Microstructural Tailoring of Ferritic/Martensitic Grade 91 Steel Using Wire Arc Additive Manufacturing

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Extreme Nuclear Environments

Advanced Reactor Design Considerations for Structural Materials

- Temp. Range: 300-1,000°C
- Damage Level: >200 dpa
- Stress: ~150 MPa
- Corrosion

Advanced Reactor Radiation Effects

- Radiation hardening and embrittlement
- Phase instabilities
- Irradiation creep
- Swelling
- He embrittlement

Desired Material Features

Fine, stable precipitates

- Good long-term thermal aging
- Resist radiation embrittlement
- Creep resistance
- Resist void swelling
- High strength & good ductility

9-20% Cr Alloy Development for Nuclear Reactor Core Internal and External Components

Ingot Metallurgy

Composition, Heat Treatment, TMT Optimization

9-12% Cr FM Steels

MX: 10^{19}-10^{20} m^{-3}

9-12% Cr CNA Steels

MX: 10^{21}-10^{22} m^{-3}

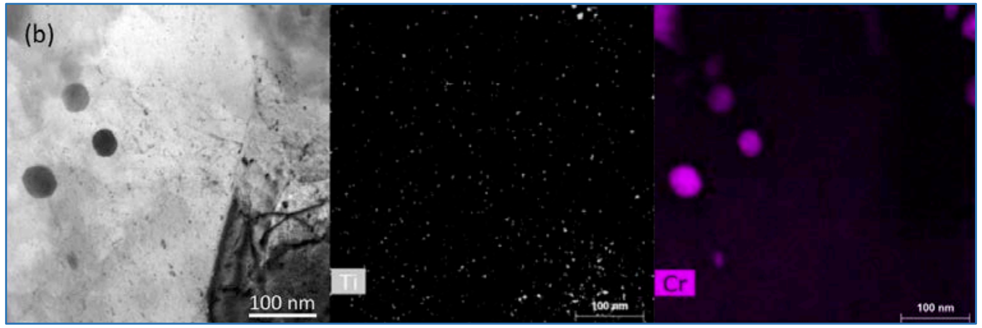
Nanoparticle Optimization

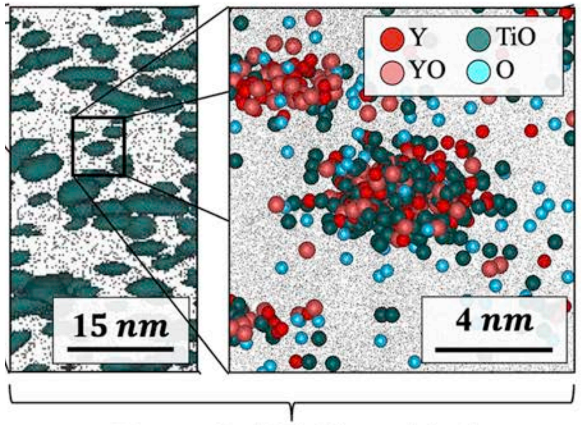
Powder Metallurgy

9-20% Cr ODS FM Steels

Oxides: 10^{21}-10^{24} m^{-3}

How can we efficiently fabricate FM steels with high nanoparticle densities?





Nanoscale (Y,Ti,O) precipitation

T.R. Allen et al. / Journal of Nuclear Materials 375 (2008) 26–37
L. Tan et al. / Journal of Nuclear Materials 509 (2018) 267-275
C.P. Massey et al. / Journal of Nuclear Materials 522 (2019) 111-122

FM=Ferritic/Martensitic, RAFM=Reduced Activation Ferritic/Martensitic, ODS=oxide dispersion strengthened

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Nanoparticle Optimization

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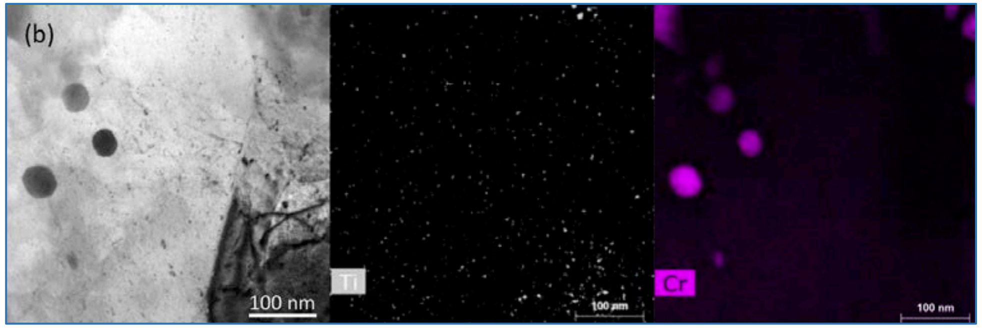
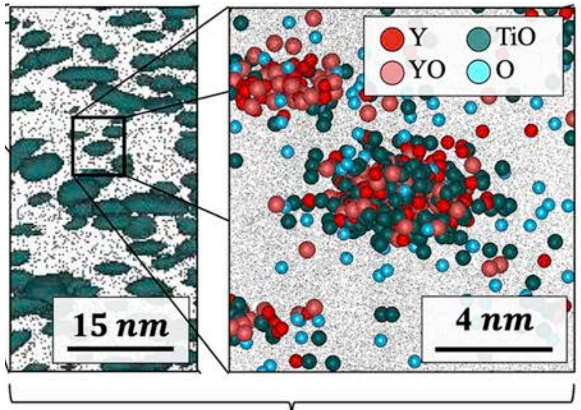
Fabrication Optimization

Additive Manufacturing

Directed Energy Deposition 9-12% Cr FM Steels

- Wire arc — MX: 10^{21} m^{-3}





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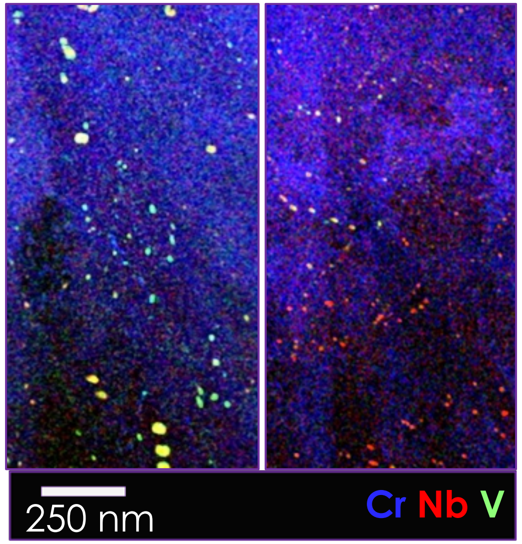

