Ion Irradiation of Bulk Metallic Glass Composites for Infrastructure Resilience

Consortium for Hybrid Resilient Energy Systems Technical Forum

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Collaborators

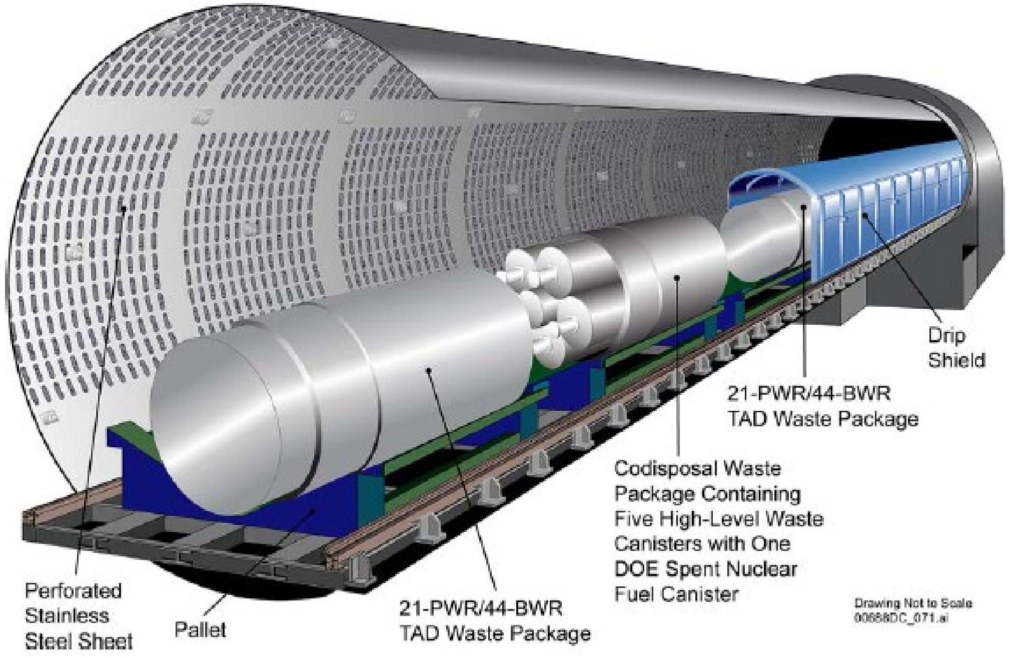
- Lawrence Livermore National Laboratory
  - Andrew Hoff, National Lab Mentor, UNM Thesis Committee Member
- University of New Mexico
  - Osman Anderoglu, Faculty Advisor, Dept. of Nuclear Engineering, UNM
- Additional Sponsors
  - Nuclear Science and Security Consortium

CHRES

NSSC NUCLEAR SCIENCE and SECURITY CONSORTIUM

Motivation: Infrastructure Resiliency

- High temperature corrosion in industrially relevant corrosive environments is a key challenge in maintaining US infrastructure
  - Corrosion costs the US 3% GDP per year[1]
- Metallic glasses can be used in corrosive and radioactive environments
  - Bulk Metallic Glasses (BMGs) lack grain boundaries and crystal structure, so they're radiation damage and corrosion resistant
- Applications include energy (e.g., oil & gas, geothermal), industrial production, and transportation (e.g., aeronautics)
- Metallic Glasses may serve as criticality control materials for waste packages
  - Boron is both a neutron absorber and a common BMG constituent

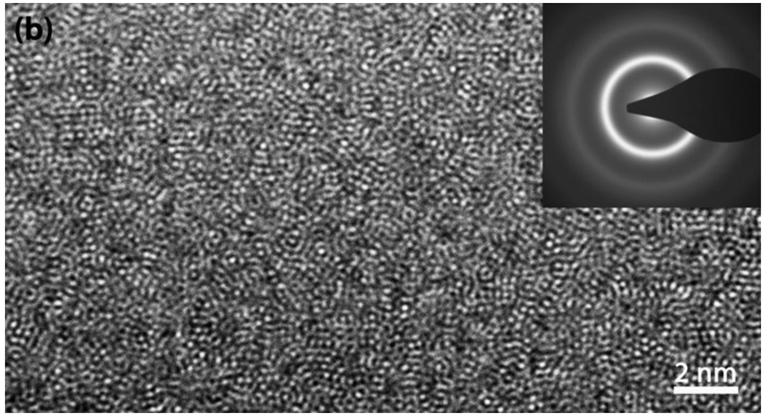


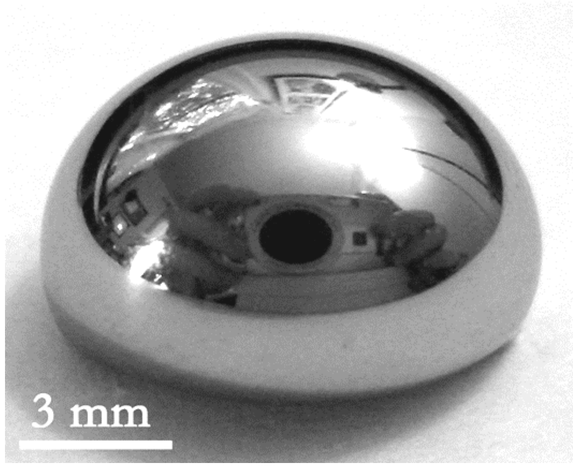
Blink et al. (2009)

