FEAA152-Evaluating Ni-Based Alloys for A-USC Component Manufacturing and Use

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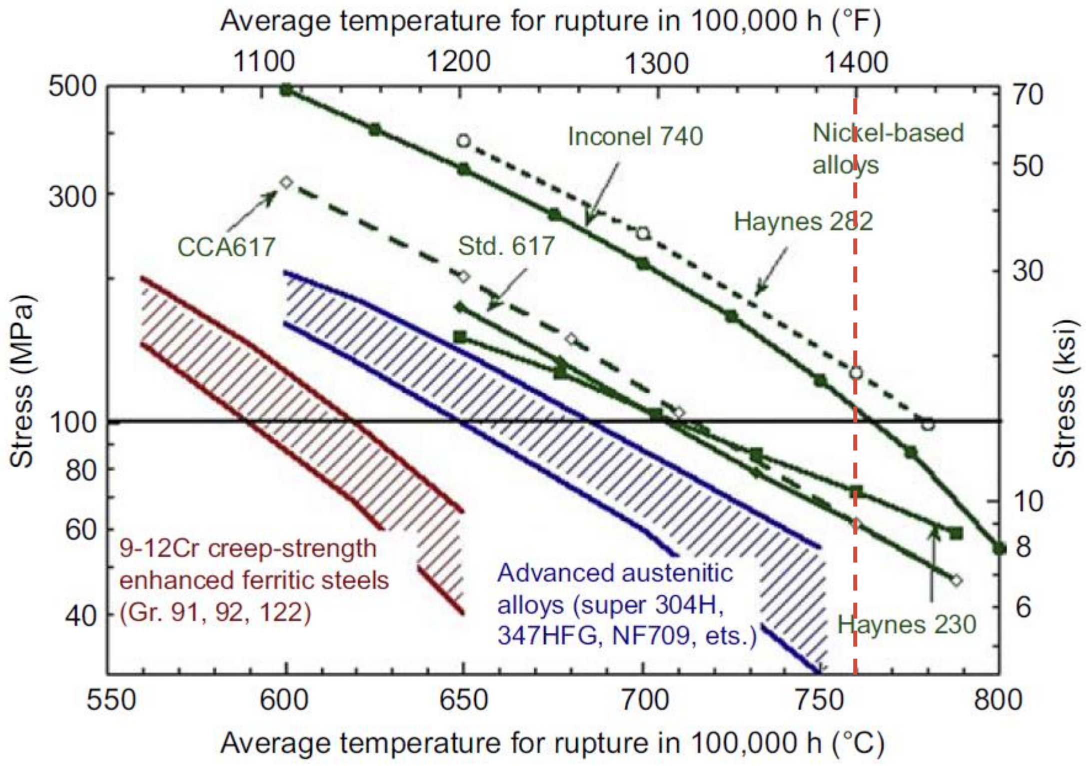
Background (1/3)

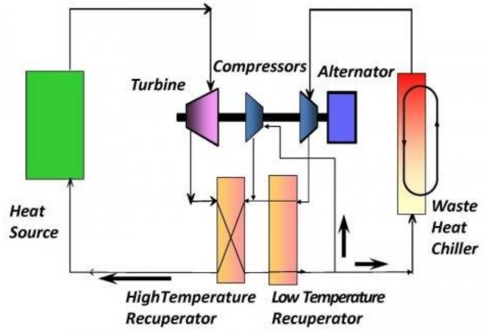
- Advanced Ultra-Supercritical (A-USC) power plants promise higher efficiency and lower emissions achieved by steam conditions up to 760°C/35 MPa
- Two precipitation-strengthening Ni-based alloys, **Haynes® 282 ® and Inconel® 740H®,** are considered as leading candidate materials for A-USC applications
- Due to their high temperature strength and corrosion resistance, both materials may also find applications in **hydrogen turbine, sCO_2 plants, concentrated solar, and advanced HRSGs**



100 kh creep rupture strength as a function of temperature

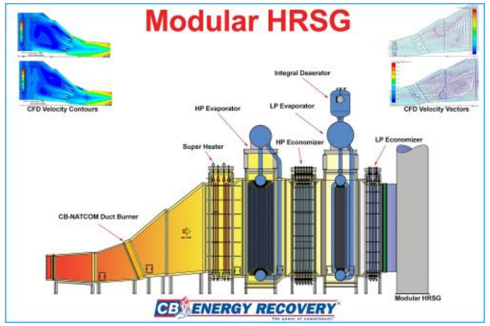
Shingledecker et al 2013

Hydrogen turbine



sCO2 plants

concentrated solar



advanced HRSGs

Background (2/3)

- Ni-based alloys account for an important portfolio of the Fossil Energy and Carbon Management materials program

2001-2015

Boiler materials for ultra supercritical coal power plants

2009-2015

Materials for advanced ultrasupercritical steam turbines

2015-2018

ComTest Phase 1

2018-2022

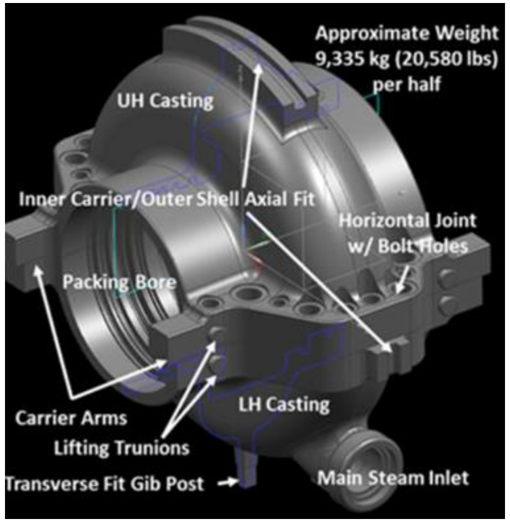
ComTest Phase 2

IN740H pipe
15" OD, 8" ID, 34.5 ft long

Viswanathan et al 2009

Haynes 282 triple-melt forged disk

Purgert et al 2015



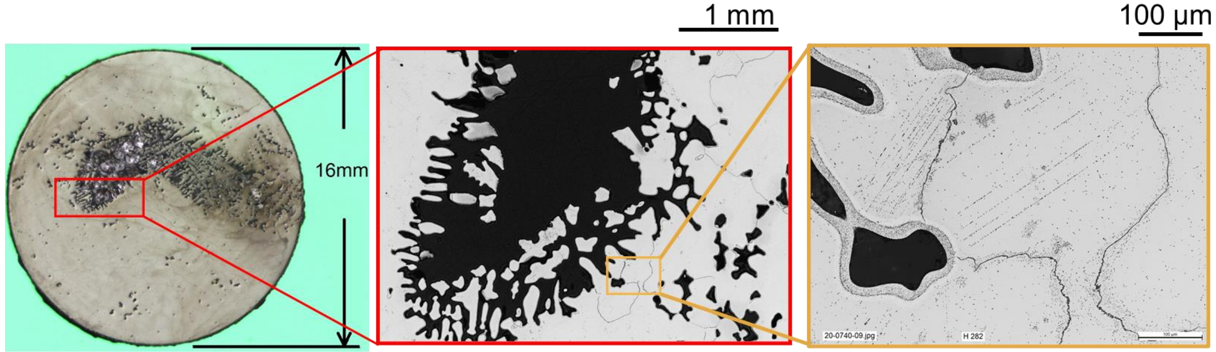
10-ton Haynes 282 nozzle carrier casting

