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

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2023 FECM / NETL Spring R&D Project Review Meeting
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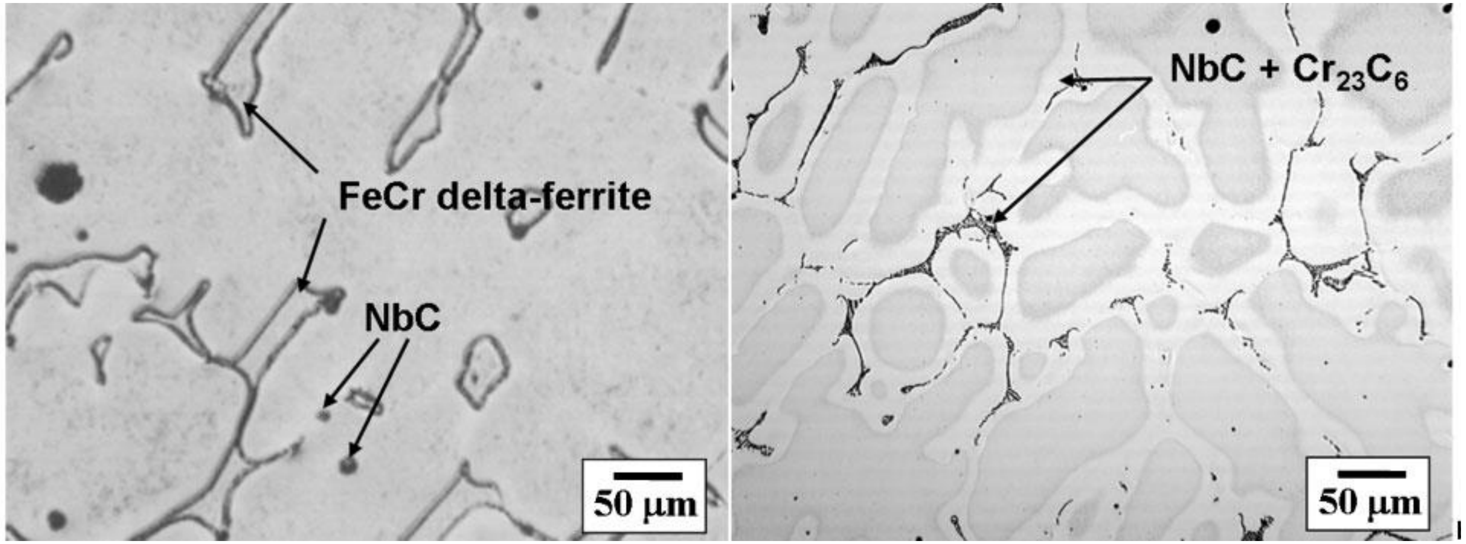
Pittsburgh, PA

Background (1/3)

- **<u>CF8C-Plus</u>** 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)

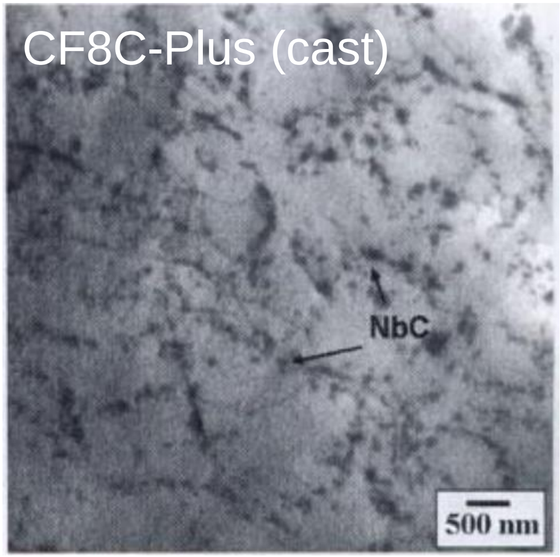
Composition (wt%)

	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)

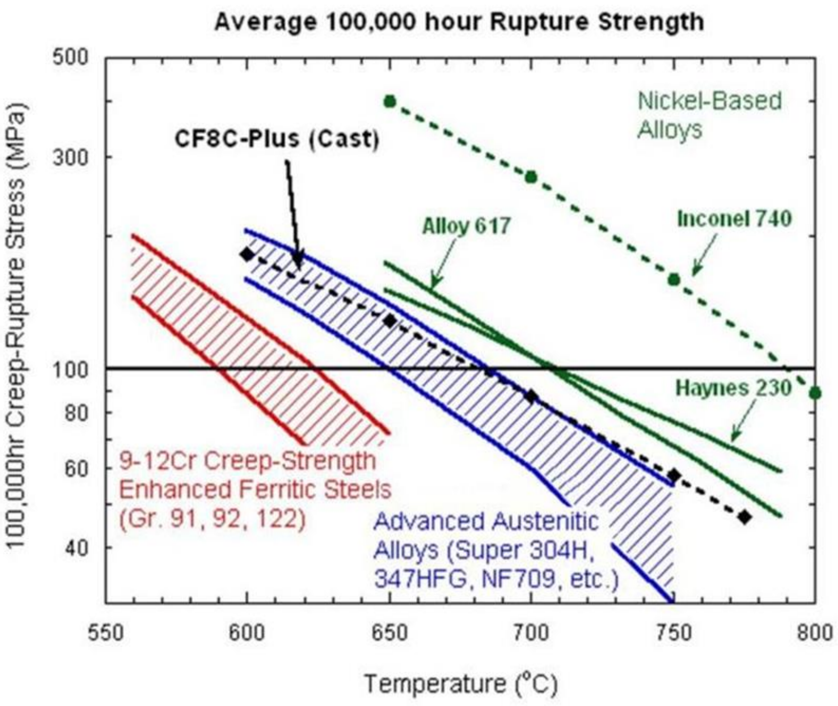
Shingledecker et al., Energy Materials 2006



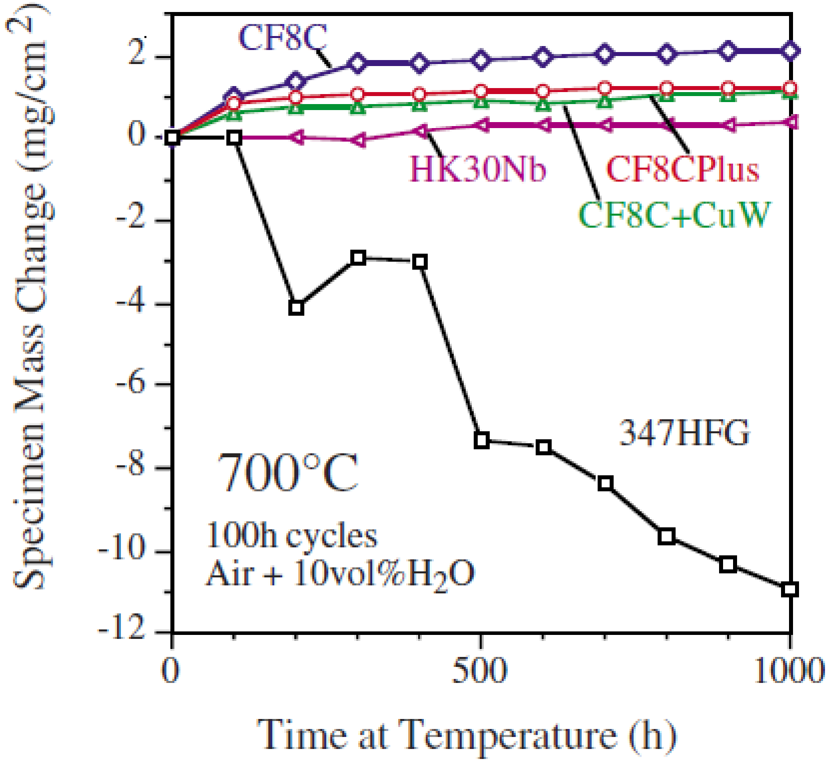
Nanoscale NbC precipitates in CF8C-Plus (courtesy of EPRI)

Background (2/3)

- CF8C-Plus shows unique combination of **high temperature strength, corrosion resistance, castability, and weldability**
- Moreover, the strength advantages and weldability 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)



