MICROSTRUCTURE AND DEFORMATION BEHAVIOR OF THERMALLY AGED CAST AUSTENITIC STAINLESS STEELS

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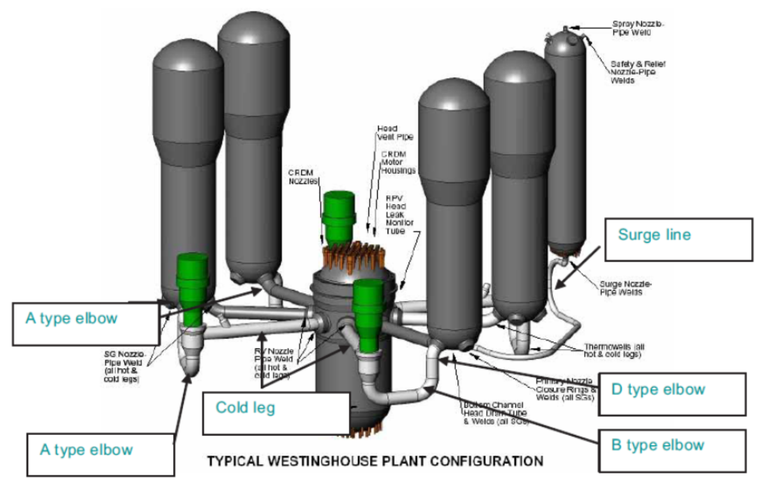
Background

- **CASS alloys, ASME SA-351 grades, are used in various reactor components at primary pressure boundaries and reactor core internals**
  - Crucial for functionality, safety, and reliability
- **A dual-phase microstructure of γ-austenite and δ-ferrite:**

  $L \rightarrow L + \delta \rightarrow L + \delta + \gamma$

  $\rightarrow \delta + \gamma$
- **Ferrite fraction depends on:**
  - Composition
  - Cooling rate …

Jet Pump, Nelson, 2008



Heavy Component replacement, IAEA, 2008

Delta Ferrite …

- **The good:**
  - **Help prevent "hot cracking"**
  - **Provide a strengthening mechanisms for solidification microstructure**
  - **Improve the resistance to sensitization and SCC**
- **The bad:**
  - **Unstable when exposed to elevated temperatures**
    - **Formation of Cr-rich α' phase through spinodal decomposition**
    - **Precipitation and growth of carbides and G-phase**
  - **Deteriorated properties … Embrittlement**

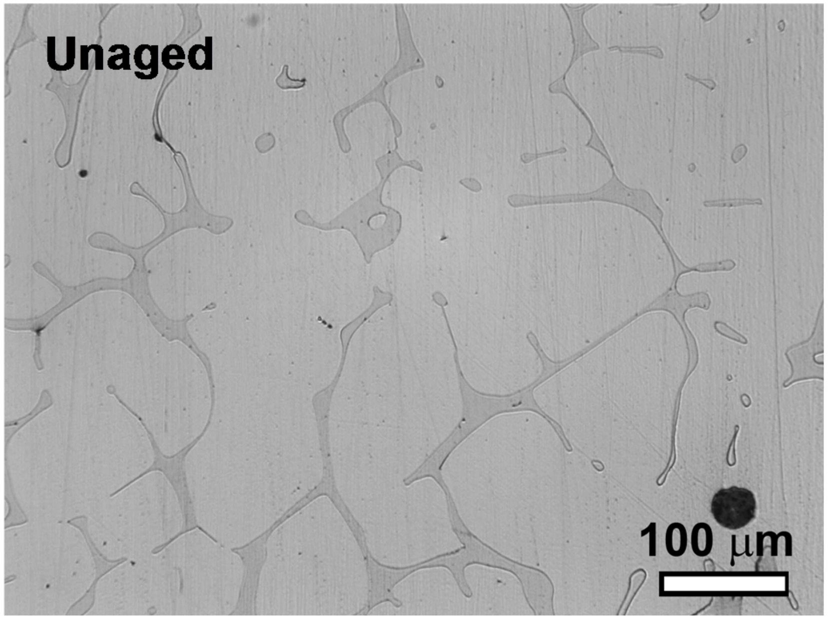
Objective – to understand the thermally induced embrittlement behavior in CASS alloys

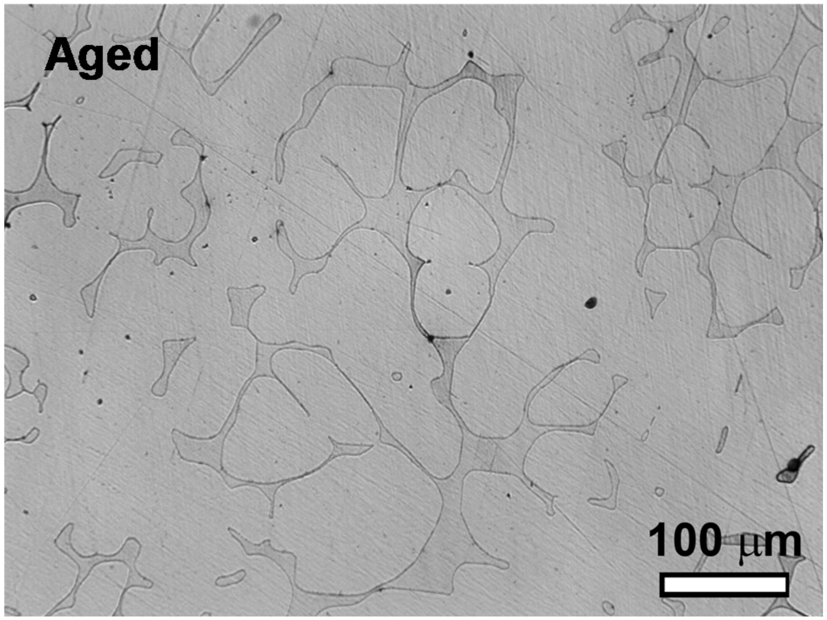
Material

- **A CF8 static casting with 23% ferrite**

Heat ID	Delta ferrite	Composition (wt. %)								
		Mn	Si	P	S	Mo	Cr	Ni	N	C
68	23%	0.64	1.07	0.021	0.014	0.31	20.46	8.08	0.062	0.063