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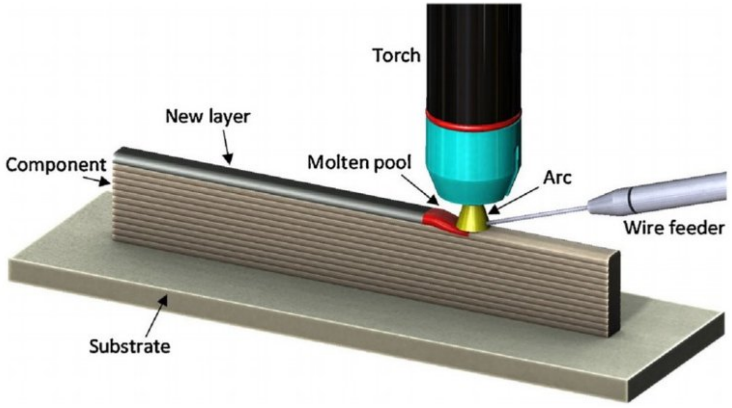
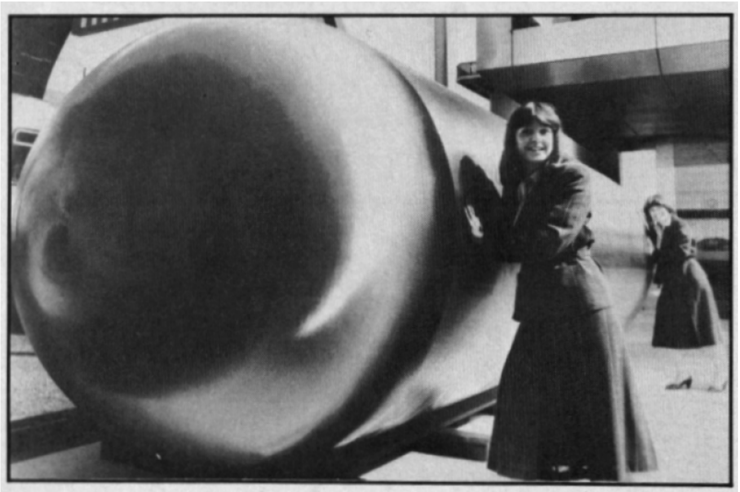
WAAM is preferred technique for RPV Fabrication

Wire arc AM process



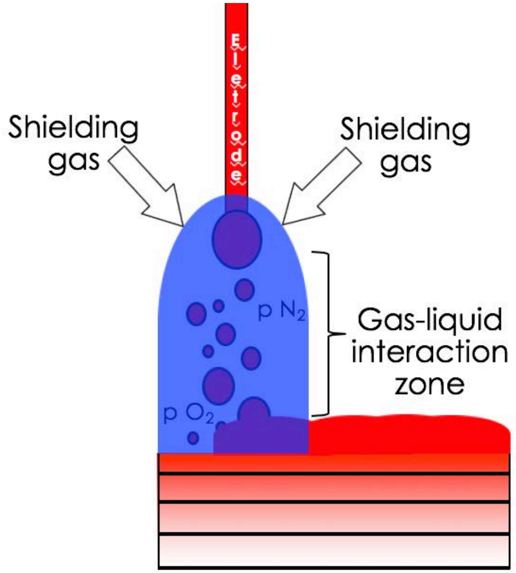
High deposition rates achievable

Fabricate large, non-complex geometries



58 metric ton pressure vessel with dome fabricated with submerged arc welding (SAW)

Tailor structure of materials via control of processing parameters



This experiment aims to:

