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NSUF Nuclear Science User Facilities

ASSESSMENT OF IRRADIATED MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FECRAL ALLOY FABRICATION ROUTES

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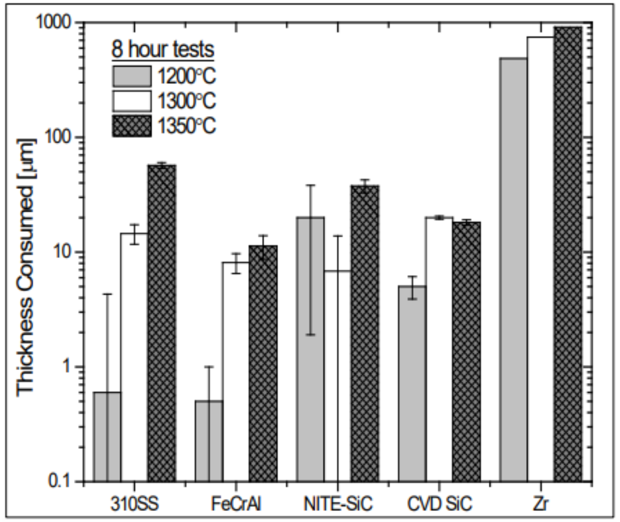
GE Vernova Advanced Research

2024 NSUF Annual Review Meeting (Virtual)

The Need for Accident Tolerant Fuels

$$Zr_2 + 2H_2O \xrightarrow{Heat} 2H_2 + ZrO_2$$



- In March 2011, an earthquake and tsunami caused a loss of coolant accident at the Fukushima Daiichi nuclear power plant
- Excessive decay heat cause high temperature steam oxidation of Zircaloy fuel cladding
- Oxidation of cladding caused significant release of hydrogen gas
- Hydrogen gas build up eventually led to explosion releasing radioactive fission products into environment
- In 2012, congress authorized funding for DOE to lead development of accident tolerant fuels

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GE's Accident Tolerant Fuel Program

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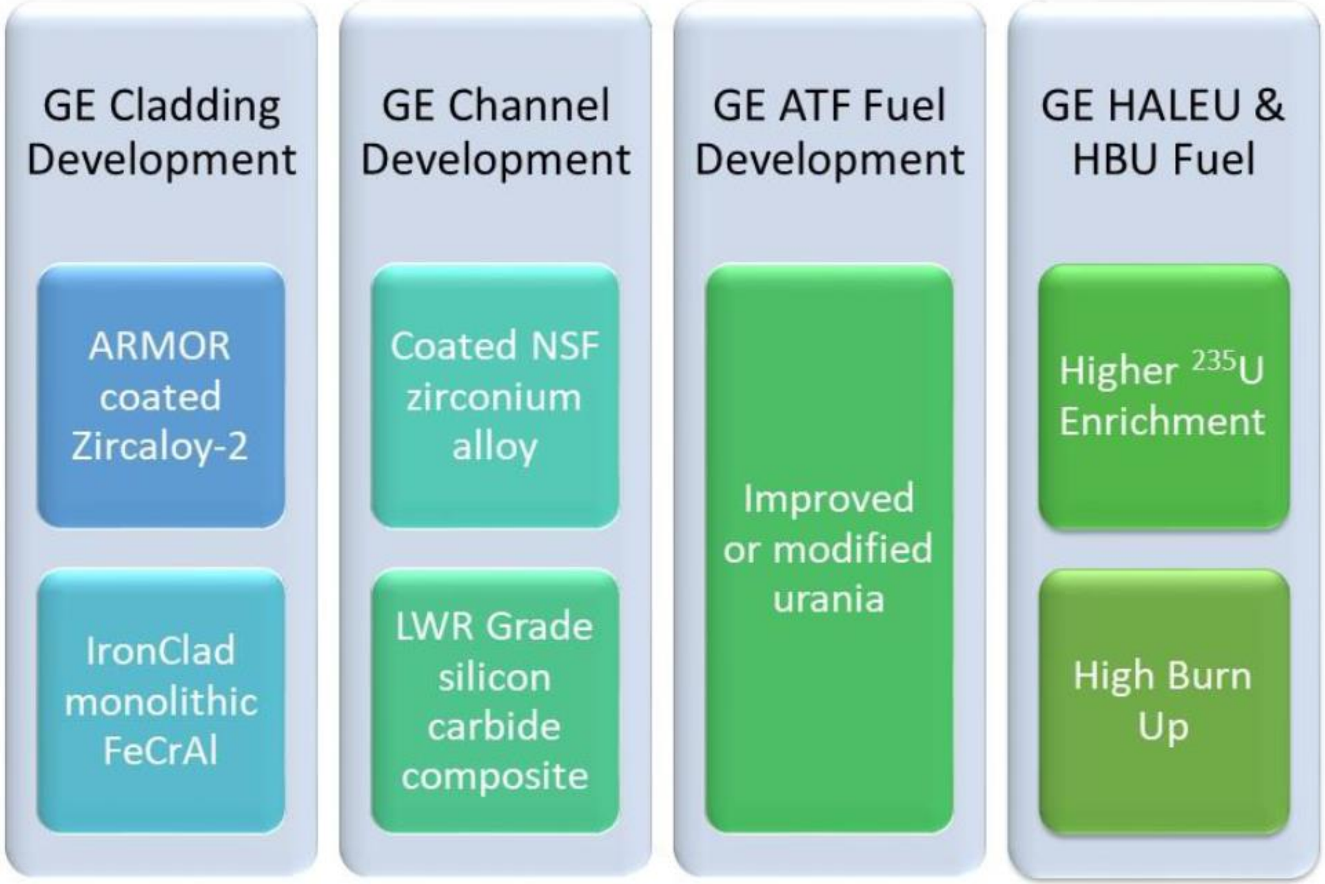
- Collaboration between US Department of Energy, GE Research, Global Nuclear Fuel, GE-Hitachi, and several US national labs
- Short term cladding concept is coated Zircaloy (ARMOR)
- Mid-term cladding concept is FeCrAl (Ironclad)
- Long term concept is developing SiC-SiC CMCs for fuel channel materials



Why FeCrAl?

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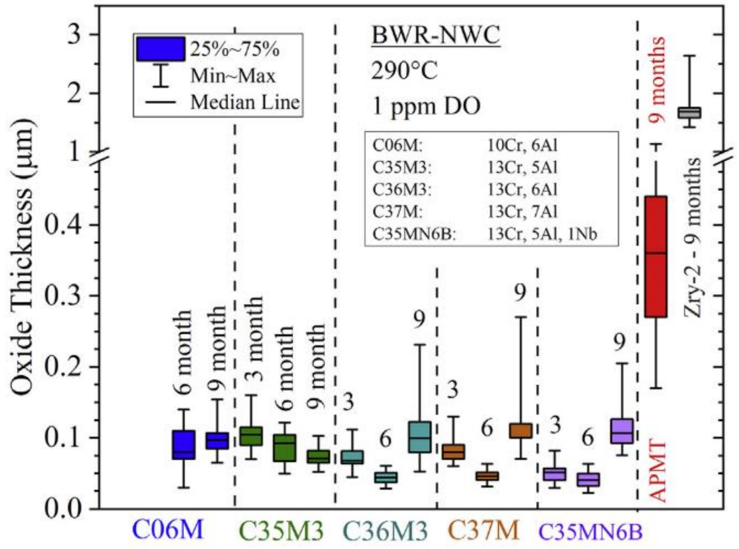
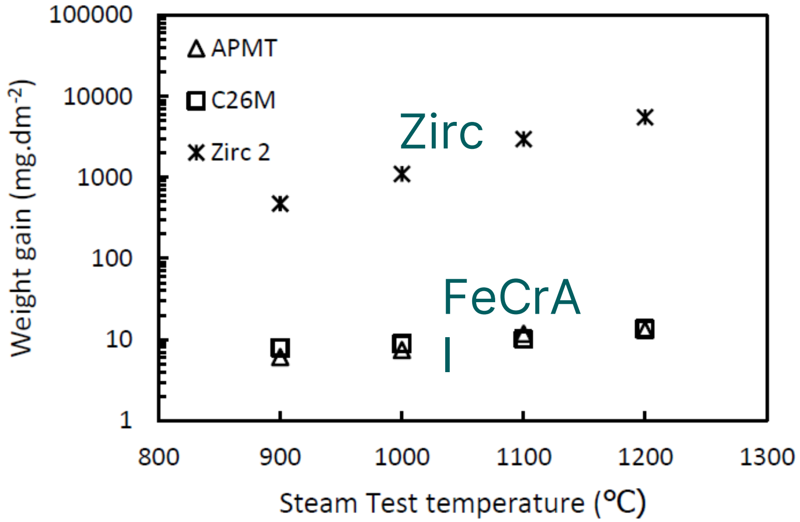
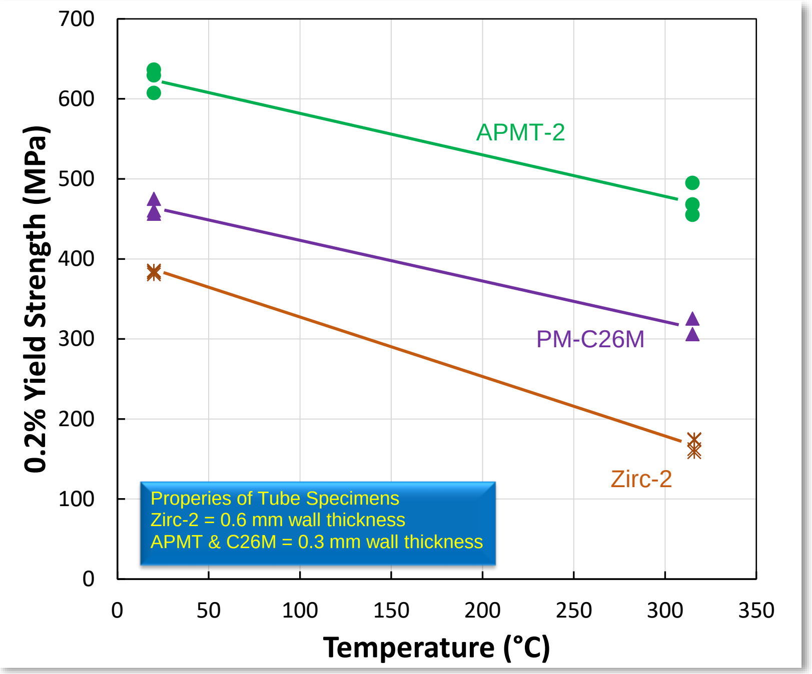


