FEAA133-Low Cost High Performance Austenitic Stainless Steels for A-USC

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Crosscutting (High Performance Materials) Virtual Session
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Acknowledgment

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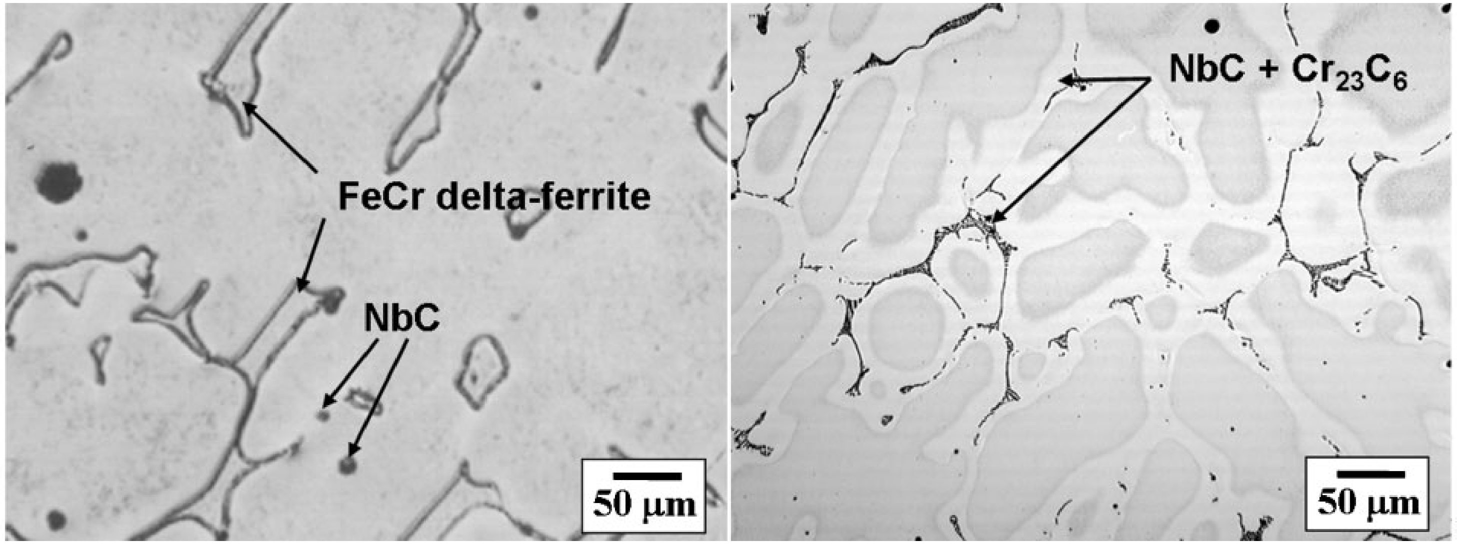
- **NETL: Sarah Nathan** for the programmatic support
- **ORNL: Eric Manneschmidt, Jeremy Moser, Shane Hawkins, Kelsey Hedrick, Doug Kyle, and Doug Stringfield** for their technical assistance
- **EPRI: Scott Bailey** for welding support

Background (1/3)

- **CF8C-Plus** is a heat- and corrosion-resistant cast austenitic stainless steel developed by the Oak Ridge National Laboratory and the Caterpillar Technical Center (**US Patent 7,153,373 B2**)

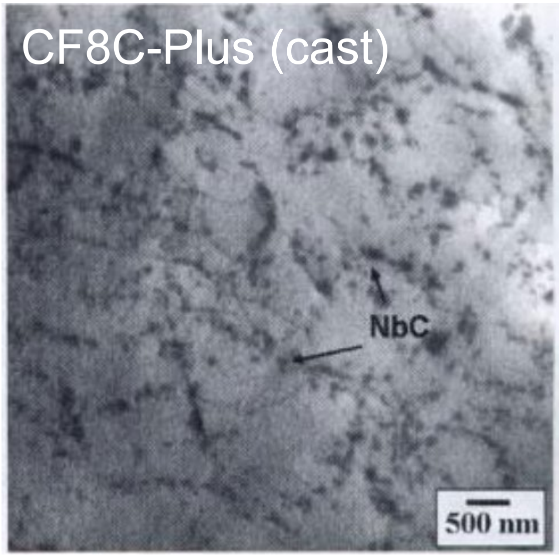
Composition (wt%)

	C	Si	Mn	Cr	Mo	Ni	Nb	N	Fe
CF8C-Plus	**0.08**	**0.5**	**4.0**	**19.0**	**0.3**	**12.5**	**0.80**	**0.25**	**Bal**
CF8C	0.1	1.0	1.0 max	19.0	0.3	10	0.80	-	Bal



As-cast microstructure: ***CF8C (left) & CF8C-Plus (right)***

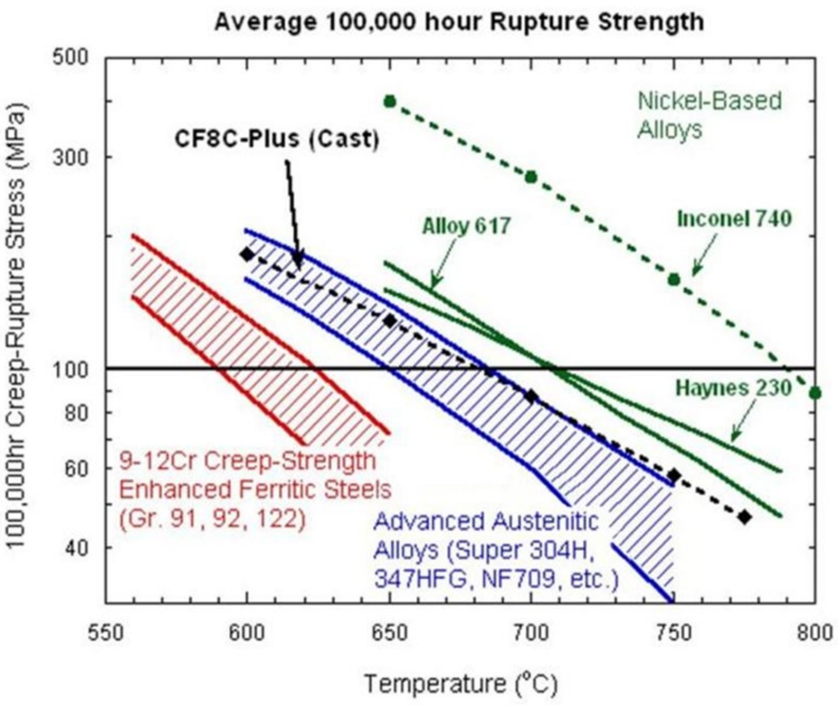
Shingledecker et al., Energy Materials 2006



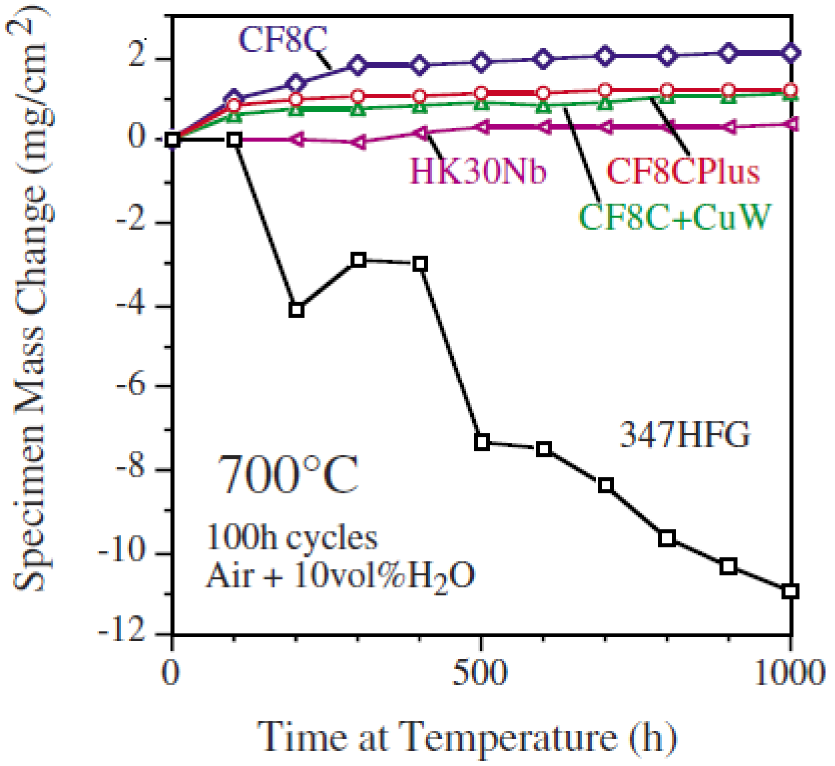
Nanoscale NbC precipitates in CF8C-Plus (courtesy of EPRI)

Background (2/3)

