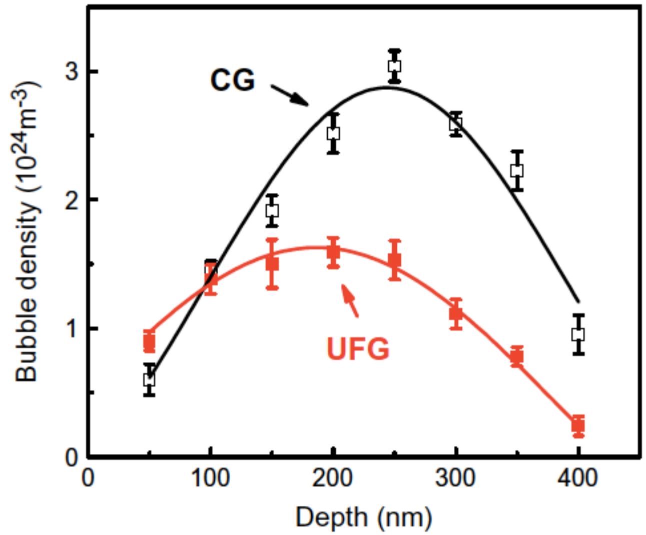
- In-situ TEM imaging during ion irradiation of NC Ni films
- Grain boundaries as sinks for irradiation-induced dislocation loops and segments

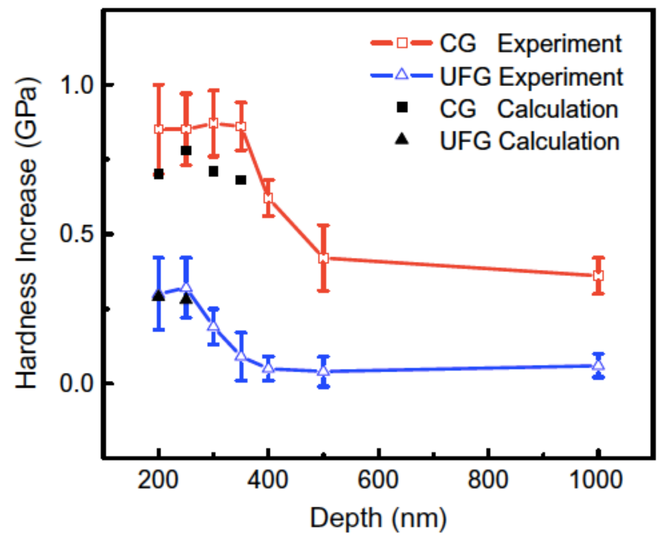
Sun C, et al., Metall Mater Trans A 44 (2013) 1966