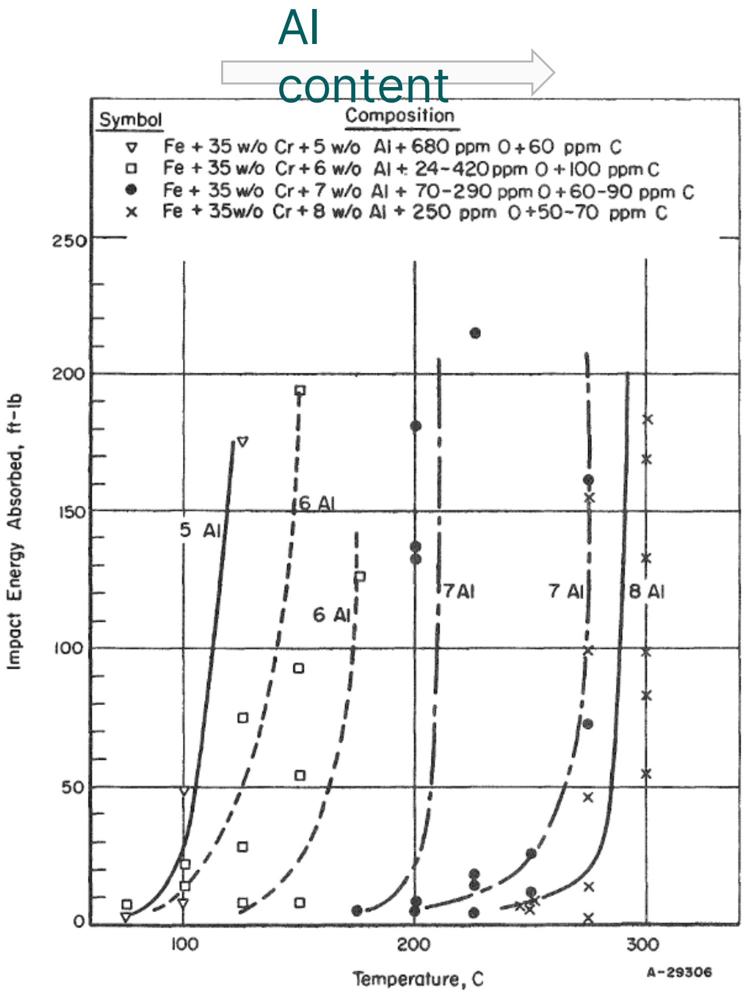




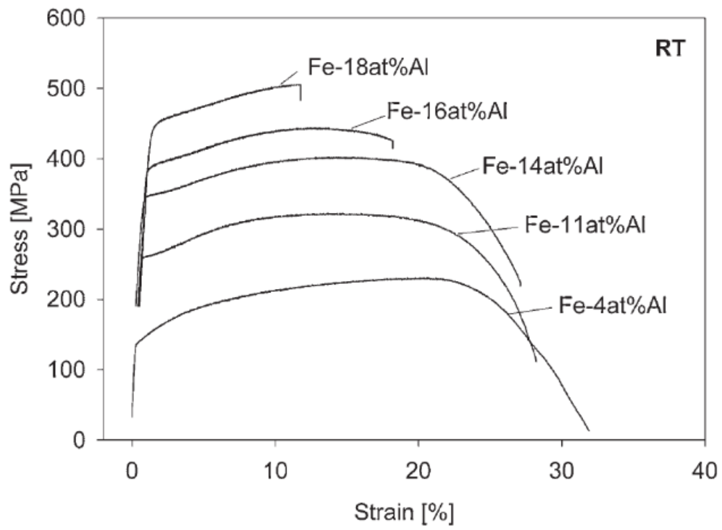
- FeCrAl alloys have similar hydrothermal corrosion performance to Zry-2
- **Enhanced high temperature steam oxidation resistance** due to Al (forms protective passive Al oxide film)
- Better mechanical properties (especially at elevated temps) than Zry-2 allow for thinner cladding (less neutron absorption)

*R.B. Rebak, K.A. Terrani, R.M. Fawcett, FeCrAl Alloys for Accident Tolerant Fuel Cladding in Light Water Reactors, Vol. 6B Mater. Fabr. (2016) V06BT06A009.
**S.S. Raiman, K.G. Field, R.B. Rebak, Y. Yamamoto, K.A. Terrani, Hydrothermal corrosion of 2nd generation FeCrAl alloys for accident tolerant fuel cladding, J. Nucl. Mater. 536 (2020) 152221.

Mechanical Properties of Al Containing Ferritic



W. Chubb, S. Alfant, A.A. Bauer, E.J. Jablonowski, F.R. Shober, R.F. Dickerson, Constitution, Metallurgy, and Oxidation Resistance of Iron-Chromium-Aluminum Alloys: BMI-1298, 1958.



J. Herrmann, G. Inden, G. Sauthoff, Acta Mater. 51 (2003) 2847–2857.

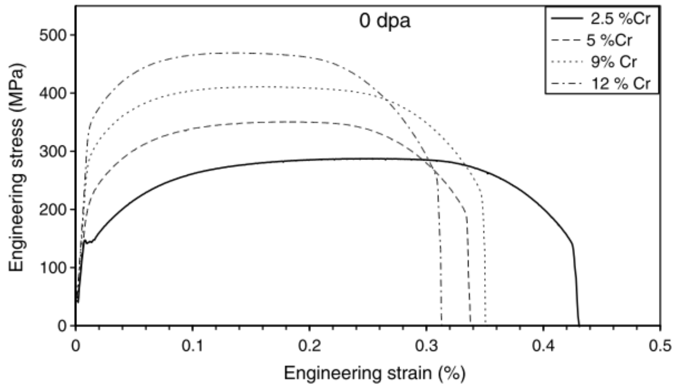


Fig. 3. Engineering stress and strain curves at RT of the model alloys before irradiation.

M. Matijasevic, A. Almazouzi, J. Nucl. Mater. 377 (2008) 147–154.

- Adding Al in solution to a ferritic matrix shifts DBTT to higher temps and significantly reduces ductility
- Hardening comes from SSS and possibly Al producing excess vacancies
- Adding Cr also increases SSS and reduces ductility

Mechanical Properties of Al Containing Ferritic Alloys

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Table 2
Average grain sizes, Vickers hardness values, and tensile properties of the studied alloys.

ID	Grain size (μm)	Hardness (HV)	RT YS (MPa)	RT UTS (MPa)	RT US (%)	RT FS (%)
APMT-heat #1	~ 192	272 ± 6	579 ± 4	597 ± 11	0.8 ± 0.2	0.8 ± 0.2
APMT-heat #2	10–16	307 ± 9	727 ± 9	837 ± 22	12.1 ± 0.3	25.9 ± 1.0
APMT-heat #1-HR800	35–50	254 ± 6	569 ± 5	743 ± 26	11.6 ± 4.1	18.8 ± 4.0
IM-APMT	60–86	241 ± 5	494 ± 12	581 ± 14	2.8 ± 0.2	2.8 ± 0.2
10Cr-HR800	110–161	211 ± 5	448 ± 5	561 ± 5	11.8 ± 1.0	17.9 ± 6.6
13Cr-HR800	131–236	218 ± 4	461 ± 9	584 ± 4	12.3 ± 1.4	21.0 ± 8.1
10Cr-HR650	41–57	217 ± 5	471 ± 10	619 ± 3	13.7 ± 0.8	28.6 ± 0.9
12Cr-HR650	39–60	274 ± 8	769 ± 18	789 ± 21	1.1 ± 0.5	3.8 ± 1.4
13Cr-HR650	37–50	283 ± 9	760 ± 14	774 ± 14	1.5 ± 1.2	10.1 ± 7.4
13Cr-HR650-Ann	37–50	229 ± 5	545 ± 7	646 ± 16	10.4 ± 0.9	23.2 ± 0.7

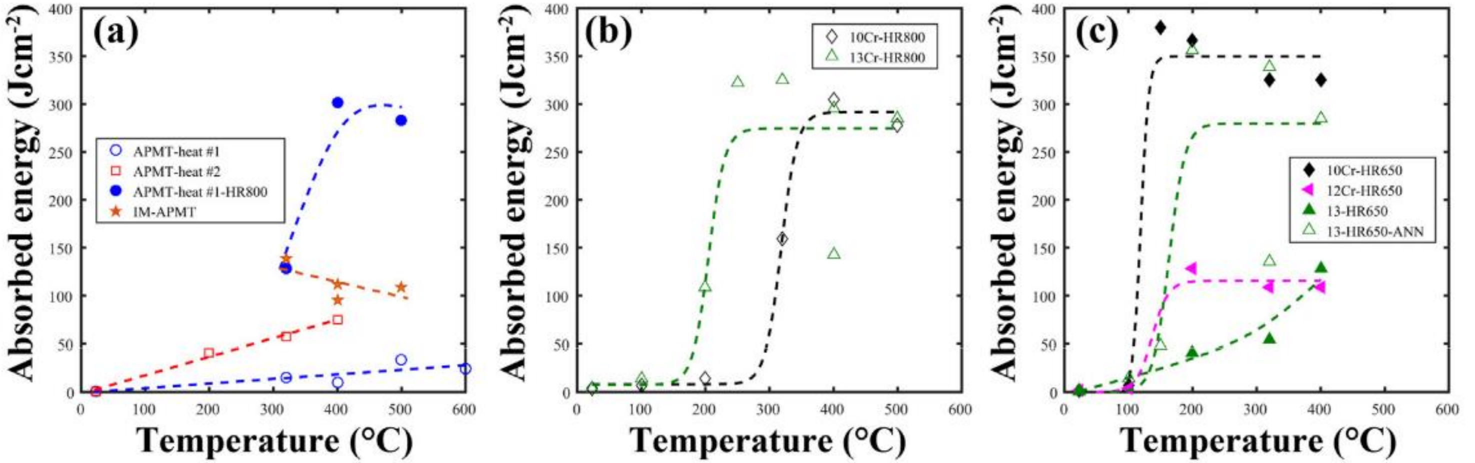

Fig. 8. Impact absorbed energy in the temperature range from RT to 600 °C for (a) commercial APMT alloys and their variations; (b) wrought FeCrAl alloys hot-rolled at 800 °C; and (c) wrought FeCrAl alloys hot-rolled at 650 °C.

- Work done by ORNL showed impact toughness of low Cr and APMT FeCrAl variants
- Best performers were fine grained, equiaxed, and homogenous microstructures
- Retained strain had severe effect on impact

Sun, Z., Yamamoto, Y., & Chen, X. (2018). Impact toughness of commercial and model FeCrAl alloys. Materials Science and Engineering: A, 734, 93-101.

