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Low-Cost HIP Fabrication of Advanced Power Cycle Components and PM/Wrought Inconel 740H Weld Development

DOE-NETL 2020 FE R&D Virtual Project Review Meeting - High Performance Materials Alloy Manufacturing Panel

Phase 1 Project (10/01/2019 ~ 3/31/2021)
Contract # DE-FE0031818

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Background & Motivation

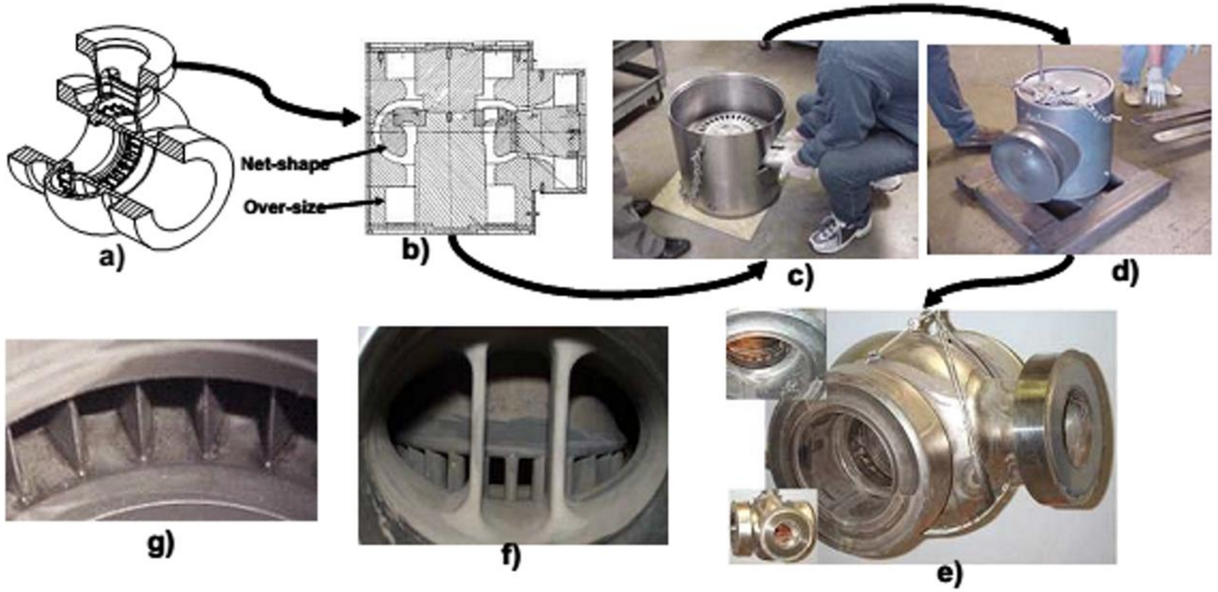
High capital costs offset efficiency gains using γ' strengthened Ni-based superalloys in AUSC and sCO_2 components

- 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 input material than wrought
- Minimum machining
- 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.)

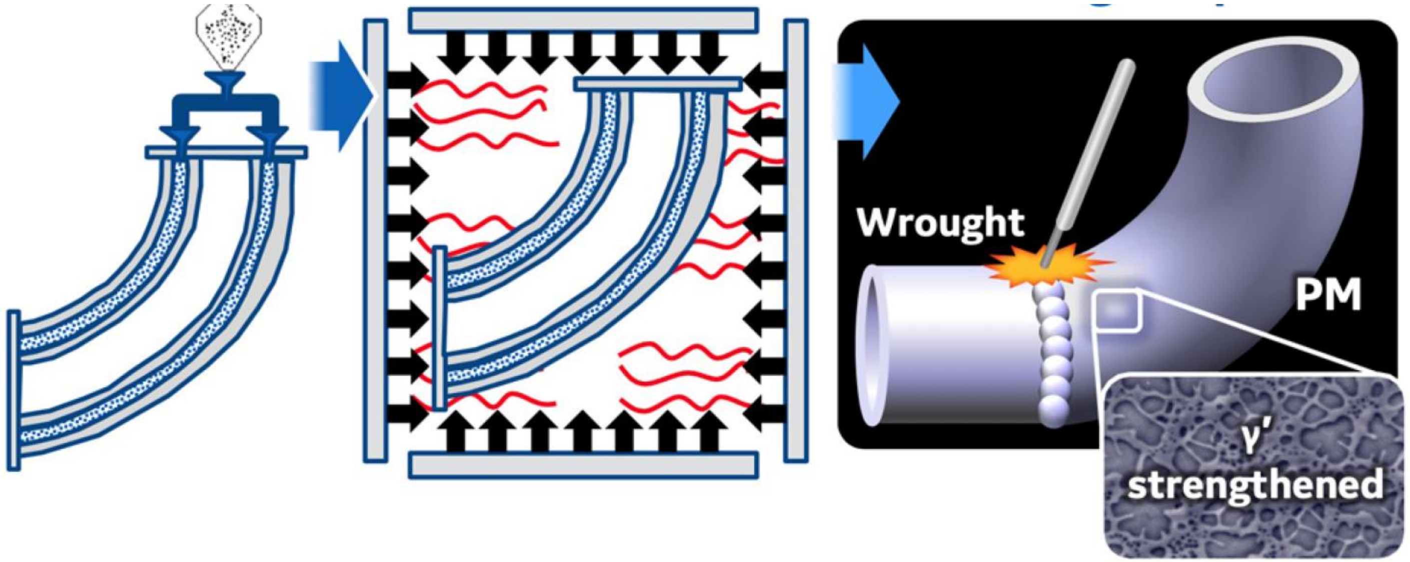
Project Description and Objectives

<u>Objectives of Phase 1</u>

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

<u>Technical Approach to Address Challenges/Risks</u>

- 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 microstructure/property improvement
- PM/wrought IN740H cross weld microstructure/property evaluations



