Characterization of INCONEL alloy 740H for Tube, Pipe and Fittings for Advanced-Supercritical CO_2 Systems

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Special Metals Corporation

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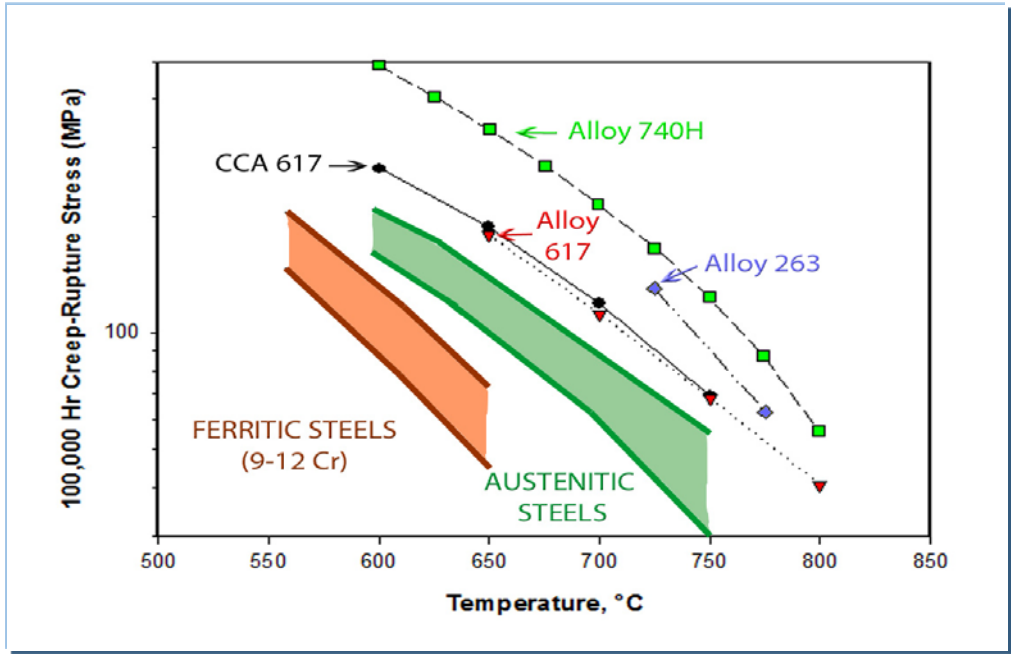
Presentation Outline

- Background – 740H and A-USC
- Metallurgy and Microstructure
- Mill Product Forms and Properties
- Welded Tube
- Fittings and Pipe Bends
- Welding
- Fabrication Experiences
- Where are we now?

Background

- Advanced-USC Programs in Europe and USA
- Service Conditions in USA: 760°C (1400°F), 35MPa (5,076 Psi)
- Creep-Rupture: >100 MPa (14.5 Ksi) in 100,000hr
- Corrosion: <2 mm in 200,000 hr (in coal ash)
- Other attributes: weldability, fabricability, phase stability, damage tolerance, manufacturability
- Modification of an alloy used for gas turbine ducts
- 740H specifically designed for A-USC
- Characterized under many DOE led programs



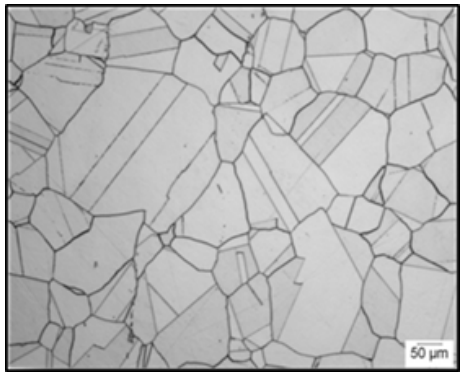
Creep-Rupture Properties of Boiler Materials

Cr	Co	Mo	Al	Ti	Nb	C	Ni
24.5	20	0.5	1.4	1.4	1.5	0.03	Bal

Nominal Composition of 740H

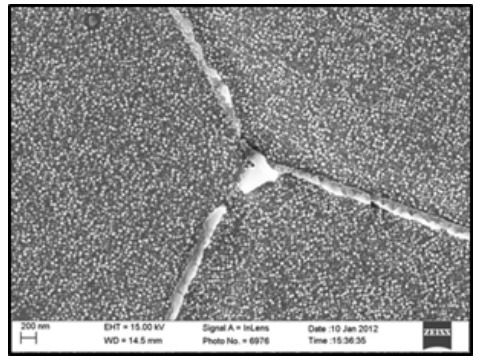
Metallurgy and Microstructure

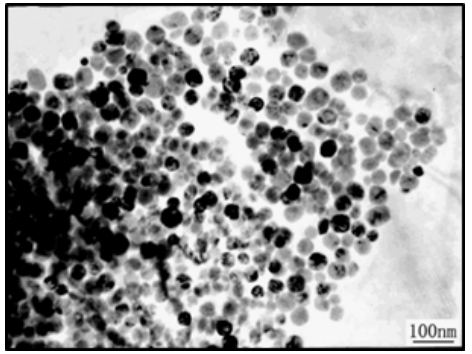
- γ′ (Ni_3M) strengthened by Al, Ti, Nb
- Composition balanced to avoid TCP phases and solidification segregation
- VIM melt and ESR or VAR remelt
- Ingots, 7,000-30,000lb
- Batch process to customer order
- Heat treat: Solution anneal >1100°C (2012°F) + age harden 760-816°C (1400-1500°F) 4hr
- Hardness: SA - Rb 85; SA+A Rc 35
- Mill Products: Tube, Pipe, Bar, Sheet, Plate, Weld wire