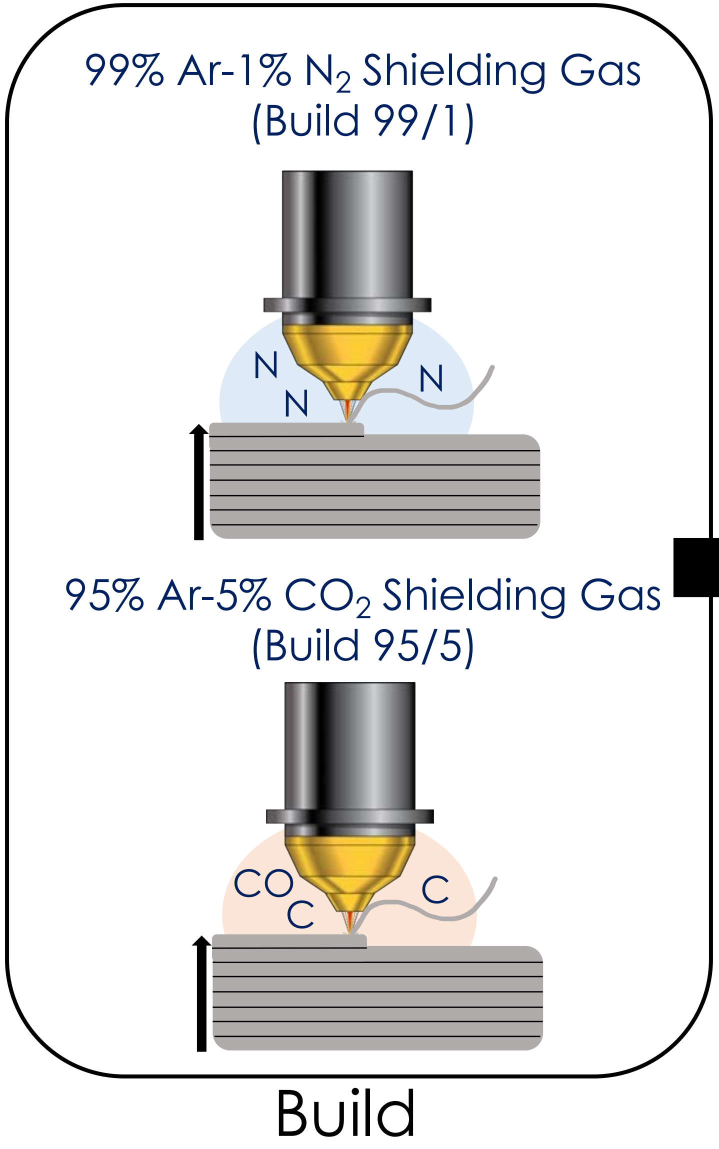
Assess WAAM for FM fabrication

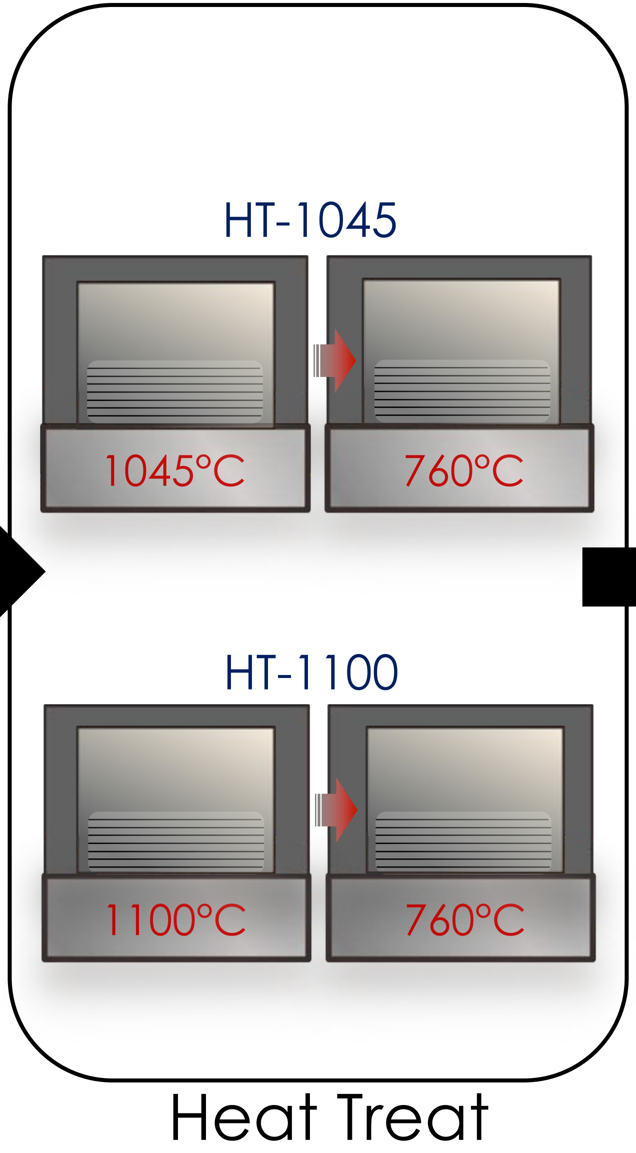
Mimic or improve upon wrought properties

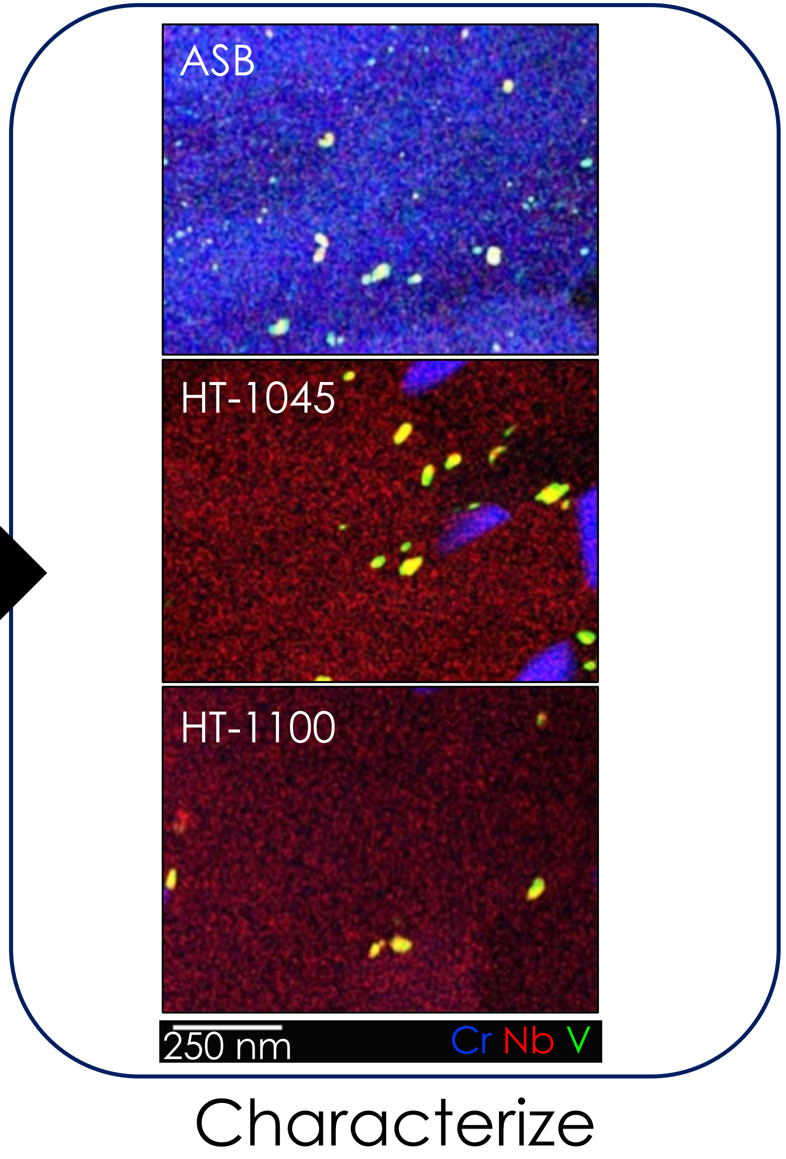
Control precipitate structure with AM processing parameters

WAAM Grade 91 Experimental Details

Control MX precipitate structure with C and N additions using different shielding gases