[1]Koch, G. H., Brongers, M. P.H., Thompson, N. G. et al. *Cost of Corrosion in the United States*. Handbook of Environmental Degradation of Materials, William Andrew Publishing. (2005).

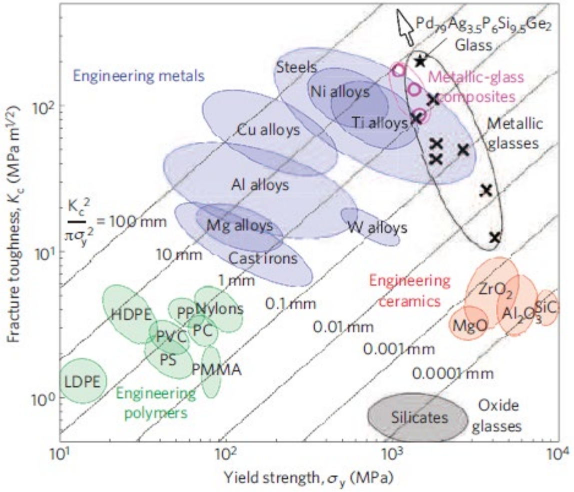
Metallic Glass

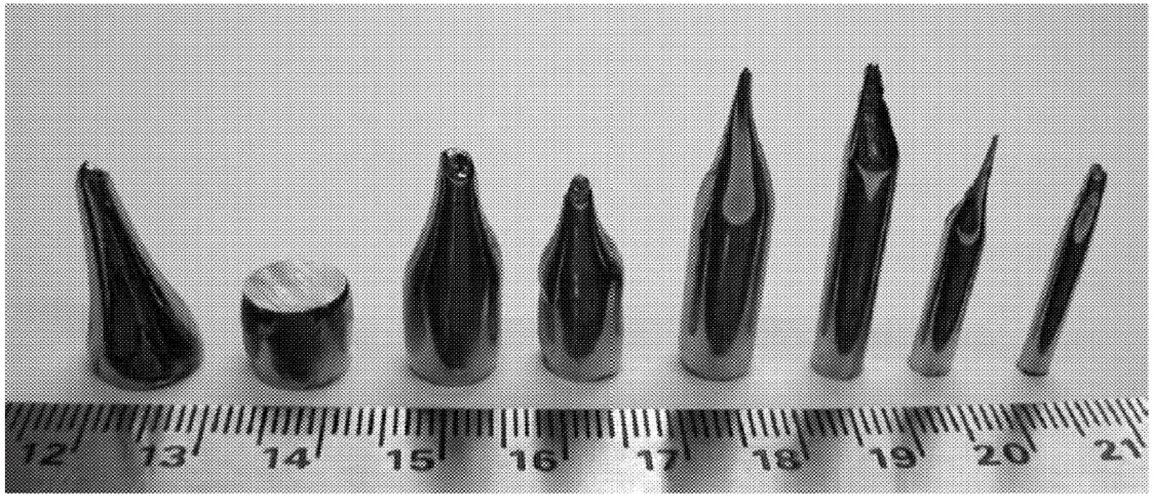
- Metals with an amorphous atomic structure → no long-range atomic order
- Mechanical properties between a metal and ceramic
- Created by rapidly cooling alloy: “flash freezing”
- GFA: Largest diameter rod that can be cast
- Bulk Metallic Glasses: Critical diameter above 2 mm
- Temperature Limited: Bound by glass trans. temperature