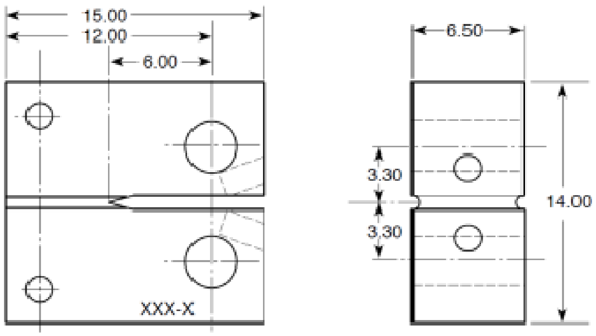
- **Thermal aging at 400°C for 10,000 hr**

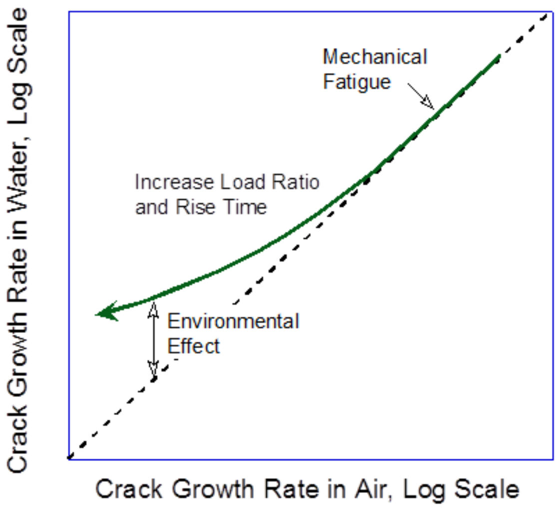




Tests and Specimens

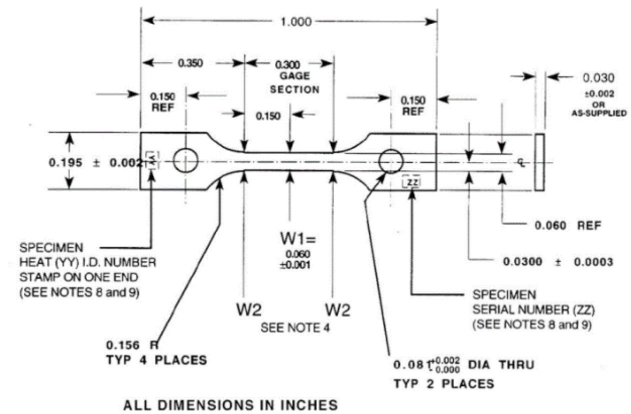
- CGR test – 1/4T-CT with side grooves
  - Tested in low-DO high-purity water: DO<10 ppb, Conductivity 0.07 µS/cm.
  - ~1800 psig, ~315°C, Flow rate: 20-30 ml/min
  - Pre-crack in environment for enhanced cracking
  - SCC CGRs measured with and without periodical partial unloading
- J-R curve test – 1/4T-CT
  - Use a SCC starter crack.
  - Very slow displacement rate, ~0.43 mm/s.
- Microstructural characterizations – 3 mm dis
  - TEM observation before and after aging
  - Atom Probe Tomography (APT) – FIBed from ferrite in TEM disk