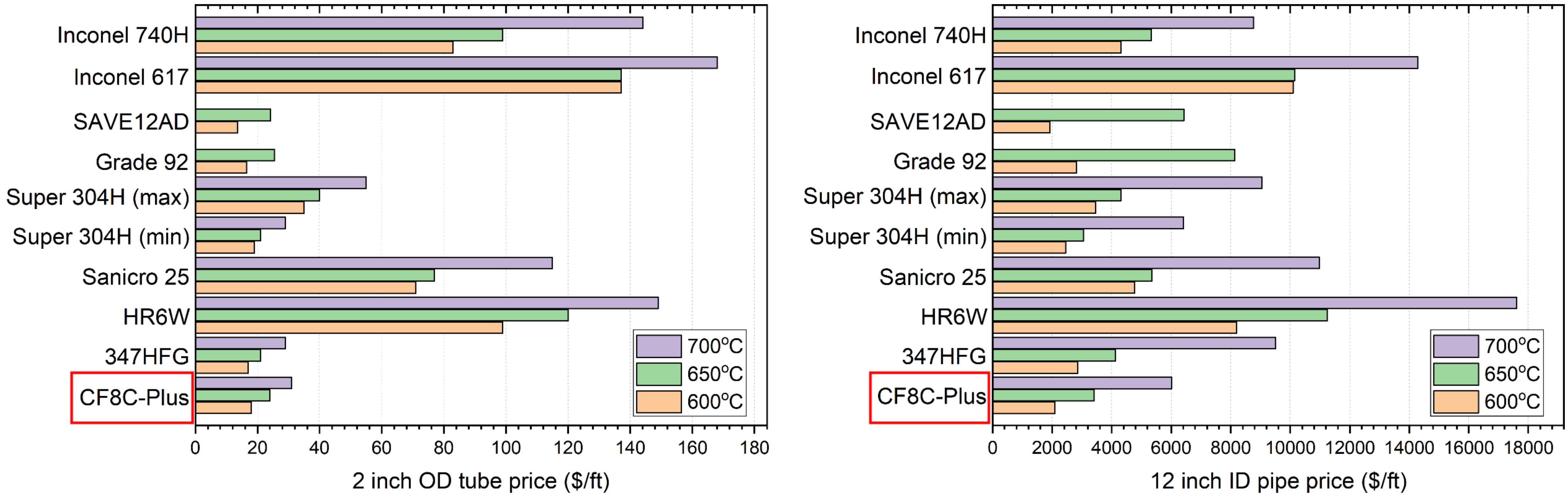
CF8C-Plus shows better corrosion resistance in 700°C humid air than 347HFG

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 A-USC candidate materials for the temperature range of 600-700°C

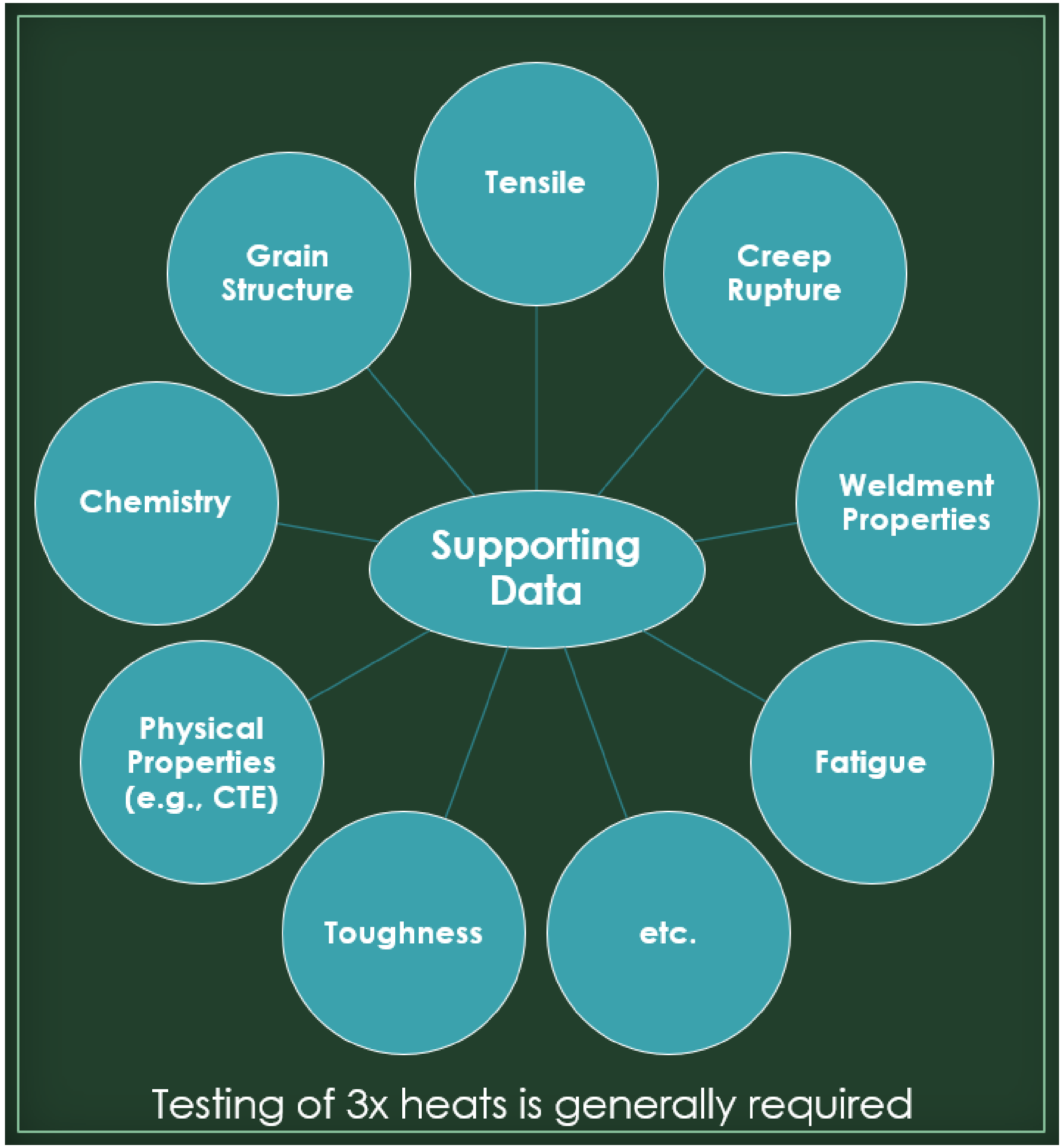


Material price per foot to withstand 24MPa steam pressure between 600 and 700°C

X. Chen, E. Lara-Curzio, ORNL/TM-2021/1943

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

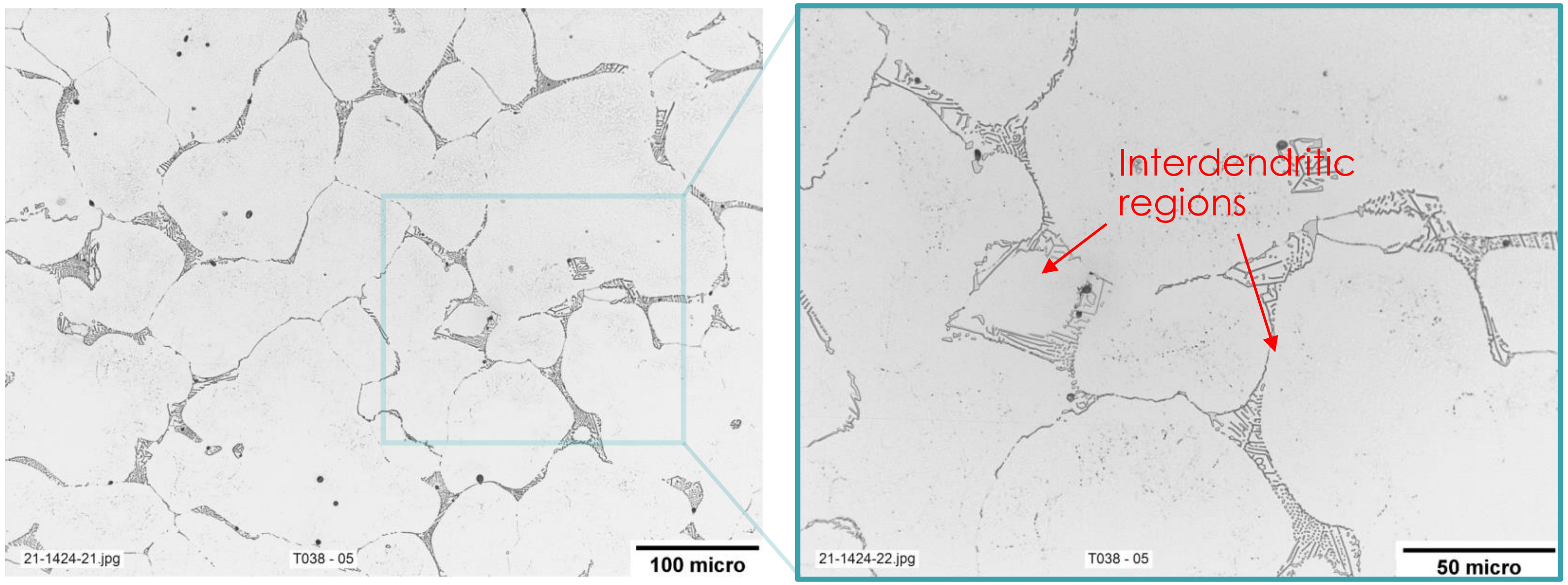
- ASME Code Case for New Materials – General Process
  - Inquirer submits request to ASME
  - Application contains:
    - Intended ASME Section(s) / Division(s)
    - Intended service: temperature limits, cyclic vs static, …
    - Product forms, size ranges, specification…
    - Chemistry limits
    - Heat treatment / microstructure
    - **Supporting data**
  - Data requirements vary case-by-case
    - Dependent on design rules and type of material