Anticipated Benefits & Impacts Aligned with FE Strategic Goals

- 50% cost reduction in manufacturing large components ($115/kW, $13/kW reduction in CAPEX for sCO2, AUSC power cycles)
- US manufacturing supply chain for NNS HIP

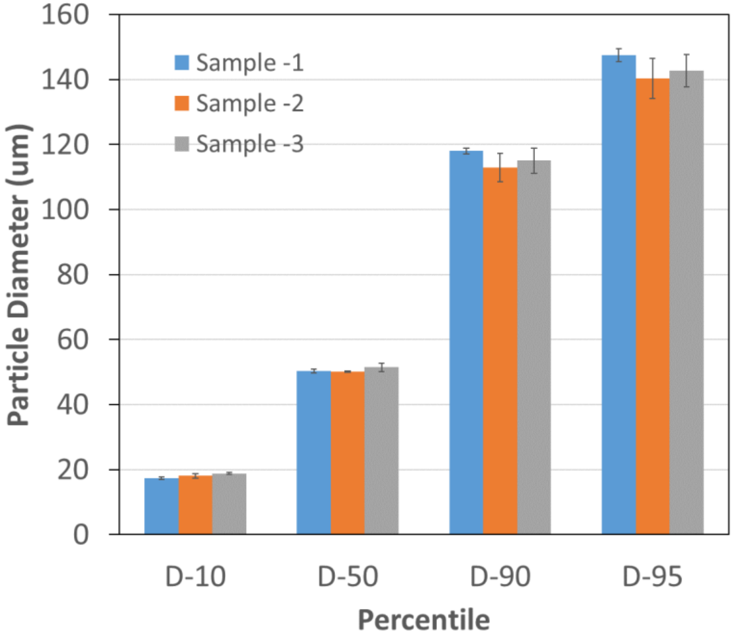
Project Milestones Status

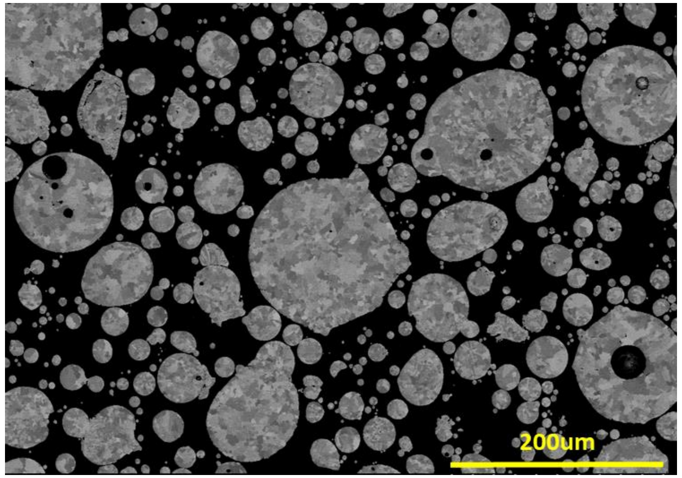
Milestone Number	Task/ Subtask	Milestone Title & Description	Planned Completion Date	Actual Completion Date	Verification Method
M-1	1	Project Management Plan (PMP)	10/31/2019	**10/10/2019**	Revised PMP submitted to NETL project manager
M-2	1	Project Kick-off Meeting	12/31/2019	**11/21/2019**	Presentation from the meeting submitted to NETL project manager
M-3	1	Workforce Readiness Plan	12/31/2019	**12/09/2019**	Workforce Readiness Plan submitted to NETL project manager
M-4	2	IN740H powder and HIP property measurements up to 1150°C completed	3/31/2020	**5/22/2020**	Properties of IN740H powder and HIP for model input will be summarized in quarterly report
M-5	2	Effect of HIP cycle and powder cut on density, PPB evaluated	12/31/2020		Data will be provided in quarterly report to show the interrelationship among various parameters, and suggest improved powder and HIP cycle
M-6	3	HIP tooling designed	8/31/2020	**5/30/2020**	Images of the designed HIP tooling in CAD will be provided by Synertech
M-7	3	Desired dimension, surface condition, microstructure of prototype elbow achieved	12/31/2020		The resulting dimension, surface condition of the prototype elbow will be compared with the targets. The microstructure will be characterized
M-8	5	500 hr creep properties evaluated	2/28/2021		Results of 500 hr creep properties will be summarized in quarterly report by EPRI

Argon Gas Atomized IN740H Powder

Composition (in weight percent, wt. %)

