INL/PRO-22-67453-Revision-0

Development of Lightweight Structural Materials with Improved Properties for Fission Batteries

May 2022

Changing the World's Energy Future

Rongjie Song

Idaho National Laboratory

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Development of Lightweight Structural Materials with Improved Properties for Fission Batteries

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Co-investigators: Dewen Yushu (NS&T), Donna Guillen (EES&T), Jia-Hong Ke (NS&T), Michael McMurtrey (NS&T), Michael Moorehead (NS&T), Michael Heighes (EES&T), Timothy Yoder (EES&T) Kevin Field (Univ. of Michigan)

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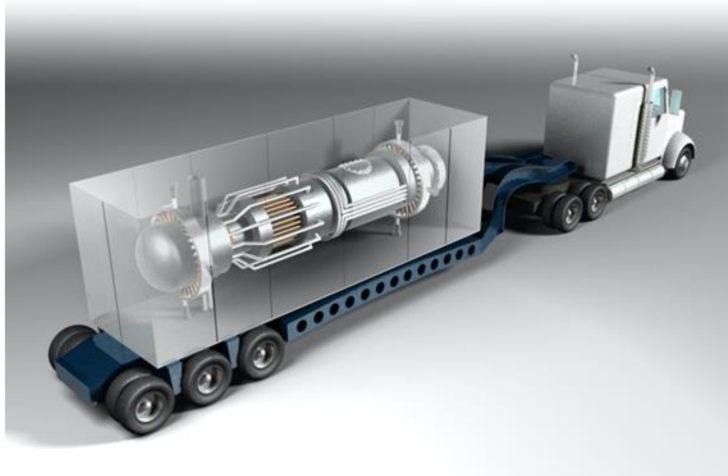
Introduction

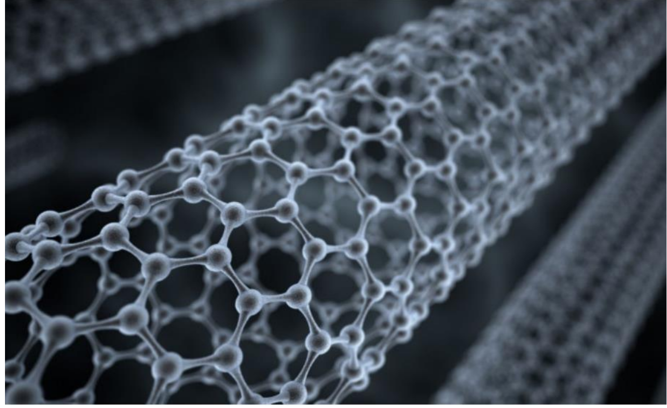


- **Need**
  - Fission batteries require lightweight structural materials that demonstrate structural resilience

- **Objective**
  - **Primary** objective: Produce lightweight structural materials whose strength-to-weight ratios, strength, and fatigue resistance exceed current SS316
  - **Additional** objective: Enhance radiation damage tolerance of SS316 over a suitable service temperature range

- **Gaps**
  - Inadequate fatigue performance of Additive Manufacturing (AM) material due to surface roughness, residual stresses, defects such as pores and lack of fusion particles
    - More research is needed to solve the issue
  - Lack of carbon nanotubes application in steels due to oxidization during process
    - Little research being carried out on carbon-nanotube-reinforced steels