Wire Arc AM Experimental Details

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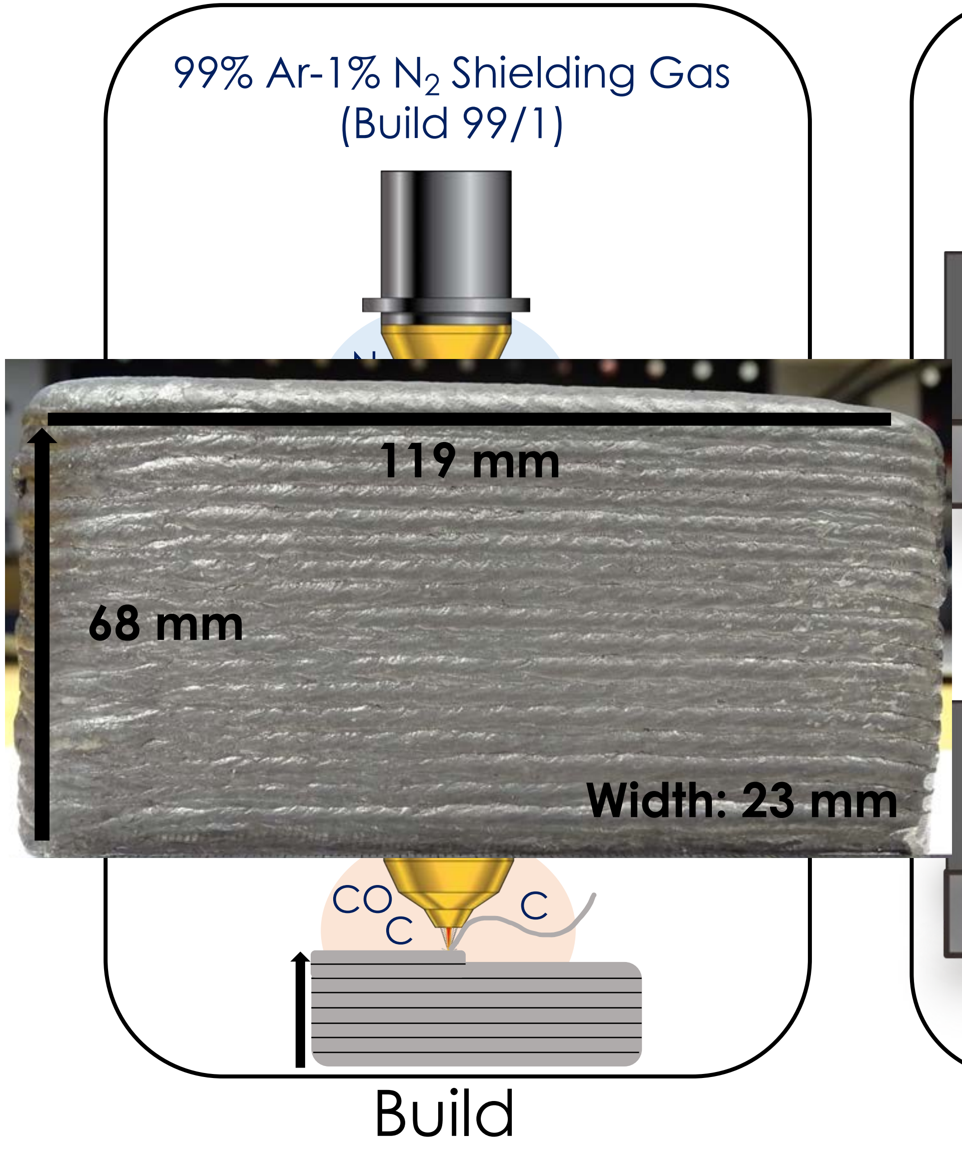
