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Accelerated Printability Feasibility and Prioritization of Additively Manufactured Structural Materials

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Material Identification

Decision making through Diverse Surveying

Develop materials as an integrated part of advanced manufacturing (AM)

Performance, Scalability, Reproducibility, Economics, Supply

Short Term Needs → Long Term Needs

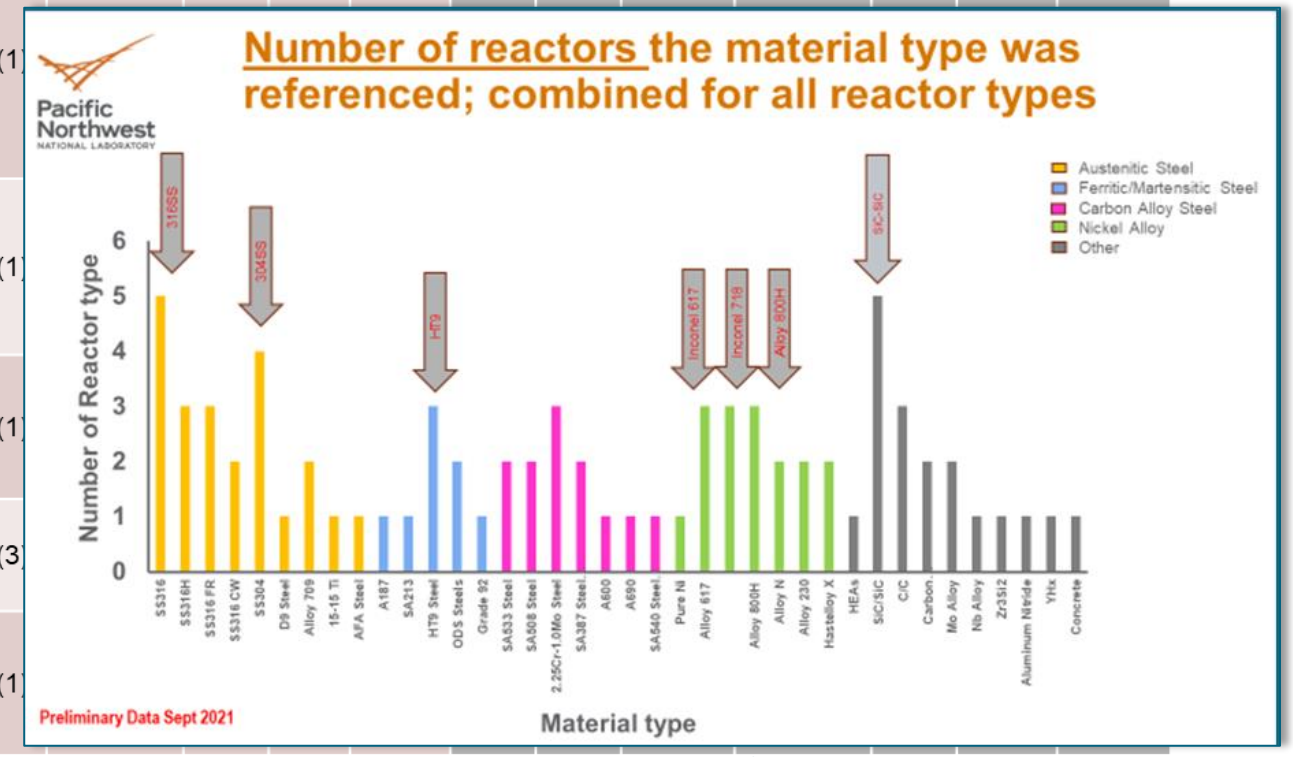
- Understanding Industry Requirements
- Upscale & Large Scale
- Next Generation Materials & Manufacturing Processes
- 316SS AM Variability
- Diverse Component & Geometry Manufacturing
- Critical minerals/materials

Multi - Laboratory and -Stakeholders effort to accelerate development and implementation

Examples of Specific Reactor Type Score Card

Material Score Cards 2020/2021

ID	Criteria	Guidance	MSR									VHTR						
			316	316H	304	Alloy 800H	Alloy N	Graphite	SiC	HT9	IN617	316	304	Alloy 800H	Graphite	SiC	IN617	IN718
1	**Code Availability**	Codes are available for all areas = 5 For two of the three areas = 3 For one area = 1	3 (3)	0 (1)	3 (3)	1 (2)	0	1 (2)	2 (2)	2	1 (2)	1 (3)	2 (3)	1 (2)	1 (2)	2 (2)	1 (2)	1 (1)
2	**Minimal Gaps in Data Availability for Performance Values and Measurements**	No or few gaps in data availability = 5 Moderate gaps in data availability = 3 Large gap in available data = 1	3 (3)	1 (1)	3 (3)	1 (2)	0 (1)											
3	**Technical Maturity for End Use/Development Stage**	TRL 8-9 and/or MRL 8-10 = 5 TRL/MRL 7-8 = 4; TRL/MRL 5-6 = 3; TRL/MRL 3-4 = 2; TRL/MRL1-2 = 1	3 (3)	1 (1)	3 (3)	2 (3)	0 (1)											
4	**Deployment readiness requirements**	Ready for industry deployment within 2 years = 5; In 3-5 years = 4; In 6-7 years = 3; In 8-9 years = 2; In ≥10 years = 1	3 (5)	1 (1)	3 (5)	2 (5)	0 (1)											
5	**Supply Chain Availability**	No anticipated supply chain risks or impacts = 5; Moderate impacts = 3; Major impacts = 1	3 (3)	1 (1)	3 (3)	3 (3)	1 (3)											
6	**Programmatic Factors**	Applications across all reactor types and/or multiple industry entities interested in a reactor type = 5	5 (5)	1 (1)	5 (5)	4 (4)	4 (1)											



New Materials Decision criteria matrix and scoring criteria

Environmental Compatibility

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Environmental Compatibility	Radiation Resistance	The ability of a material to maintain its shape, size, and properties after exposure to radiation	Material exhibits <1% volumetric change and limited mechanical property degradation at doses of ≥300 dpa	Material exhibits <1% volumetric change and limited mechanical property degradation at doses between 200 and 300 dpa	Material exhibits <1% volumetric change mechanical property degradation at doses between 100 and 200 dpa	Material exhibits <1% volumetric change and limited mechanical property degradation at doses between 50 and 100 dpa	Material exhibits <1% volumetric change and limited mechanical property degradation at doses ≤50 dpa
	Elemental Transmutation	Elemental stability of a material and impact of transmutation	Transmutation of elements in the material is not a concern	Transmutation of elements in the material results in at least one of the concerns or only causes concern when dose received is comparable with the reactor or material lifetime, meaning the material would be replaced before transmutation was cause for concern	Transmutation of elements in the material results in two of the concerns, or transmutation is only a concern in one neutron spectrum (either fast or thermal) but not the other	Transmutation of the elements in the material leads to premature material failure or three of the major concerns	Transmutation of constituent elements disqualifies the material from consideration or results in all of the major concerns
	High-Temperature Oxidation Resistance	The ability of a material to resist oxidation at high temperatures	Oxidation initiation occurs at temperatures ≥800°C	Oxidation initiation occurs at temperatures ≥600°C	Oxidation initiation occurs at temperatures ≥400°C	Oxidation initiation occurs at temperatures ≥200°C	Oxidation initiation occurs at temperatures <200°C
	Neutronics Compatibility	Degree of negative impact to the neutron economy of reactors	Material has a low thermal and fast neutron capture cross section and exhibits no detrimental reactions to either spectrum of neutrons	Material has moderately low thermal or fast neutron capture cross sections	Material has a low neutron capture cross section in one of either thermal or fast spectrums	Material has moderately high thermal or fast neutron capture cross sections, making it likely unsuitable for in-core applications	Material is a known neutron absorber or has a large neutron capture cross section at both fast and thermal energies
	Coolant Compatibility and Corrosion Resistance	Number of coolants, corrosion, erosion considerations The material's relative stability in a given coolant, including its resistance to corrosion, erosion, and other chemical reactions	Material is compatible with all types of coolants, showing no significant degradation	Material is compatible with 3/4 types of coolants, exhibiting good stability and inertness	Material is compatible with two types of coolants, exhibiting good stability in those coolants	Material is compatible in only one type of coolant, exhibiting significant instability in the other types of coolants	Material is not compatible with any of the coolant types, showing significant degradation in short periods of time

New Materials Decision criteria matrix and scoring criteria

Physical and mechanical properties

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Physical and Mechanical Properties	Thermal Conductivity	Capability (with high thermal conductivity) to increase the thermal efficiency of an energy system and reduce transitional thermal stress in the components	Maintain >100 W/(m·K) over lifetime	Maintain 50–100 W/(m·K) over lifetime	Maintain 10–50 W/(m·K) over lifetime	Falls to <10 W/(m·K) in the end of lifetime	Begins with a low thermal conductivity < 10 W/(m·K)
	Thermal Capacity	General thermal capacity such as melting point, softening point, phase stability across temperature range	Operation temperatures in all reactor types <0.4 T_M	Operation temperatures in most reactor types in 0.4–0.6 T_M	Operation temperatures in some reactor types in 0.4–0.6 T_M	Operation temperatures in some reactor types >0.6 T_M	Operation temperatures in most reactor types >0.6 T_M
	Tensile Properties	High-temperature tensile properties including strength, ductility, and type of failure	Yield strength >200 MPa; uniform ductility >2%; no brittle failure mode over lifetime	Yield strength >150 MPa; uniform ductility >2%; no brittle failure mode over lifetime	Yield strength >100 MPa; uniform ductility >2%; no brittle failure mode over lifetime	Yield strength >100 MPa; uniform ductility >2%; possibly brittle failure mode in lifetime	Yield strength >100 MPa; uniform ductility <2%; possibly brittle failure mode in lifetime
	Creep Performance	Risk of losing dimension stability in long-term service	No creep rupture expected in lifetime. No measurable creep strain (<0.001% in lifetime) in all reactor types	No creep rupture expected in lifetime. Little creep strain <0.01% in lifetime in most reactor types.	No creep rupture expected in lifetime. No creep strain <0.1% in lifetime in most reactor types.	No creep rupture expected in lifetime. Creep strain >0.1% in lifetime in some reactor types.	Possible creep rupture in lifetime. Creep strain >1% in lifetime in some reactor types.
	Fatigue	Risk of component failure owing to crack growth by cyclic loading	Load conditions in most reactor types are more than 20% below the fatigue limit	Load conditions in some reactor types are more than 20% below the fatigue limit	Load conditions in most reactor types are close but below the fatigue limit	Load conditions in some reactor types are above the fatigue limit	Load conditions in most reactor types are above the fatigue limit
	Fracture Toughness	Capability to avoid the most probable failure mode with aging and degradation	Fracture toughness >150 MPa√m over lifetime	Fracture toughness >100 MPa√m over lifetime	Fracture toughness >50 MPa√m over lifetime	Fracture toughness >50 MPa√m over most of lifetime	Fracture toughness <50 MPa√m over most of lifetime
	Microstructural Dependency	The sensitivity of material's properties to its microstructure	Properties are not sensitive to microstructure and processing route. Microstructure is highly stable in any service environment	Properties are not sensitive to microstructure and processing route. Microstructure is reasonably stable in most of service environments.	Properties are somewhat dependent on microstructure and processing route. Microstructure is reasonably stable in most of service environments.	Properties are sensitive to microstructure and processing route. Microstructure is reasonably stable in most of service environments.	Properties are sensitive to microstructure and processing route. Microstructure is not stable in some service environments.
	Scope For Microstructural Enhancement	The possibility of enhancing material properties by microstructural engineering through feasible processing routes	Microstructure is easily controlled for desirable properties within traditional and advanced processing means. No limitation in mass production and product size.	Microstructure is easily controlled for desirable properties within traditional and advanced processing means. Some limitations in mass production and product size.	Microstructure can be controlled for desirable properties through a few limited processing methods only	Microstructure can be controlled for desirable properties through a specially designed processing method only	Microstructure can be controlled for a few properties through a specially designed processing method only