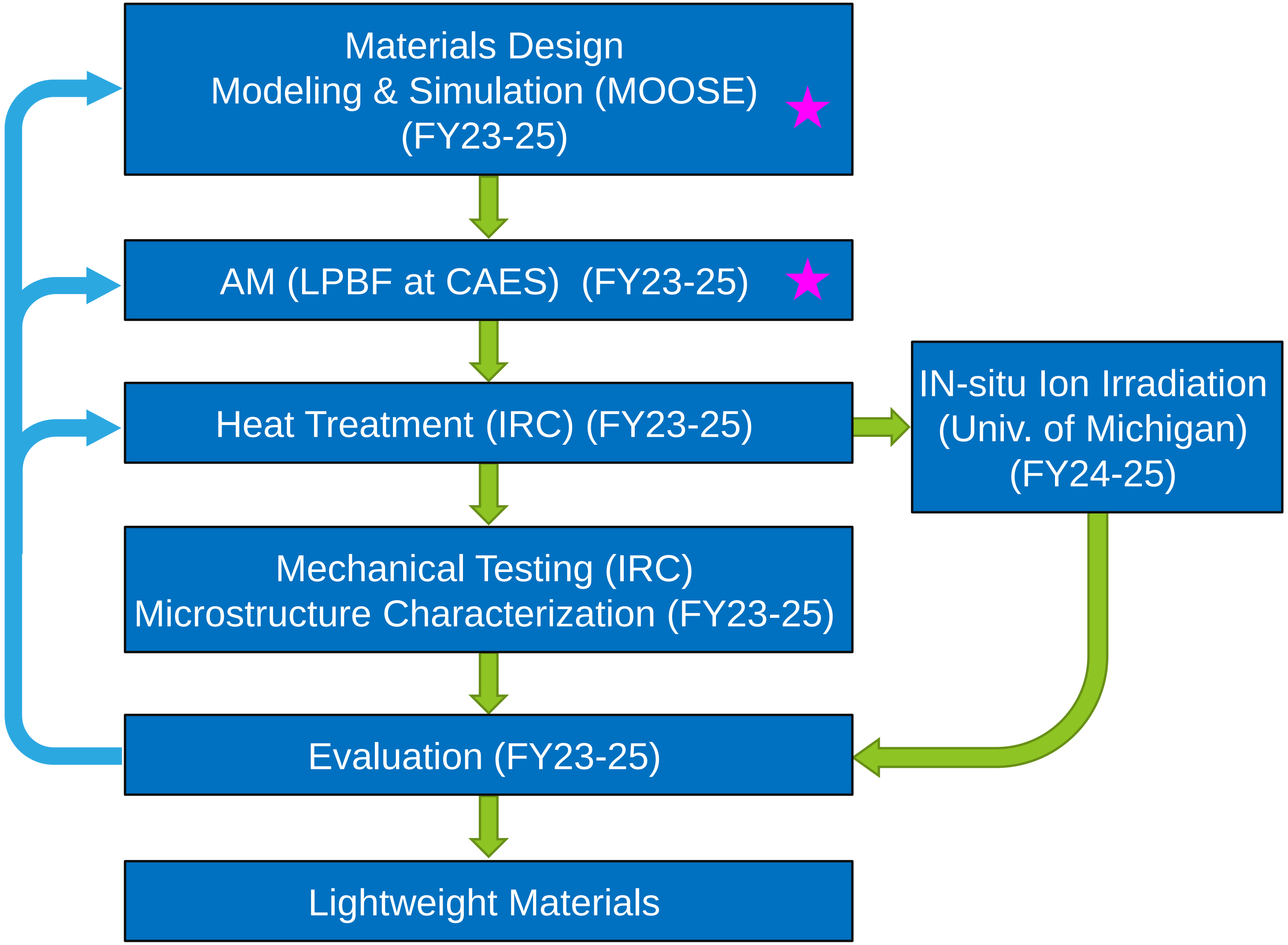
Approach and Significance



https://interestingengineering.com/nanotube-material-better-than-kevlar

- **Approach**
  - Improve fatigue performance of AM material
    - Use Laser Powder Bed Fusion (LPBF)
    - Apply lattice design
  - Maintain carbon nanotubes (1-D) shape in steel matrix
    - Eliminate moisture and air around carbon nanotube before and during AM
    - Explore a suitable application temperature range
- **Significance**
  - Foster a greater understanding of how lattice design affects the fatigue behavior of AM materials under cyclic loading
    - Essential for widely adopting AM materials
  - Create lightweight structural materials for fission batteries and microreactors
  - Develop radiation-tolerant and robust nuclear structural materials
    - Reduce the cost and improve environmental footprint of nuclear energy

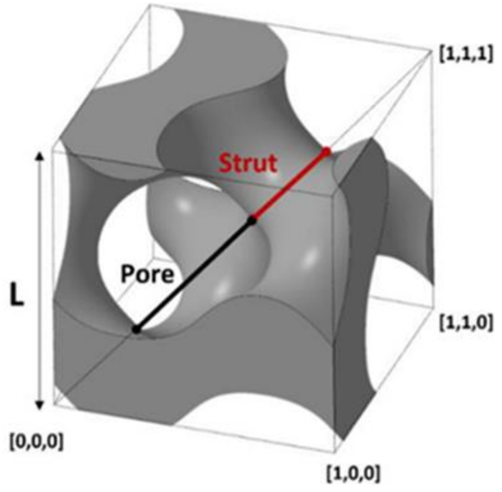
Research Plan



- **Material composition**
  - SS316
- **Materials processing**
  - Conventional wrought
  - AM solid material
  - AM lightweight lattice structure material

