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Testing Approach and Initial Results on PM-HIP Ni-Based Alloys

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Outline

- History and timeline
- Approach
  - Materials
  - Test types and methods
  - Additional considerations
- Examples of Initial Results

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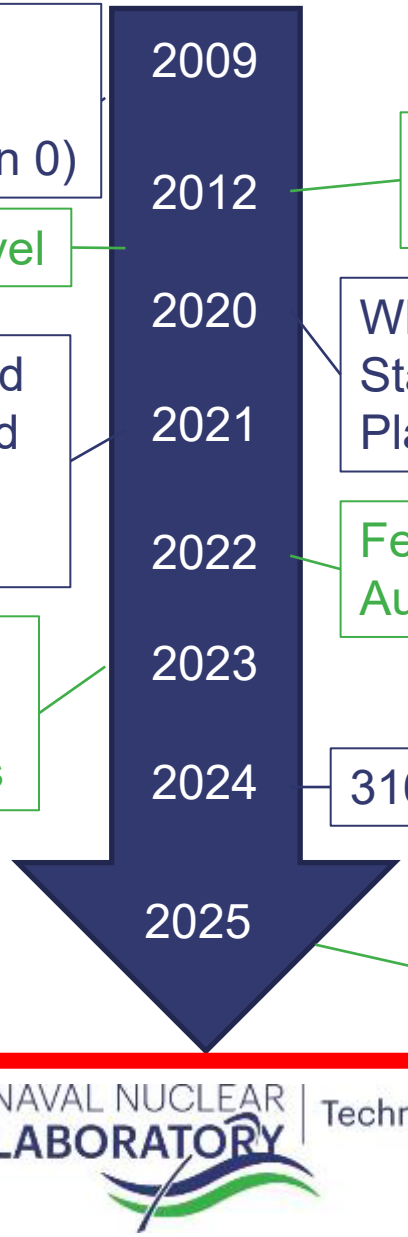
History and Timeline of 'Modern' PM-HIP Materials Program



2009

Interest in PM-HIP 600
Testing plan formed
Procurements for 2 billets initiated (gen 0)

2012

Testing continued at a low level

Interim report on measured properties
Interest waned, primarily due to cost

2020

Whitepaper on cost/benefit analysis
Started procuring contemporary material (1st gen)
Plan for 600/625/690/316 testing issued

2021

Machining and testing contracts initiated
Environmental testing contracts initiated
2nd gen billet procurements
Original specifications issued

2022

Feb: 1st gen Alloy 600 results (Air)
Aug: 1st gen 625/690 results (Air)

2023

3rd gen billet procurements
June: 2nd gen 625/690 results (air)
Oct: 1st gen 600/625/690 env. results

2024

316L results (air)

2025

3rd gen follow up results
Final environmental results
Specification revision
Program wrap-up

"Finished"

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Parallel efforts on:
UT inspectability
Weldability
NNS design

Approach: Scope of Materials

- 4 Alloys: 600, 625, 690, 316L SS*
  - Each alloy tested in 2 conditions
    - “Reference” per the specification and modeled after wrought processing
    - “Alternate” seeking to improve properties/economy by altering HIP parameters and post-HIP heat treatment
- 4 Vendors (2 considered minimum): A, B, C, and D
  - 2 Vendors considered “Generation 1” material
  - 2 Vendors considered “Generation 2” material
  - Generation 3 material utilized the same vendors but modified processing requirements as necessary
- In-spec material is:
  - Vacuum induction melted
  - N_2 gas atomized
  - 250 µm maximum particle size
  - 150 ppm oxygen max
  - 2000 ppm nitrogen max

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Approach: Scope of Materials