Radiation resistance of UFG Fe-Cr-Ni alloy





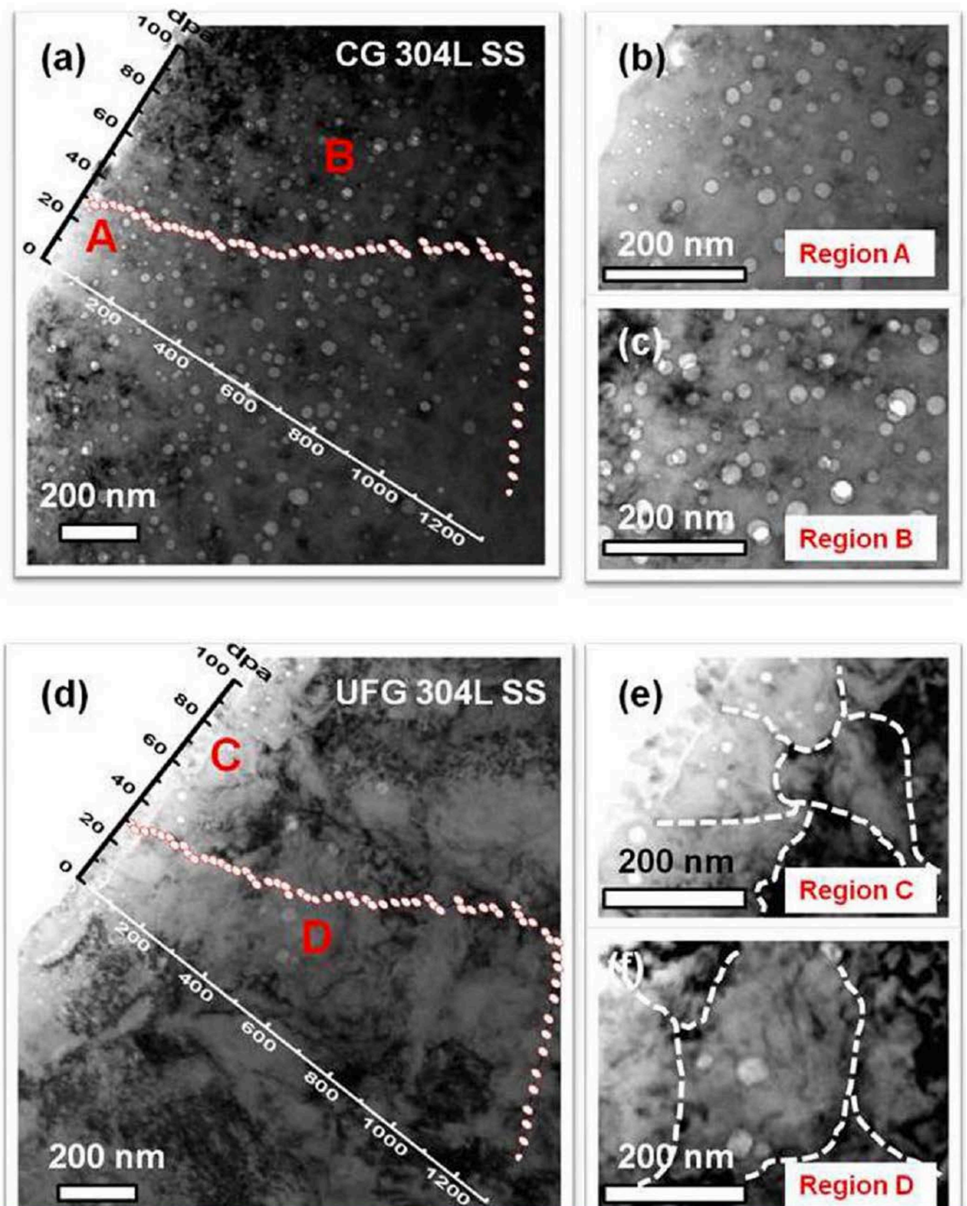


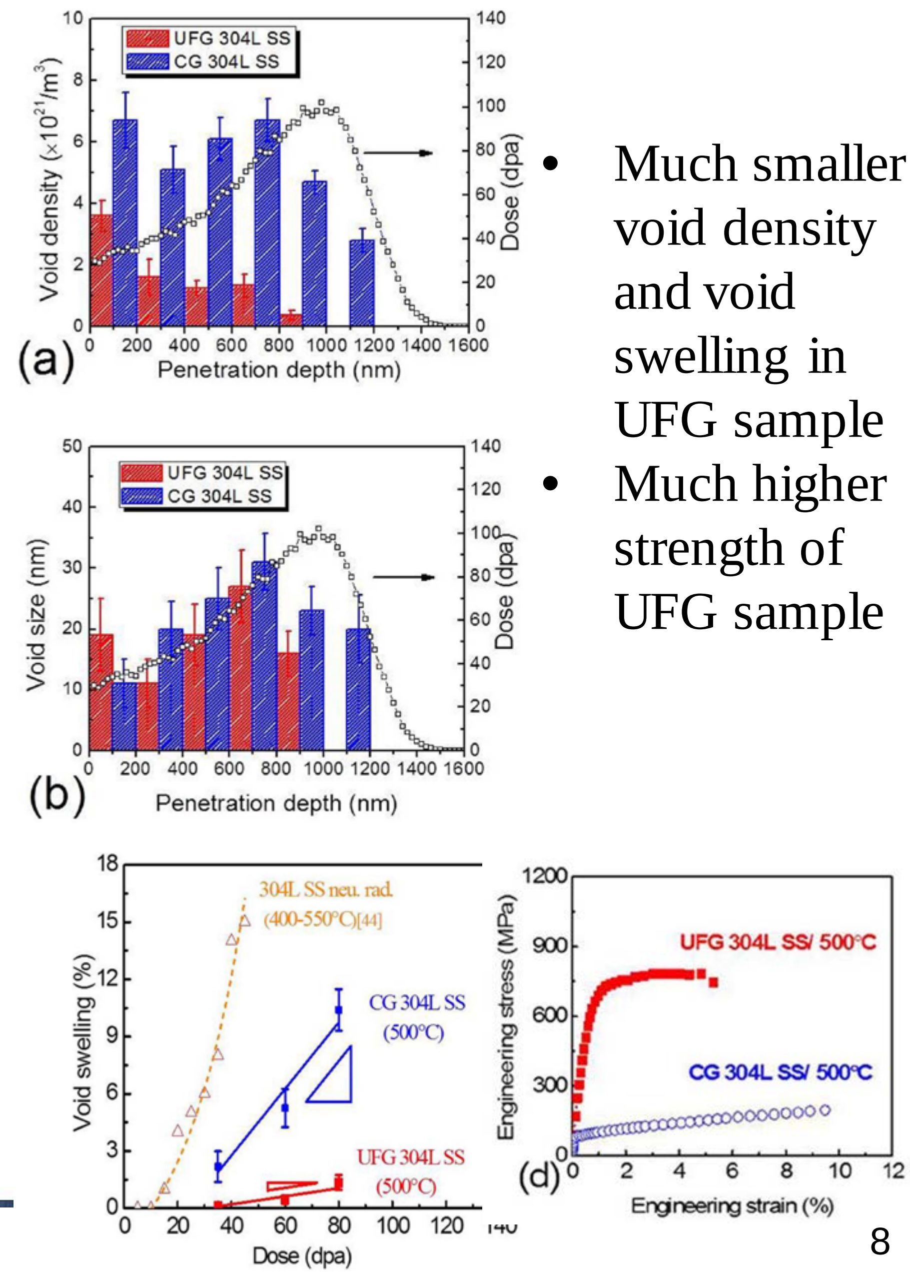


Sun C, et al., J Nucl Mater 420 (2012) 235