New Materials Decision criteria matrix and scoring criteria

Manufacturability

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Manufacturability	Reproducibility/Consistency	Degree of reproducibility and consistency in product quality for various manufacturing routes/methods of the same material (e.g., for the same material, 3D printing is not consistent, but casting is)	Number of critical parameters that need to be carefully monitored >1	Number of critical parameters that need to be carefully monitored >3	Number of critical parameters that need to be carefully monitored >5	Number of critical parameters that need to be carefully monitored >7	Number of critical parameters that need to be carefully monitored >9
	Process Complexity	Number of processing steps (when writing, provide post processing information)	If it involves: 0 preprocessing steps but a maximum of 1 postprocessing steps	If it involves: 0–1 preprocessing steps but a maximum of 2 postprocessing steps	If it involves: 0–2 preprocessing steps but a maximum of 3 postprocessing steps	If it involves: 0–3 preprocessing steps but a maximum of 4 postprocessing steps	If it involves: 0–4 preprocessing steps but a maximum of 5 postprocessing step
	Cost	Overall cost for production of components (considering the same concern as reproducibility/consistency)	If it the overall cost is 30%–50% lower than the current commercial processing method	If the overall cost is 10%–30% lower than the current commercial processing method	If the overall cost is comparable with the current commercial processing method	If the overall cost is 10%–30% higher than the current commercial processing method	If the overall cost is 30%–50% higher than the current commercial processing method
	Scalability	The ability to increase the overall # of components being produced with a certain material, and the ability to produce dimensionally larger components	Zero concerns in terms of time delay/additional required equipment/ for scaling up	1–3 concerns in terms of time delay/additional required equipment/ for scaling up	3–5 concerns in terms of time delay/additional required equipment/for scaling up	5–7 concerns in terms of time delay/additional required equipment/for scaling up	Almost impossible to scale up
	Production Method Technological Readiness Level (TRL)	The already qualified processing techniques receive a score of 5, and the ones still in the process a 3, and completely new processes receive 1	The processes with TRL between 7 and 9	The processes with TRL between 5 and 7	The processes with TRL between 3 and 5	The processes with TRL between 1 and 3	First report on the process
	Raw Material Supply	Precursor availability in the United States	If all the raw materials required for the process are manufactured and supplied in the United States. Also, the supplier/manufacturer is cheapest among the available sources internationally.	If all the raw materials required for the process are manufactured and supplied in the United States. Also, the supplier/manufacturer is not cheapest among the available sources internationally.	If all the raw materials required for the process are not manufactured in the United States but the supplier is based in the United States	If all the raw materials required for the process are not manufactured in the United States but can be shipped internationally	If all the raw materials required for the process are not manufactured in the United States but cannot be shipped internationally

New Materials Decision criteria matrix and scoring criteria

Manufacturability (continue)

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Manufacturability	Flexibility Of Manufacturing	# of methods which can be used to manufacture material	If the material can be manufactured via 100% of the available processing techniques	If the material can be manufactured via 80% of the available processing techniques	If the material can be manufactured via 60% of the available processing techniques	If the material can be manufactured via 40% of the available processing techniques	If the material can be manufactured via 20% of the available processing techniques
	Conventional Machining	Need for drilling, joining, welding, riveting, etc.	A ready-to-go part can be directly manufactured without any postprocessing	A ready-to-go part can be directly manufactured with negligible postprocessing	Multiple subparts need to be manufactured with minimal postprocessing but require joining/welding/riveting	Multiple subparts need to be manufactured with significant postprocessing but require joining/welding/riveting	Parts with reasonable size scale cannot be manufactured
	Near Net Shaping (Complexity Of Shape)	How complex of a shape can the manufacturing process of a material make?	Not limited by the complexity of the design	Somewhat limited by the complexity of the design	Limited but few complex geometries can be achieved	Only simple geometries can be achieved	Only 1D/2D geometries are possible

Prioritization of current reactor materials for advanced manufacturing: Nickel Alloys

INL & ORNL

- Three Ni-based alloy categories based on potential applications: (1) **Low Co, (2) High temperature High Strength & (3) Molten Salt Compatible**
- Extensive literature review was conducted
- **Most promising alloys were further evaluated**

INL	ORNL
625	718
282	282
244	Hastelloy N
233	230
617	800H
740H	740H
GRX810	

Low Co	High temperature strength	Molten salt (Low Cr)
718 (20Cr-5Nb-3Mo)	282 (20Cr-10Co-8.5Mo-2.1Ti-1.5Al)	Hastelloy N (7Cr-16Mo)
625 (22Cr-9Mo-3.5Nb)	230 (22Cr-14W-<5Co)	244 (8Cr-22.5Mo-6W)
800H (32Ni-21Cr-40Fe)	617 (22Cr-12.5Co-9Mo)	

Prioritization of current reactor materials for advanced manufacturing: Lo Co Ni-based alloys justification

INL & ORNL

718: Used in various reactors (PNNL Scorecard report), well-known & available AM alloy

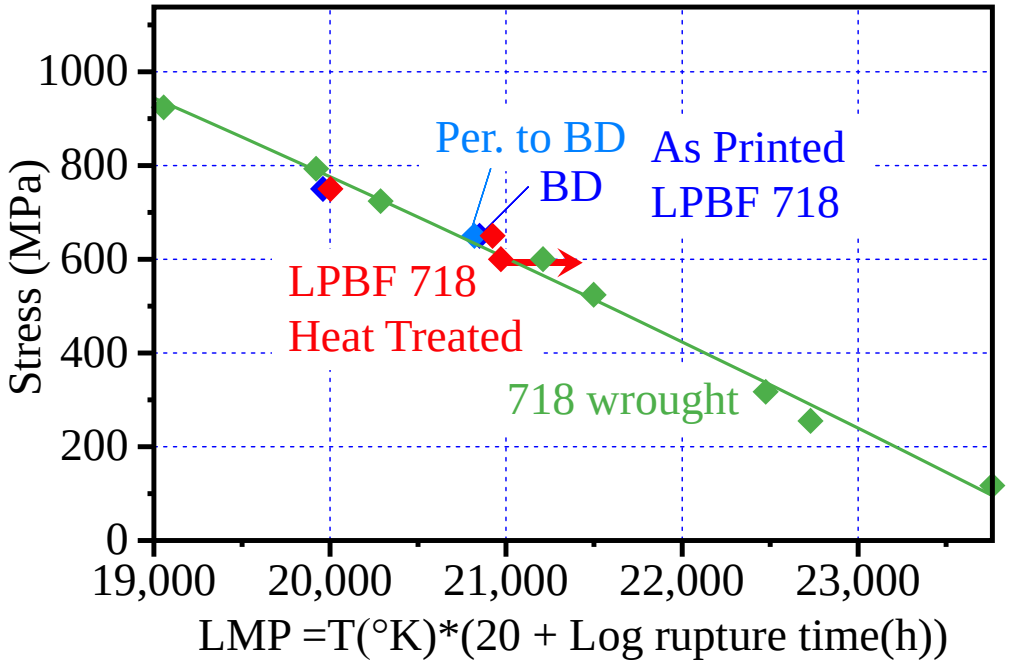
- Irradiation campaign initiated under TCR
- **Creep data were generated and was consistent with wrought 718**

625: Well-known & available AM alloy

- Growing interest from industry
- Also considered for molten salt reactors

800H: Code qualified but very limited AM data & difficulty in procuring powder

- Carpenter needs an order >500kg
- Lower priority compared to 718 & 625



- Similar results between as printed and heat treated (2h@1174°C+6h@1204°C+1h@945°C+8h@718°C, 8h@621°C)
- Similar results along and perpendicular to BD

Prioritization of current reactor materials for advanced manufacturing: High temperature high strength alloys

INL & ORNL

282: Not currently used by NE industry but powder is widely available with several academic and industrial [projects on AM 282

- Defects density varies in builds fabricated for extensive characterization

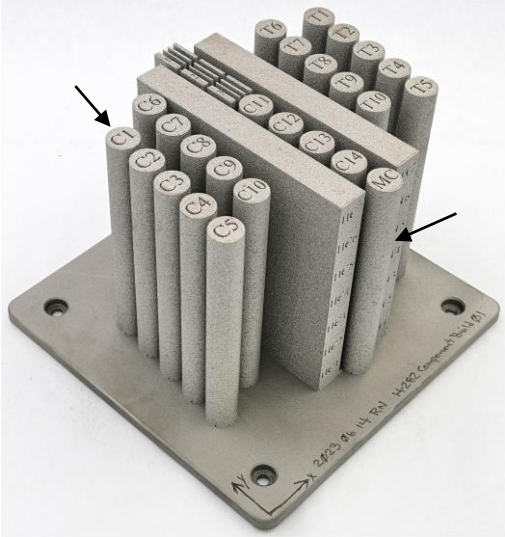
- SA, 1h@1180°C+ aging 4h 800°C for recrystallization and grain size control

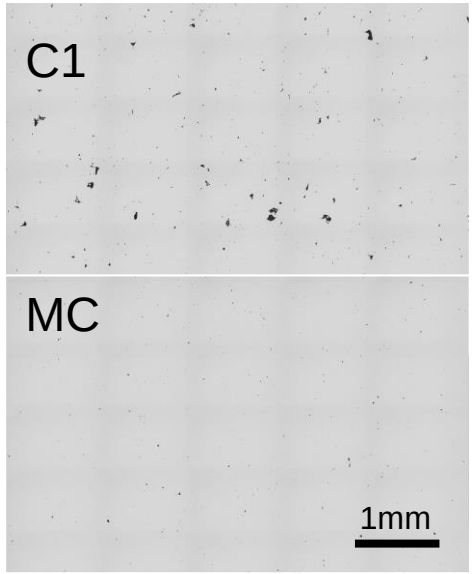
230 : Not currently used by NE industry but powders is available with limited studies

- Initial results show crack propensity

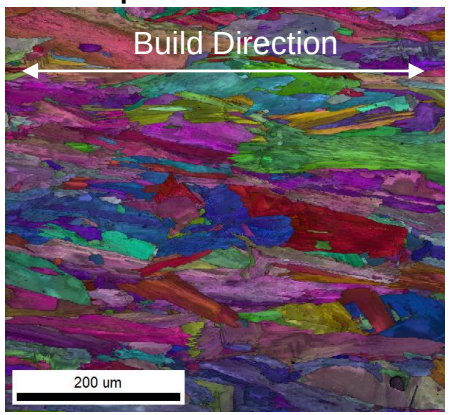
617: Code qualified alloy but limited AM work (wire-based), 90lbs was received for printing trials

Lower priority for other alloys **(233, 740H,etc.)**

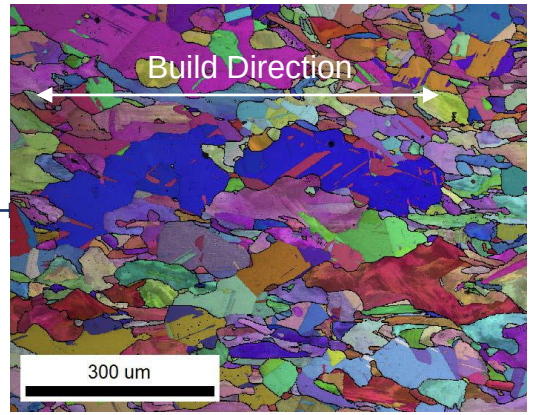




As printed 282



SA at 1180 °C for 1 hrs



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Prioritization of current reactor materials for advanced manufacturing: Low-Cr Molten Salt-Compatible Alloys

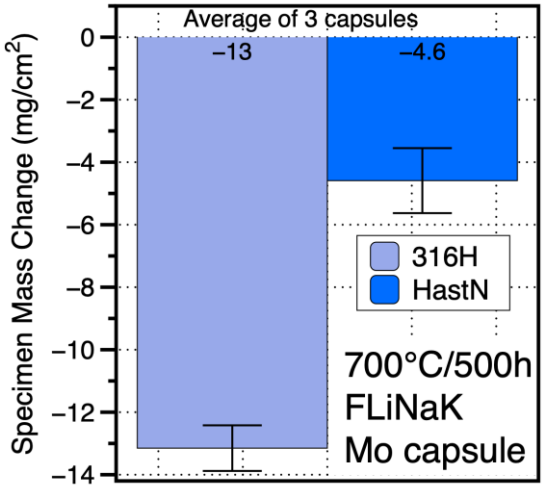
INL & ORNL

Hastelloy N.