Alloy, wt.%	Ni	Cr	Co	Al	Ti	Nb	C	Mo	Si	Fe	Mn	Cu	P	S	B	O	N
IN740H, norm	bal.	24.5	20	1.35	1.35	1.5	0.03	0.1	0.15								
Min (IN740)	bal.	23.5	15	0.2	0.5	0.5	0.005								0.0006		
Max (IN740)	bal.	25.5	22	2	2.5	2.5	0.08	2	1	3	1	0.5	0.03	0.03	0.006		
2019 IN740H powder	bal.	24.6	20.2	1.34	1.34	1.5	0.039	0.06	0.15	0.2	0.2	0.01	0.004	0.0009	0.001	0.0062	0.0059
2020 IN740H powder	bal.	24.5	20.2	1.31	1.33	1.4	0.039	0.06	0.14	0.2	0.2	0.02	0.004	0.0006	0.001	0.0095	0.0067





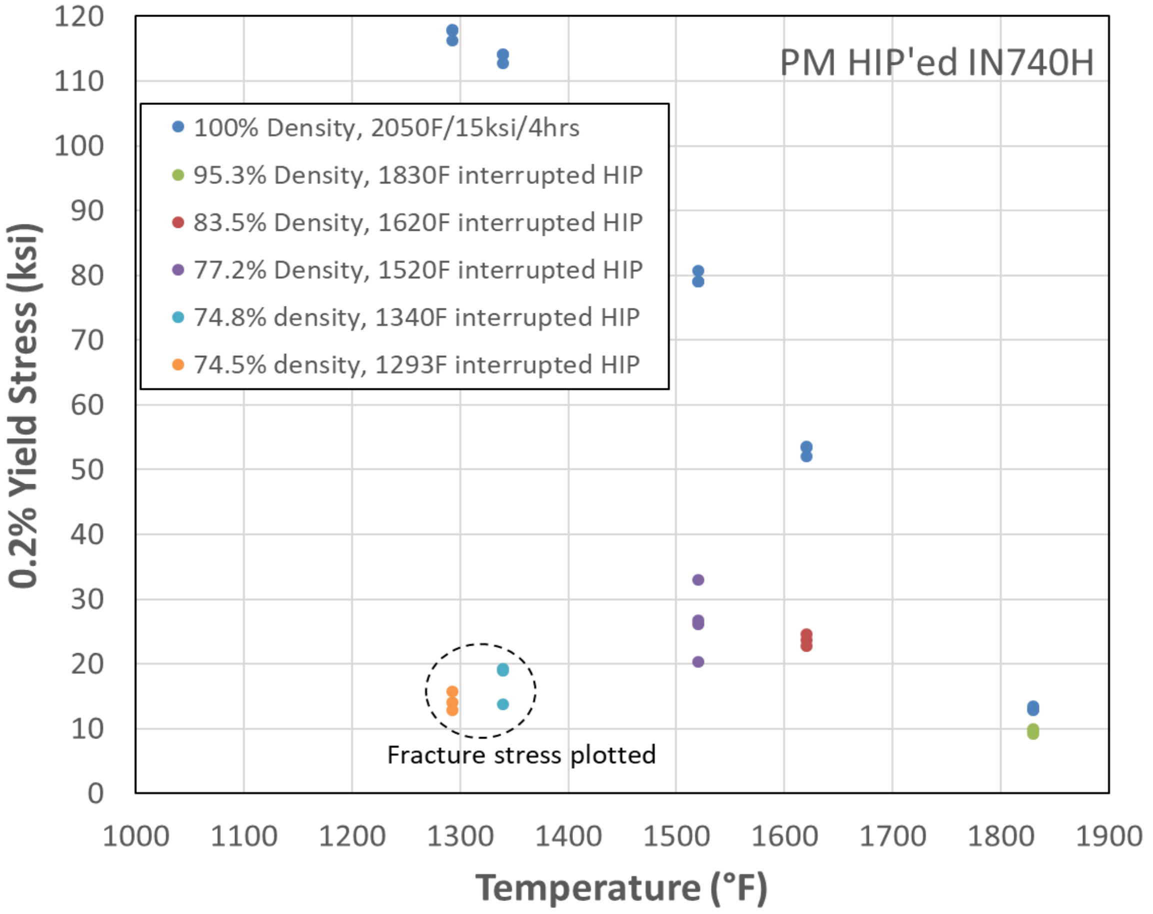
220lbs IN740H powder delivered for pipe elbow

- Successful argon gas atomization trials at Wyman-Gordon Princeton R&D
- Powder composition within specification (reasonable oxygen, nitrogen)
- Good repeatability in powder size distribution and tap density (~67%)

M-4: Properties of IN740H Consolidated Powder for HIP Model

Completed IN740H powder property measurements for HIP model input

1. Compressive stress-strain properties for IN740H powder HIPed to 70~100% density
2. Specific heat, density, coefficient of thermal expansion and thermal conductivity



