2021 FE/NETL Annual Review
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Low Cost HIP Fabrication of Advanced Power Cycle Components and PM/Wrought Inconel 740H Weld Development

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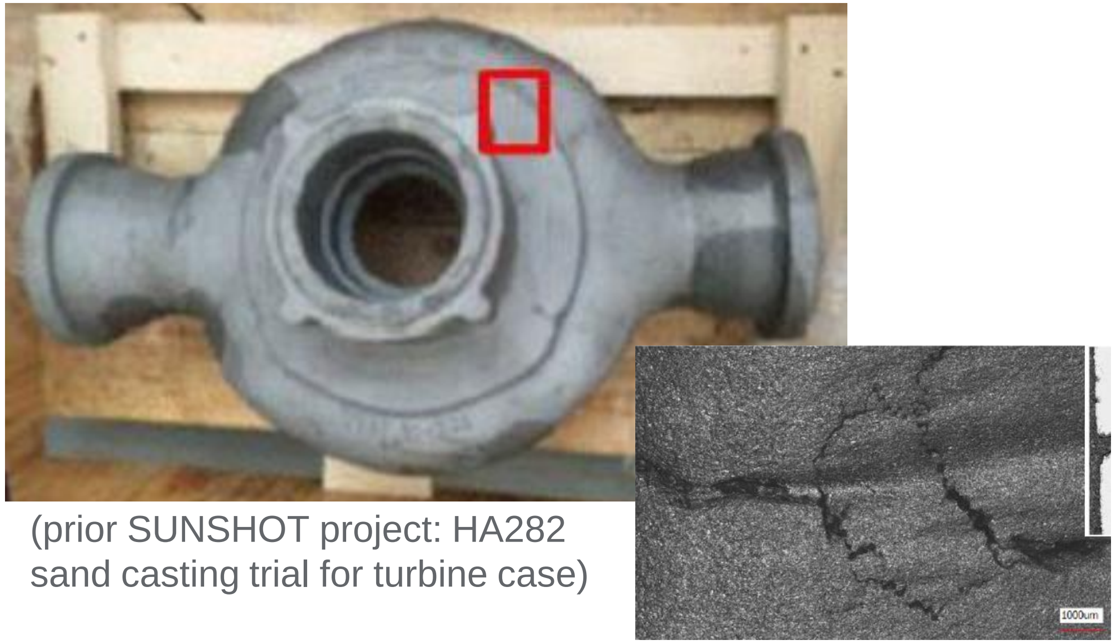
Background & Motivation

High capital costs offset efficiency gains using γ′ strengthened Ni-based superalloys in AUSC components

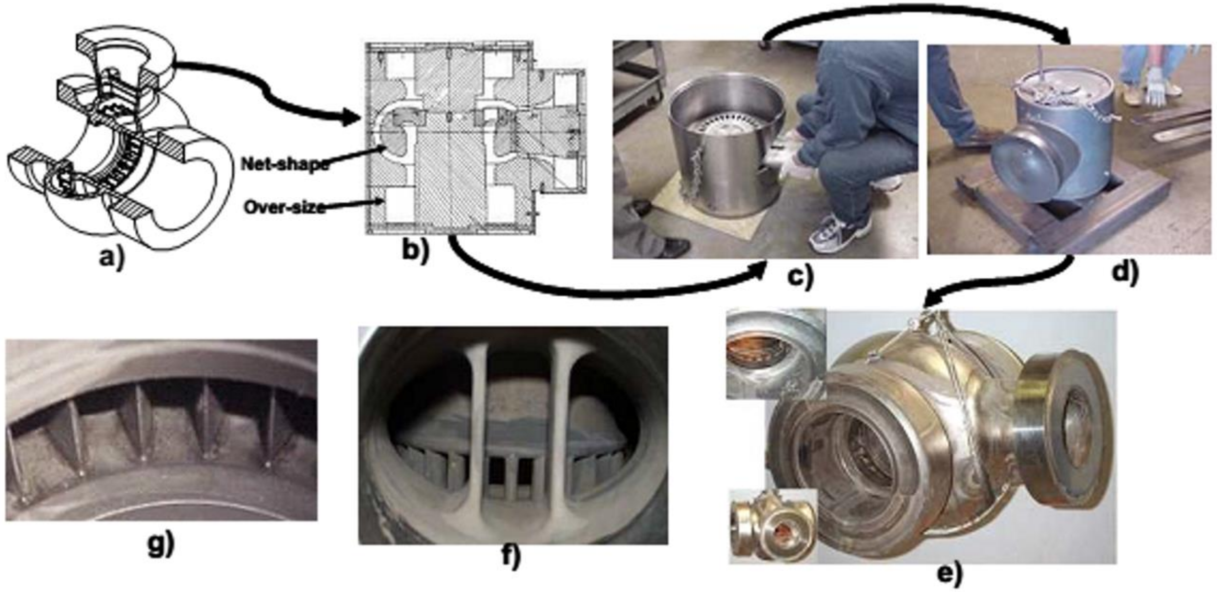
- Limited supply chain of large components using cast or wrought IN740H or HA282
- Extensive machining of complex features
- Technical difficulties in sand casting thick walls or complex shapes

Alternative manufacturing modality for cost reduction Powder Metallurgy (PM) Near-Net-Shape (NNS) Hot Isostatic Pressing (HIP)

- Reduced 2~3X volume of material vs wrought
- Reduced machining costs
- Reduce welds & weld repair
- Chemical & structural homogeneity
- Ultrasound inspectability



(prior SUNSHOT project: HA282 sand casting trial for turbine case)



(C. Bampton, W. Goodin, T. Van Daam, G. Creeger, S. James. International Conference of Hot Isostatic Pressing, 2005.)

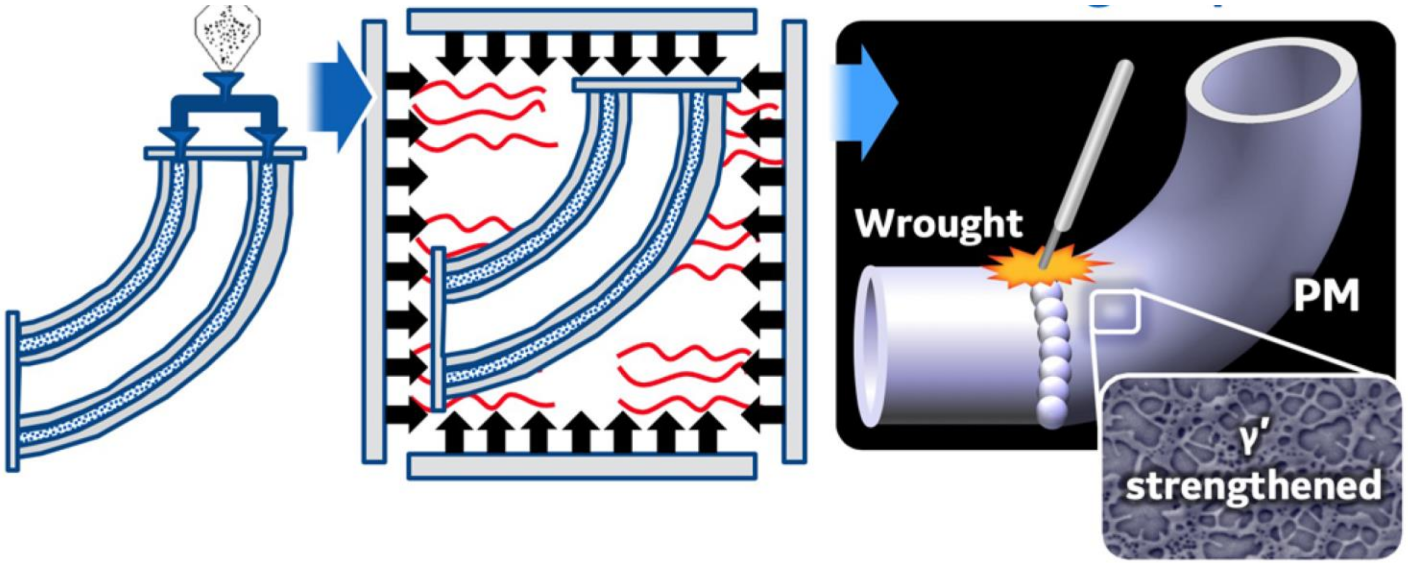
Objectives & Impacts

Objectives

- Demonstrate NNS HIP feasibility by a prototype pipe elbow using IN740H powder
- Develop PM/wrought IN740H welding procedure and evaluate microstructure, properties
- Deliver technoeconomic analysis of IN740H NNS HIP components for AUSC power plants

Technical Approach

- Dimension control by accurate design of HIP tooling via modeling non-uniform shrinkage
- HIP cycle and powder size distribution studies to show a clear path for property improvement
- PM/wrought IN740H cross weld microstructure/property evaluations