Optical Micro: Only Carbides Visible

SEM: Grain Boundary Carbides and γ′ (Xie)

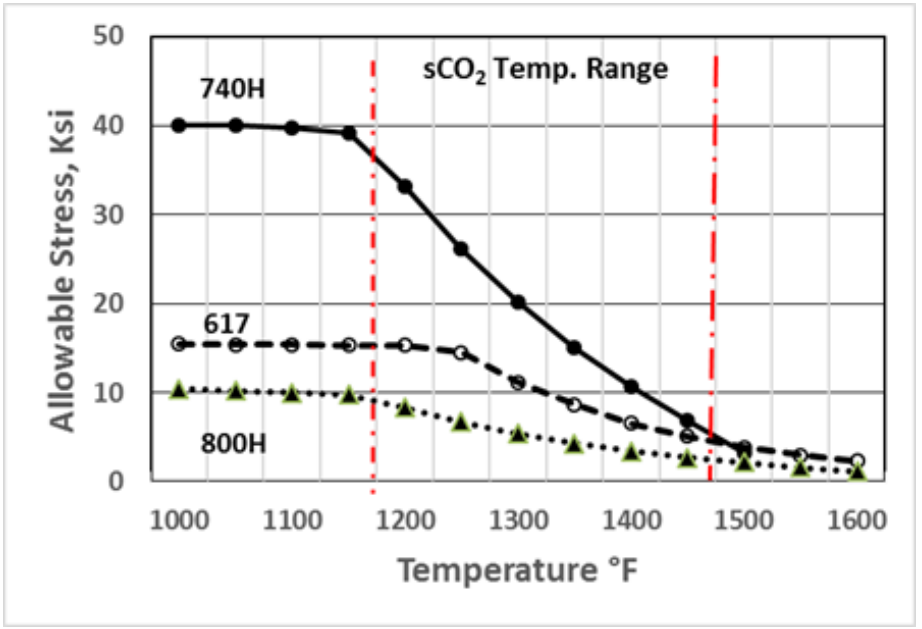




TEM: Reveals γ′ Structure (Xie)

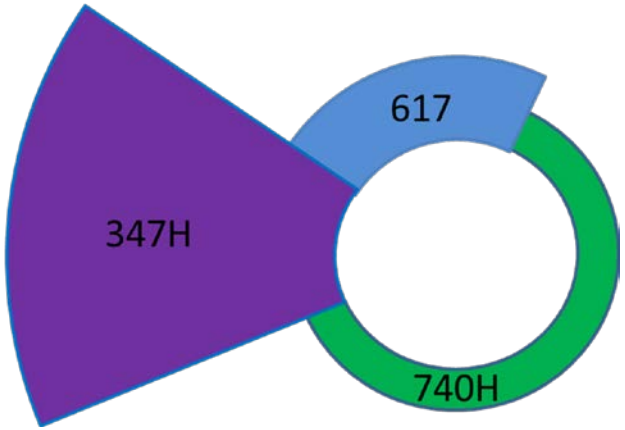
US A-USC Consortium

- DOE, EIO, EPRI
- Babcock & Wilcox, Foster Wheeler, Riley, Alstom, GE
- Material & Component Supply Chain
- Mechanical Property Evaluations
  - ORNL, NETL Albany
- ASME Code Design Stress Allowables
  - 740H first age hardened alloy in 2011
- Current Plan of AUSC
  - Demonstrate manufacturing of full scale components