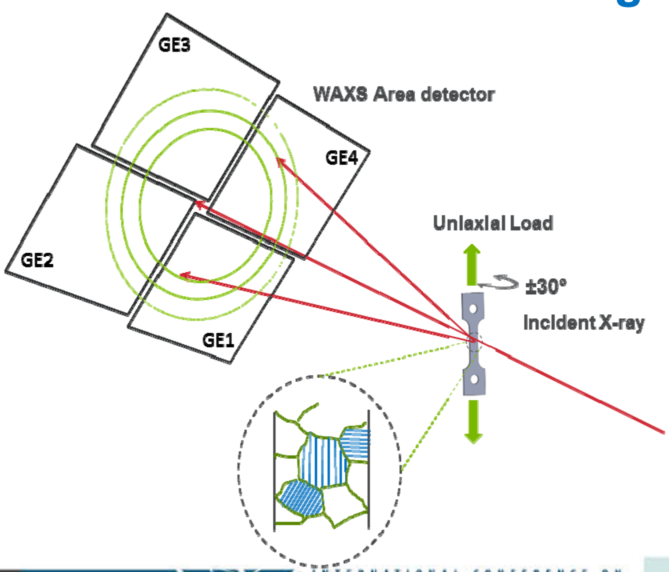


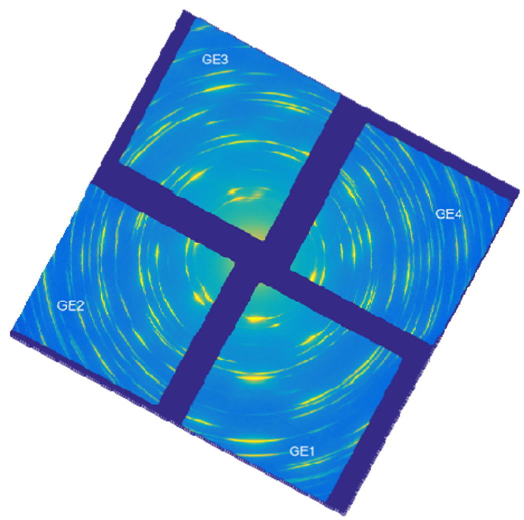


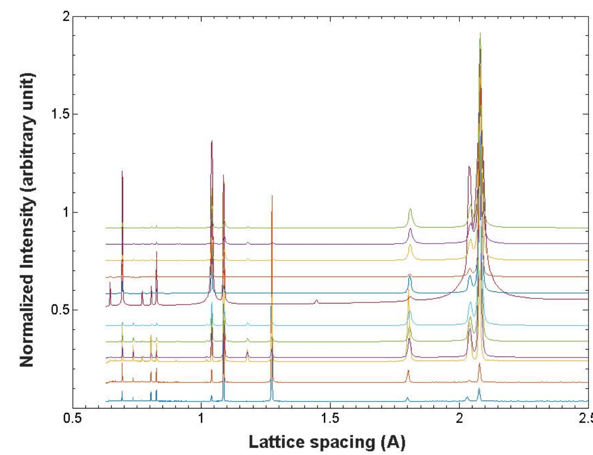
Tensile test with *in-situ* WAXS

- **Tensile test:**
  - Flat tensile specimen with a gauge dimension of 7.6x1.5x0.8 mm
  - In air atmosphere at room temperature
  - Strain rate: 0.5-1 x10^{-4} s^{-1}
- **Wide-angle X-ray scattering (WAXS)**
  - High-energy X-ray: ~72-123 keV
  - Large beam size and sample rotation (±30°
  - Scan the whole gauge length continously