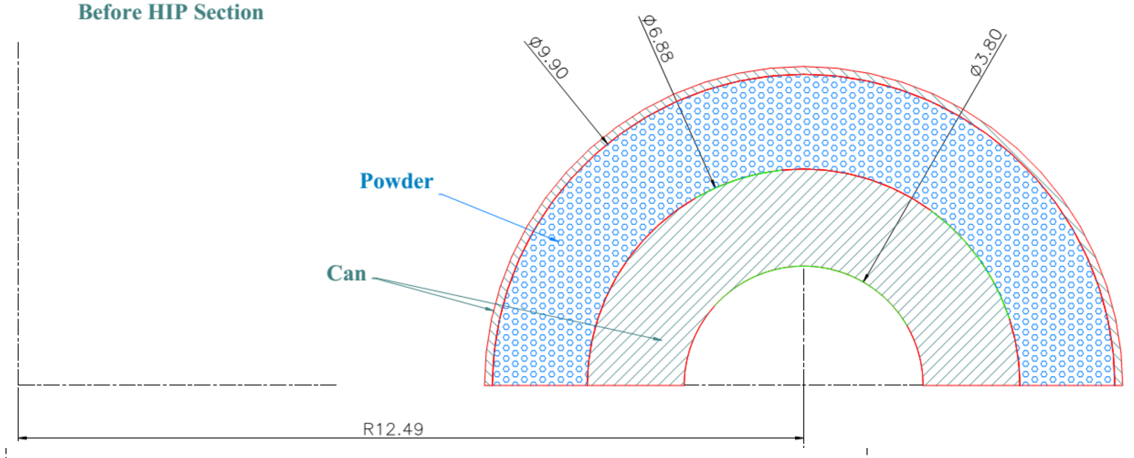


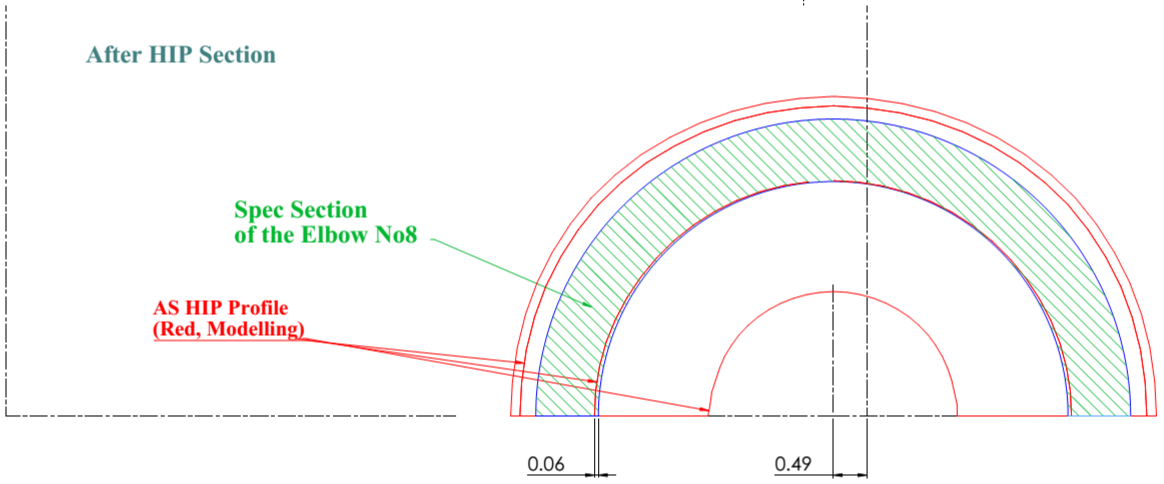
Anticipated Benefits & Impacts

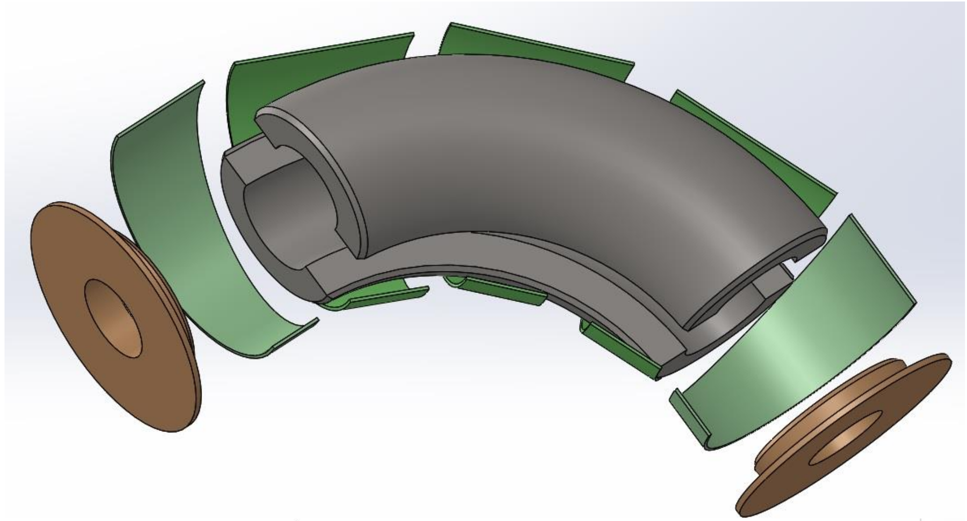
- 50% cost reduction in manufacturing large components for AUSC power plant
- US manufacturing supply chain for NNS HIP

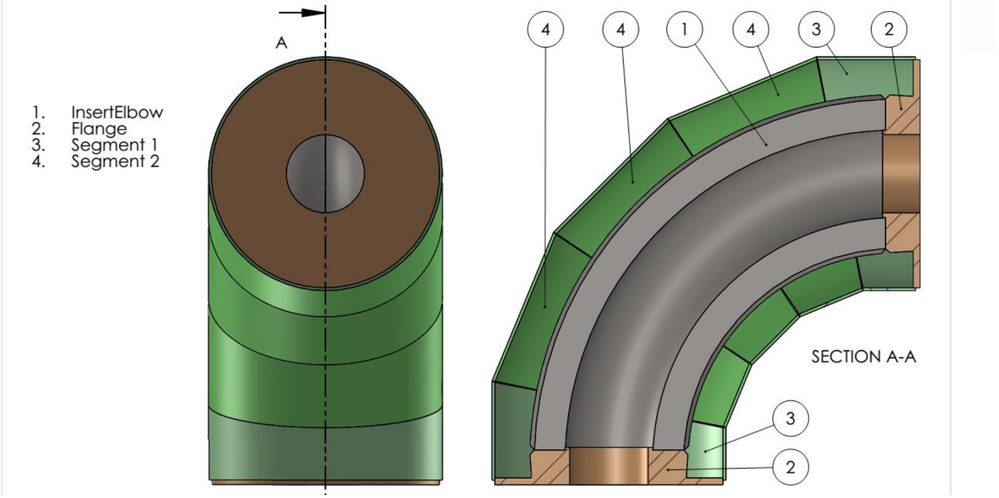
Pipe Elbow HIP Tooling Design

Schedule160 pipe elbow, nominal size #8 (OD 8.6", ID 6.8", wall 0.9", center to end 12")



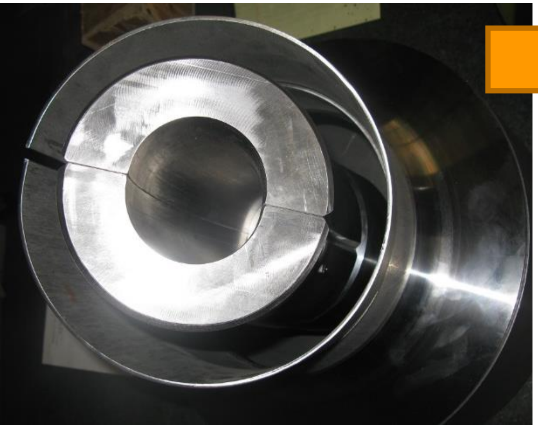


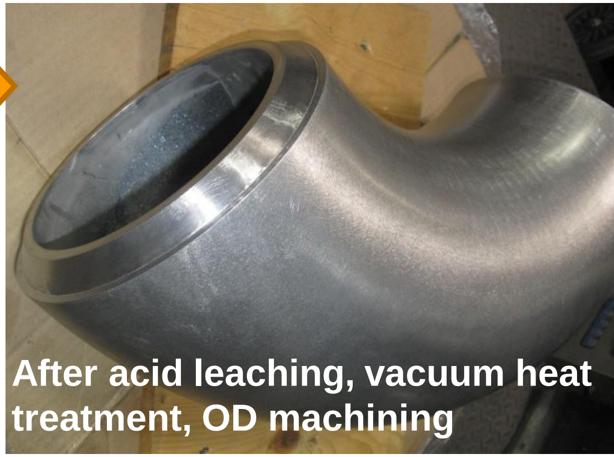




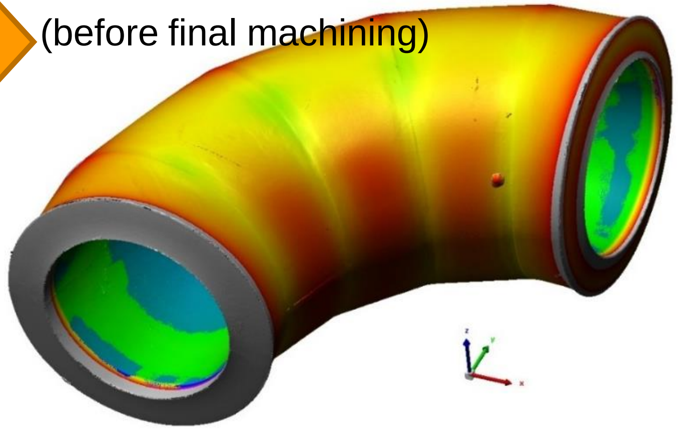
- **HIP densification and shrinkage modeled with the goal of achieving net shape at interior surface**
- **HIP tooling for pipe elbow designed based on HIP model results**

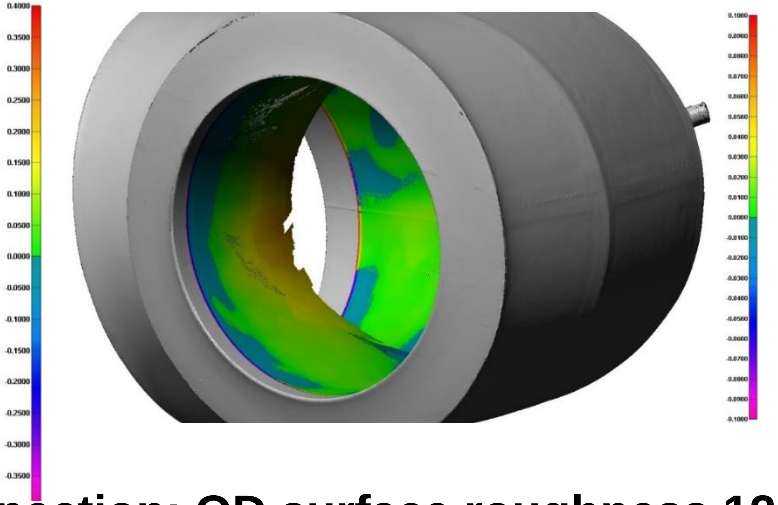
Pipe Elbow NNS HIP Fabrication

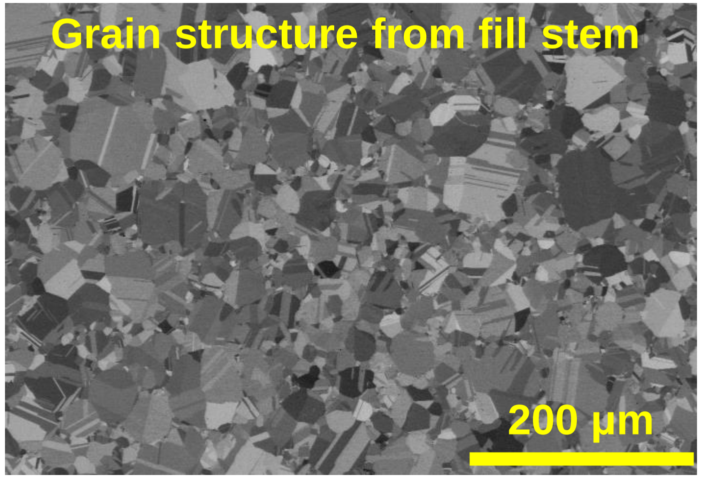




Dimensional Scan
(before final machining)

