Nanoscale Stable Precipitation-Strengthened Steels for Nuclear Applications

Nuclear Energy Enabling Technologies (NEET) Reactor Materials

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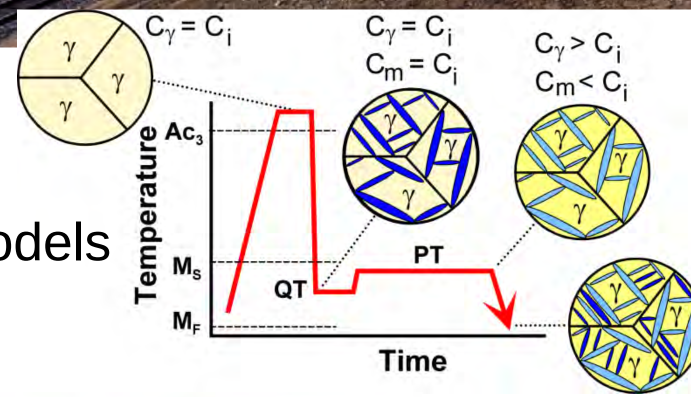
UNCLASSIFIED

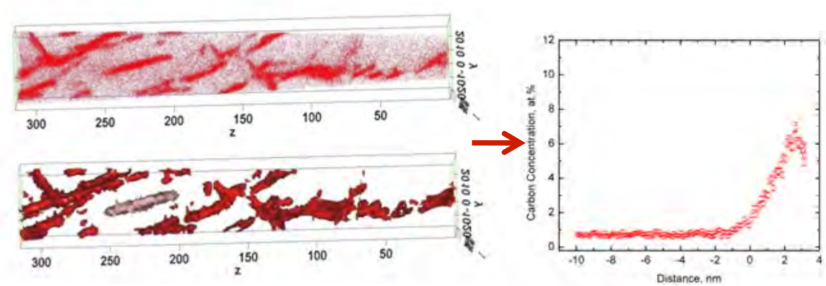
Overview

- **Background**
- **Investigative Team**
- **Materials Processing Strategies**
  - Colorado School of Mines (CSM)
  - Northwestern University (NU)
- **Material production**
- **Experimental Plan**
  - Thermal studies
  - Mechanical testing
  - Irradiation studies
  - Characterization

Theory/Models



Characterization/Testing

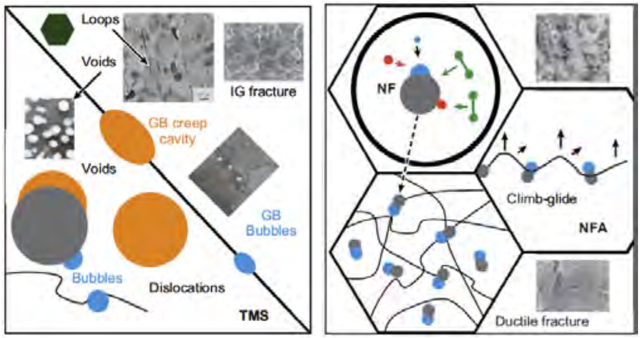


Project Background and Objectives

- Thermal conductivity
- Compatibility
- High-temperature strength
- Ductility
- Creep resistance
- Irradiation resistance
- Affordability

Nuclear Enabling Technologies (NEET) Workshop Report, July 29, 2010, Rockville, Maryland, accessed March 9, 2012 at http://www.ne.doe.gov/pdfFiles/Neet_Workshop_07292010.pdf

Stable, nanoscale precipitates and stable dislocation sinks improve irradiation resistance in steels.



Odette, G.R., Alinger, M.J., and Wirth, B.D., *Annu. Rev. Mater. Res.*, vol. 38, 2008, pp. 471-503.