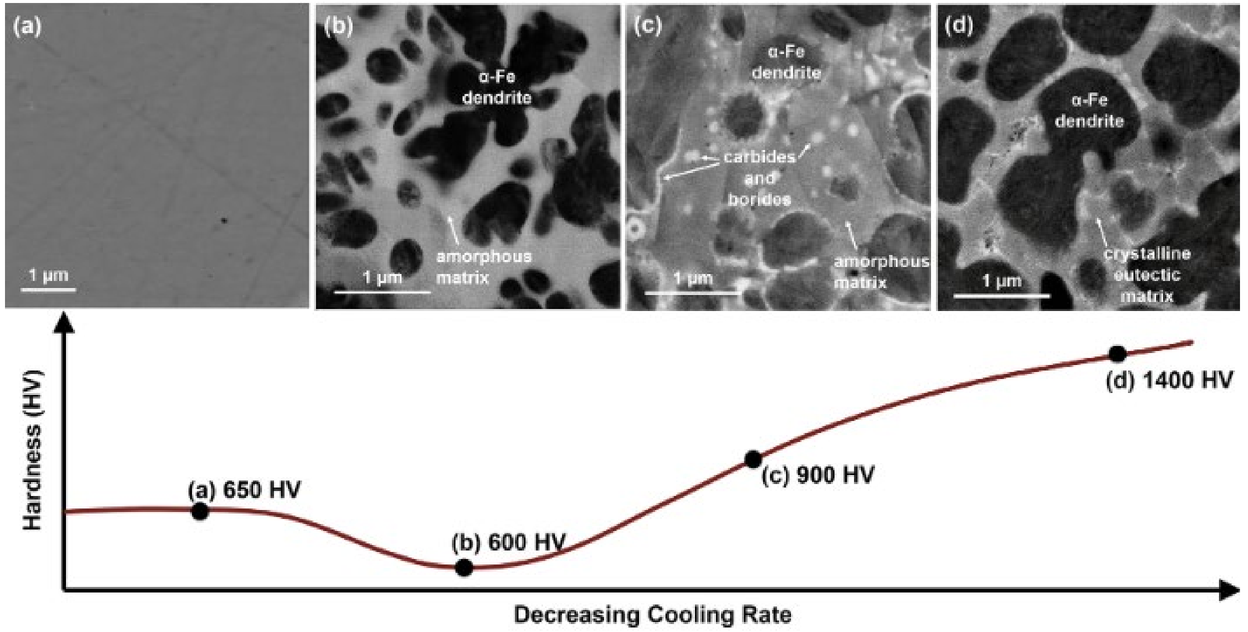
M.D Demetriou et al. (2011)