- Reduced He bubble density and irradiation hardening in UFG sample

Radiation resistance of UFG 304 steel

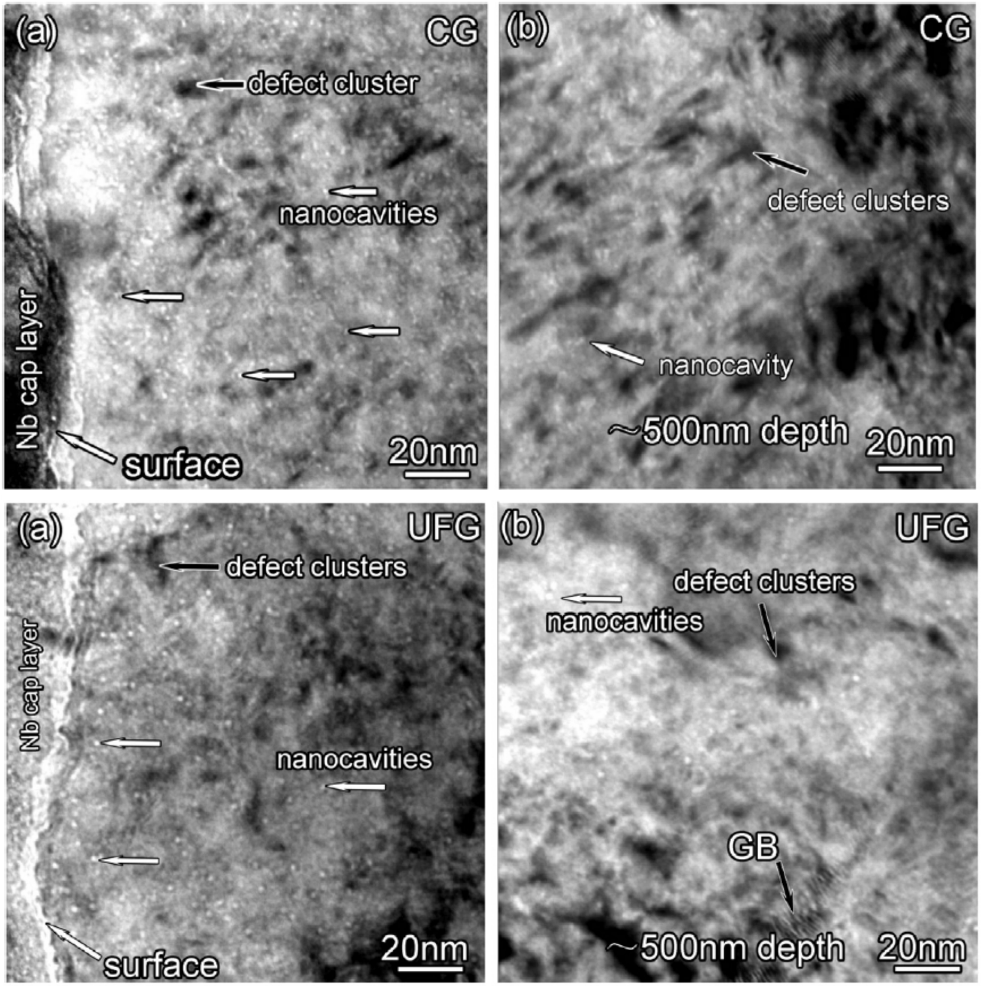