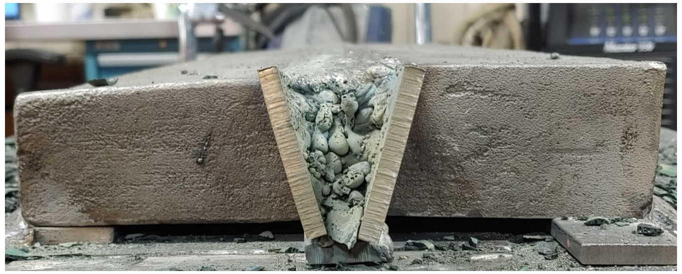
- CF8C-Plus shows unique combination of high temperature mechanical properties, corrosion resistance, castability, and weldability
- Moreover, the strength advantages are found in the **as-cast condition** without additional heat-treatment



CF8C-Plus offers a bridge between 9-12Cr CSEF steels and nickel-based alloys (courtesy of EPRI)



CF8C-Plus shows better corrosion resistance in 700°C humid air than 347HFG

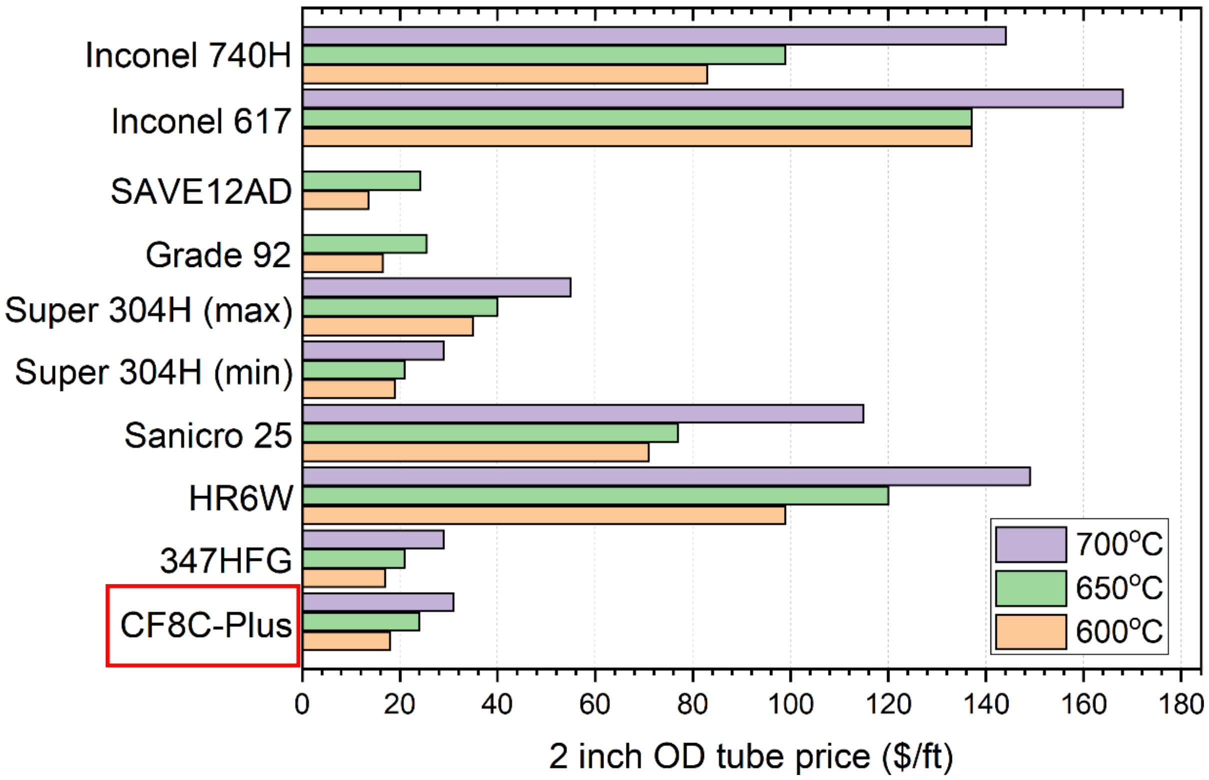


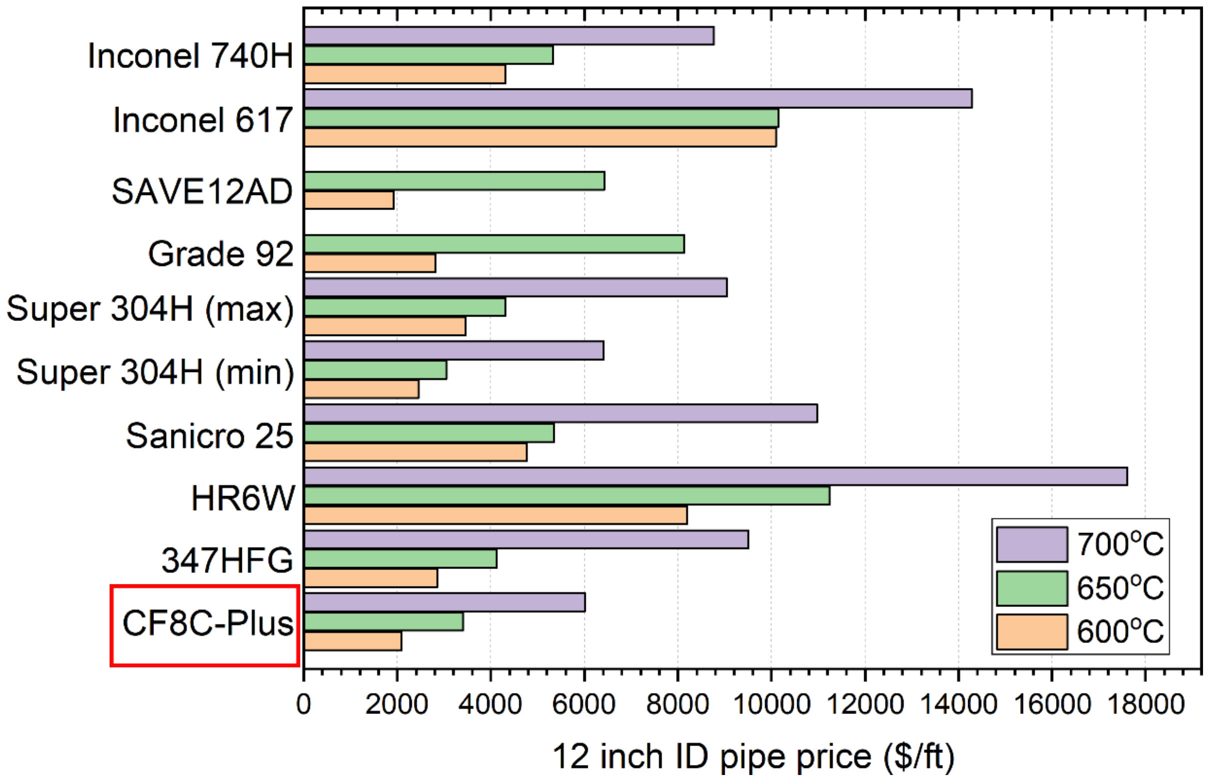
Cross-section view of SMAW of CF8C-Plus

Maziasz and Pint, J ENG GAS TURB POWER, 2011

Background (3/3)

- CF8C-Plus offers impressive economic advantage over other AUSC candidate materials for the temperature range of 600-700°C





Material price per foot to withstand 24MPa steam pressure at designated temperatures

X. Chen, E. Lara-Curzio, Reanalysis of Cost and Moist Air Oxidation Performance for CF8C-Plus and Other Alloys for AUSC Applications, ORNL/TM-2021/1943, https://www.osti.gov/biblio/1782110