Purgert and Hack 2019

Background (3/3)

- Characterization of Ni-based alloys provides
  - Data needed for materials qualification
  - Insights into potential manufacturability issues

Sand casting 7.7-ton Haynes 282, *Purgert et al 2015*



Cast Haynes 282 shrinkage defect, *Wang et al., 2021*

Case 2702-6
Ni-25Cr-20Co Material
Section I

Inquiry: May precipitation-hardenable Ni-25Cr-20Co alloy (UNS N07740) ASTM B983-16 seamless alloy pipe and tube, ASTM B1007-17 welded tube, and ASTM B637-18 bars, forgings, and forging stock; wrought plate, sheet, strip, and fittings material conforming to the chemical requirements shown in Table 1, the mechanical properties listed in Table 2, and otherwise conforming to the applicable requirements in the specifications listed in Table 3 and in this Case be used in welded and nonwelded construction under Section I rules?

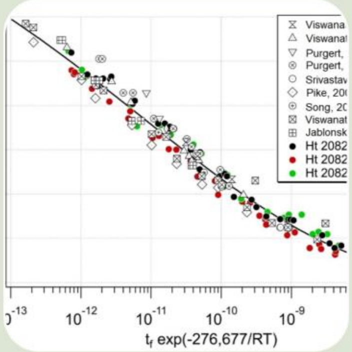
ASME code case for Inconel 740H

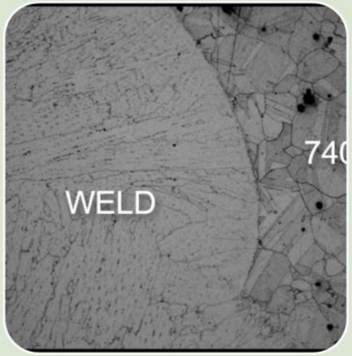
Case 3024
Ni-Cr-Co-Mo-Ti Precipitation Hardened Alloy UNS N07208
Section I; Section VIII, Division 1

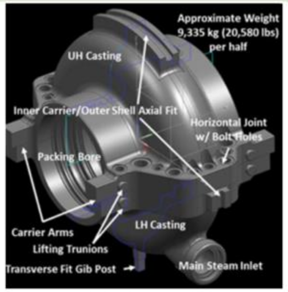
Inquiry: Under what conditions may Ni-Cr-Co-Mo-Ti Precipitation Hardened Alloy (UNS N07208) wrought bar, fittings, forgings, forgings stock, plate, sheet, strip, seamless pipe and tube, and welded pipe and tube be used in welded and nonwelded construction under the rules of Section I and Section VIII, Division 1?

ASME code case for Haynes 282

Objective: This research provides a critical evaluation of advanced Ni-based alloys supporting the manufacturing and use of components under A-USC and other extreme environment conditions







Planned 10-ton Haynes 282 nozzle carrier casting

Haynes 282 sand casting	Haynes 282 forged disk	Cast Haynes 282 GTAW	Creep modeling	Inconel 740H SMAW	ComTest Phase 2 materials

Publications under this project

1. Santella et al., Materials Science and Engineering: A vol. 838, 2022
2. Santella et al., Welding in the World vol. 65, 2021
3. Wang et al., Materialia vol. 15, 2021
4. Render et al., Met Trans. A. vol 52, 2021
5. Wang et al., Materials Science and Engineering: A, vol. 828, 2021
6. Unocic et al., JOM vol 72, 2020
7. Chen et al., Joint EPRI-123HiMAT International Conference on Advances in High Temperature Materials, 2019

ComTest Phase 2 Haynes 282 Nozzle Carrier Casting Heat Treatment Study

Raw Materials

- ComTest Phase 2 manufactured a variety of large-scale components using Inconel 740H and Haynes 282
- Several components were shipped to ORNL which include a **Haynes 282 nozzle carrier casting with a weight of 9.2 tons (20,260 lbs)**

GE steam header assembly

Haynes 282 nozzle carrier casting

Inconel 740H pipes

Inconel 740H pipes

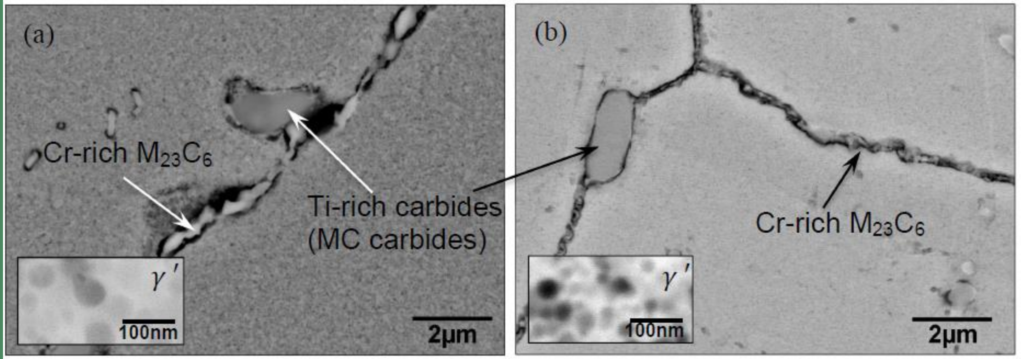
Haynes 282 rotor forging

Heat Treatment – 1 Step Aging vs. 2 Step Aging

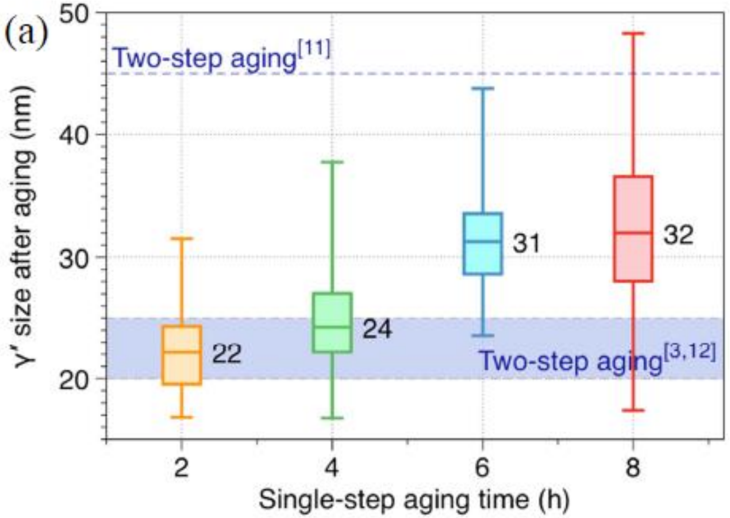
- The standard 2-step aging treatment (**1010°C/2 h/AC+ 788°C/8 h/AC**) for Haynes 282 can be time-consuming and costly
- ASME code case for wrought Haynes 282 only requires 1-step aging (**800°C/4h/AC**)
- Similar **microstructure, hardness, tensile, and creep properties** between 1-step aging and 2-step aging for wrought Haynes 282