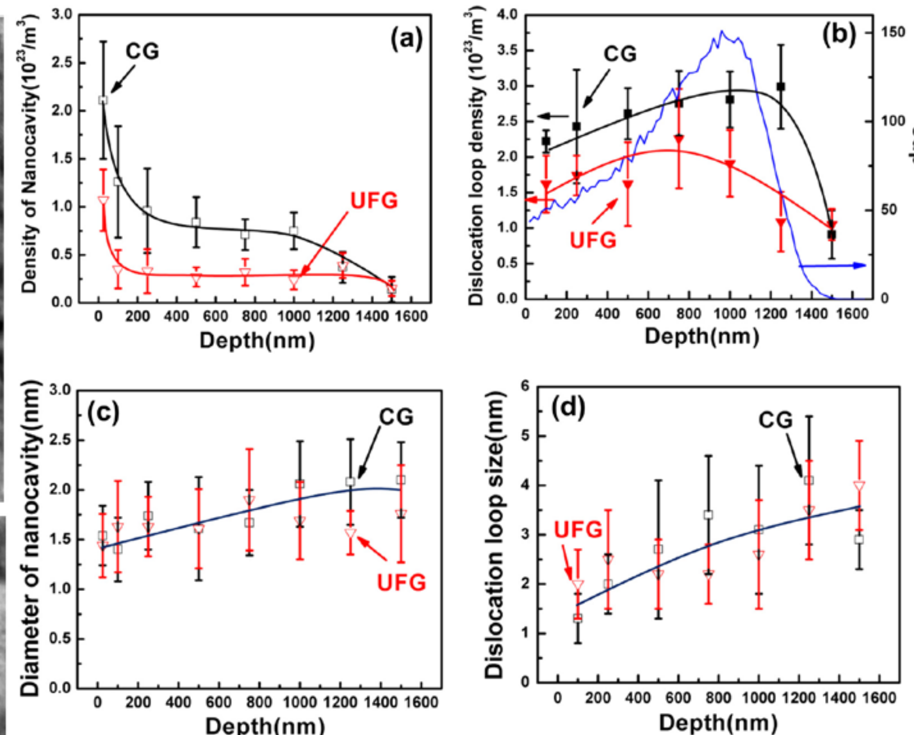


- Much smaller void density and void swelling in UFG sample
- Much higher strength of UFG sample