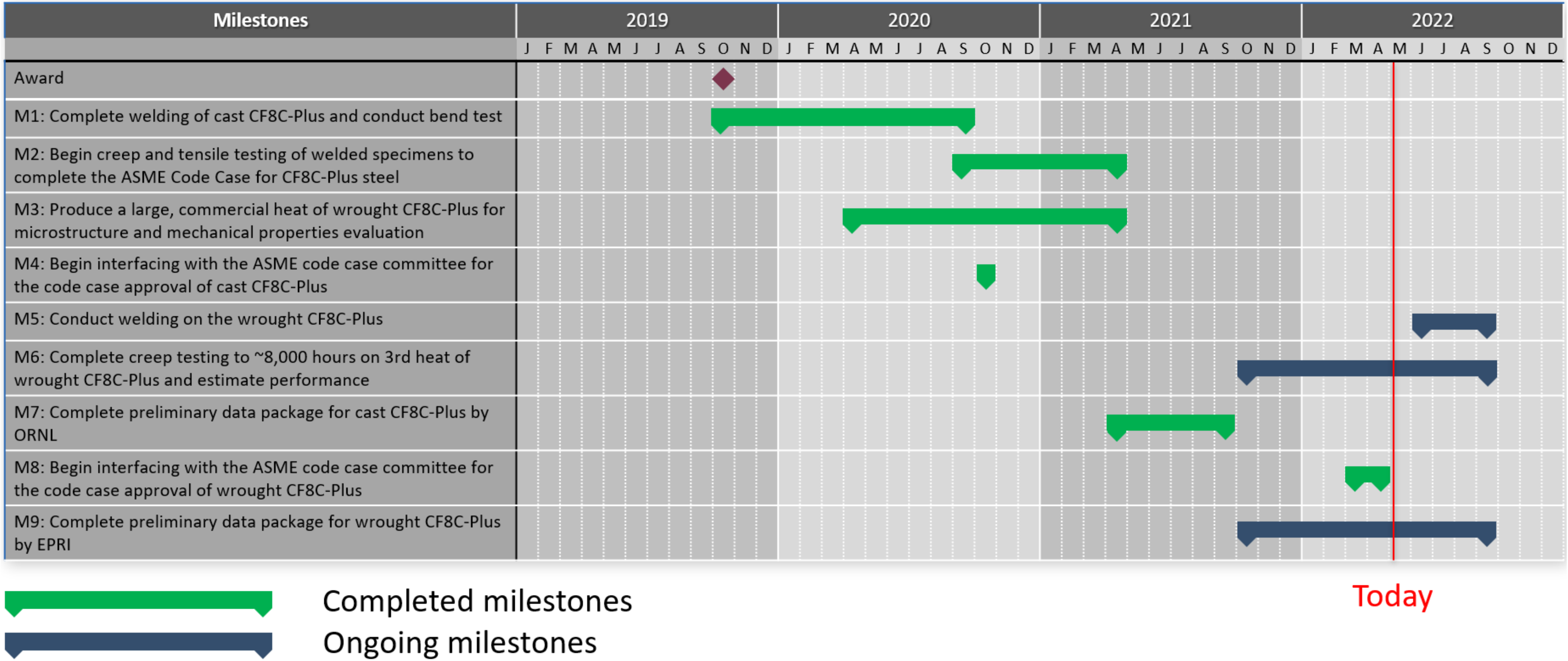
Objective: create cast (ORNL lead) and wrought (EPRI lead) CF8C-Plus data packages and pursue ASME code case approvals

- Major tasks:
  - Perform welding of cast CF8C-Plus and obtain tensile and creep data from the weld
  - Complete the ASME code case data package for the cast CF8C-Plus
  - Produce a 5th heat of wrought CF8C-Plus; evaluate the microstructure induced by processing and how it affects the creep rupture strength; conduct tensile, creep rupture, and welding necessary to support a code case data package

Caterpillar regeneration system housing exhaust component using CF8C-Plus, 550 tons cast made from 2006 - 2011

A 6,700 lbs gas-turbine end-cover component made with cast CF8C-Plus (Maziasz et al., J PRESS VESS-T ASME, 2009)

Milestone Status

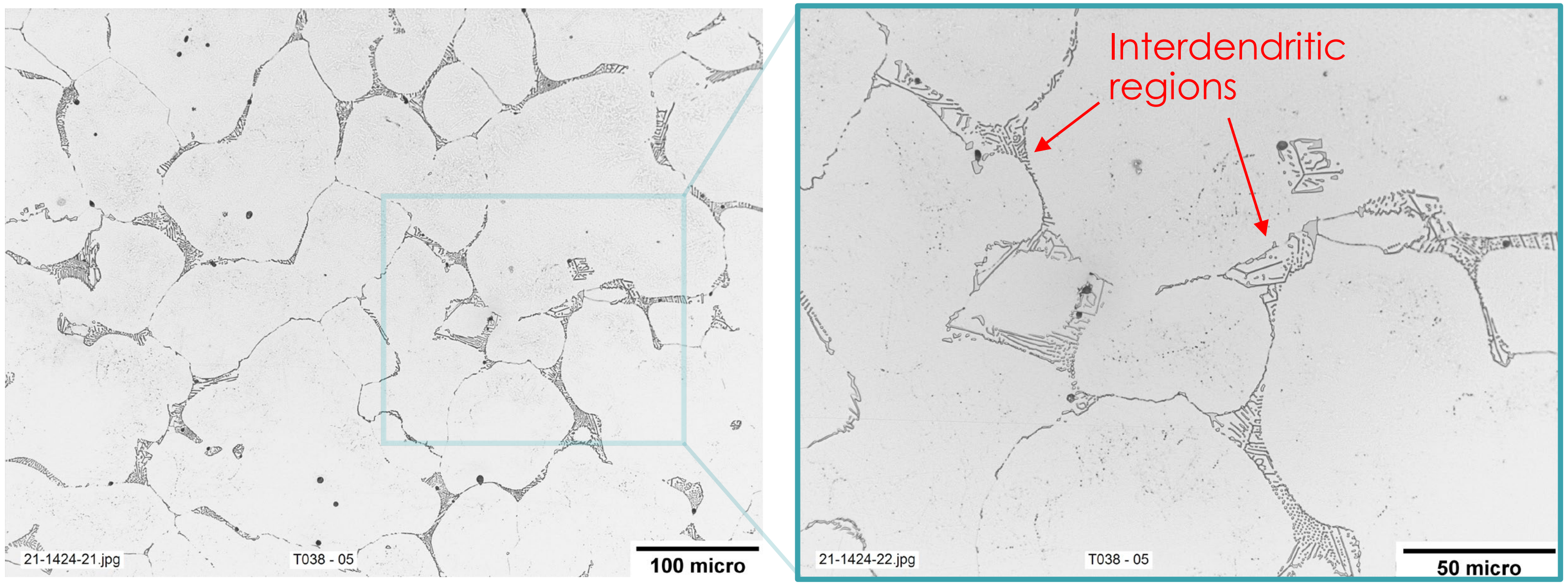


Cast CF8C-Plus Code Case Application*

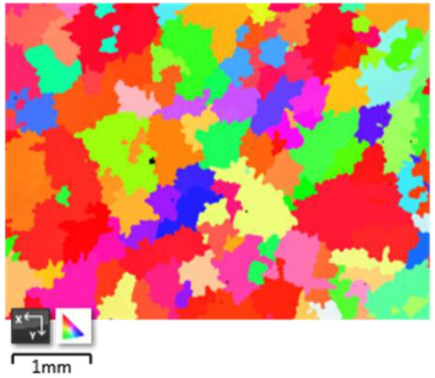
*95% of the code case data completed with funds from the American Recovery and Reinvestment Act

As-Cast Microstructure and Heat-to-Heat Variation

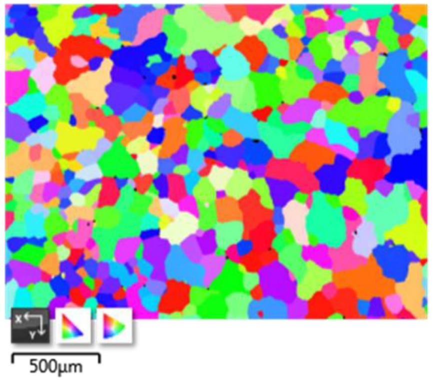
- Dendritic features and interdendritic regions are well defined
- Large heat-to-heat variation of grain sizes were observed without affecting the tensile and creep properties
- No ferromagnetic readings were found using a ferrite meter for all four heats used in ASME code case testing



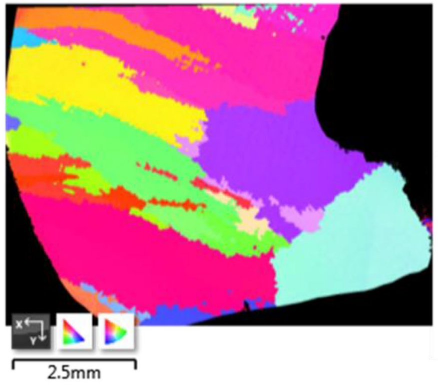
Optical metallography of cast CF8C-Plus, heat T038