- 2nd Ni-based alloy with score card.
- Superior performance in molten salt compared to 316H
- No powder available and limited AM data
- Interest specific to molten salt reactors

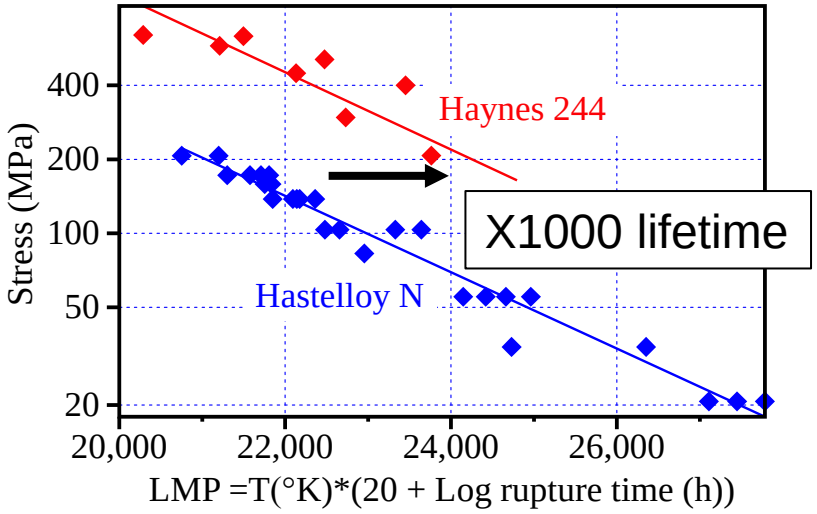
Haynes 244

- Superior strength compared to Hastelloy N
- Initial results indicate higher corrosion resistance in molten salt likely due to high W concentration
- No commercial powder and AM data. Limited data even for wrought alloy



Low mass change for Hastelloy N compared to 316H (courtesy B.A. Pint)

Superior creep strength for Haynes 244 compared to Hastelloy N



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Prioritization of current reactor materials for advanced manufacturing: Further Alloy Selection

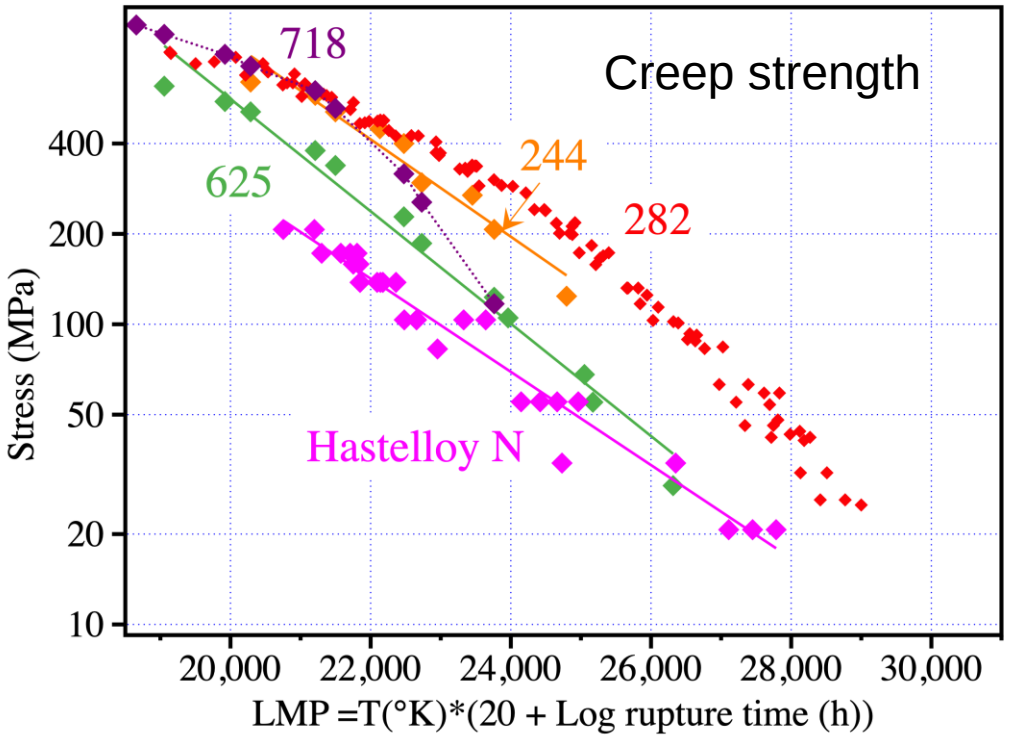
INL & ORNL

Low Co printable & available alloys.

- 718: Lower cost, strength at T<700°C, AM irradiation data
- 625: Higher temperature capability & corrosion resistance

High Strength alloys: 282 selected based on current AM data & availability

- Further optimization of 282 printing parameters
- Continue comparison with LPBF 230 & 617



Molten Salt Compatible, Hast. N versus 244

- Hastelloy N: Wrought data available, superior compatibility
- 244. Very high strength, Better corrosion resistance in molten salt than high Cr alloys?

FY24 objectives

- Generate relevant database using optimized LPBF materials & collaborate with digital manufacturing team to establish processing-microstructure-properties correlation

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Prioritization of current reactor materials for advanced manufacturing: Fe-based Alloys

ANL & PNNL

Austenitic	Ferritic/Martensitic
A-709 ★	→ HT-9
→ AFA alloys	Grade-91 ★
→ Ti-modified 316SS (D9)	Grade -92 ★

→ FY23

★ FY24

Ferritic/Martensitic Steels

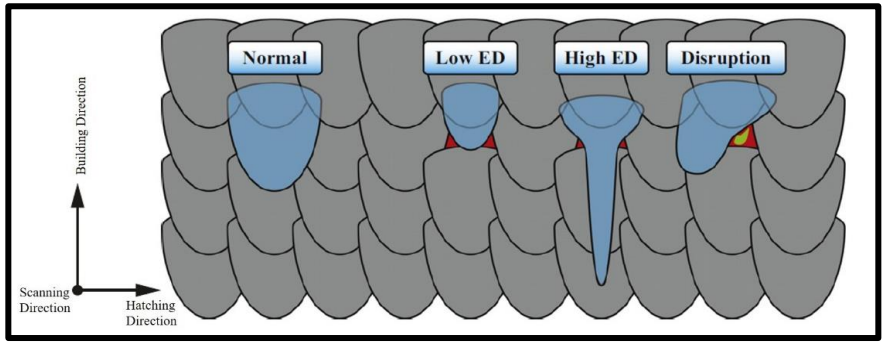
- 9Cr-1Mo based alloys (Grade-91, Grade-92) code qualified, practically no AM work, powder not commercially available.
- HT9: Key alloy in PNNL score scorecards report. Has wider cross-industry appeal. Powder not commercially available, and limited AM work.

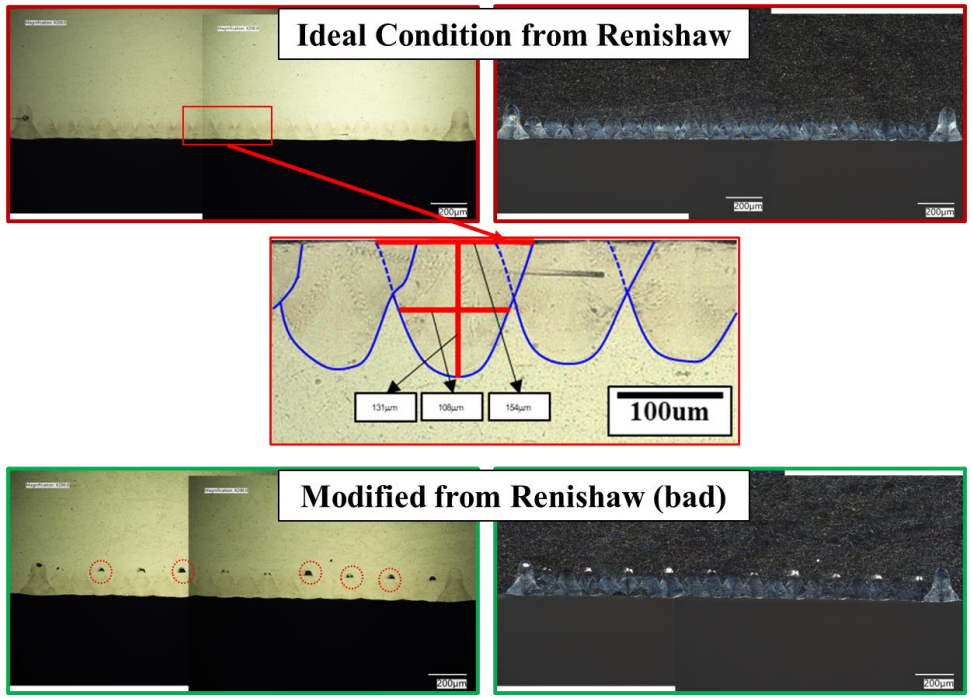
Austenitic Steels

- A-709: Close to being code qualified. No work on AM, powder not available commercially. cross-industry appeal.
- D-9: Titanium modified SS-316. Similar aspects to SS-316 can be implemented. Powder not commercially available, and no AM work.
- AFA Steel: Cross-industry appeal. Better SCC properties than SS-316. Powder is not available commercially, no AM work.
- ODS FeCrAl: High strength, corrosion resistance, collaborate with ORNL

Single Track Experiments to Optimize Process Parameters

- Single track studies are performed to determine optimal process parameters to produce a conduction/slight keyholing welds
- Weld mode produces fully dense parts
- **72** parameter sets are initially planned for Grade 91
- Laser Power, Exposure Time, and Point distance varied: Finalizing initial conditions based of literature review and inputs from Renishaw
- Variations in volumetric energy density kept within ~10% of "optimized condition" for each "set".