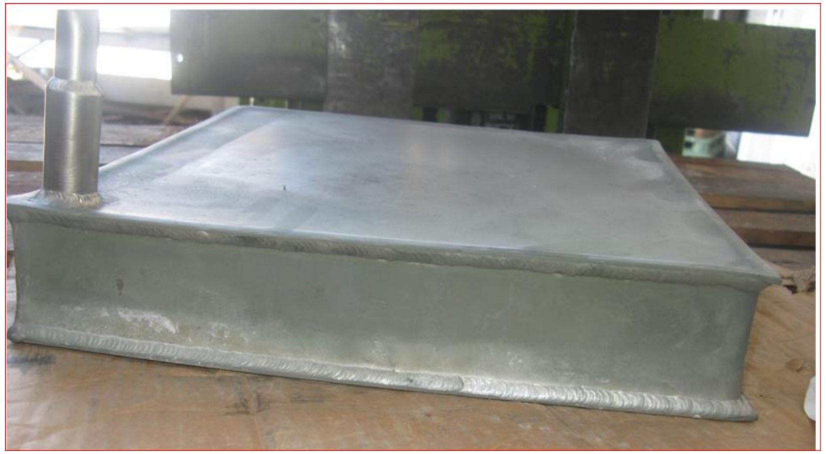


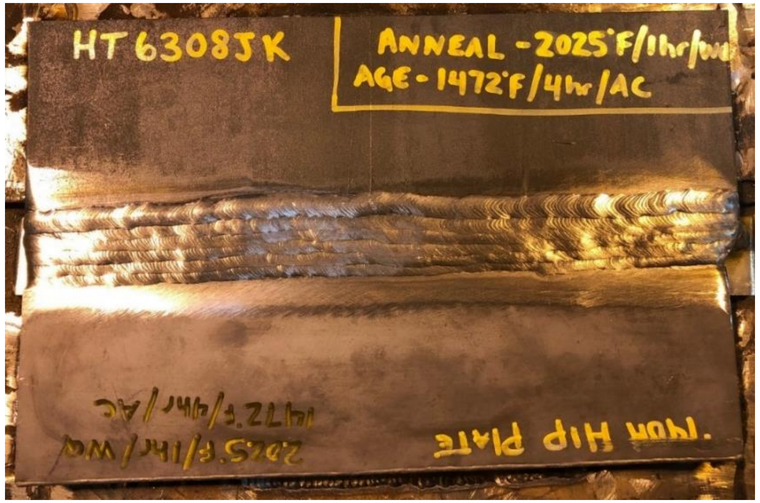




- **No linear defects by ultrasonic inspection; OD surface roughness 125 RMS; ID surface roughness > 63 RMS**
- **OD positive stock 0.1~0.22''; ID 0.04'' deviation → "net shape" achieved at ID, HIP model validated**

PM/Wrought IN740H Weld Development



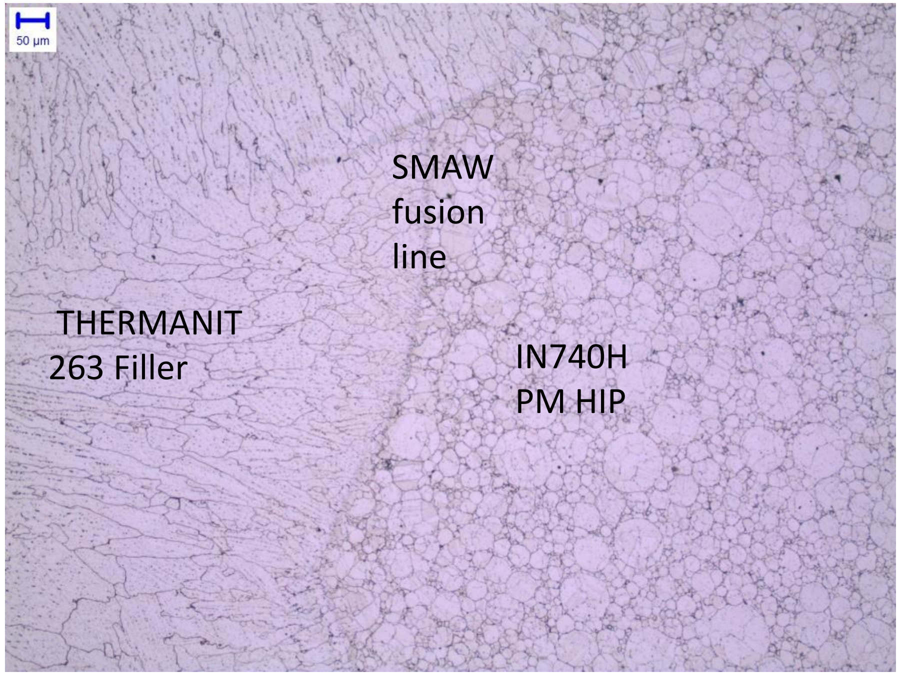


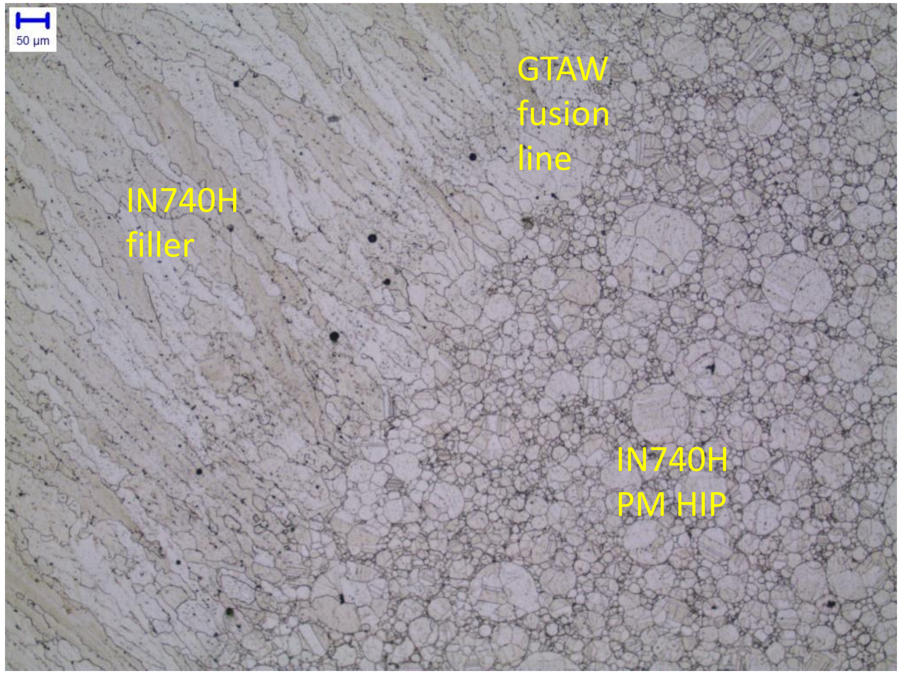
Test ID, material	0.2% YS (ksi)	UTS (ksi)	Elong. %	ROA %
RTE497811001 HIP/wrought GTAW	125.2	164	16.2	33.3
RTE497811002 HIP/wrought GTAW	126.2	164.5	17.4	34.5
Wrought cross weld	118.2	164.6	21.3	22.8
Wrought cross weld	116.4	162.8	21.2	24.9
Wrought cross weld	110.6	159.3	24.6	22.3

- **A PM HIP to wrought IN740H welding procedure on 1'' thick plates has been successfully qualified to ASME section IX.**
- **RT cross weld tensile properties pass yield stress > 90ksi, ultimate tensile strength > 150ksi, with reasonable elongation >12%. RT side bend tests pass a 4T minimum bend radius.**

PM/Wrought IN740H Weld Development

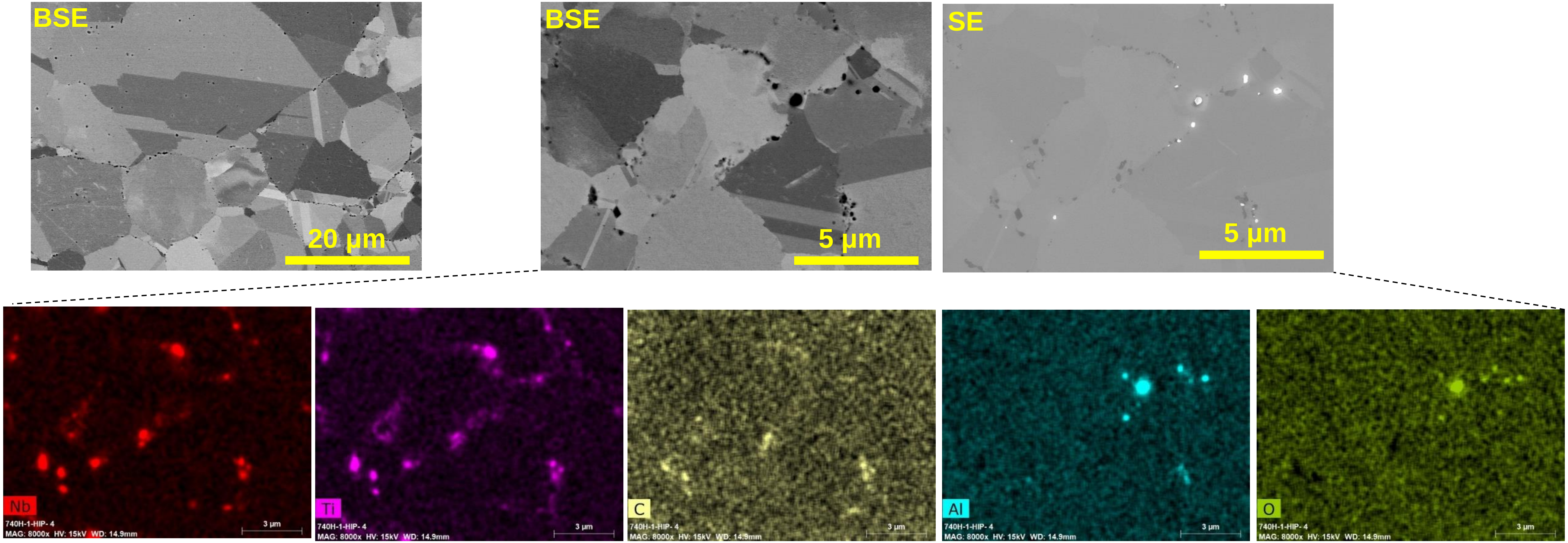
Test I.D.	Weld Process	Weld Filler	Pre-Weld	Post-Weld	0.2% YS (Ksi)	UTS (Ksi)	Elong. (%)	ROA (%)	Failure Location
RTE509711001	GTAW	740H	SA	AG	114	162.8	24.7	23.2	Weld
RTE509711002	GTAW	740H	SA	AG	126.6	162.7	19.1	35	Weld
RTE509811001	SMAW	263	SA+AG	AG	113.2	146.9	12.2	21.2	Weld
RTE509811002	SMAW	263	SA+AG	AG	112.3	149.4	13.8	25.6	Weld





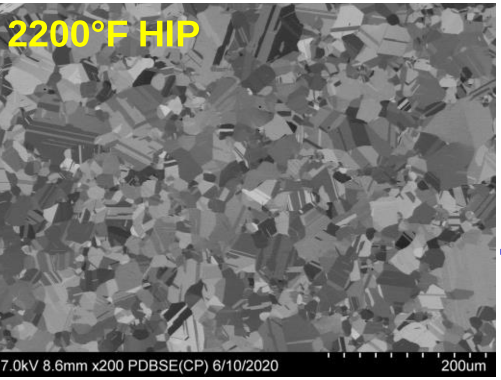
- **Different weld process, weld filler material, pre-weld heat treatment condition all show good cross-weld tensile properties and side bend test results**
- **Low risk of thermally induced argon porosity in HAZ or weld (small amount, size within ASME limits)**