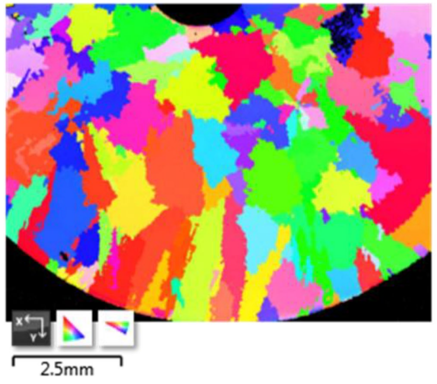
Heat 257R, GS: 525 μm



Heat T038, GS: 126 μm

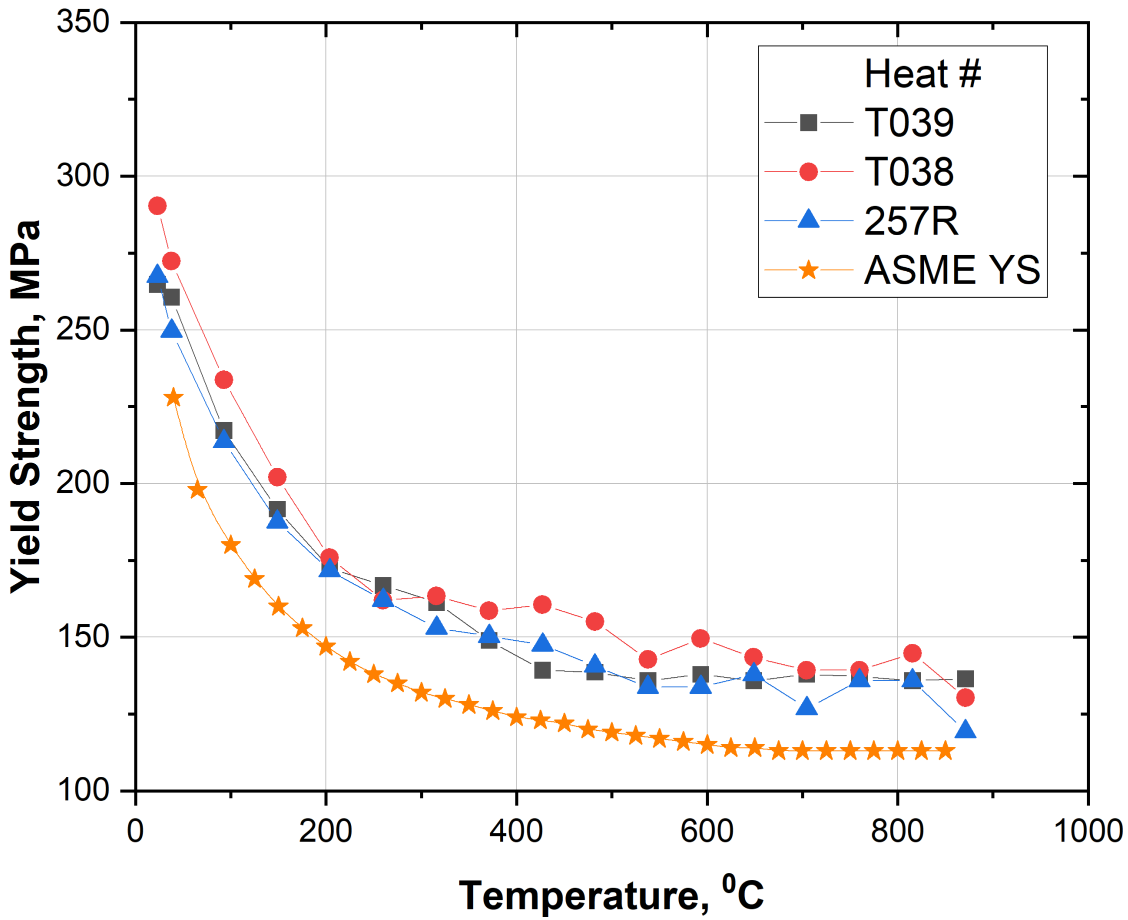


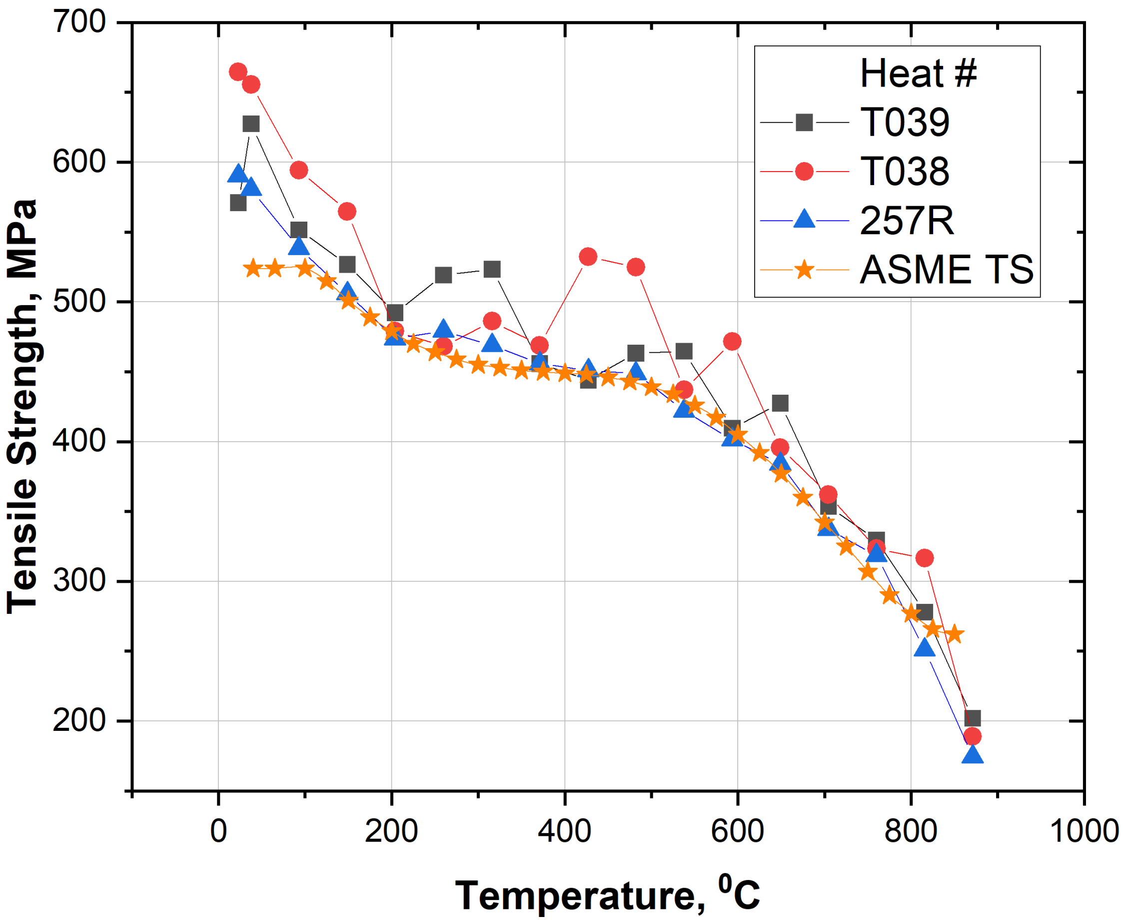
Heat T039, GS: 1,430 μm



Heat DA20, GS: 837 μm

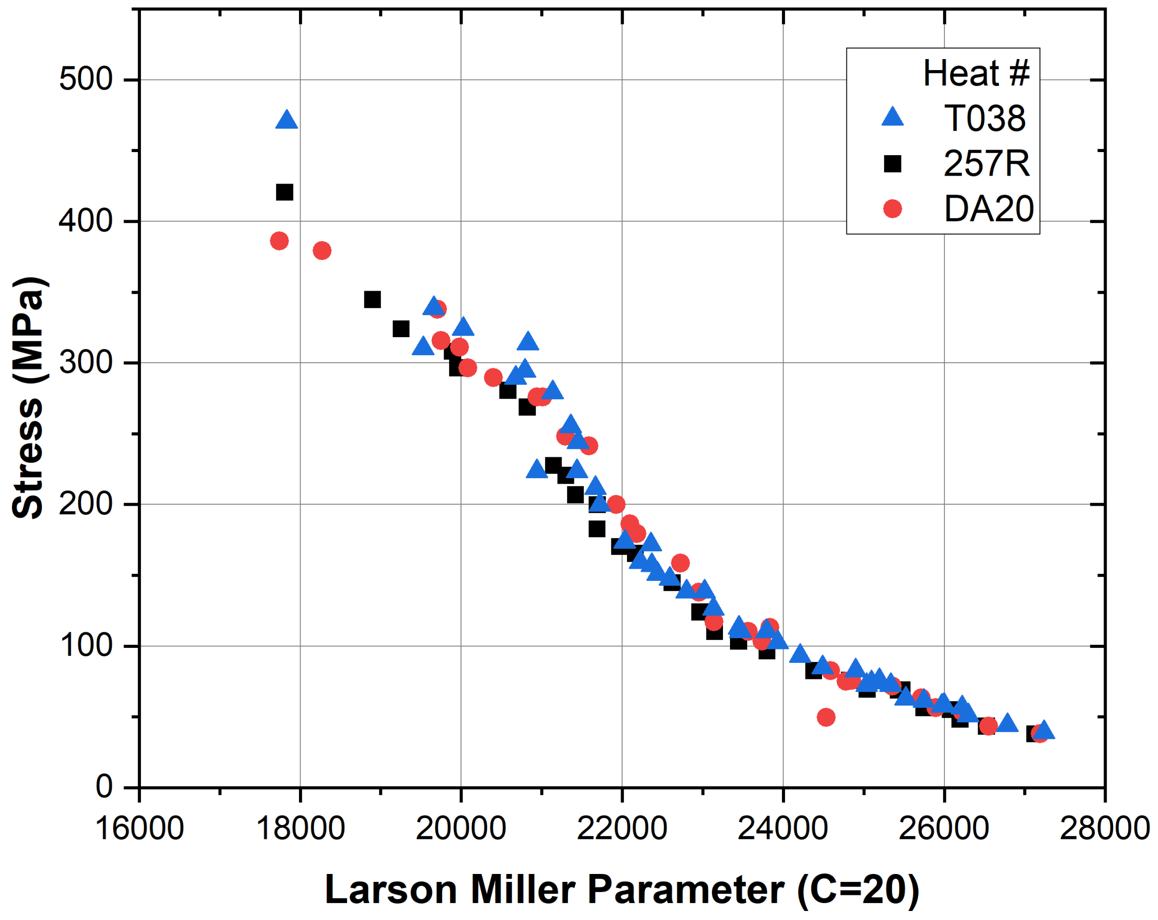
Yield and Tensile Strength Values

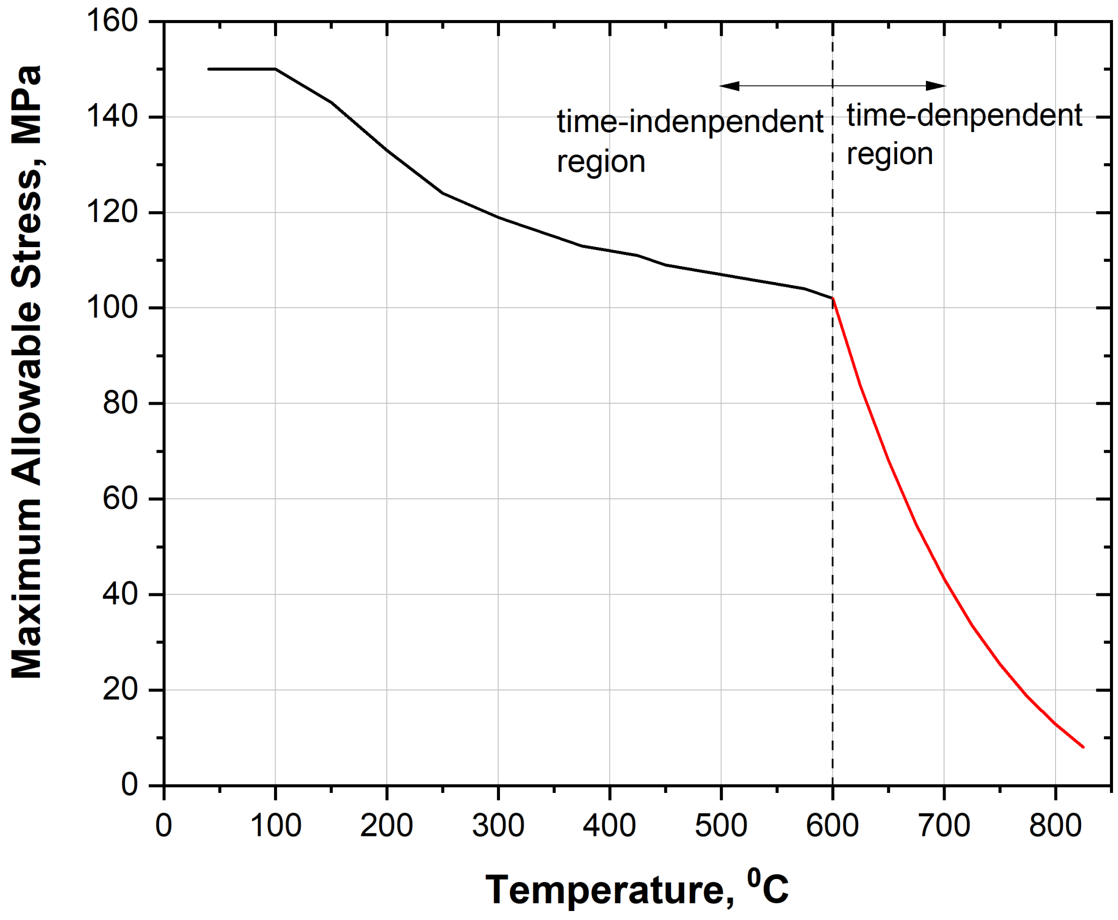




- 51 tensile tests have been performed from 22 to 871°C for three heats of materials
- ASME Sec. II Part D subpart 1 yield and tensile strength values have been determined

Maximum Allowable Stress Values



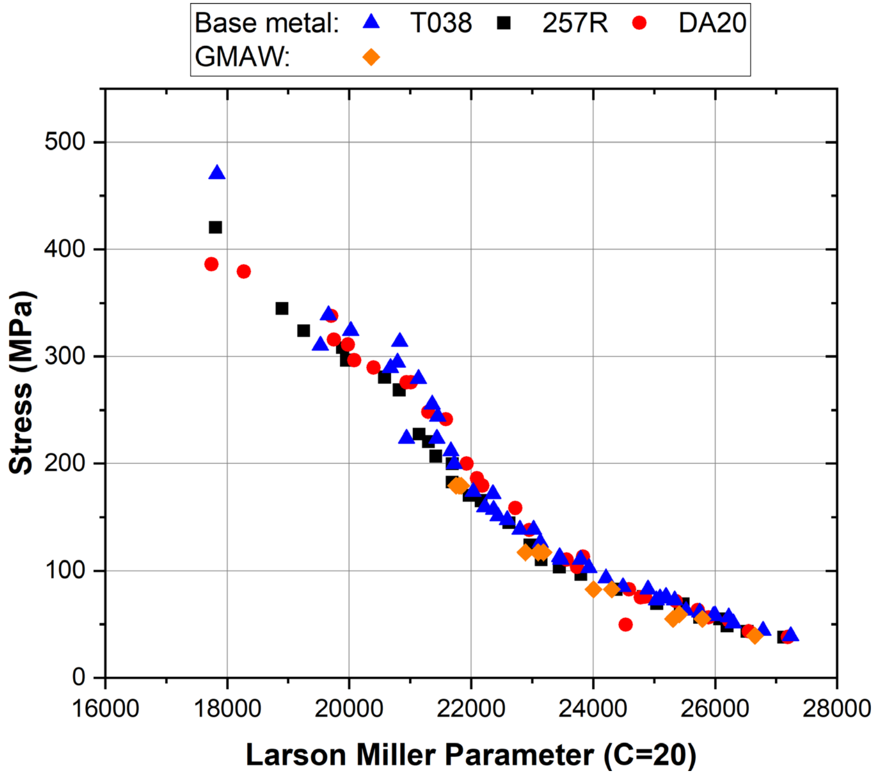


- 103 creep tests previously performed from 482 to 871°C for three heats of materials accumulating 457,403 hrs (**~52 yrs**) were used to calculate the ASME maximum allowable stress values

Weld Procedure Qualification and Creep Testing

- Two welding procedures have been qualified for cast CF8C-Plus
  1. Shield Metal Arc Welding (SMAW) with alloy 117 filler metal
  2. Gas Metal Arc Welding (GMAW) with alloy 617 filler metal
- Creep tests on GMAW showed similar Larson Miller Parameter (LMP) as the cast base metal (BM) indicating no weld strength reduction.
- Creep tests on SMAW are still ongoing