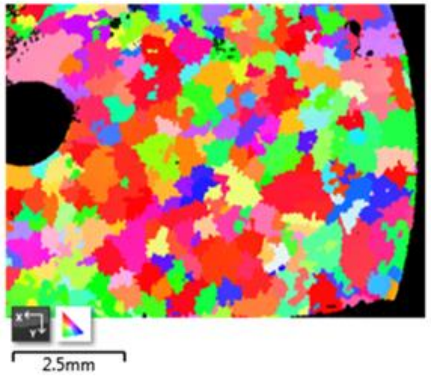
Cast CF8C-Plus ASME Code Case Application

As-Cast Microstructure and Heat-to-Heat Variation

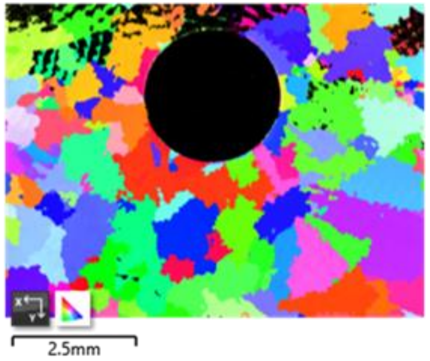
- Dendritic features and interdendritic regions are well defined
- **Heat-to-heat variation of grain sizes were observed**
- No ferromagnetic readings were found using a ferrite meter for all heats
- Small percentage of porosity (0.09-0.15%) with pore diameter ~2-3 μm was observed



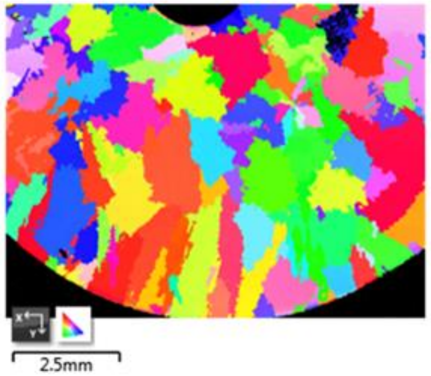
Optical metallography of cast CF8C-Plus, heat T038