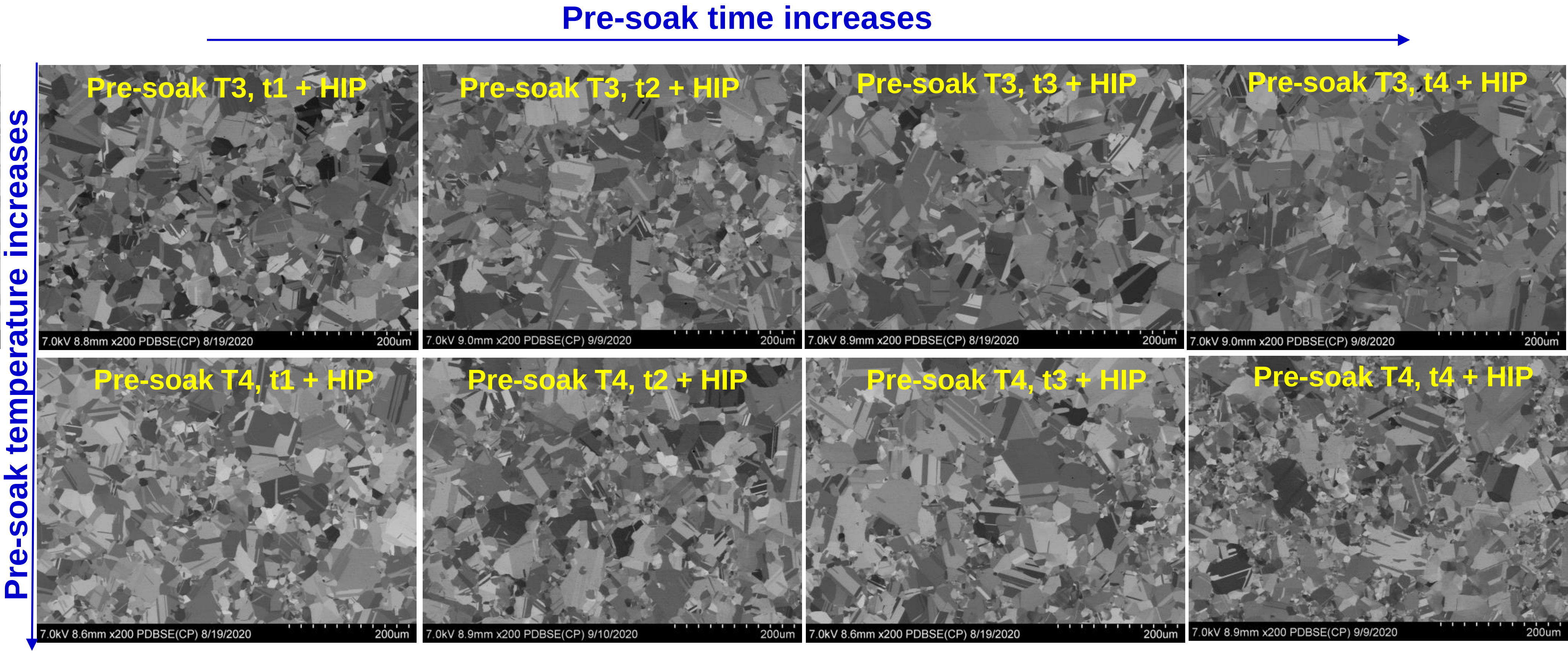
Prior Particle Boundary (PPB) Particles



- **Discrete particles decorating PPB: Nb, Ti rich carbides/carbonitrides and Al rich oxides**
- **PPB particles effectively pin grain boundary migration, control grain size, influence mechanical properties**

Pre-soak Heat Treatments Prior to HIP





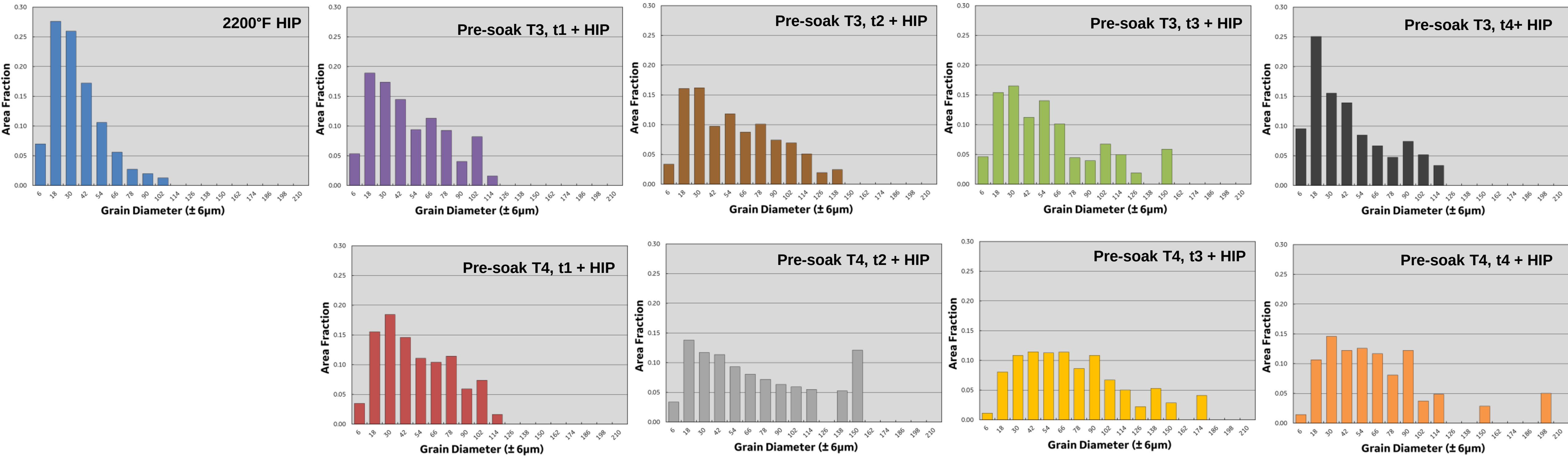
Zener Pinning

$$Ps = 3F_v * \gamma / 2r$$

- Ps: pinning pressure
- F_v: particle volume fraction
- γ: boundary of energy per unit area
- r: particle radius

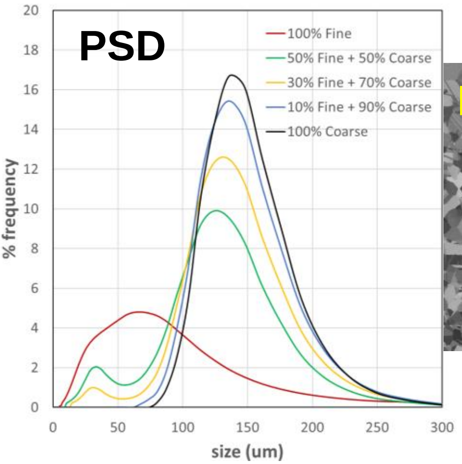
- **Pre-soak heat treatment applied before HIP to coarsen PPB particles and grain size**

HIP and Pre-soak Heat Treatments

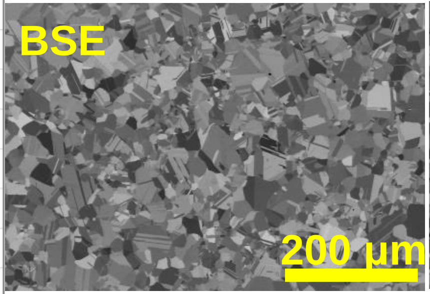


- **Grain size distribution measured by EBSD**
- **Higher pre-soak temperature and time yields larger grain size and wider grain size distribution**