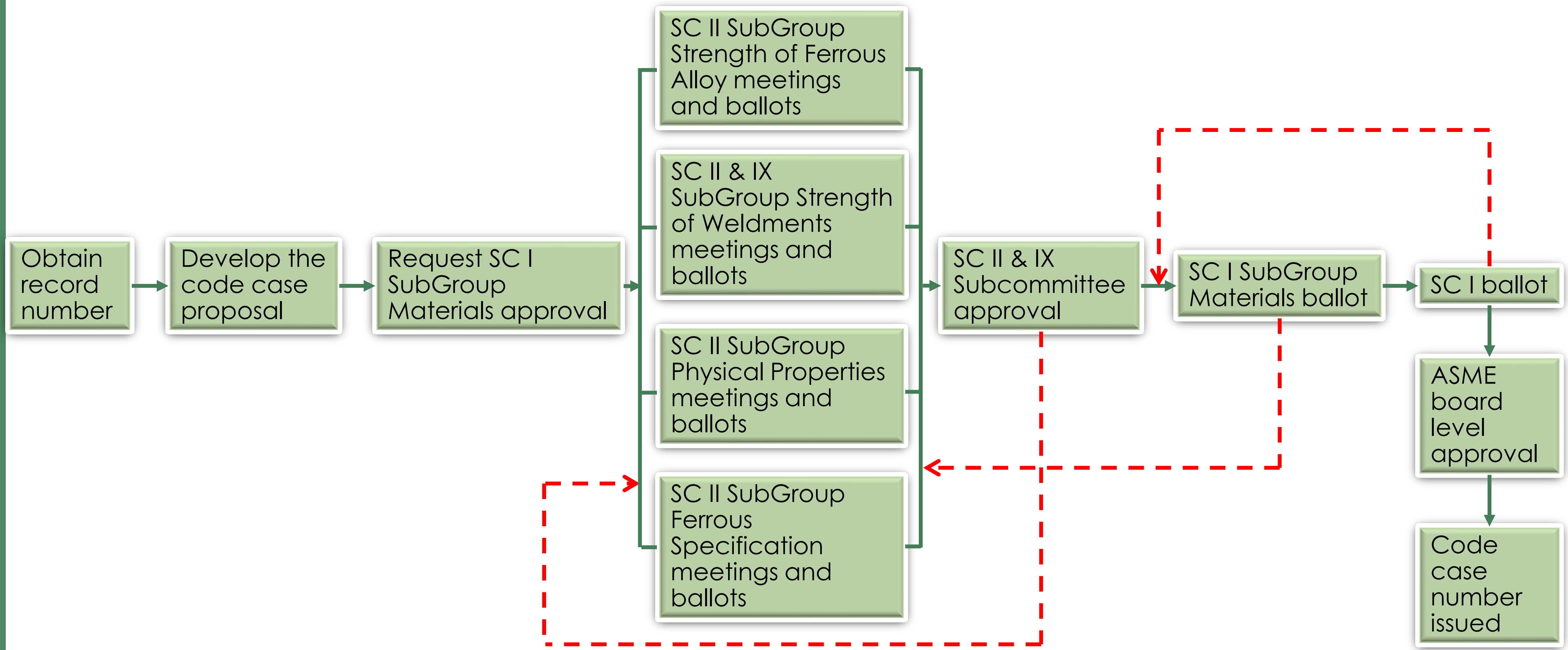
Weld tensile and guided bend tests



Comparison of LMP between BM and GMAW of cast CF8C-Plus

Code Case Application Process

- Code cases for cast CF8C-Plus have been pursued for ASME BPVC Sec I Power Boiler and ASME B31.1 Power Piping



ASME Section I code case application process for CF8C-Plus

Cast CF8C-Plus Code Case Status

- **ASME BPVC Sec I code case has been approved** with the final code case document undergoing editing by ASME editorial staff
- **ASME B31.1 code case** is balloting at the B31 standard committee level and expected to be approved in this FY
- Once the creep welding on cast CF8C-Plus SMAW is completed, the maximum allowable stress values in the code case for the weld will be re-evaluated
- Additional code case applications of the material are also being evaluated

SC I RN 20-978
(V8) 1/6/2022
In Response to LB 21-3328

Code Case xxx
ASTM A351/A351M-14 Grade HG10MnN (UNS J92604)
Section I

Inquiry: May austenitic stainless steel castings conforming to A351/A351M-14 Grade HG10MnN (UNS J92604) be used in welded and non-welded construction under Section I?

Reply: It is the opinion of the committee that austenitic stainless steel castings conforming to A351/A351M-18 Grade HG10MnN (UNS J92604) may be used in welded and non-welded construction under Section I, provided the following additional requirements are met:

a. The physical properties for UNS J92604 are found in ASME Section II Part D as follows:
  1) Thermal Expansion properties shall be taken from Group 3 austenitic stainless steel in Table TE-1;
  2) Thermal Conductivity and Thermal Diffusivity shall be taken from Material Group K in Table TCD;
  3) Elastic Moduli shall be taken from Material Group G in Table TM-1
  4) Poisson's Ratio and density values shall be the same as shown for 300-Series austenitic stainless steels in Table PRD

b. The maximum allowable stress values for the material shall be those given in Tables 1 and 1M. The maximum design temperature shall be 1500°F (816°C). A casting quality factor in accordance with PG-25 shall be applied to these allowable stresses.

c. The yield strength and tensile strength values for use in design shall be as shown in Tables 2 and 2M.

d. The chemical composition shall be as shown in Table 3.

e. The casting shall be inspected in accordance with the requirements of Supplementary Requirements S5 of A351/A351M-14 (Radiographic Inspection).

f. With respect to heat treatment, castings shall be used in the as-cast condition. After weld repair, post weld heat treatment is neither required nor prohibited.

g. Welding procedure and performance qualifications shall be conducted in accordance with Section IX. Separate welding procedure qualification is required for this material. For performance qualifications, this material shall be considered P-No. 8.

h. Weld repairs to castings shall be made with the following welding process and consumable:

Approved Sec I code case proposal

OAK RIDGE National Laboratory

CF8C-Plus Wrought Product Development

Dan Purdy, EPRI

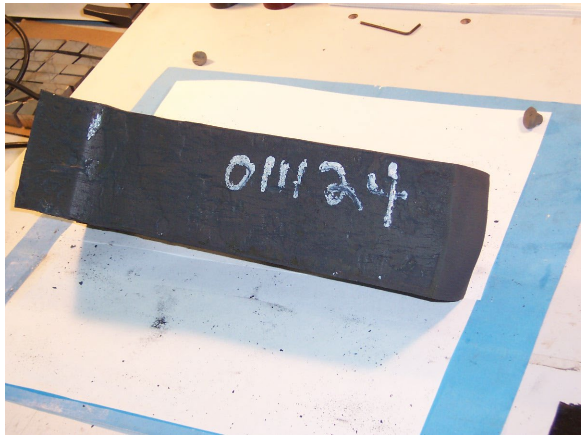
Wrought CF8C-Plus for Power Piping

- Power generation industry has interest in advanced austenitic stainless steels for boiler components
  - Qualified alloy options support economic, flexible, and high efficiency piping in all extreme environments: Gen IV Nuclear, advanced HRSGs, AUSC conditions, sCO_2 plants, concentrated solar, etc.
  - Alloys like: NF709, Super 304H, Sanicro 25, and now a derivative of CF8C-Plus
- EPRI is leading product development and commercial-scale demonstration of wrought/extruded CF8C-Plus alloy chemistry: alloy design, manufacturing, metallurgical and mechanical evaluation, and ASME approval
  - To-date, five heats have been produced and tested including forged, extruded, and powder metallurgy components
  - This project's scope of work is the largest commercial heat (12,600kg), ingot size (760mm Ø), and extrusion

Timeline of Previous EPRI Work on Wrought CF8C-Plus

2009

Carpenter produced
188 kg VIM heat
Open-die forged 5:1 and 12:1



2011

Special Metals produced
two 472 kg VIM heats
Extruded to pipes >130 mmØ

2016

Carpenter produced 4th 2800 kg
powder metallurgy heat
Wyman-Gordon extruded 400 mmØ pipe

2017

Detailed SEM and TEM
microscopy of precipitates
following mechanical testing

2020

This project with ORNL
kicks off to produce
5th heat and ASME code case

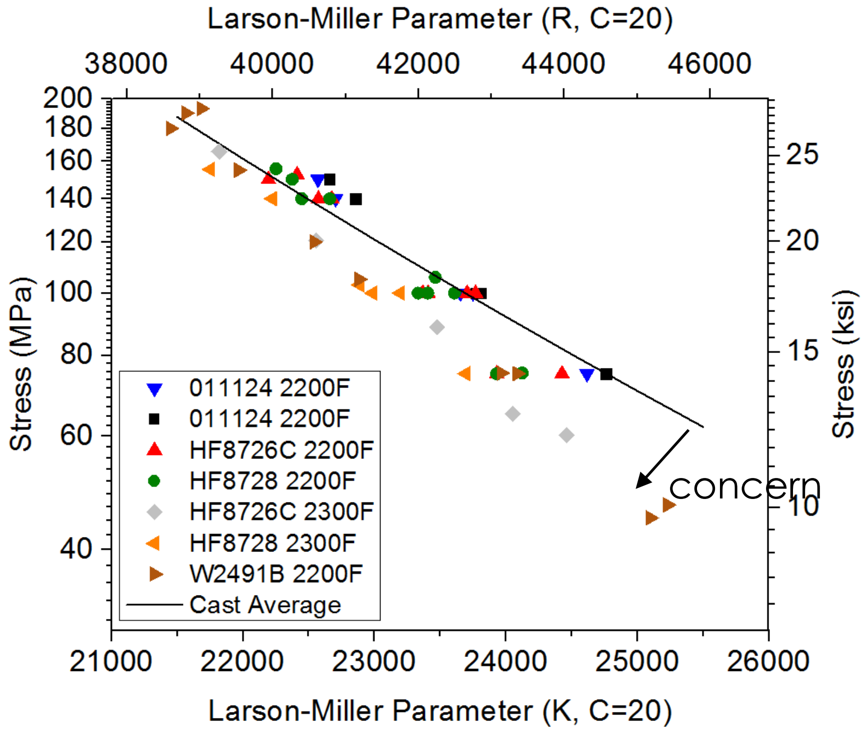
2021

Produced large ESR heat
using optimized chemistry
Process mapping and production

Manufacturing Studies of a High-Temperature Stainless Steel (2017)
EPRI Report 3002009212