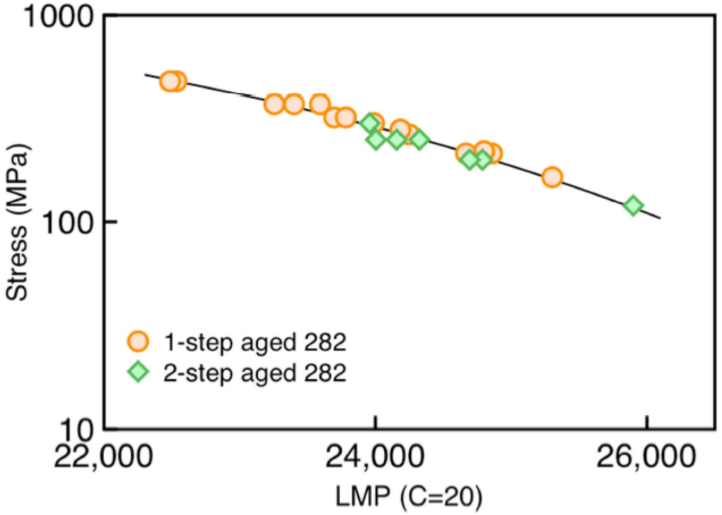
Wrought Haynes 282

Unocic et al., Scripta Materialia 2019



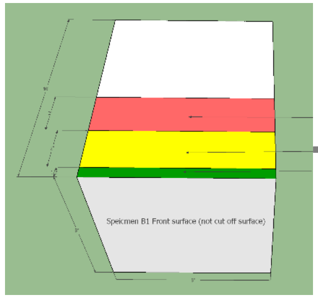
2-step aging   1-step aging





- **If the 1-step aging treatment can be applied to cast Haynes 282 and produce favorable structures and properties, it would be highly beneficial**

This study aims to determine the effect of heat treatment on microstructure and mechanical properties of cast Haynes 282



As-received
(homogenization after casting)

Solution anneal:
1149°C/1h/air cool
"SA + AC"

Solution anneal:
1149°C/1h/water quench
"SA + WQ"

1 step aging (800°C/4 h/air cool)
"AC + 1-Step"

2 step aging (1010°C/2 h/air cool + 788°C/8 h/air cool)
"AC + 2-Step"

1 step aging (800°C/4 h/air cool)
"WQ + 1-Step"

2 step aging (1010°C/2 h/air cool + 788°C/8 h/air cool)
"WQ + 2-Step"

Microstructure

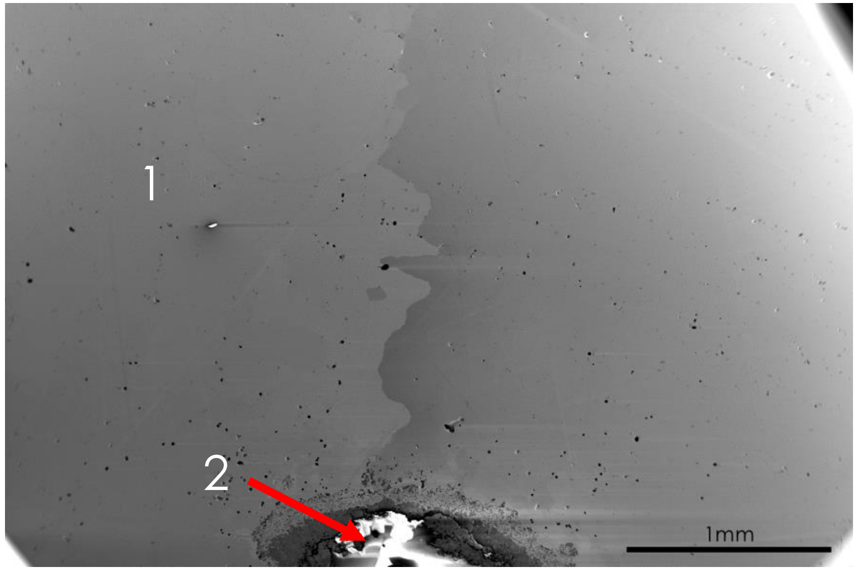
Microhardness

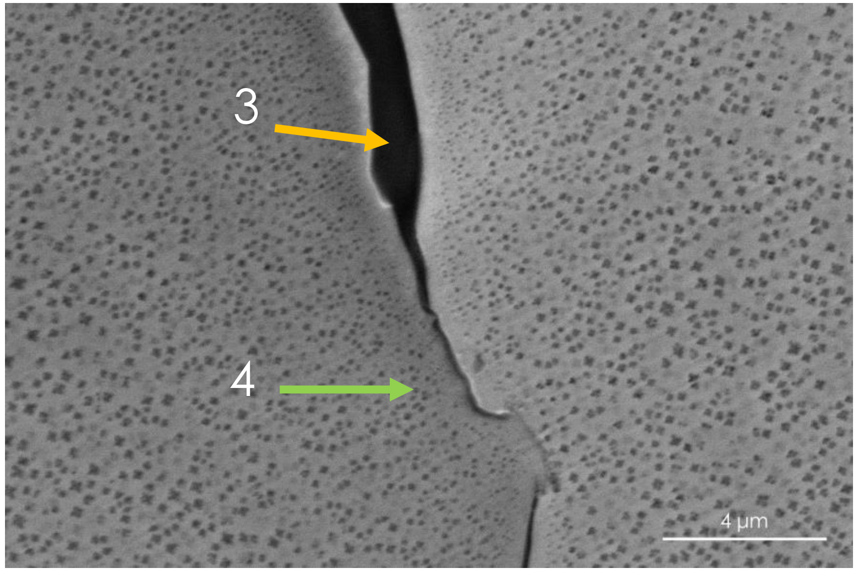
Tensile

Creep

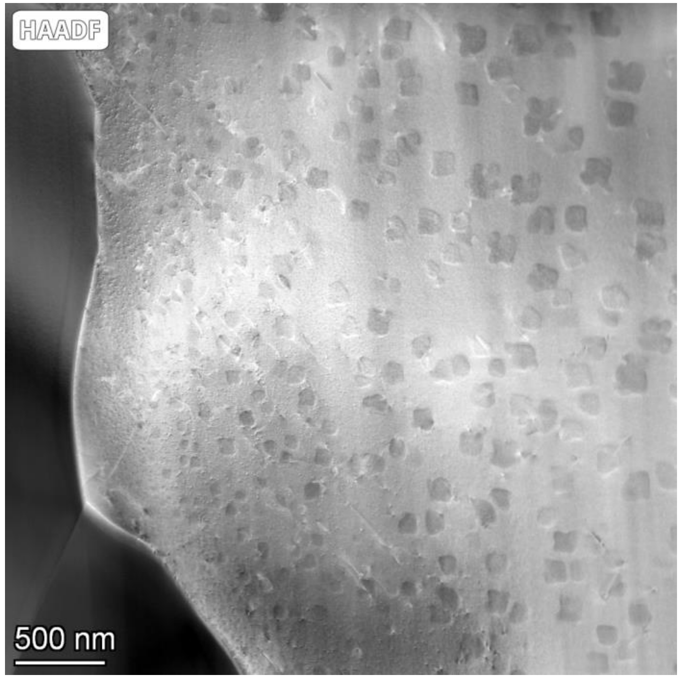
Haynes 282 Casting: as-received microstructure

