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Sandia National Laboratories

Effect of thermal aging on mechanical properties and microstructural development of Hastelloy C and C276

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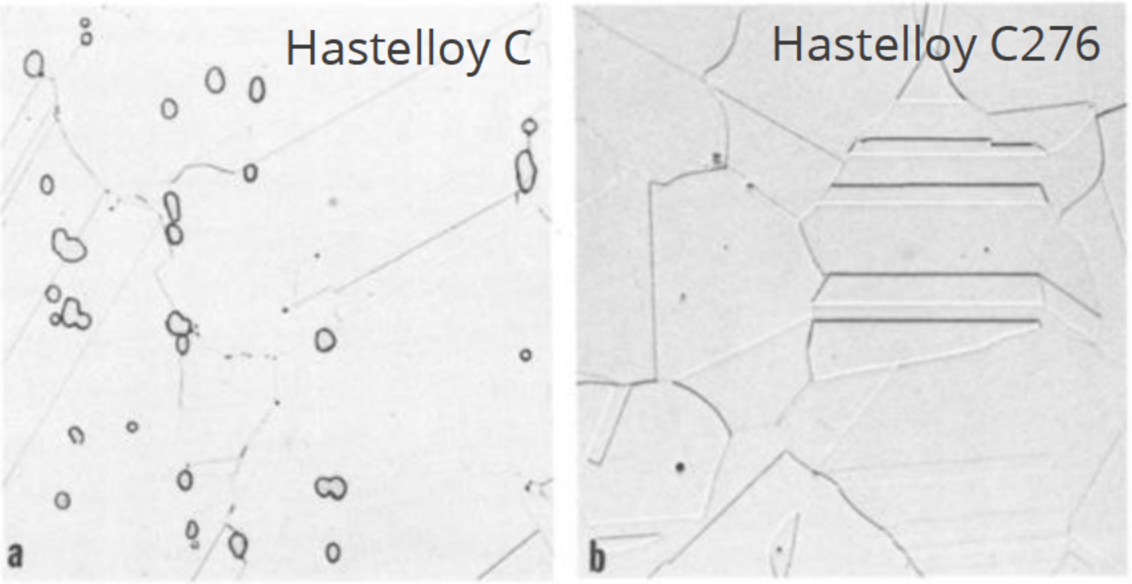
Background

Hastelloy C and C276 are chemically similar alloys, with the exception of Si and C content.

Published work on low temperature aging in these alloys is sparse (most work >600°C)



Tawancy, H.M., Herchenroeder, R.B. & Asphahani, A.I., High Performance Ni-Cr-Mo-W Alloys, JOM 35, 37-43 (1983).

Element	Hastelloy C (wt%)	Hastelloy C276 (wt%)
Ni	Balance	Balance
Mo	15 – 17	16
Cr	14.5 – 16.5	16
Fe	4 – 7	5
W	3 – 4.5	4
Co	2.5 (max)	2.5 (max)
Si	1 (max)	0.08 (max)
C	0.08 (max)	0.01 (max)
Mn	1 (max)	1 (max)
V	0.35 (max)	0.35 (max)

Hastelloy C has higher wt.% C and Si (impurities) → more precipitates

Hastelloy C276 properties adapted from from Haynes Intl, datasheets. Hastelloy C properties from Gehrke et al, The Processing and Properties of Hasteloy C, Battelle Report AD461825 (1964).

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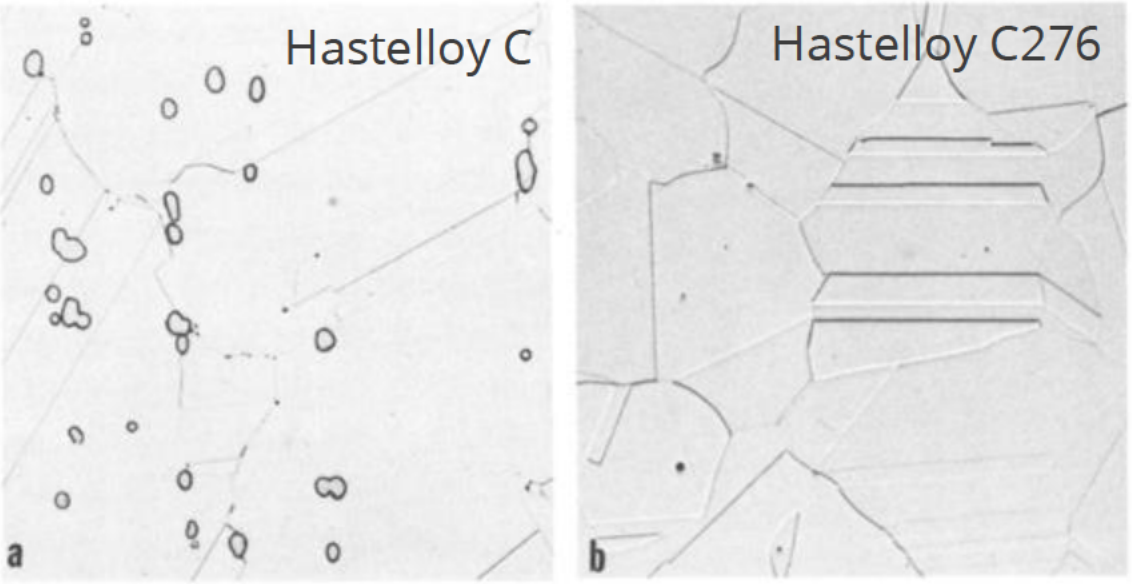

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Thermal Aging of Hastelloy C & C276

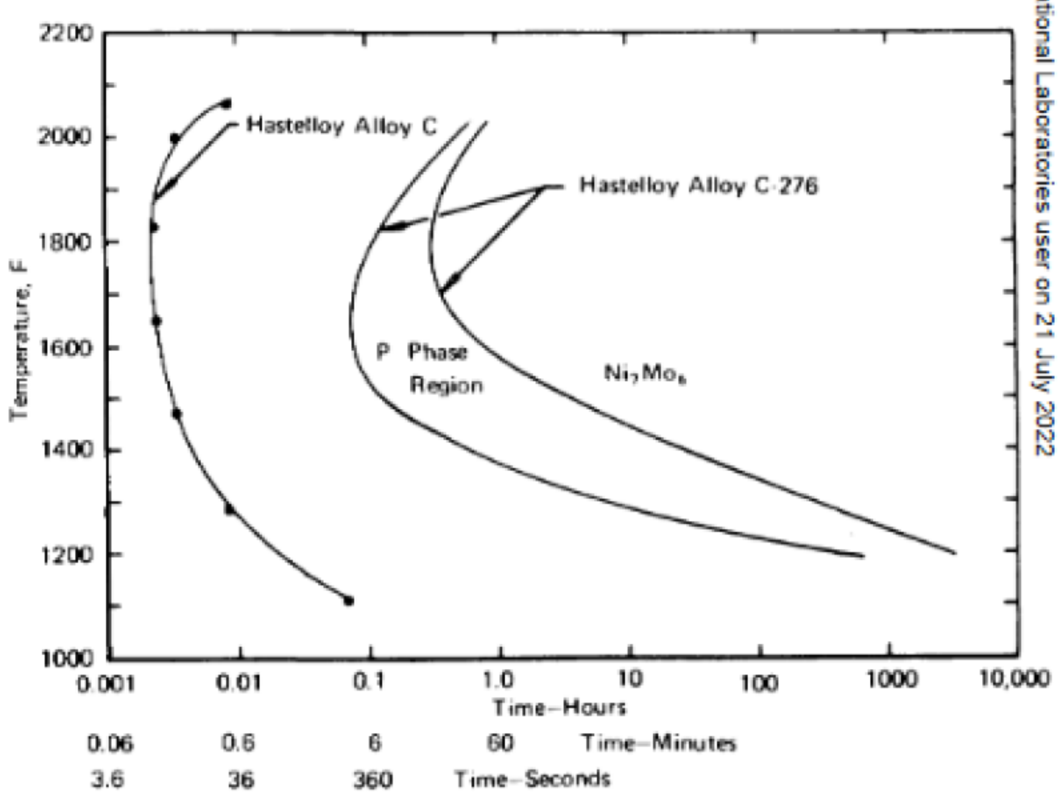
Aging mechanism (and effect on material properties) changes with temperature and time.

- 200-500˚C= Ordered domains form (disordered FCC → Pt_2Mo type superlattice), Strength ↑, Ductility ↓
- >500˚C = Long range ordering & precipitation of deleterious intermetallics/carbides

Other factors

- Kinetics
- Prior processing

...thus , the combined effect of processing and thermal aging on mechanical and microstructural properties of Hastelloy C and C276 is the subject of investigation.



Adapted from Leonard, R.B., Thermal Stability of Hastelloy Alloy C-276, Corrosion 25, 222-228 (1969).