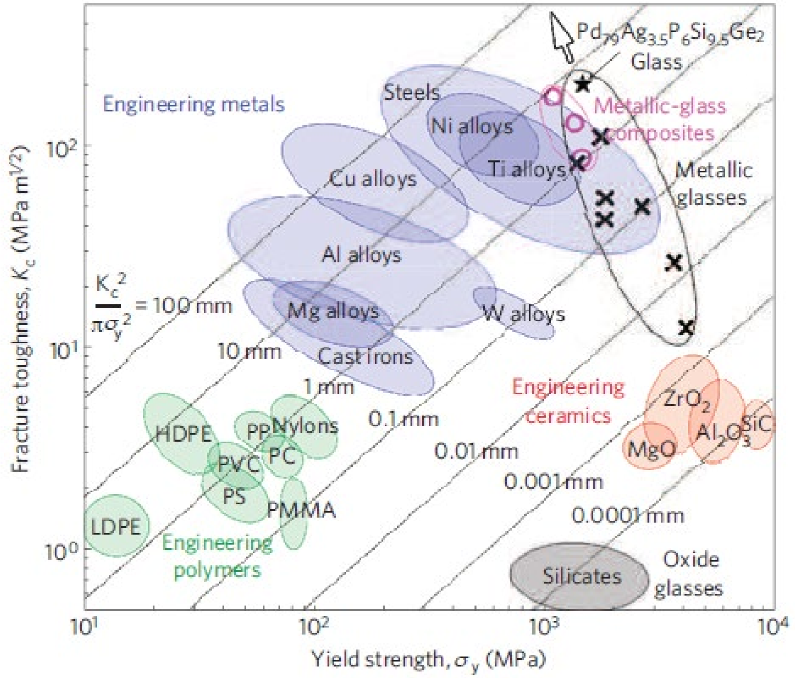




Metallic Glass Composites

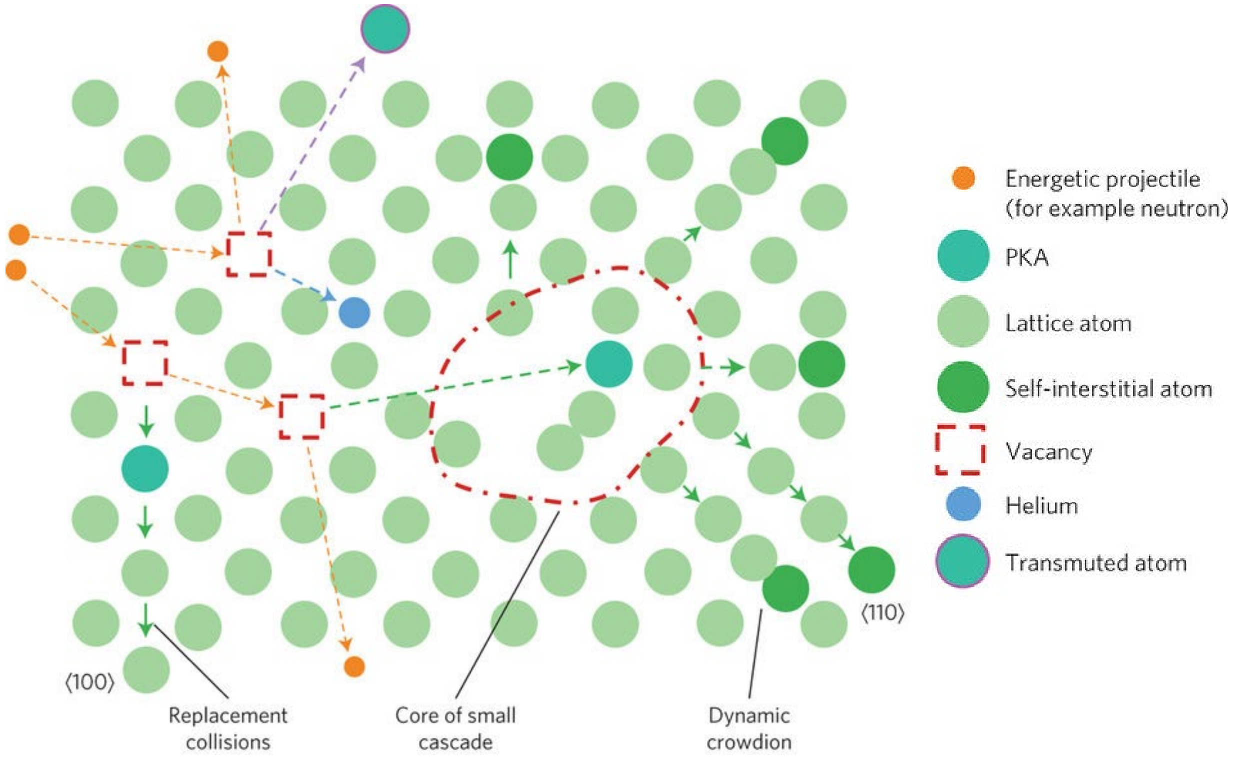
- Some metallic glasses suffer from poor fracture toughness
- Ductility an issue for nearly all BMGs
- Composites offer improvements
  - Crystalline phases present in an amorphous matrix
  - Requires precise cooling rates





Bordeenithikasem et al. (2021)

Radiation Damage in Materials



Knaster et al *Nature Physics* (2016)

- Irradiation hardening and loss of ductility
- Phase instability from radiation precipitation/dissolution, segregation (<0.3-0.6 T_M, >0.1 dpa)
- Void swelling (0.3-0.6 T_M , >10 dpa)
- Irradiation creep (<0.5 T_M, >10 dpa)
- High temperature He embrittlement (>0.5 T_M, >10 dpa)

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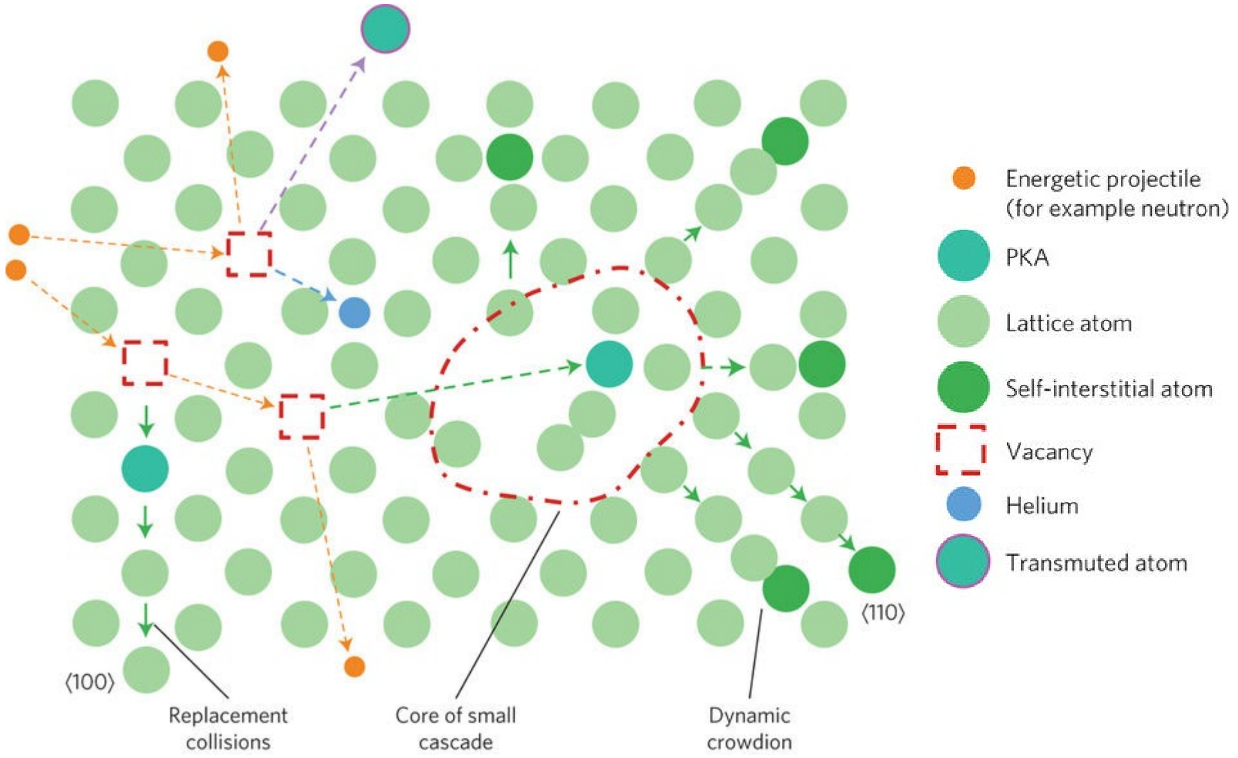