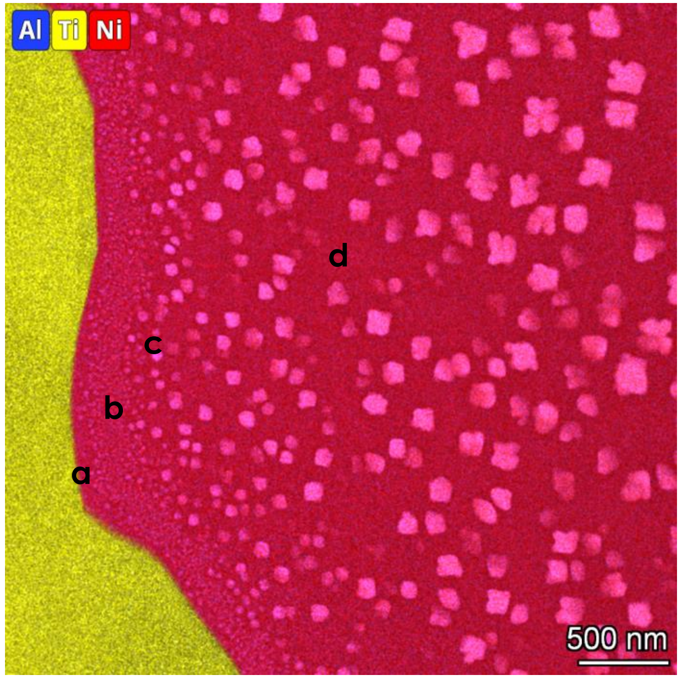
- The as-received material went through a **homogenization** treatment followed by **forced air cooling**





1. Large mm+ size grain structure
2. Occasional large oxide inclusions
3. Intragranular and grain-boundary carbides
4. $Ni_3(Al,Ti)$ γ' precipitate showed size gradient near carbides with the largest matrix precipitates ~100-130nm

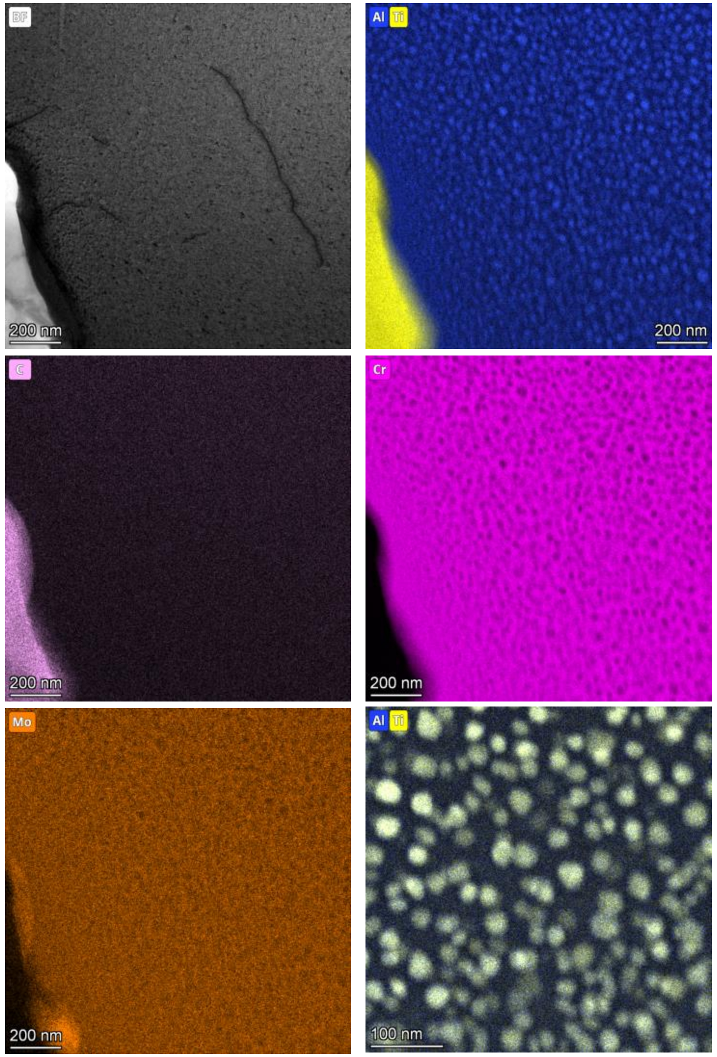




Solution Anneal + Air Cool vs. Water Quench

- Solution annealing at 1149 °C for 1 hour followed by air cooling or water quenching
  - Solution annealing should dissolve all γ' particles
  - Cooling rate determines if there was reprecipitation of γ' particles