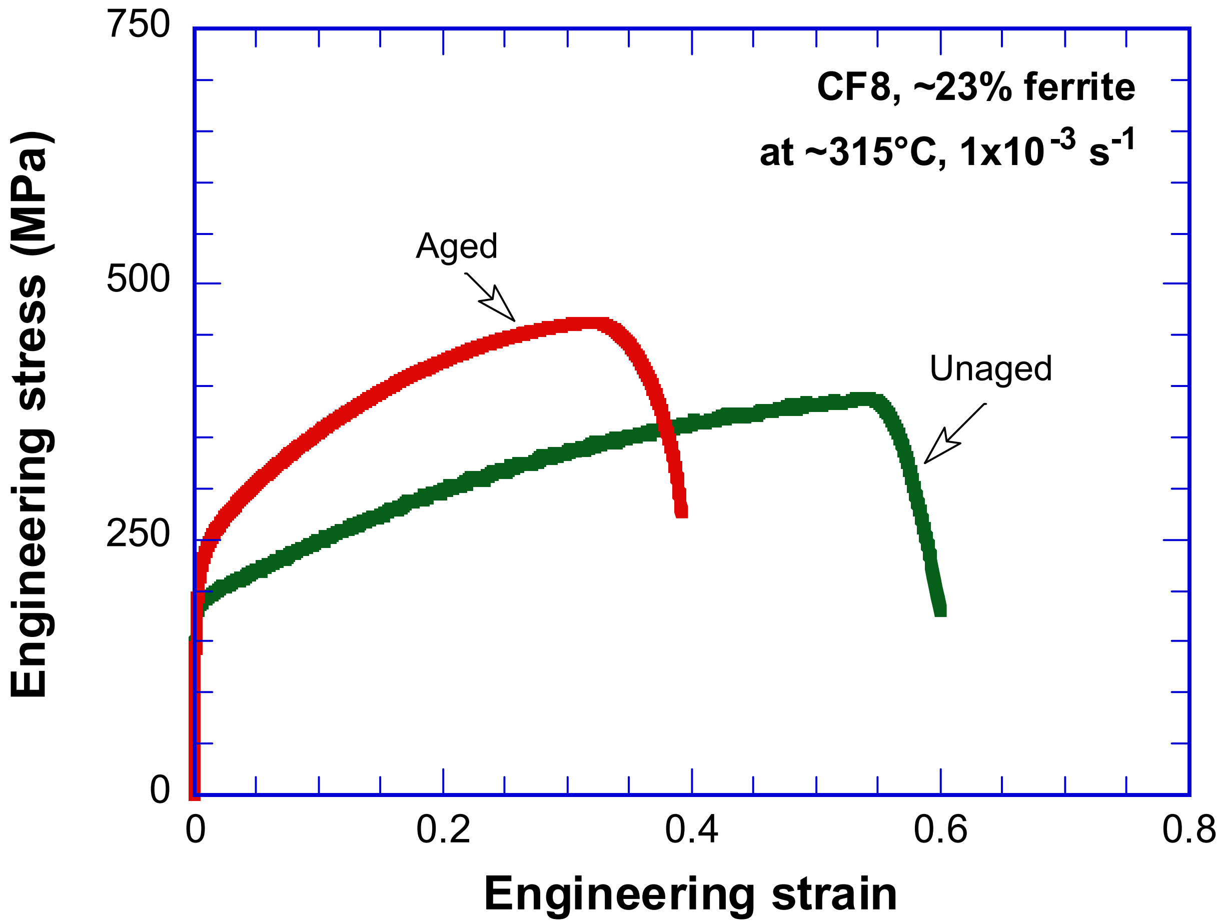








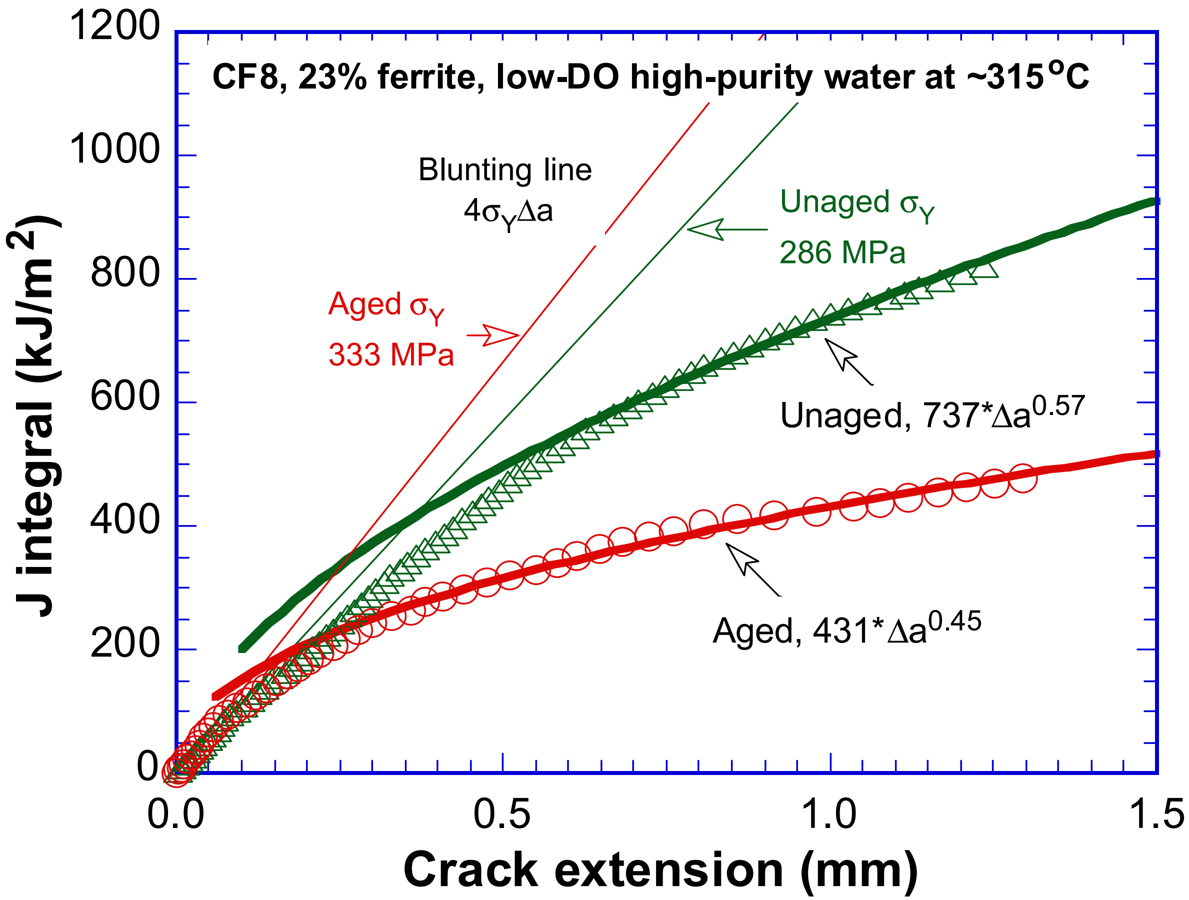
Tensile Test Results



Flow stress:
Unaged – 286 MPa
Aged – 333 MPa

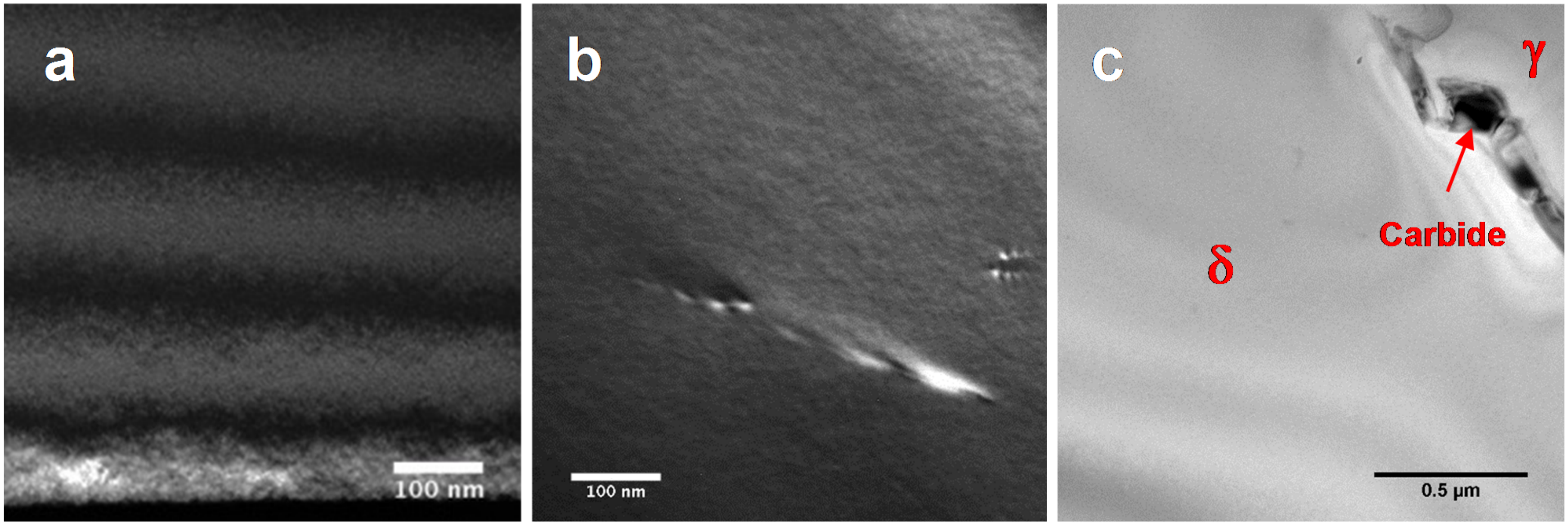
Thermal aging increases the strength and reduces the ductility of CF8.