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PhD Research Plan

Research Goal:

(1) Develop an understanding of microstructure evolution of BMG composites under irradiation

(2) Discover candidate refractory based metallic glasses with high T_g, high radiation tolerance good corrosion resistance, low cost, and acceptable processability

Hypothesis: Phase instability in composites leads to increased radiation hardening relative to non-composite BMGs

Summer Project: Investigate irradiation behavior of bulk FeCrMoBC BMG composite

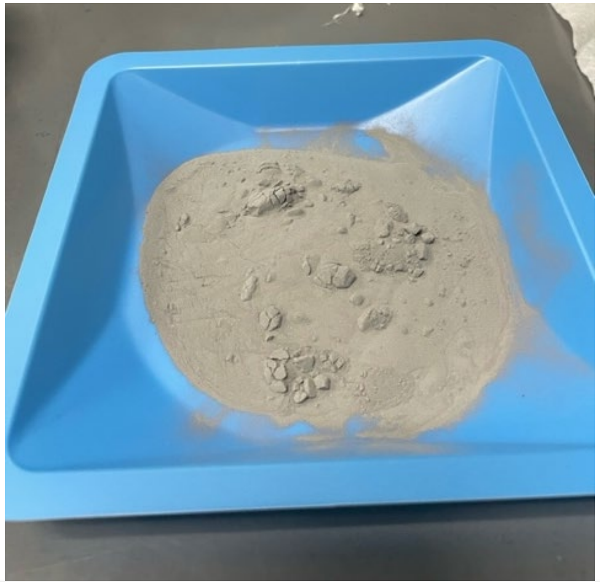
- Sample Production and Preparation
- Ion irradiation
- Simulation

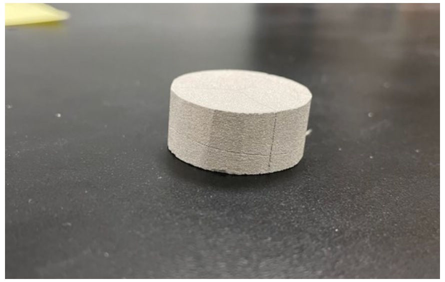
Further Work:

- Post irradiation analysis
- Further BMG explorations
- Neutron irradiation

Sample Preparation

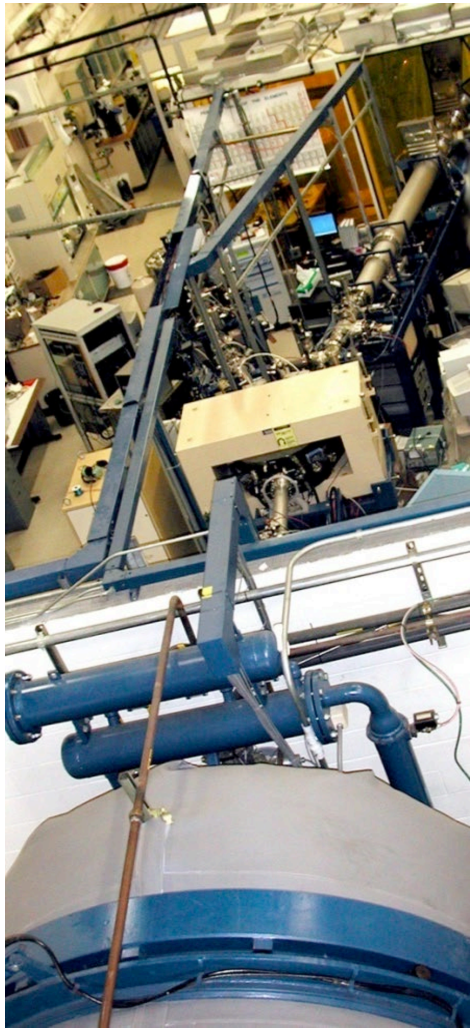
- Powder Feedstock consolidated via SPS
- Glass formed in an Arc Melter; cast into 1/4’’ diameter tubes
  - Diameter of the tubes controls the cooling rate, and therefore the resultant microstructure
- Samples cut and polished to mirror finish
- Verification of amorphous microstructure – XRD