- M_6C type phases – Diamond cubic structure
- P phase – Tetragonal TCP
- μ phase – A_7B_6 type HCP TCP

Test Matrix

Research questions:

- How do Hastelloy C and C276 evolve with thermal aging below 600°C?
- How closely related are the aging behaviors of Hastelloy C and Hastelloy C276?

Materials
- Hastelloy C

Thermal Aging
- 200°C, 400°C, 600°C
- 100, 500, 1000 hrs

Characterization
- Microstructural Analysis (OM & SEM)
- X-ray Diffraction
- Hardness Testing

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Materials
- Hastelloy C276

Thermal Aging
- 210°C,410°C
- 20+ years

Characterization
- Microstructural Analysis (OM & SEM)
- X-ray Diffraction
- Hardness Testing

Test Matrix

Research questions:

- How do Hastelloy C and C276 evolve with thermal aging below 600°C?
- How closely related are the aging behaviors of Hastelloy C and Hastelloy C276?

Materials

- Hastelloy C
- Hastelloy C276

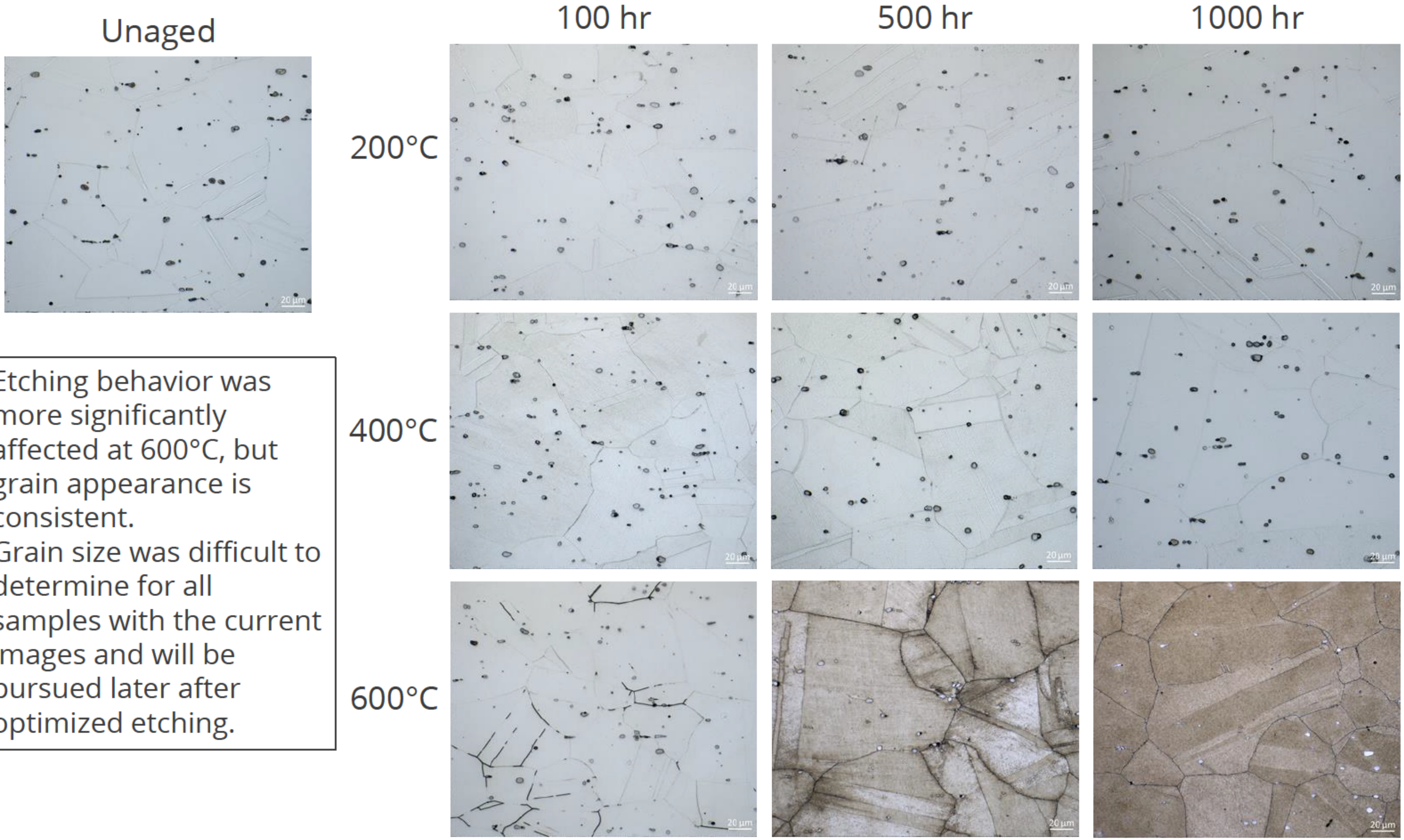
Thermal Aging

- 200-210°C, 400-410°C, 600°C
- 100, 500, 1000 hr + 20+ years

Characterization

- Microstructural Analysis (OM & SEM)
- X-ray Diffraction
- Hardness Testing

Microstructural Analysis – Hastelloy C

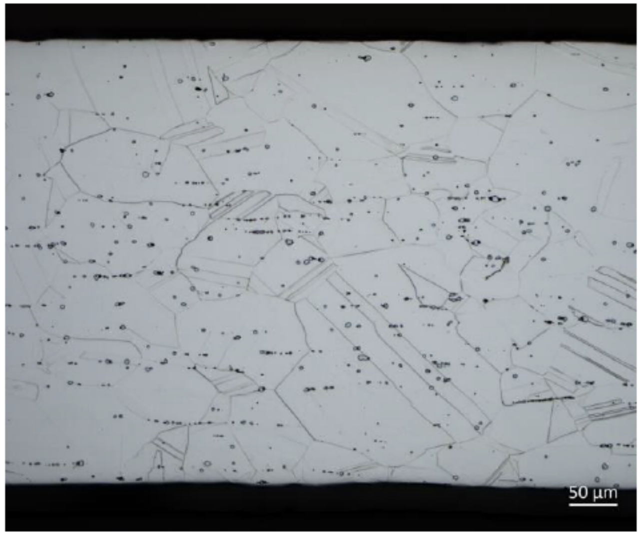


- Etching behavior was more significantly affected at 600°C, but grain appearance is consistent.
- Grain size was difficult to determine for all samples with the current images and will be pursued later after optimized etching.

Etched with Lucas' Reagent (150 mL HCl, 50 mL lactic acid, 3 g oxalic acid). 1V for 20-40 seconds depending on aging condition.
500X magnification

Microstructural Analysis – Hastelloy C vs C276

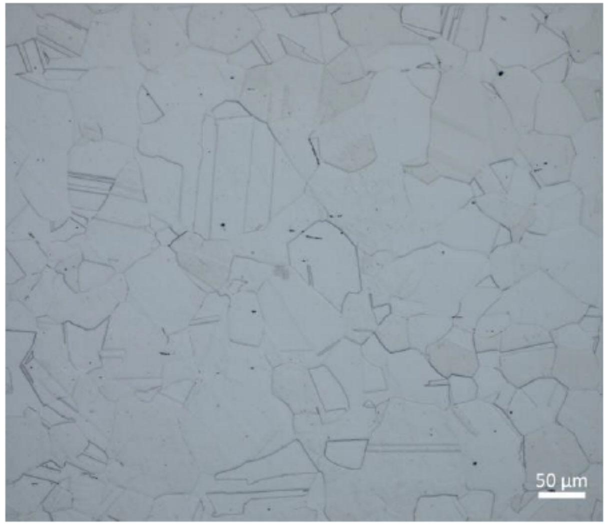
Unaged (Alloy C)



1000 hr (Alloy C)

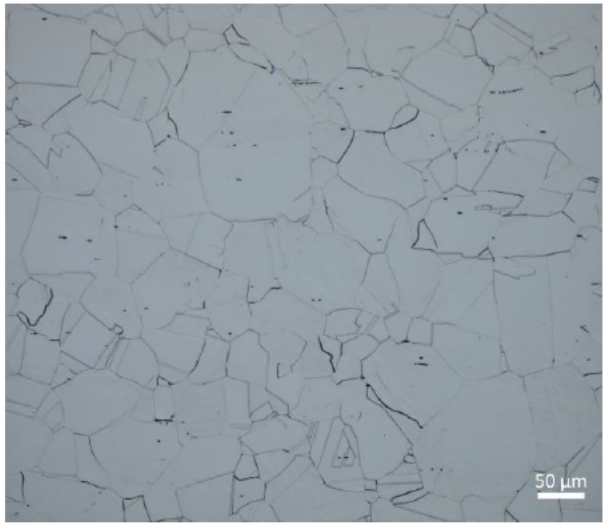
~190k hr (Alloy C276)

200-210°C



- As expected, alloy C276 has less carbides than alloy C.
- Alloy C276 etched readily with ASTM 83, while alloy C did not.
- There was no difference in etching duration or behavior for either Hastelloy C276 aging condition.