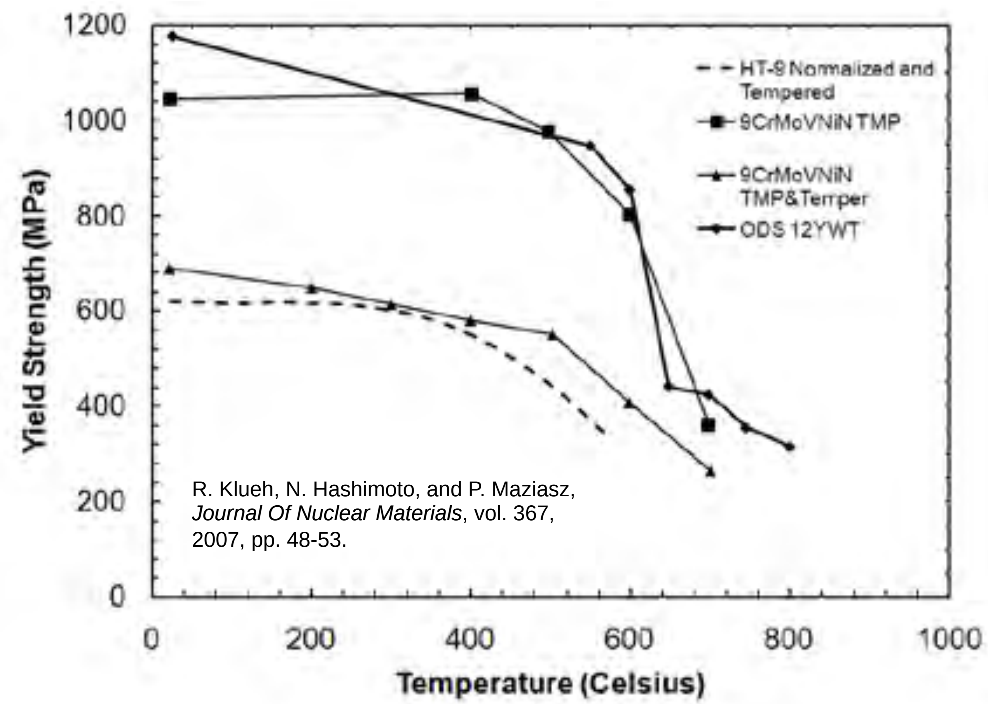
- **Create precipitation-hardened steels with improved thermal stability.**
  - Develop alloying strategies to improve irradiation performance of steels.
  - Manufacture by conventional methods, with focus on manufacturability and affordability.
  - Produce desired microstructures: stable precipitates and dislocation structures.
  - Perform ion-beam experiments to determine irradiation resistance.
  - Examine microstructural effects on mechanical properties.

Partnership - CSM, NU, NETL and LANL

- **NETL**
  - Produce and process steels with desired compositions and microstructures
  - Thermodynamic/kinetic expertise for alloy design
- **CSM - Advanced Steel Processing and Products Research Center**
  - Global leader in automotive and structural steel development
  - History of developing novel steels using thermal/mechanical processing
- **NU - Infrastructure Technology Institute**
  - Pioneers of tailored-precipitation hardened steels for structural uses
  - Understanding of precipitation strengthening and kinetic control
- **LANL**
  - Materials Science & Technology: Metallurgy (MST-6) steel physical metallurgy expertise
  - Facilities for materials characterization
  - Irradiation testing (IBML)

Material Design Strategies - CSM and LANL

- **Advanced High-Cr martensitic or ferritic-martensitic steels**
  - Traditional material in reactors
  - Optimize alloying and deformation processing for strength and creep resistance

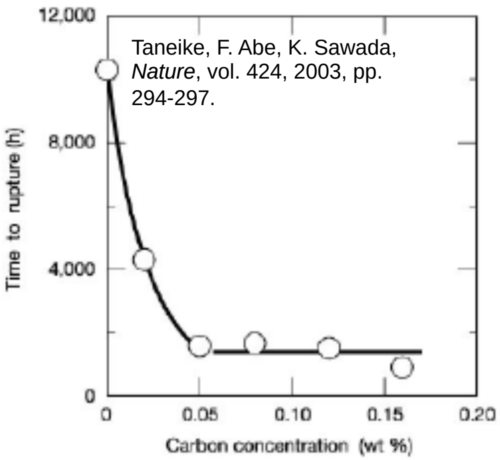


Material Design Strategies - CSM and LANL

Table 1 - Composition of NF616, wt. pct.