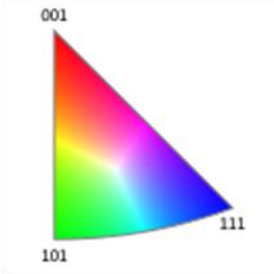
Heat 257R, GS: 481 μm



Heat T038, GS: 591 μm

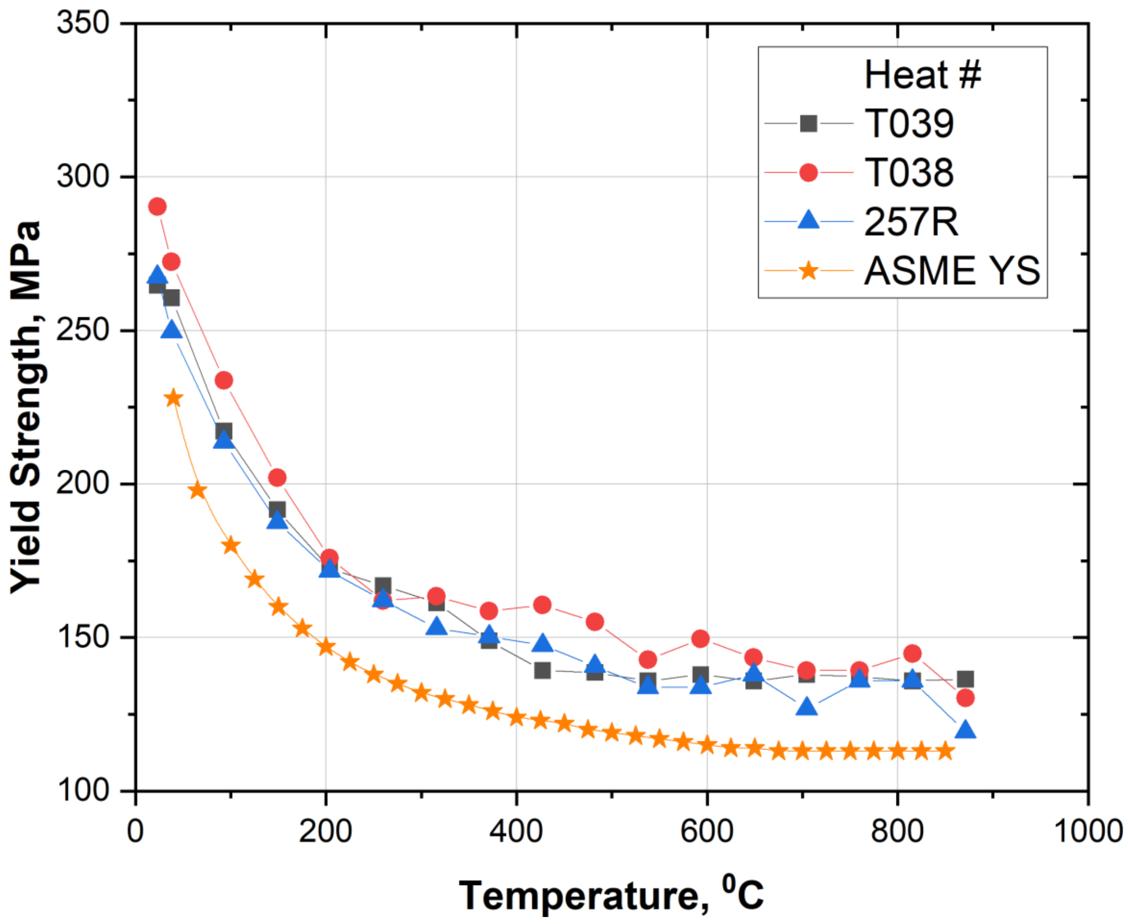


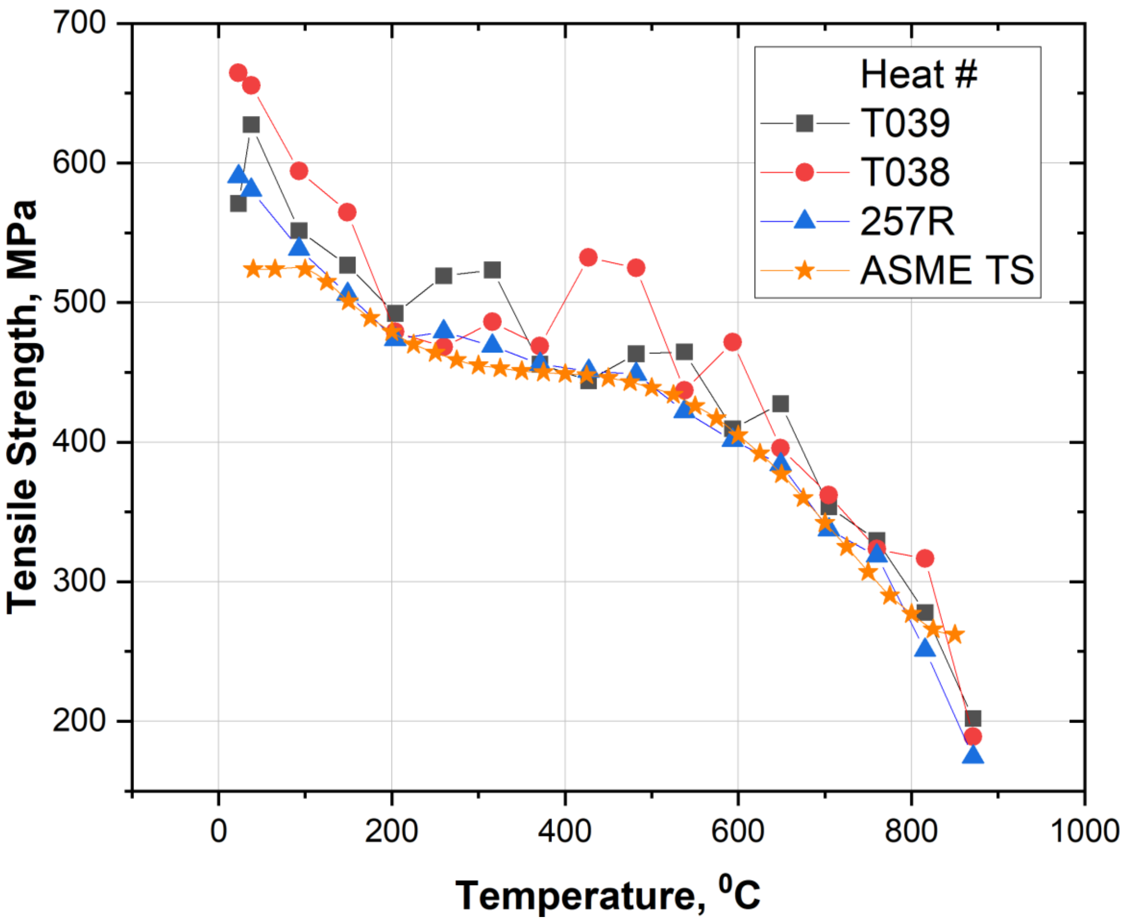
Heat DA20, GS: 746 μm



Yield and Tensile Strength Values

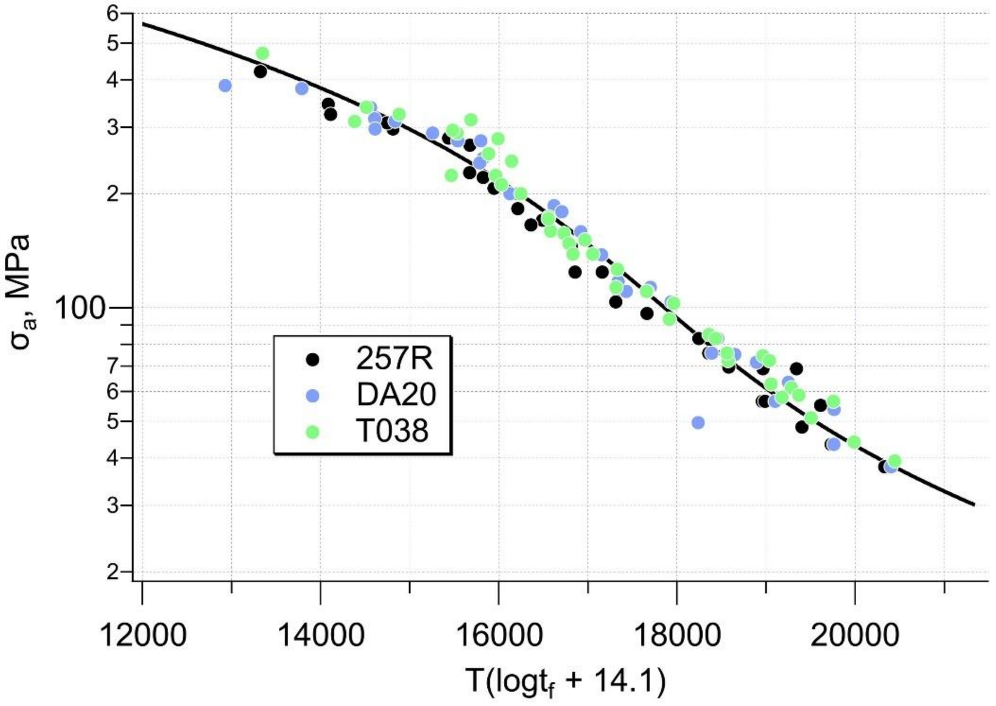
- 51 tensile tests have been performed from 22 to 871°C for three heats of materials
- **<u>ASME Sec. II Part D subpart 1 yield and tensile strength</u>** values have been determined



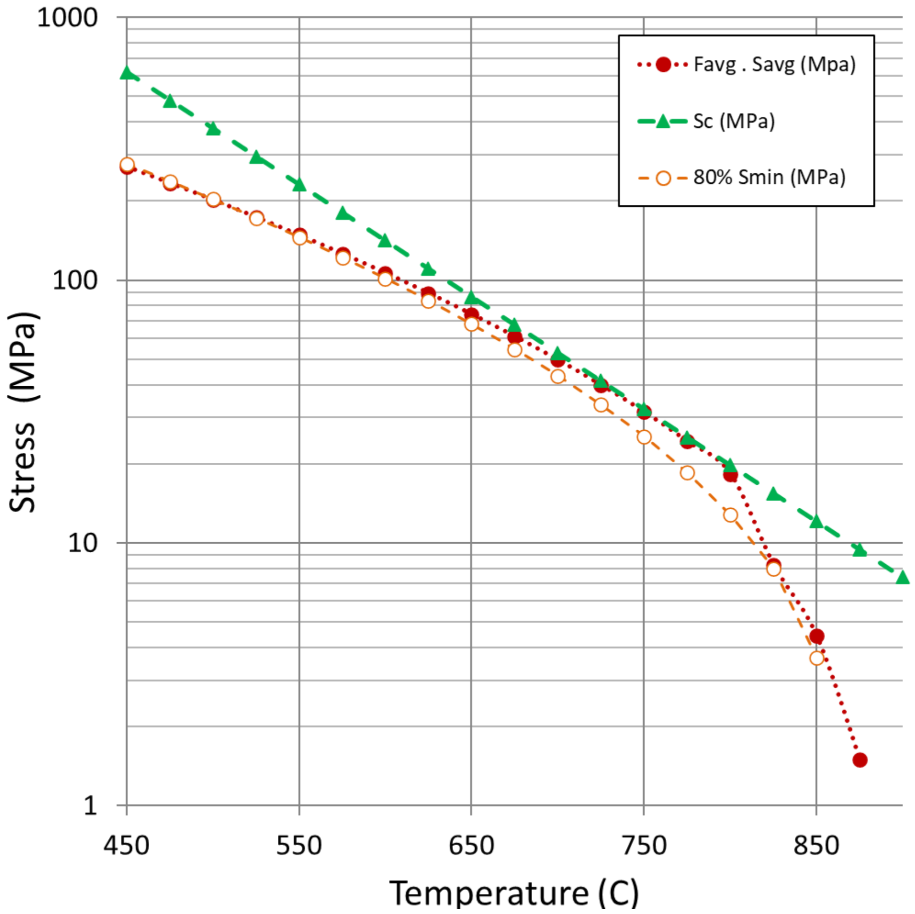


Creep Rupture Life

- 103 creep tests performed from 482 to 871°C for three heats of materials accumulating 457,403 hrs (**~52 yrs**)
- **<u>The maximum allowable stress in creep-domain</u>** have been determined



Larson Miller Parameter as a function of stress



Maximum allowable stress based on creep results

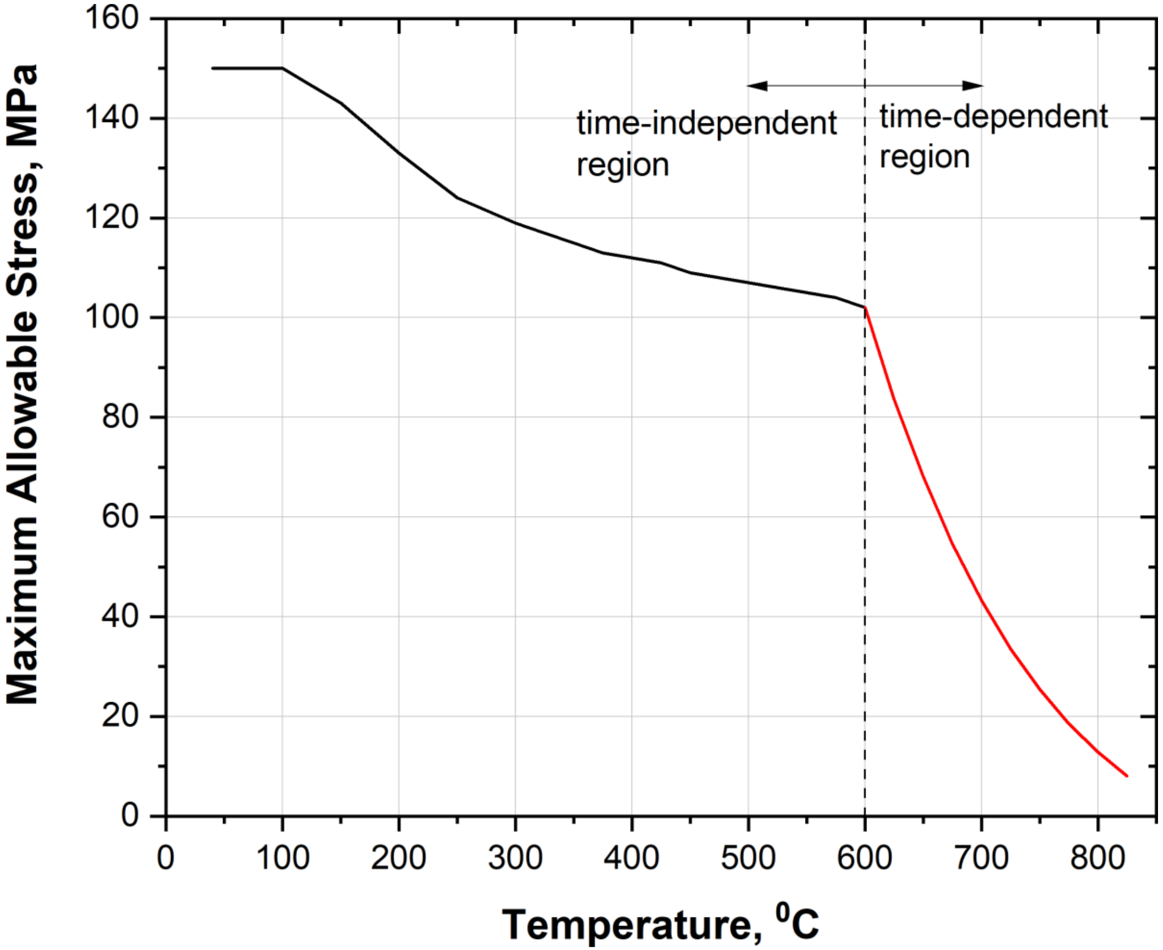
F_{avg} x S_{avg}= multiplier x average stress to cause rupture at the end of 100,000 hr