Effects of Microstructure on DBTT of C26M

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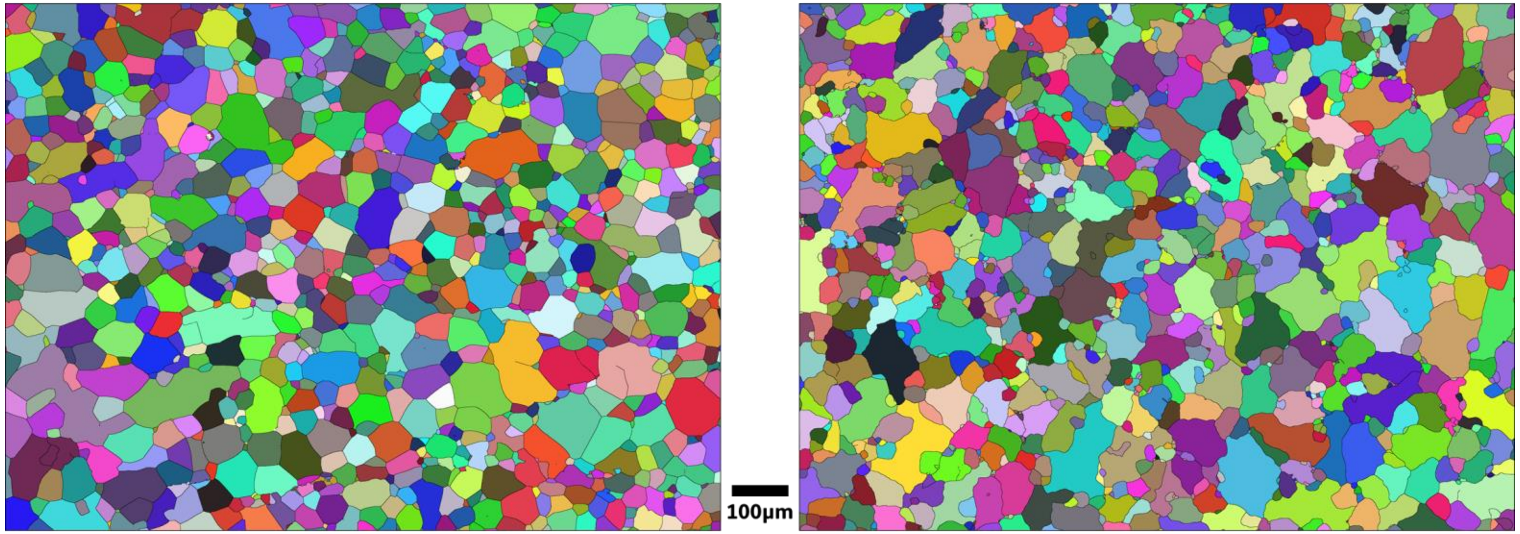

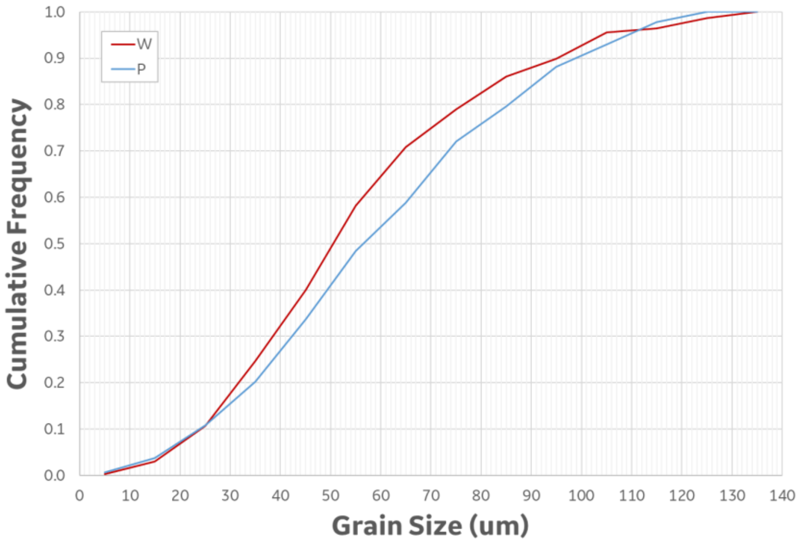

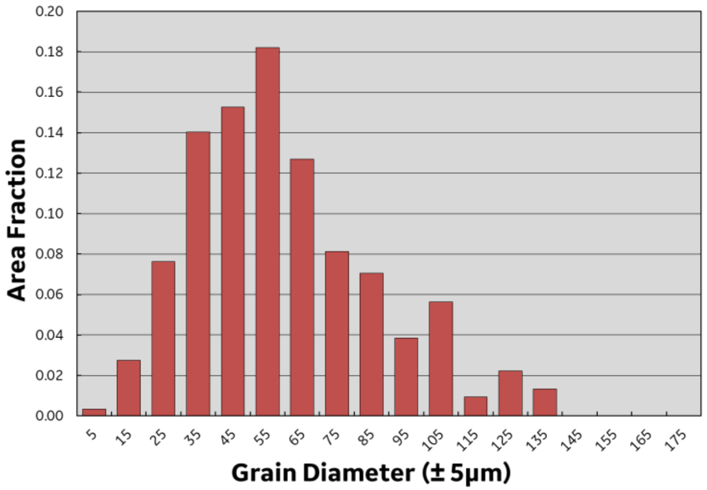

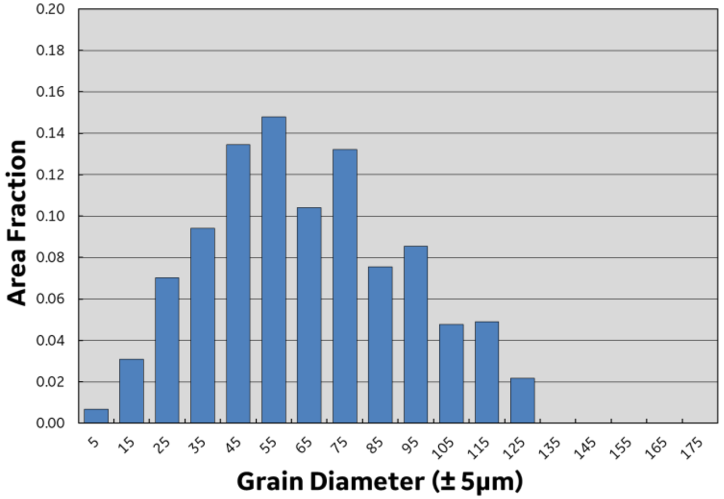

- Compared wrought (cast/forged) and powder (PM-HIP and extruded) C26M
- Both Wrought and Powder C26M have similar avg. grain size (~60 microns)
- Powder C26M sample has broader grain sizer distribution

Hoffman, A. K., Umretiya, R. V., Crawford, C., Spinelli, I., Huang, S., Buresh, S., ... & Rebak, R. B. (2023). The relationship between grain size distribution and ductile to brittle transition temperature in FeCrAl alloys. Materials Letters, 331, 133427.

Effects of Microstructure on DBTT of C26M

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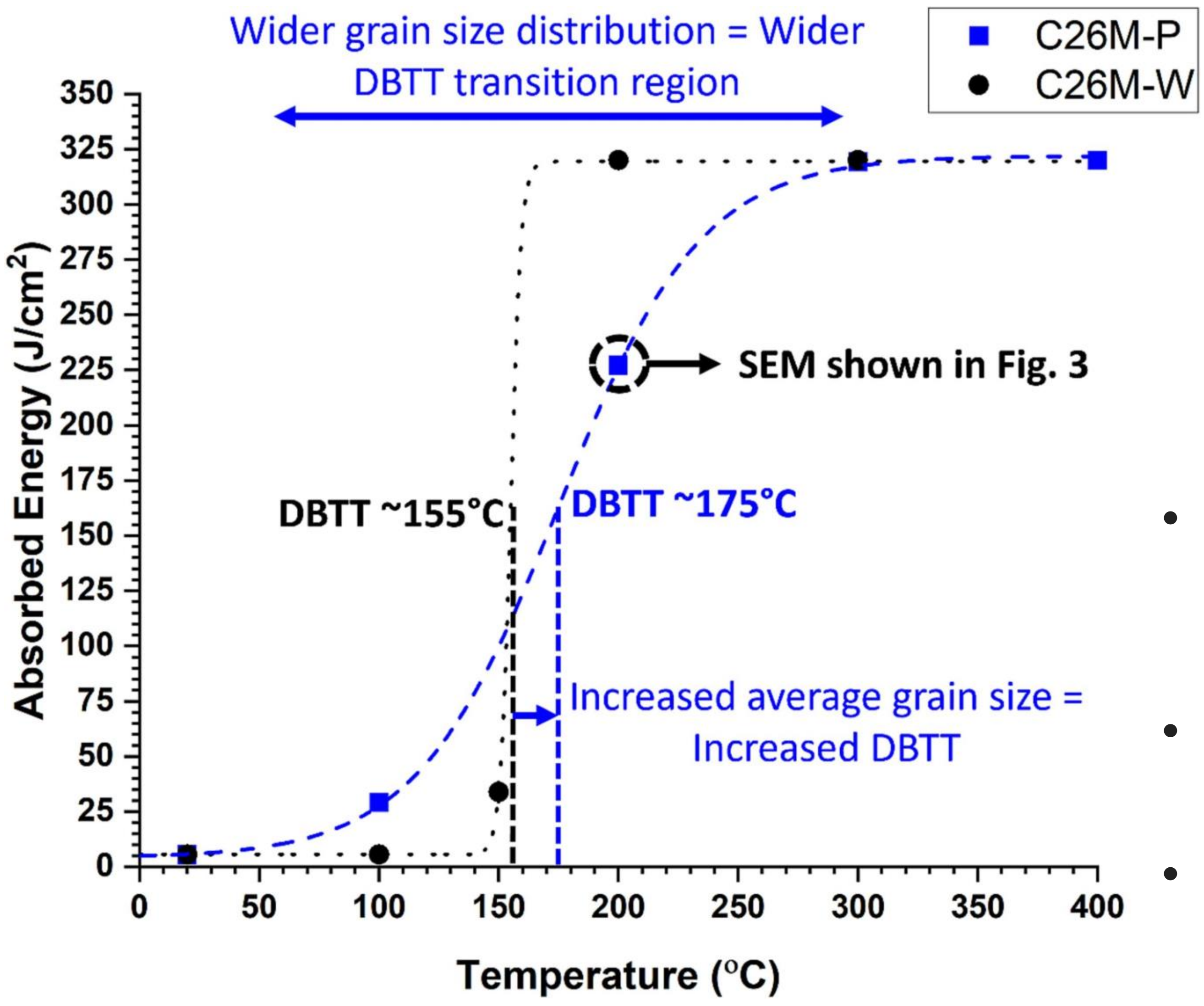

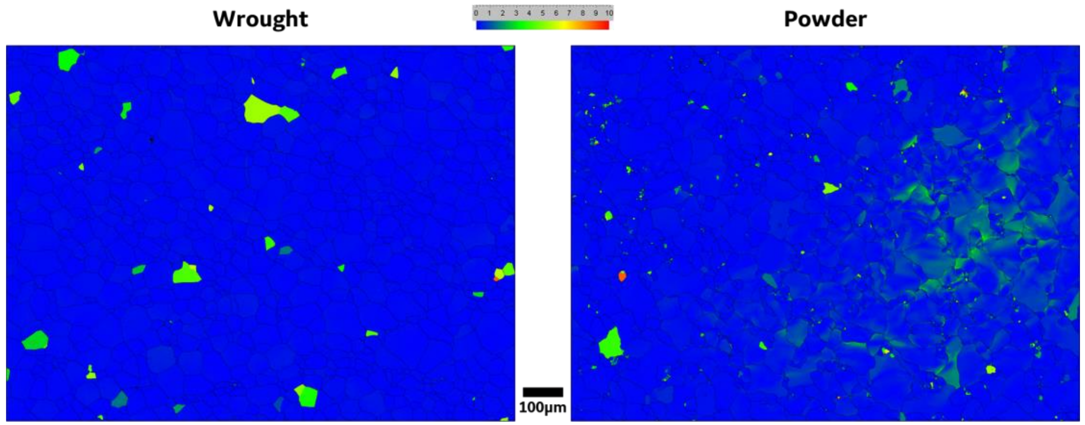

Misorientation maps from EBSD

- Both C26M-P and C26M-W have similar DBTT and upper/lower shelf toughness
- C26M-P has much broader transition region than C26M-W
- Difference is assumed to be due to grain size distribution
- Small amount of retained strain in powder sample could also be

Hoffman, A. K., Umretiya, R. V., Crawford, C., Spinelli, I., Huang, S., Buresh, S., ... & Rebak, R. B. (2023). The relationship between grain size distribution and ductile to brittle transition temperature in FeCrAl alloys. Materials Letters, 331, 133427.