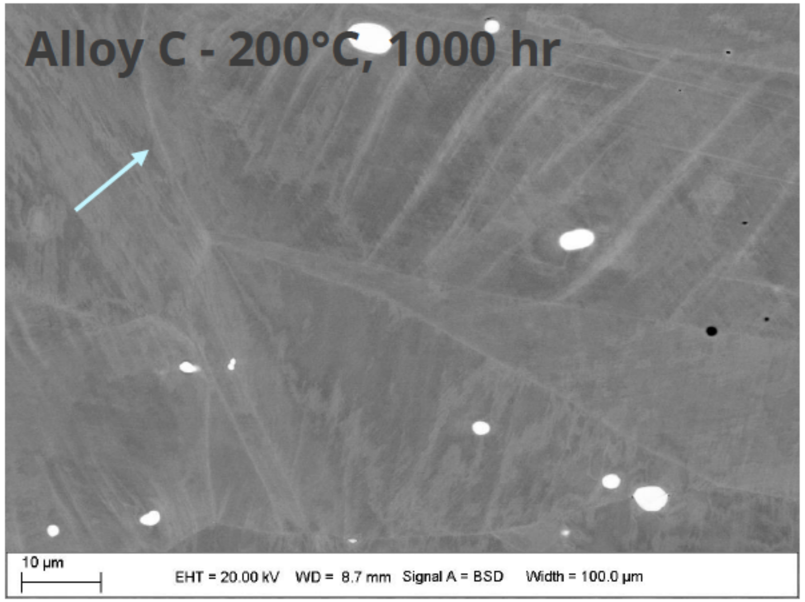
400-410°C

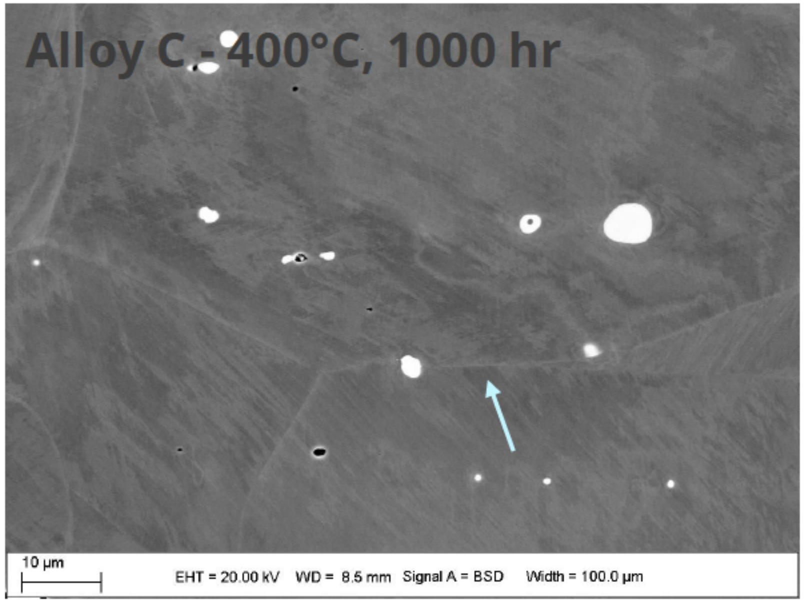


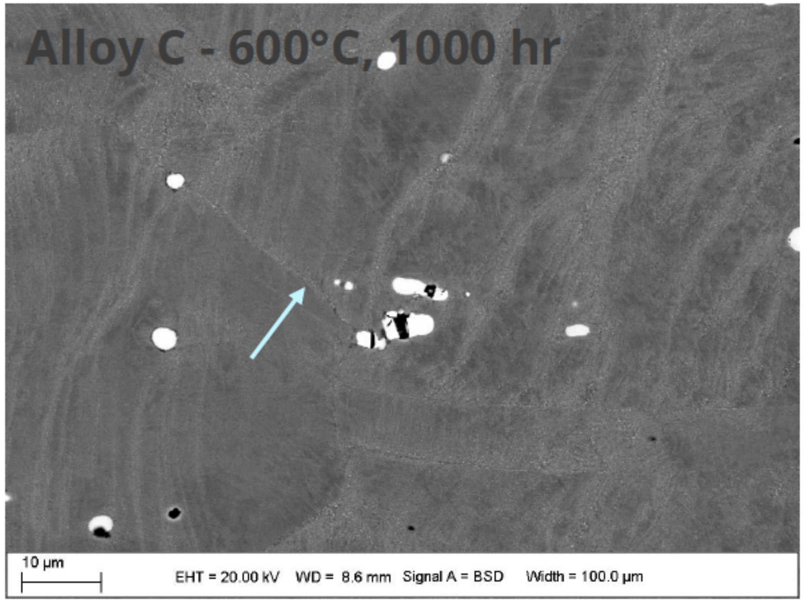
Etched with Lucas' Reagent (150 mL HCl, 50 mL lactic acid, 3 g oxalic acid), 1V for 20-40 seconds depending on aging condition. 200X magnification