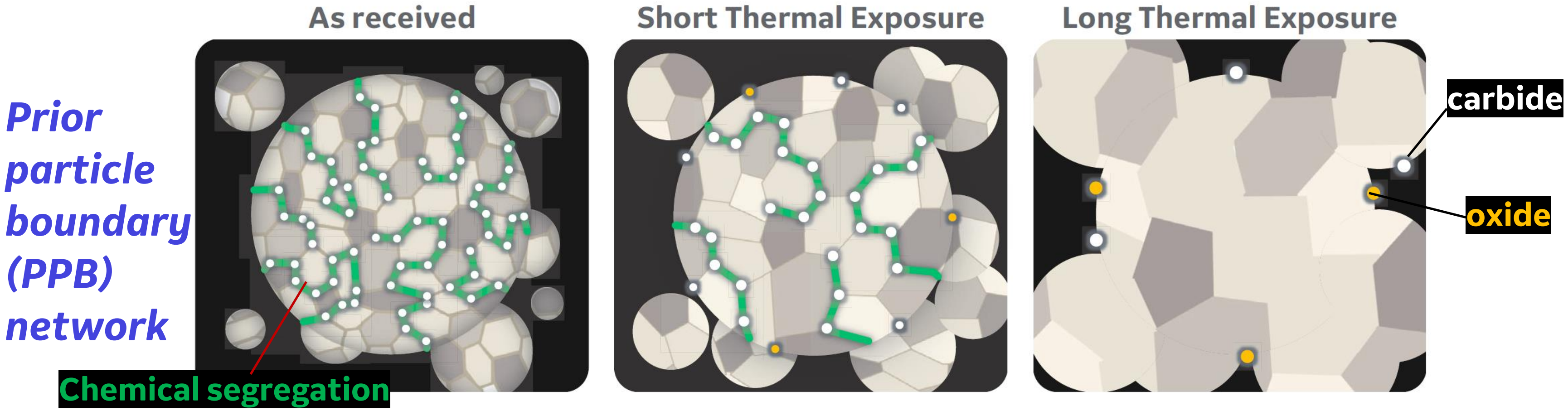
Model powder shrinkage during HIP: **plasticity**, creep, diffusion

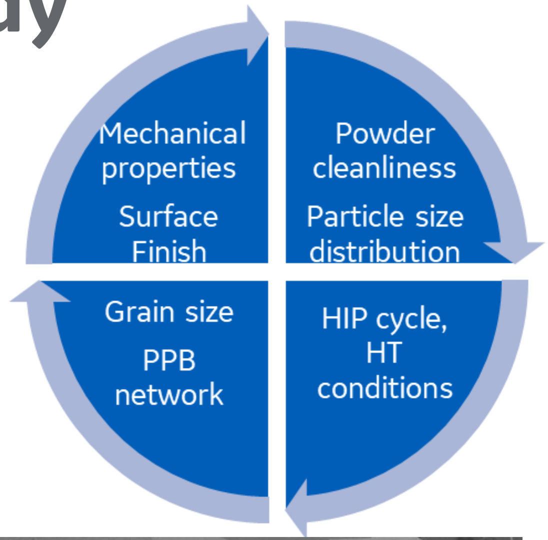
Green's Plasticity Criterion

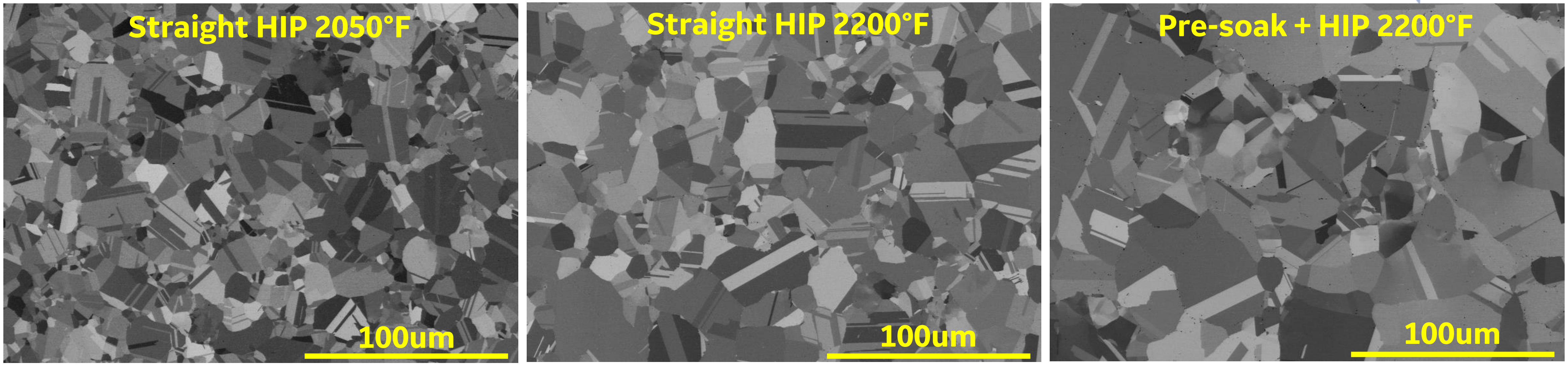
$$\frac{T^2}{f_1^2} + \frac{\sigma_0^2}{f_2^2} = \tau_s^2$$

σ_0 - average stress
T – stress intensity factor
τ_S – yield strength
f_1 – function of average stress, density
f_2 – function of sheer stress, density