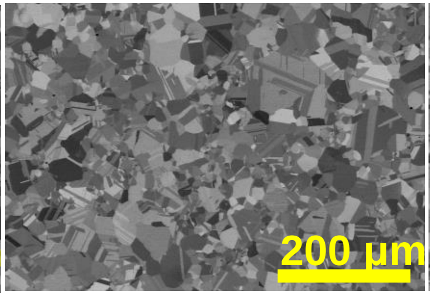
Powder Size Distribution



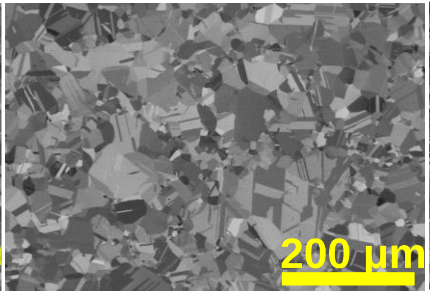
100% Fine



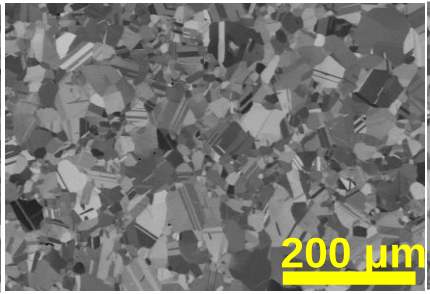
50% Fine + 50% Coarse



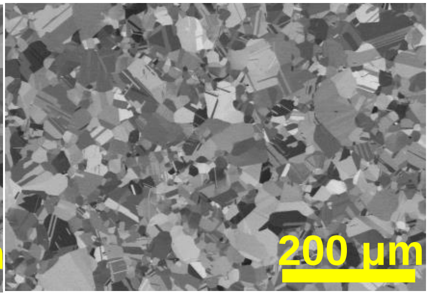
30% Fine + 70% Coarse

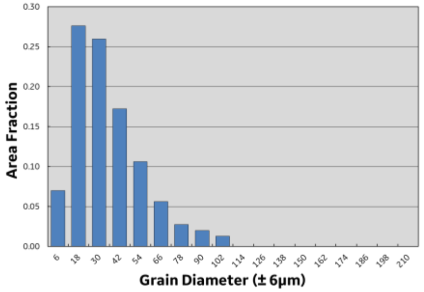


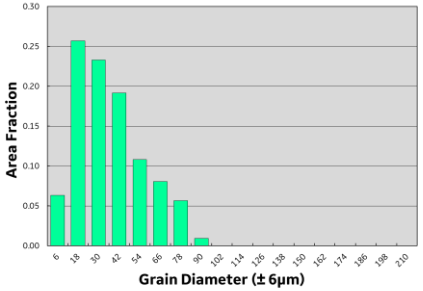
10% Fine + 90% Coarse

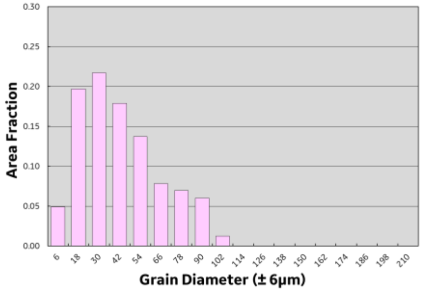


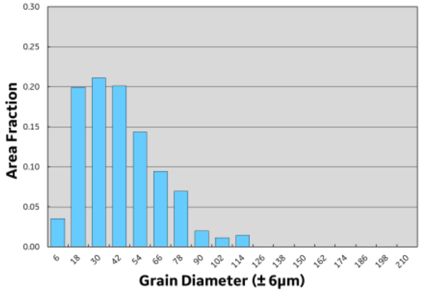
100% Coarse

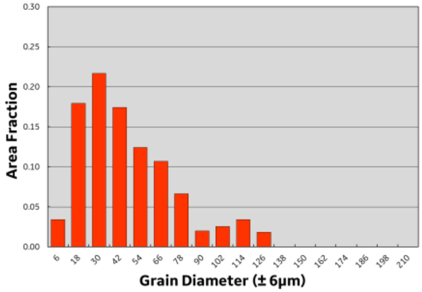






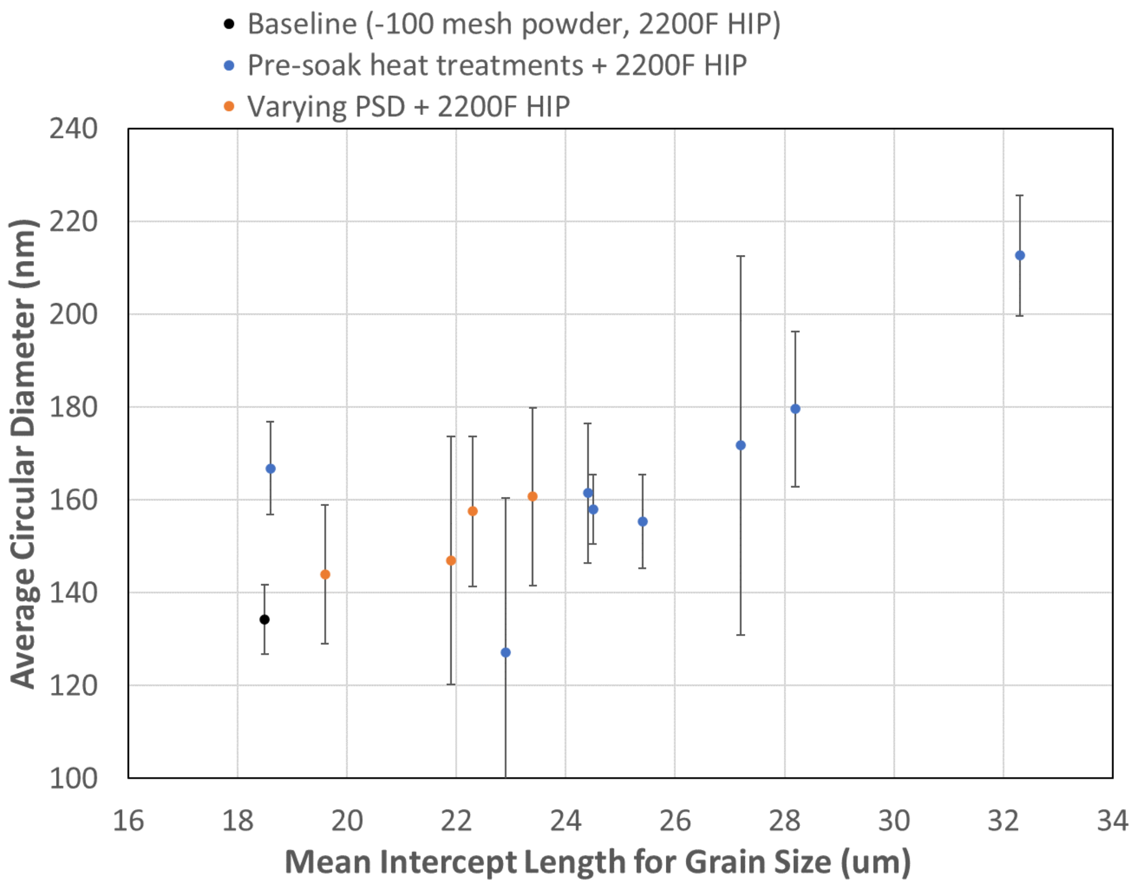


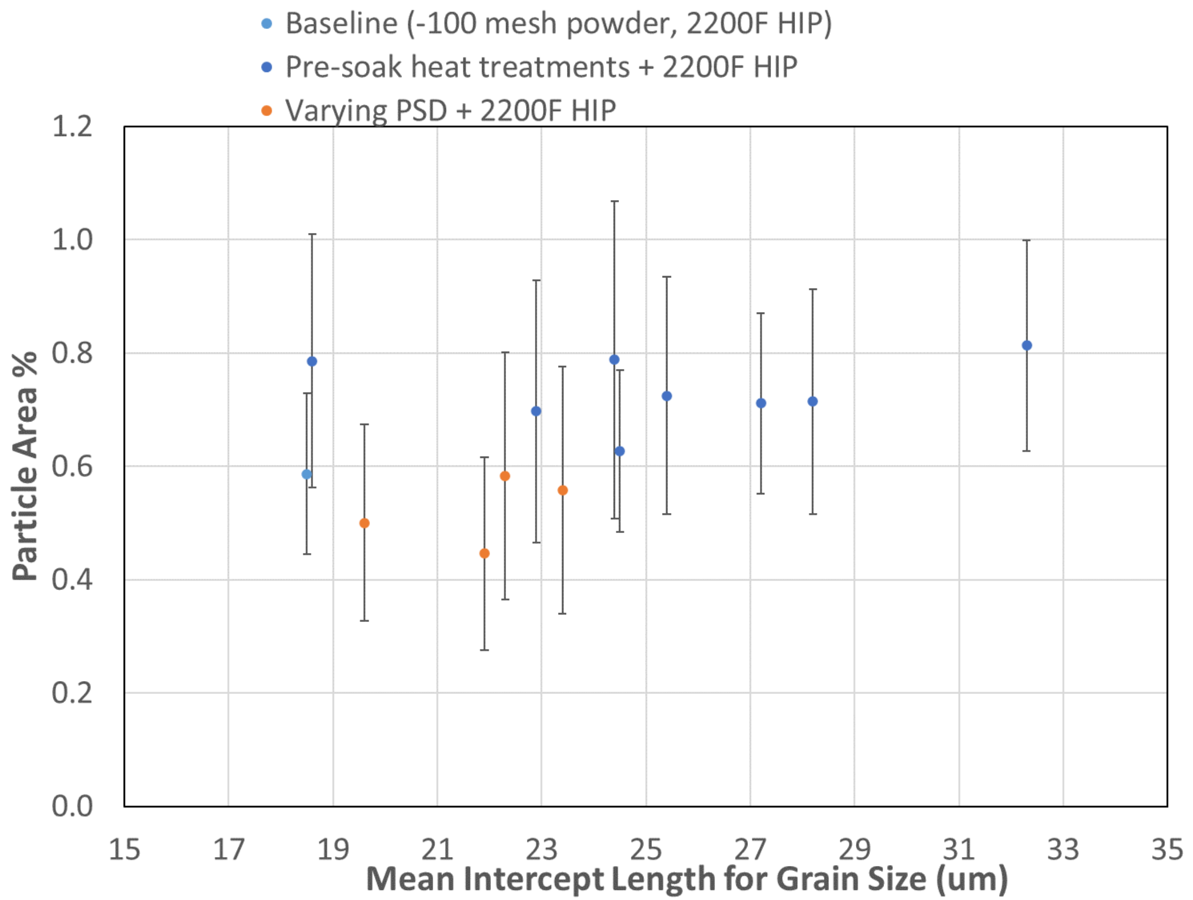




- 5 PSD generated by blending -100 mesh and +100 mesh powder in various fractions
- Powder oxygen varies from 100ppm in fine powder to 55ppm in coarse powder
- Grain size distribution becomes wider and shifts to larger size with increased coarse powder

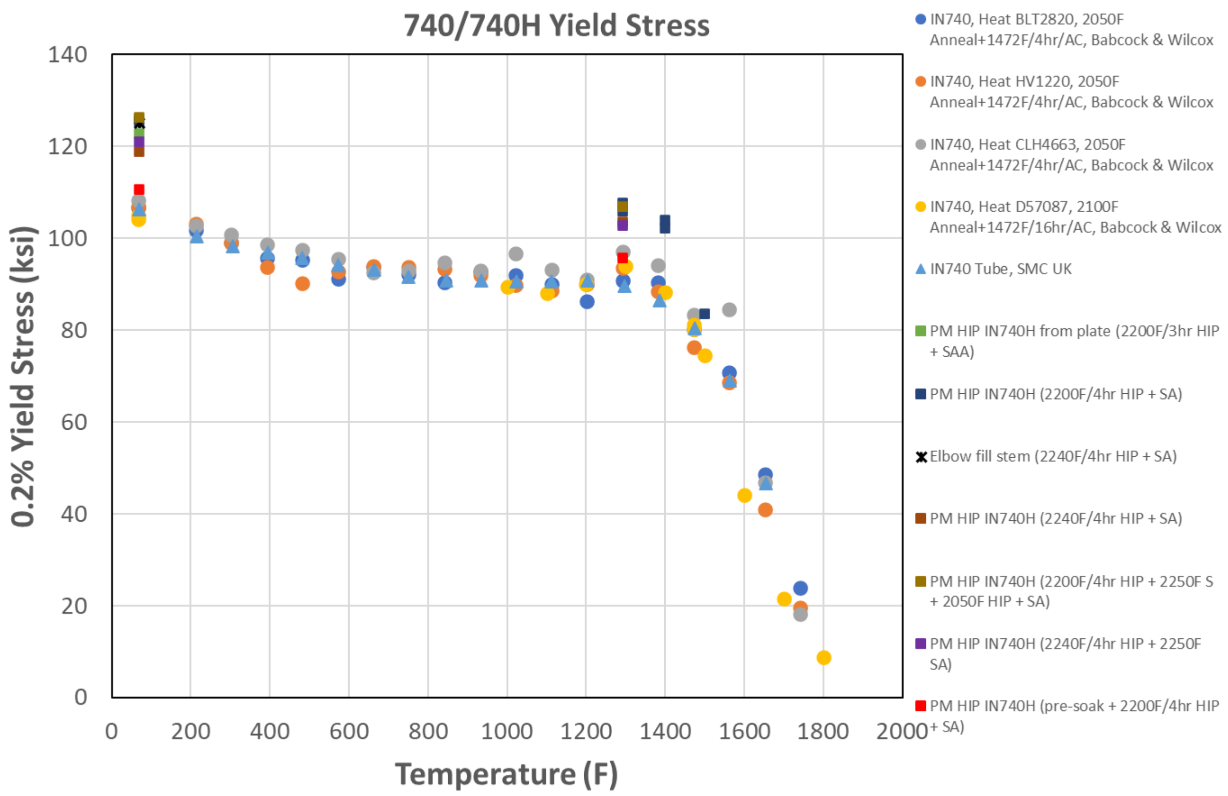
Effect of Pre-soak HT and PSD on Grain Size