C

D

A

Rectangular Billets:
4 x 8 x 24 inches or
5 x 10 x 30 inches

B

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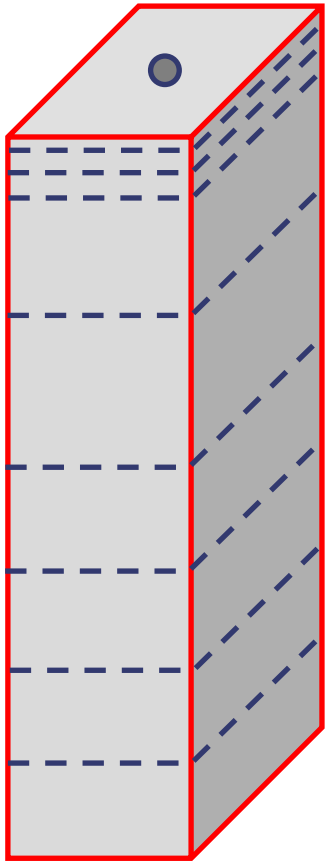
Approach: Billet Sectioning



A, 0.5, Scrap
B, 0.5 Retainer Slice
C, 0.5, Metallography/Microcleanliness/Hardness

D, 5.5, Mechanical Properties
Orientation effects

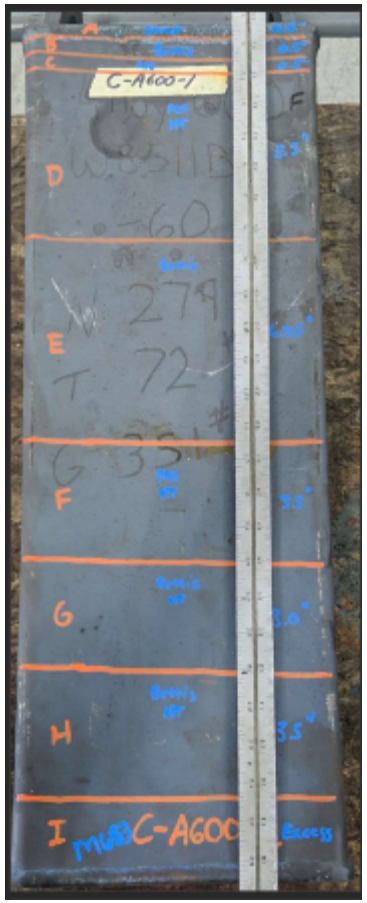
E, 6.25, Weld Mock Up

F, 3.5, Mechanical Properties
Position Effects

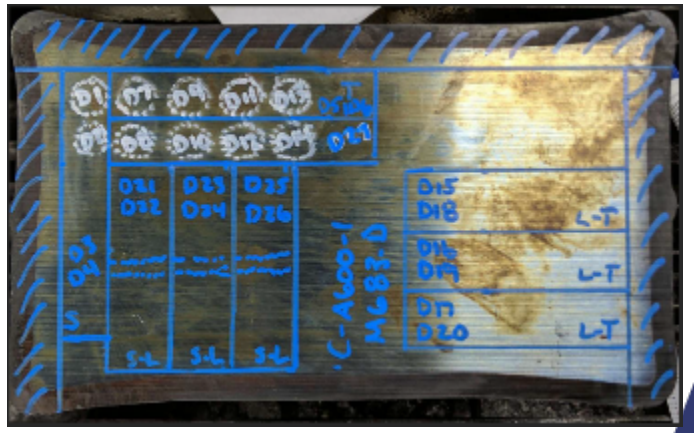
G, 3.0, Thermo-
physical Properties

H, 3.5,
Environmental
Testing

I, Excess



Heat Treat,
per spec



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Approach: (Air) Material Properties Tested

- Metallography: Grain size (ASTM E112), Microcleanliness (ASTM E45)
- Mechanical:
  - Tensile (ASTM E8, E21)
  - Fatigue Crack Growth Rate (ASTM E647)
  - Fatigue Initiation (ASTM E606)
  - Fracture Toughness (ASTM E1820)
  - Charpy Impact (ASTM E23)
- Thermo-physical
  - Young's Modulus (ASTM E111)
  - Poisson's Ratio (ASTM E132)
  - Thermal Expansion (ASTM E228)
  - Thermal Conductivity (ASTM E2584)
  - Density (ASTM B311)