C	Si	Mn	Cr	Mo	W	V	Nb	B	N
0.07	0.06	0.45	9.0	0.5	1.8	0.2	0.05	0.004	0.06

- **Base alloy, NF616 - Normalized and Tempered**
  - Lower C content to promote MX precipitation over $M_{23}C_6$
    - More resistant to coarsening
    - Excellent creep strength
  - Increased Mn and N
    - Stabilize austenite for thermomechanical processing
    - Coarsening resistance (VN)
  - Mo, W alloying optimized for solid solution strengthening

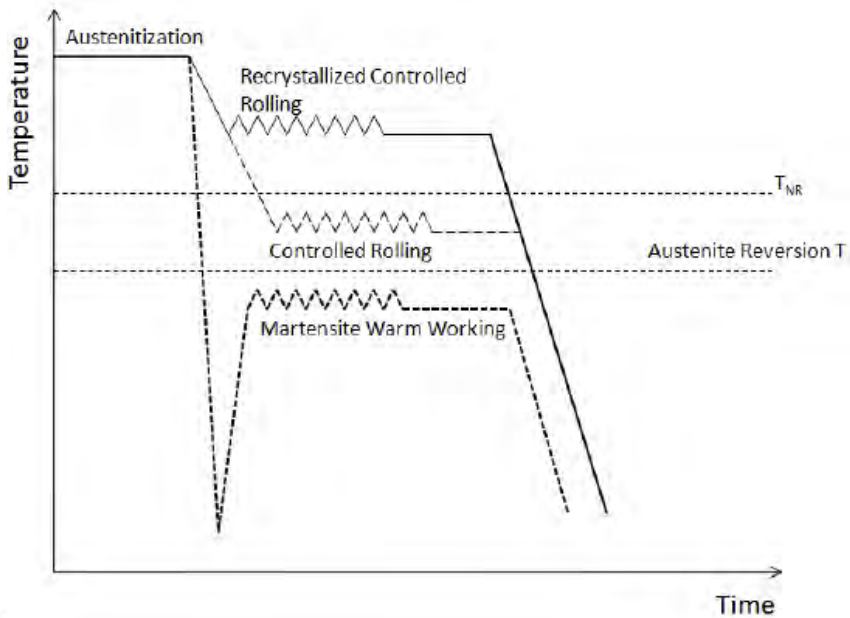


What is effect of C content on precipitation, aging stability, and resulting mechanical behavior?

To what extent can excess N improve austenite stability and coarsening resistance?

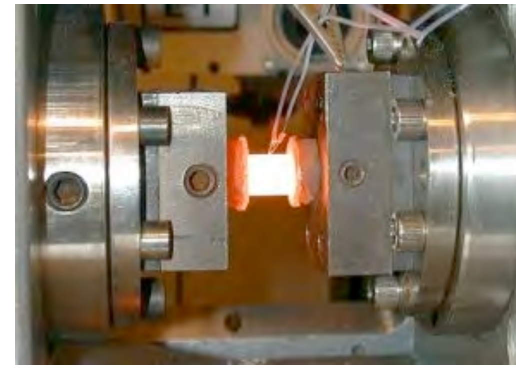
Material Design Strategies - CSM and LANL

- **Thermomechanical Processing (TMP)**
  - Thermal solutionizing treatments
  - Cooling rate
  - Hot- or warm-working
- **Initial Material supplied by NETL**