J-R Curve Test Results



The energy release rate for propagating crack is much lower for the aged sample.

TEM Microstructure - Austenite

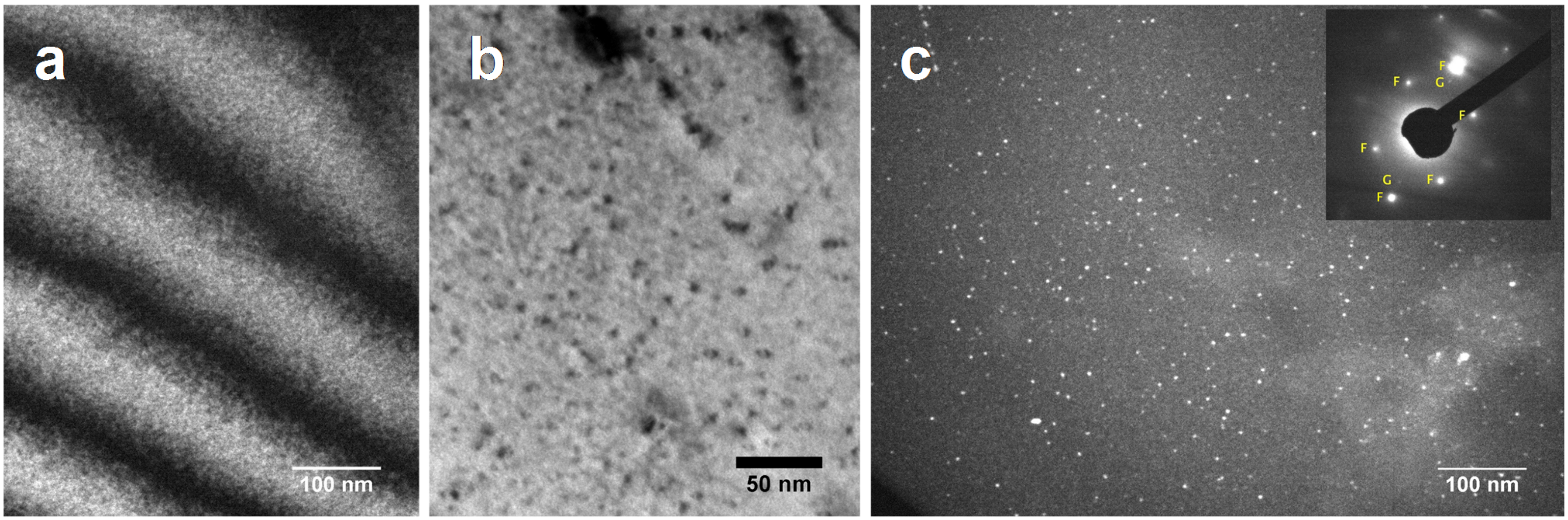


Before aging

After aging

No visible change in austenite before and after thermal aging