Sun C, et al., Scientific Reports 5 (2015) 7801

Radiation resistance of UFG T91 steel



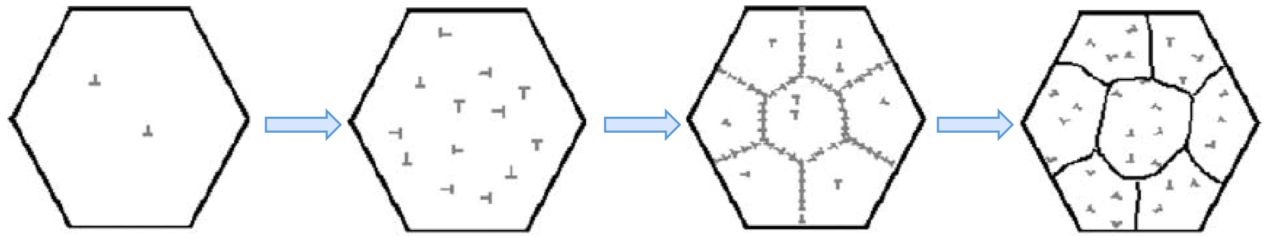


- Lower density of nanocavity and dislocation loops in UFG sample

Song M, et al., Acta Mater 74 (2014) 285

Manufacturing of bulk nanostructured metals

Grain refinement process

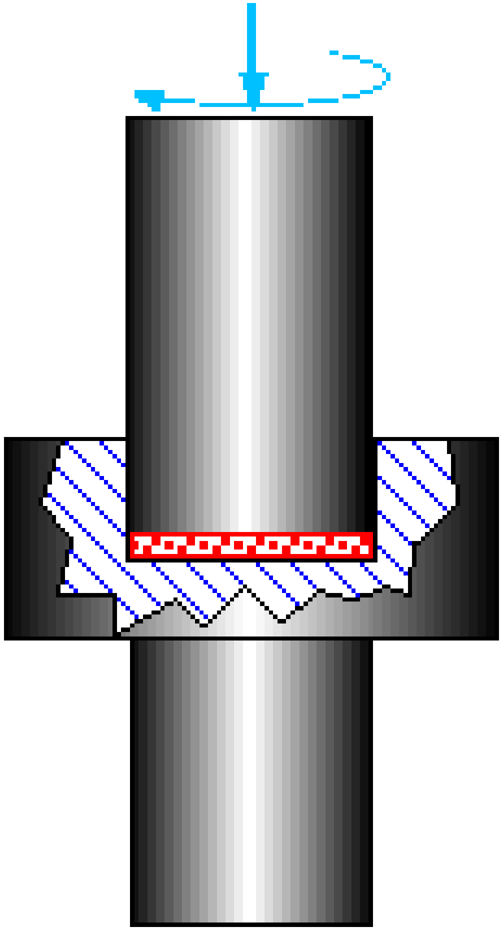


- Top-down approach
  - severe plastic deformation (SPD)
    - equal-channel angular pressing (ECAP)
    - high pressure torsion (HPT)
- Bottom-up approach
  - Step I: producing particles or agglomerates
    - inert gas condensation
    - Mechanical milling
    - chemical methods
  - Step II: consolidating particles or agglomerates
    - CIP/HIP
    - quasi-isostatic forging
    - spark plasma sintering
    - SPD
      - ECAP
      - HPT