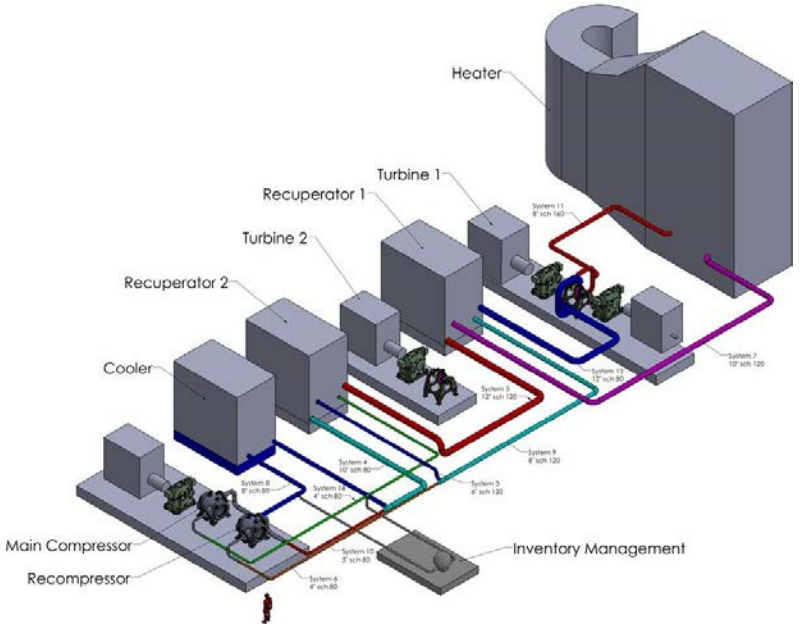
ASME Code Stress Allowables

Illustration of minimum wall thickness at constant flow and pressure



sCO_2 Systems

- **How different**
  - **No coal ash or steam but other environments such as sCO2, salt**
  - **Lower pressure**
  - **Smaller but still big and complex**
  - **Many systems with different requirements**
    - **Solar receiver**
    - **Thermal reservoir**
    - **Gas fired heater**
    - **Heat exchanger**
    - **Transfer piping**
    - **Valves**
    - **Turbine components**



Artist Sketch of STEP Project

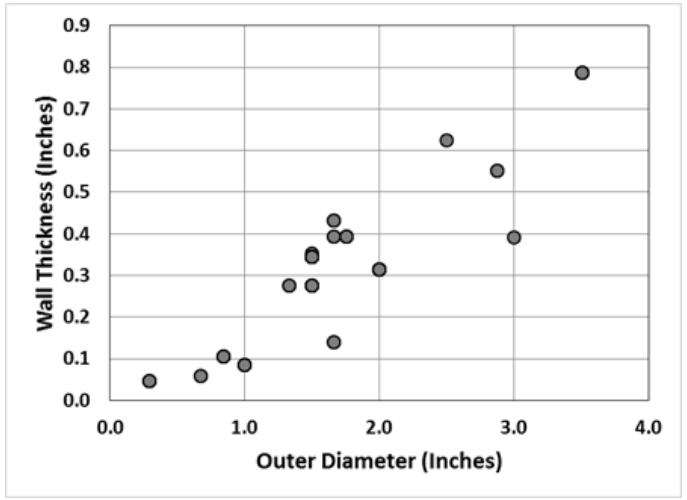
sCO2 System at Sandia NL Illustrating Piping Complexity

Tubular Product Sizes

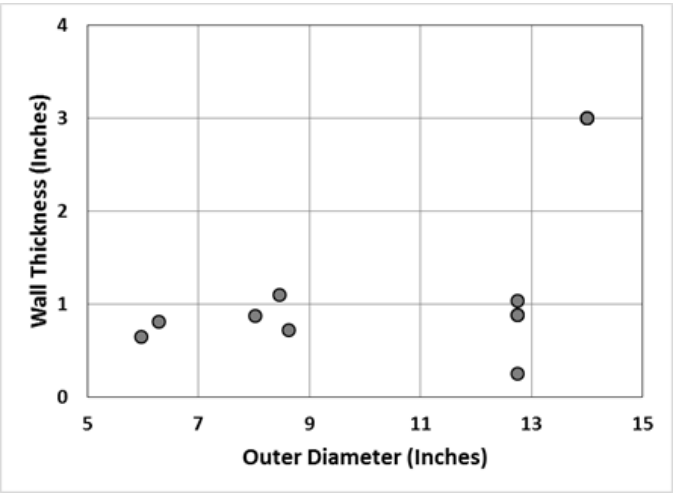
- Cold Worked Tube
  - Extruded, cold drawn or pilgered, heat treated
  - Similar to other “hard” Ni-base alloys
- Extruded Pipe
  - Heavier wall, extruded and heat treated
- Other Tubulars
  - Drilled rods (for short lengths)
  - Roll formed hollows (large diameter/thin wall)