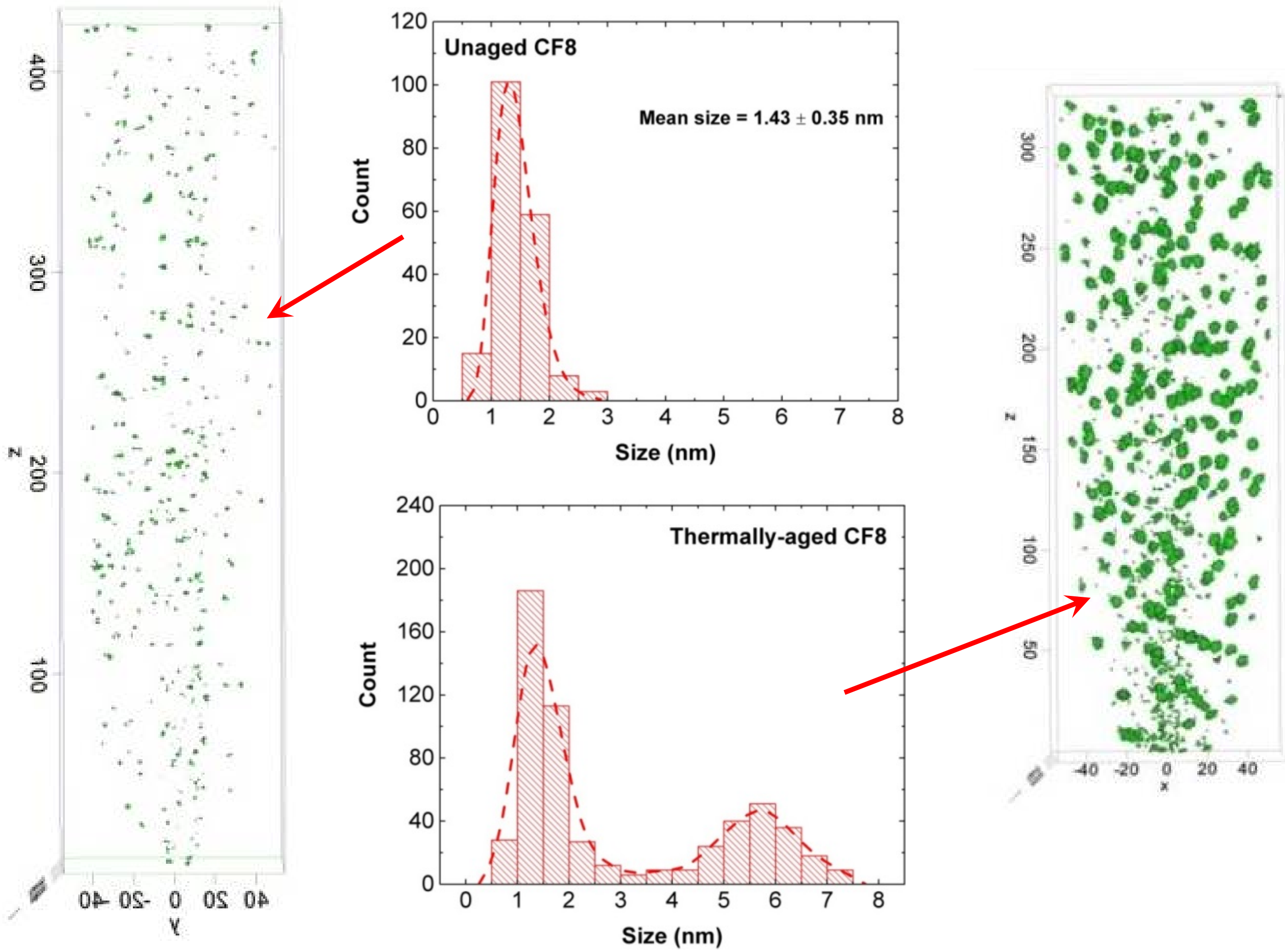
TEM Microstructure - Ferrite



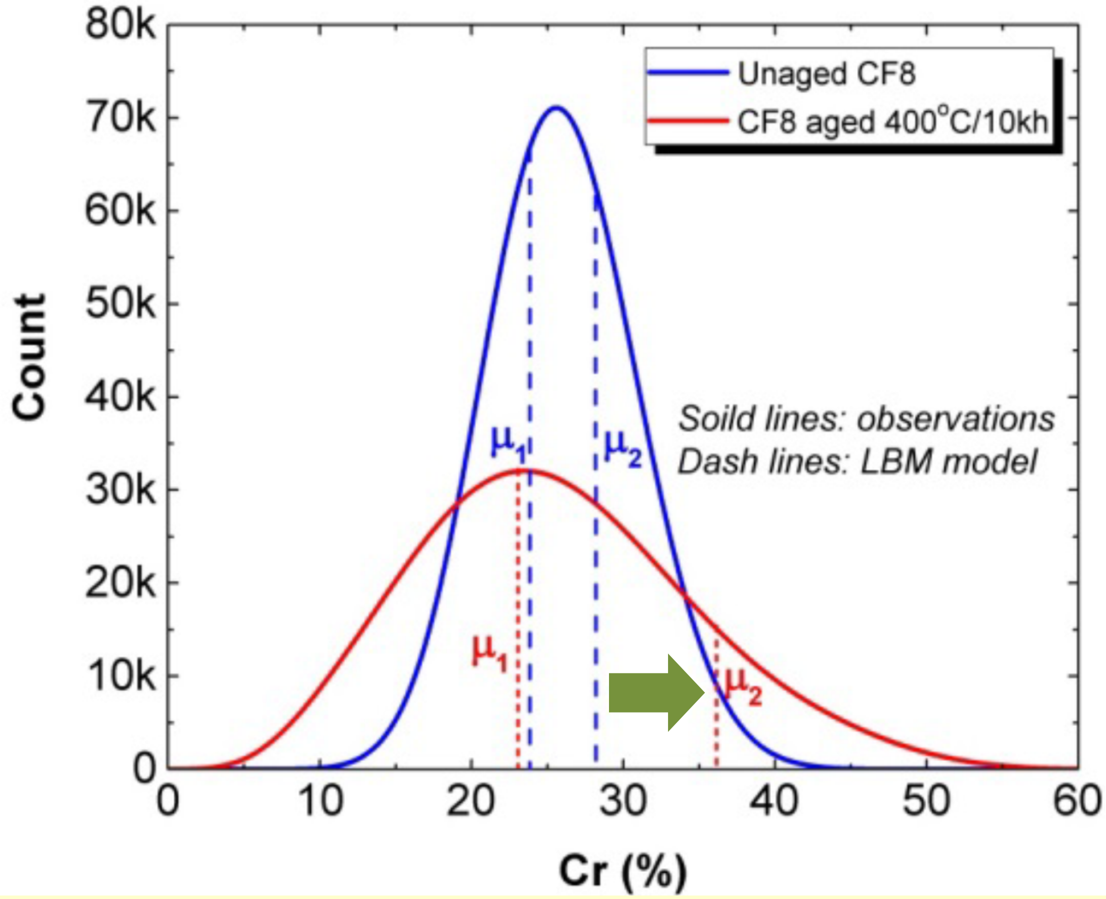
Before aging After aging

A high density of G-phase precipitates after thermal aging can be observed.