M-5: HIP Cycle and Powder Cut Study



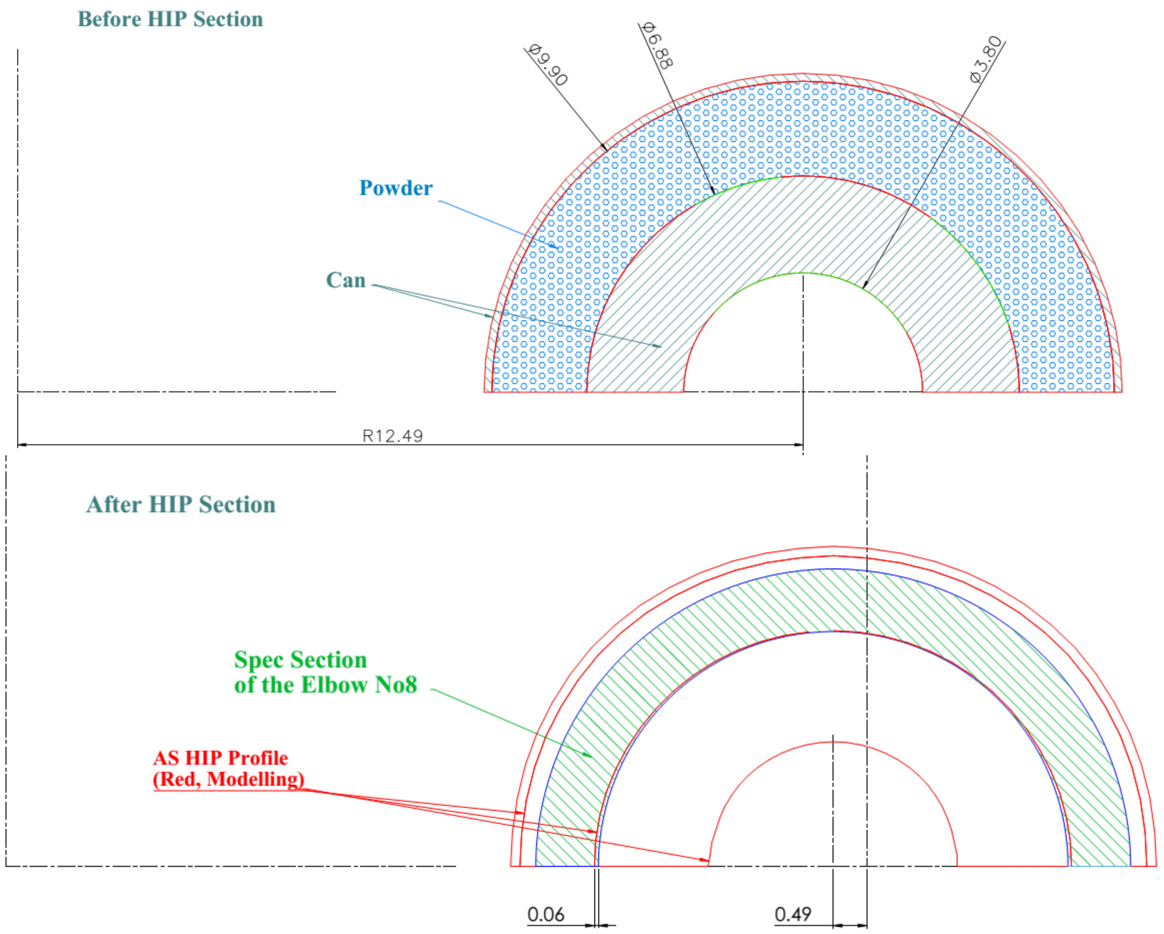


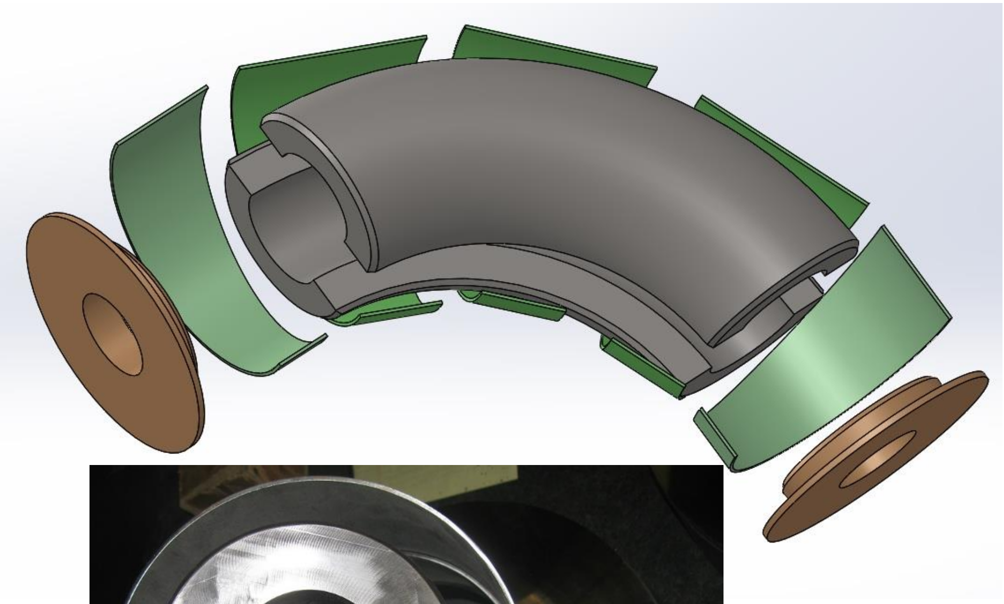


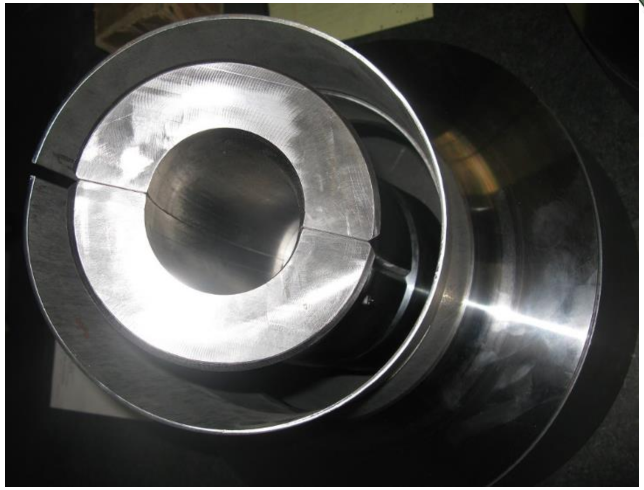
Effect of HIP, HT conditions and PSD on PPB network and grain size distribution

- Designed 16 pre-soak conditions before HIP cycle to coarsen PPB particles with less grain boundary pinning