Smallest tube made at Greenville Tube

Largest pipe made at Wyman-Gordon



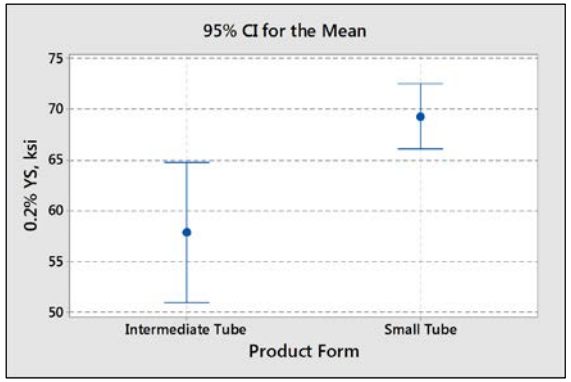
Tube sizes made to date



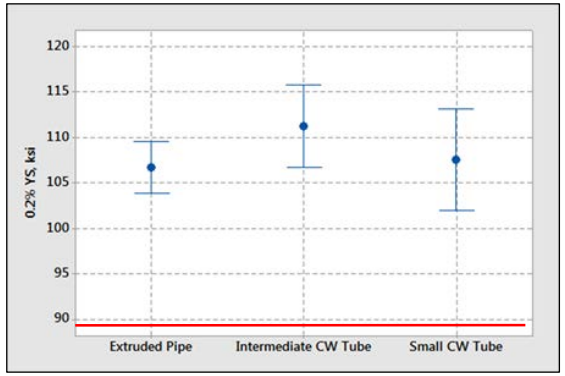
Pipe sizes made to date

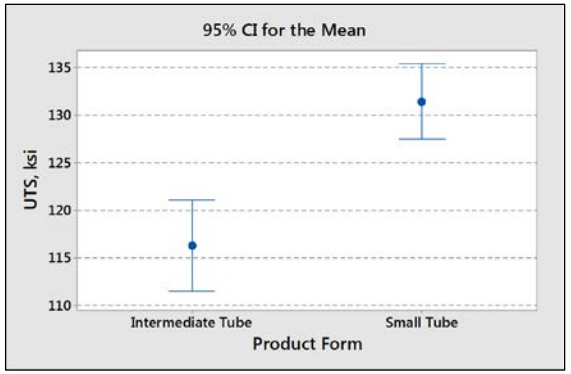
Tube and Pipe Properties

- **As Solution Annealed**
  - **Preferred where bending or flaring will be done**
  - **Certified with capability heat treatment**
  - **No defined tensile limits at present**
  - **Material must be reannealed after bending**
- **Fully Heat Treated ASME min Tensile**
  - **YS: 90 Ksi (620 MPa)**
  - **TS: 150 Ksi (1035 MPa)**
  - **El in 2”: 20%**