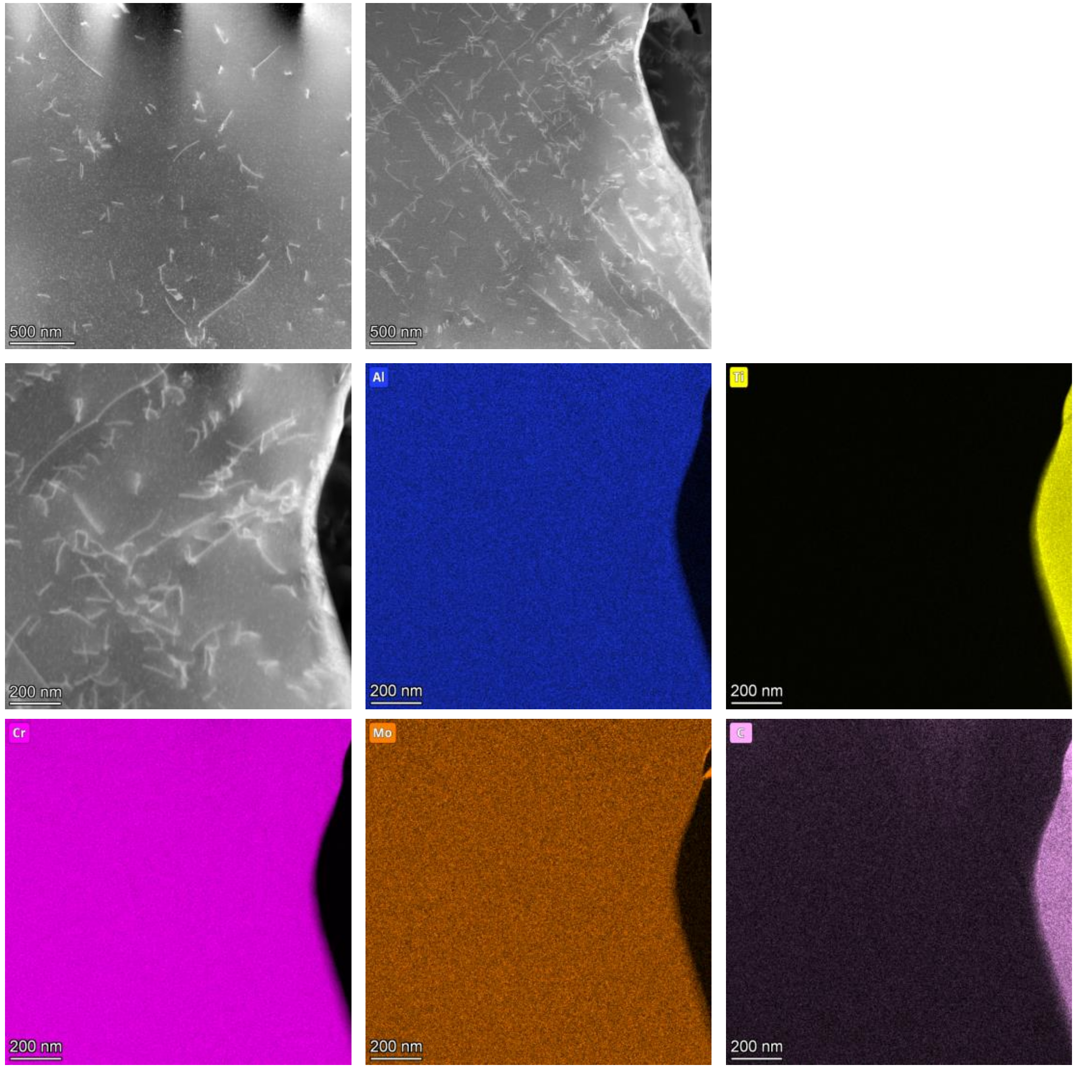
Air Cooled



- **SIMILAR**
  - Grain-boundary carbides

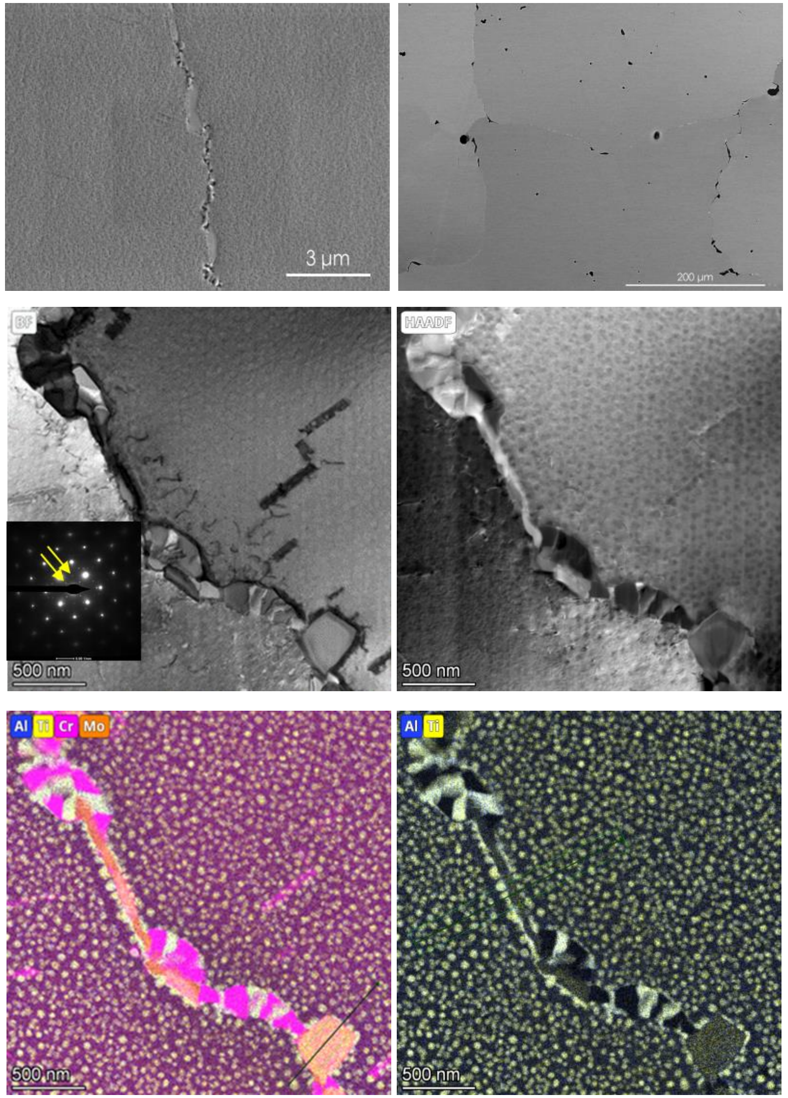
- **DIFFERENT**
  - **Air-cooled** had a high density of fine γ' particles
  - **Water-quenched:**
    - had no γ' particles
    - had a relatively high density of dislocations, particularly near GB/GB-carbide

Water Quenched



Solution Anneal + Air Cool + 1-step vs. 2-step aging

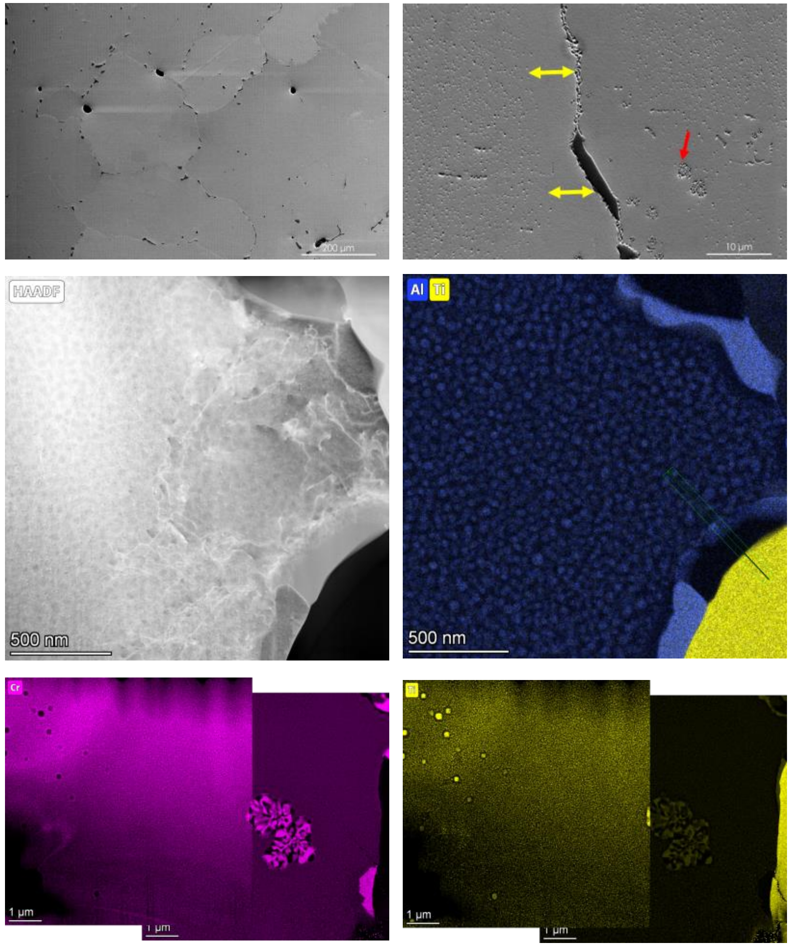
AC + 1-step aging



- **SIMILAR**
  - Grain-boundary carbides/ phases of various sizes and types
    - ❑ Ti-C; Mo-Cr; Mo-Si-Cr-Co-C; Cr-C; γ-phase
  - No gradient in particle size from grain boundary carbides
  - High density of fine γ' particles