S_c= average stress to produce a creep rate of 0.01%/1,000 hr

80% S_{min} = 80% of the minimum stress to cause rupture at the end of 100,000 hr

ASME Sec. II Part D Subpart 1 Maximum Allowable Stresses

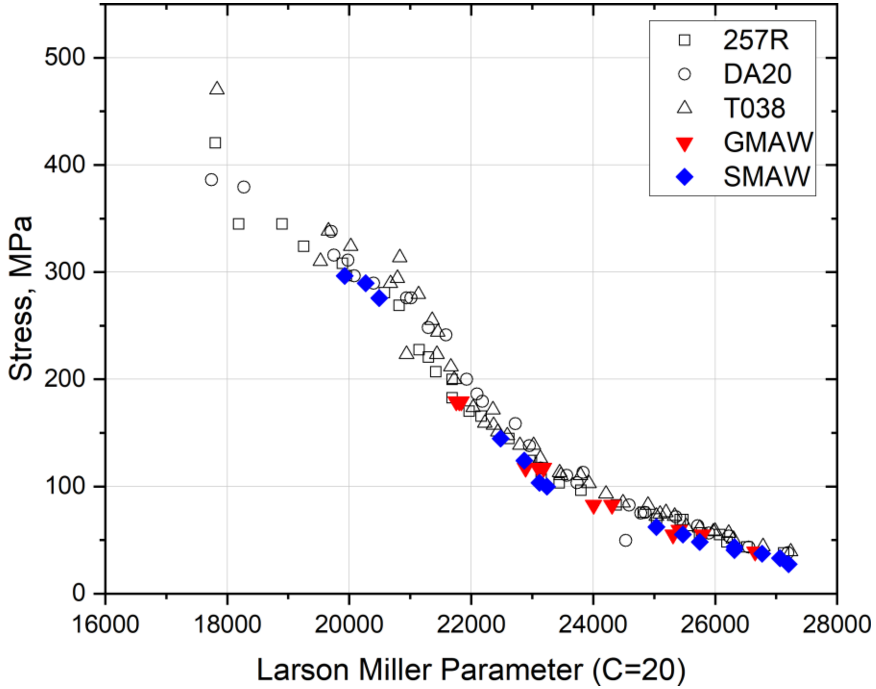
- **Time-independent** region governed by tensile properties – lowest of
  - the specified minimum tensile strength at room temperature divided by 3.5
  - the tensile strength at temperature divided by 3.5
  - two-thirds of the specified minimum yield strength at room temperature
  - two-thirds of the yield strength at temperature
- **Time-dependent** region governed by creep properties – lowest of
  - $F_{avg} \times S_{avg}$
  - S_c
  - 80% S_{min}



Weld Procedure Qualification and Weld Creep Testing

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

Weld tensile and guided bend tests



Comparison of LMP between BM and weld

Cast CF8C-Plus Code Case Status

- **ASME BPVC Sec I code case #3049 approved for use in power boilers**
- **ASME B31.1 code case #199-1 approved for use in power piping**
- Both code cases are going through a revision to further increase maximum allowable stress

ASME BPVC.CC.BPV.S6-2021

CASE
3049

Approval Date: May 4, 2022

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case 3049
ASTM A351/A351M-14 Grade HG10MnN (UNS J92604)
Section I

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

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

(a) The physical properties for UNS J92604 are found in 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 1,500°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 Requirement S5 of ASTM A351/A351M-14 (radiographic inspection).

(f) With respect to heat treatment, castings shall be used in the as-cast condition. After weld repair, postweld 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 consumables:

(1) Welding process – SMAW

(-a) Specification SFA-5.11/SFA-5.11M

(-b) AWS Classification ENiCrCoMo-1

(-c) UNS Number W86117

(2) Welding process – GMAW and GTAW

(-a) Specification SFA-5.14/SFA-5.14M

(-b) AWS Classification ERNiCrCoMo-1

(-c) UNS Number N06617

(i) Weld repairs to castings as part of materials manufacture shall be made following welding procedures and by welders qualified in accordance with Section IX. All weld repairs shall be recorded with respect to their location on the casting. Supplementary Requirement S12 of SA-703 shall apply. For weld repairs performed as part of materials manufacture, the documentation shall be included with the Materials Test Report. For weld repairs performed by the Manufacturer, documentation shall be included with the Manufacturer's Data Report.

(j) A manufacturer's test report meeting certification requirements of SA-703 shall be provided.

(k) This Case number shall be shown in the material certification and marking of the material.

(l) This Case number shall be shown on the Manufacturer's Data Report.

CAUTION: Austenitic alloys are subject to stress corrosion cracking, intergranular attack, pitting, and crevice corrosion when used in boiler applications in aqueous environments. Factors that affect the susceptibility of these materials are applied or residual stress, water chemistry and deposition of solids, and material condition. Susceptibility to attack is enhanced when the material is used in a sensitized condition or with residual cold work. Concentration of corrosive agents (e.g., chlorides, caustic, or reduced sulfur species) can occur under deposits formed on the surface of these materials and can result in severe underdeposit wastage or cracking. For successful operation in water environments, careful attention must be paid to continuous control of water chemistry.

This material may be expected to develop embrittlement after exposure at moderately elevated temperatures.

See Section II, Part D, Nonmandatory Appendix A, A-207 and A-208.

B31 Case 199-1
Approval Date: June 6, 2022
ASTM A351 Grade HG10MnN, UNS J92604
ASME B31.1

Inquiry: May austenitic stainless steel castings conforming to ASTM A351 Grade HG10MnN (UNS J92604) be used in welded and non-welded construction under ASME B31.1?

Reply: In the opinion of the committee, yes, provided the following additional requirements to the published ASME B31.1 Code book are met:

a) The physical properties for UNS J92604 are found in ASME BPVC or ASME B31.1 as follows:
   1. Thermal Expansion properties shall be taken from austenitic stainless steels in ASME B31.1 Table B-1;
   2. Thermal Conductivity and Thermal Diffusivity shall be taken from Material Group K in Table TCD of ASME Section II Part D;
   3. Elastic Moduli shall be taken from austenitic stainless steels in ASME B31.1 Table C-1;
   4. Poisson's Ratio and Density Values shall be the same as shown for high alloy steels (300-Series) in Table PRD of ASME Section II Part D.

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 paragraph 102.4.6 shall be applied to these allowable stresses.

c. The casting shall be inspected in accordance with the requirements of Supplementary Requirements S5 of ASTM A351 (Radiographic Inspection).

d. The casting shall not require any additional heat treatment.

e. Separate welding procedure qualifications conducted in accordance with ASME Section IX shall be required for this material. For the purposes of performance qualification, the material shall be considered P-No.8 material.

f. Weld repairs to castings or cast pipe shall be made with the following welding process and consumable:
   1) Welding Process – SMAW
      a. Specification - A5.11/A5.11M
      b. AWS Classification - ENiCrCoMo-1
      c. UNS Number - W86117
   2) Welding Process – GMAW and GTAW
      a. Specification - A5.14/A5.14M
      b. AWS Classification – ERNiCrCoMo-1
      c. UNS Number – N06617

g. Weld repairs to castings as part of materials manufacture shall be made following welding procedures and welders qualified in accordance with ASME Section IX.

h. All weld repairs shall be recorded with respect to their location on the casting. Supplementary Requirement S12 of ASTM A703 shall apply. For weld repairs performed as part of materials manufacture, the documentation shall be included with the Materials Test Report. For weld repairs performed by the Manufacturer, documentation shall be included with the Manufacturer's Data Report.

i. Postweld heat treatment is neither required nor prohibited

j. A manufacturer's test report meeting certification requirements of ASTM A703 shall be provided.

k. This Case number shall be shown in the material certification and marking of the material.

l. This Case number shall be shown on the Manufacturer's Data Report.