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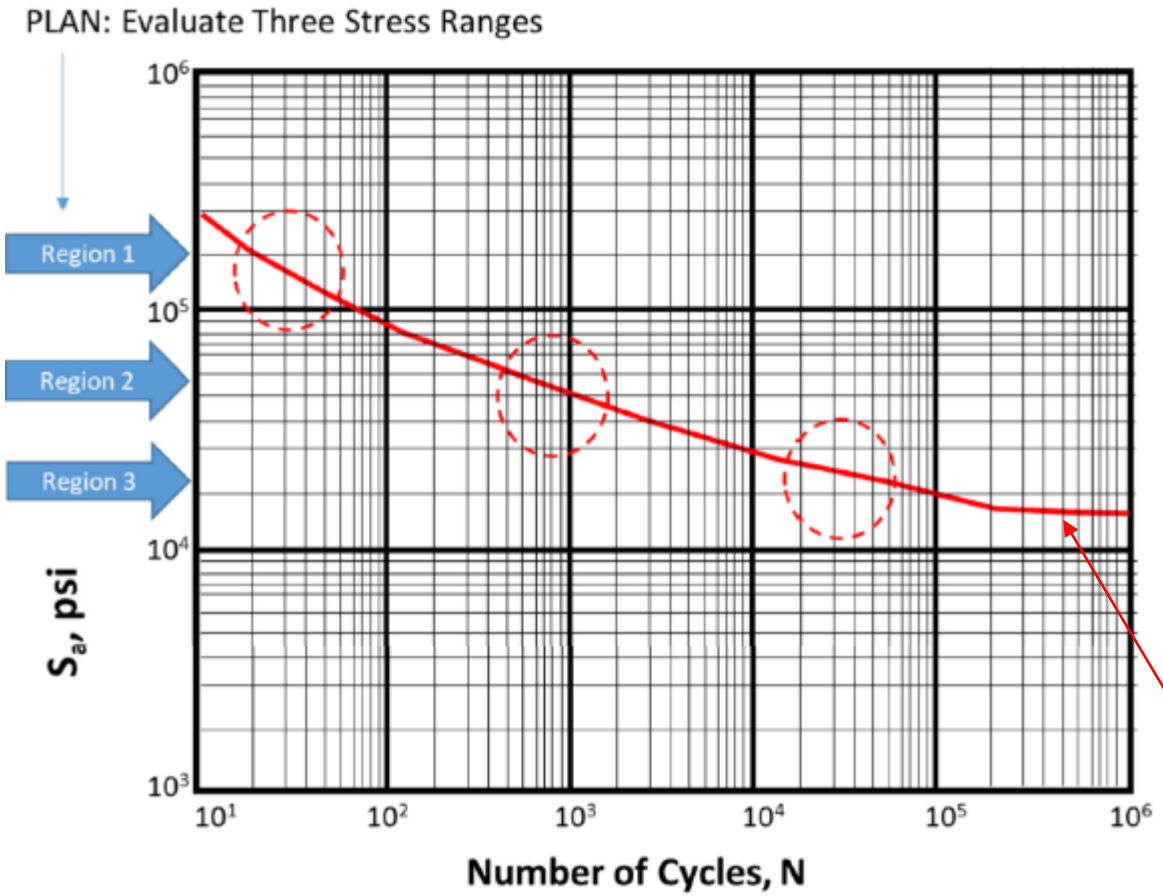
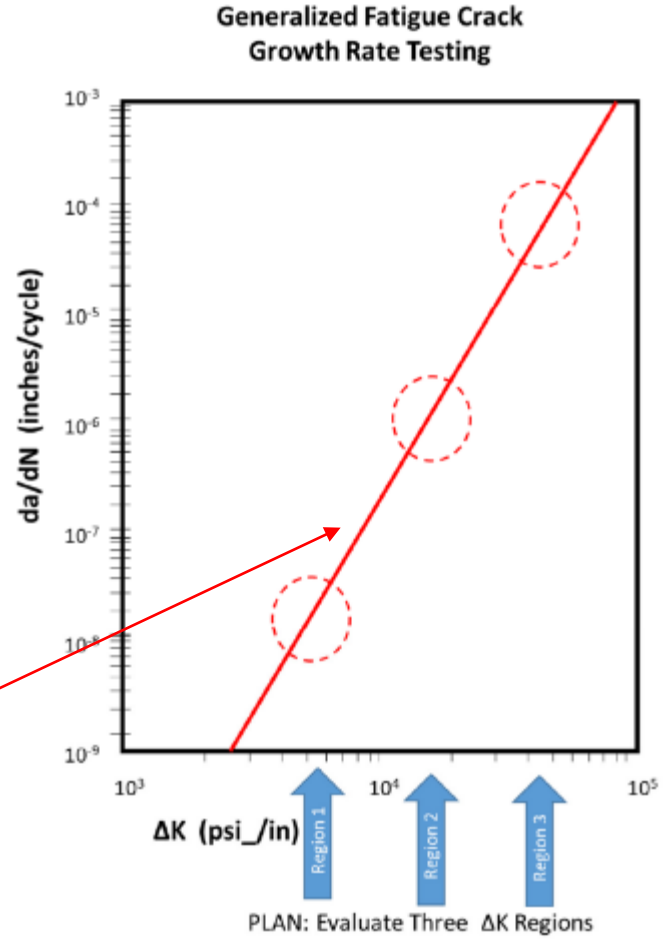
Approach: Scope of testing