- Prepared 5 powder size distributions (fine, coarse, bimodal)

M-6: Pipe Elbow HIP Tooling Design

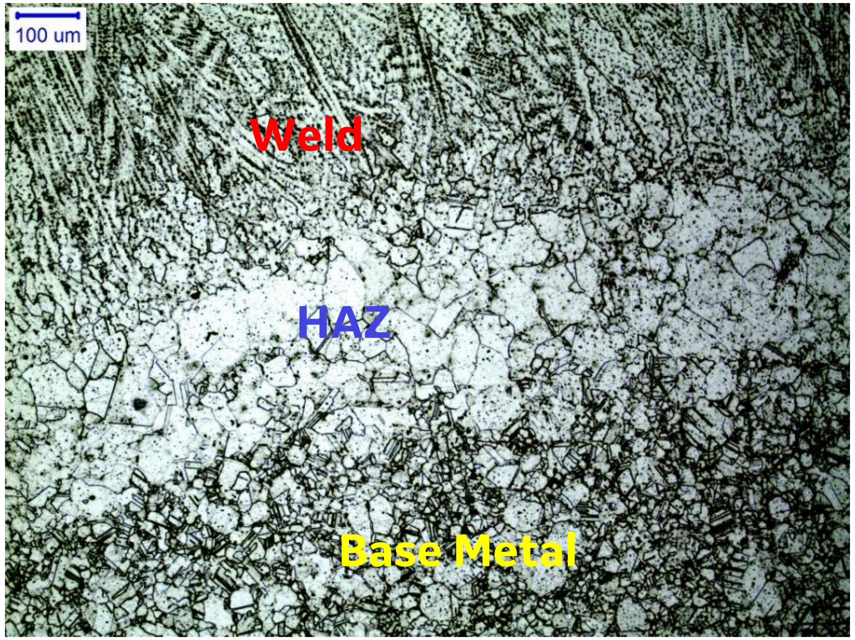


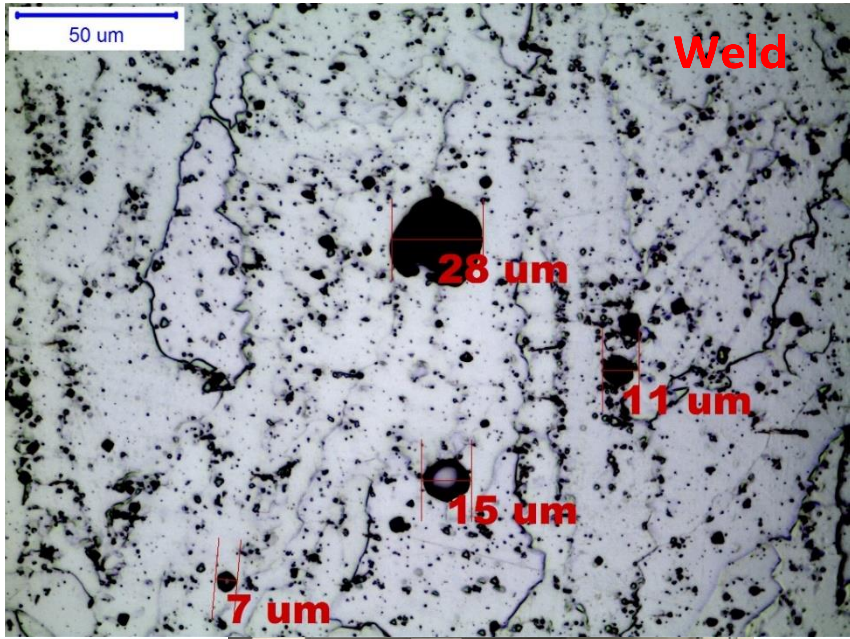




- HIP densification and shrinkage modeled with the goal of achieving net shape at interior surface
- HIP tooling for pipe elbow designed, manufacturing & assembly procedure defined
- In progress of fabricating HIP tooling