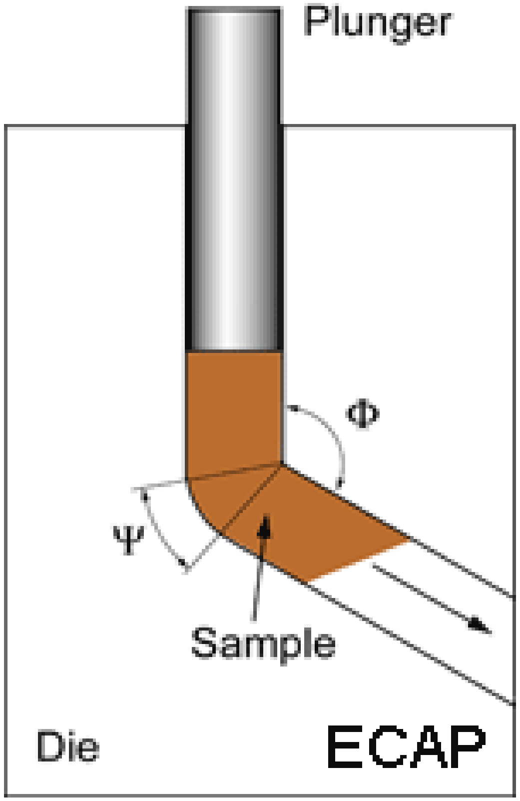
Lavernia EJ, et al., Progress in Materials Science 51 (2006) 1

Severe plastic deformation (SPD)

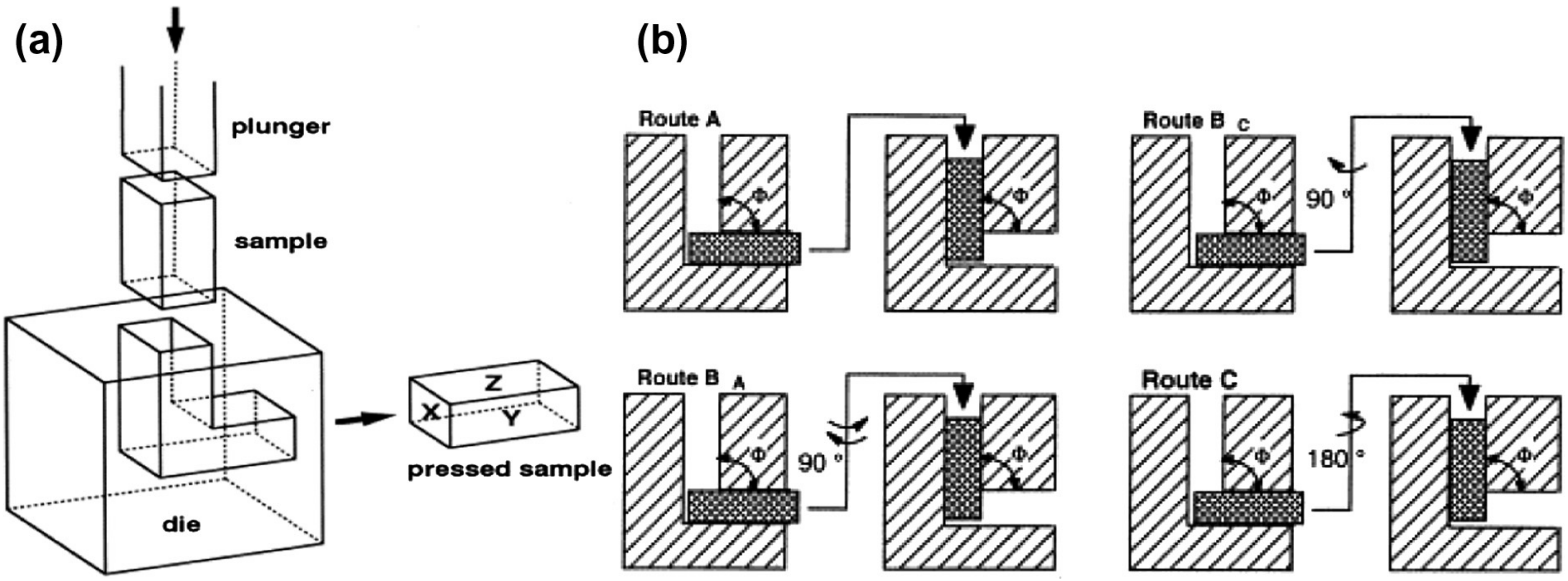
High pressure torsion (HPT)



Equal-channel angular pressing (ECAP)



Equal-channel angular pressing



New project

- **Enhancing irradiation tolerance of steels via nanostructuring by innovative manufacturing techniques**
- **Team members:**