Generalized Fatigue Initiation



Example wrought best estimate curve

Generalized Fatigue Crack Growth Rate



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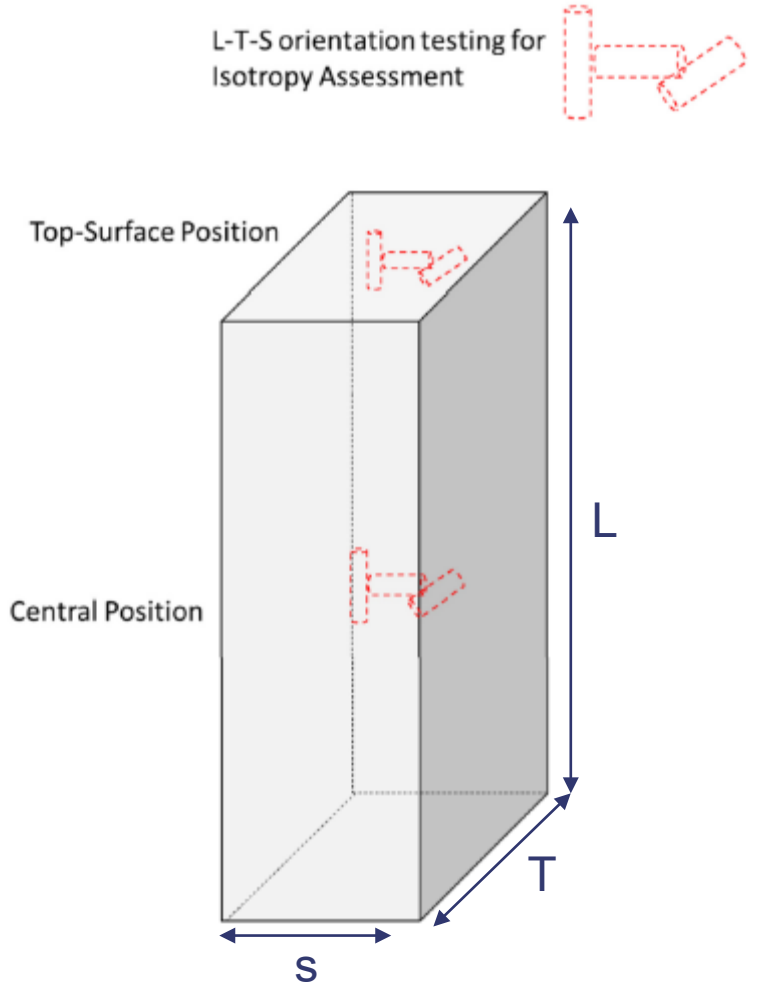
Approach: Additional Considerations