Volumetric Energy Density

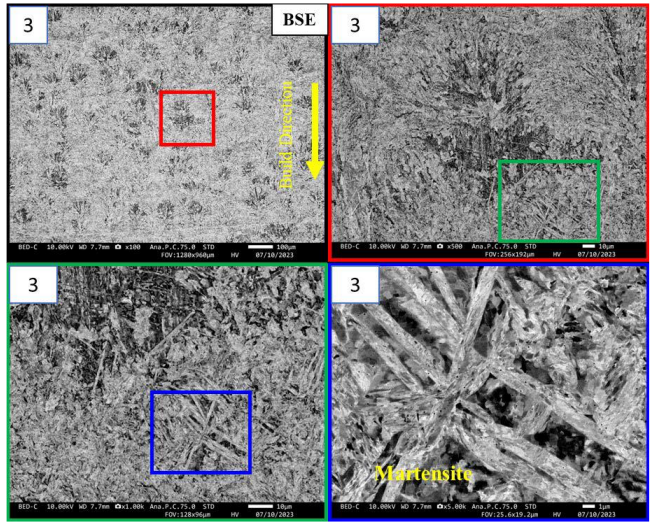
$$E_{vol} = \frac{P}{vhd}$$

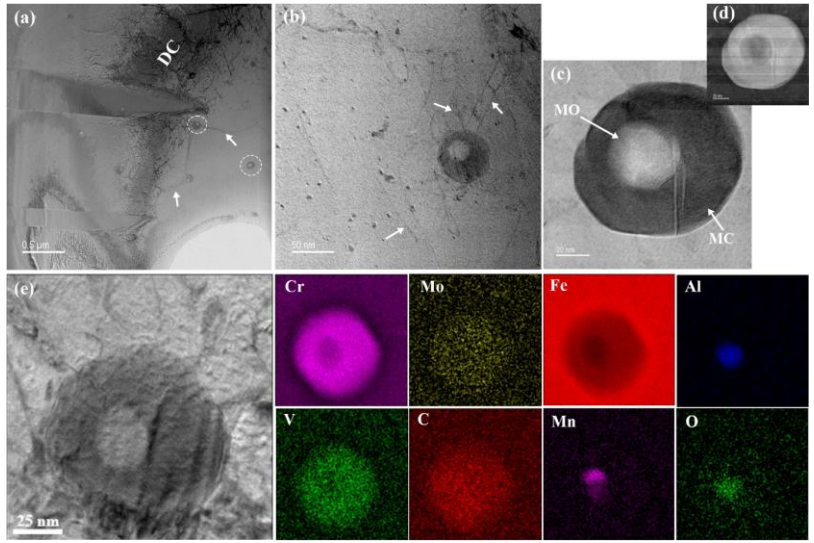
P is power (W) — h is hatch spacing
v is velocity (mm/s) — d is layer thickness

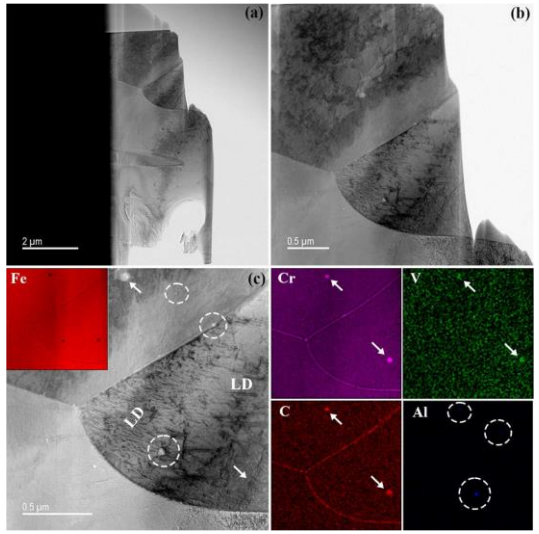
- NORMAL "Conduction mode" = adequate penetration and overlap to the previous layers and adjacent melt pools
- LOW ED = low laser power or high lasing speeds that produce a much smaller "conduction mode" shaped melt pool. Results in lack of fusion between layers and among adjacent melt pools
- HIGH ED = excessively high laser power and low lasing speeds that concentrates the heat making it penetrate through too many layers. Forms keyholing, and lack of fusion among adjacent melt pools from insufficient overlapping.
- DISRUPTED = poor process parameters, corrupt material properties, contaminants, etc.

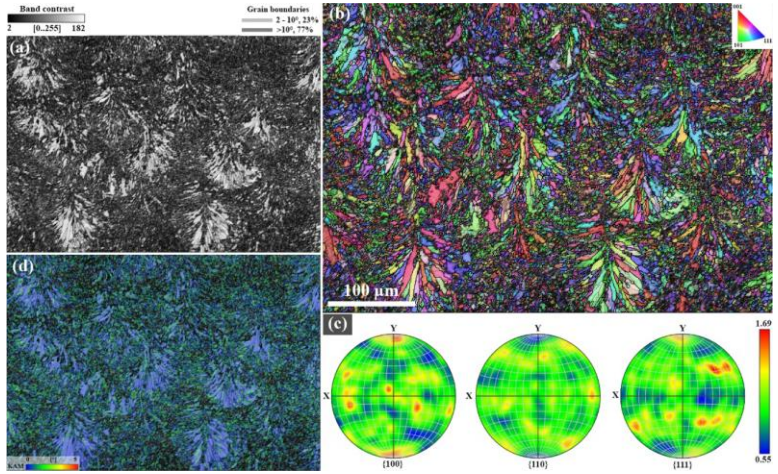
Printability Studies HT9 Alloy (Ferritic/Martensitic)

ANL & PNNL





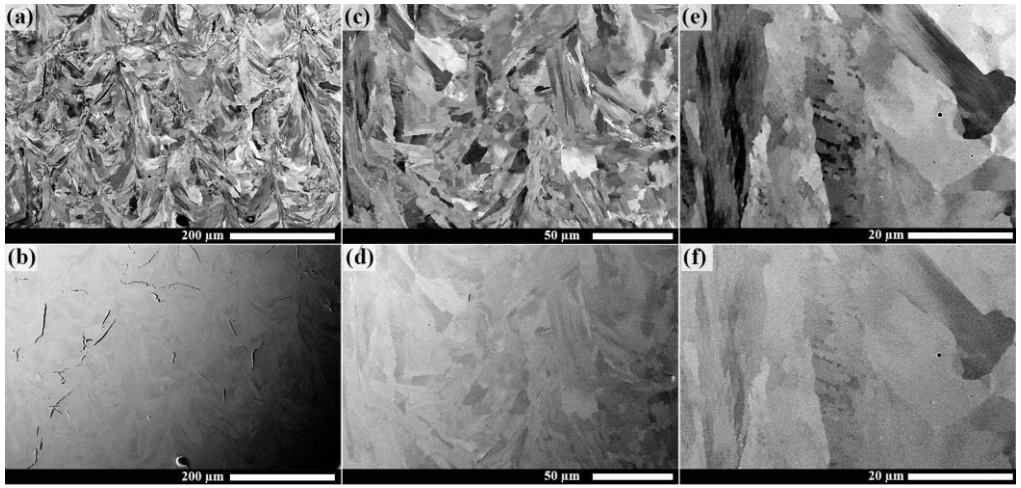


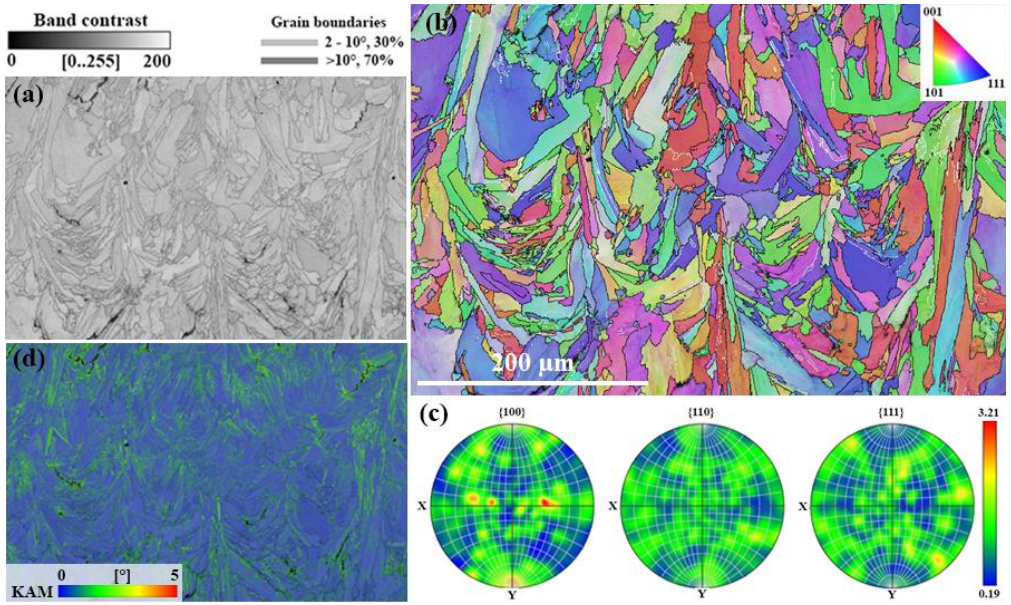


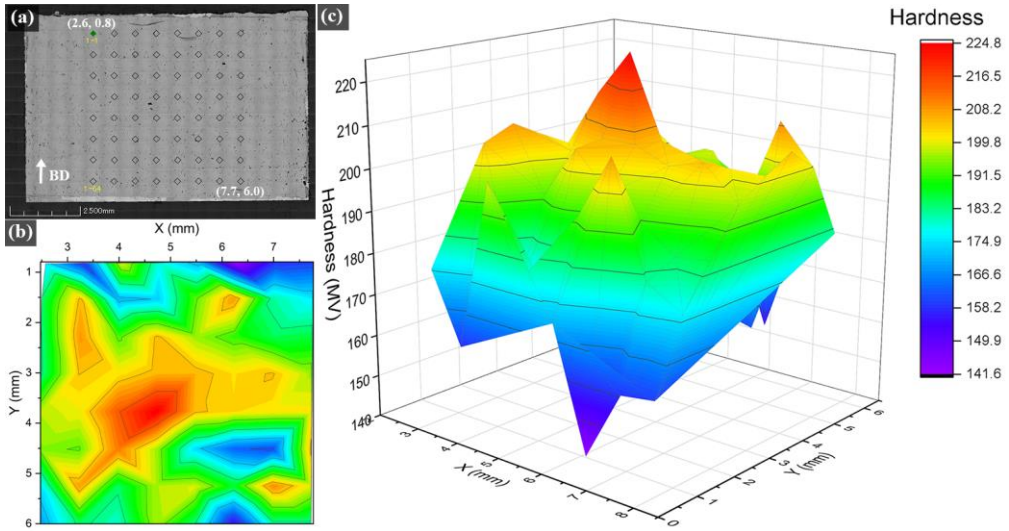
- Build quality good with low porosity
- SEM shows columnar grains with agglomerated smaller equiaxed grain morphology
- STEM results show presence of nanoparticles containing Cr, Mo, V, Al, Mn, O, and C
- Some grain boundary are enriched in Cr and C suggesting formation of Cr carbides
- Average hardness is 411.6 ±24.7 HV

Printability Studies D-9 (Austentic steel)

ANL & PNNL







- SEM and EBSD analyses show well crystalized columnar grains
- No significant texture is observed in D-9
- Average microhardness is 189 ±16.8 HV