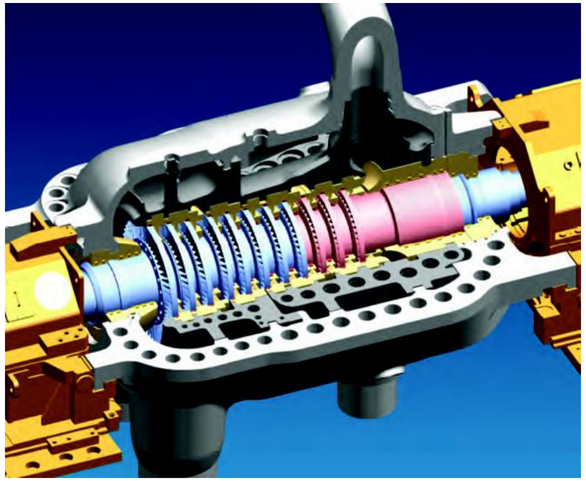
Code case 3049 (left) and code case 199-1 (right)

Oak Ridge National Laboratory

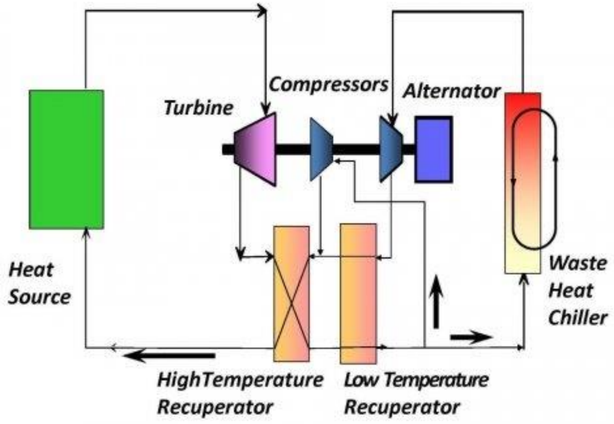
Wrought CF8C-Plus Development and ASME Code Case Application

Wrought CF8C-Plus for Power Piping

- Power generation industry has interest in advanced austenitic stainless steels for boiler components
  - Qualified alloys support economic, flexible, and high efficiency piping in all extreme environments

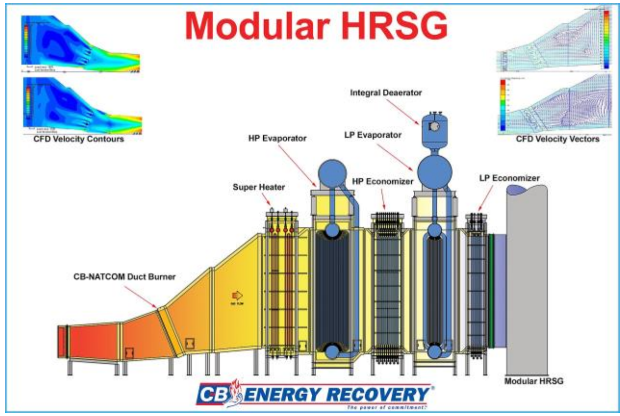


A-USC



sCO2 plants

concentrated solar

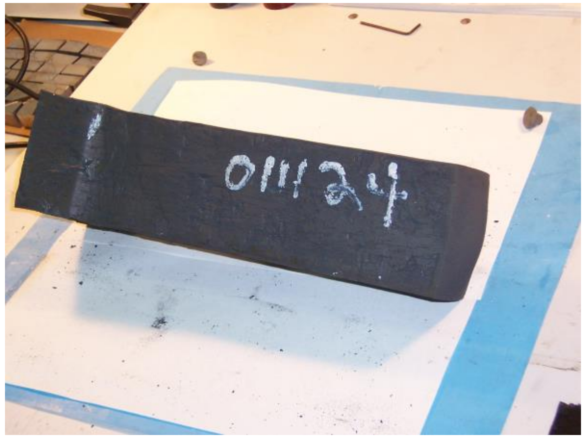


advanced HRSGs

  - Candidate alloys: 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

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

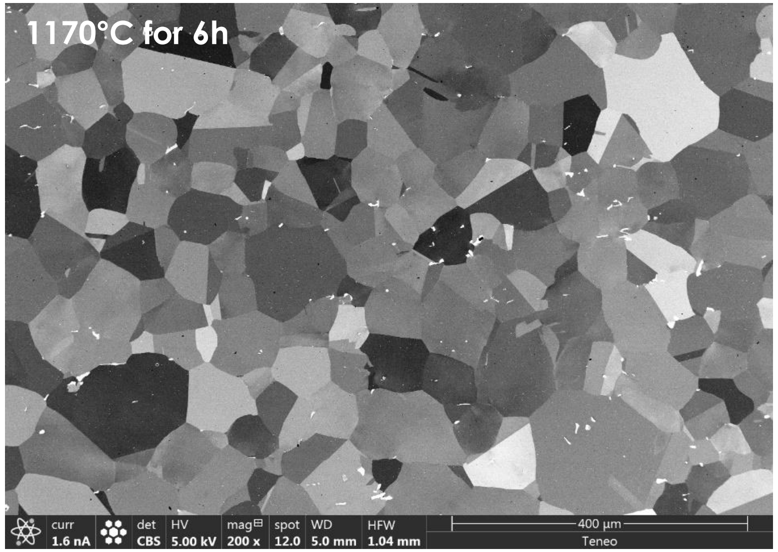
2020
This project with ORNL
kicked off to produce
5th heat and ASME code case

2021
Produced large ESR heat
using optimized chemistry
process mapping and production

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

Development of 5th Heat

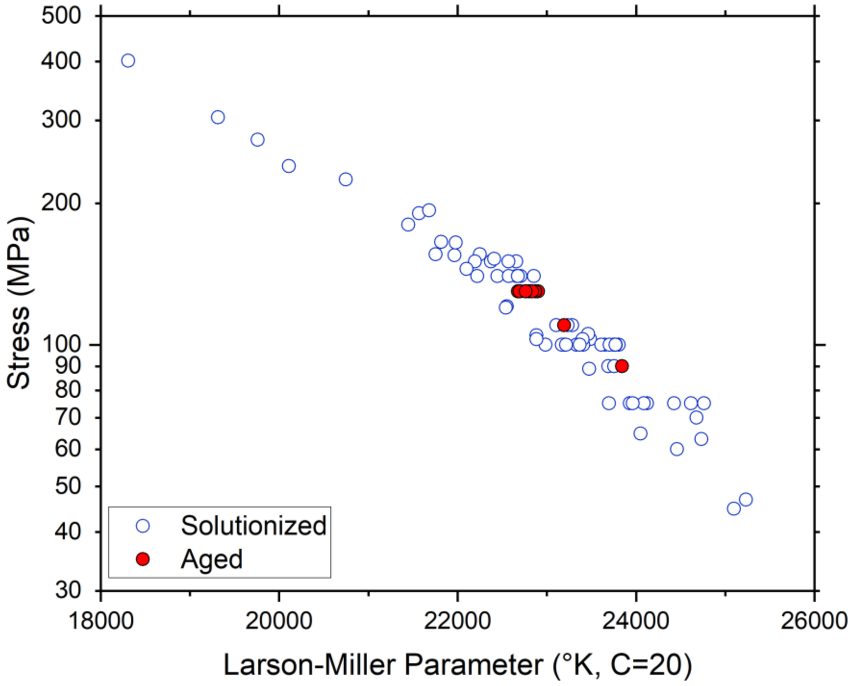
- Alloy design and chemistry targets
  - Computational thermodynamic assessment of carbide and nitride stability
  - TEM/STEM work on precipitates from several heats
  - Optimized chemistry targets from cast formulation
- Ingot production at Carpenter
  - EAF+AOD, ESR, 2 ingots ≈ 12,600kg
- Gleeble-based study for thermomechanical properties
- Extrusion at Wyman Gordon
  - 3,500 kg segment to produce a pipe with 900 mm length X 400 mm OD X 44 mm wall thickness
- Microstructure evaluation and heat treatment optimization…