Effects of Microstructure on DBTT of C26M

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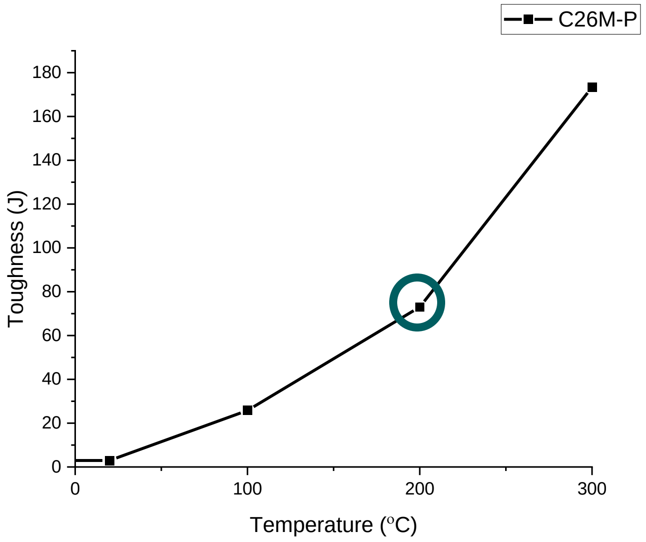
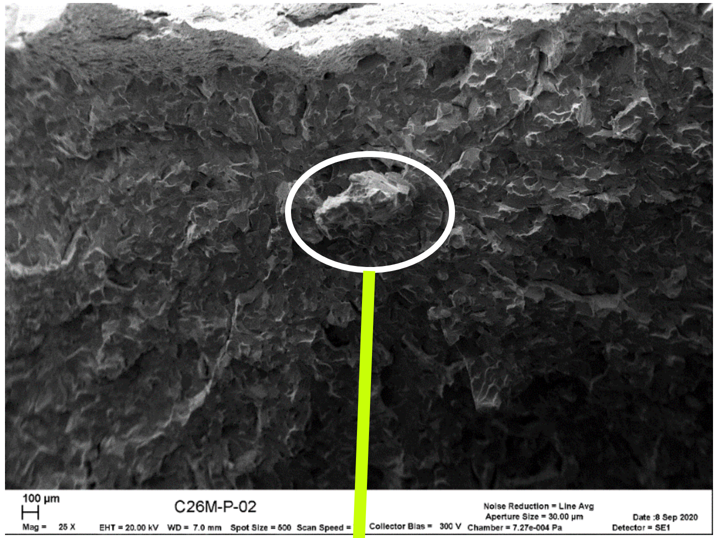
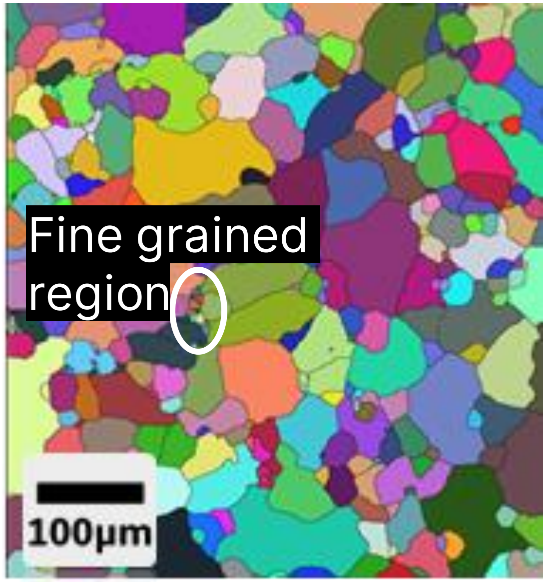
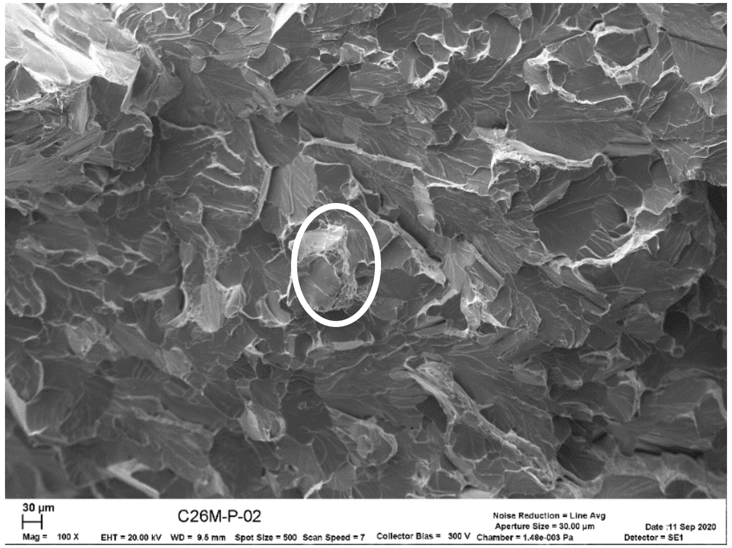
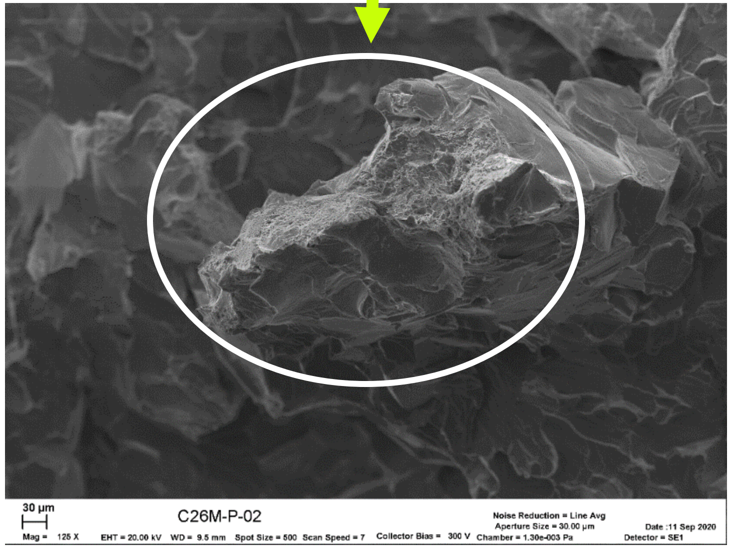






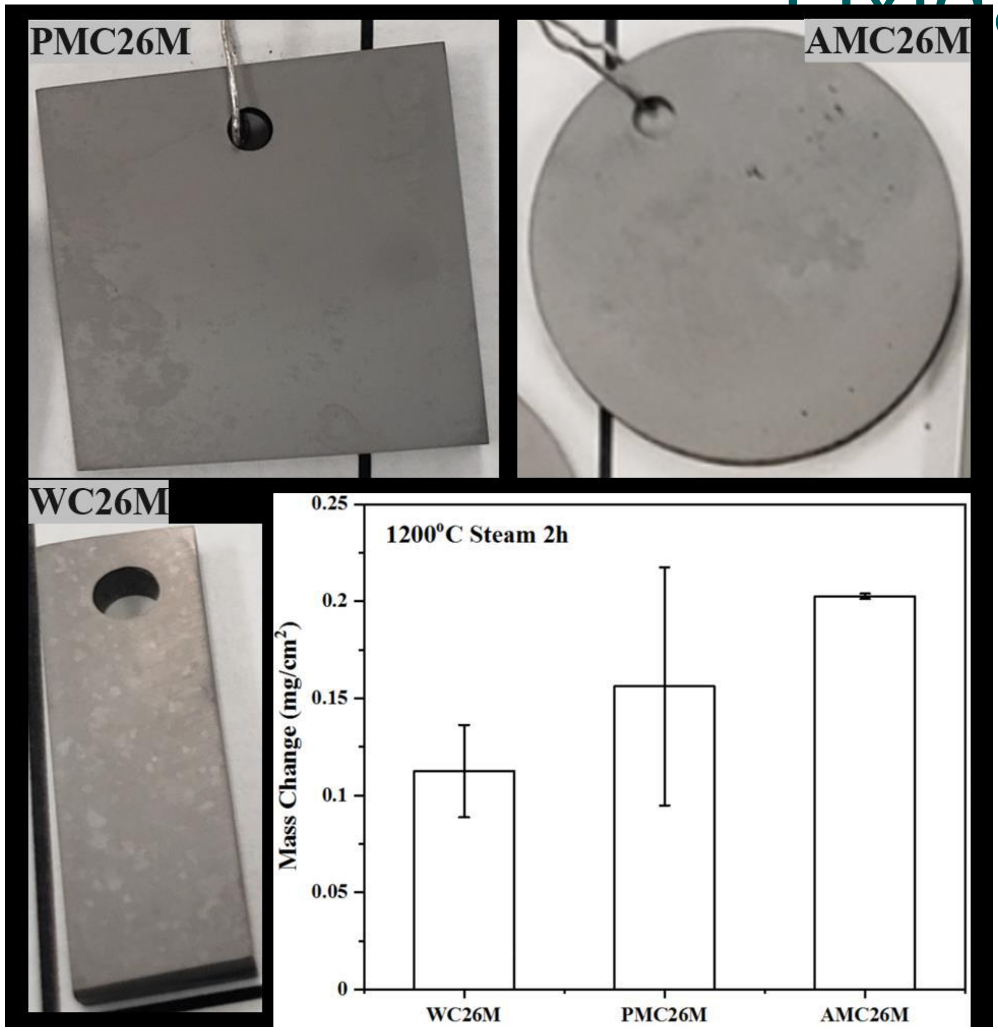


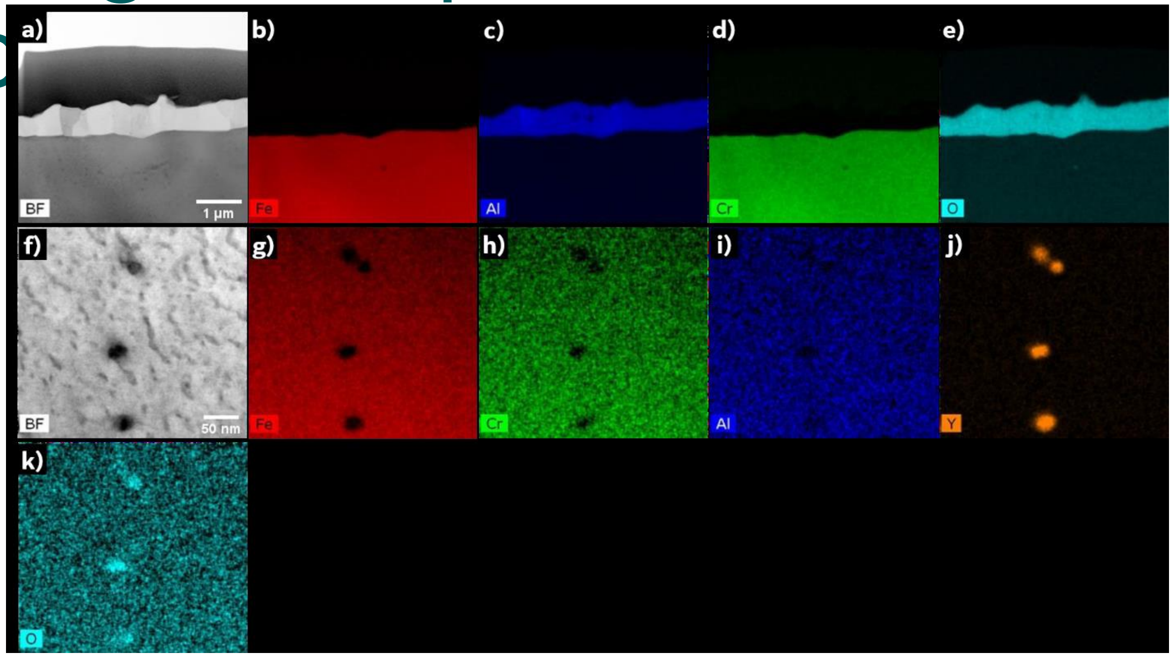


- Mostly brittle fracture within transition region temps
- Pockets of ductile fracture appeared, assumed to be fine grained regions

Hoffman, A. K., Umretiya, R. V., Crawford, C., Spinelli, I., Huang, S., Buresh, S., ... & Rebak, R. B. (2023). The relationship between grain size distribution and ductile to brittle transition temperature in FeCrAl alloys. Materials Letters, 331, 133427.