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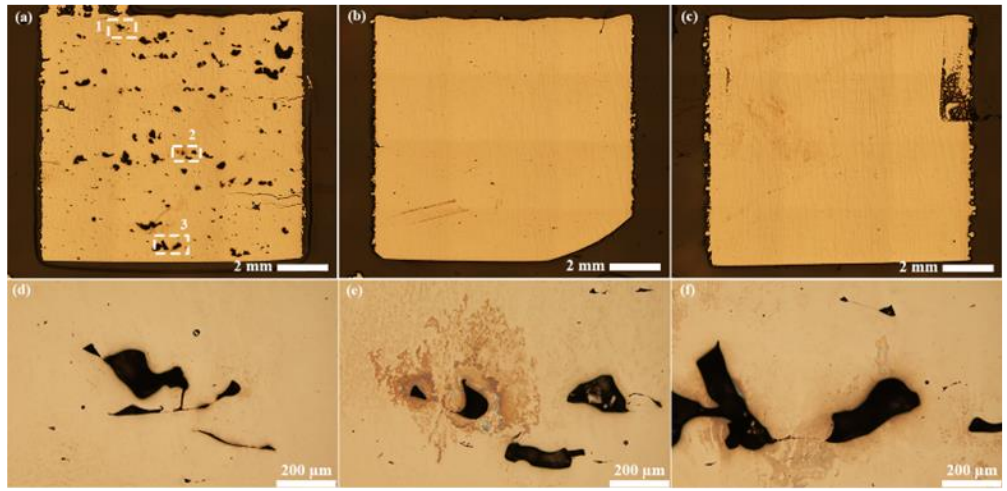
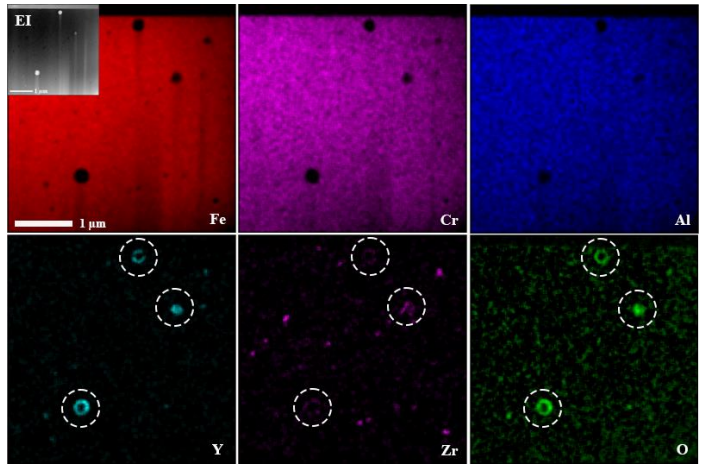
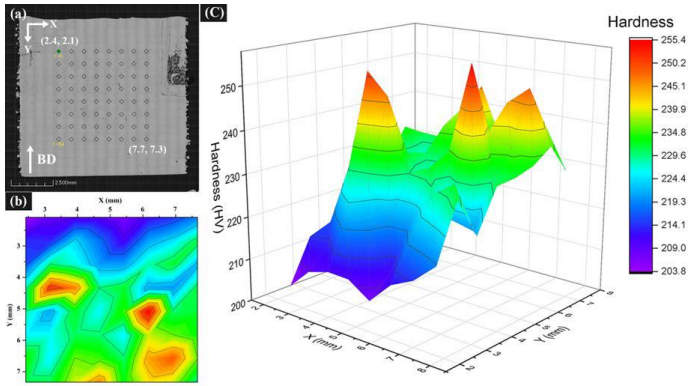
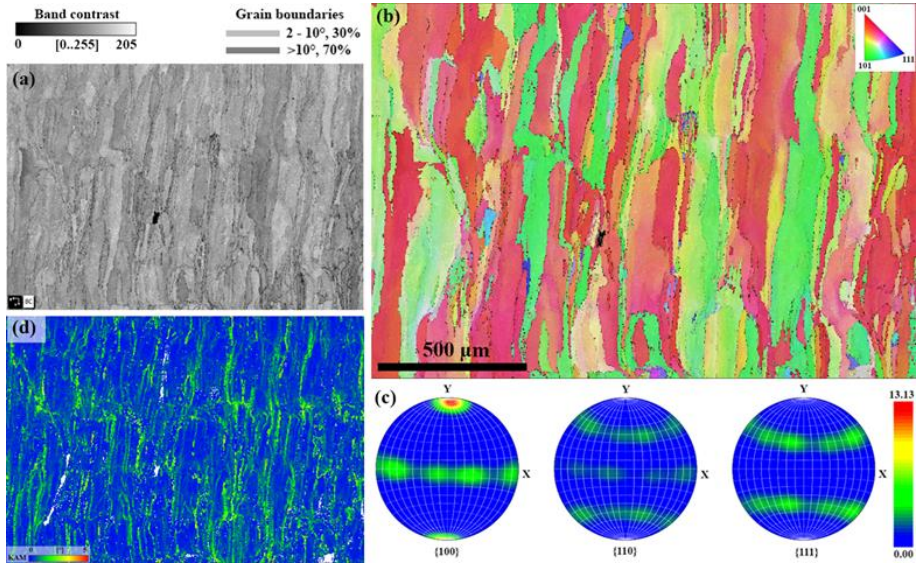
Printability Studies ODS Fe–Cr–Al

ANL & PNNL









- Fabricated at ORNL
- TEM results show presence of nanoscale precipitate with Y, Zr, O.
- EBSD indicate the directional residual stress
- Variation in microhardness value, highest near substrate with value of (227.9 ±11.0 HV)

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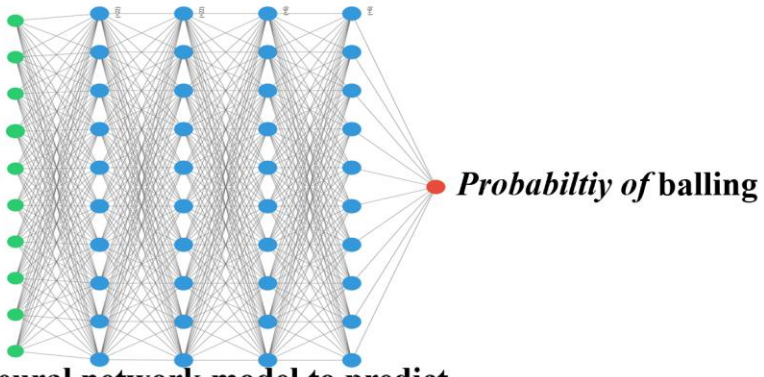
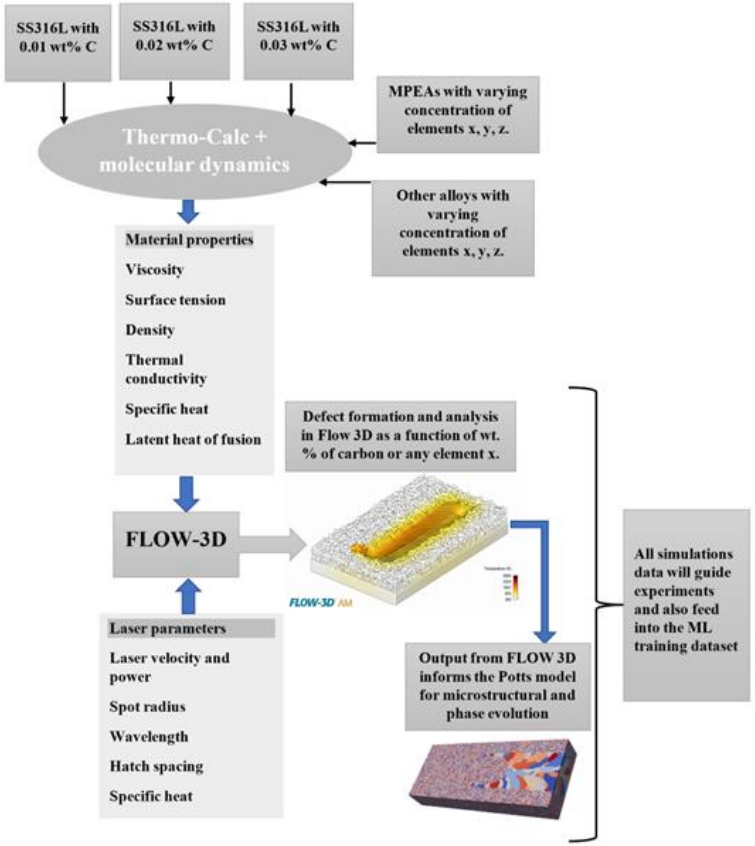
Printability Study using Machine Learning
ANL & PNNL

Printability: the ability to avoid defects like cracking, balling and lack of fusion, that are caused by thermal stresses

Alloy	Al	Fe	…	Element X	Power	Scan speed	Other process parameters	Balling probability
AlSi10Mg	0.89	0.001	0.03	0.05	130	50	xx	1
SS316	0	0.67	0.03	0.01	150	100	xx	0
Co-Cr	0	0.01	0.40	0.03	170	90	xx	0
More single principal alloys	0	0.80	0.01	0.10	140	130	xx	1
CoCrFeMnNi	0	0.20	0.25	0.20	220	170	xx	1
VNbMoTaW	0	0	0.20	0.20	190	140	xx	0
$Al_{0.5}CoCrFeNi$	0.11	0.22	0.22	0.22	110	80	xx	0
More HEAs	0.20	0.25	0.35	0.10	140	120	xx	1



Neural network model to predict balling probability in alloys shows 92 % accuracy on 240 training data and 26 testing data



- Neural network (NN) model using 240 training data and 26 testing data predicts the tendency of **balling** defect formation for a **given composition**, under a given set of processing conditions

FY24 work will demonstrate a methodology for the rapid prediction of alloy printability as a function of composition using Thermo-Calc and FLOW-3D software followed by ML prediction

ICAM 2023 presentation: Chemical composition-based machine learning model to predict deformation in additive manufacturing,. Roy A., A.R. Swope, R. Devanathan, M. Komarasamy, and I. van Rooyen

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Preliminary feasibility studies of new materials for advanced manufacturing – ORNL

Additively Manufactured ODS Alloys

To accelerate the development, evaluation, and deployment of oxide-dispersion strengthened (ODS) alloys by employing advanced manufacturing technologies.

Scientific Achievement

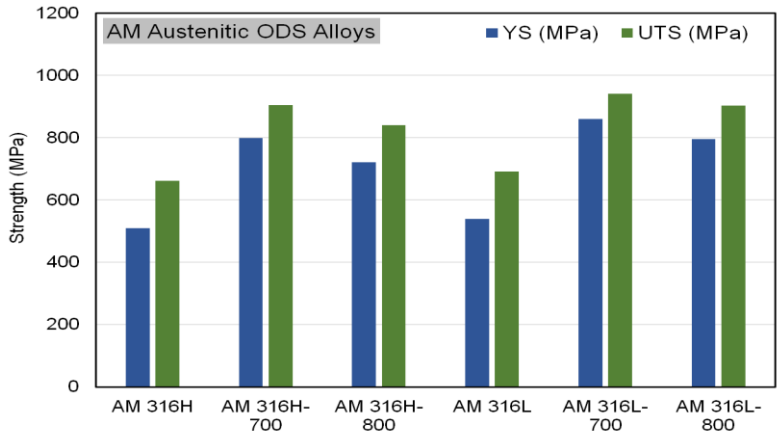
- New ODS alloy processing routes employing AM processes, but not mechanical milling, were designed and applied.
- Desirable mechanical properties were achieved, depending on alloy and processing route.