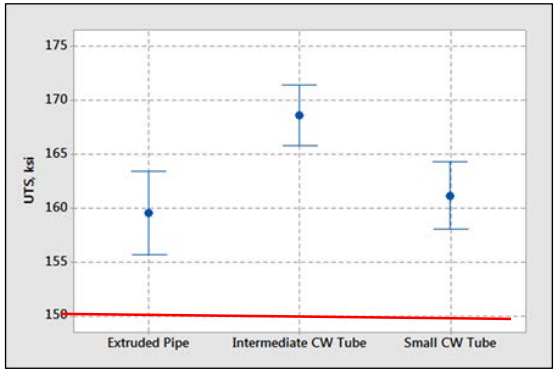


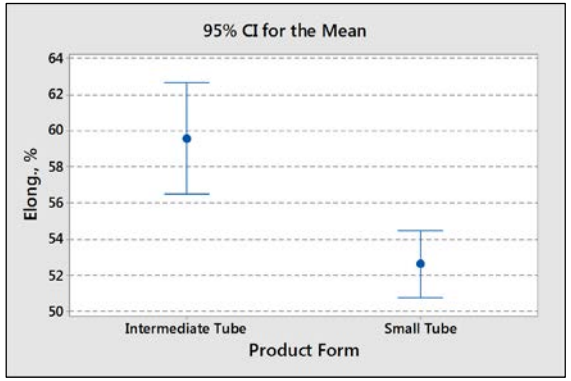
0.2% Offset YS, Ksi





TS, Ksi

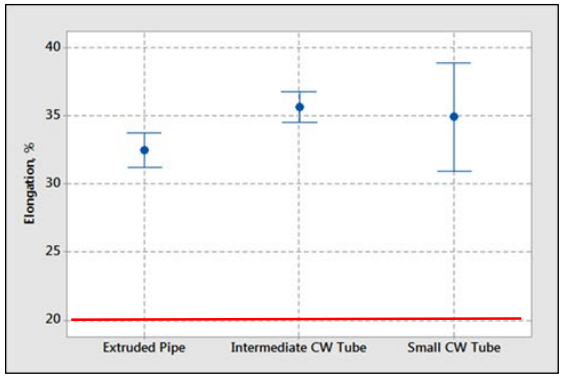




Elong, %

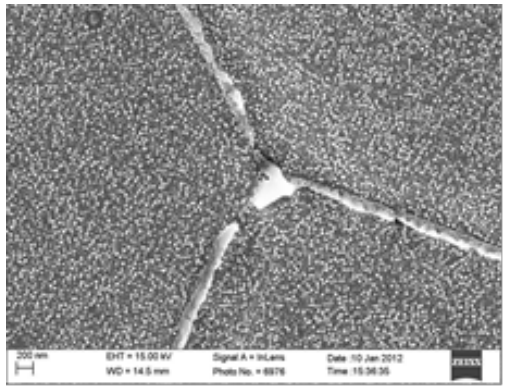
SA Tube

SA + A Tube

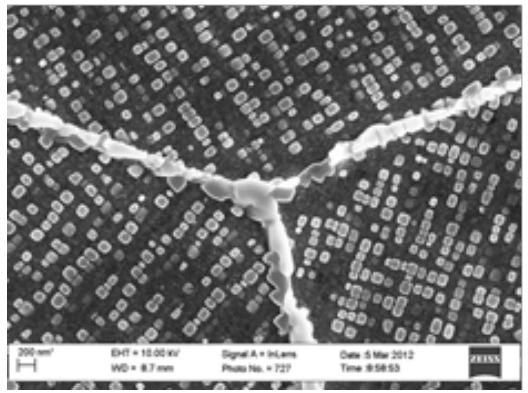


Microstructure Stability

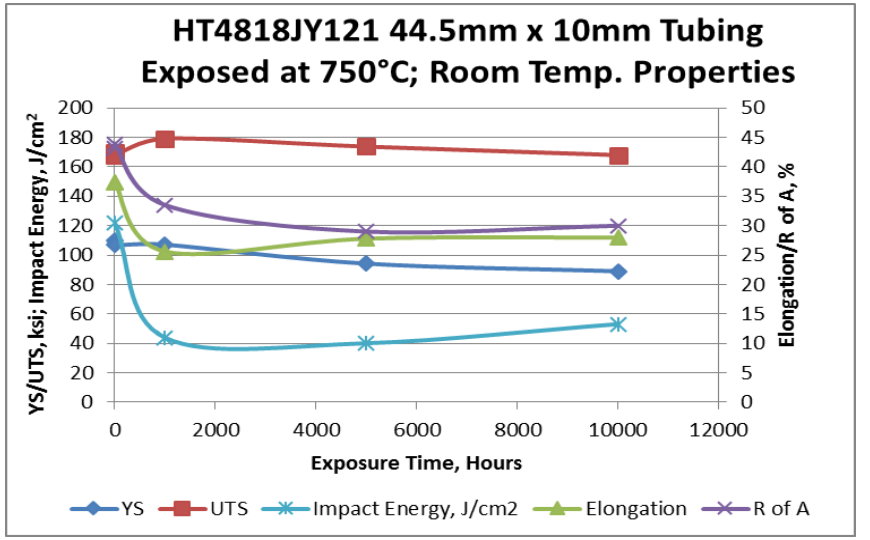
- **PhaComp Simulation**
  - **Predicts only γ' between 650-892°C (1202-1638°F)**
- **Previous studies on Experimental Material**
  - **Loss of Toughness in first 1000hr exposure. Gradual recovery after that**
- **Recent work on boiler tube, 10,000 hr, unstressed exposure at 750°C (1382°F)**
  - **Room temp**
  - **750°C**

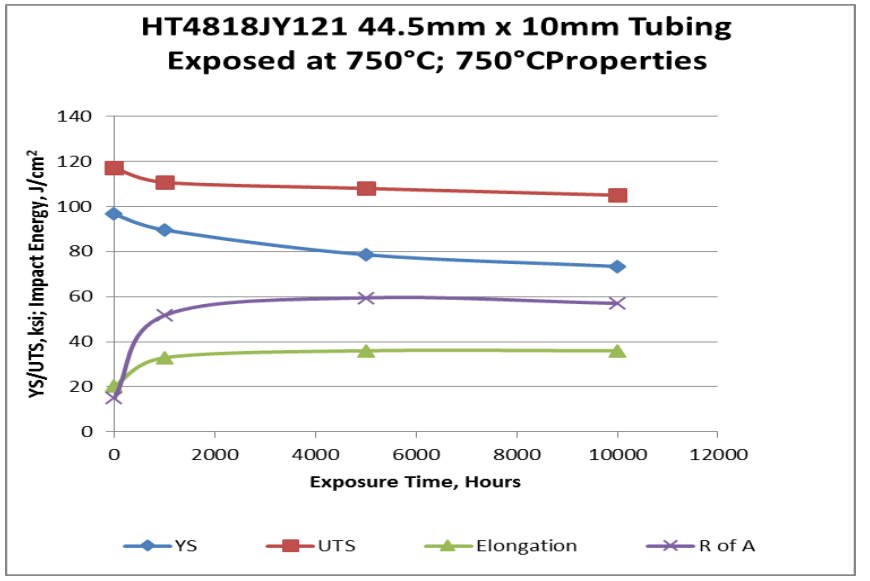


Annealed & Aged (Xie)



After 10,000 hr Exposure at 750°C (Xie)