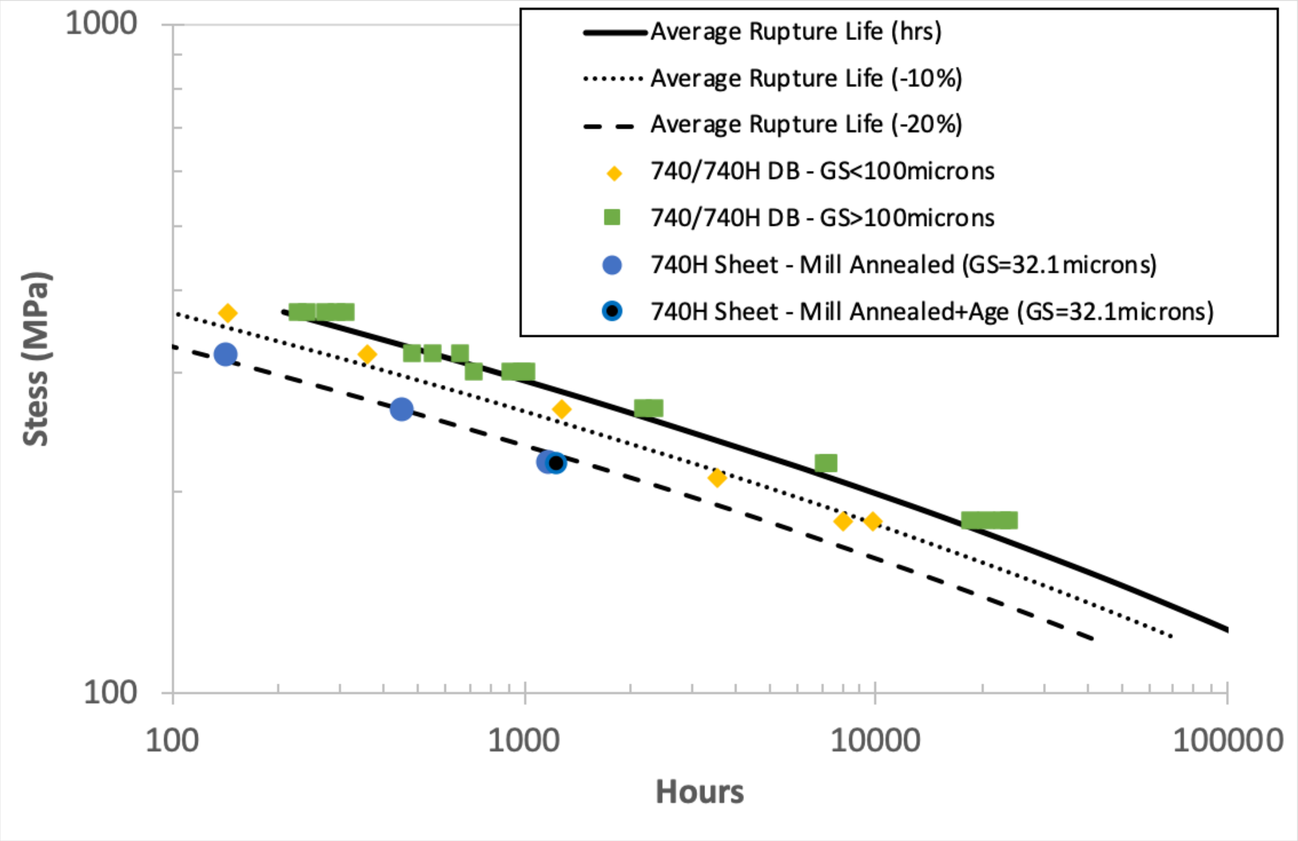
PM/Wrought IN740H Weld Development





- Preliminary weldability evaluated by autogenous Gas Tungsten Arc Welding on HIP IN740H
- Argon induced porosity observed in the weld metal, but acceptable per ASME
- In preparation of HIP IN740H plate for PM/wrought plate weld development

M-8: Preliminary Creep Evaluation



A clear technical path to improve creep

1. Pre-soak before HIP
2. Powder size distribution
3. HIP temperature
4. Solution treatment
5. Alternative powder production for cleanliness
6. Minor alloy composition modification