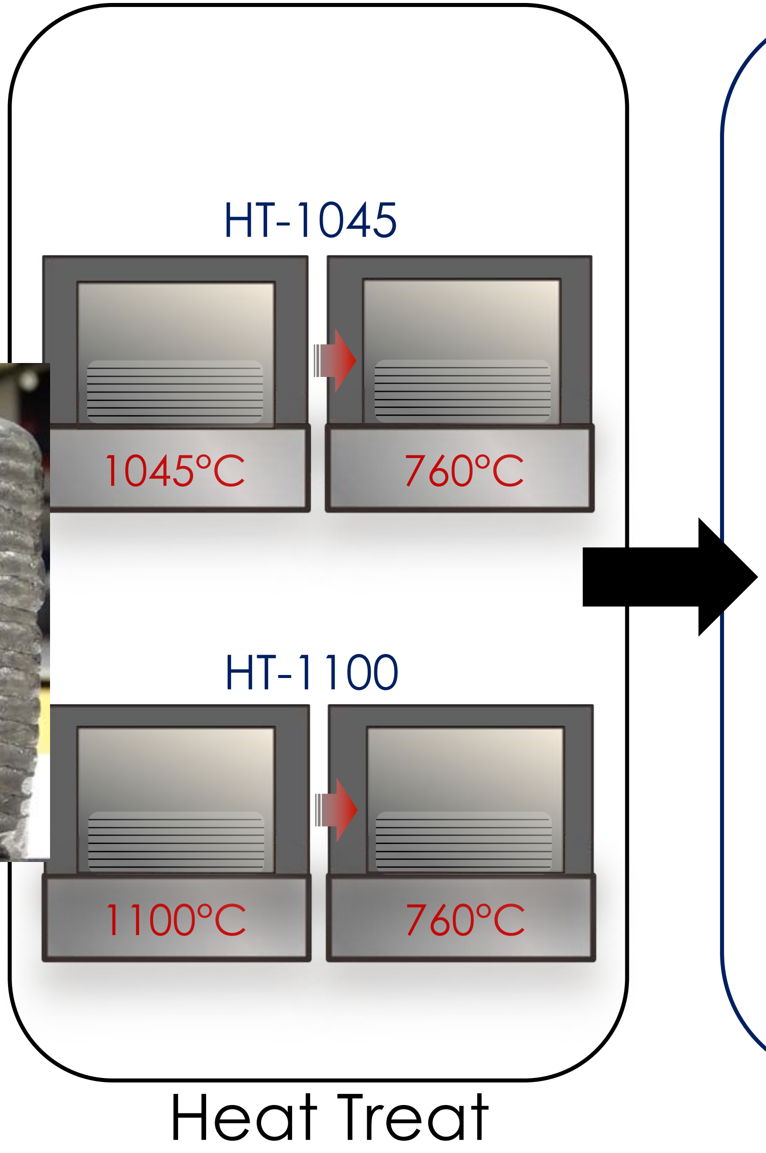
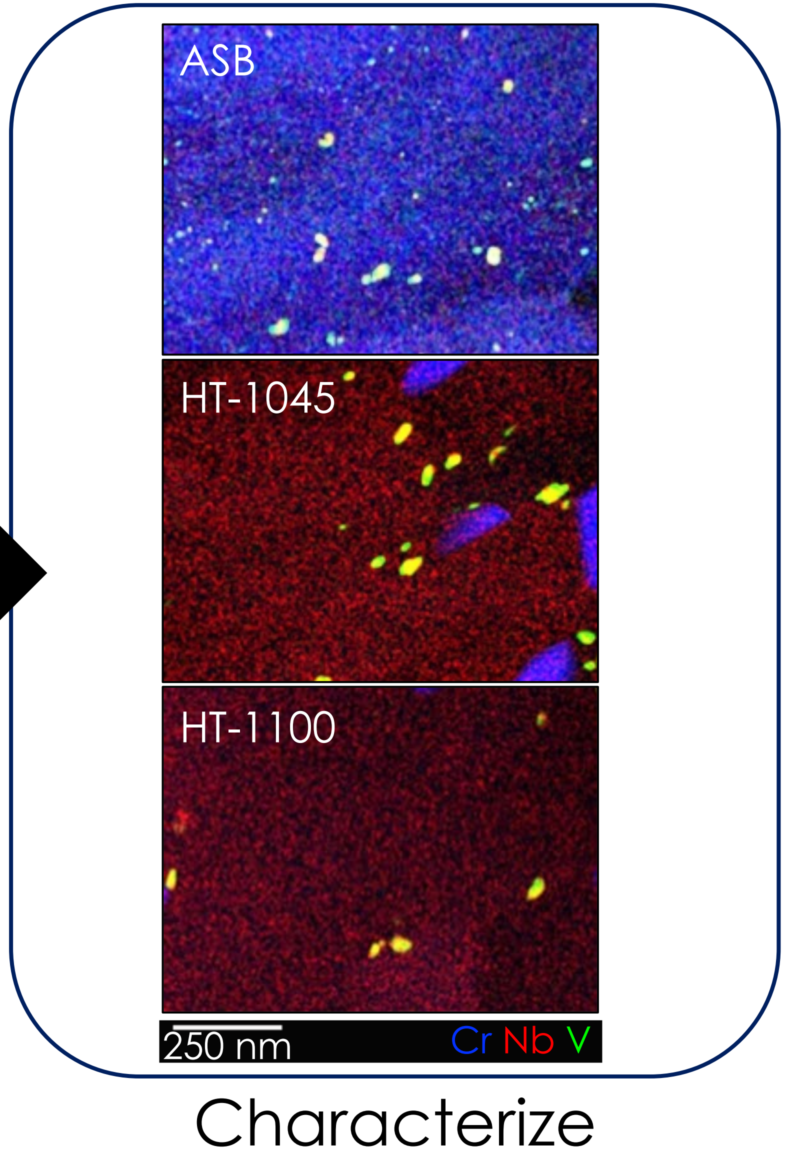
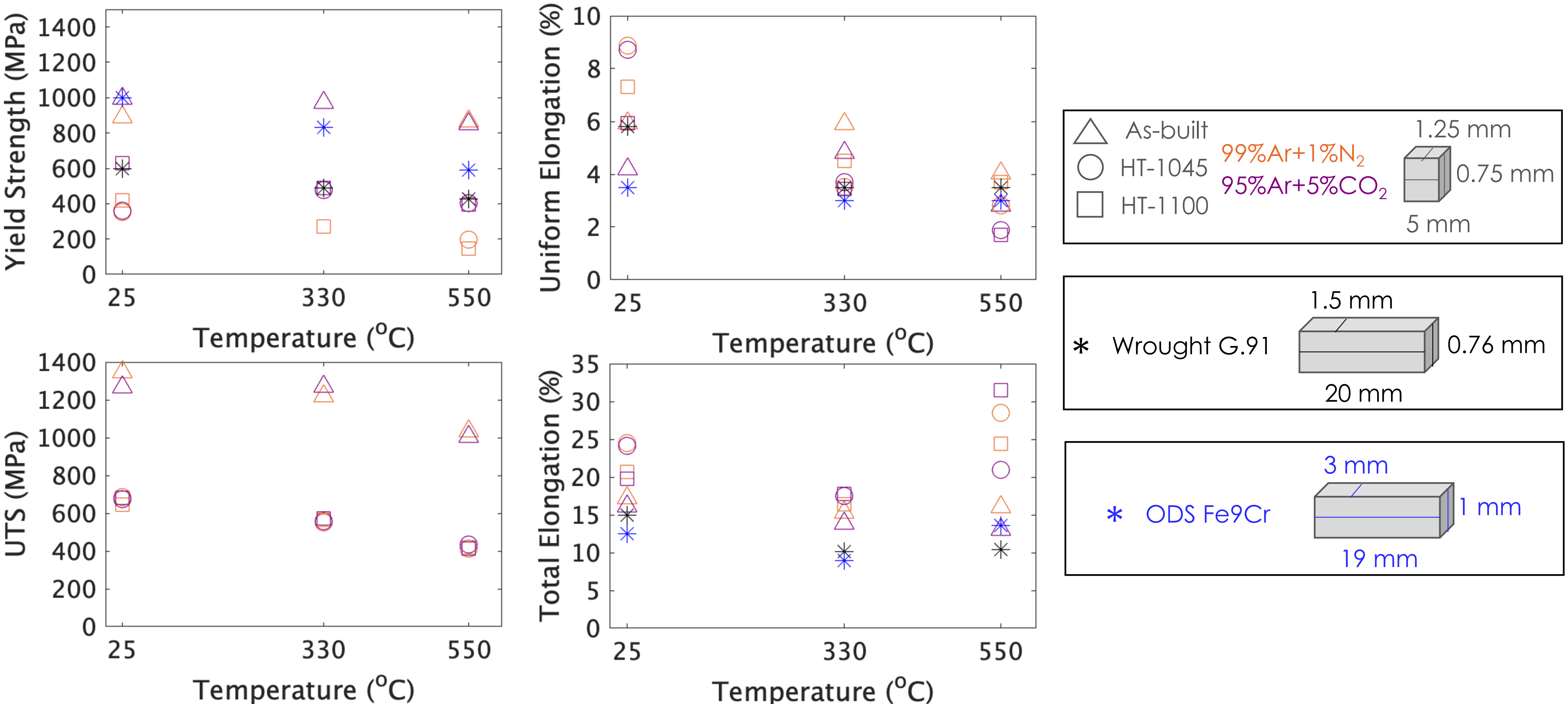