- **PSD is not as effective as pre-soak heat treatment to coarsen grain size**
- **Multiple methods for migrating grain boundaries beyond PPBs (HIP temperature, pre-soak, higher solution temperature) require optimization and avoid thermally induced porosity**

Preliminary Tensile Properties



5 Processing conditions

1) Baseline 2200°F HIP with baseline solution and aging: 2200°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hr/AC

2) Higher temperature 2240°F HIP with baseline solution and aging: 2240°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hr/AC

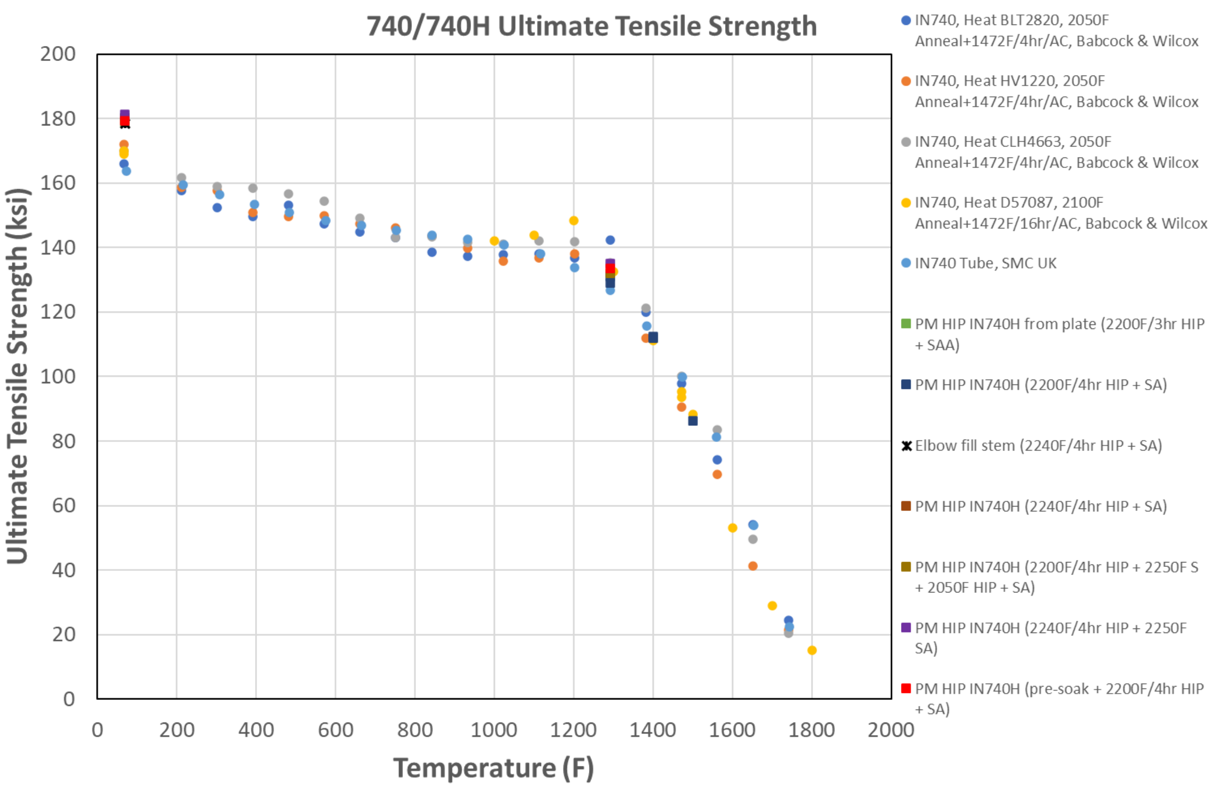
3) 2nd HIP after higher solution: 2200°F/15ksi/3hr HIP + 2250°F/1hr/WQ + 2050°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hrs/AC

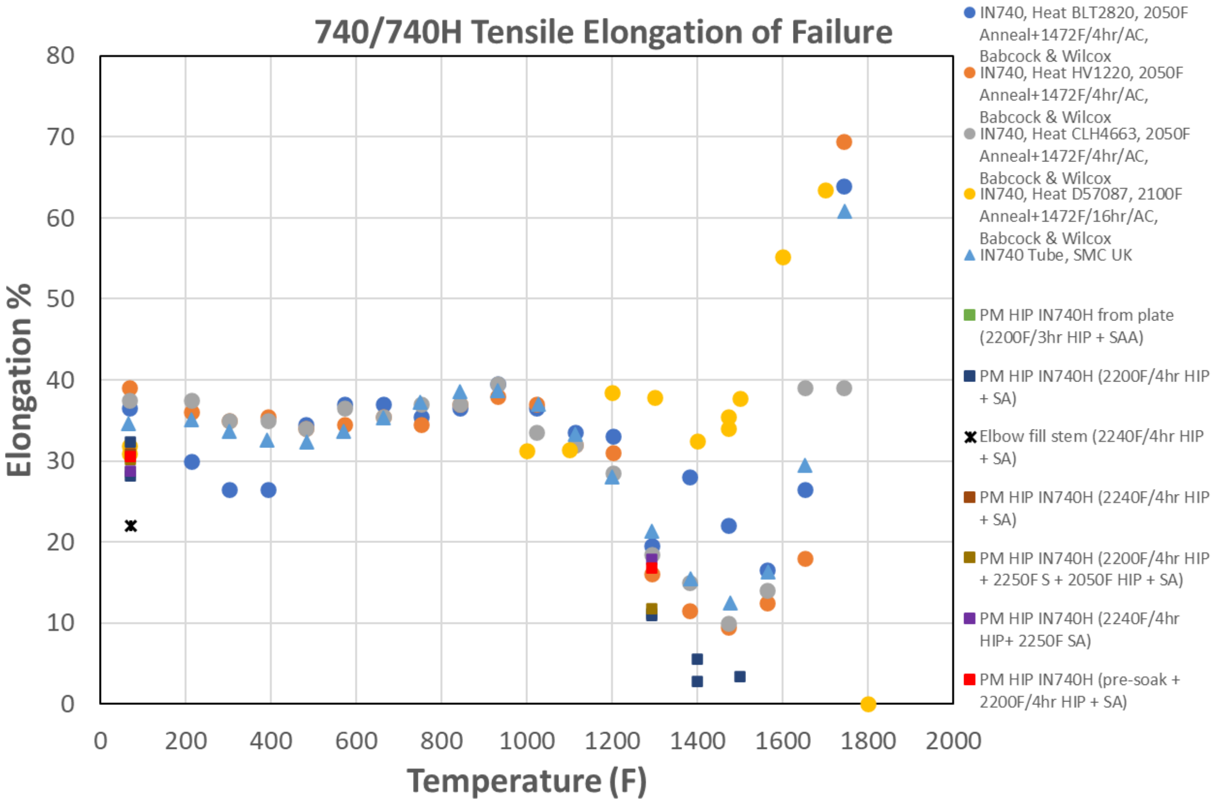
4) Higher temperature 2240°F HIP with higher solution and normal aging: 2240°F/15ksi/4hr HIP + 2250°F/1hr/WQ + 1472°F/4hr/AC

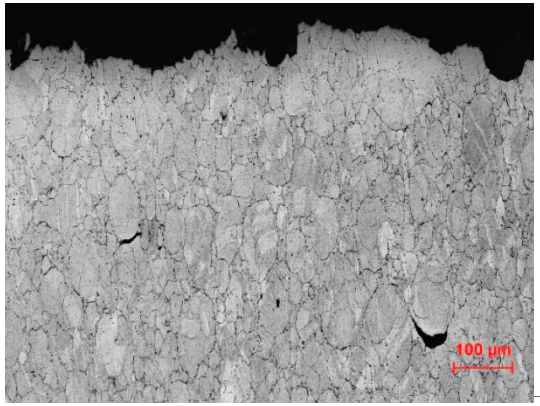
5) Pre-soak heat treatment before HIP: pre-soak HT + 2200°F/15ksi/4hr HIP + 2050°F/1hr/WQ + 1472°F/4hr/AC

- **PM HIP IN740H with processing conditions #1~4 shows higher yield stress than wrought IN740H (likely due to finer grain size)**
- **Pre-soak before HIP (condition #5) with 32um average grain size and wide distribution shows comparable yield stress as wrought IN740H**

Preliminary Tensile Properties

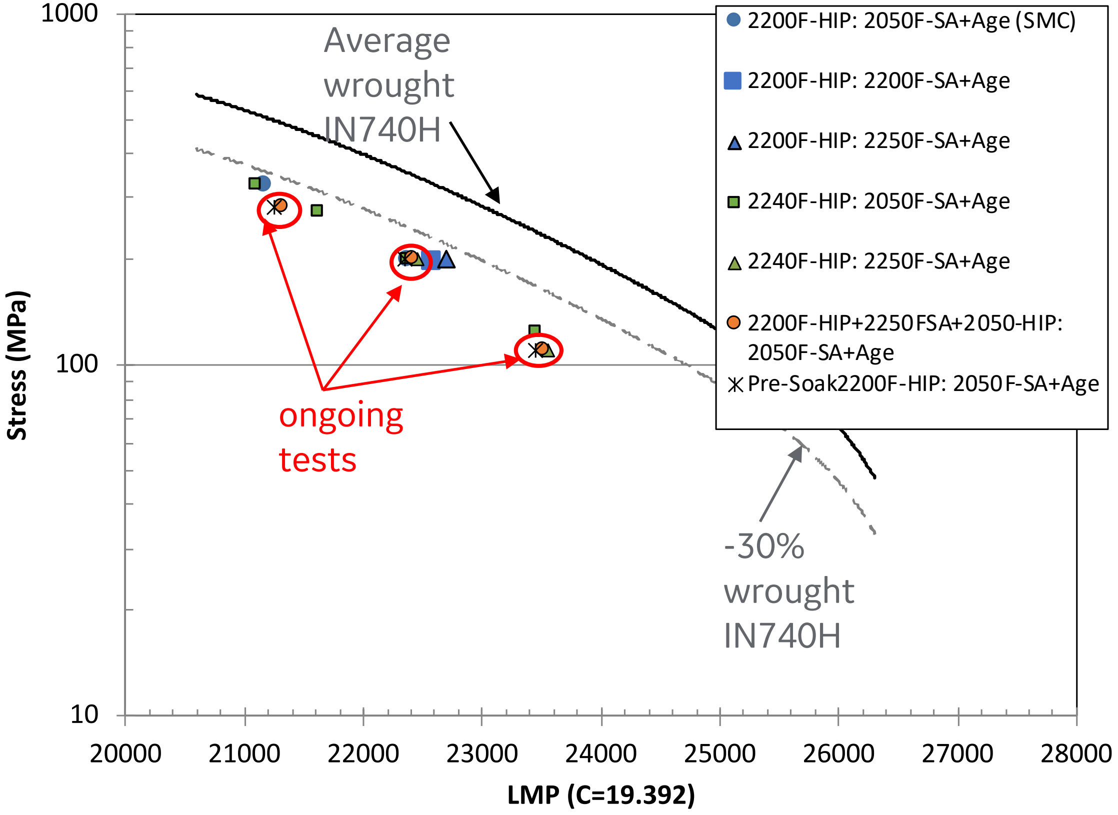






- **PM HIP IN740H shows ~10ksi higher UTS at room temperature, comparable UTS at 1292F as wrought IN740H**
- **Lower tensile ductility than wrought IN740H (likely due to PPB)**