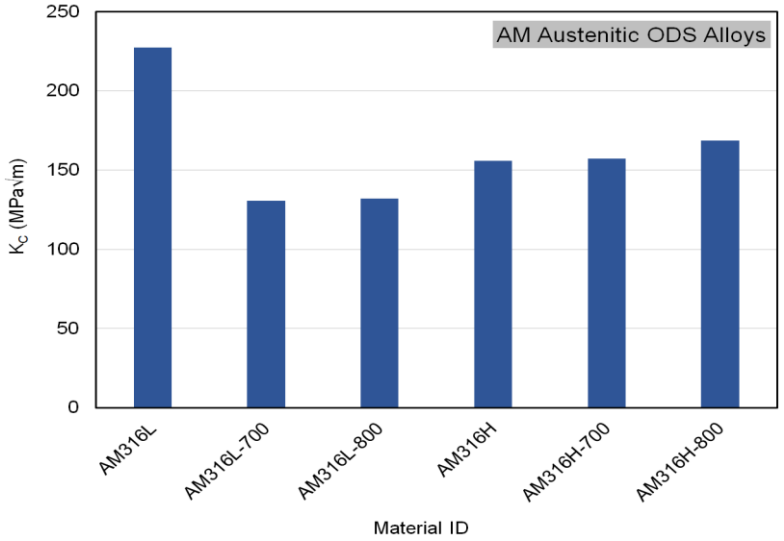
Impact & Potential Application Space

- The processing route without mechanical milling might enable the economical mass production of ODS reactor components.

Details

- Seventeen ferritic and austenitic ODS variants were produced via new processing routes combining AM and TMT processes.
- The highest strength (YS > 1 GPa) was measured from a ferritic ODS alloy; the highest ductility (TE > 40%) and fracture toughness (K_C > 200 MPa√m) were from austenitic ODS alloys.
- Application of decision criteria matrix led to the downselection of austenitic ODS alloys for nearer application.





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AM oxide dispersion strengthened (ODS) steels

Experiment Details

ORNL Team

TS Byun (PI, MSTD, Process Design, Mechanical Testing)

Blane Fillingim/Thomas Feldhausen (MDF, DED Processing); Holden Hyer (NEFCD, LPBF Processing); Kevin Hanson (MSTD, TMP)

David Hoelzer/Tim Lach/Yan-Ru Lin/David Collins (MSTD, Microscopy, Mechanical Testing)

AM oxide dispersion strengthened (ODS) steels

AM 14YWT

AM ODS 316SS

14YWT-YY
- DED
- 0.3 wt.% Y_2O_3

14YWT-YYF
- DED
- 0.3 wt.% Y_2O_3+ , 0.1 wt.% Fe_2O_3

14YWT-YF
- DED
- 0.3 wt.% Y_2O_3 + 0.3 wt.% Fe_2O_3

316H-Y
- LPBF
- 0.5 wt.% Y_2O_3

316L-Y
- LPBF
- 0.5 wt.% Y_2O_3

Post-Build Thermomechanical Processing Condition

Characterization and Testing
- 700 °C and 800 °C for post-build TMP.
- Testing Temperatures: Room Temperature – 600 °C

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Application of Decision Criteria Matrix & Score Card

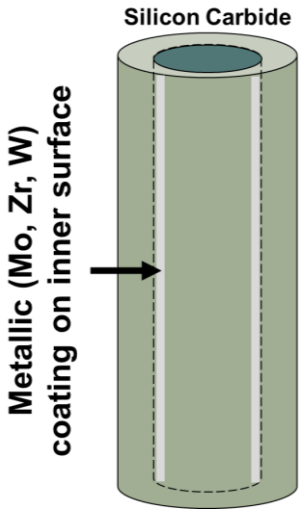
ODS Alloys

Category	Criteria	Ferritic Steels	Austenitic Steels
Application Space	Applicability to Different Reactor Types	4	3
	Other Industry Experience	1	1
	Data Availability	3	2
	Code & Standards Availability	1	1
	Component Versatility	3	3
Environmental Compatibility	Radiation Resistance	4	4
	Elemental Transmutation	4	3
	High Temperature Oxidation Resistance	3	4
	Neutronics Compatibility	4	3
	Coolant Compatibility & Corrosion Resistance	3	4

Category	Criteria	Ferritic Steels	Austenitic Steels
Physical & Mechanical Properties	Thermal Conductivity	3	3
	Thermal Capacity	4	4
	Tensile Properties	3	4
	Creep Performance	4	4
	Fatigue	4	4
	Fracture Toughness	2	4
	Microstructural Dependency	3	3
	Scope for Microstructural Enhancement	4	4
Manufacturability	Reproducibility/Consistency	3	4
	Process Complexity	3	3
	Cost	2	2
	Scalability	2	2
	Production Method TRL	3	3
	Raw Material Supply	4	4
	Flexibility of Manufacturing	4	4

- **The ODS austenitic alloys yielded slightly higher average score than the ODS ferritic alloys (3.26 vs. 3.07).**

Assessment of Advanced Manufacturing Techniques for Composite and Refractory Alloy Structures - LANL



Objective: To identify, vet, and develop advanced manufacturing techniques for refractory lined composites and refractory alloys for nuclear energy applications.

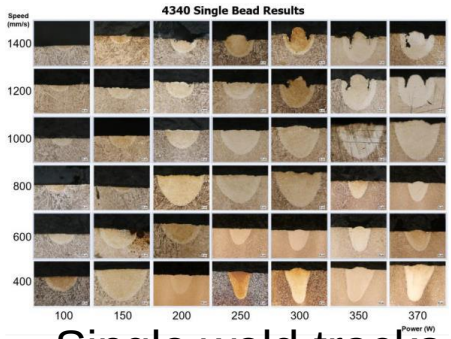
Composite	C-C	W/C-C	Mo/C-C	Zr/C-C	SiC-SiC	W/SiC-SiC	Mo/SiC-SiC	Zr/SiC-SiC
Overall score	94	91	90	89	102	95	93	94

The most significant variances in scoring are linked to Data Availability, Elemental Transmutation, Thermal Capacity, and a small variance in Raw Material Supply.

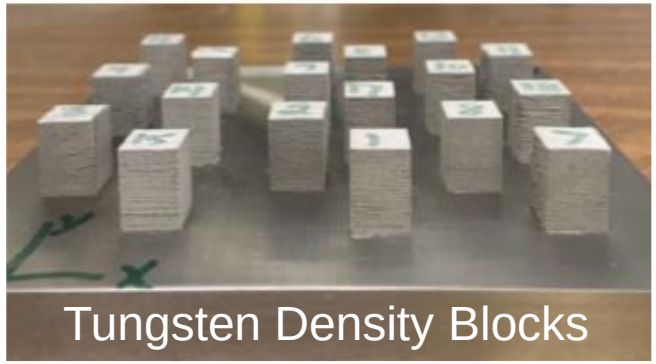
Refractory Alloy	TZM	WTa	WNiFe	C-103
Overall score	106	87	97	105

Single weld studies performed on TZM, W, and Ta were performed to inform the scoring of refractory alloys.

- W/SiC-SiC will maintain its structural integrity at elevated temperatures, is thought to have satisfactory neutronics properties, and sufficient compatibility with liquid metal coolants (Pb, Li) and coolants used in MSRs and GFRs. It is seen as a candidate material for both in-core and out-of-core structural components.
- C-103 has been used in other industries, such as the aerospace industry. It is anticipated to have superior creep performance, fatigue, fracture toughness, and neutronics compatibility compared to WTa and WNiFe.



Single weld tracks


Tungsten Density Blocks

Bryant A. Kanies and Miles F. Beaux II, Michael J. Brand, Robin A. Montoya, Erofili Kardoulaki, A. David Andersson

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Preliminary Feasibility Studies of New Materials for Advanced Manufacturing - LANL

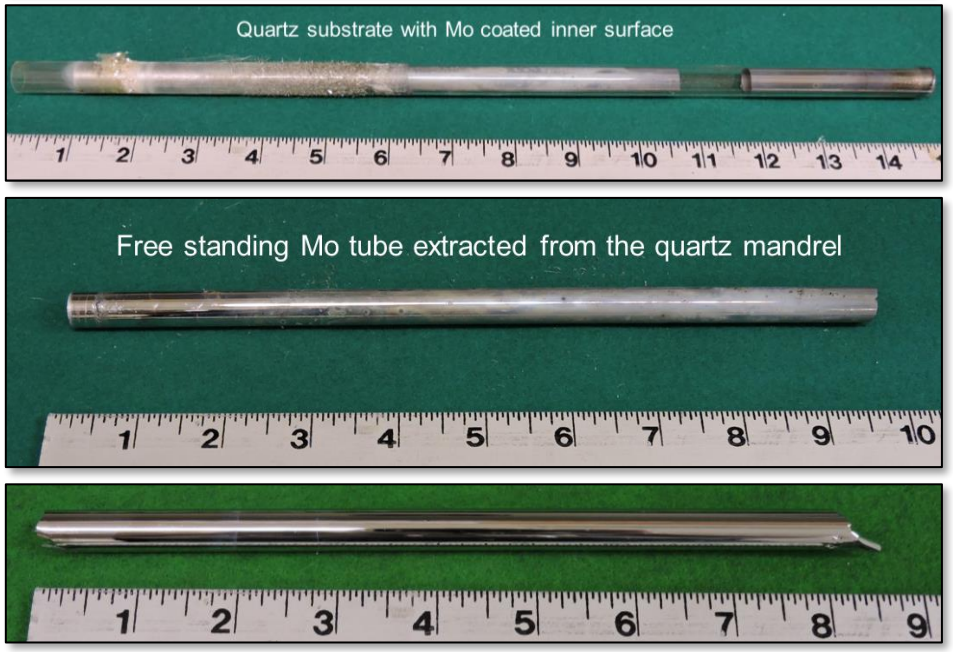
Prior and Ongoing Work at LANL

- Previous work & capabilities:
  - Inspired idea for composites
  - Informed decision criteria matrix/down-selection
  - Provided proof of concept for manufacturability
- Previous project produced free-standing molybdenum tubes via CVD
- LANL Capability: Ion Sputtering Physical Vapor Deposition (PVD) of tube interiors

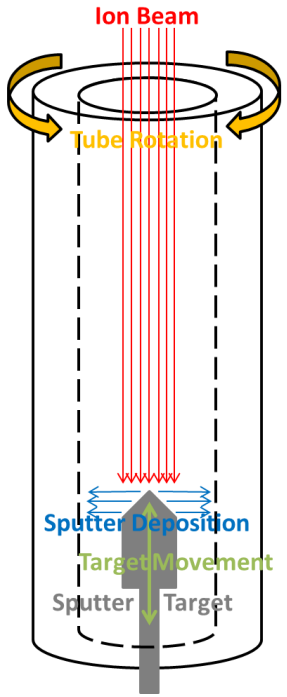
CVD of Mo Tubes

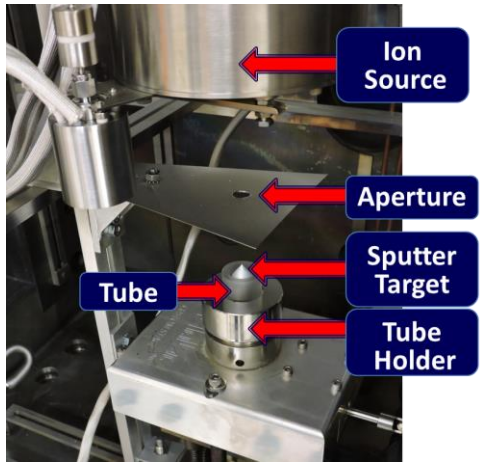
$$Mo(s) + Cl_2(g) \xrightarrow{200-400^\circ C} MoCl_5(g)$$