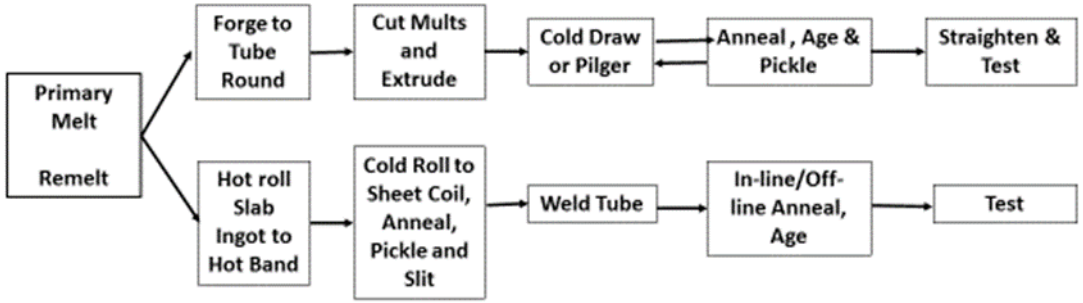




Welded Tube Manufacturing

- Manufacturing Process
- Advantages for small diameter, thin-wall tube
  - Production cost and time
  - Potential production volume
  - Accepted for molten salt solar receiver (230,625)
- Issues
  - Continuous linear structural anomaly
  - No treatment for creep range design in ASME
  - Conflicts with current ASME Code restrictions for 740H
- First manufacturing demonstration
  - 0.065” (1.6 mm) thick x 3.02” (76 mm) wide coiled strip
  - 2” (50 mm) dia tube made at RathGibson Tube

Welded tube mill entrance line at RathGibson



Finished Tubes

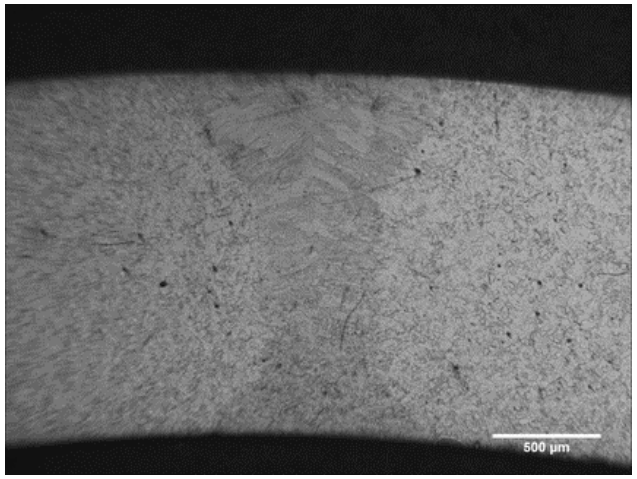
Welded Tube Microstructure and Properties

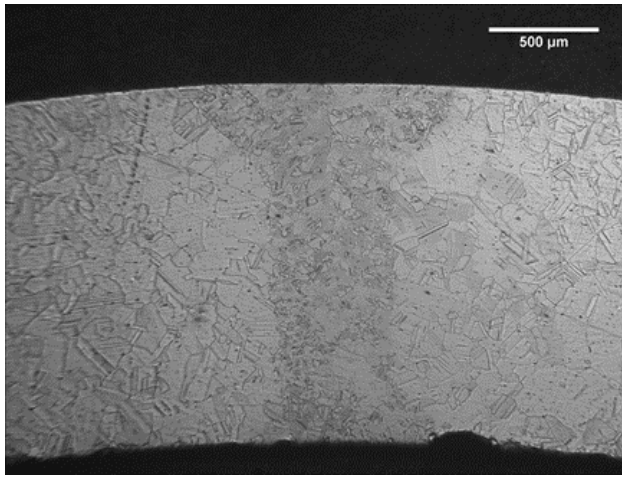
- In-line flash anneal at 1950°F (1066°C)
- Continuous offline re-anneal at 2075°F (1135°C)
- Static Age at 800°C (1472°F)
- Properties consistent with seamless
  - Flare, Flattening, Bend
- Re-annealed weld substantially recrystallized

Item	Heat Treatment	Sample	0.2% Offset Yield Strength, ksi(MPa)	Tensile Strength, ksi(MPa)	% Elongation
Welded Tube	In-line anneal 1950°F (1066°C)	1	65 (448)	126 (869)	55
		2	73 (503)	125 (862)	54
Welded Tube	Cont. Reanneal 2075°F (1135°C)	1	71 (490)	130 (896)	50
		2	71 (490)	131 (903)	60
Welded Tube	Reanneal + Static Age	1	110 (758)	168 (1159)	37
		2	116 (800)	171 (1179)	34
Seamless Tube*	Cont. Ann 2075°F (1135°)	1	72 (496)	139 (958)	56
Seamless Tube*	Cont. Ann + Static Age	1	123 (848)	177 (1220)	43
0.065" Sheet	Continuous Ann 2025°F (1107°C)	1	72 (496)	139 (958)	47
	Cont. Ann + Static Age	1	124 (855)	177 (1220)	30
ASME Min			90 (620)	150 (1035)	20
* 0.84 in (21.3 mm) OD x 0.11 in (2.74 mm) W					
Age hardening treatment 4 hr at 1472°F (800°C)					