Heat Treatment Optimization on 5th Heat

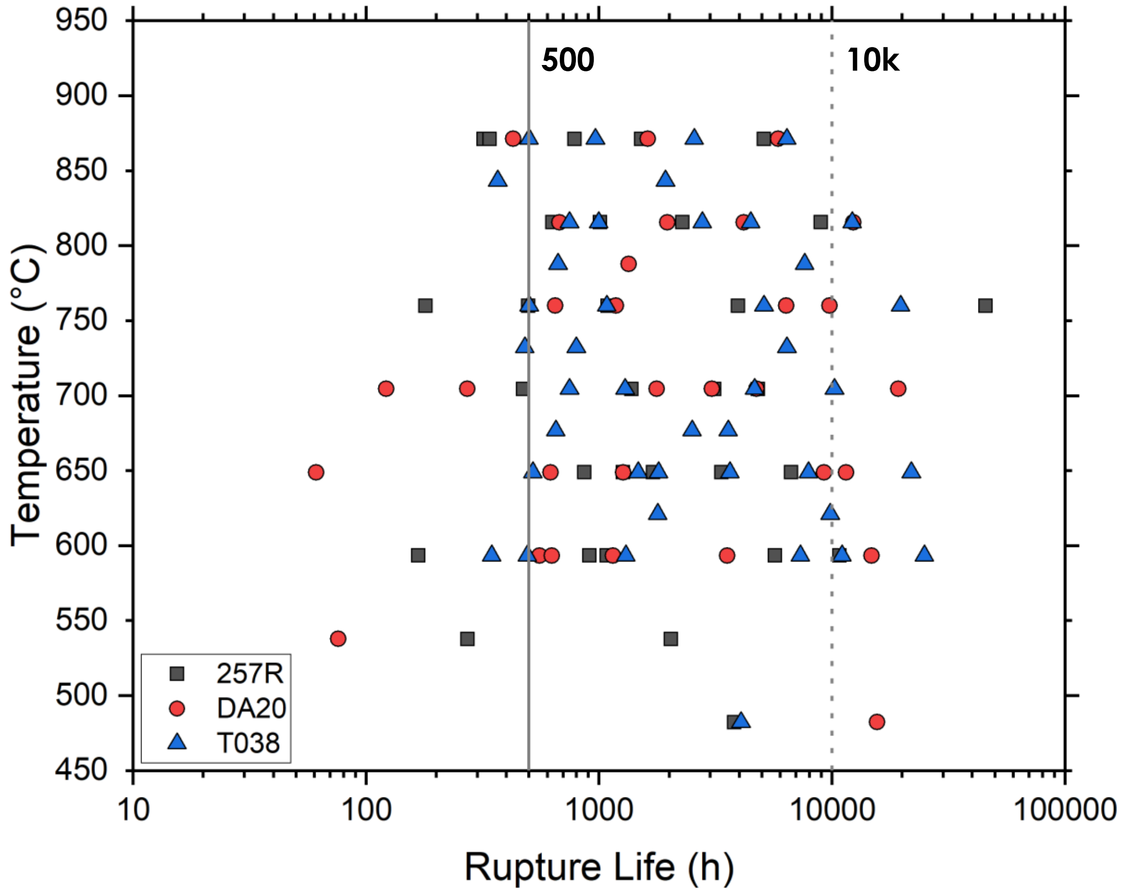
- Hardness measured for different heat treatment (HT) conditions
  - Average **solutionized** condition: 181 HV
  - Average **aged** condition: 191 HV
- Short-term creep behavior
  - Tested at 750°C, rupture lives ~200-2000hr
  - Aged conditions fell within scatter of solutionized data
- **Relatively insignificant influence of HT on final properties across tested conditions**
- Final heat treatment for the remainder of 5th heat: solutionized at 1170°C for 2hr performed at Wyman-Gordon

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

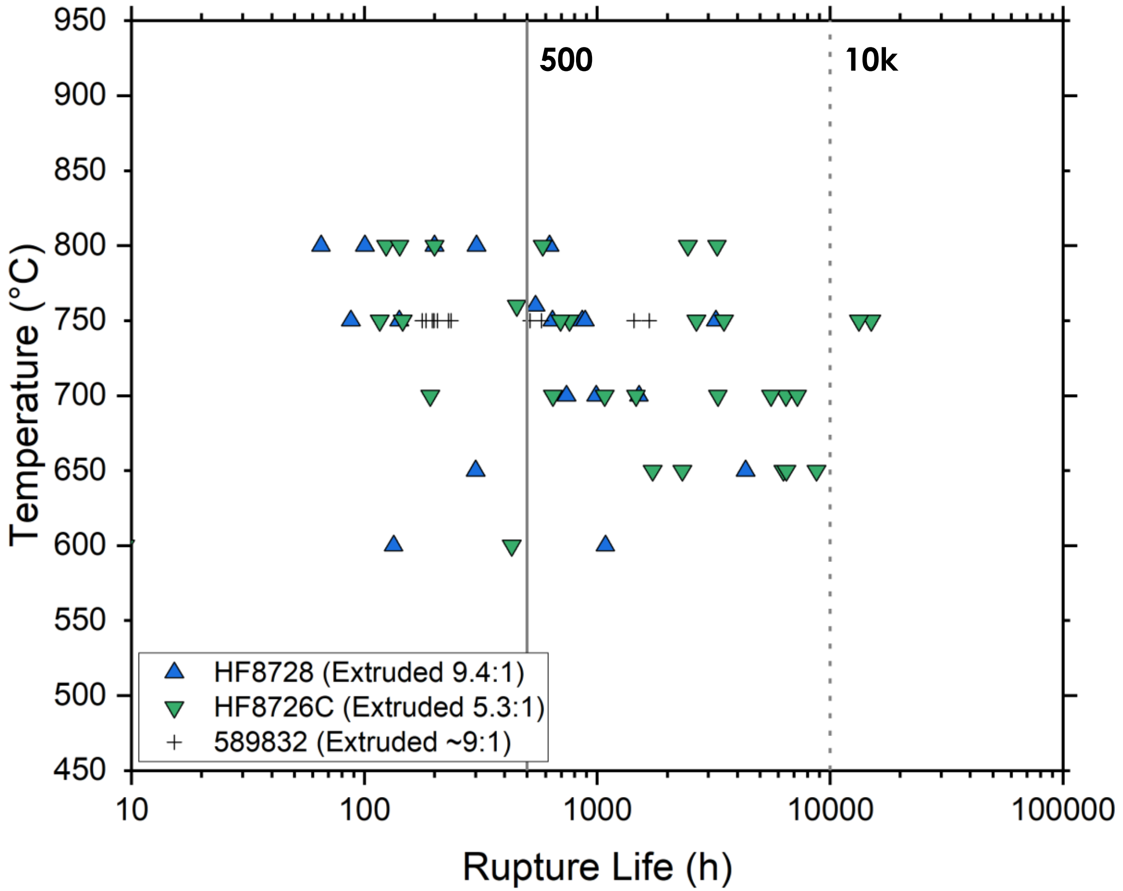


Comparison of Creep Rupture Databases (Cast vs. Wrought)