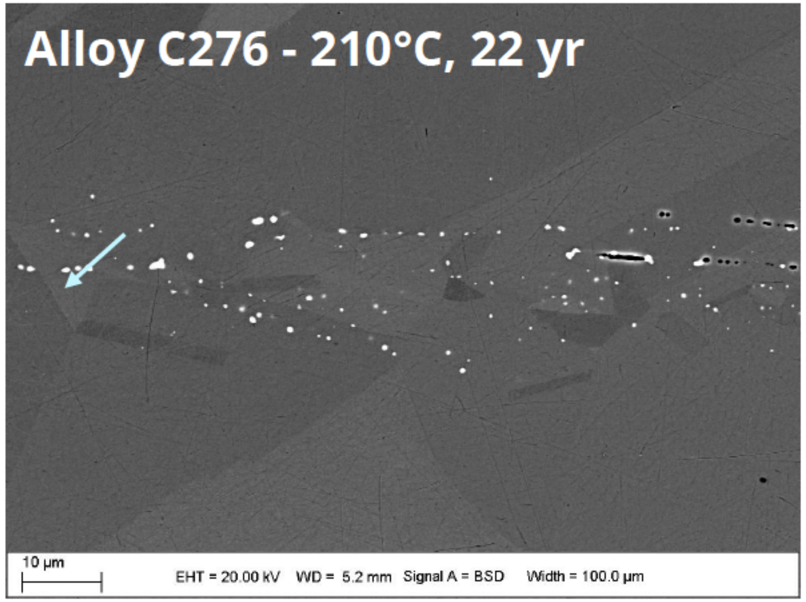
200X

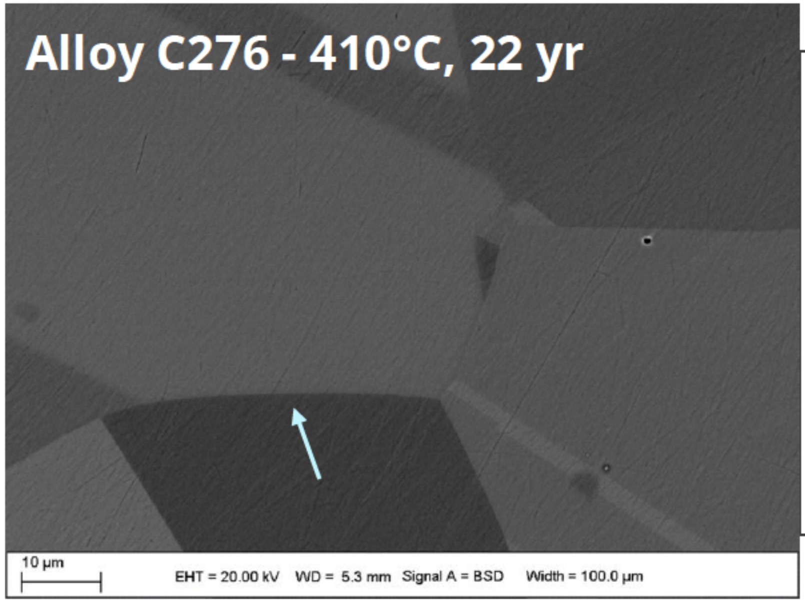
SEM – Hastelloy C and C276





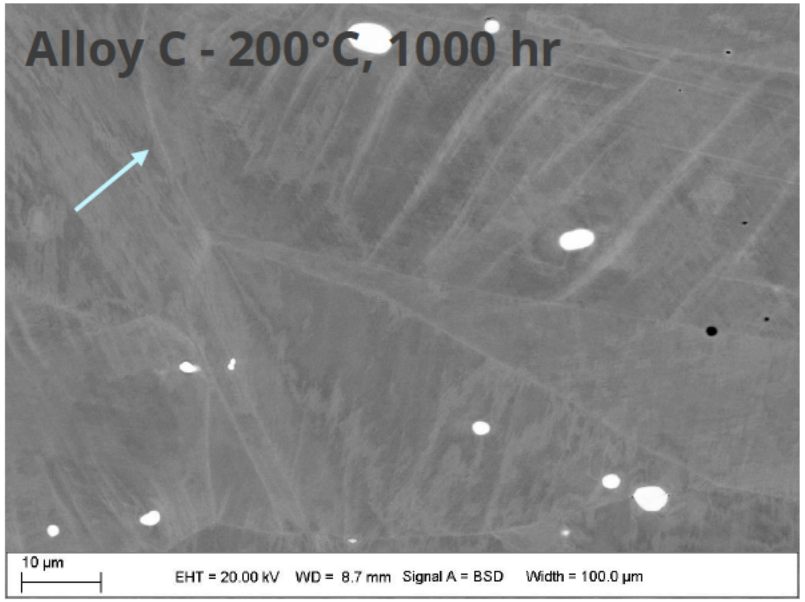


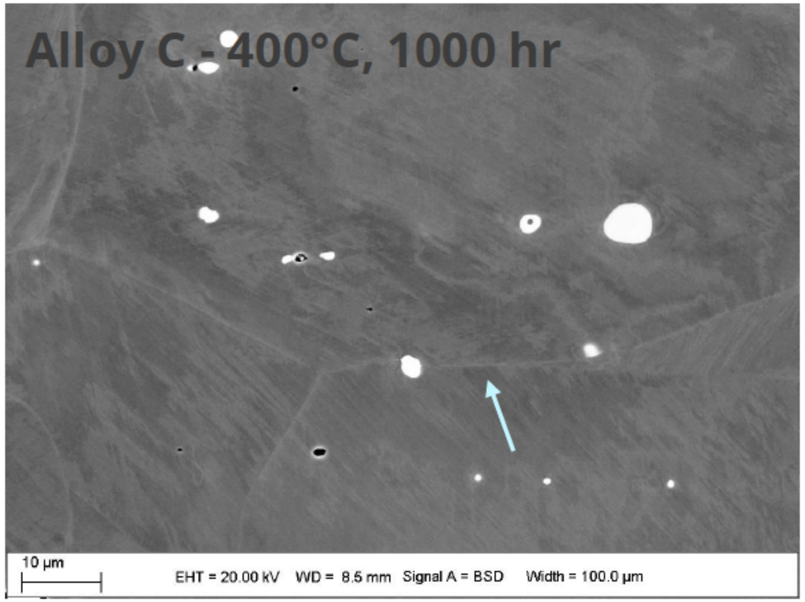


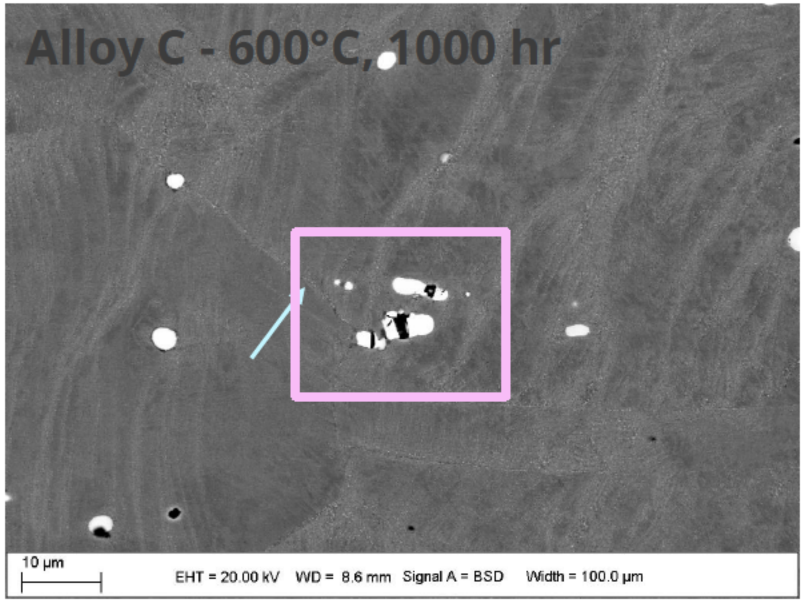


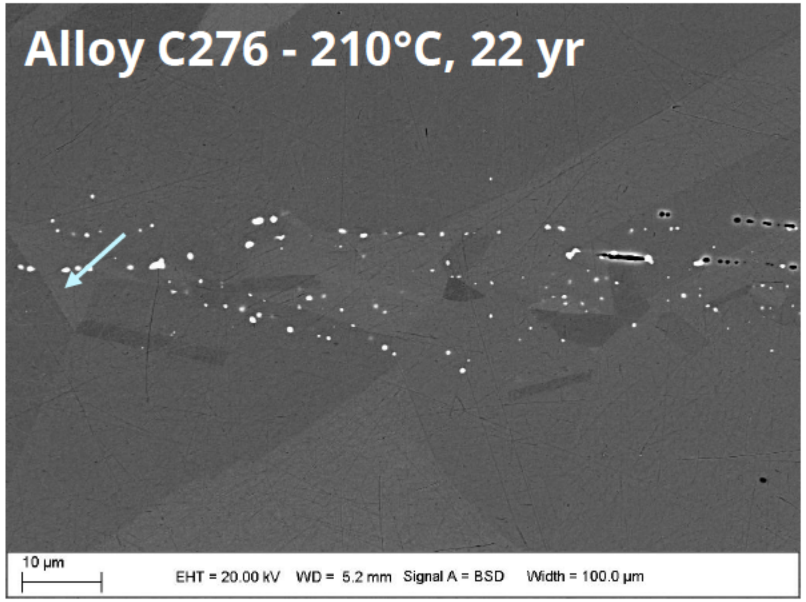
- The 600 °C sample aged for 1000 hours is the only sample with grain boundary precipitation resolvable with SEM.
- The 200-210°C and 400-410°C aged samples did not have evidence of grain boundary precipitation.