Ion Irradiation

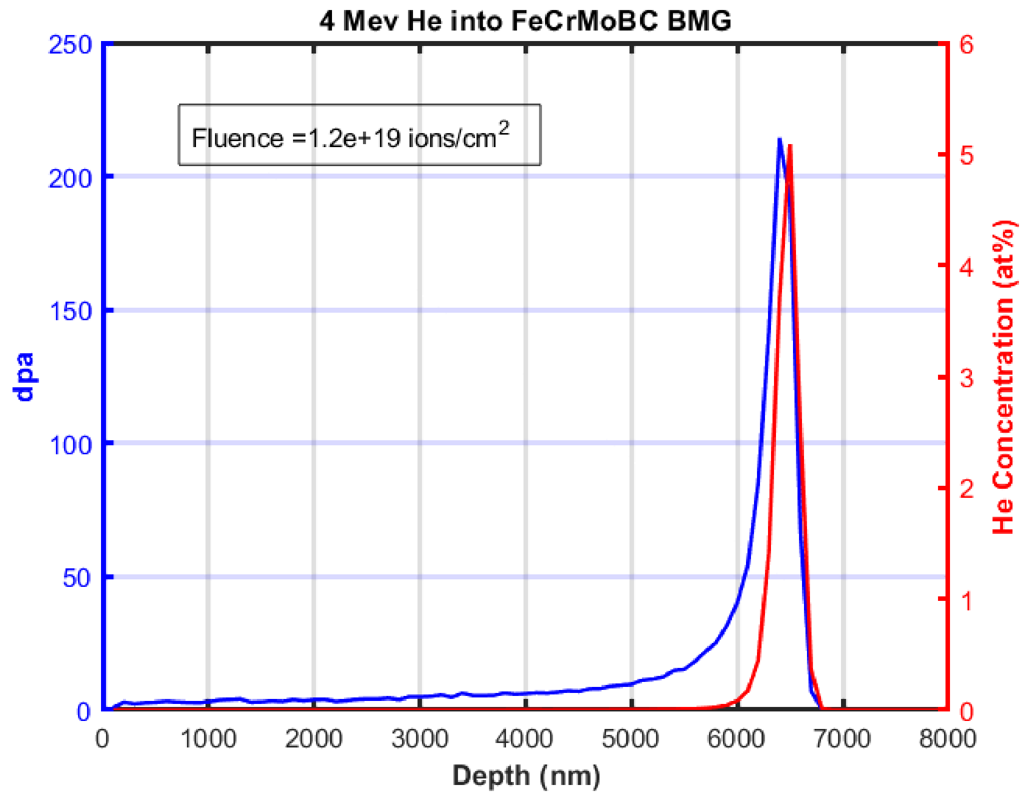
- Ions can be used to simulate neutron damage in materials with less difficulty
  - High dose neutron sources are rare – ATR and HFIR
  - Neutron Irradiation campaigns require long exposure time and cool down time
    - Neutrons activate samples, leaving them “hot”; sufficient time must pass before post irradiation analysis can be performed
- Ion Irradiation offers several benefits
  - High dose particle accelerators are more readily available
  - High dose irradiations can be performed quickly (<1 day vs months)
  - Samples not left activated, post irradiation analysis begins immediately
- Drawbacks of Ion Irradiation
  - Materials must be neutron irradiated for licensing purposes
  - No transmutation reactions
  - Low penetration depth/uniformity



Courtesy of S. Kucheyev

Simulated Ion Irradiation of FeCrMoBC BMG Composite

- Simulated 4 MeV He Ion beam interacting with FeCrMoBC using SRIM software
- SRIM – Stopping Range of Ions in Matter
  - Monte Carlo code use for studying damage effects in materials
  - Simulation run over 100,000 ions
  - Uses Kinchin-Pease model for displacement
  - No crystal effects considered
  - Threshold displacement energies taken from literature
- Test region of ~4-5 dpa



Future Work

Post Irradiation Investigations

Microstructure evolution under irradiation

- Crystallization and changes in T_g

UNM posses a wide range of testing capabilities for small samples:

- SEM/TEM Analysis
- XRD
- DSC
- Micro Hardness Testing
- Nano Mechanical Testing

Further BMG Exploration

Composites:

- Forming composites requires precise cooling rates
- Microstructure evolution not well understood