Effects of Grain Size on High Temperature Oxidatio





- Fabrication route as very little influence on high temperature steam oxidation
- Stable passive Al layer forms on all materials, differences may be due to chemistry rather than microstructure

Hoffman, A. K., Umretiya, R. V., Gupta, V. K., Larsen, M., Graff, C., Perlee, C., ... & Rebak, R. (2022). Oxidation resistance in 1200° C steam of a FeCrAl alloy fabricated by three metallurgical processes. JOM, 74(4), 1690-1697.

Effects of Microstructure on Irradiation Response

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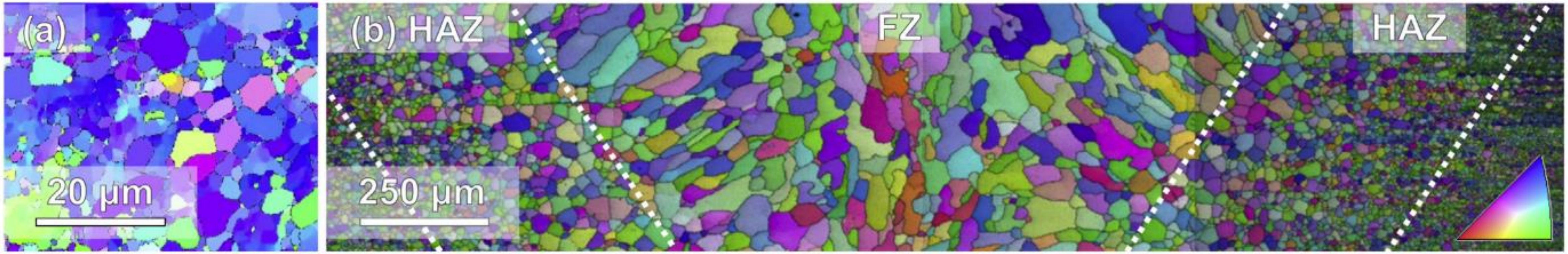
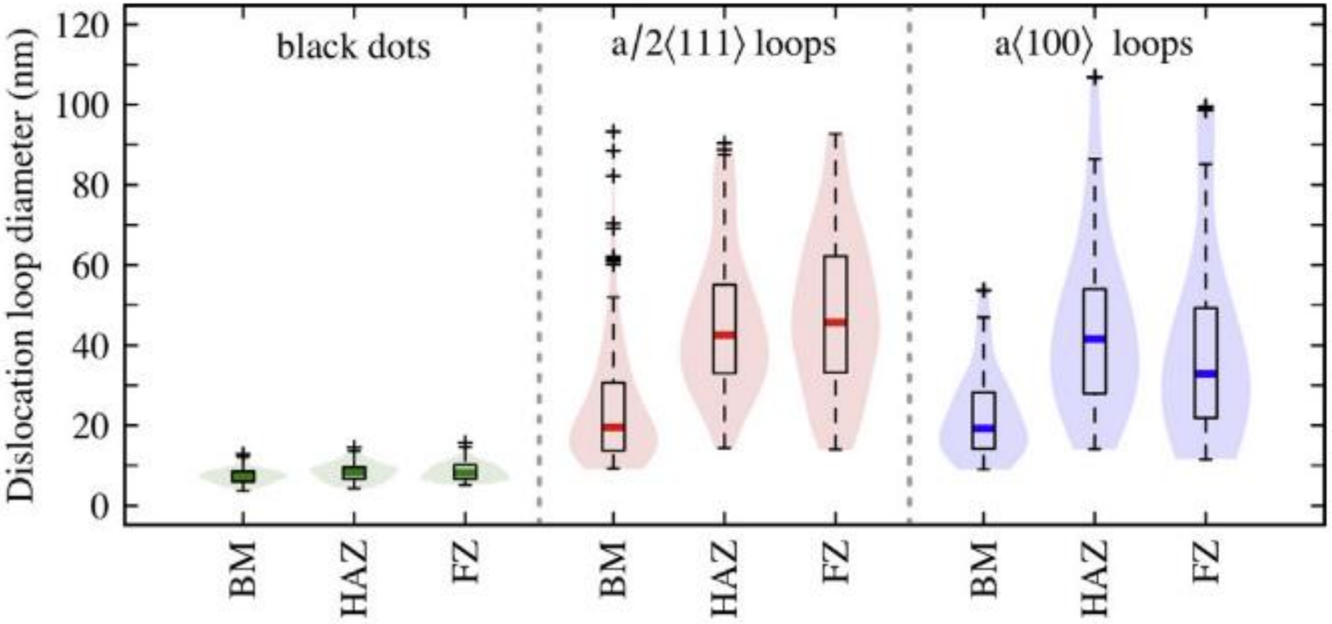
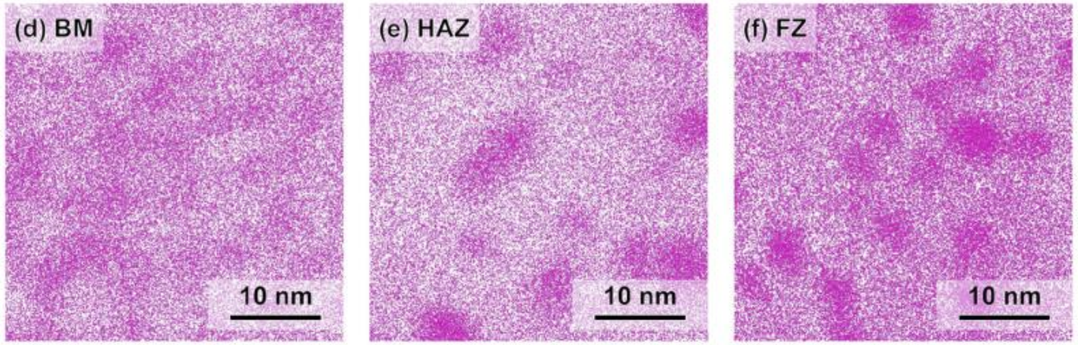




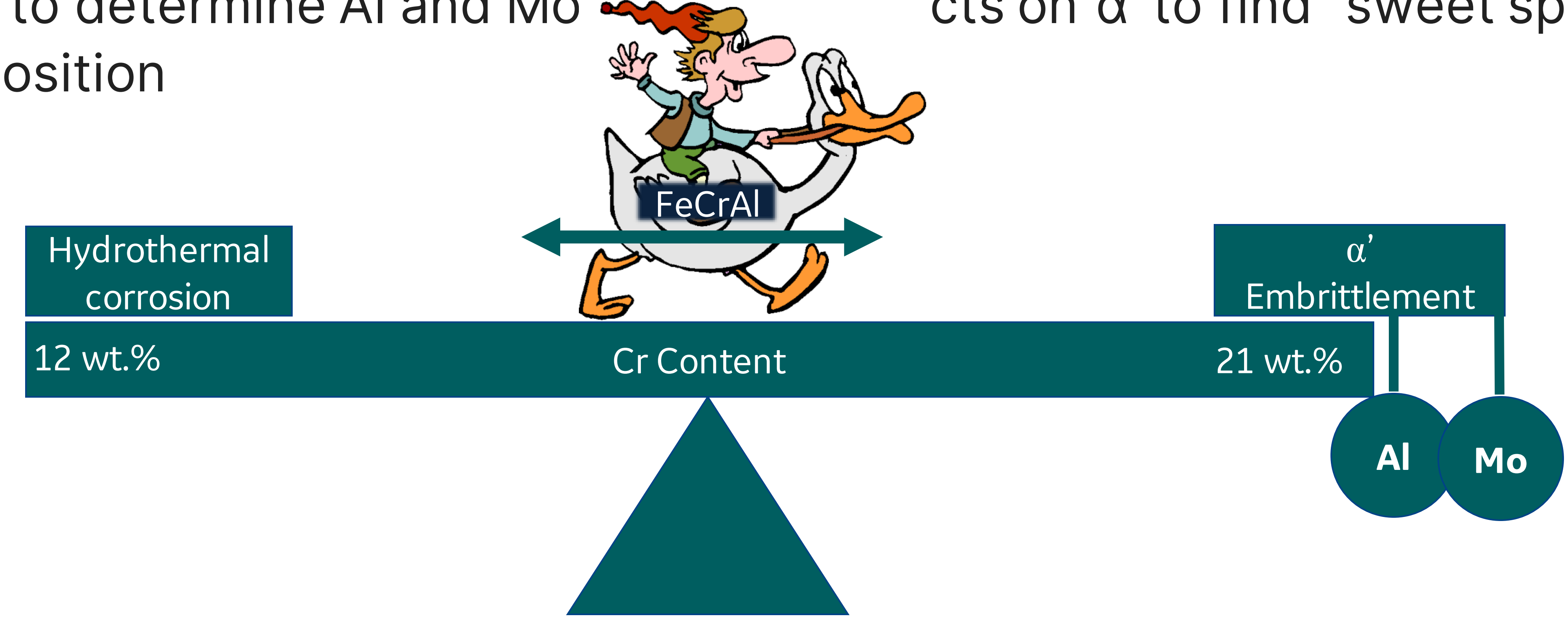


- Microstructure has significant impact on loops and α' after irradiation

D. Zhang, S.A. Briggs, P.D. Edmondson, M.N. Gussev, R.H. Howard, K.G. Field, Influence of welding and neutron irradiation on dislocation loop formation and α' precipitation in a FeCrAl alloy, J. Nucl. Mater. 527 (2019). https://doi.org/10.1016/j.jnucmat.2019.151784.