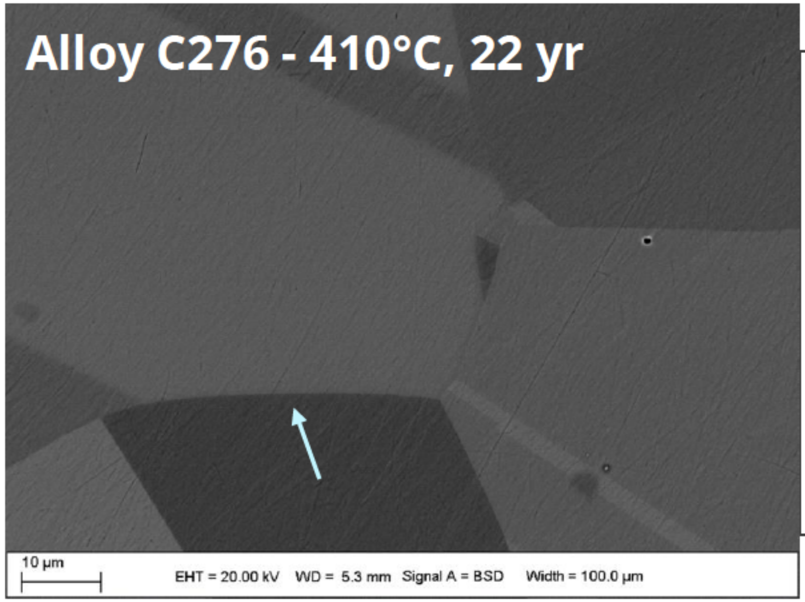
SEM – Hastelloy C and C276











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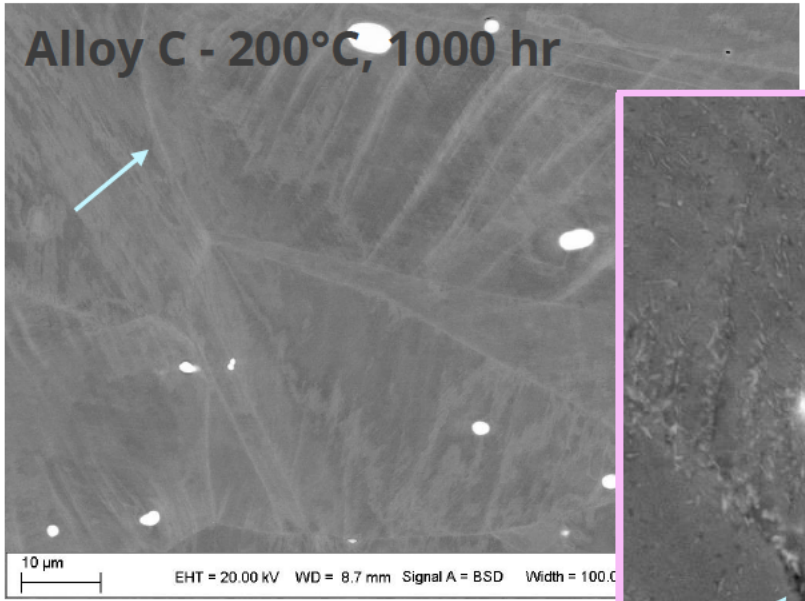
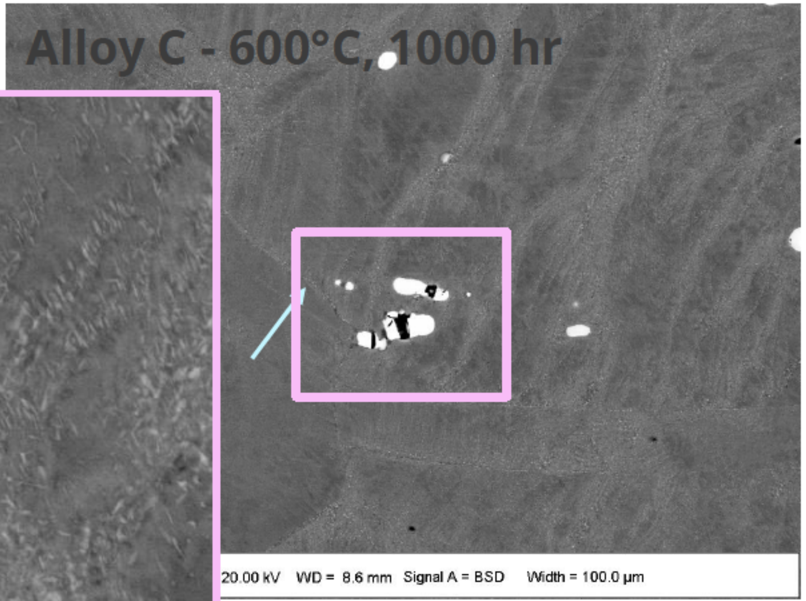
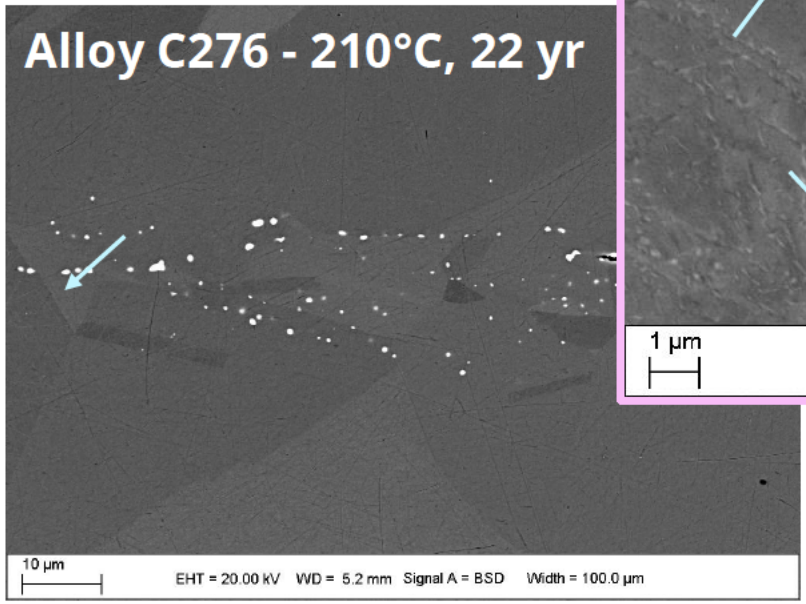
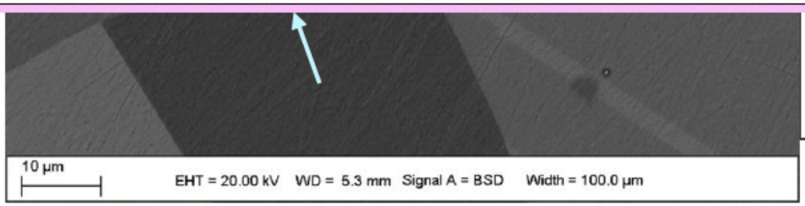