Alloy Design and Chemistry Targets

- Characterization of early heats showed scatter in rupture life
  - Significant deviation from cast material in the powder metallurgy heat
- Led to more work to understand the impact of processing on microstructure
  - Detailed thermodynamic predictions looking at carbide/nitride stability
  - Quantified TEM/STEM work on precipitates from several heats
  - Optimized chemistry targets from cast formulation:



	Cr	Ni	Mn	Nb	C	N	Cu	W	Si
Cast	19.5	12.5	4.0	0.9	0.09	0.25	<0.3	<0.01	0.7
Wrought	20.0	13.0	4.0	0.7	0.07	0.25	<0.3	<0.01	0.7
PM-HIP	20.0	13.0	4.0	0.4	0.04	0.25	<0.3	<0.01	0.7

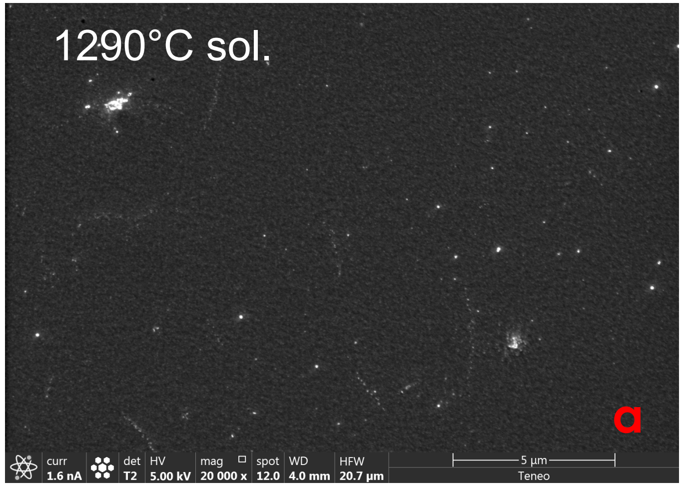
5th Heat: Ingot Production

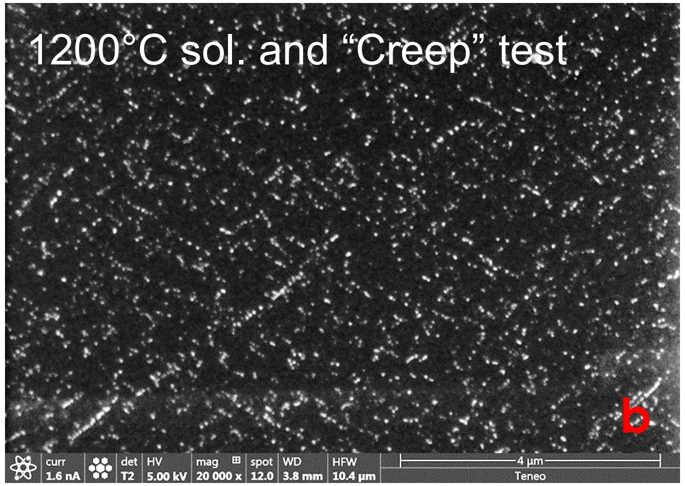
- Carpenter manufactured two 760-mm ingots, total weight of 12,600 kg
- Electric arc furnace + argon-oxygen decarburization melted initial total weight
- Poured into two molds for electro-slag remelting
- Ingots supplied in fully homogenized condition for further processing

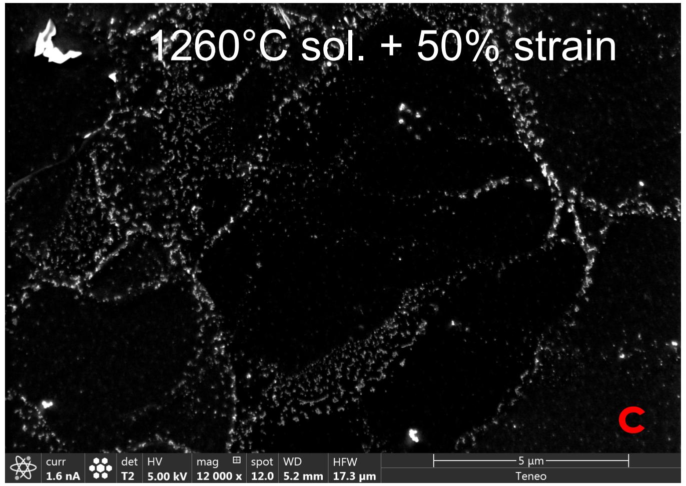
	Cr	Ni	Mn	Nb	C	N	Cu	W	Si
Min	19.5	12.5	3.7	0.6	0.05	0.23			0.5
Max	20.5	13.5	4.5	0.8	0.1	0.28	<0.3	<0.01	1
589832	19.9	12.8	4.0	0.7	0.08	0.26	0.05	0.02	0.9

Gleeble-based Study for Thermomechanical Properties

- Gleeble used for optimal solutionizing heat treatment and modeling high temperature extrusion
  - Effect of increased solutionizing temperature on NbC precipitates
  - Impact of high temperature deformation (50% stretch)
  - Elevated temperature iso-stress test (“mock-creep test”)
- Key microstructural parameters to monitor across these tests
  - All solutionizing (15 min) dissolved fine (<50 nm) NbC precipitates with no impact to larger precipitates
  - The mock-creep test showed precipitation of fine precipitates in all samples
    - No significant differences across samples with different solutionizing temperature
  - High temperature deformation appears to instigate nonuniform precipitation, or increases the driving force such that precipitation occurs on cool-down (<5 minutes)

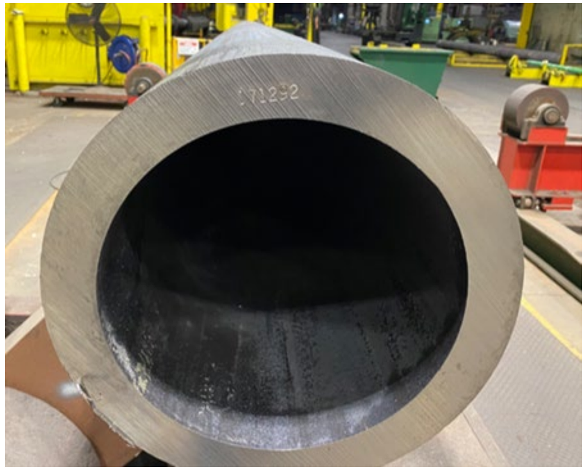






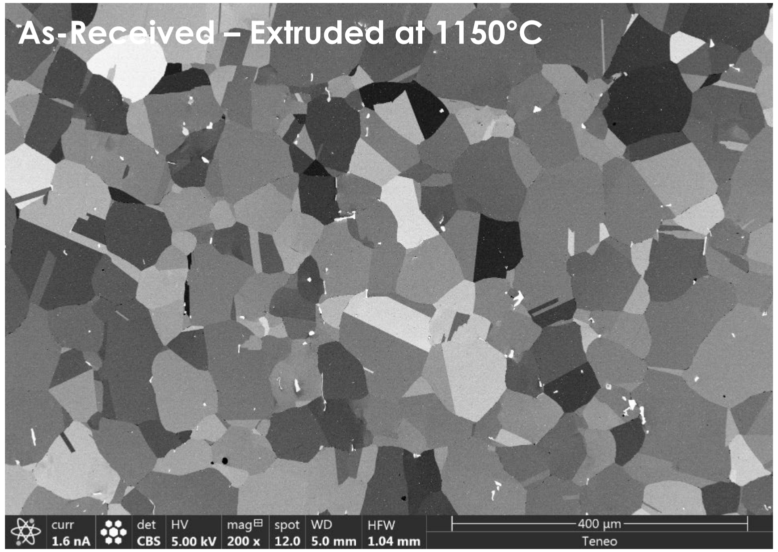
5th Heat: Extrusion

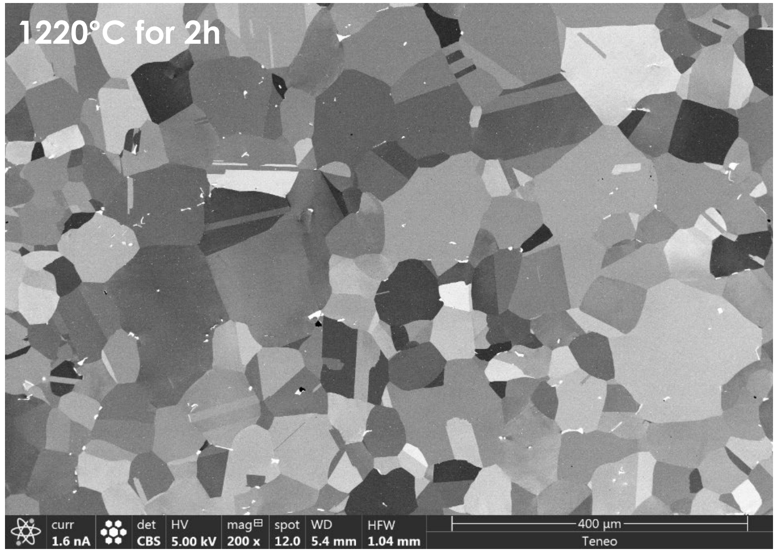
- 3,500 kg segment (900 mm length) of ESR ingot 589832-1A extruded by Wyman Gordon Pipes and Fittings
  - 400 mm OD x 44 mm wall thickness
- First ~1 m of extrusion provided to EPRI for heat treatment study
  - This material provided in as-extruded condition
  - Some tearing observed over this region of extrusion
  - Microstructural and creep rupture characterization will determine heat treatment instructions for remainder of the extrusion