APT Result on NiSi Clusters



APT Result on α/α' decomposition

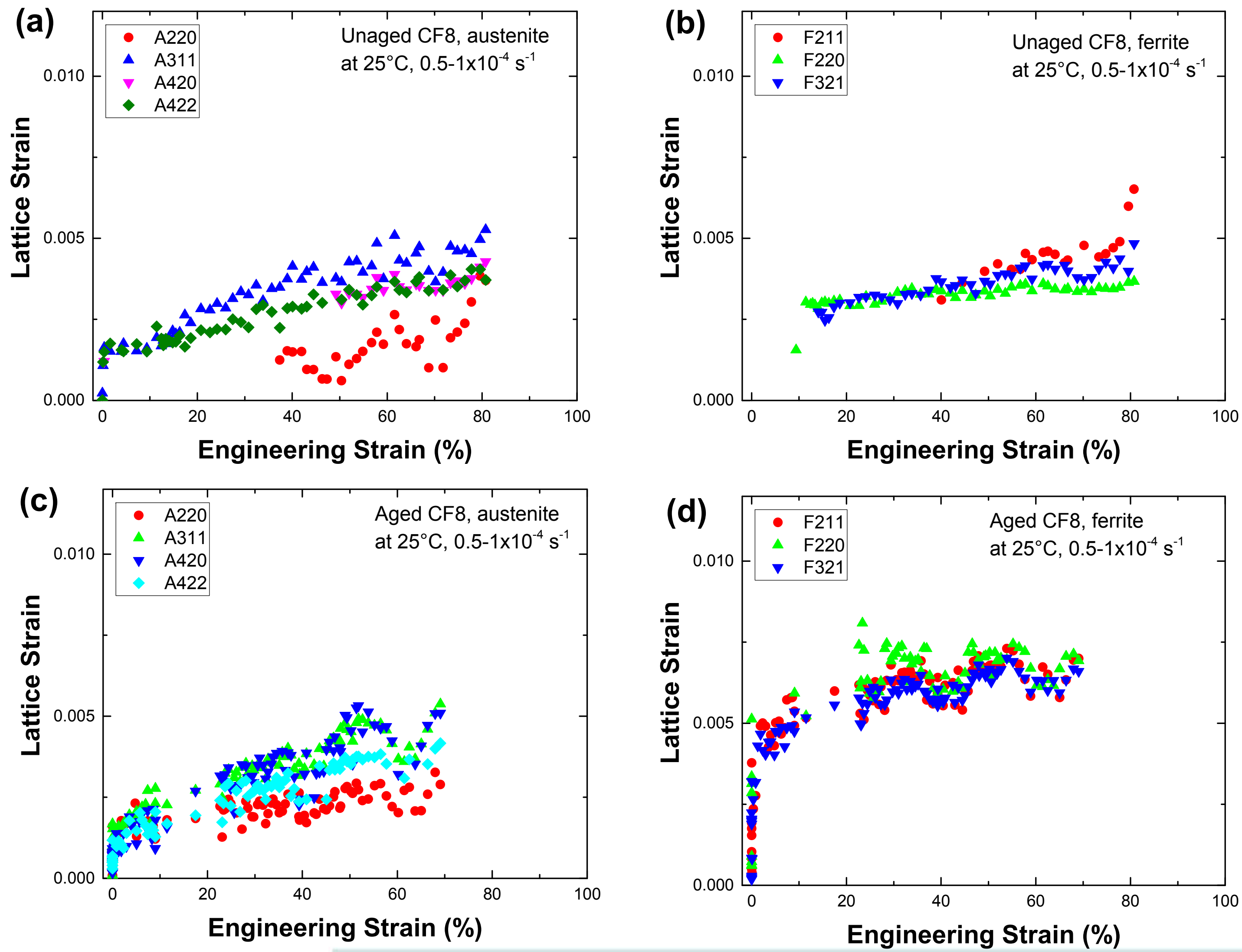


Thermal aging at 400°C induces phase separation of α/α'.

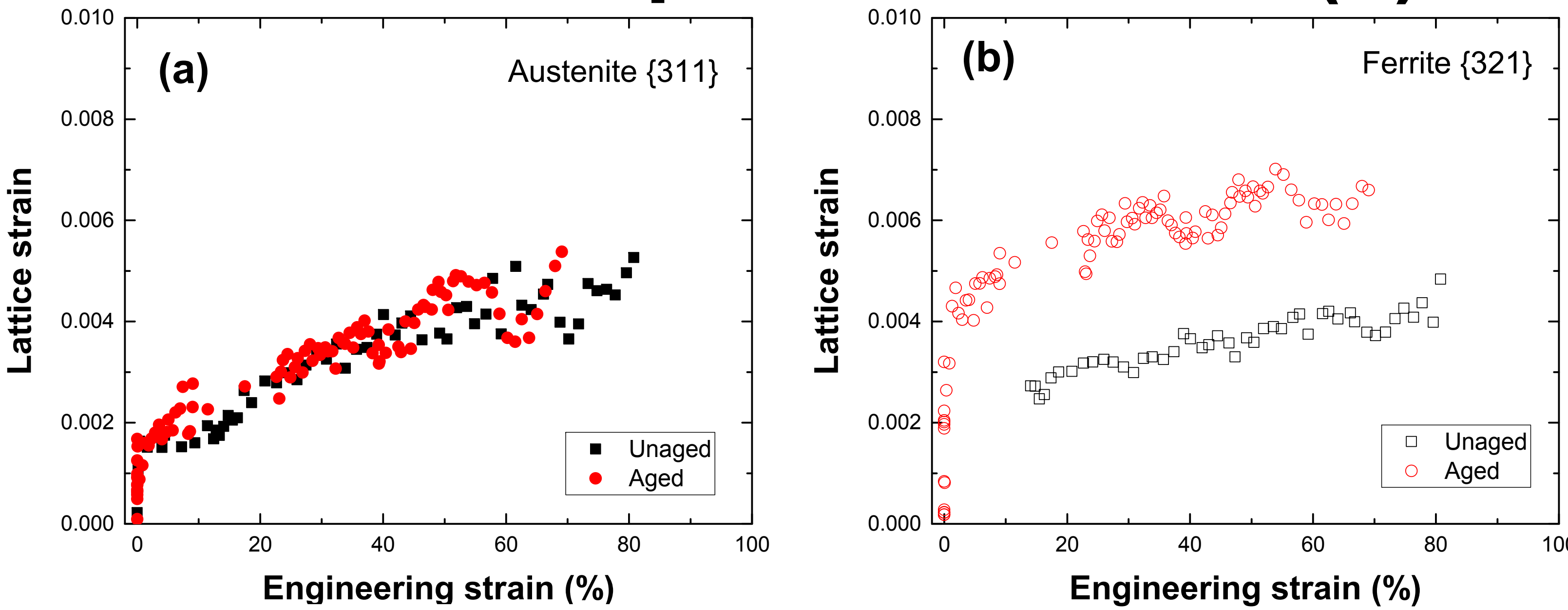
Phase-Specific Strains (1)