Alloy C - 400°C, 1000 hr

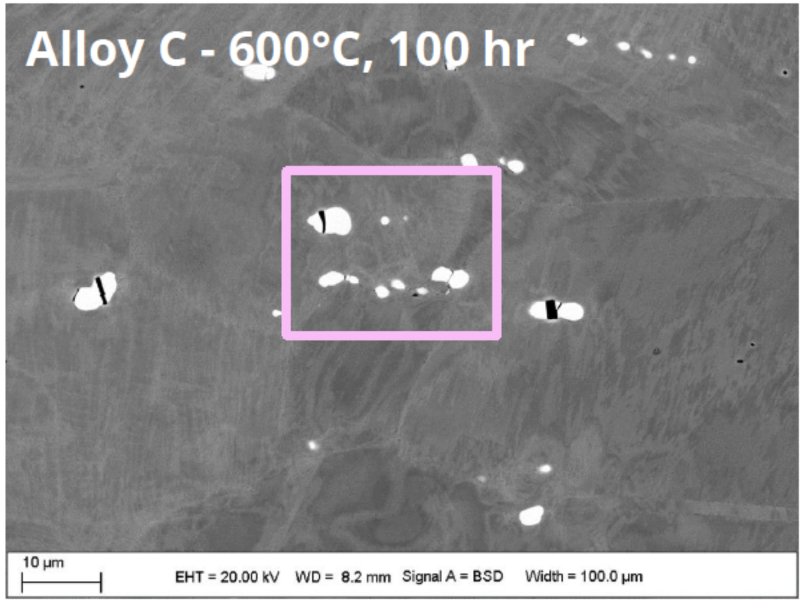


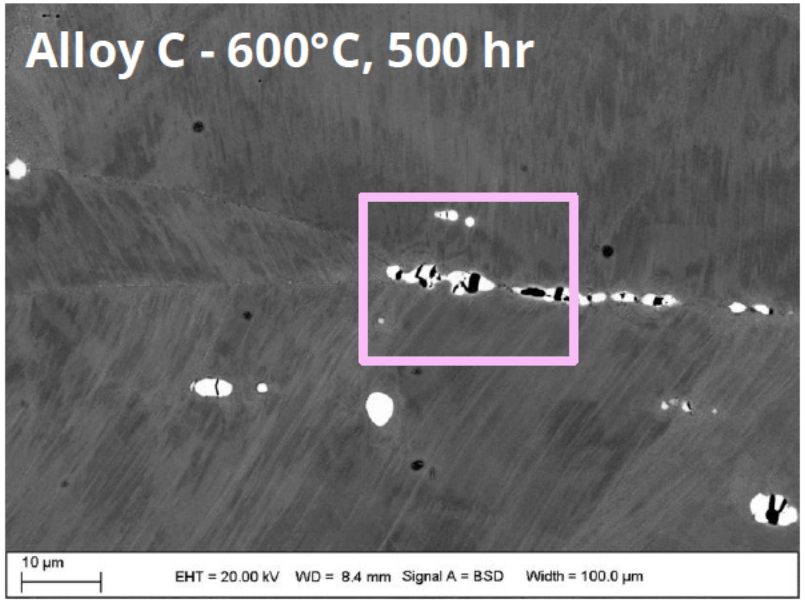


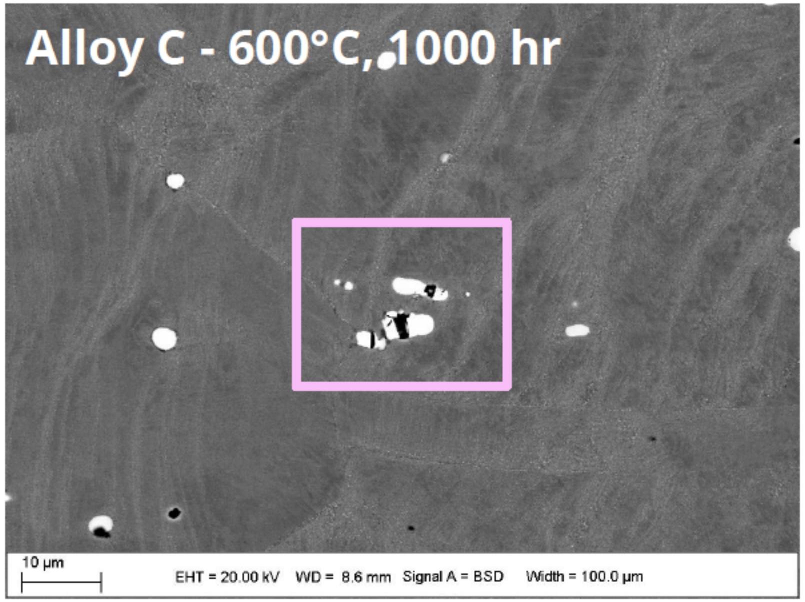


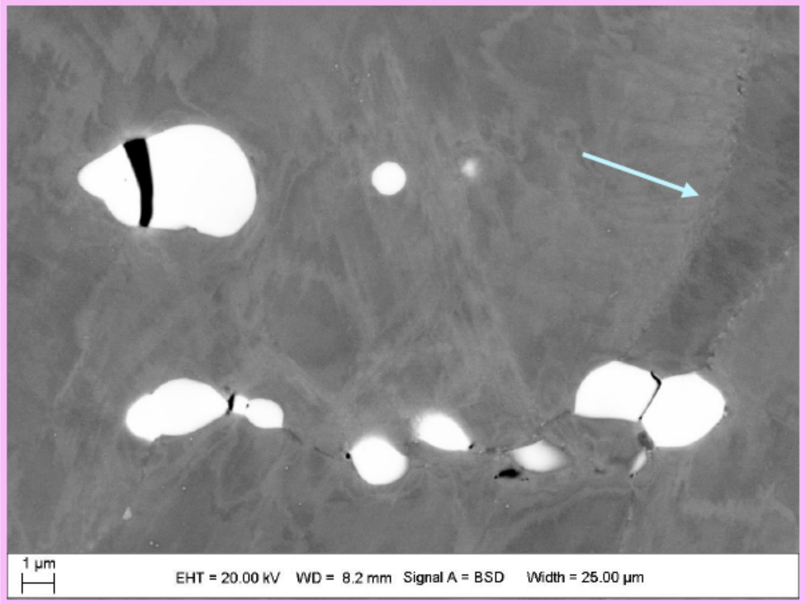
0 °C sample aged for 1000 s is the only sample with boundary precipitation esolvable with SEM. 00-210°C and 400-410°C d samples did not have evidence of grain boundary precipitation.