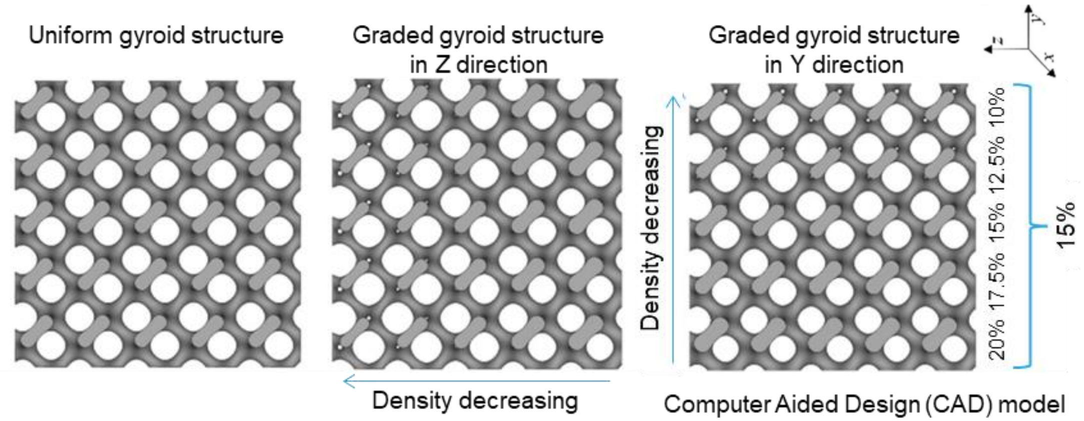
Lattice Design

- **Gyroid structure with open pores**
  - Lightweight and high strength-to-weight ratio
  - Better fatigue resistance
- **Parameters for optimization**
  - Unit cell size
  - Pore size
  - Pore size distribution