In-line Anneal

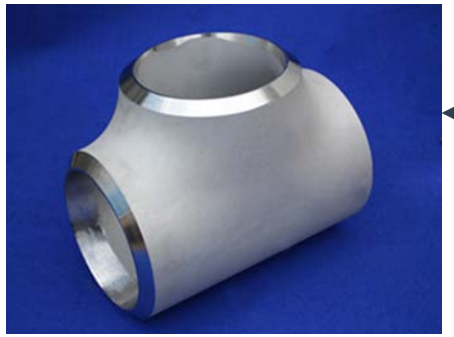
Off-line Reanneal





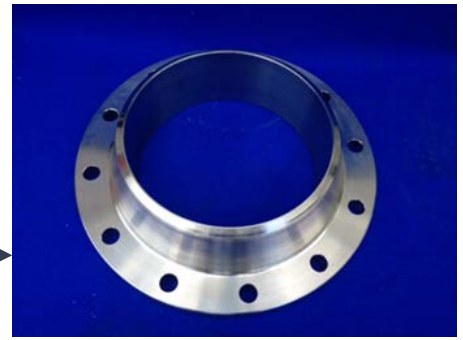
Fittings, Rings, Valves and Turbine Parts

- Wide variety of fittings, bolts and valves needed
- Not now available from supplier stock
- Demonstrations at shops with experience in 625
  - Flange made by hammer forging at Maass Flange from 4” bar
  - Elbow by press forge at CB&I APP from 8” pipe
  - Concentric reducer by cold pressing at CB&I
  - Tee by cold hydroforming at CB&I
  - Parts formed with minimal cracking
- Heavy wall rolled ring made at Carlton Forge
  - Application for gas and sCO_2 turbine components
  - Upset press forged from 11” dia. bar
  - Punch center
  - Roll to 34” OD x 25” ID x 6.5” L



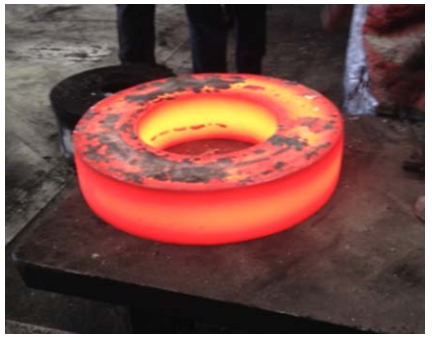
Tee

Flange



Reducer

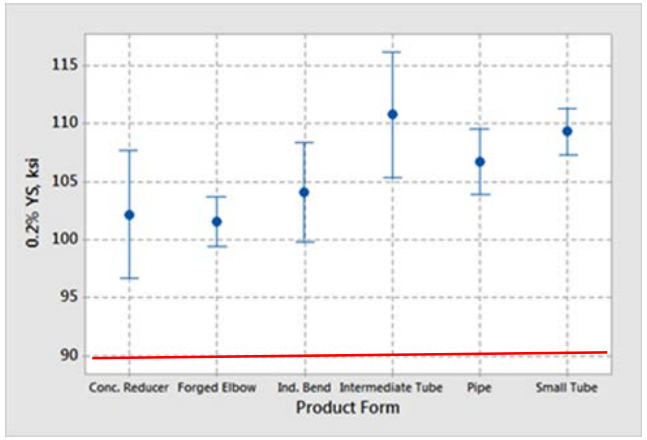
Elbow



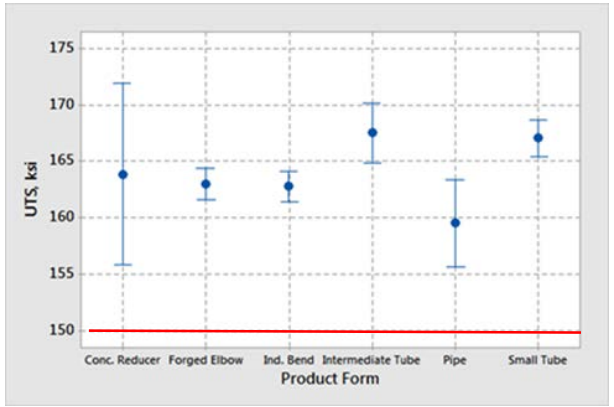
Rolled Ring

Fittings Properties

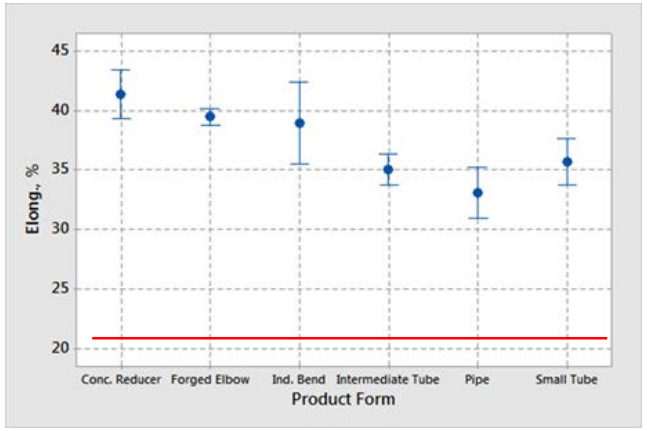
- All Fittings Surveyed
  - Grain size
  - Hardness
  - Microstructure
  - Room Temp Tensile and Impact at Selected Locations
- Mechanical Properties
  - Exceed ASME mins
  - Variability, process not optimized
- Very Large Fittings
  - Subject to Auto-aging (Wye, Valve body)
  - Demonstration in A-USC ComTest Project in 2018-19
  - Machinability Testing
  - Creep and Fatigue Testing