- Orientation effects
  - Tensile: L, S, and T
  - FCGR: SL and LT
  - Metallography: L, S, and T
- Position Effects
  - Tensile: Top and Middle
  - FCGR: Top and Middle
  - Metallography: Top and Middle, Center and Near Can



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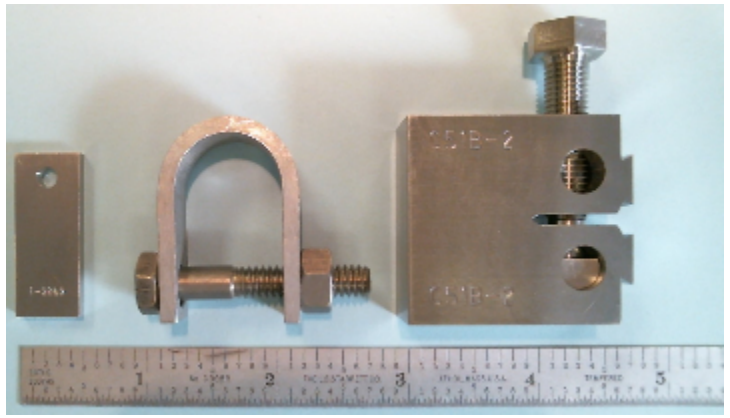
Approach: Environmental Testing



- General Corrosion
  - Aerated and deaerated high temperature water
- Stress Corrosion Cracking
  - Aerated and deaerated high temperature water
  - Active load (compact tension) CGR measurements
  - Passive load (single U bends, bolt loads, and ring loads) at multiple Kmax levels
- Corrosion Fatigue Crack Growth Rate
  - Deaerated high temperature water
  - Active load (compact tension) CGR measurements at multiple R, ΔK)
  - Reduced test scope compared to air. Rely on Air testing to prove equivalence
- Also testing HAZ Specimens

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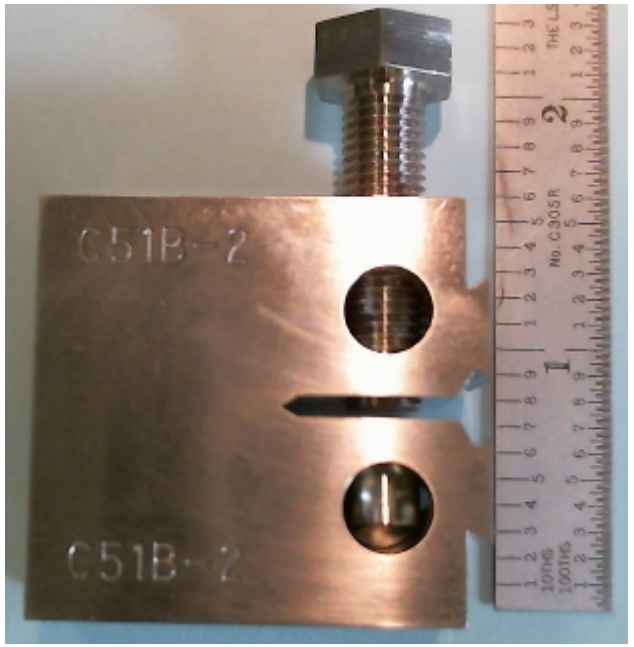
Approach: Environmental Testing