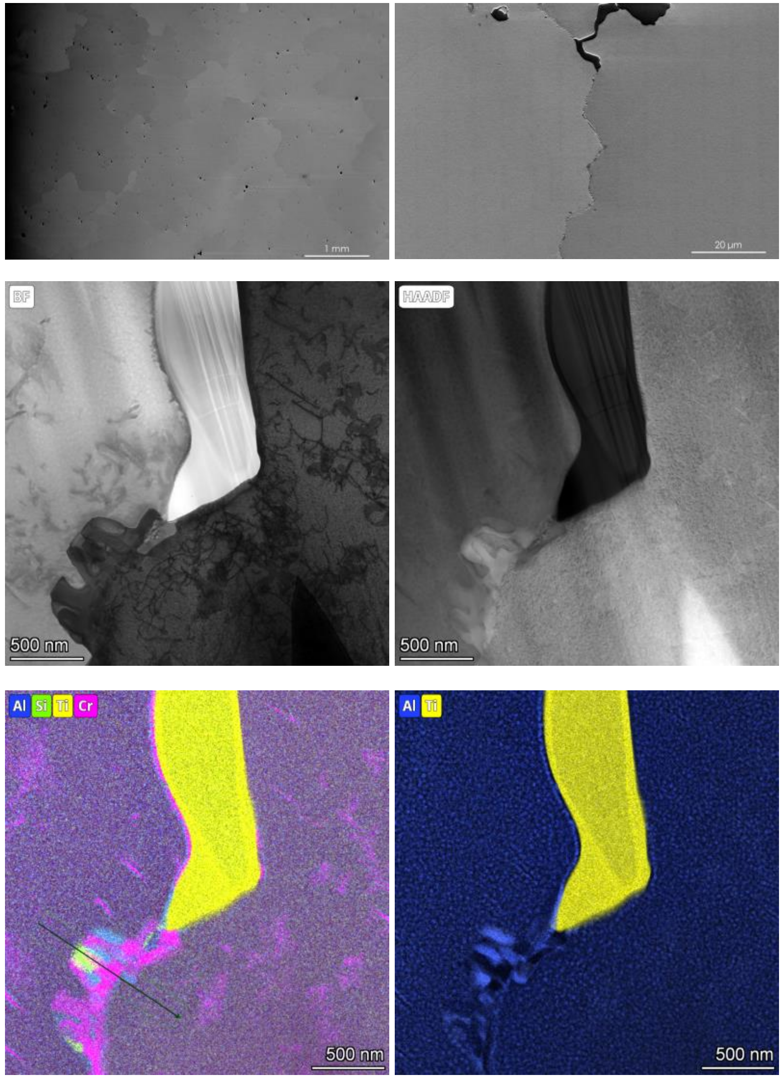
- **DIFFERENT**
  - **2-step aging:**
  - ➢ might have more of the large blocky carbides
  - ➢ had coarse γ' with ~110 nm radius and 1 × 10^{19} m^{-3} number density. Such coarse γ’ was depleted with ~10 μm from grain boundary carbide
  - ➢ had large 2 μm-size particles in matrix are intertwined Cr-C and γ-phase
  - **1-step aging had** small platelets of Cr-C in matrix in

AC + 2-step aging



Solution Anneal + Water Quench + 1-step vs. 2-step aging

WQ + 1-step aging

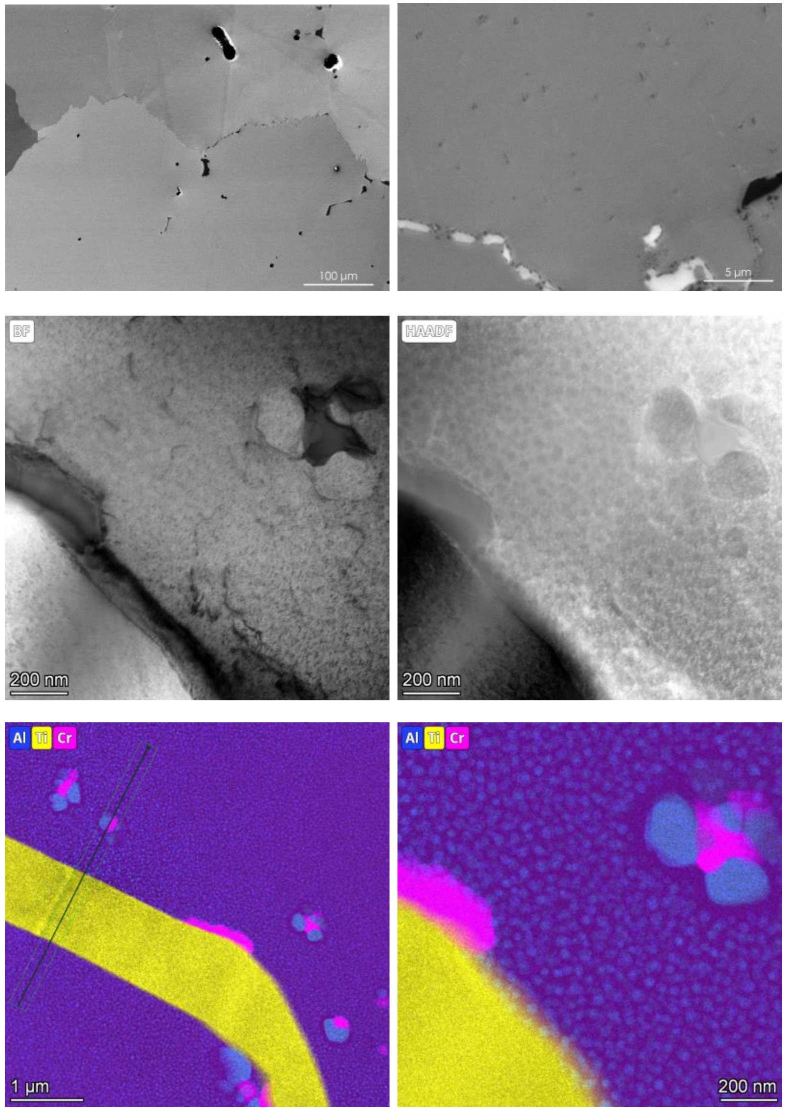


- **SIMILAR**
  - Grain-boundary carbides/ phases of various sizes and types
    - ❑ Ti-C; Mo-Cr; Mo-Si-Cr-Co-C; Cr-C; γ-phase
  - No gradient in particle size from grain boundary carbides
  - High density of fine γ' particles

- **DIFFERENT**
  - **2-step aging:**
    - ➢ might have more of the large blocky carbides
    - ➢ had 200-500nm diameter particles in the matrix (Cr-C intermixed with γ' phase)
  - **1-step aging** had relative high density of Cr-C platelets form in matrix; likely on [001]-type directions; some spherical Cr-rich particles

- Cr-C phases might have formed with help from high dislocation density after **WQ**

WQ + 2-step aging



Microstructural Characterization Key Take-aways

- Cooling rate after solution annealing (and likely homogenization) influenced the size and distribution of γ' precipitates
- 1-step and 2-step aging treatments produced similar fine distribution of γ' precipitates
- Secondary precipitates in matrix (Cr-C and/or larger γ') more likely to form after 2-step aging
- Several different grain-boundary carbides were present with no major difference between 1-step and 2-step aging

What are the effects on mechanical properties?