PI: Haiming Wen

Co-PIs: James I. Cole (INL), Yongfeng Zhang (Co-PI, INL)

Isabella J. van Rooyen (INL)

NSUF Technical Lead: James K. Jewell

Other ISU team members: Ishtiaque Robin (graduate student) and a postdoc (to be hired)

- **Project duration:** 10/1/2016 – 09/30/2021
- **Funding amount:** \$500 K + NSUF facility access in the value of ~\$2.4 million

Objectives

- Establish/enhance our fundamental understanding of irradiation effects in ultrafine-grained or nanocrystalline steels produced by ECAP or HPT.
- Assess the potential applications of ECAP and HPT in fabricating materials for applications in current and advanced reactors

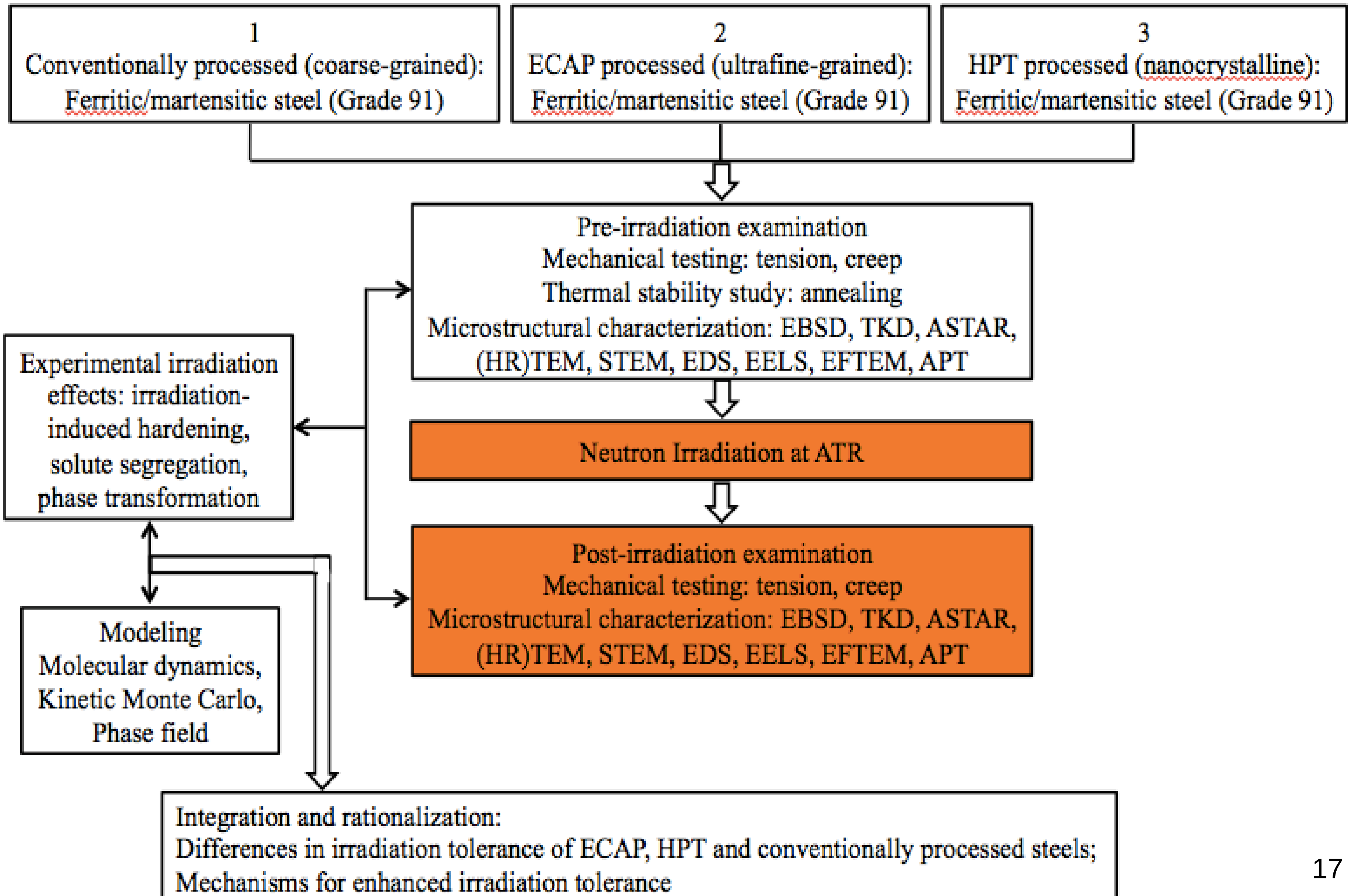
Novelty

- UFG or NC austenitic or F/M steels have not been neutron irradiated, and their performance under neutron irradiation is not established.
- This work will establish the performance of UFG and NC variants of reactor structural and cladding steels produced by ECAP or HPT, under neutron irradiation at relevant reactor operating temperatures, which has not previously been accomplished.

Samples

- Sample set 1: conventionally processed (coarse-grained) F/M Grade 91 steel
- Sample set 2: ECAP processed (ultrafine-grained) F/M Grade 91 steel
- Sample set 3: HPT processed (nanocrystalline) F/M Grade 91 steel
- Sample set 4: conventionally processed (coarse-grained) austenitic 316 steel
- Sample set 5: ECAP processed (ultrafine-grained) austenitic 316 steel
- Sample set 6: HPT processed (nanocrystalline) austenitic 316 steel
- Sample set 7: conventionally processed (coarse-grained) austenitic 304 steel
- Sample set 8: ECAP processed (ultrafine-grained) austenitic 304 steel
- Sample set 9: HPT processed (nanocrystalline) austenitic 304 steel
- Sample set 10: conventionally processed (coarse-grained) ferritic Kanthanl D
- Sample set 11: ECAP processed (ultrafine-grained) ferritic Kanthanl D
- Sample set 12: HPT processed (nanocrystalline) ferritic Kanthanl D

Project flow chart



Pre-irradiation characterization

- ***Mechanical testing***

  tensile and creep tests