Single U-Bends



Bolt Loaded Compact Tension Specimens

Corrosion Coupons

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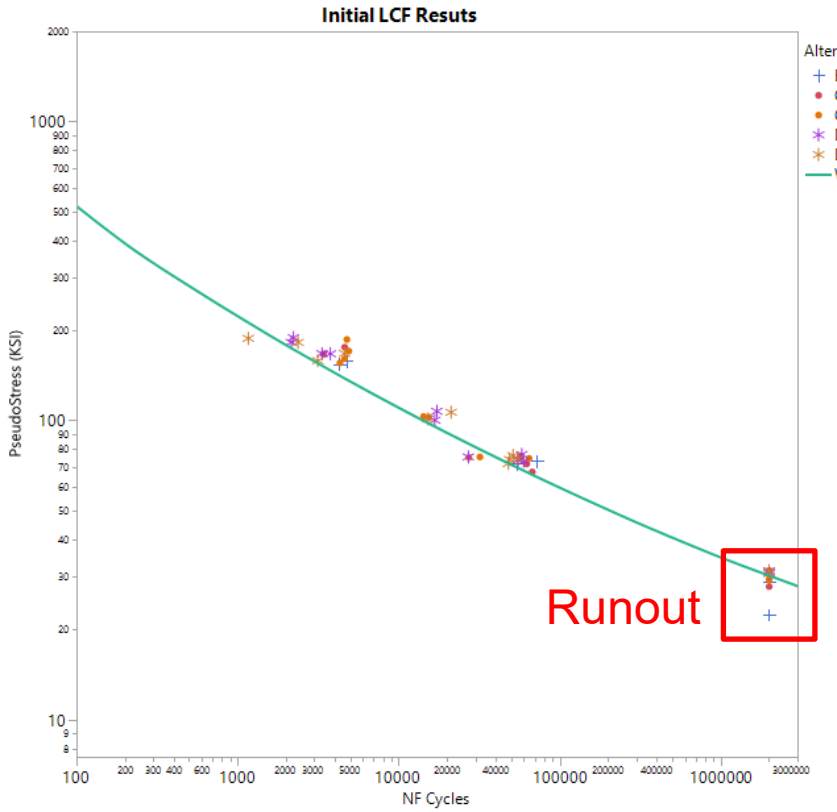
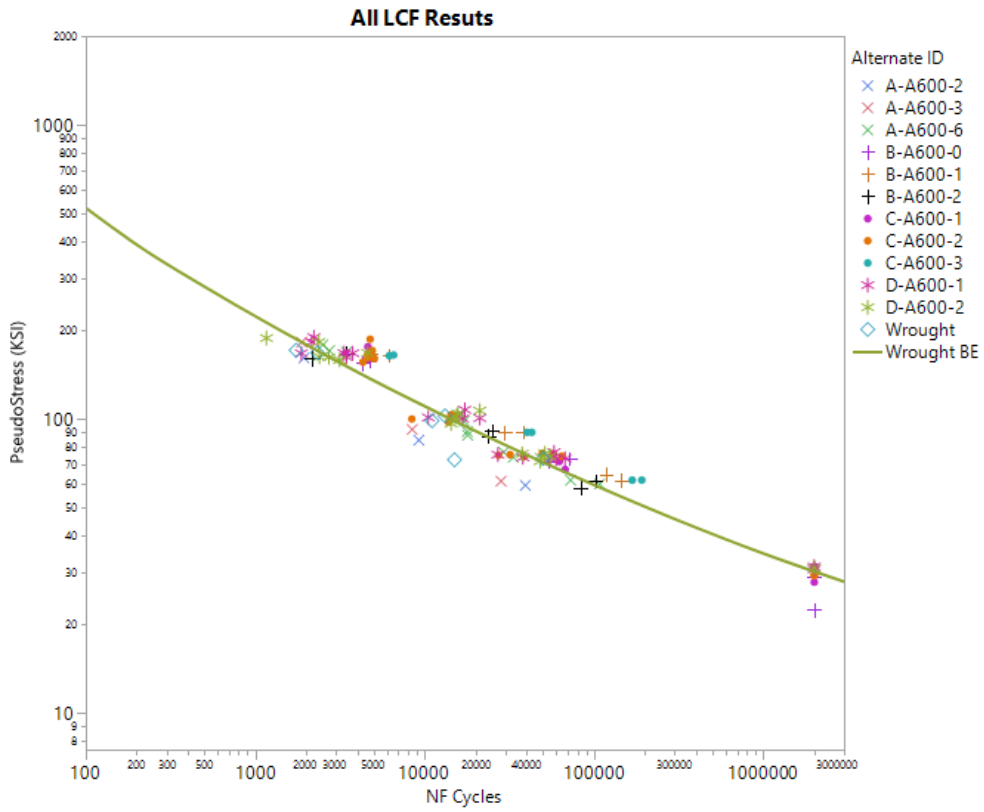
Example Results: Fatigue Initiation in Alloy 600