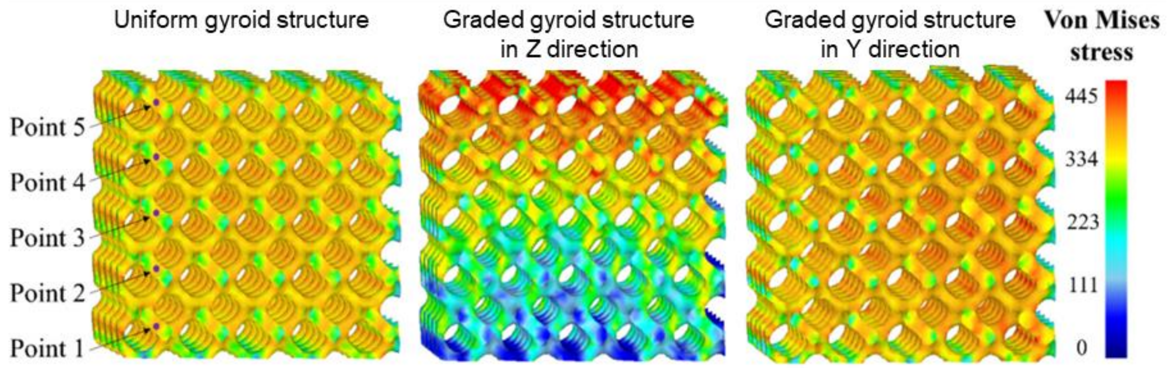


Geometry of a gyroid unit cell

L. Riva, et al. J. of Adv. Manuf. Technol. 113 (2021) 649.
L. Yang et al. Mater. and Design 162 (2019) 394.



Computer Aided Design (CAD) model

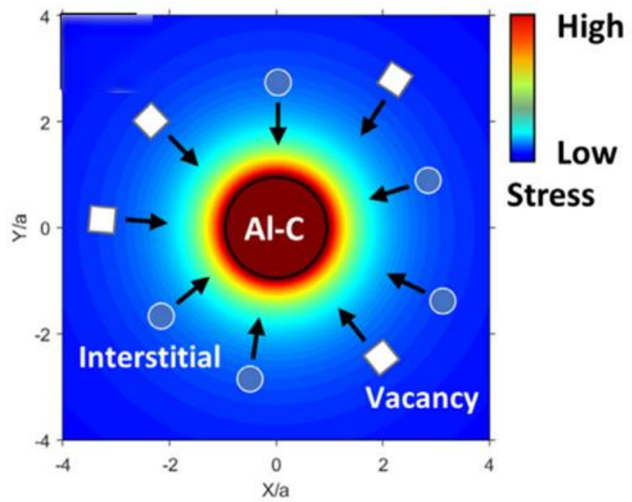


FE results of the compressive tests

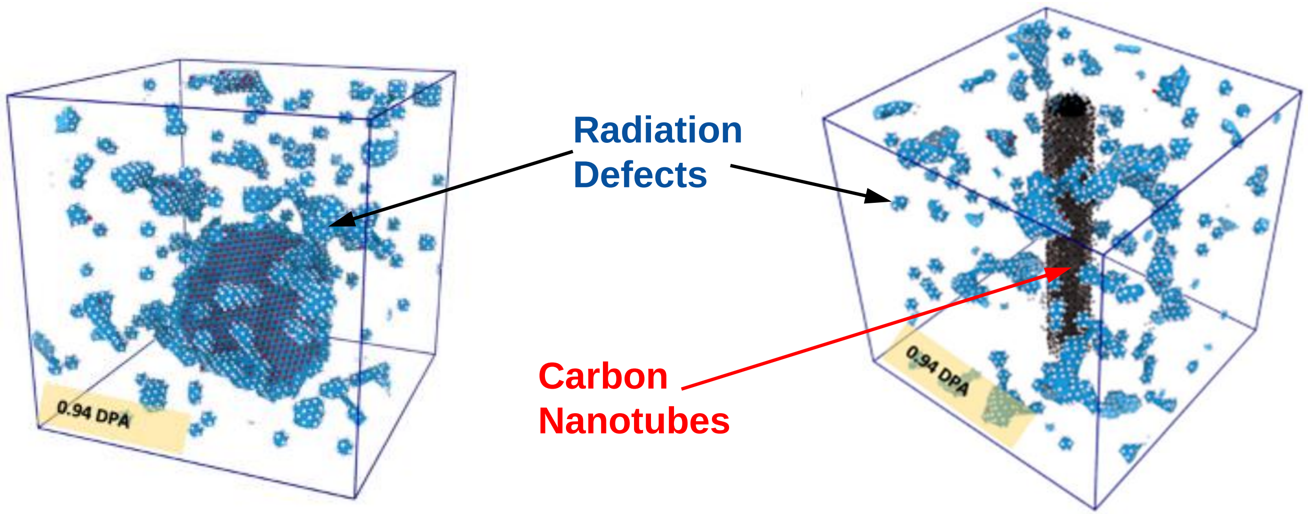
Carbon Nanotube Addition

- **Improved radiation damage tolerance**
  - Defect sink
  - Self healing
  - Better than 0-D oxide nanoparticles and 2-D multilayer structures

- **Higher strength**



Convergent defect migration caused by the stress field gradient



Molecular dynamics simulation of radiation-induced defect structures

P. Cao et al. Acta Materialia 203 (2021) 116483

Laser Powder Bed Fusion

- **High resolution**
  - Use a fine laser beam, point-by-point and one layer at a time
- **Shape complexity**
  - Possible to manufacture virtually any shape
  - Flexibility is the key to innovative product development
  - Multi-scale structures can be designed and fabricated in one step
- **This proposal will develop capability and experience in this important technique at INL**
- **Would significantly expand AM research at INL**

Key Deliverables

- **FY23**
  - Determine lattice structure parameters
  - Identify the effects of printing parameters on the microstructure and mechanical behavior of samples
- **FY24**
  - Develop a preliminary model for lattice structure design
  - Establish printing parameters for the samples without carbon nanotube
  - Provide the optimized heat treatment for AM residual stress relieve and the thermal stability of carbon nanotubes
  - *Present the innovative lattice design work at **MS&T conference***
- **FY25**
  - Delivery a software for lattice design
  - Establish printing parameters for the samples with carbon nanotube
  - Delivery lightweight materials with improved mechanical properties
  - *Present the additive manufacturing of steel with carbon-nanotube at **TMS conference***
  - *Submit **manuscripts** to peer reviewed journals: 1) lattice design and macroscopic properties prediction to **Materials and Designs** (impact factor: 7.99); 2) lightweight material with improved properties to **Additive Manufacturing** (impact factor: 10.99); 3) effect of carbon nanotubes on radiation tolerance in steels and its service temperature range to **Acta Materialia** (impact factor: 8.20).*
- **3-Year Outcomes**
  - New <u>lightweight structural materials</u> with improved mechanical properties
  - New <u>materials design methods</u> using advanced manufacturing
  - New <u>models</u> that can accurately predict the macroscopic behavior of materials