SEM – Hastelloy C with 600°C Aging

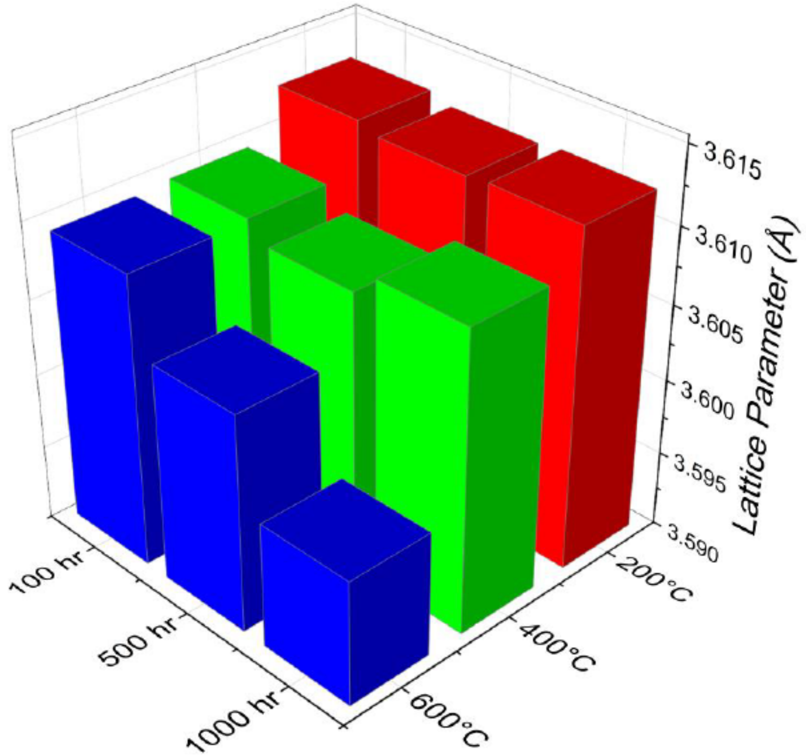


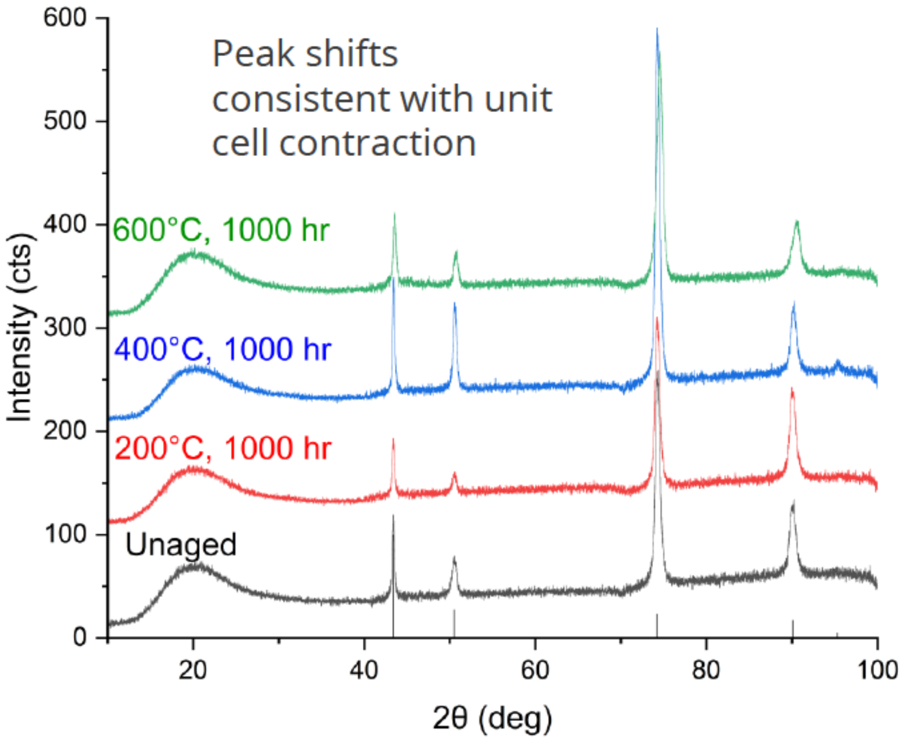






X-ray Diffraction – Hastelloy C

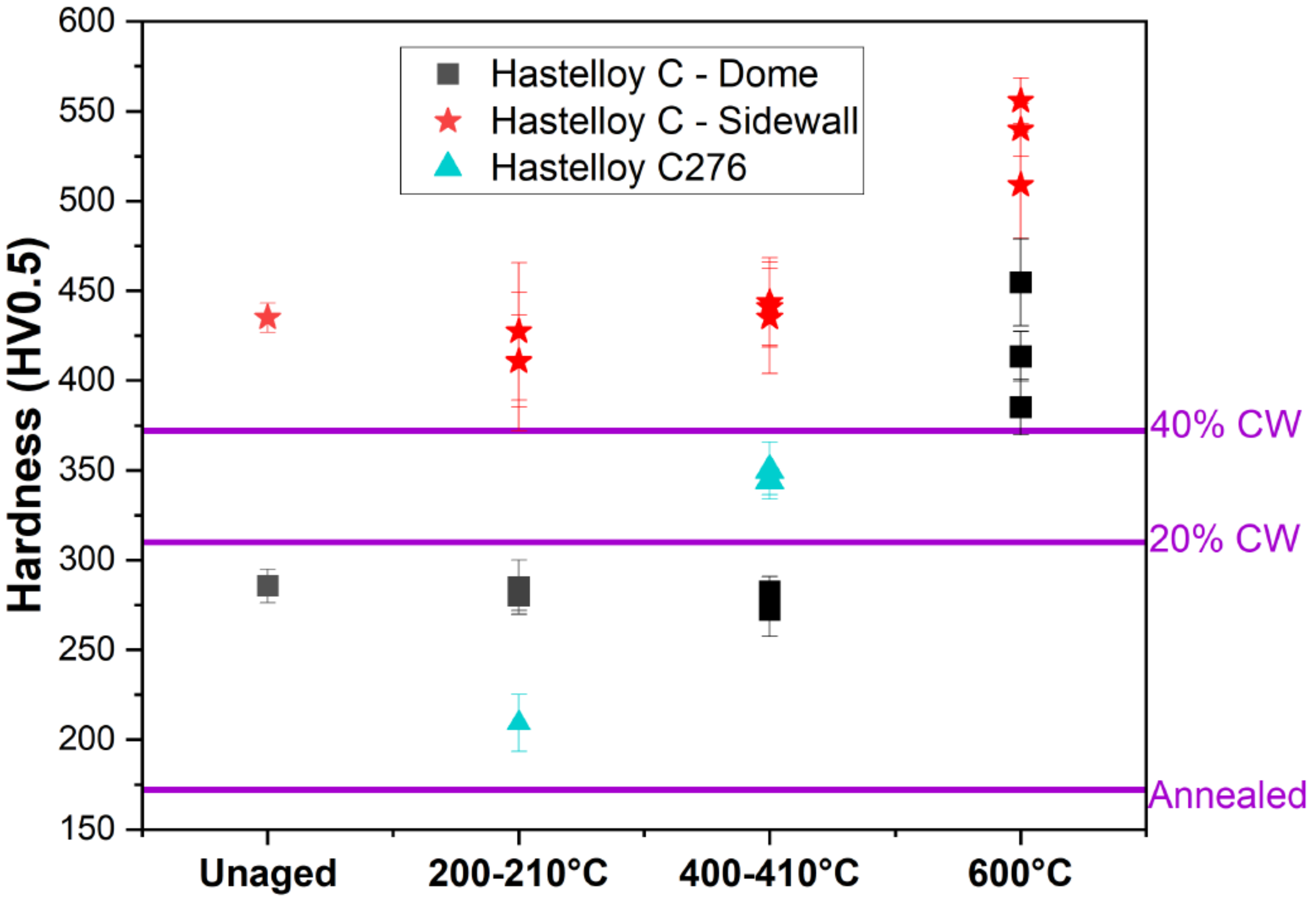




- XRD scans were not sensitive to detection of a 2nd phase.
- The 400°C aged samples had a lattice parameter decrease, though not duration dependent.
- There was a decrease in lattice parameter with aging duration for 600°C.
- Results suggest evidence of ordering in the cubic lattice → resulting in change in lattice parameter (most prevalent at 600°C)

Hardness – Hastelloy C and C276

- Aging duration plays a larger role in hardness at 600°C.
- Hardness does not change substantially in Hastelloy C for the 200°C and 400°C aging temperatures, despite aging duration.
- Hastelloy C276 has a drastic change in hardness between 210°C and 410°C aging conditions – potentially a function of processing.
- Ordering, suggested by XRD, is not strongly correlated to hardness for Hastelloy C at or below 400°C.



Graph shows average hardness for all aging durations. Purple lines reference C276

Summary

There are no notable microstructural changes in Hastelloy C when aged below 600°C, but there is a distinct effect on etching response.

A lattice parameter decrease with aging duration at 600°C suggests long range ordering in the cubic lattice.

Only the 600°C aged Hastelloy C samples showed evidence of grain boundary precipitation resolvable with SEM.

Aging temperatures <500°C had differing effects on hardness for Hastelloy C, where there was little change in hardness, versus Hastelloy C276, where the difference in hardness was pronounced. This is likely due to processing history.

The 600°C aging temperature in Hastelloy C produced more notable effects on material behavior, including grain boundary precipitation, lattice parameter shift, hardness increase.

The 200°C and 400°C aging temperatures produced less significant material effects for Hastelloy C, though not negligible. Further study is needed to separate processing and aging effects for Hastelloy C276.

Acknowledgements

Acknowledgement to Riley O'Connor, Mark Reece, Christina Profazi, Johnathon Brehm, Alex Hickman, James Whitaker, Mark Rodriguez, Nichole Valdez and Landon Schnebly for their experimental and characterization support

Questions?

Microstructural Analysis – Hastelloy C (200°C age)

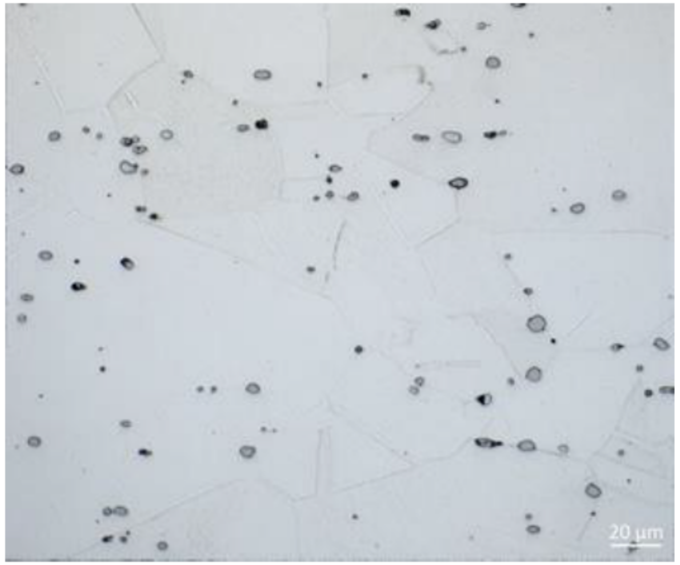
Unaged

Other etchants tested:

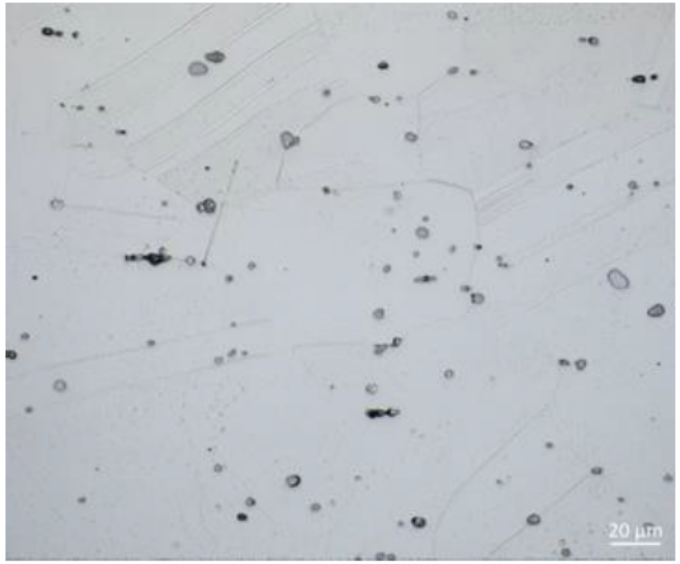
- ASTM 83 - CrO_3, water (electrolytic) → Nodules
- ASTM 94 – Kalling's 2 (swab) → No response
- Haynes oxalic/HCl (electrolytic)→ Inconsistent etching
- ASTM 36 – $FeCl_3$, HCl, water (swab)→ No response
- ASTM 219 – HNO_3, water (electrolytic) → Only etched 600°C
- ASM 12 Heat Resistant Alloys– HCl, acetic acid, HNO_3 (swab)→ Inconsistent etching
- ASM 24 Heat Resistant Alloys – Lucas' reagent (electrolytic) → Success!

200°C

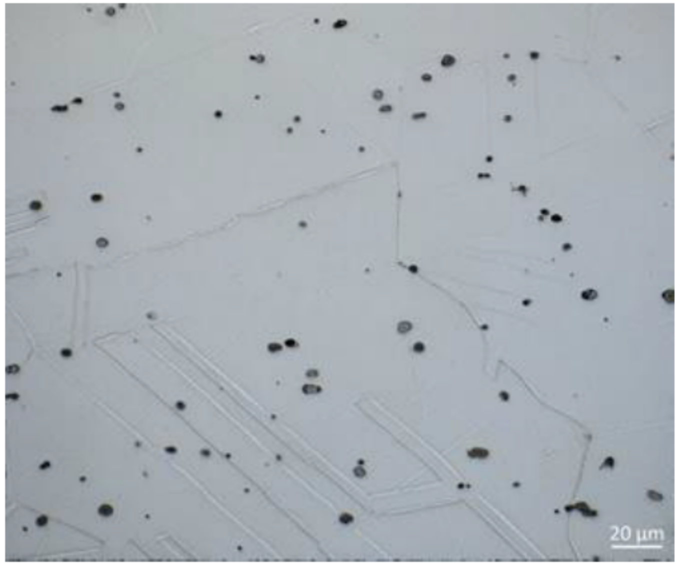
100 hr



500 hr



1000 hr



Etched with Lucas' Reagent (150 mL Hcl, 50 mL lactic acid, 3 g oxalic acid). 1V for 20-40 seconds depending on aging condition.
500X magnification

Microstructural Analysis – Hastelloy C (400°C age)