Additional Testing Necessary



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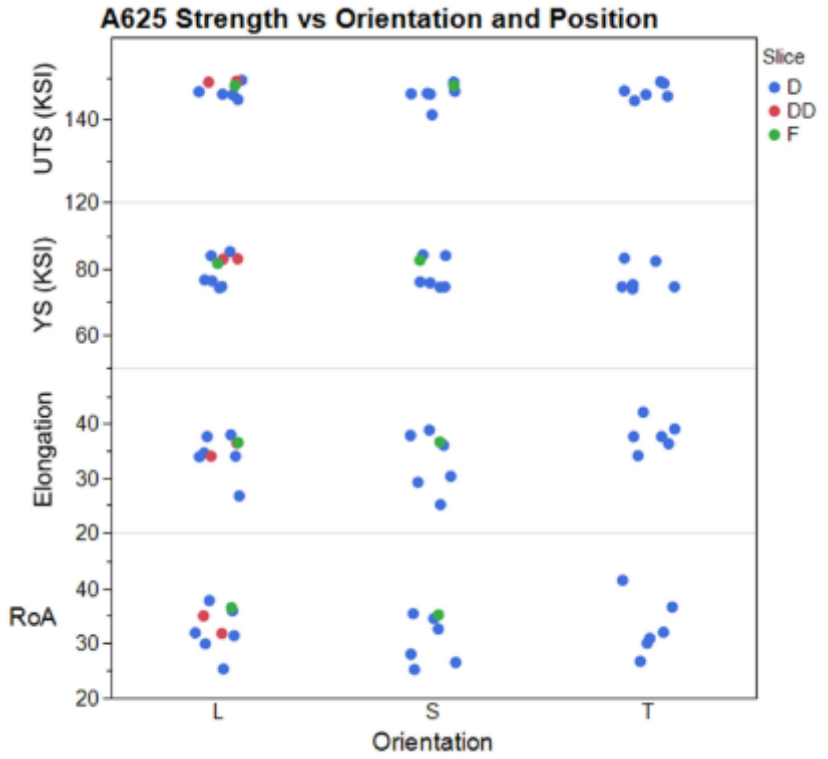
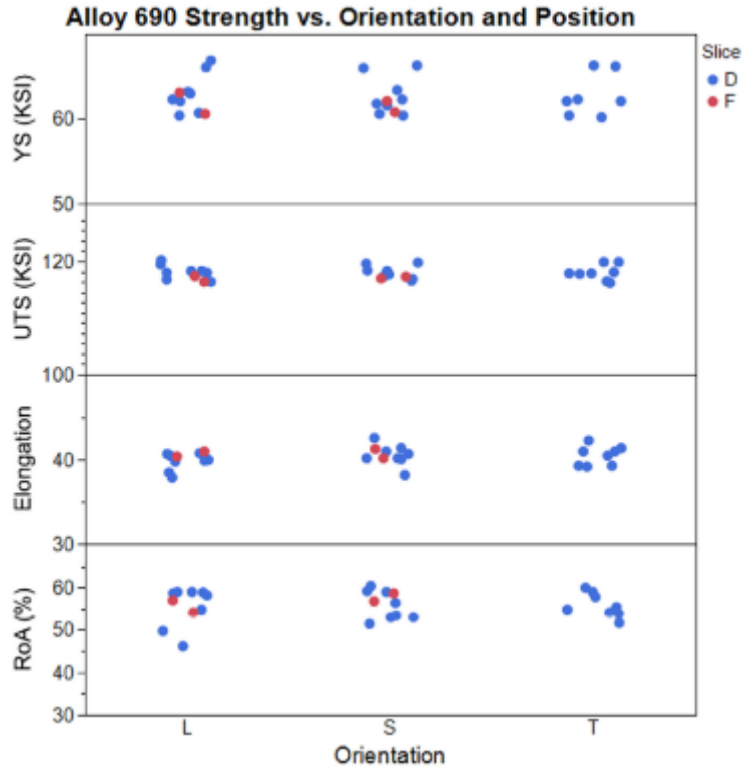
Example Results: Position and Orientation Effects