Harvest Strategy

- **The U.S. Department of Energy (DOE) Office of Nuclear Energy's**
  - Nuclear Energy Advanced Modeling and Simulation (NEAMS) program
  - Advanced Materials and Manufacturing Technologies (AMMT)
  - Microreactor Program (MRP)
  - Consolidated Innovative Nuclear Research's (CINR) Reactor Concepts Research, Development, and Demonstration programs
    - Nuclear Science User Facilities program (NSUF)
- **The DOE Office of Energy Efficiency and Renewable Energy's**
  - Advanced Manufacturing Office Research and Development Projects
    - Innovative Process and Materials Technologies program
    - Emerging Research Exploration program
    - Next Generation Materials program
  - Vehicle Technologies Office Lightweight and Propulsion Materials Projects
    - Stronger and lightweight materials for vehicles
- **INL's strategic initiatives**
  - Nuclear Reactor Sustainment and Expanded Deployment
  - Advanced Materials and Manufacturing for Extreme Environments

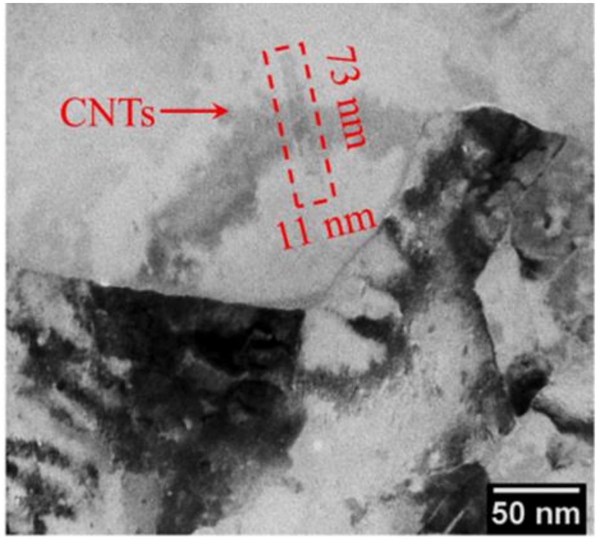
Research Team and Budget

	Name	Department	Role in this project
PI	**Rongjie Song**	C610	Materials design, heat treatment, characterization, evaluation and optimization
INL Co-investigator	**Dewen Yushu**	C650	Macroscale modeling of structural optimization and mechanical responses under different loading conditions, develop integrated simulation tool for additively manufactured structures in MOOSE
	Donna Guillen	B611	Apply computational techniques to advanced manufacturing, oversee LPBF printing
	Jia-Hong Ke	C650	Microstructure models, multiscale crack modeling
	Michael McMurtrey	C610	Materials scientist, fatigue test design and property evaluation
	Michael Moorehead	C610	Microstructure characterization
	Michael Heighes	B613	Fatigue testing
	Timothy Yoder	B613	Tensile testing
External Co-investigator	**Kevin Field**	Univ. of Michigan	Ion radiation test design, testing and characterization

Budget Summary	Funding Recipient	Budget ($)
Fiscal Year 2023	Idaho National Laboratory	549.9k
Fiscal Year 2024	Idaho National Laboratory	544.1k
	University of Michigan	55.4k
Fiscal Year 2025	Idaho National Laboratory	547.9k
	University of Michigan	50.9k
	Total:	1748.2k

Technical Review Response

- What is the mitigation strategy if CNT are damaged and not adding any value to the base material?
  - The preventative mitigation strategy is to dry the powder at 100 ^{o}C for about 6 hours before printing, and LPBF print in an inert gas environment to minimize oxidation.
  - Even if damaged, carbon nanotube can help to improve the strength of materials regardless of the shape.



- What are the irradiation parameters (fluence, temperature, time etc.)?

Material	**Sample**	**Ion irradiation, dpa**	**Ion irradiation temperature, ^{o}C**	**Radiation defects characterization**	**Nanoindentation**
AM SS316	TEM disc	0, 5, 10, 15	300	Size distribution and counts, volume fraction, morphology of radiation defect as a function of radiation dose	On 0, 5, 10 and 15 dpa samples
	TEM disc	15	350, 400		
AM SS316 with carbon nanotube	TEM disc	0, 5, 10, 15	300		
	TEM disc	15	350, 400		

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