Molybdenum Based Glass:

- High T_g
- High corrosion resistance
- Relatively cost effective
- Low GFA
- Leverage AM to map large composition space

Neutron Irradiations

- Needed for validation and licensing
- Only to be performed on candidate materials
- Likely requires time in HFIR/ATR
- UNM is developing hot cell capabilities for post neutron irradiation analysis

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Conclusion: BMGs Can Potentially Improve Infrastructure Resiliency

This research seeks to:

- Validate BMGs use in radioactive environments by understanding microstructure evolution under irradiation
- Support the use of BMGs in higher temperature environments by developing refractory based BMG composites
- Evaluate BMG composites for structural components supported by increased ductility

BMG composites may prove to be a viable materials for in highly corrosive, high dose, elevated temperature environments

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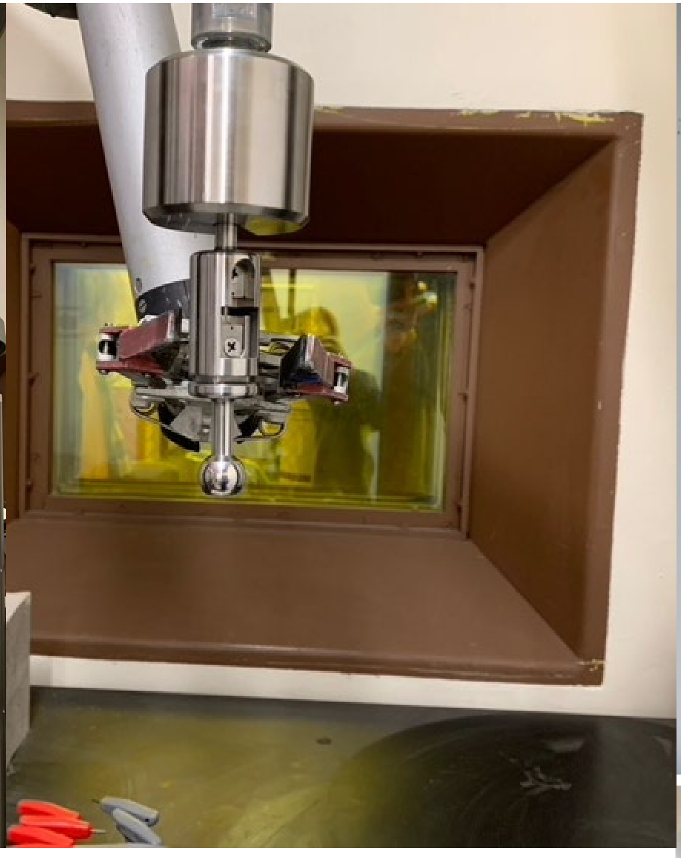
Lawrence Livermore National Laboratory

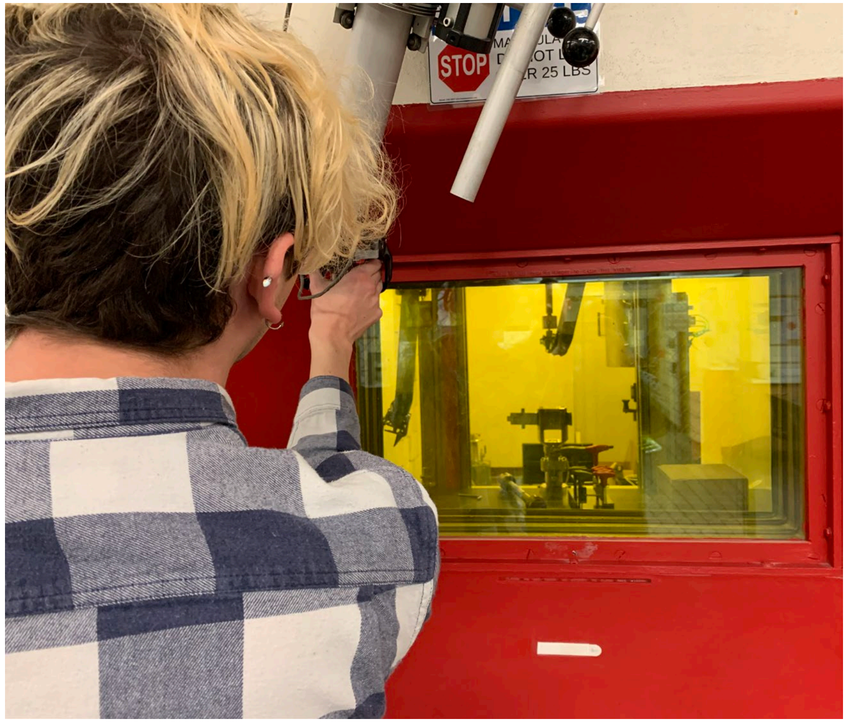
UNM is capable of remote mechanical testing in NE hot cell (up to 900°C)