- No position or orientation effects observed.
- Gen 1 materials (especially 625) had some ductility (% Elongation and RoA) concerns.

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Example Results: Specification Compliance – A690

A690 Material Specification Compliance Matrix								
Billet	**A-A690-1**	**A-A690-2**	**A-A690-3**	**A-A690-6**	**B-A690-1**	**B-A690-2**	**C-A690-3**	**C-A690-4**
Particle Size Max (μm)	250	250	250	*500*	250	250	250	250
Powder Oxygen (wt%)	0.0141	0.0141	0.0141	0.0141	0.0147	0.0147	0.0143	0.0143
Powder Nitrogen (wt%)	*0.209*	*0.209*	*0.209*	*0.2138*	0.109	0.109	0.114	0.114
Consolidated Chemistry Violations	*N, O*	*Fe, N*	*N, O*	*N, O*	*B*	*O*	*B, C, Fe*	*B, C, Fe*
HIP T (°F)	Ref	*Alt*	*Alt*	*Alt*	Ref	*Alt*	*Alt*	*Alt*
Post HIP HT	None	*Alt*	None	None	None	None	None	None
Room T YS (ksi)	*High*	*High*	*High*	*High*	*High*	*High*	*High*	Pass
Room T UTS (ksi)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Room T Elong. (%)	Pass	*Low*	*Low*	*Low*	Pass	Pass	Pass	Pass
Room T RoA (%)	Pass	*Low*	Pass	*Low*	Pass	Pass	Pass	Pass
600°F YS (ksi)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
600°F UTS (ksi)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Grain Size	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Microcleanliness	Pass	*Fail*	*Fail*	*Fail*	Pass	Pass	Pass	Pass
Density[1] (lb/in^3)	Pass	Pass	Pass	Pass	DNM	Pass	DNM	DNM
DNM = Did not measure								

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Tested one billet with higher PSD

Minor chemistry violations. O and N most undesirable

Tested various HIP T

High strength and low ductility commonly observed, improved through HIP T modifications and in Spec nitrogen

Some failing microcleanliness measurements, but additional examination showed no major concern

Summary of PM-HIP Testing Approach

- Goal: 4 materials in 5 years
  - Rely on existing wrought properties and prove equivalence
  - Generate material specifications up front, and work to them
  - Test to ASTM standards whenever possible
  - Standardize approach and perform testing all in parallel
- PM-HIP material is generally proving to be homogenous and equivalent to wrought
  - Perform targeted “extra” testing and characterization as required to feel comfortable with properties
  - Perform simultaneous parallel testing aimed at proving material properties and/or process economy → revise specification later to take advantage

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