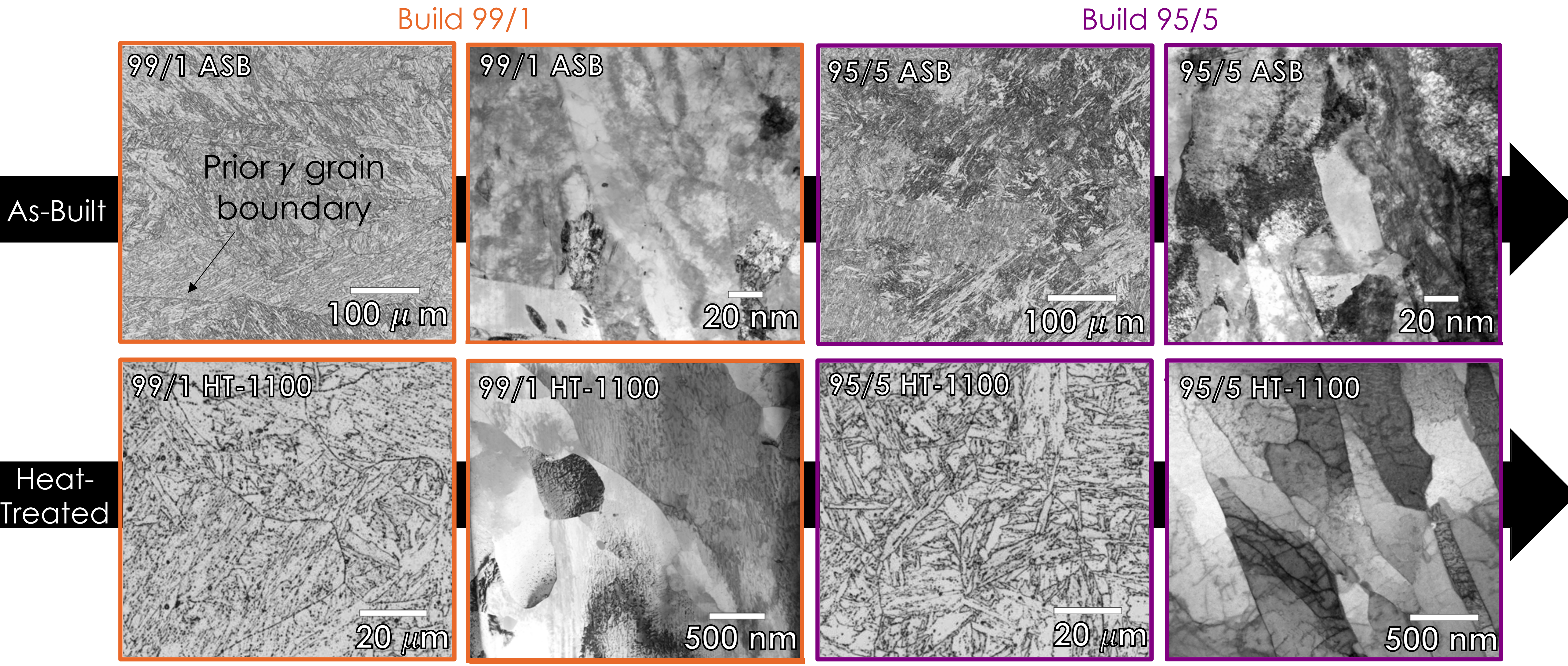
Mechanical Properties

- Shielding gases caused no difference in strength
- All as-built specimens had higher strength than the heat-treated AM, wrought, and ODS Fe9Cr specimens



General Microstructure of As-Built G. 91

Representative of wrought FM steels: laths, packets, and prior austenite grain boundaries



Shielding Gas Effect on Composition

Element	Initial Content (wt. %)	Build 95/5 Content (wt. %)	Build 99/1 Content (wt. %)
O	0.008	**0.0316**	0.0178
C	0.08	0.093	0.072
N	0.04	0.0386	**0.0648**

Build 95/5

16.25% increase in C

Build 99/1

62% increase in N

How do these changes compare to values from literature?

ASME Code for Wrought Grade 91

C

0.06-0.15 wt.%

N

0.025-0.08 wt.%

Welded Grade 91

SAW: no shielding gas

18% decrease in C

34% decrease in N

C content Base Material	C Content from welding
<0.1wt.%	increase
>0.1wt.%	decrease