Hardness Comparison

	Hardness (HV1)	γ' radius (nm)	γ' number density (m^{-3})	Area fraction
As-received	280.2 ± 8.1	70 ± 44	1.4×10^{20}	0.21
SA+AC	313.2 ± 16.1	14 ± 9	6.9×10^{21}	0.41
SA+WQ	203.4 ± 13.8	-	-	-
AC + 1-step	340.4 ± 8.9	22 ± 12	2.9×10^{21}	0.44
AC + 2-step	334.1 ± 19.9	20 ± 11	3.7×10^{21}	0.45
WQ + 1-step	351.3 ± 20.8	11 ± 7	1.2×10^{22}	0.49
WQ + 2-step	354.2 ± 12.2	19 ± 12	4.8×10^{21}	0.53

- The **four aged samples** had higher hardness than the **as-received** and **two solution-annealed** materials

Hardness Comparison

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- The solution annealed plus **water-quenched** sample had the lowest hardness
  - No γ' particles for hardening

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- The solution annealed plus **air-cooled** material had higher hardness than the **as-received** and **water-quenched** material
  - More refined γ’ in air-cooled material

Hardness Comparison

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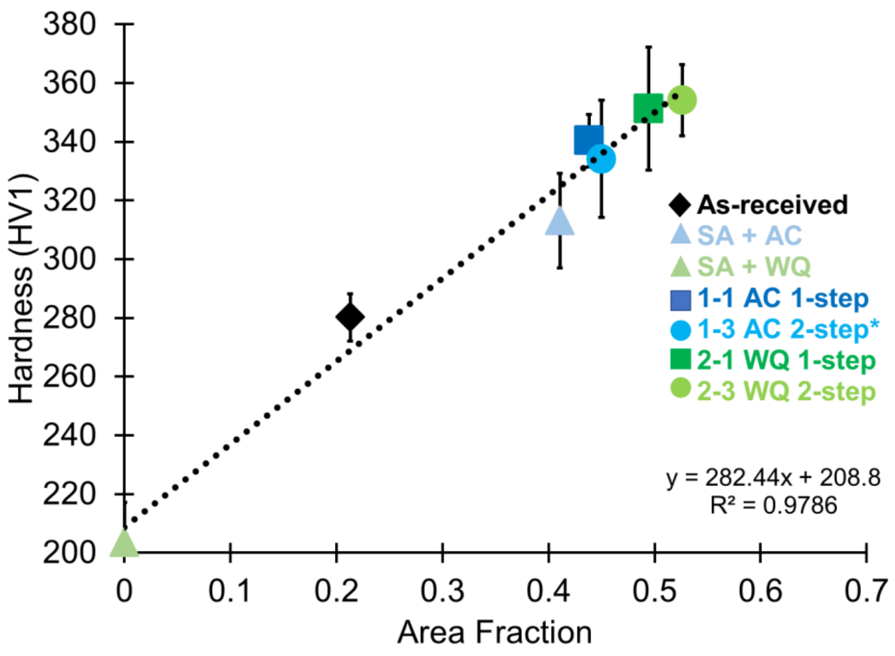

- Hardness trends most strongly with the area fraction of γ' particles

Hardness Comparison

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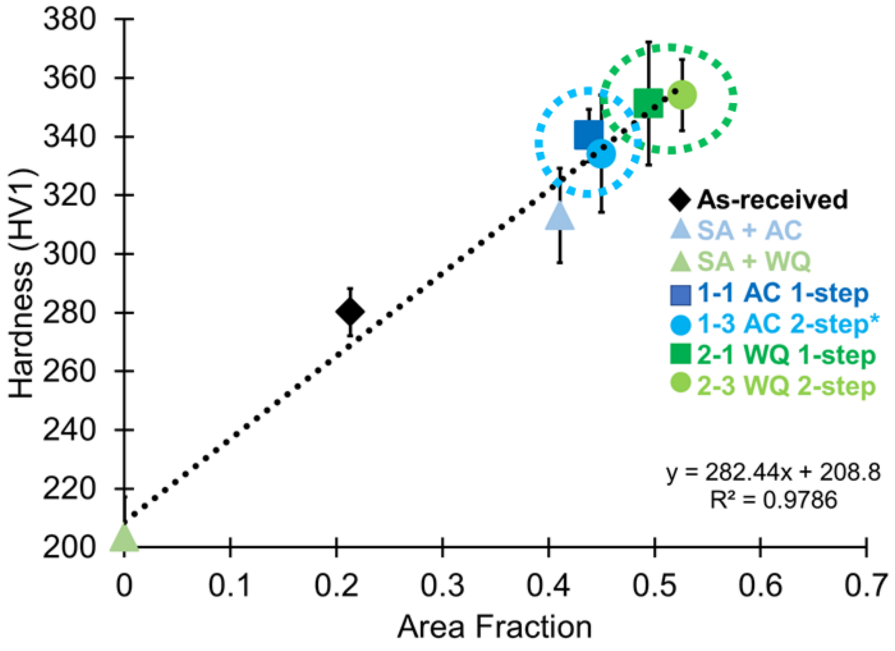
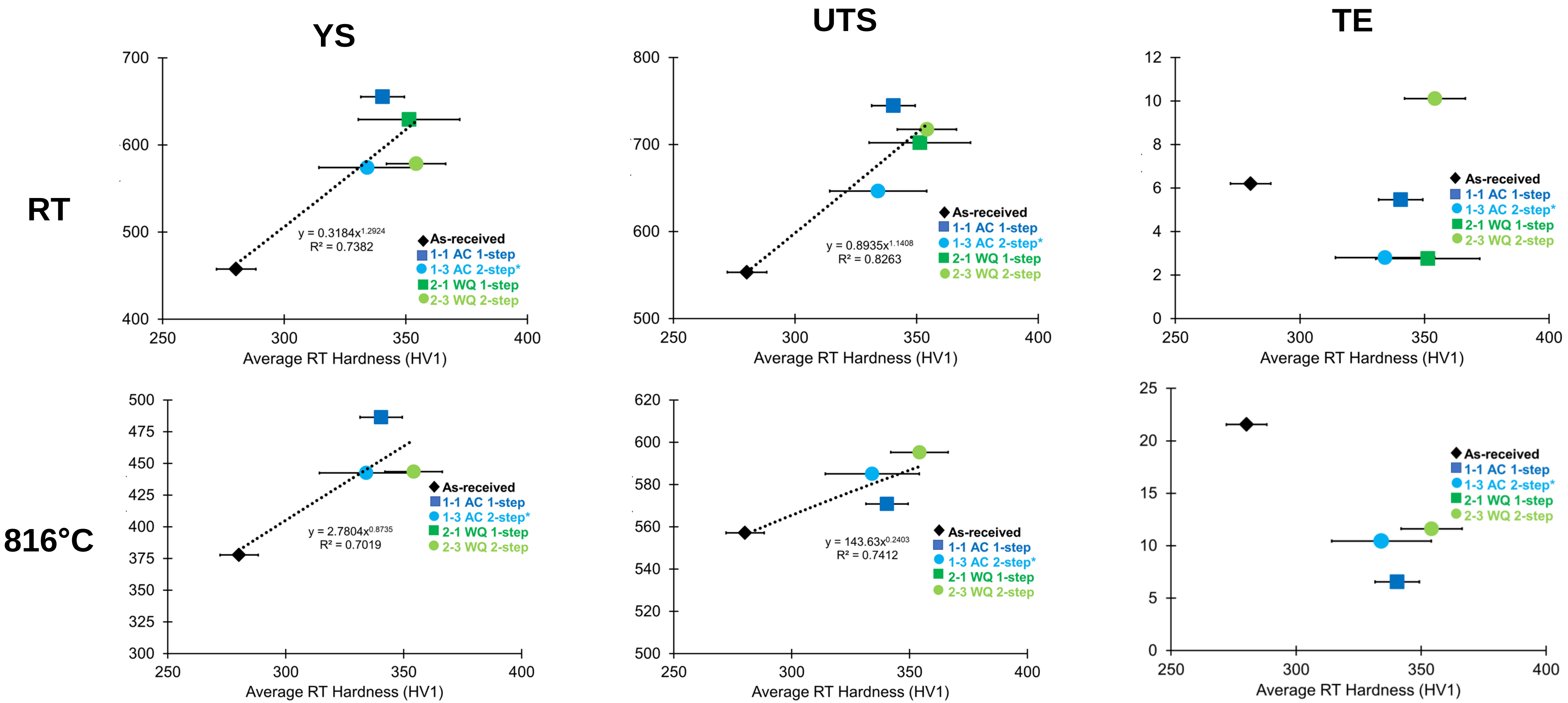