$$MoCl_5(g) + \frac{5}{2}H_2(g) \xrightarrow{500-800^\circ C} Mo(s) + 5HCl(g)$$



PVD Tube Coater





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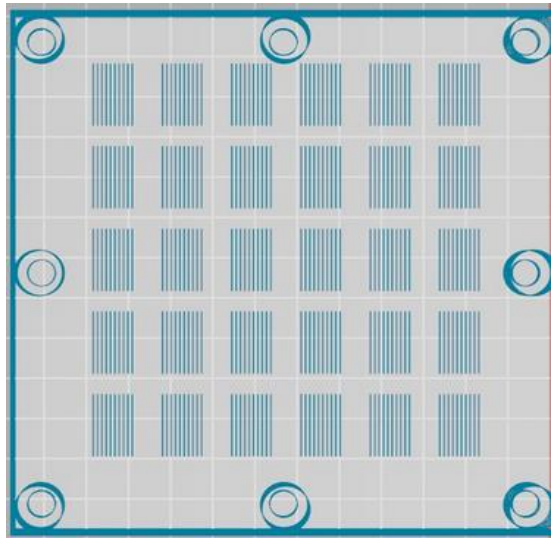
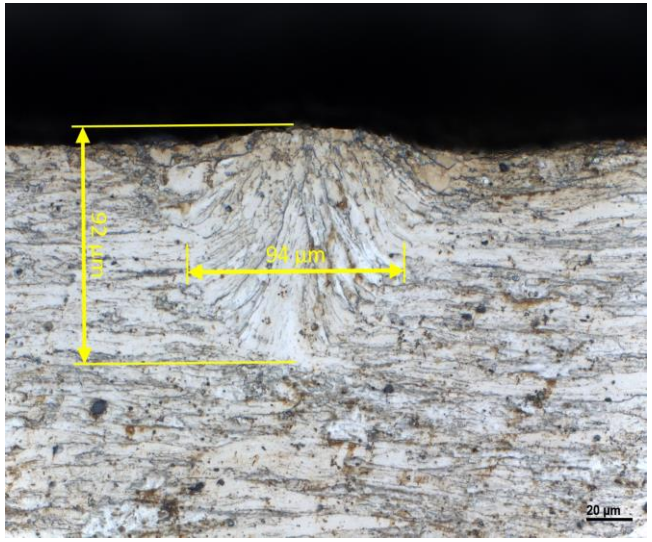
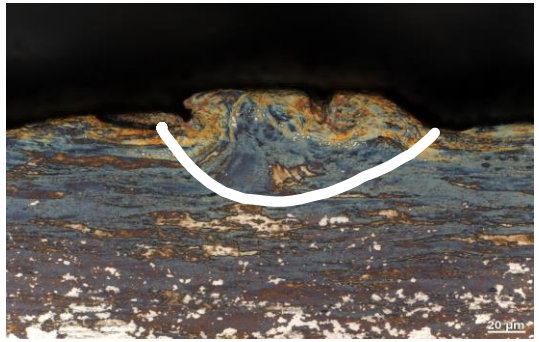
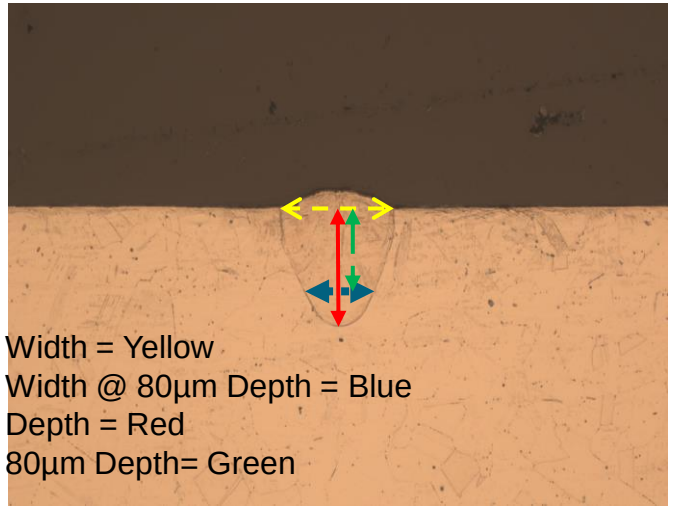
Preliminary Feasibility Studies of New Materials for Advanced Manufacturing - LANL

Prior and Ongoing Work at LANL:







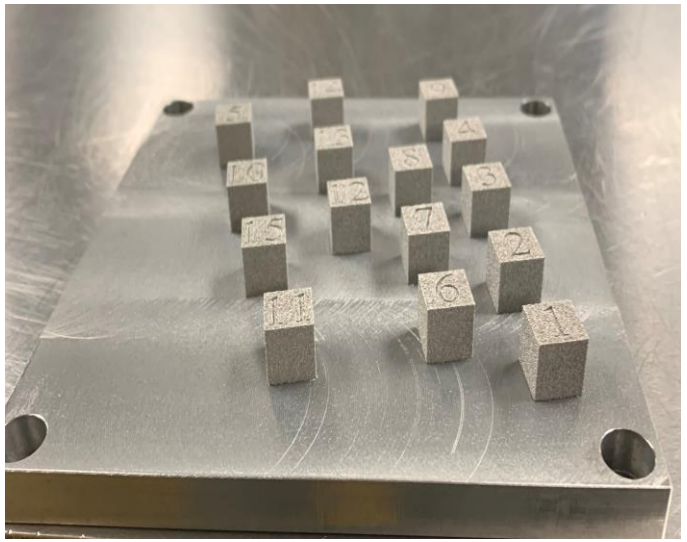


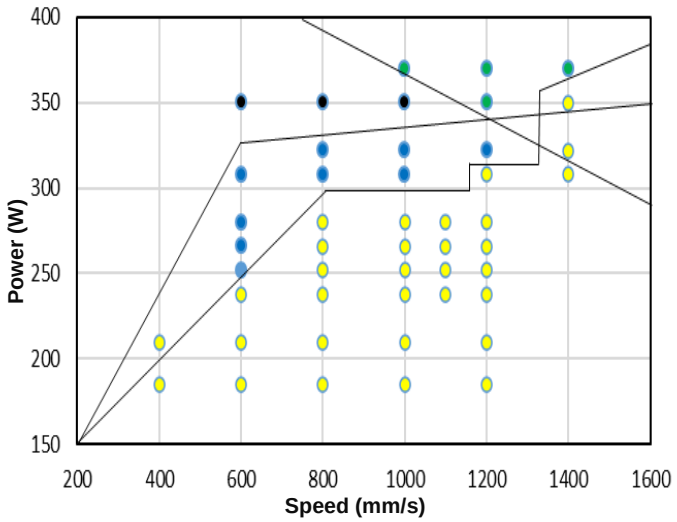
Bulk Refractory Alloys Considerations:

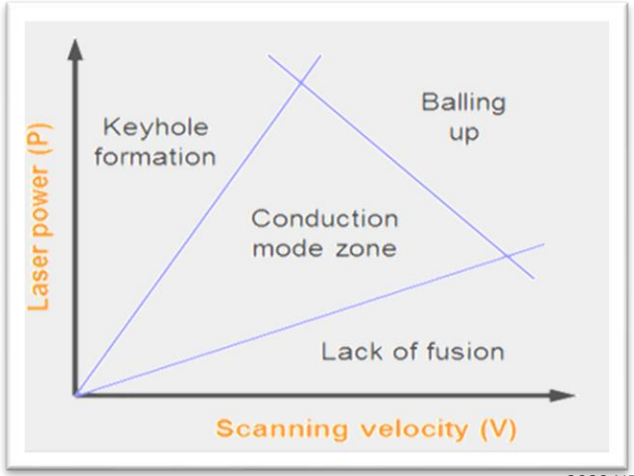
- LANL Microreactor Program
  - Used single bead welds to elucidate relationship between scanning time and laser power
  - Demonstrated capability to produce AM TZM alloy
- Feasibility and material down select was being informed by:
  - Previous/ongoing work on stainless steels, TZM, and other refractory alloy cube production and analysis
  - Broad literature review

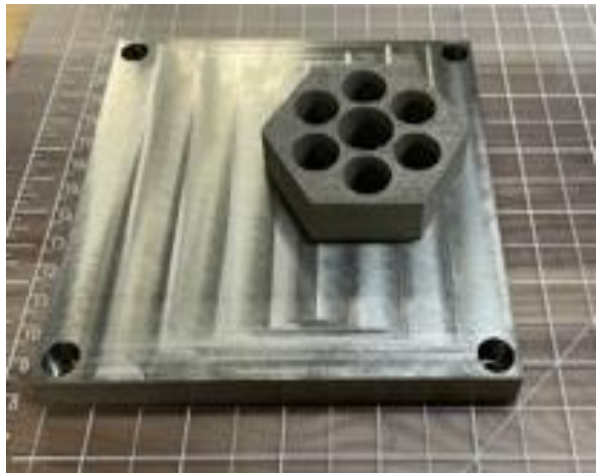
Preliminary Feasibility Studies of New Materials for Advanced Manufacturing - LANL

Prior and Ongoing Work at LANL:









Bulk Refractory Alloys Considerations:

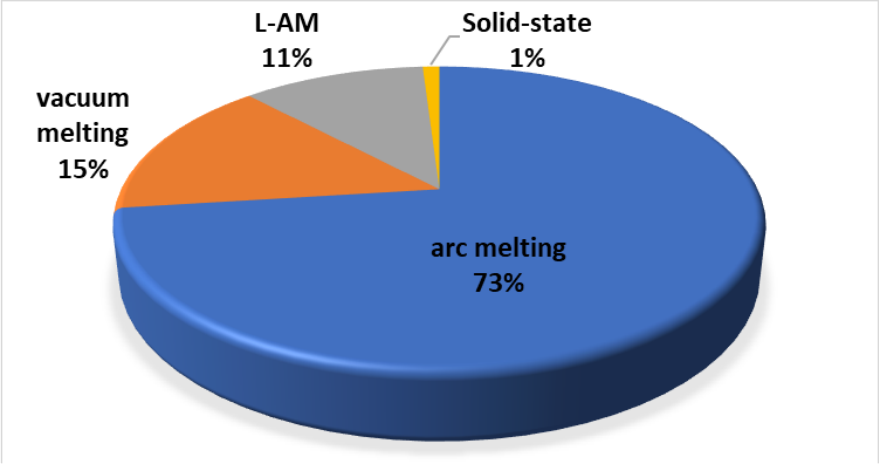
- AMMT Project :
  - Decision matrix evaluation of a broad range of bulk refractory alloys that could be produced by a Laser Powder Bed Fusion (LPBF)
  - Optimization of AM process for select alloys
  - Production and characterization of refractory lined backbones and alloys.
- Next Steps & Future Work:
  - Additional refractory alloys will be identified and evaluated and down selected in early fiscal year 2024.
  - Powders needed to investigate refractory alloys will be obtained.
  - Cubes for selected refractory alloy and tubes coated with refractory liners will be produced and characterized for feasibility in fiscal year 2024.
  - Beyond FY24: Production of a multichannel part from selected alloy or refractory lined backbone.