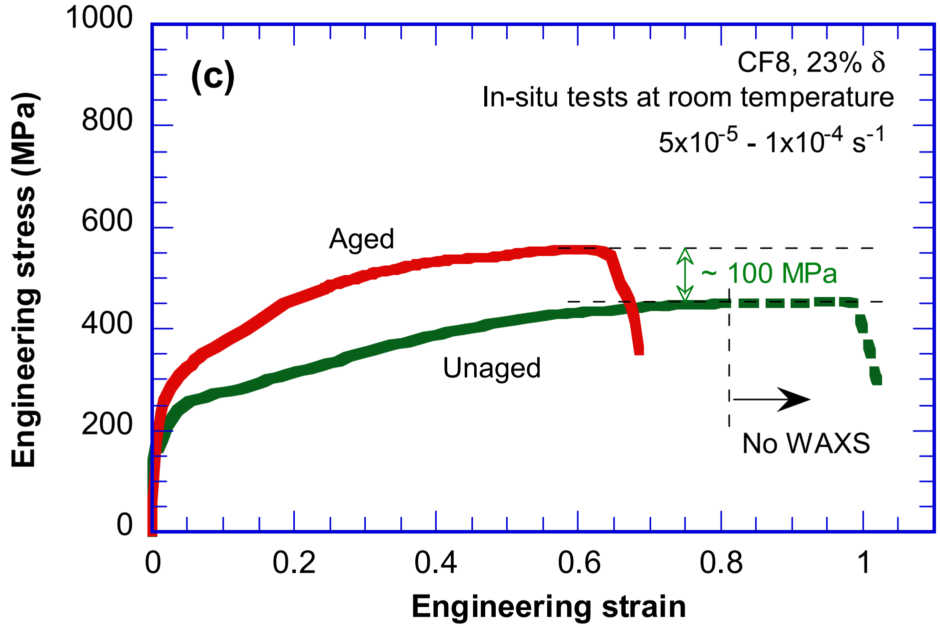
Austenite | **Ferrite**

Unaged / **Aged**



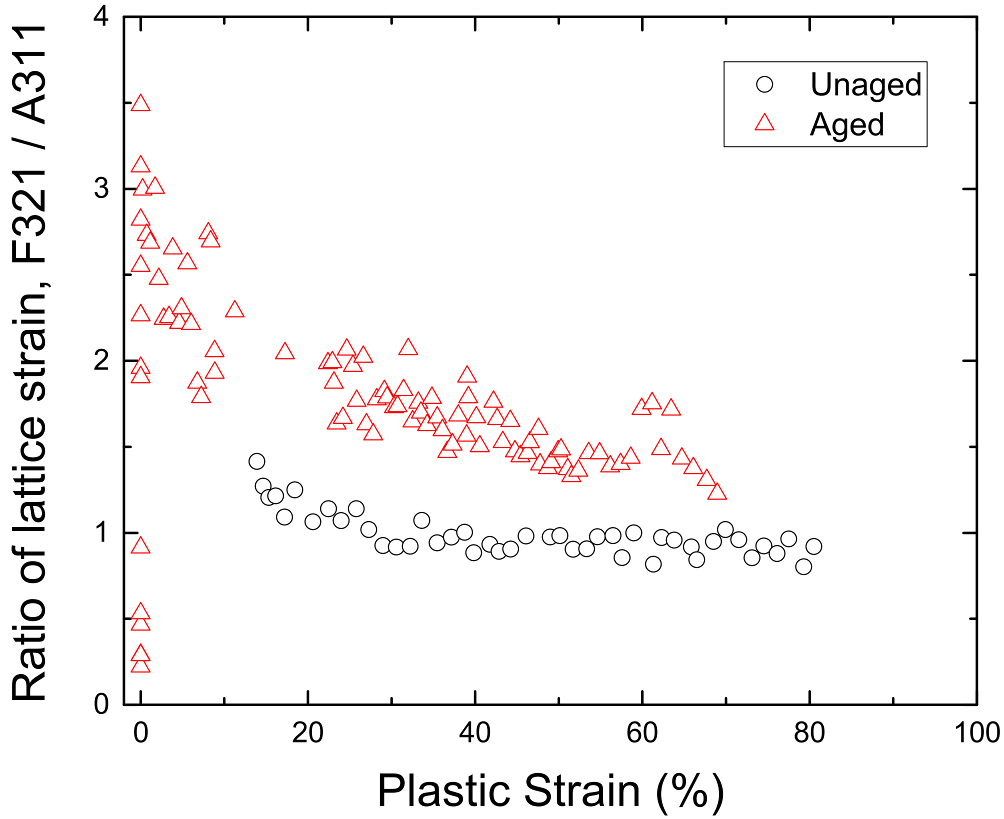
Phase-Specific Strains (2)





Both G-phase precipitates and α/α' separation contribute to the hardening resulting from thermal aging.

Load Partitioning Between δ and γ



- **Load carried by ferrite and austenite continues to evolve during deformation.**
- **Incompatible strain between austenite and ferrite may be a critical factor in prompting embrittlement.**

Conclusion

- **Significant embrittlement can be observed in CF8 with 23% ferrite after thermal aging at 400°C for 10,000 hr.**
- **The microstructure of austenite phase was unaffected by thermal aging. G-phase precipitates and α/α' phase separation were observed in ferrite.**
- **In-situ straining tests showed much higher lattice strains in aged ferrite, and the observed phase-specific hardening can account for the overall increase in flow stress of the aged sample.**
- **The differences in lattice strains between ferrite and austenite were much higher in the aged than unaged samples, suggesting a higher degree of incompatible strain between ferrite and austenite is responsible for the observed thermal-aging embrittlement.**

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Thank You