- The **water-quenched** plus aged materials generally had slightly higher hardness than the **air-cooled** plus aging condition
  - Dislocation network after water-quench promoted more Cr-C formation?
  - More Ti and Al in matrix after water-quench promoted finer γ' and higher number density?
  - Air cool after solution annealing allows some γ' coarsening?

From hardness perspective, similar behaviors were observed between 1-step and 2-step aging

Tensile Property Comparison

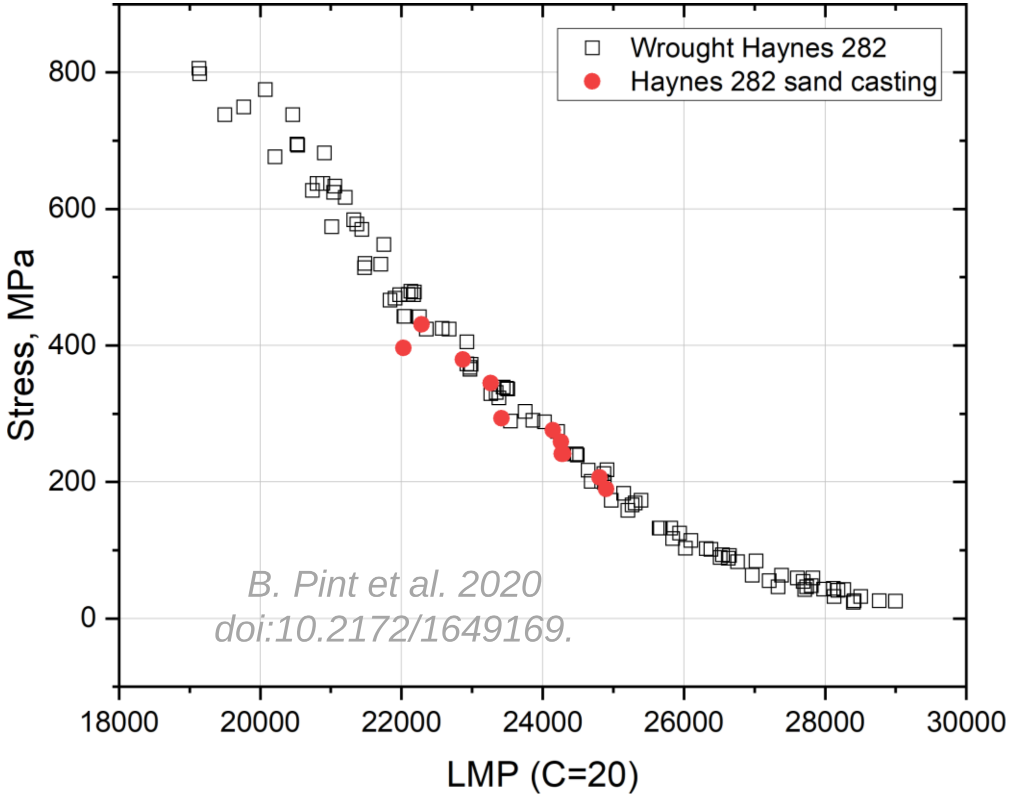
- Tensile testing at room temperature and 816 °C has revealed that yield strength (YS) and ultimate tensile strength (UTS) correlated reasonably well with hardness
- Total elongation (TE) has limited correlation with hardness



Creep testing underway to evaluate the effect of heat treatment on creep rupture life

- Hypothesis is that 1-step aging would give similar creep lives as the 2-step aging

Heat treatment condition	Temp (ºC)	Stress (MPa)
WQ+1-step	649	600.00
WQ+2-step	649	600.00
AC+1-step	649	600.00
AC+2-step	649	600.00
WQ+1-step	760	290.00
WQ+2-step	760	290.00
AC+1-step	760	290.00
AC+2-step	760	290.00
WQ+1-step	871	100.00
WQ+2-step	871	100.00
AC+1-step	871	100.00
AC+2-step	871	100.00



Haynes 282 wrought (1-step) and cast (2-step) creep life data

Comparison with Wrought Haynes 282 after Thermal Aging

- The aging treatment for the cast Haynes 282 appears to have similar effect as that for the wrought Haynes 282
  - 1-step aging yields similar microstructure and hardness as those of 2-step aging for both materials
  - Similar hardness and γ' size between cast and wrought Haynes 282 after the 1-step aging

Cast Haynes 282

	Hardness (HV1)	γ` radius (nm)	γ` number density (m^{-3})	Area fraction
As-received	280.2 ± 8.1	70 ± 44	1.4×10^{20}	0.21
SA+AC	313.2 ± 16.1	14 ± 9	6.9×10^{21}	0.41
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Wrought Haynes 282

Unocic et al., Scripta Materialia 2019

	Hardness (HV1)	γ` radius (nm)
Solution annealed	275 ± 15	-
2hr at 800C	353 ± 13	11.2 ± 1.5
4hr at 800C	361 ± 7	12.4 ± 2
6hr at 800C	362 ± 6	15.6 ± 2
8hr at 800C	372 ± 12	16.4 ± 3

Conclusions

- Cooling rate after solution annealing (and likely homogenization) influenced the size and distribution of γ' precipitates
- **1-step and 2-step aging treatments in cast Haynes 282 resulted in**
  - Similar fine distribution of γ' precipitates
  - Similar hardness values
  - Similar tensile strength
- Hardness trends most strongly with the area fraction of γ' particles
- The water-quenched plus aged materials generally had slightly higher hardness than the air-cooled plus aging condition
- The 1-step vs. 2-step aging treatments for the cast Haynes 282 appears to have similar effect as that for the wrought Haynes 282

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