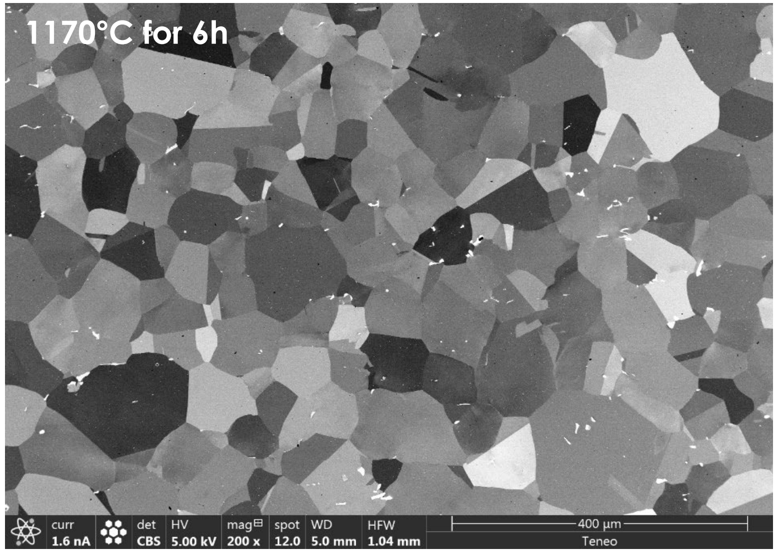


Present Work: Microstructure Evaluation and Heat Treatment Study

- Microstructure evaluated after several heat treatment conditions
  - Solution heat treating at 1220, 1170, and 1120°C (1170°C is practical limit for supply chain)
  - Condition examined in unaged and aged condition (750 ° C for 8 hours)
- Conclusion 1: Grain Size
  - As-extruded, the microstructure is completely recrystallized with a small degree of residual strain
  - Solution heat treatment has insignificant impact on grain size; grains are 50 to 100 μm (ASTM 4-5)







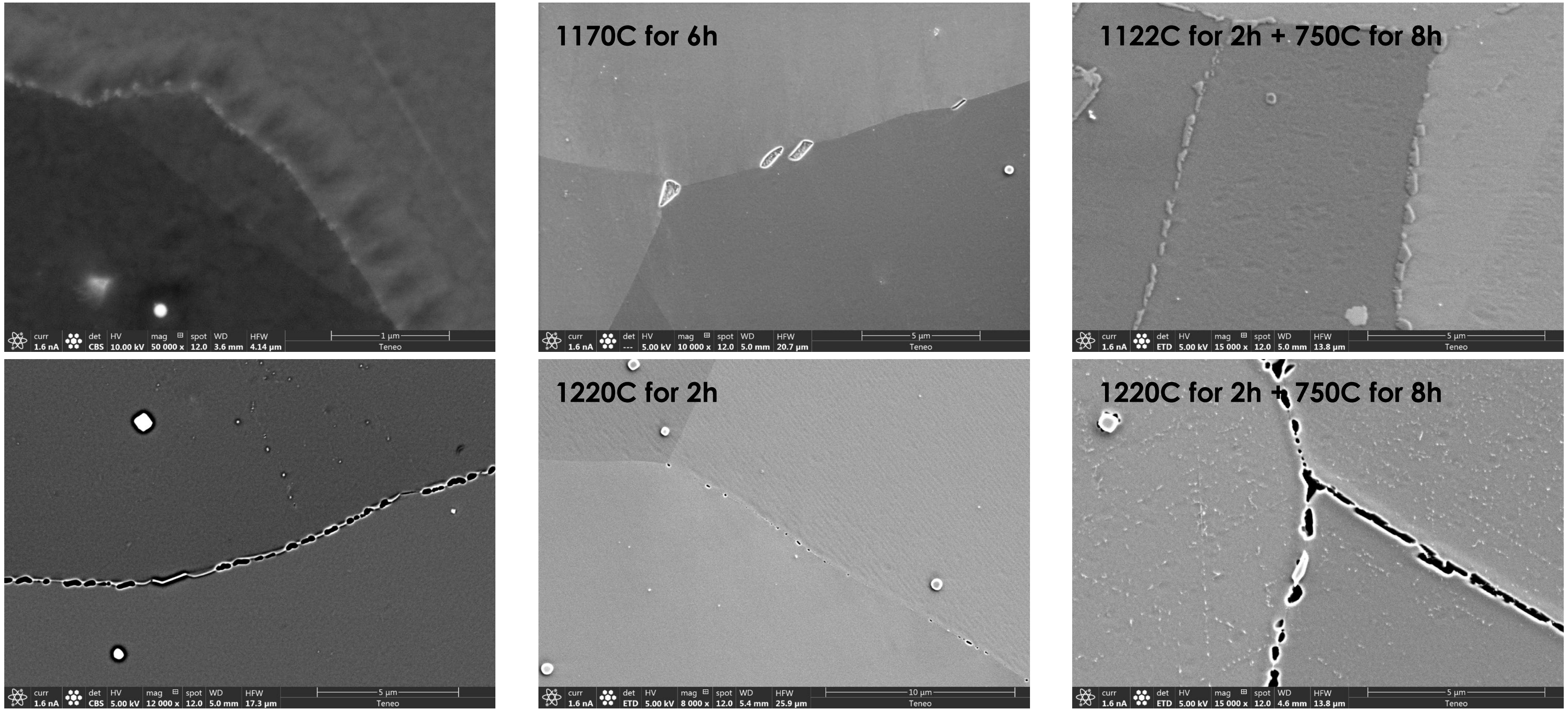
Present Work: Microstructure Evaluation and Heat Treatment Study

- Conclusion 2: Carbide Precipitation
  - Overall: oxalic etching reveals fine NbC at the detriment of grain-boundary precipitation ($M_{23}C_6$)
  - As-extruded: grain boundary $M_{23}C_6$ and fine NbC present; residual strain fields surround particles
  - Solutionized: blocky Nb-rich particles remain, suspect that intragranular sub-nano-scale NbC remain
  - Aged: significant discontinuous grain boundary $M_{23}C_6$ precipitation and fine intragranular NbC (5-10 nm)

As-extruded **Solutionized** **Solutionized+Aged**

Unetched

Etched, electrolytic oxalic



Next Steps for Further Evaluation

ID	Average (HV)	Solution Temp (C)	Solution Time (h)	Ageing Temp (C)	Ageing Time (h)
AR0	176	As-Received			
AR1	182	As-Received		750C	8
A1	177	1220	2		
A2	190	1220	2	750C	8
A3	183	1220	6		
A4	192	1220	6	750C	8
B0	175	1170	2	Air cool	
B1	184	1170	2		
B2	188	1170	2	750C	8
B3	185	1170	6		
C1	177	1120	2		
C2	193	1120	2	750C	8
C3	182	1120	6		
C4	191	1120	6	750C	8

- Hardness measured for heat treatment conditions
  - Average Solutionized: 181 HV
  - Average Aged Condition: 191 HV
- Full heat treatment matrix being tested for:
  - RT and elevated temperature tensile properties
  - Benchmark creep testing, limited moderate-time testing for now
  - Hardness evolution over time
- Mechanical evaluation of HT matrix informs quality heat treatment of remaining extruded pipe (~6 m length)
  - Production-scale heat treated component to receive more extensive testing as part of ASME BPVC code case data package

Conclusions

- Cast CF8C-Plus Code Case
  - As-cast CF8C-Plus exhibited dendritic features and interdendritic regions with large heat-to-heat variation of grain size
  - Tensile, creep, and weld qualification tests have been performed to support ASME code case application
  - ASME BPVC Sec I code case has been approved and ASME B31.1 code case is balloting at the B31 standard committee level
- Extruded Pipe and Wrought CF8C-Plus Code Case
  - Manufacturing of extruded pipe 400 mm OD x 44 mm wall thickness complete
    - Both ingot processing and mechanical extrusion show the alloy is manufacturable
  - Heat treatment optimization testing underway
    - Solutionizing is relatively insensitive and robust
  - ASME BPVC code case data package under development, supplemented by 5th heat in 2022/23