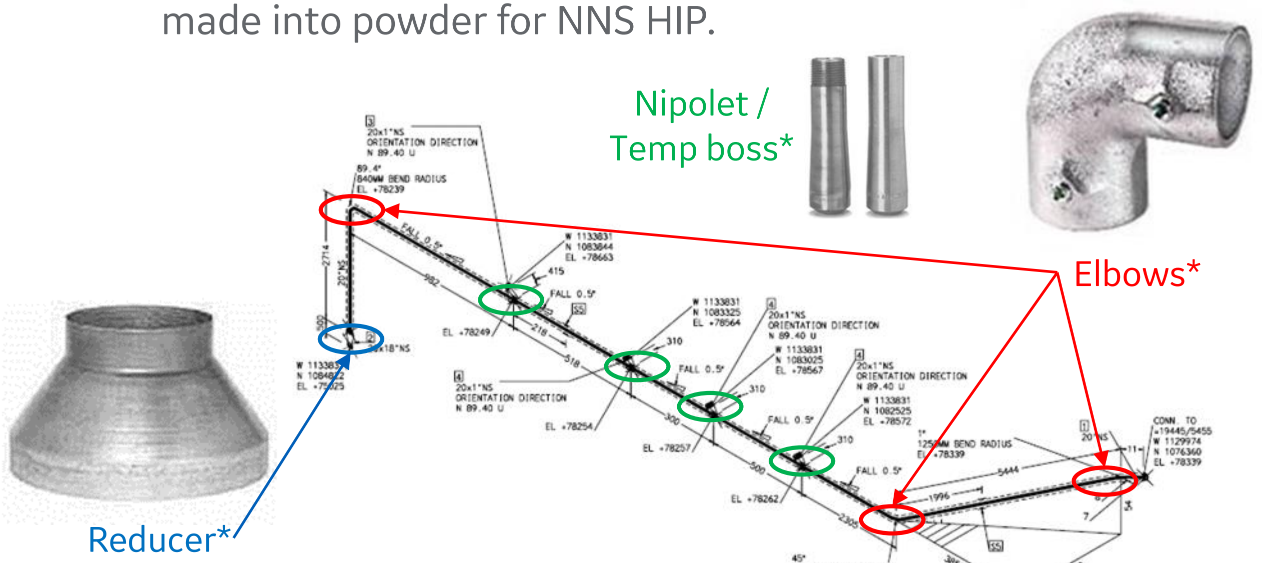
- Goal is to evaluate creep properties with different HIP conditions/microstructure and compare with wrought IN740H
- Literature review on wrought IN740H shows a trend between grain size and creep life

Preparing Projects for Next Steps: Market Benefits/Assessment

Market Gap

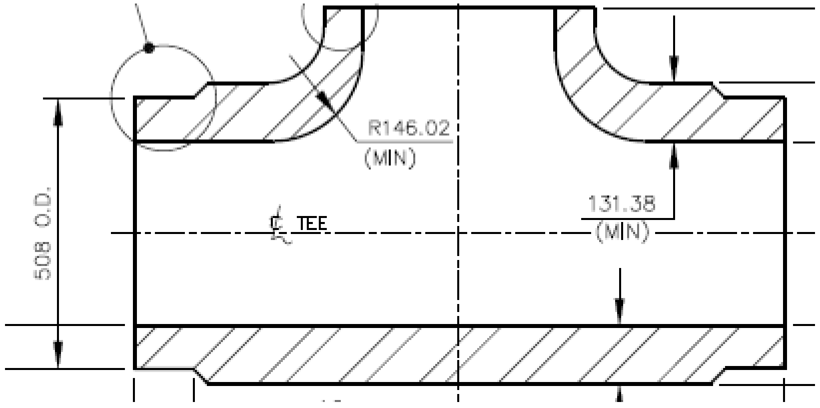
Pipe fittings are currently very costly as they are machined out of forged blocks of material:

- Excessive waste of material and machining time.
- IN740H is not an easily sand castable alloy but can be made into powder for NNS HIP.



1 of 32 high temperature pipe segments

- Two USC (600/630 °C) reference plants (600 & 1080MWe)
- A-USC (>620/630 °C) reduced piping concept



20” 2,000lb tee

Market Benefit

- Program proposal: 15 pipe features at $300k machined verses $150k NNS HIP plus TSV: $13/kW.
- Updating market study benefit increasing to $35 to 70/kW (Over $20MM per plant):
  - Standard steam plant ~130 major pipe fittings
  - Reduced piping AUSC design: >80 major fittings
  - Actual IN740H forging for 2,000lb tee is 2x estimate

Preparing Projects for Next Steps: Technology-to-Market Path

Technology Integration

- Based on value story, code case finalized backed by industry (GE Power, EPRI and other OEMs)
- Post code case: hardware incorporated in future A-USC designs; supply chain established.

Remaining Technology Challenges

- Improved creep rupture life – trade-off with pipe wall thickness which equates to cost
- ASME B31.1 & BPVC code case/approval (i.e., creep, weld optimization)
- First application plant identified (first piece qualifications)

Current Industry Collaborators Span from End-user to Material Supplier

- PCC: Special Metals, Wyman-Gordon (IN740H material supplier), *project partner*
- Synertech PM (NNS HIP), *project partner*
- GE Power Steam Power Systems (plant developer), *consultant*
- EPRI (Power plant consortium), *project partner*
- Future collaborators: sub-tier suppliers

Concluding Remarks

- Applicability of NNS HIP manufacturing to Fossil Energy
  - Cost saving for manufacturing large, complex components in Ni-based alloys for AUSC, sCO2 power cycles (Forging $/lb ↑ with component size, HIP $/lb ↓ with component size)

- Alignment to Fossil Energy strategic goals
  - Affordability of AUSC, sCO2 power cycles
  - US manufacturing competitiveness

- Project's next steps
  - To complete Phase 1 tasks and de-risk for Phase 2
  - To prepare Phase 2 proposal building on successful proof-of-concept elbow
    - Detailed cost/performance trade-off with IN740H PM HIP material properties
    - Valve body development with complex shapes and sizes (5 tons, 5 feet)
    - Market evaluation of smaller pipe fitting components as well as boiler, turbine components