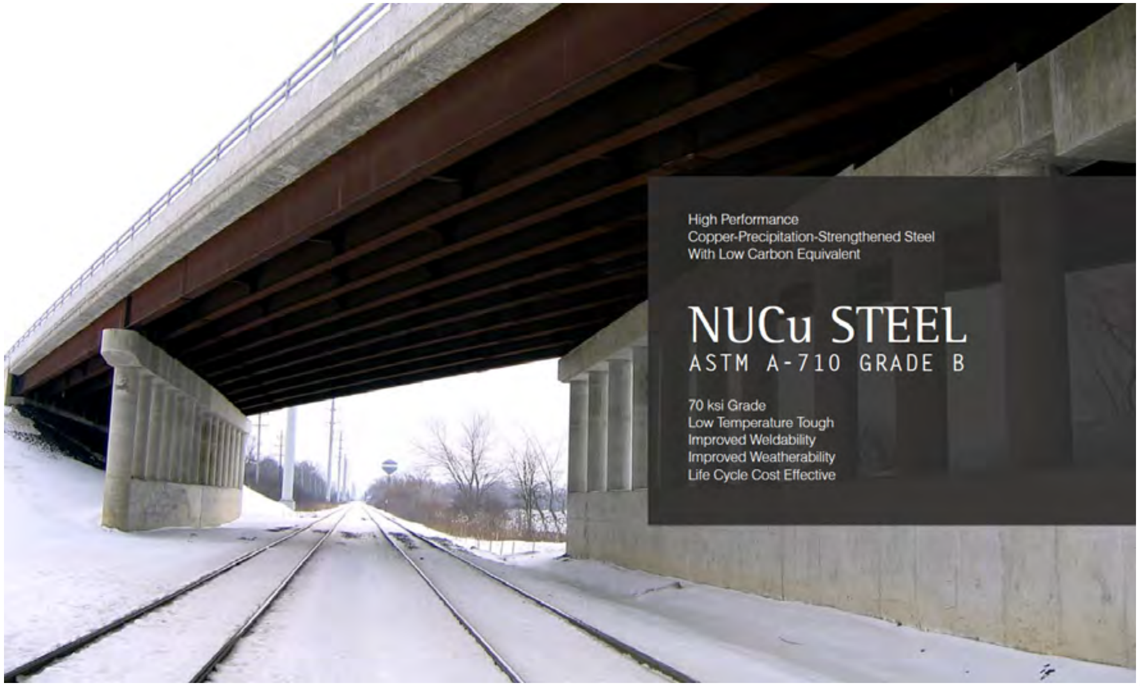
Material Design Strategies - CSM and LANL

- **Thermomechanical Processing (TMP)**
  - Recrystallized controlled rolling
    - Decrease austenite grain size for nucleation sites
    - Decrease martensite packet/block size for strength
    - Increased interfacial area
  - Controlled rolling
    - Retain dislocation substructure for nucleation sites
    - Increased strength
  - Martensite warm working
    - Precipitate orientation relationship to matrix altered
    - Control precipitate growth kinetics
- **Laboratory-scale processing for promising processing routes**



Material Design Strategies - NU and LANL

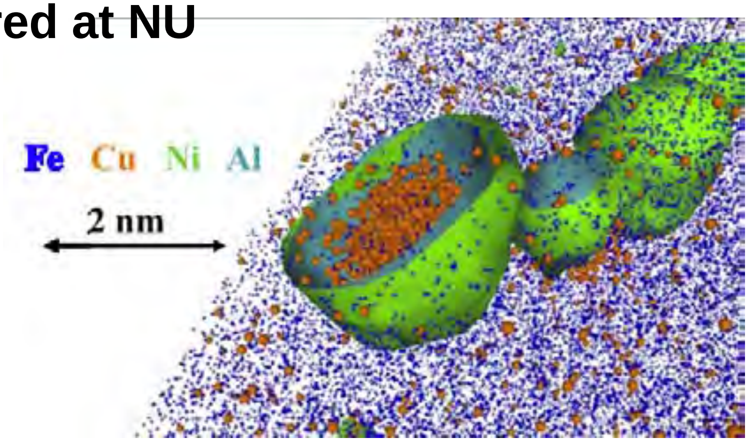
- **Novel Tailored-Precipitate Ferritic (TPF) steels**
  - Designed nanoscale fine Al, Cu, Nb, or Mo-based precipitates plus deformation processing.
  - Optimize for strength, corrosion resistance, irradiation resistance, weldability, and thermal stability.



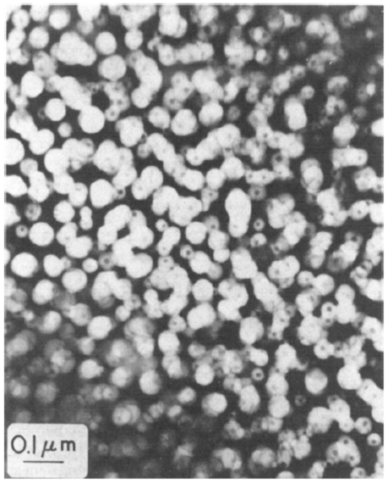
Front Cover:
Bridge in Lake Villa, Illinois, build with NUCu 70W (ASTM A710 Grade B) Steel

Material Design Strategies - NU and LANL

- **Corrosion resistant structural steels tailored at NU**
  - 1.3-2.5 Cu, 2.7Ni, 0.6Al
  - YS = 1000 Mpa
  - El% = > 20%
  - Impact energy > 70 J at -40 °C
  - Unique structure - Ni-Al "shell"
  - Initial irradiation testing being initiated