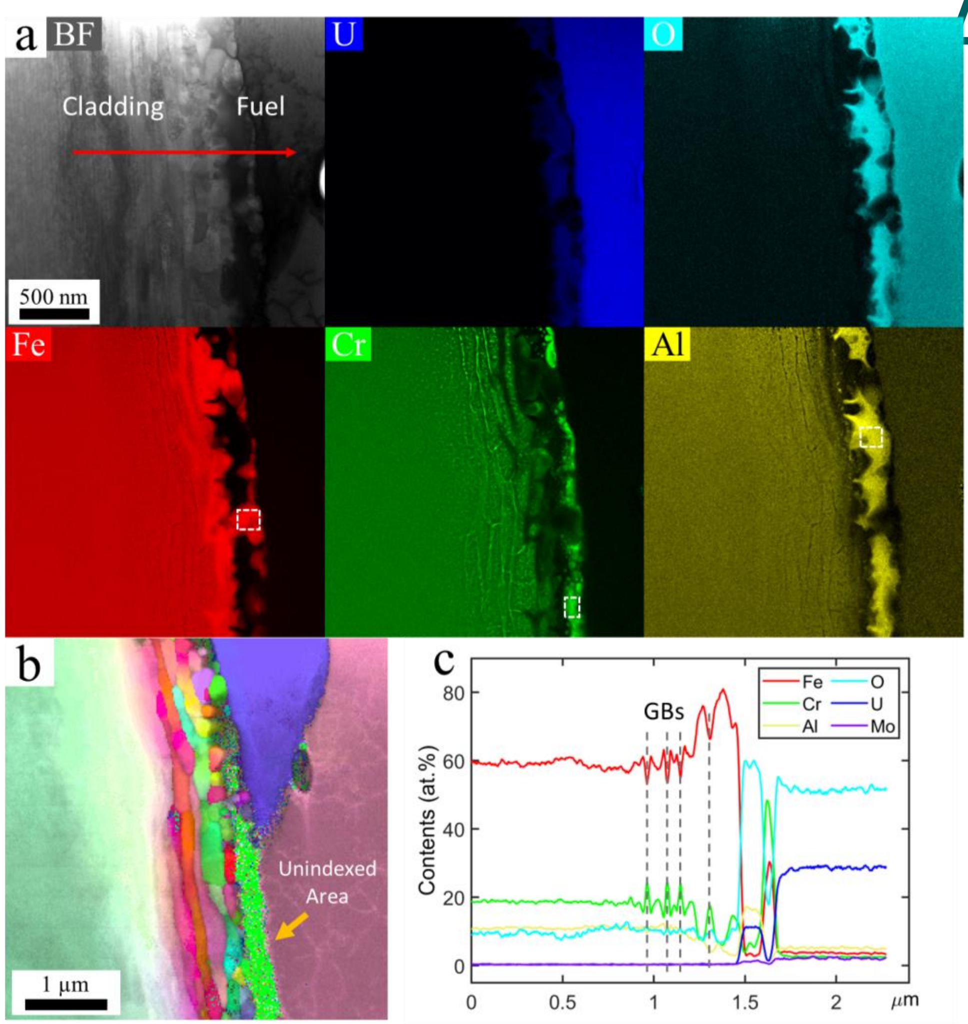
Finding a Balance in FeCrAl Alloys

- Ferritic Fe-Cr based alloys suffer from embrittlement due to α' precipitation, accelerated by irradiation
- Cr important for corrosion resistance, but need to find a good balanced composition
- Need to determine Al and Mo chemical effects on α' to find "sweet spot" composition

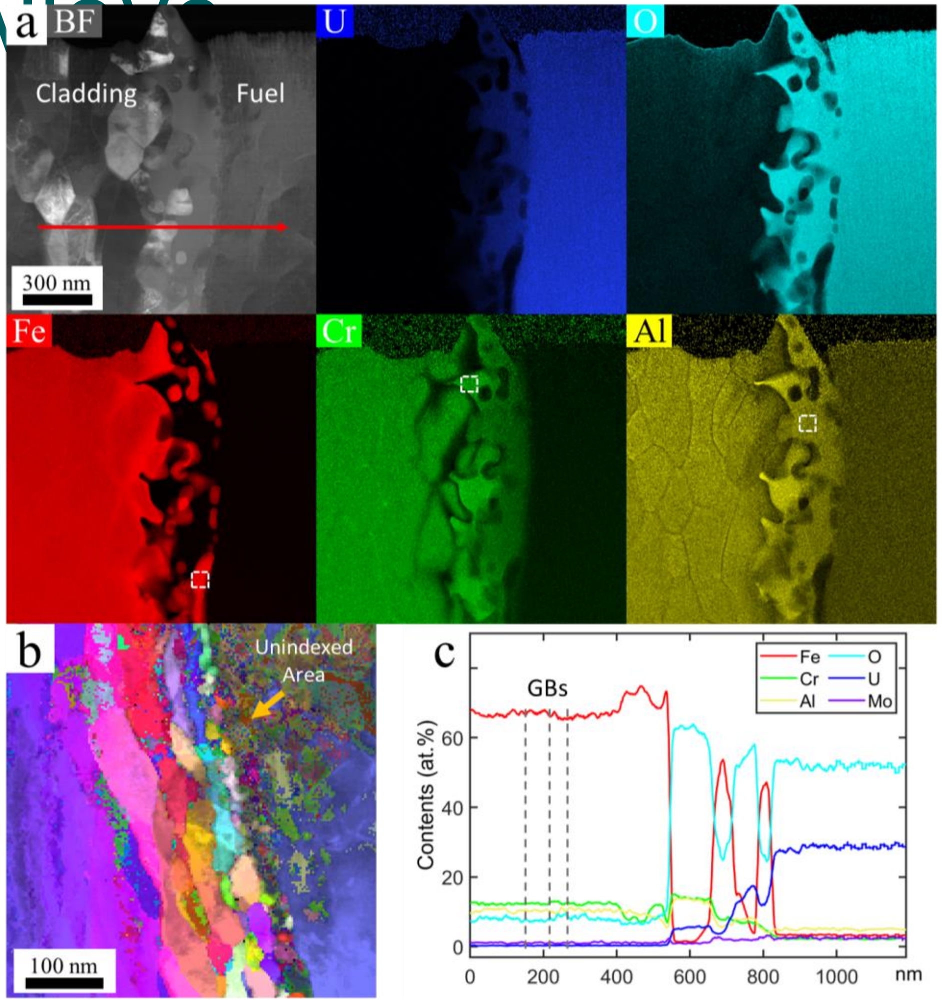


Qu, Assessment of Irradiated Microstructure and Mechanical Properties of FeCrAl Alloy Fabrication Routes

NSUF RTE on FCCI Behavior of FeCrAl Alloys



APMT



C35M

- NSUF-RTE-20-4108
- Diffusion couples from ATF-1 experiments (ATR) show formation of amorphous U-Al-Cr oxide at fuel-clad interface.

Qu, H. J., Higgins, M., Abouelella, H., Cappia, F., Burns, J., He, L., ... & Rebak, R. B. (2023). FeCrAl fuel/clad chemical interaction in light water reactor environments. Journal of Nuclear Materials, 587, 154717.

NSUF Project Overview

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Program Team

Expertise in FeCrAl alloys, commercial nuclear materials, advanced manufacturing

UNIVERSITY OF MICHIGAN

Expertise in ion irradiation, post-irradiation examination, and nuclear materials

Idaho National Laboratory

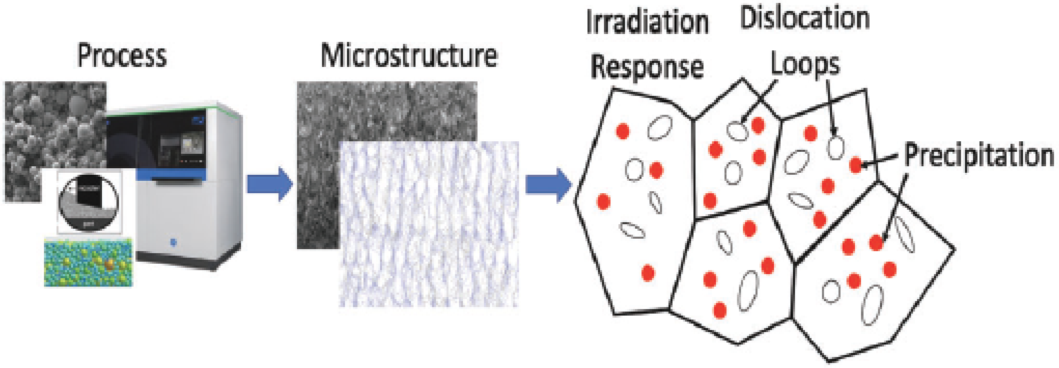
Expertise in neutron irradiation, post-irradiation examination, and nuclear fuels

Relevant Prior Work

- GE's ATF program with eight years of FeCrAl alloy development
- Prior evaluation of various compositions and grain sizes
- Various mechanical testing and corrosion experiments on a variety of FeCrAl alloys including advanced manufactured FeCrAl alloys

A 7-Year, $2.2MM Project to Study Irradiation Effects on FeCrAl Alloys Fabricated Using Advanced Manufacturing Techniques

Program Objective: *Determine the impact of how fabrication route affects the irradiation response in FeCrAl alloys. Three fabrication routes of C26M (F12Cr6Al2Mo) are investigated: wrought, PM-HIP, and LPBF AM.*



Technical Approach

- Proton irradiation of FeCrAl alloys up to 2.0 and 5.0 dpa
- PIE of proton-irradiated FeCrAl alloys using microhardness and TEM
- Neutron irradiation of FeCrAl alloys up to 0.5 and 2.0 dpa
- PIE of neutron-irradiated FeCrAl alloys including microhardness, tensile, TEM, and APT

Technical Challenges

- Temperature dependence of irradiation-induced precipitation
- Characterization and testing of "hot" materials

Program Deliverables

- Report the effectiveness of proton irradiation damage in FeCrAl alloys
- Evaluate the process-microstructure-irradiation response relationships for wrought, PM-HIP, and LPBF-AM FeCrAl alloys through proton, neutron irradiation
- Evaluate commercial viability for advanced manufacturing routes of FeCrAl alloys
- Provide community with insight into the radiation response of advanced manufactured ferritic stainless alloys through manuscripts submitted to scientific journals

Anticipated Benefits of the Proposed Technology

- Significant cost savings for manufacturing using techniques with inherent grain refinement
- Enabling more efficient/less wasteful manufacturing technologies
- Enhanced knowledge of irradiation response of various FeCrAl microstructures to accelerate commercialization of accident-tolerant fuel cladding

NSUF Project Overview

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- Multi-objective approach to maximize value of irradiation matrix
  - Compare proton to neutron irradiation of FeCrAl alloys for accelerated testing using ion beam facilities
    - Focus is on α’ (number density, volume fraction, average size) and loop formation, hardness studies to provide general idea of mechanical behavior
  - Provide comparison of wrought alloys (current commercial irradiations) to new powder metallurgy route
    - Allow GE to make programmatic decisions based on Hatch/Clinton LTRs/LTAs
  - Provide first comparison of irradiation response between three manufacturing routes for FeCrAl alloys (first irradiation of additive FeCrAl)
  - Provide test specimens to NSUF library with model FeCrAl alloys and diffusion multiples-understand effects of composition on irradiation response