Preliminary Creep Evaluation

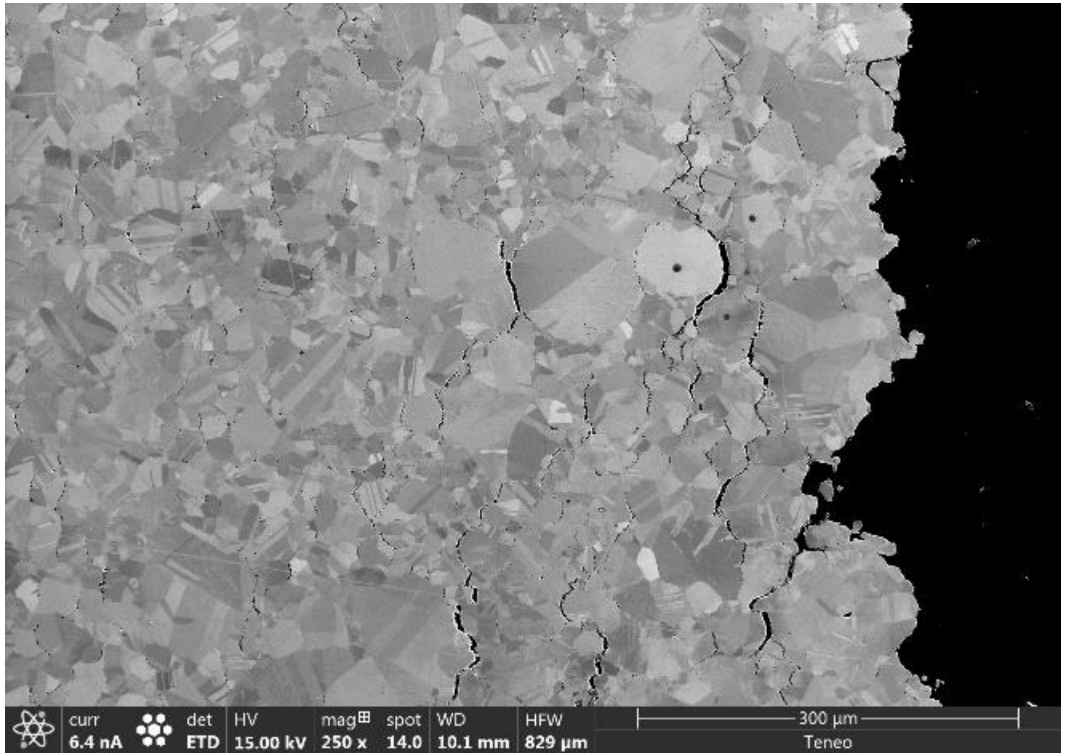


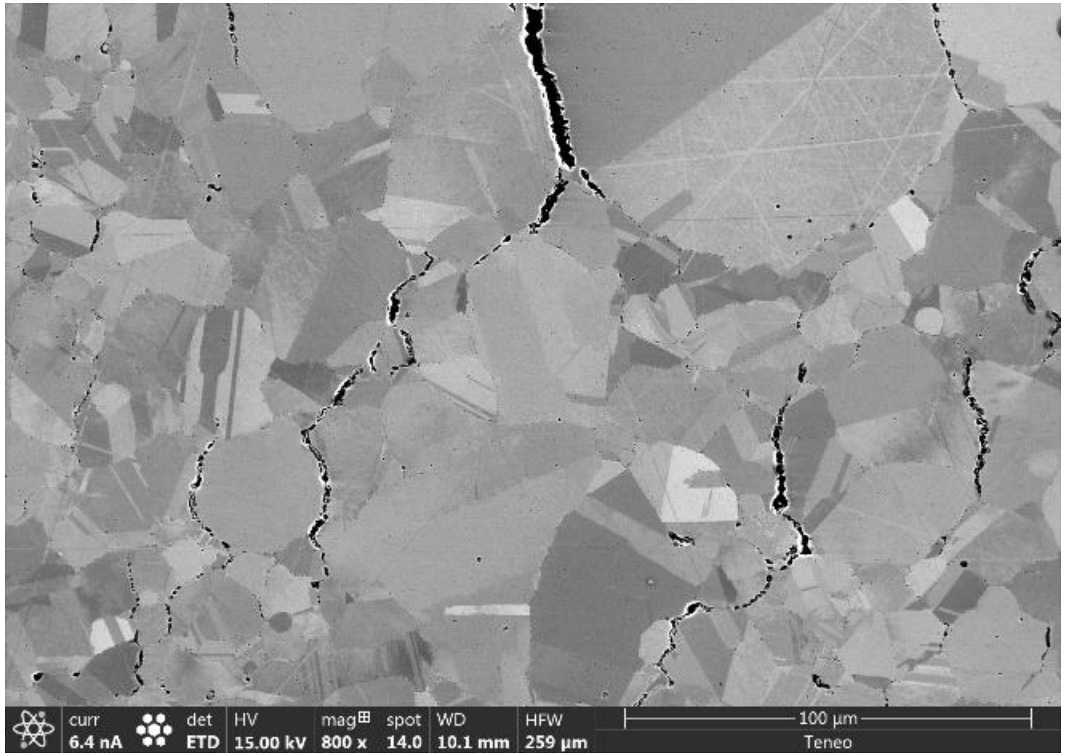
- **Current data show more than -30% debit in creep stress capability**
- **Higher solution temperature improves creep, but may result in thermally induced porosity**
- **No improvement with higher HIP temperature**

HIP	Solution	Stress, MPa	Temperature, °C	Time to rupture (hrs)	Elongation
2200°F/15ksi/4hr	2050°F/1hr/WQ	325	750	19.9	3.5
2200°F/15ksi/4hr	2050°F/1hr/WQ	200	750	297.8	5.6
2200°F/15ksi/4hr	2200°F/1hr/WQ	200	750	461.4	2.9
2200°F/15ksi/4hr	2250°F/1hr/WQ	200	750	625.4	1.8
2240°F/15ksi/4hr	2050°F/1hr/WQ	275	700	697.1	2.5
2240°F/15ksi/4hr	2050°F/1hr/WQ	325	750	16.9	0.7
2240°F/15ksi/4hr	2050°F/1hr/WQ	200	750	295	3.9
2240°F/15ksi/4hr	2050°F/1hr/WQ	125	800	292	10.3
2240°F/15ksi/4hr	2250°F/1hr/WQ	200	750	358	
2240°F/15ksi/4hr	2250°F/1hr/WQ	110	800	360	
2200°F/15ksi/3hr HIP + 2250°F/1hr/WQ + 2050°F/15ksi/4hr HIP + 2050°F/1hr/WQ		280	700	336	
2200°F/15ksi/3hr HIP + 2250°F/1hr/WQ + 2050°F/15ksi/4hr HIP + 2050°F/1hr/WQ		200	750	336	
2200°F/15ksi/3hr HIP + 2250°F/1hr/WQ + 2050°F/15ksi/4hr HIP + 2050°F/1hr/WQ		110	800	336	
Pre-soak + 2200°F/15ksi/4hr	2050°F/1hr/WQ	280	700	284	
Pre-soak + 2200°F/15ksi/4hr	2050°F/1hr/WQ	200	750	284	
Pre-soak + 2200°F/15ksi/4hr	2050°F/1hr/WQ	110	800	288	

(Standard aging 1472°F/4hrs/AC applied on all the creep specimens)

Preliminary Creep Evaluation





- **Creep damages of cavitation and micro-cracking form and progress along PPBs normal to loading direction**

Technoeconomic Analysis

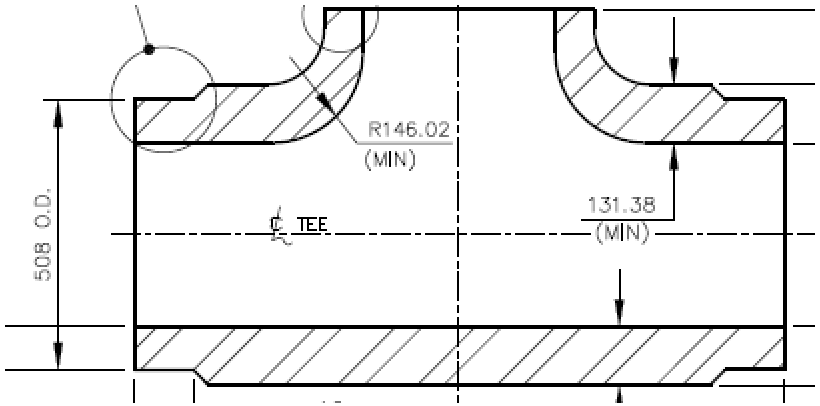
Market Gap

Challenge to make large ID pipe fittings (tees, wyes) by hot forging or cold hydroforming

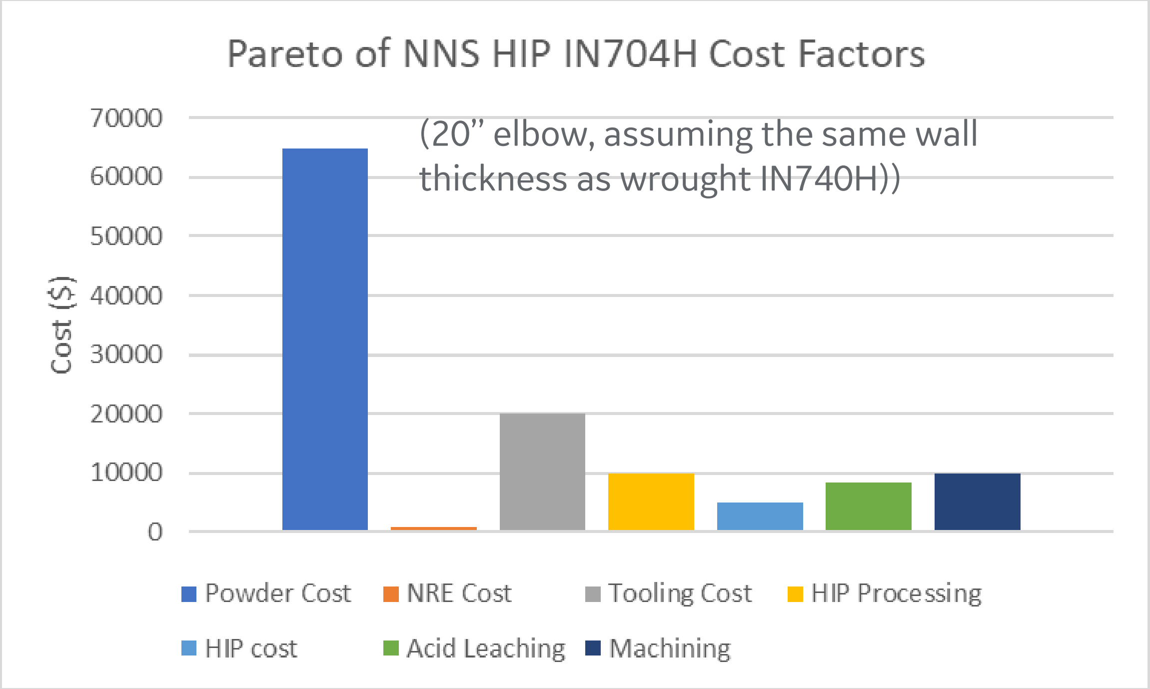
- Excessive waste of material and machining from a forged cylinder