Preliminary Feasibility Studies of New Materials for AM: High Entropy Alloys (HEAs) - PNNL

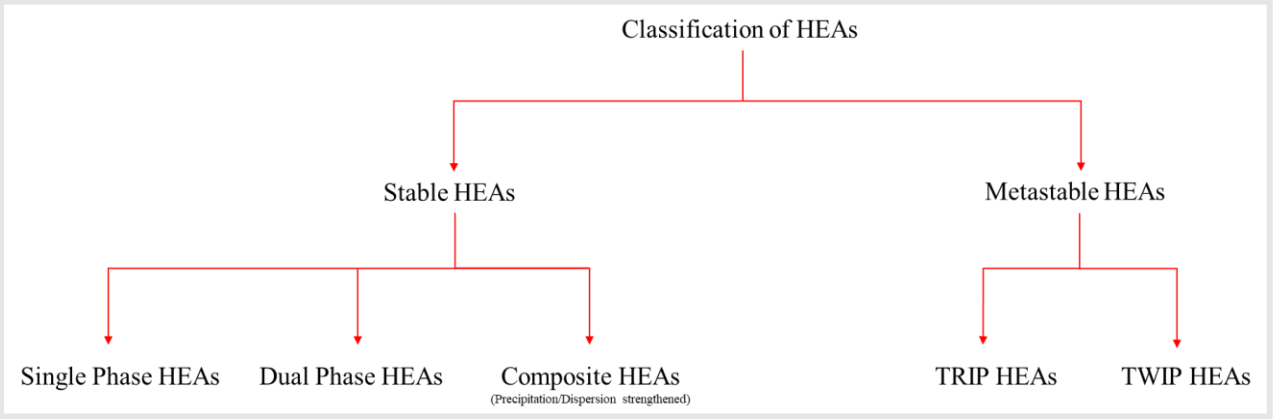
Why High Entropy Alloys?

- exhibit unusual lattice distortion and sluggish diffusion, immobilize the radiation-induced defects decreased swelling and segregation
- Tuned microstructure by exploiting their varied phase stability in different temperature regimes for enhanced sink strength.
- Multiple interfaces via secondary phase precipitation and multi-modal distribution of grain sizes enhance the sink strength

Manufacturing Process



HEA classification



This classification is based on *phase stability and mode of deformation*

- Stable HEAs deform via dislocation slip and metastable HEAs via TRIP and/or twinning induced plasticity (TWIP) upon mechanical/thermal damage.
- Stable HEAs can be further classified based on the type of phases that constitute the microstructure.

Feasibility Study of Advanced Manufacturing Techniques and Compositions of High Entropy Alloys (HEAs)

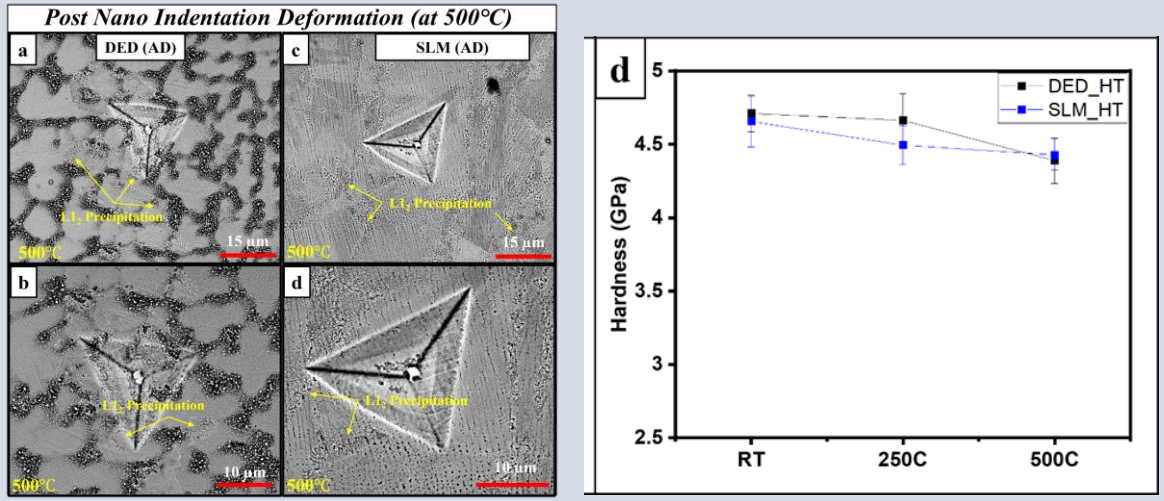
Objectives:

(1) Evaluating current ***manufacturing techniques*** addressing challenges and needs for ***upscaling***

(2) Identify & down select ***nuclear energy relevant HEAs*** using decision matrix

Scientific Achievement:

- Six promising HEAs identified for nuclear focusing on high temperature properties:
  - $Al_{0.3}Cu_{0.5}CrFeNi_2$, $Al_5Cr_{12}Fe_{35}Mn_{28}Ni_{20}$ and **$Al_{10}Cr_{12}Fe_{35}Mn_{23}Ni_{20}$***: NRC , RT high strength
  - $(Ni_2\underline{Co}_2FeCr)_{92}Al_4Nb_4$: ppt strengthened HEA (330MPA at 870°C)
  - GRX-810 (ODS-Ni<u>Co</u>Cr with minor Al, Ti, Nb, W, and C): medium HEA
  - **$Al_{0.3}Ti_{0.2}\underline{Co}_{0.7}CrFeNi_{1.7}$** *: ppt strengthened FCC HEA ; (expected high strength up to 1100°C)
- Experiments **$Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$** :
  - Characterization of **DED** and **SLM** one-step annealed conditions, high strength @ 500°C (samples manufactured by UNT)
- Experiments for bulk & economic manufacturing
  - Characterization of DED fabricated **functionally graded** HEAs: economic INL provisional patented process demonstrated with $CoCrNiFe_{0.5}$
  - **Solid phase processing** (SPP) planned in FY 24 for bulk upscaling for alloys*



DED and SLM one-step annealed $Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$

Publication:
Nartu, M.S.K.K.Y., et al., Microstructure and Temperature Dependent Indentation Response of Additively Manufactured Precipitation-Strengthened $Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$ High Entropy Alloy. JOM, 2023.

Presentation:
Nartu et al., Engineering heterogeneous microstructures in Additively Manufactured $Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$ High Entropy Alloy for potential nuclear applications at Materials in Nuclear Energy Systems (MiNES 2023).

Impact & Potential Application Space:

- Preliminary decision matrix provides promising HEA compositions
- Complex high temperature components, HEA coating for high temperature application
- ($NiCoFeCrCu_{0.12}$ is researched under another DOE-NE program for extreme high irradiation dose for cladding)

Mohan Nartu, Subhashish Meher, Isabella van Rooyen, Shalini Tripathi, Nathan Canfield

Presentation:
Nartu et al., HEAs for Nuclear Energy Applications and Potential Advanced Manufacturing Methods at International Conference on Additive Manufacturing (ICAM) 2023.

Presentation:
Meher et al., Development of High Entropy Alloy based Coatings via Directed Energy Deposition (DED) Additive Manufacturing for Nuclear Applications at 3rd World Congress on High Entropy Alloys (HEA 2023),

Decision Criteria Matrix Applied to Diverse Material Types

Composite	W/C-C				Mo/C-C				Zr/C-C				W/SiC-SiC				Mo/SiC-SiC				Zr/SiC-SiC			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	19	15	25	32	18	13	25	33	17	15	24	33	19	18	26	32	17	16	26	33	17	19	25	33
Overall score	91				89				89				95				92				94			

Refractory Alloy	TZM				WTa				WNiFe				C-103			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	23	18	32	33	18	16	26	27	22	19	29	27	23	21	34	27
Overall score	106				87				97				105			

ODS	Ferritic ODS Steels				Austenitic ODS Steels			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	12	18	27	26	10	18	30	30
Overall score	83				88			

HEA	$Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$				$Al_{10}Cr_{12}Fe_{35}Mn_{23}Ni_{20}$			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	8	0	15	33.5	10	0	18	34.5
Overall score	56.5				62.5			

Material Identification

Decision making through Diverse Surveying

Develop materials as an integrated part of advanced manufacturing (AM)

Performance, Scalability, Reproducibility, Economics, Supply

Short Term Needs → Long Term Needs

- Understanding Industry Requirements
- Upscale & Large Scale
- 316SS AM Variability
- Diverse Component & Geometry Manufacturing
- Next Generation Materials & Manufacturing Processes
- Critical minerals/materials

Multi - Laboratory and -Stakeholders effort to accelerate development and implementation

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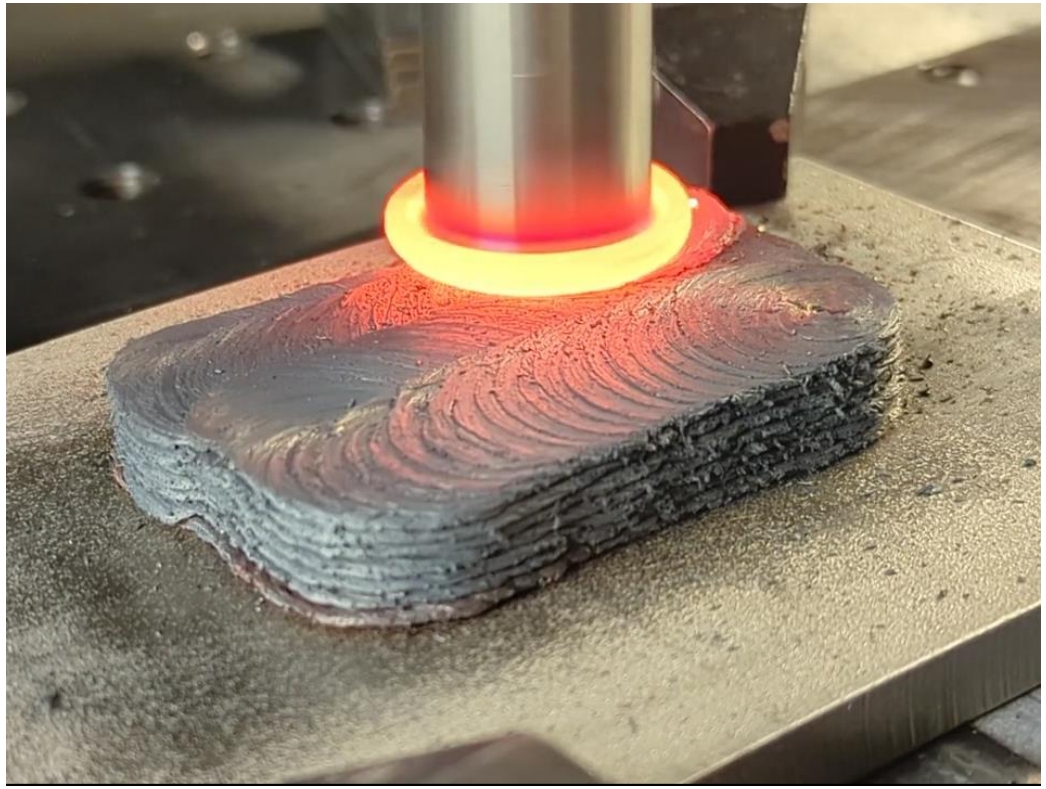
Additive Friction Surfacing (AM)

Process Description and First 316H work

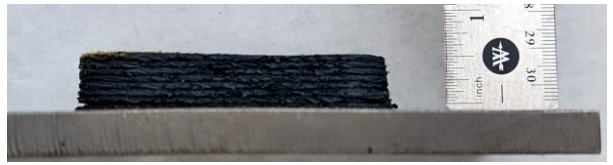
Nascent large scale manufacturing process with the potential for improved properties, cost and lead time



316-H bar stock deposited directly onto 316-L plate at PNNL

PNNL team: David Garcia, Mayur Pole, Ken Ross

- Refined grain structure produces improved properties demonstrated in aluminum
- Overmatched properties possible in austenitic stainless steels
- Potentially order of magnitude cost staving on material alone compared to fusion based methods
- High deposition rate
- Application space
  - Near-net shape additive manufacturing
  - Component life extension
  - Cladding
  - Functionally graded and dissimilar materials



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