RIS behavior after proton irradiation @ 5 dpa

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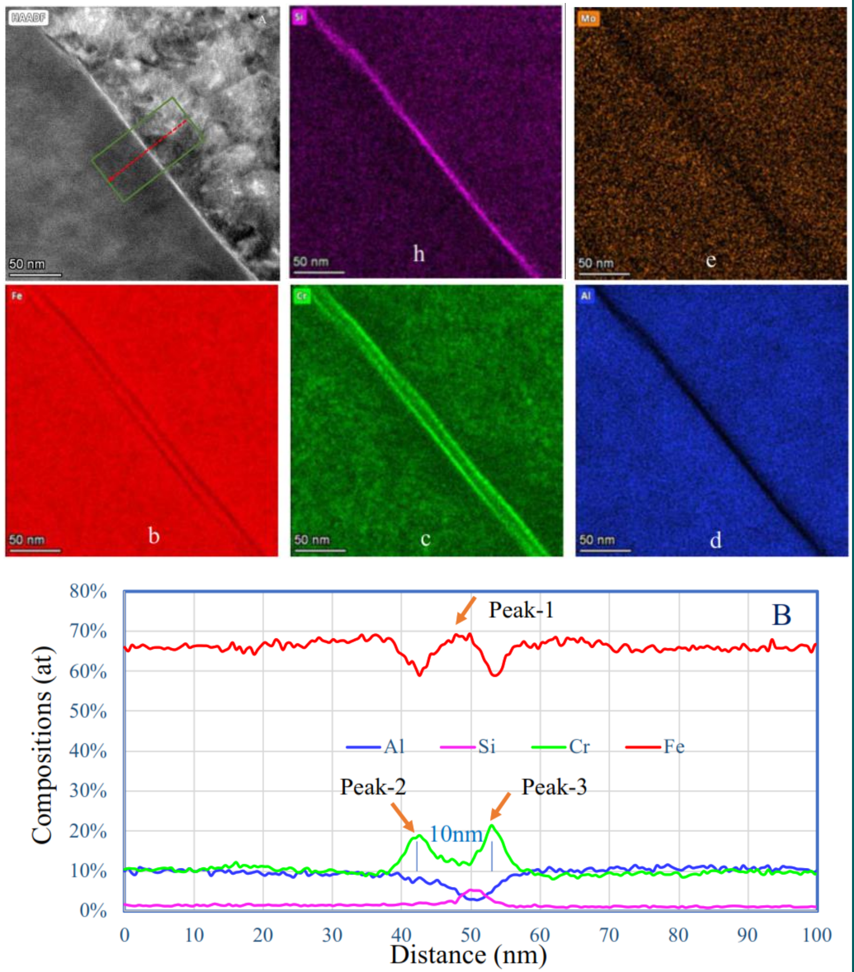
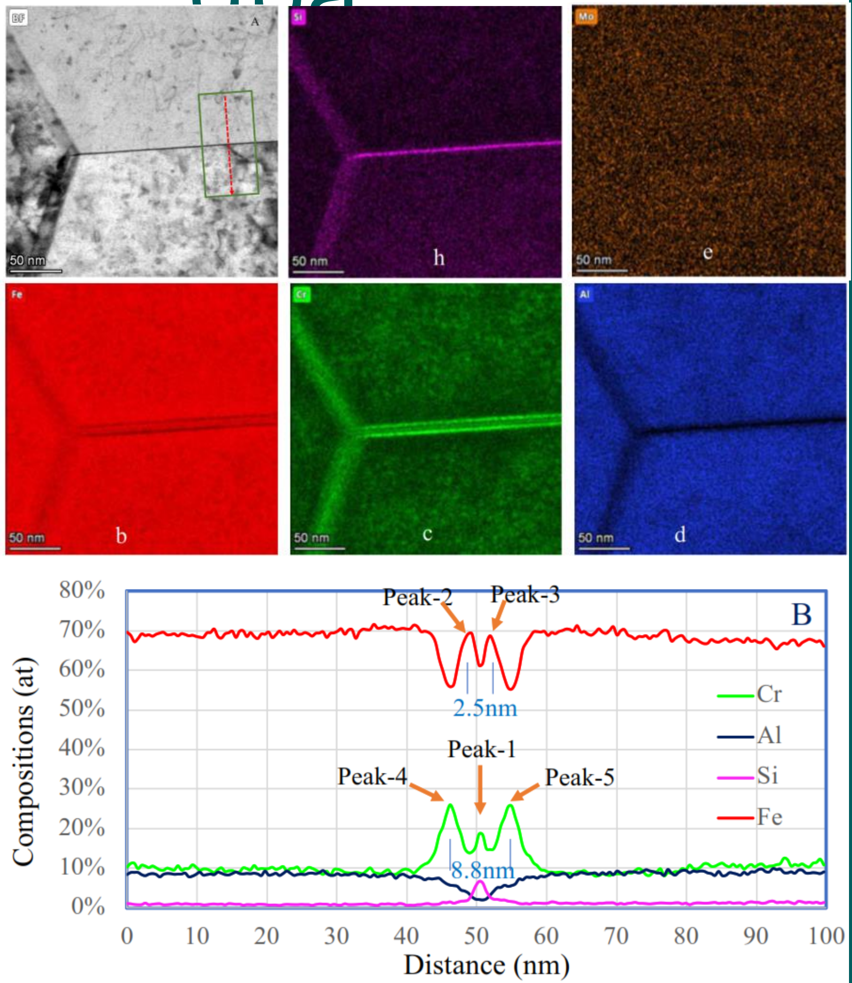
Wrought



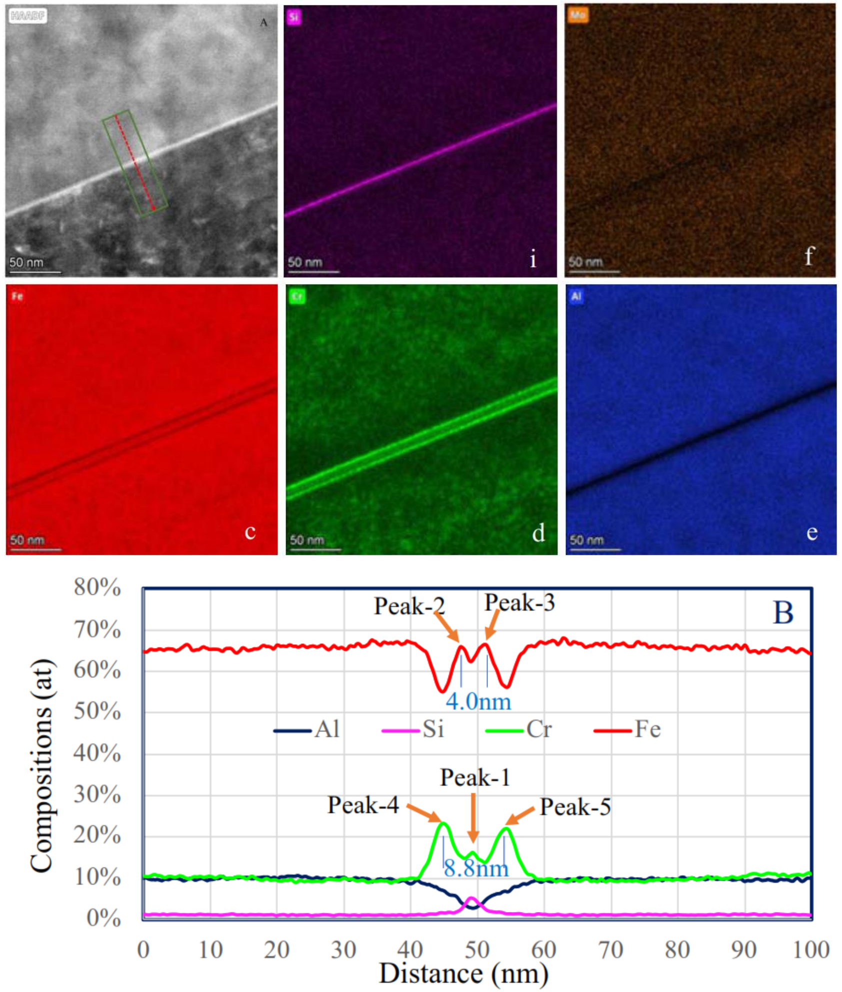
- 3-layer RIS structure at GB
- RIS thickness ~10 nm

PM



- 5-layer RIS structure at GB
- RIS thickness ~22.4 nm

AM



- 5-layer RIS structure at GB
- RIS thickness ~17.6 nm

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Comparison of precipitates and loops @ 2dpa

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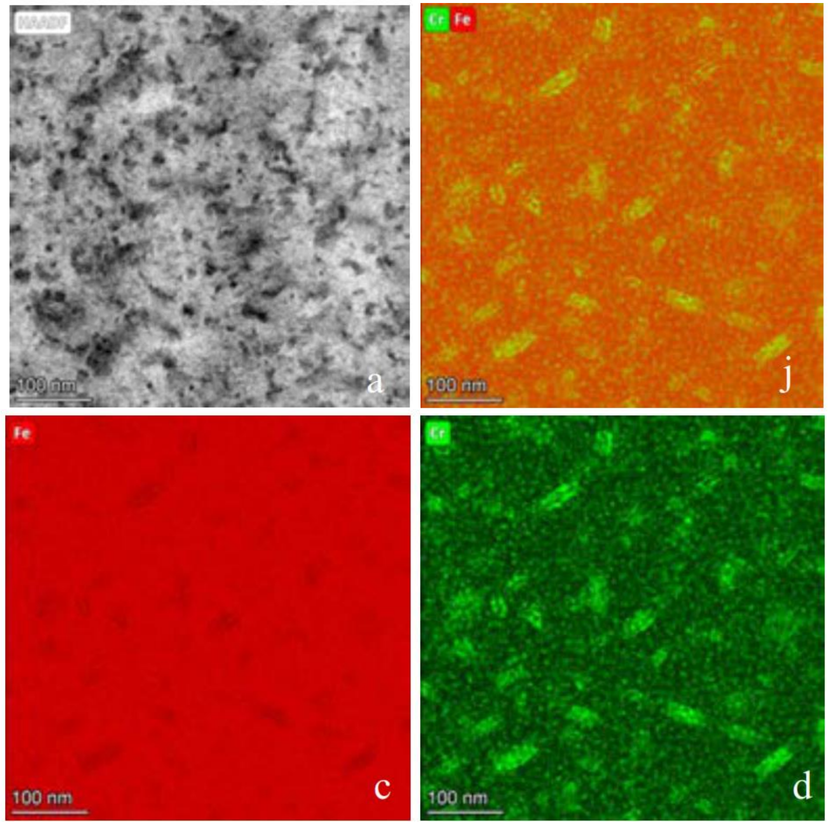
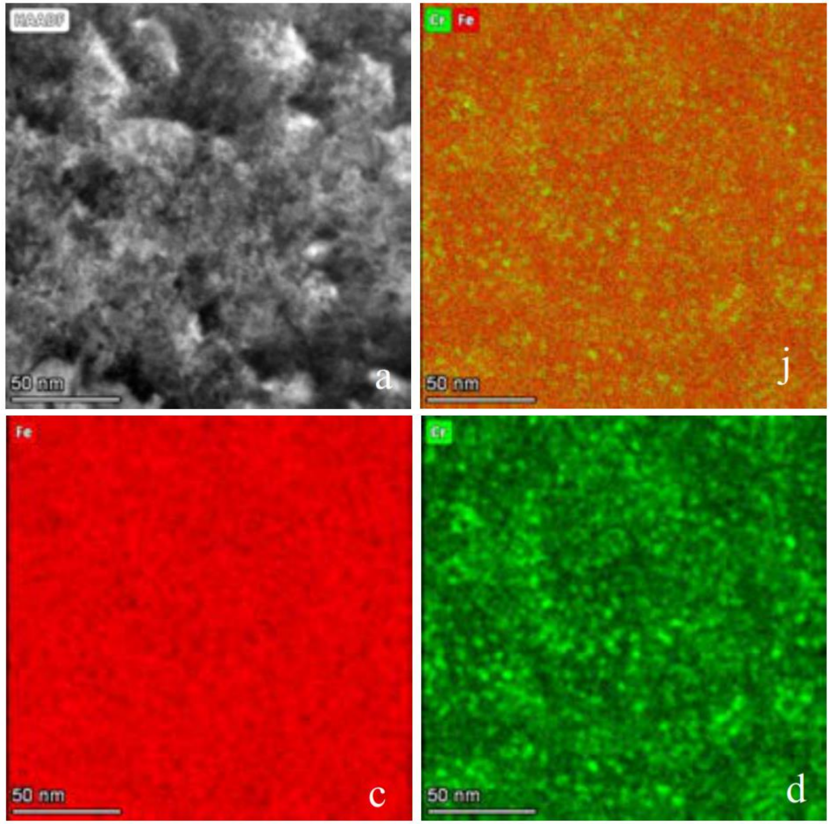
Wrought