Pipe fitting components considered for cost analysis:

- 20'' elbow (large envelop size)
- 20'' tee (more complicated geometry)

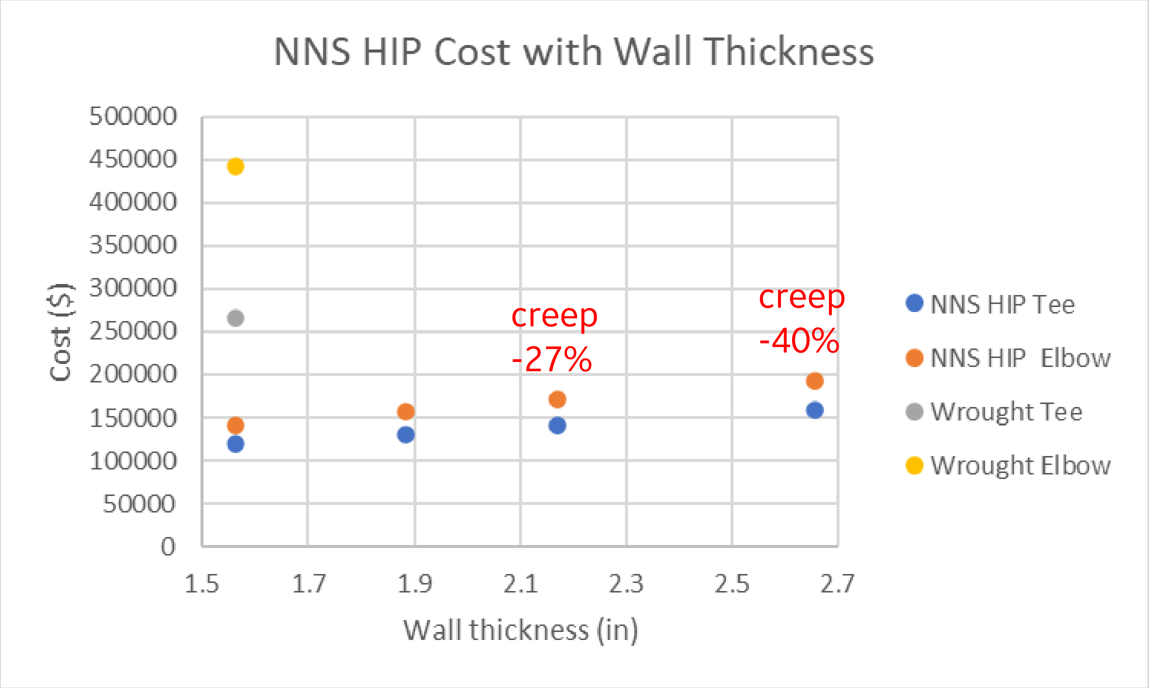


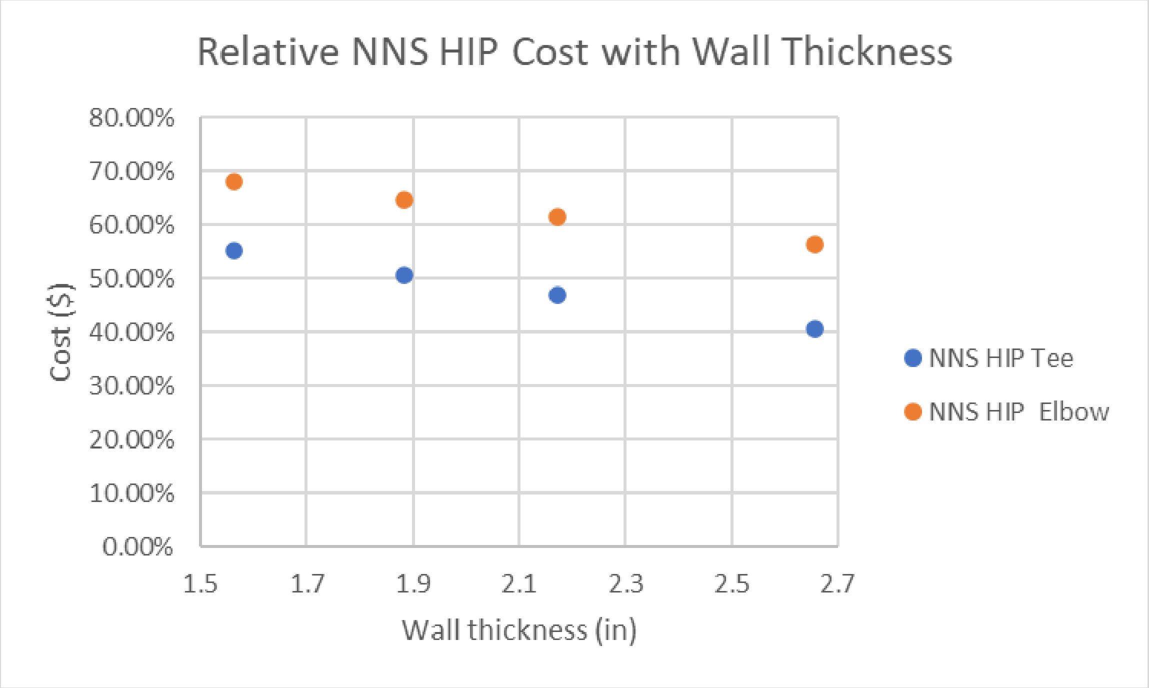
20" 2,000lb tee



- **Powder cost is the key driver for overall costs and more dominant for thicker wall**
- Breakdown cost of each processing step is confirmed by actual cost on the small elbow and quotes from US manufacturers

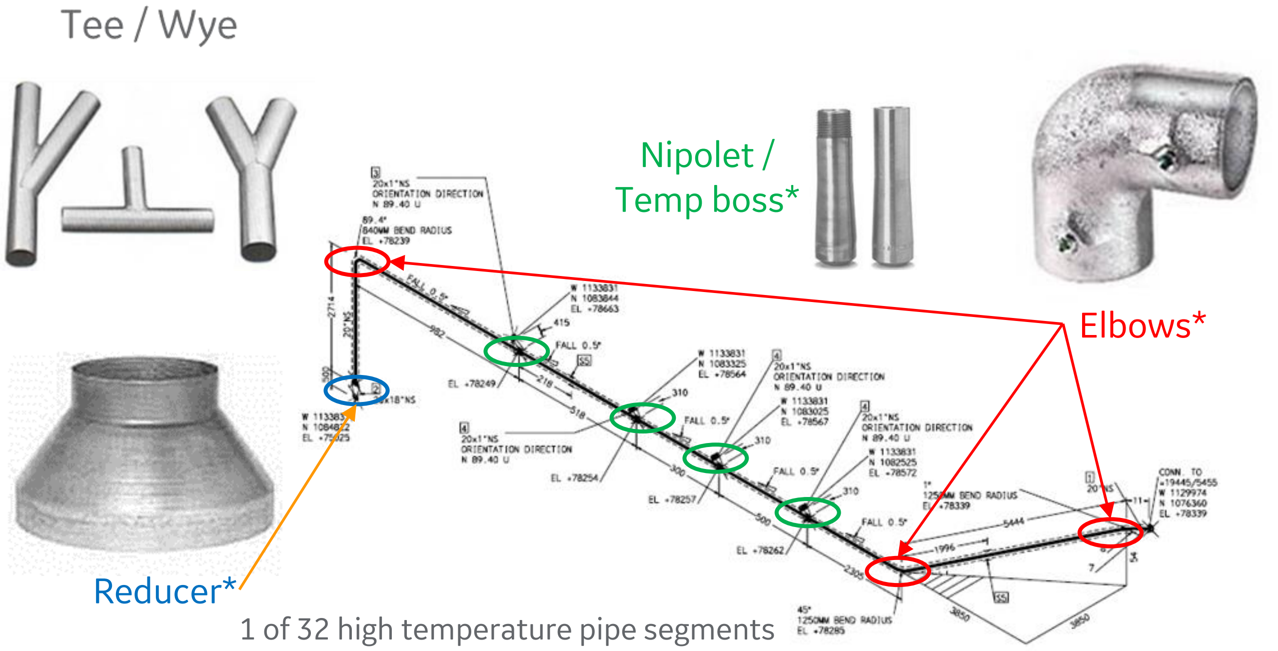
Technoeconomic Analysis





- **Cost-performance analysis:** wall thickness considered from -40% creep capability to wrought IN740H creep capability
- **NNS HIP still shows a significant cost benefit for all wall thicknesses, confirming that >50% cost saving with slight creep improvement is highly achievable**

Technoeconomic Analysis



1 of 32 high temperature pipe segments

LCOE Benefit

- Two USC (600/630 °C) reference plants (600 & 1080MWe): over 130 pipe fittings
- A-USC (>620/630 °C) reduced piping concept: over 80 pipe fittings
- Conservative estimation on only elbows, tees:
  - Over $48/kW reduction in CAPEX for AUSC (**Over $13MM per plant**)
  - Over $58/kW reduction in CAPEX for USC(**Over $39MM per plant**)

Pipe Fitting Components by NNS HIP

- Tee, Wye, elbow, nipolet, reducer

Summary of the cost savings for NNS HIP piping components

	Elbows	Tees (Wyes)	Raw Savings	Savings ($/kW)
USC (660MWe)	88	22	39,589,755	$58.5
AUSC (250 MWe)	39	12	13,033,978	$48.1

Summary

- **Demonstrated feasibility of NNS HIP in IN740H on AUSC pipe fitting components**
  - Net shape at inner diameter of pipe elbow achieved
  - HIP model prediction validated
  - PM/wrought GTAW welding procedure qualified
  - Promising tensile properties established

- **Applicability of NNS HIP manufacturing to Fossil Energy**
  - Cost saving for manufacturing large, complex components in Ni-based alloys for AUSC

- **Recommended Future Work (Beyond Phase 1 Project)**
  - Creep and ductility improvement by processing optimization
  - ASME code case

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