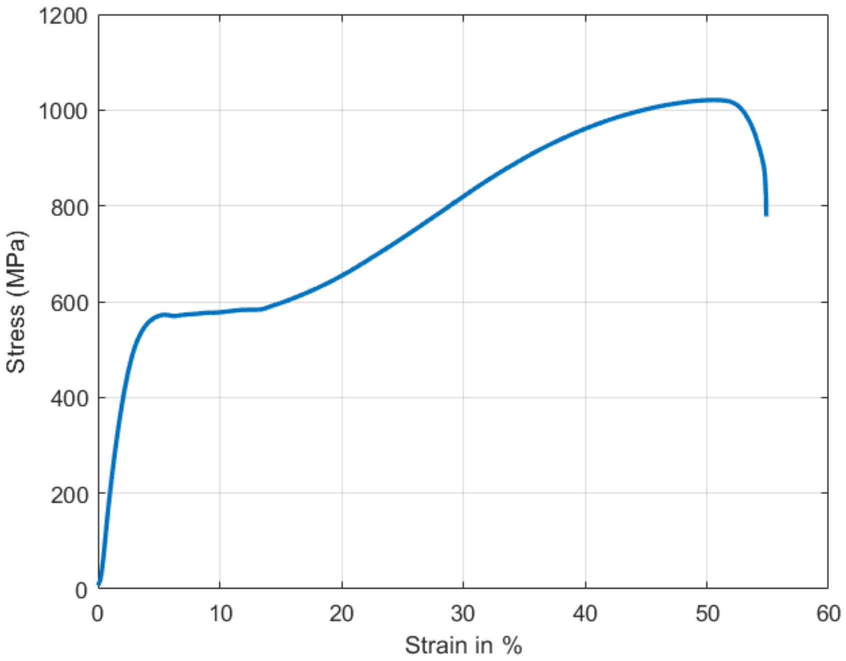


Zwick Roell AllroundLine Z020 THW was installed

A 3-zone Maytec HTO-08 furnace capable of high temperatures up to 900°C

UNM is capable of mechanical testing at cryogenic temperatures (down to -200°C)



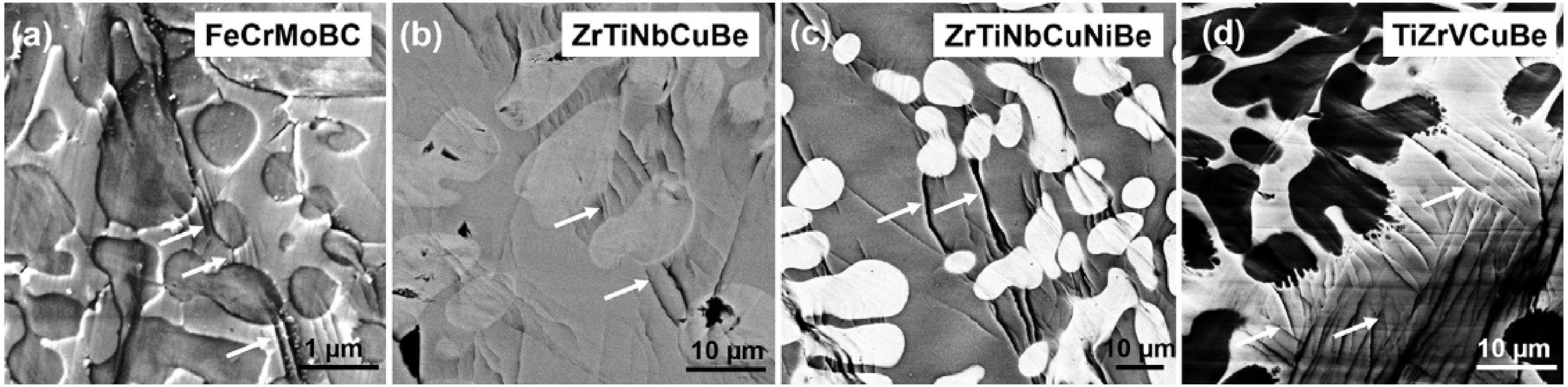


(left) J. Justice is having fun with manipulators installing specimen on Zwick Roell AllroundLine Z020 THW while LN_2 bath is being filled by the O. Anderoglu (right)

Cryogenic temperature (~80K) was performed at $5x10^{-4}$/s displacement rate on 316SS specimens (S1).

BMG Failure Mode: Shear Banding

- Failure is brittle and catastrophic
- Shear banding is a plastic deformation mode that localizes large shear strains in a thin band in the material
- Crystalline phases suppress shear band growth → composites have improved ductility



Composites showing shear band arresting by dendrites in Fe, Zr, and Ti glass families

Bordeenithikasem et al. (2021)