GTAW: 95% Ar+5% CO_2

38% increase in C

GTAW: 100% Ar

63% increase in C

GTAW: 100% CO_2

38% increase in C

GTAW: 99.7% Ar

27% decrease in C

Welded Fe

Auto-GTA: 95% Ar+5% N_2

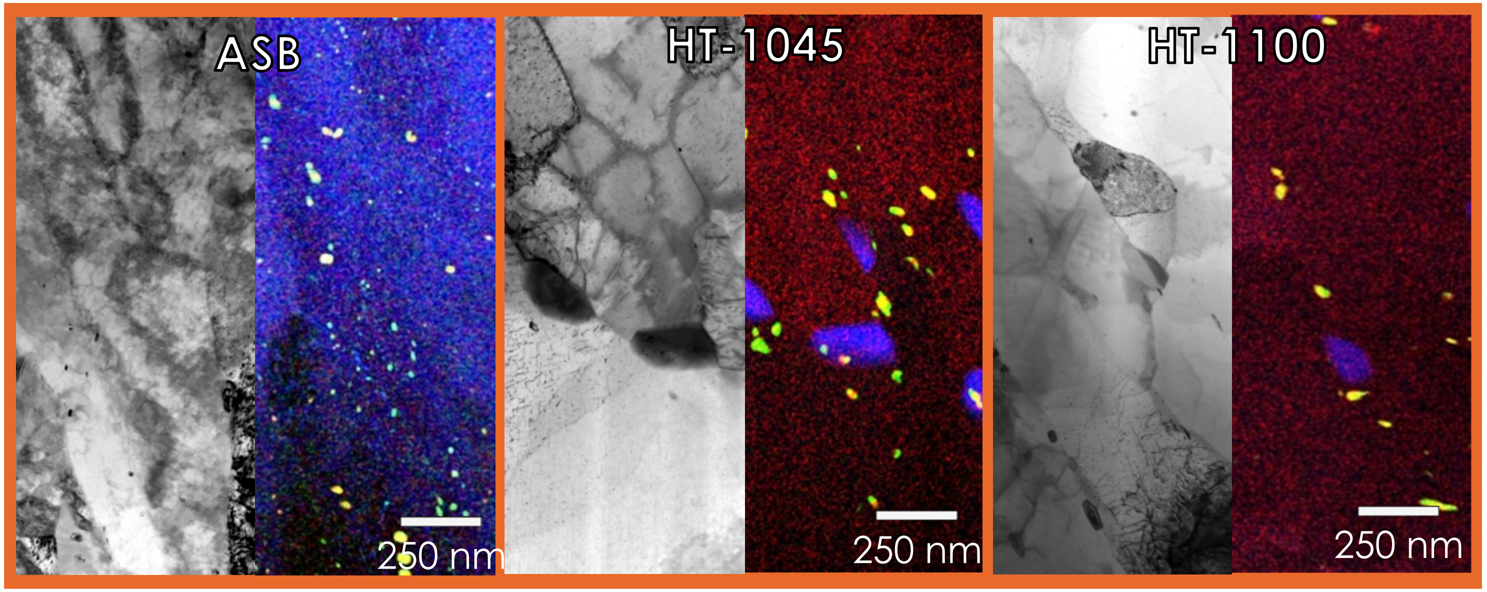
1,800% increase in N

Auto-GTA: 80% Ar+20% N_2

2,900% increase in N

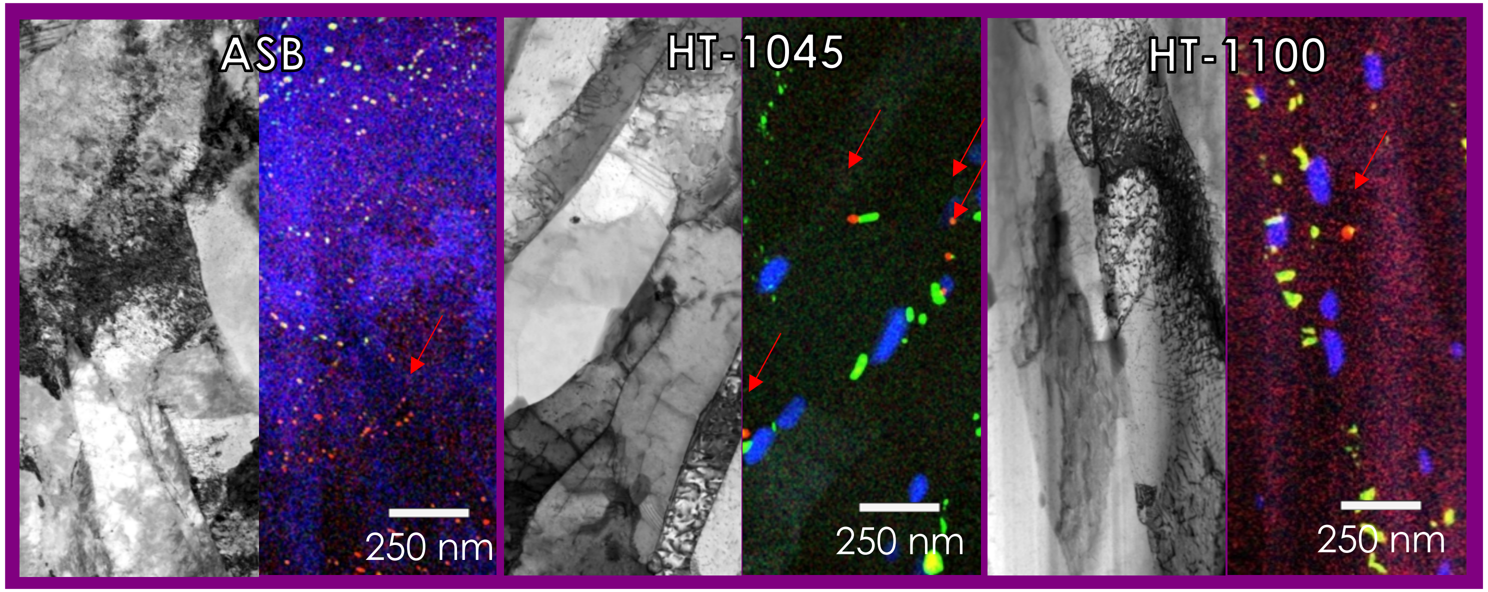
Shielding Gas Effect on MX Precipitation

Build 99/1: 62% increase in N content

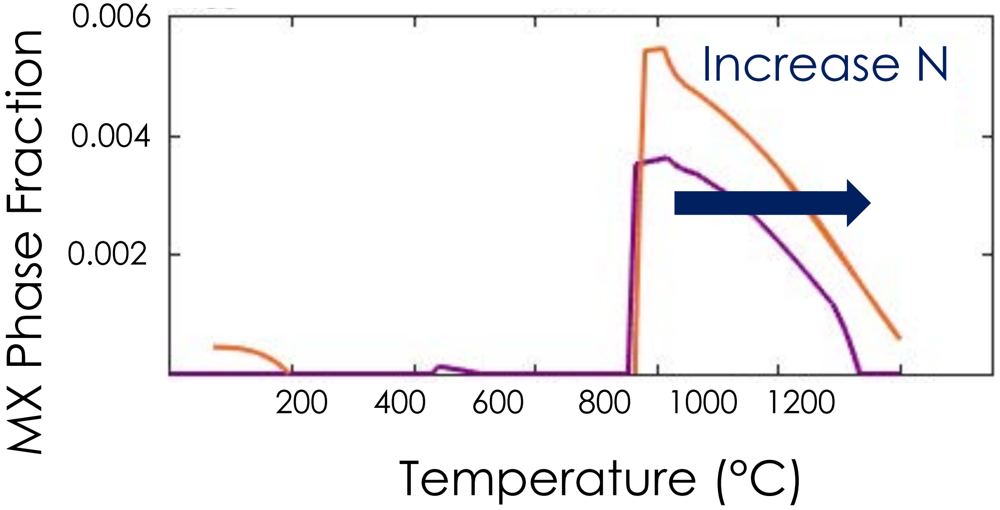


Build 95/5: 16% increase in C content

Cr Nb V



Controlled MX precipitate **chemistry** and **temperature stability** with shielding gas composition



Shielding Gas Used	MX Stability Range
99%Ar+1%N_2	765->1,200°C
95%Ar+5%CO_2	755-1,130°C

Shielding Gas Effect on MX Precipitation

		Mean Size (nm)	Number Density ($\times 10^{20}$ m^{-3})
Build 99/1	ASB	12±7	14±3
	HT-1045	28±11	1.8±0.3
	HT-1100	13±11	9.6±1.8
Build 95/5	ASB	12±5	20±4
	HT-1045	26±15	2.1±0.4
	HT-1100	20±11	3.1±0.6
Wrought		20-40	10^{19}-10^{20}

Shielding gases:

- Decreased average MX particle size
- Increased MX carbonitride precipitation by 1-2 orders of magnitude over wrought G. 91