- **NU results suggest NiAl precipitates can be optimized for irradiation resistance (i.e., 17-7 PH stainless steels)**
  - Meets strength and ductility requirements
  - Precipitate morphology shown to be adjustable with processing
  - High-temperature stability (700 °C)
  - Mo impedes morphology change/coalescence - Mo migrates to interface

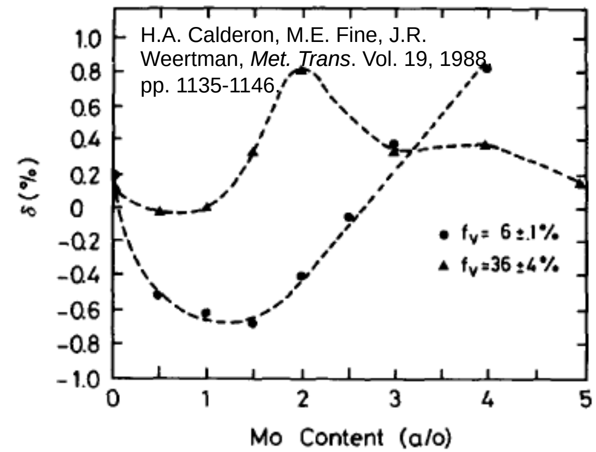


H.A. Calderon, M.E. Fine, J.R. Weertman, *Met. Trans*. Vol. 19, 1988, pp. 1135-1146.

- **Nb or V carbide optimization**

Material Design Strategies - NU and LANL

- **Design precipitates for application to nuclear reactors**
  - Alloys have been designed to take advantage of NiAl precipitate stability
    - NiAl - stable ordered phase (B2 structure)
    - Wide composition band possible - computational and experimental verification
  - Quaternary alloying strategies, Mo
    - Control lattice parameter mismatch
    - Slow coarsening rate
    - Shape control
    - Size control
  - Examination of Nb and V carbide behavior
  - Thermomechanical processing



Can FeNiAl alloys be further optimized for use in irradiation-resistant materials?

Material Design Strategies - NU and LANL

- **Weldability**
  - Previous steels have been extremely weldable, which is rare in advanced, high-strength materials. Important for manufacturability.
  - Controlled carbon equivalent and ability to control temperature during welding - no brittle heat affected zone

Partnership - CSM, NU, NETL and LANL

- **Tailored-Precipitate Ferritic Steels (TPF)**
  - NiAl - alloys have been produced at NETL
    - Four 5kg heats
      - 2.8Ni, 2.3Al
      - 2.6Ni, 3.0Al
      - 0.08C, 0.1Nb
      - 0.08C, 0.1V
  - Aging studies underway at NU - test thermal stability and mechanical properties as a function of time and temperature
  - Irradiation studies being initiated at LANL

- **Advanced Hi-Cr ferritic or ferritic-martensitic steels**
  - NF616 produced at NETL
  - Thermomechanical examinations underway at CSM
  - Irradiation studies being initiated at LANL

Experimental Plan - CSM, NU, NETL, and LANL

- **Material Production and Thermomechanical processing**
- **Aging studies (CSM, NU)**
  - 650 °C up to 5000 hours (>200 days)
  - Microstructural and mechanical evaluations to determine best-performing materials
- **Mechanical Testing (CSM, NU, LANL)**
  - Tensile testing to 700 °C
  - Creep-rupture testing
  - Nano-indentation
- **Irradiation, Ion Beam Materials Laboratory (IBML) at LANL**
  - Irradiation processes being determined
  - Mechanical and Microstructural response
- **Microstructural Characterization and Interpretation (CSM, NU, LANL, NETL)**
  - Precipitate analysis via TEM and EDS, along with 3DAP
  - EBSD for texture and grain-boundary type information
  - Understand relationships between processing, microstructure, and properties

Summary

- **Develop stable nano-precipitates for reactor applications**
- **Use flexible processes and tailored compositions to produce desired microstructures**
- **Characterize microstructures with advanced techniques**
- **Optimize microstructures for reactor applications**
- **Initial iterations of materials designed and produced through conventional steelmaking processes**
- **First stages of testing underway**