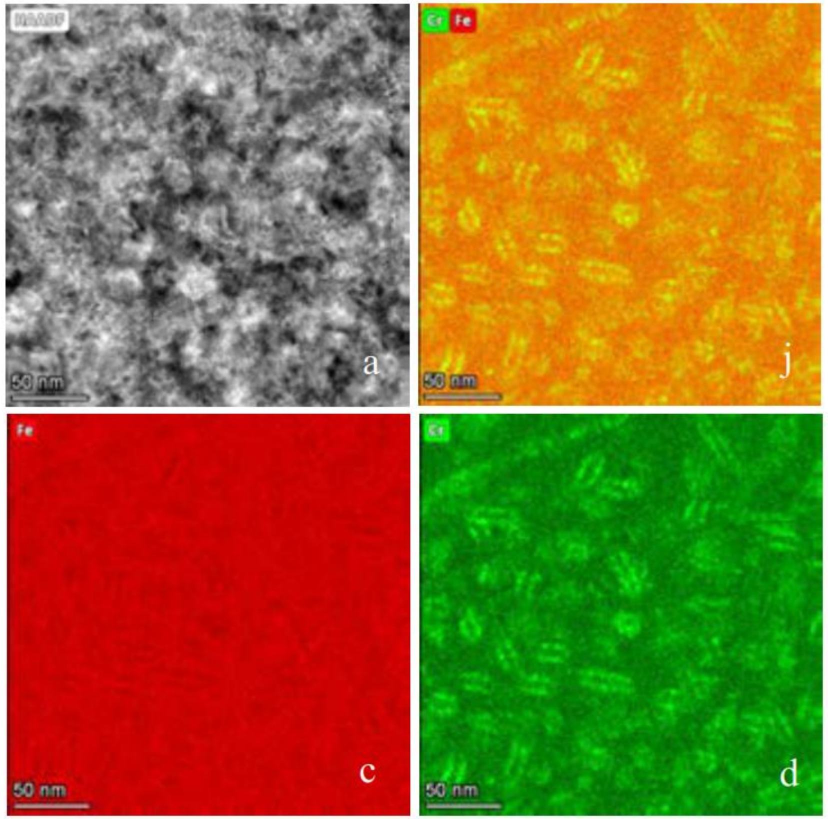
- Fe and Si enrich inside the dislocation loops and Cr enriches
- at the edges of the loops
- DL diameter is 31.4 ± 9.8 nm and density is $1.1 \times 10^{21}/m^3$

PM



- Fe and Si enrich inside the dislocation loops and Cr enriches
- at the edges of the loops
- DL diameter is 19.5 ± 4.11 nm and density is $9.43 \times 10^{21}/m^3$

AM



- Fe and Si enrich inside the dislocation loops and Cr enriches
- at the edges of the loops
- DL diameter is 19.8 ± 6.2 nm and density is $1.2 \times 10^{22}/m^3$

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APT data @ 2dpa

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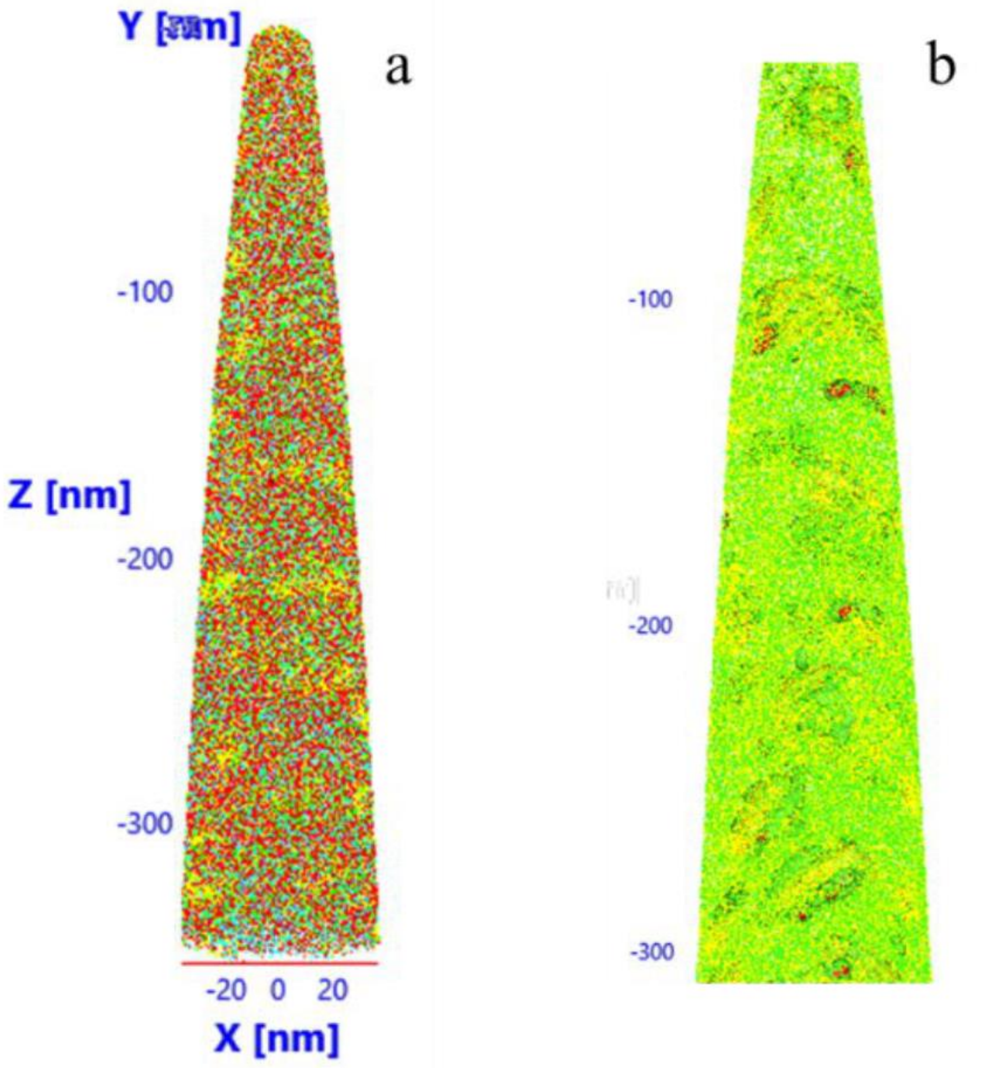

AM C26M at 2dpa

- APT 3D reconstruction shows clearly large clusters and dislocation loops in AM C26M after proton irradiation at 2dpa
- Si and Fe enrich in the loops and Cr distributes at the edges of the loops
- More precisely and comprehensively data analyses are still ongoing

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Project Timeline and Progress

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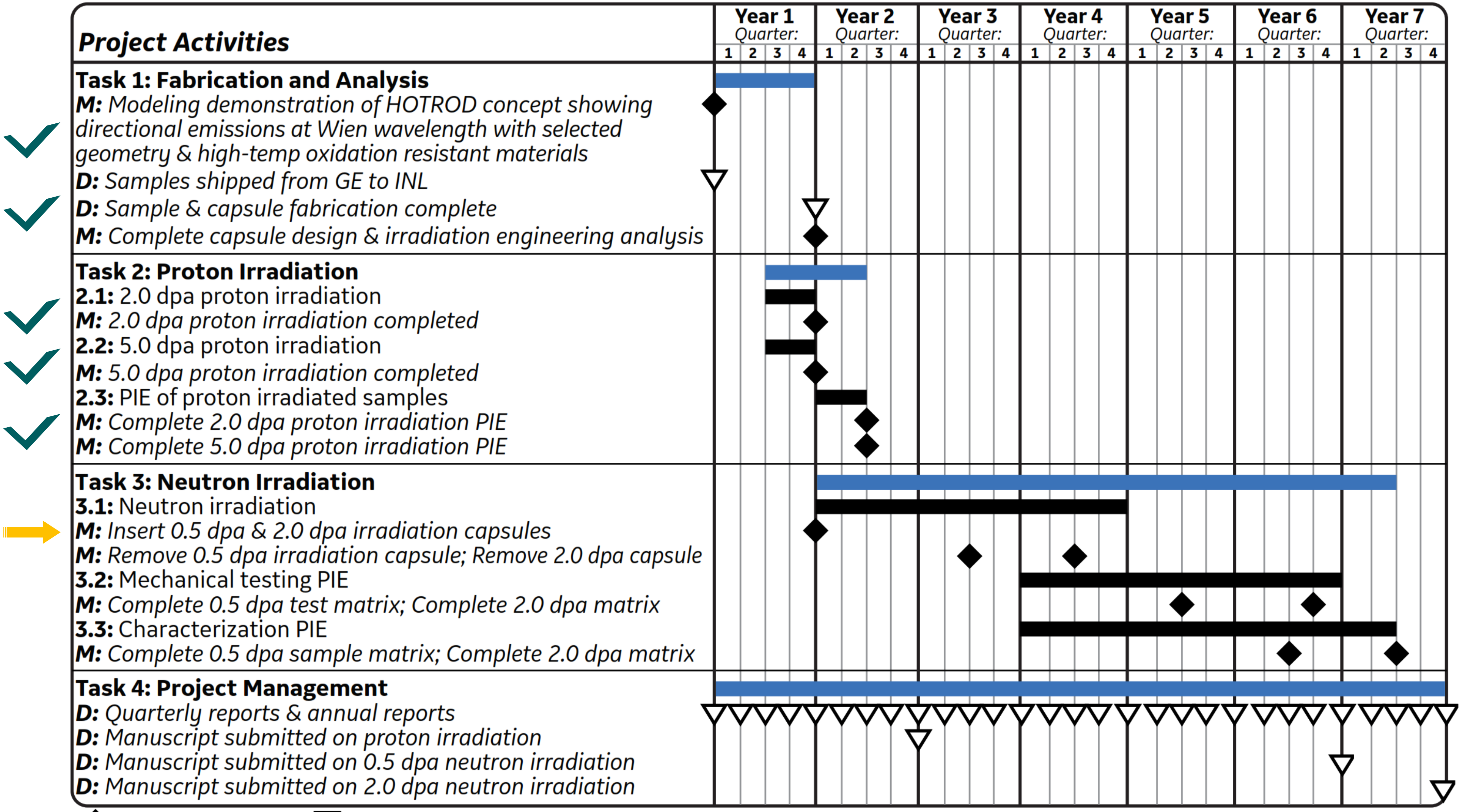

◆ Denotes ***Milestone*** ▽ Denotes ***Deliverable***

Acknowledgements

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The funding support from **Global Nuclear Fuel, GE Vernova Advanced Research,** and **GE Hitachi Nuclear** is gratefully acknowledged.

This material is based upon work supported by the Dept. of Energy under Award Number **DE-NE0009047**.

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