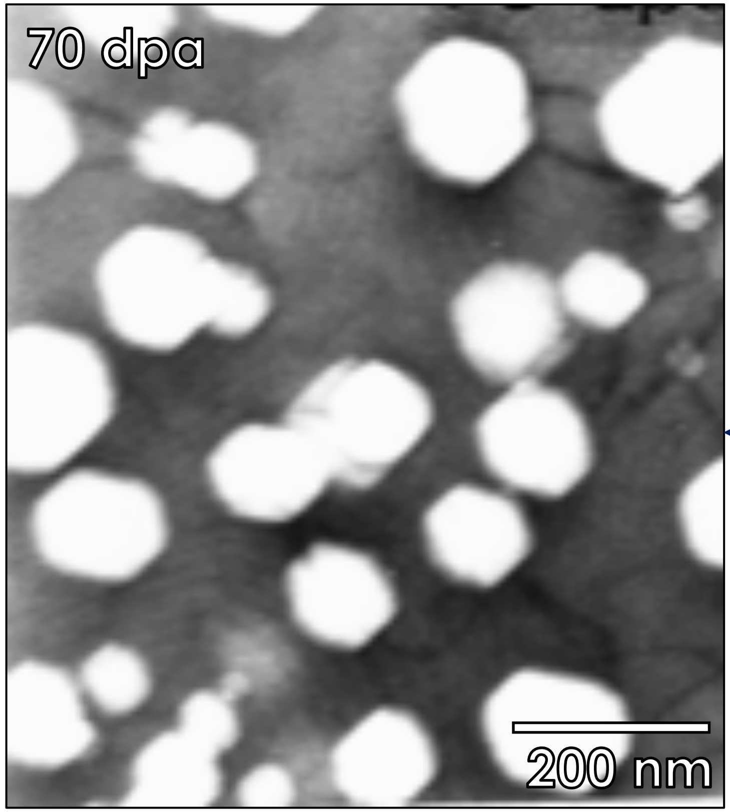
Shielding Gas Effect on Sink Strength

Nanoscale precipitation increases sink strength and hence radiation resistance of a material

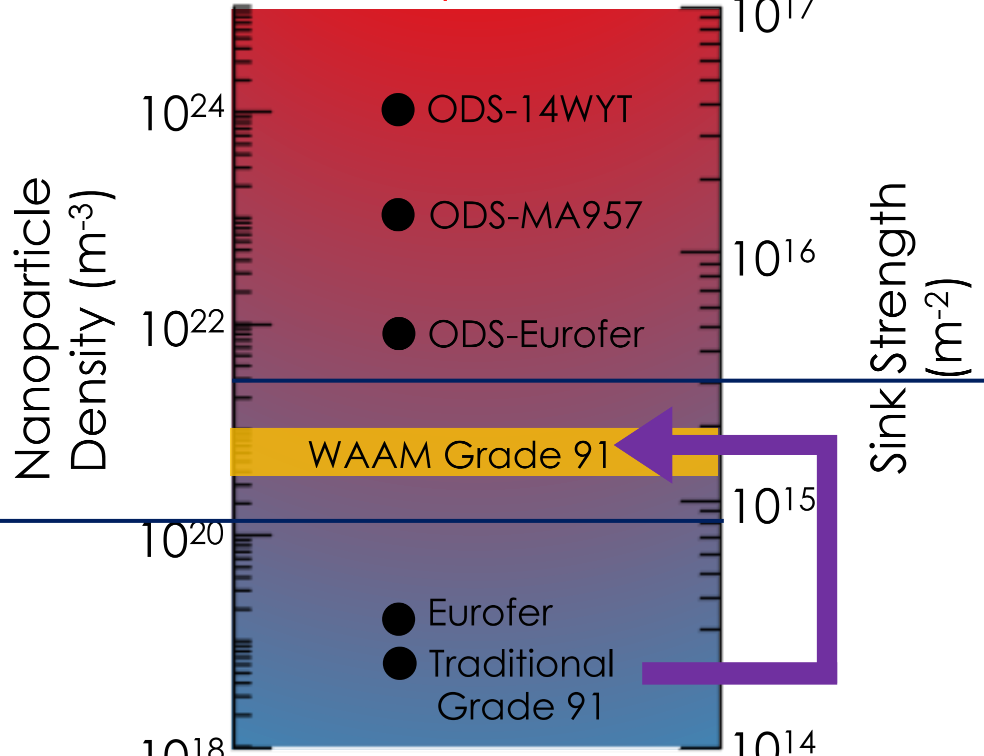
$S_{ppt} \sim 4\pi RN$

Critical sink strength value to prevent:

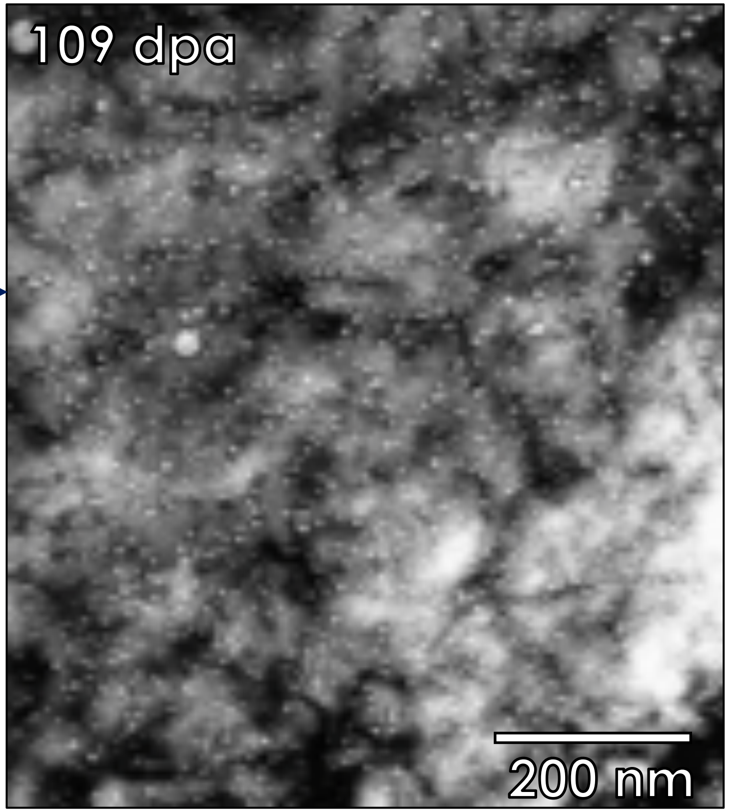
- Void swelling : 10^{15} m^{-2}
- Radiation hardening: 10^{16} m^{-2}



22% swelling



Increased gained from shielding gas use



0.5% swelling

S.J. Zinkle and L.L. Snead, Ann Rev. Mat. Res., 44 (2014) 241

Summary

Successfully fabricated FM steel Grade 91 with DED-AM technique

Improved upon wrought Grade 91 microstructure and mechanical properties

Proved ability to control MX precipitate chemistry and stability with shielding gas composition

Increased sink strength of Grade 91 using shielding gases that supersaturated C and N in the microstructure during AM

Conclusion

Small tweaks in the processing parameters during AM can produce vastly different microstructures, allowing for creative opportunities for hybrid materials processing

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