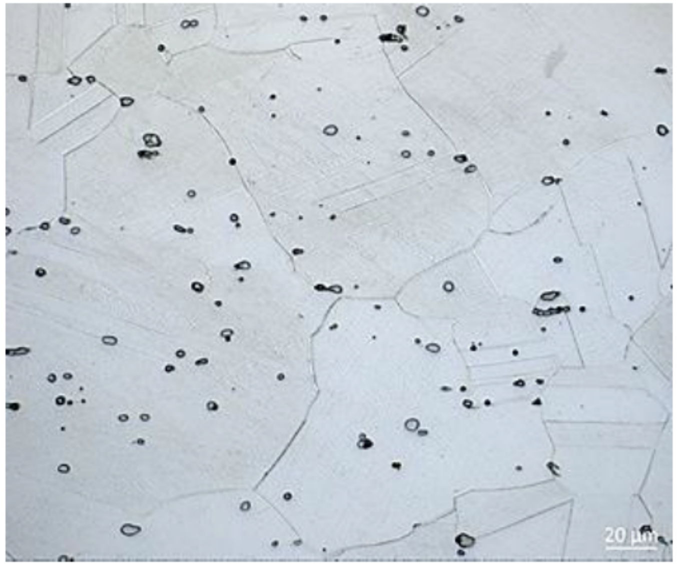
Unaged

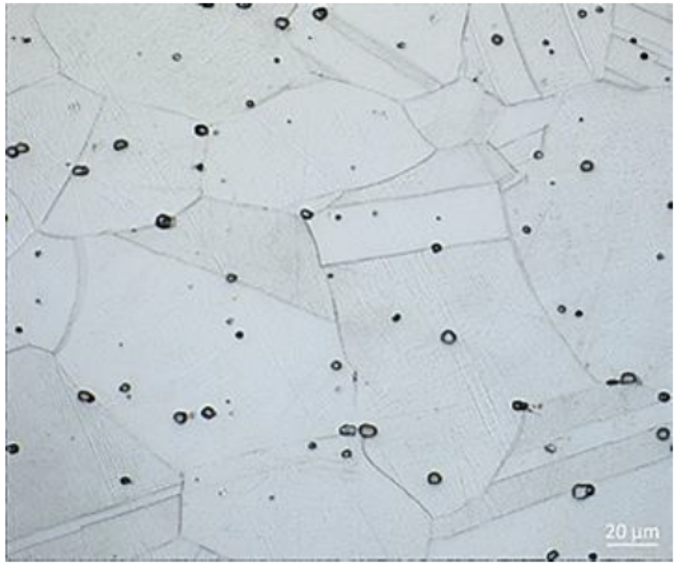
100 hr

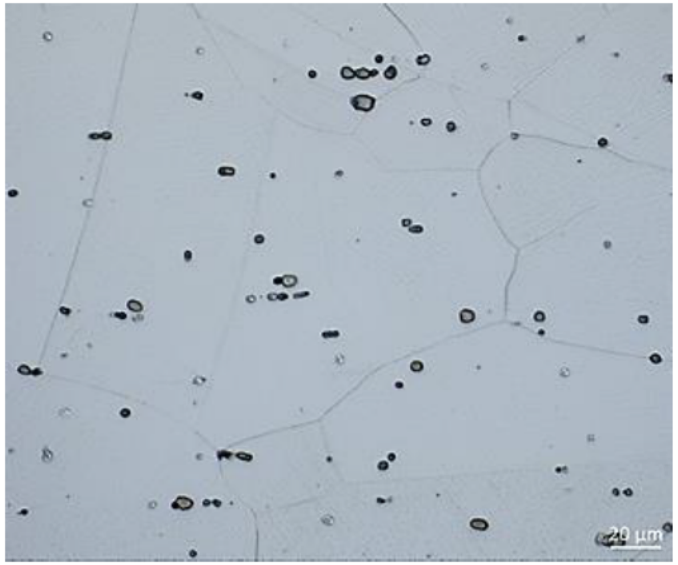
500 hr

1000 hr

400°C







Etched with Lucas' Reagent (150 mL Hcl, 50 mL lactic acid, 3 g oxalic acid). 1V for 20-40 seconds depending on aging condition.
500X magnification

Microstructural Analysis – Hastelloy C (600°C age)

Unaged

600°C

100 hr

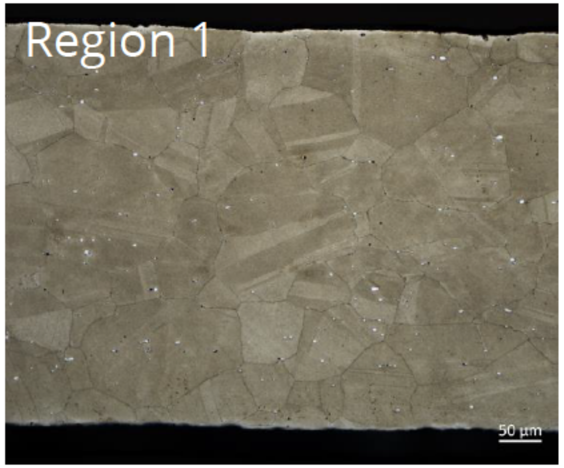
500 hr

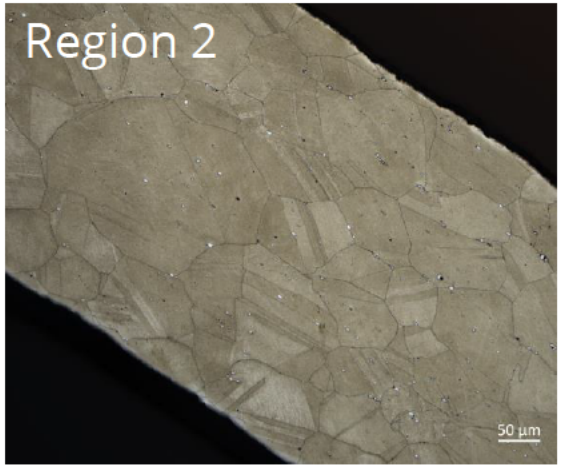
1000 hr

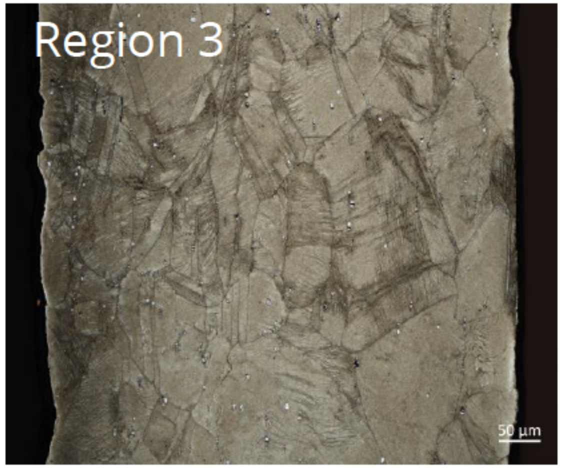
Etched with Lucas' Reagent (150 mL Hcl, 50 mL lactic acid, 3 g oxalic acid). 1V for 20-40 seconds depending on aging condition.
500X magnification

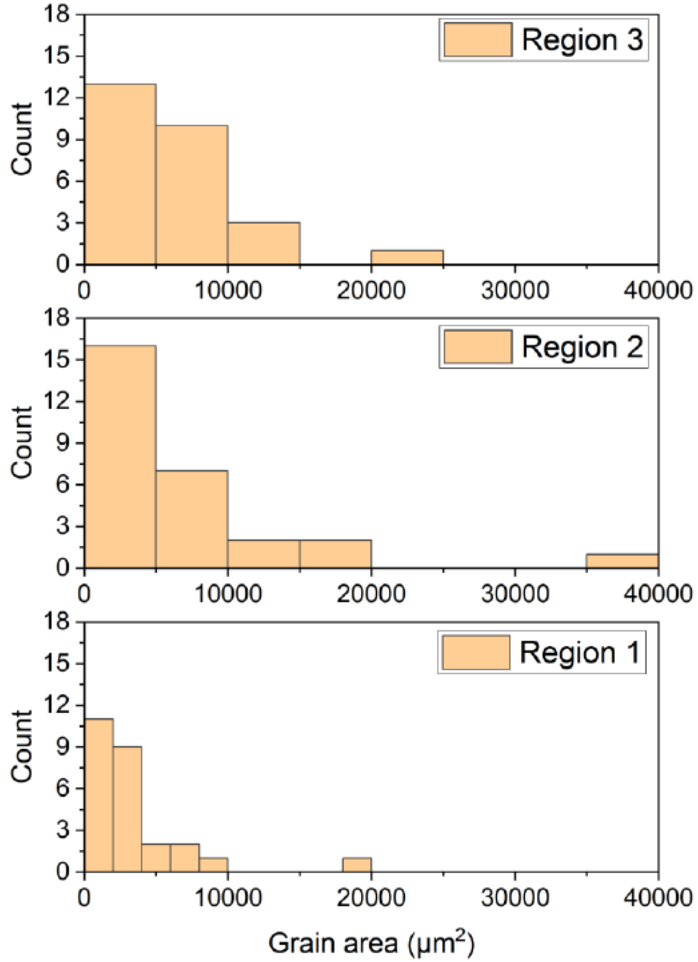
Grain size

600°C, 1000 hr (different locations)









- The 600 °C sample aged for 1000 hours has a right skewed distribution with the majority of the grains being <10000 µm².
- At different locations for the same aging condition, grain size distribution is relatively consistent.