- ***Microstructural characterization***

  grain sizes/morphologies, dislocations, grain boundary characteristics, solute segregation at grain boundaries, pre-existing precipitates, and phase boundaries.
- ***Thermal stability study: annealing***

Neutron irradiation

- Irradiation conditions

  300 ^{o}C: 2 dpa, 6 dpa;

  500 ^{o}C: 2 dpa, 6 dpa
- Non-instrumented standard capsule experiments
- Melt wires to monitor temperature

Post-irradiation characterization

- ***Mechanical testing***

  tensile and creep (?) tests

  irradiation-induced hardening and decrease in ductility

  irradiation effects less significant in UFG and NC samples

- ***Microstructural characterization***

  - ✓ Neutron irradiation induced defects (such as dislocation loops), irradiation-induced solute segregation and precipitation, grain boundary characteristics, interaction between irradiation-induced defects and grain boundaries, and irradiation-induced solute segregation at grain boundaries in relation to the specific characteristics of grain boundaries
  - ✓(HR)TEM, STEM-EDS, STEM-EELS, APT, EBSD, TKD, PED

Modelling

- Irradiation-induced segregation

  molecular dynamics simulations

  lattice kinetic Monte Carlo

- Thermal stability of nanocrystalline alloys before and after irradiation

  phase field based MARMOT code

- Irradiation-induced hardening

  molecular dynamics simulations

Integration and rationalization

- Feasibility assessment of applications of ECAP and HPT in fabricating materials with improved performance for current and advanced reactors
- Irradiation effects: irradiation-induced hardening, solute segregation and phase transformation (precipitation)
- Irradiation tolerance as a function of grain size
- Influence of specific characteristics of GBs on interaction between irradiation-induced defects and GBs
- Correlation between specific characteristics of GBs and irradiation-induced solute segregation/precipitation at GBs
- Role of solute segregation/precipitation at GBs in pinning GBs and stabilizing ultrafine-grained and nanocrystalline structures