Cast rupture data submitted for ASME code case



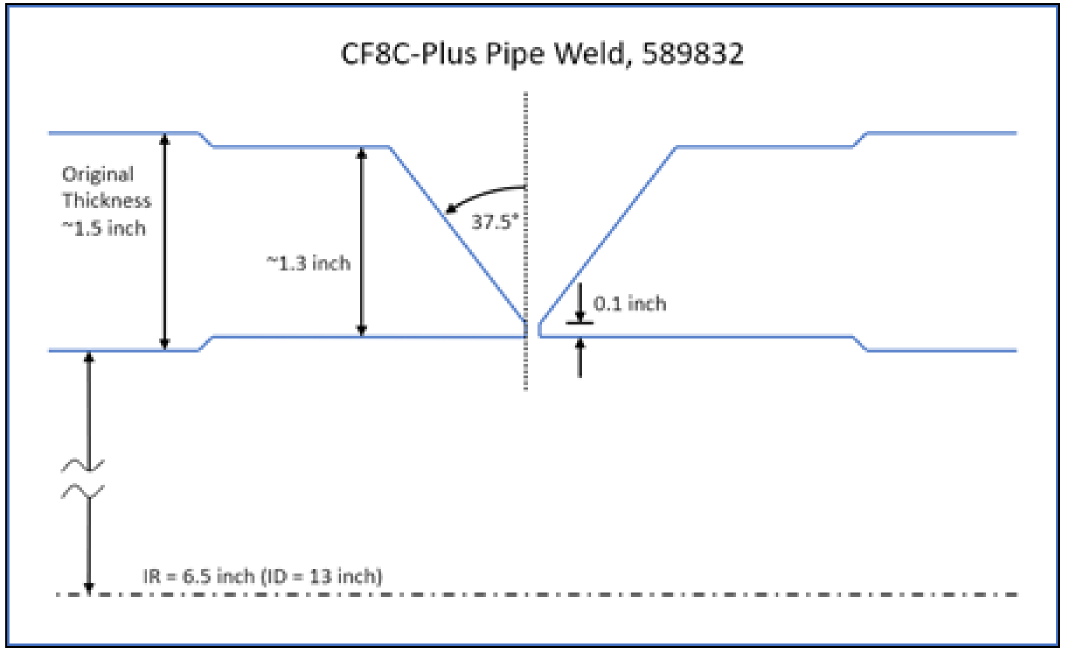
Wrought rupture data available



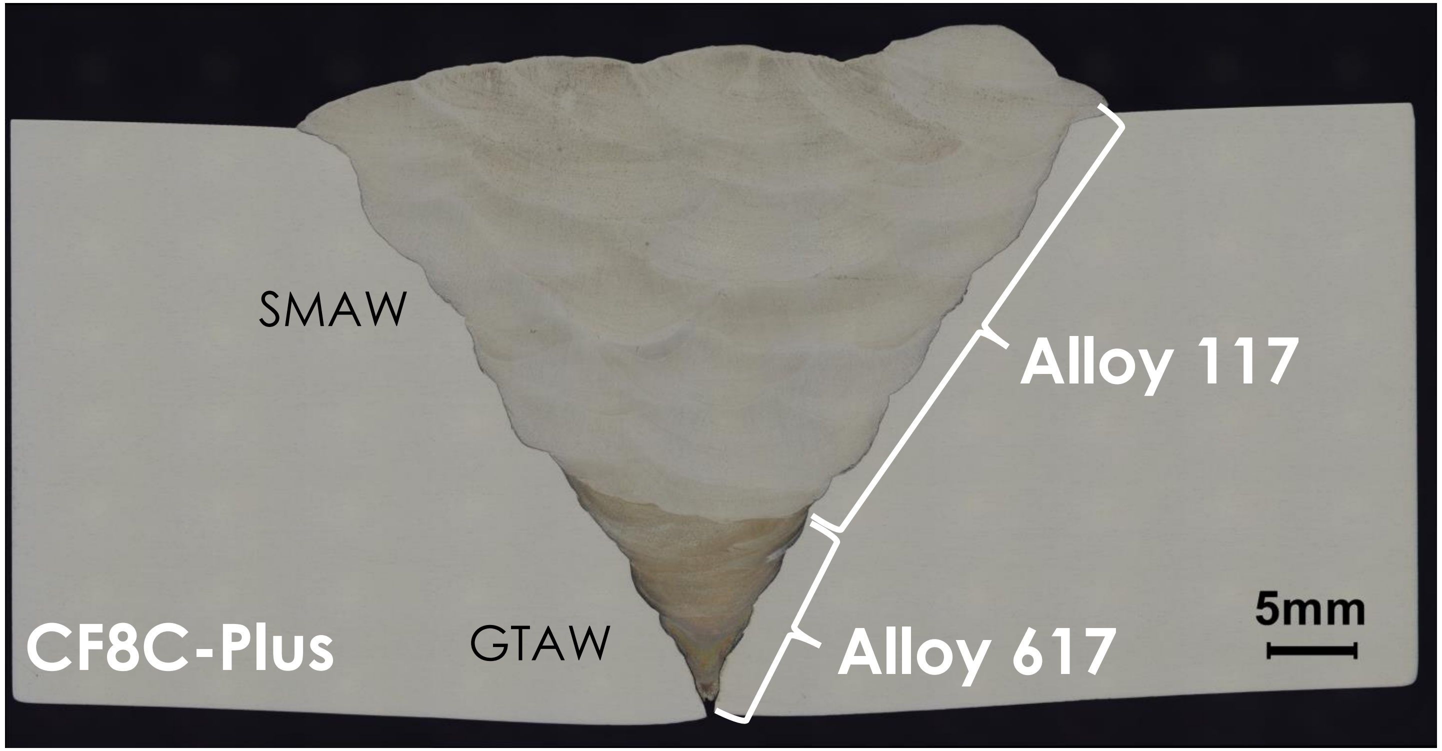
Current focus: Fill the creep rupture data gap for wrought CF8C-Plus

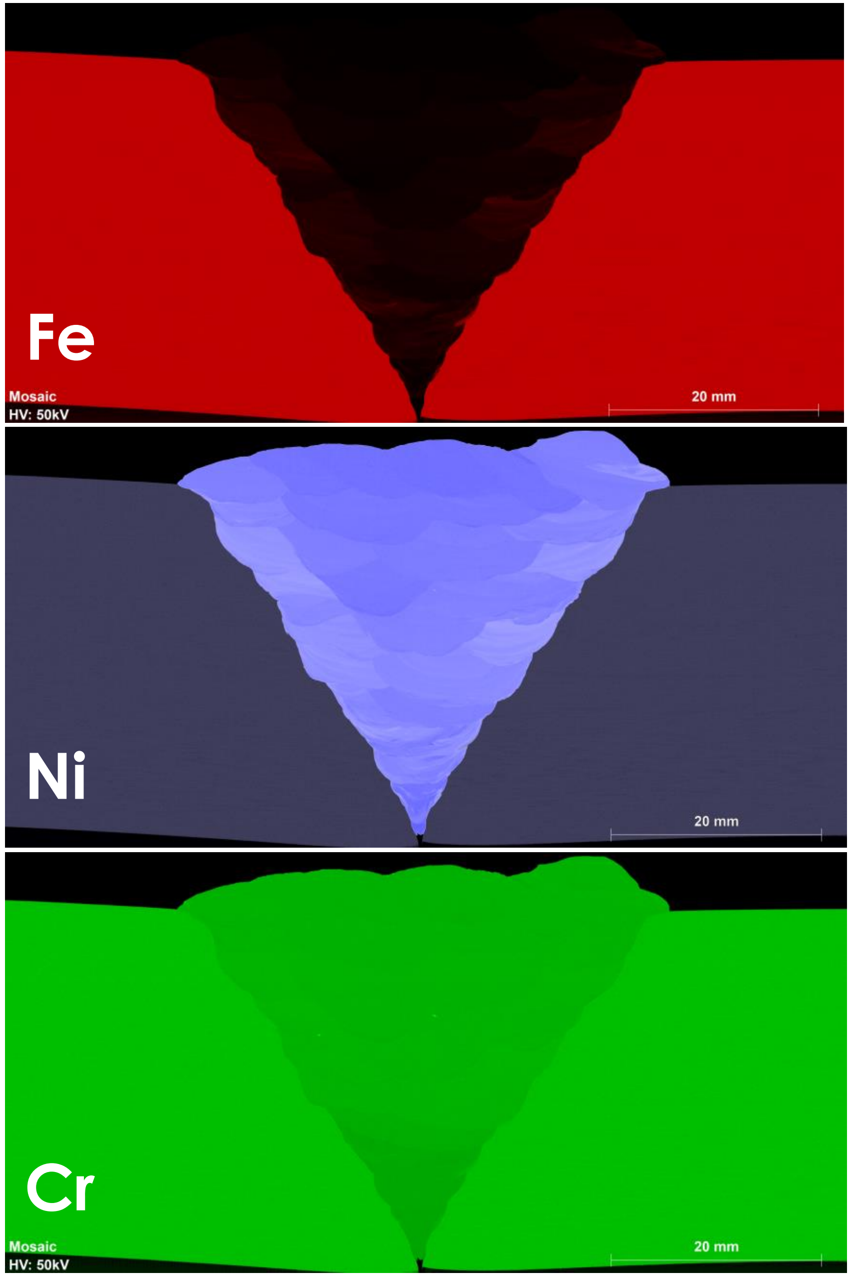
CF8C-Plus Pipe Weld

- Pipe weld produced to support ASME code case development
- Base metal: 5th Heat (589832)
- Partial GTAW / partial SMAW fill
  - GTAW (617, ERNiCrCoMo-1)
  - SMAW (117, ENiCrCoMo-1)
  - Enables dual qualification
- Following ASME Section IX weld qualification process
- Currently performing side bend and cross-weld tensile testing



CF8C-Plus Pipe Weld (cont.)





Conclusions and Future Work

- Two ASME Code Cases approved for cast CF8C-Plus. Revisions on both code cases are underway to further increase the maximum allowable stress
- CF8C-Plus Extruded pipe
  - Manufacturing of extruded pipe 400 mm OD x 44 mm wall thickness completed
    - Both ingot processing and mechanical extrusion show the alloy is manufacturable
  - Heat treatment optimization completed
    - Solutionizing is relatively insensitive and robust
    - Aging showed negligible effect
- Wrought CF8C-Plus ASME BPVC Code Case application
  - Initiated activities to modify ASTM specifications as a precursor to ASME Code Case
  - Completing mechanical property testing for ASME data package
    - Solutionized extrusions (3x heats) are the focus with forged material (2x heats) data as supplement
    - Time-independent testing to be completed within next 1-2 months
    - Long-term (~10khr) creep rupture testing is the biggest hurdle – tests to fill this gap initiated in late 2022

Acknowledgment

- This work is sponsored by the Department of Energy Office of Fossil Energy and Carbon Management Award Number **DE-FEAA133**
- **NETL: Vito Cedro III** for the programmatic support
- **ORNL: Jeremy Moser, Shane Hawkins, Kelsey Epps, Doug Kyle, and Doug Stringfield** for their technical assistance
- **EPRI: Scott Bailey** for welding support