0.2% Offset Yield Strength, Ksi



Tensile Strength, Ksi



Elongation, %

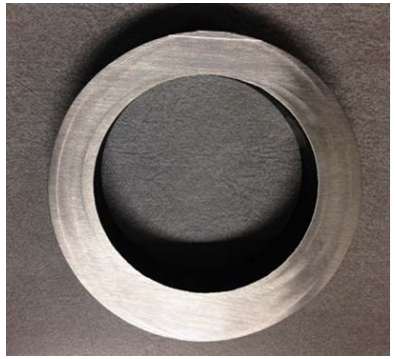
Tube and Pipe Bends

- Tube Bending
  - Annealed condition recommended
  - Shingledecker Study with pressurized creep test
  - Re-anneal Required
- Pipe Bending
  - Hot Induction Bending
  - 2.87 – 12.75” OD
  - 90° Bends demonstrated
  - Tensile properties exceed ASME mins

Induction Bending at CB&I

Welded Assembly

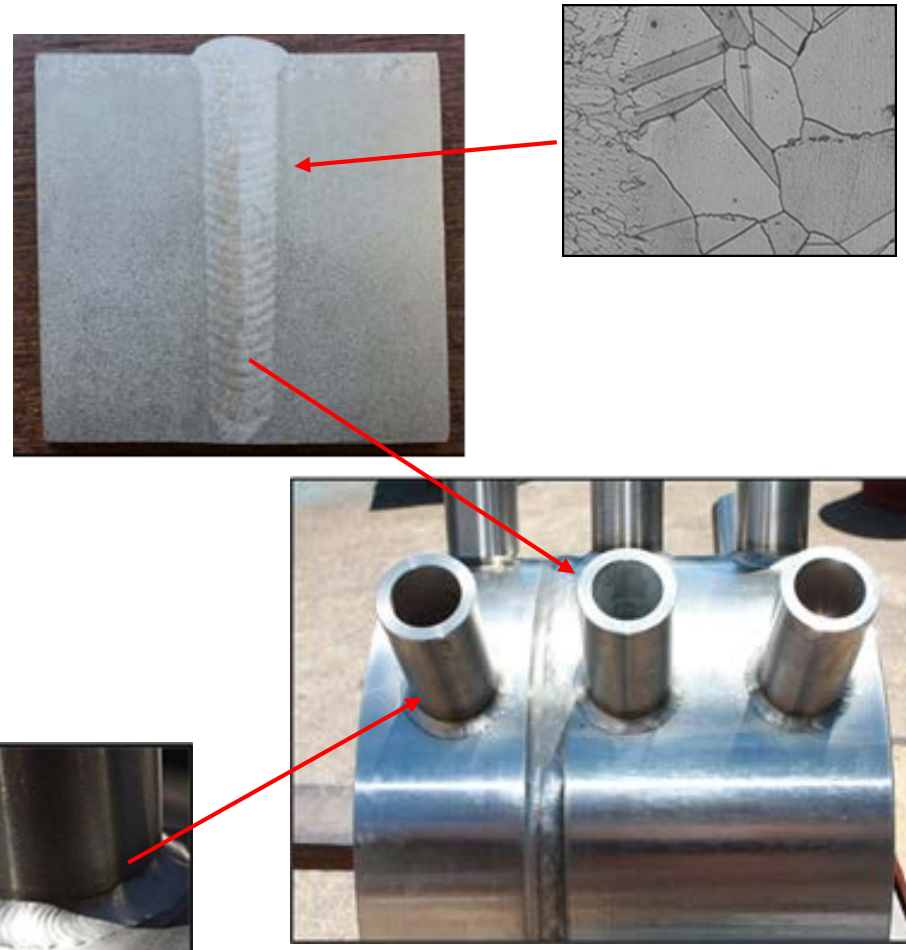
Pipe OD, in (mm)	Pipe Wall, in/mm	Location	0.2% Offset YS, ksi (MPa)	Tensile Strength, ksi (MPa)	Elongation, %
2.87 (73)	0.55 (14)	Extrados	102 (704)	163 (1121)	42
		Intrados	103 (707)	163 (1121)	39
5.25 (133)	0.75 (19)	Extrados	104 (717)	162 (1117)	38
		Intrados	108 (745)	164 (1131)	37
ASME Min			90 (620)	150 (1035)	20
Heat treatment: Solution Anneal 2100°F (1149°C) + Age 1425°F (774°C)					



Bend Cross Section

Welding 740H to Itself

- "Different, but not Difficult": Sam Kiser
  - Low heat input, bead shape, avoid oxide buildup
- Applicable Methods
  - GTAW, GMAW with matching filler
  - SMAW with 263, qualification testing underway
  - SAW unlikely
- Heat treatment
  - PWHT same as 740H aging treatment
  - Re-anneal qualification testing underway
- Properties
  - Tensile (similar to base metal)
  - 4T Bend specified
  - Creep: WJSRF of 70%
  - Good microstructure stability of weld metal

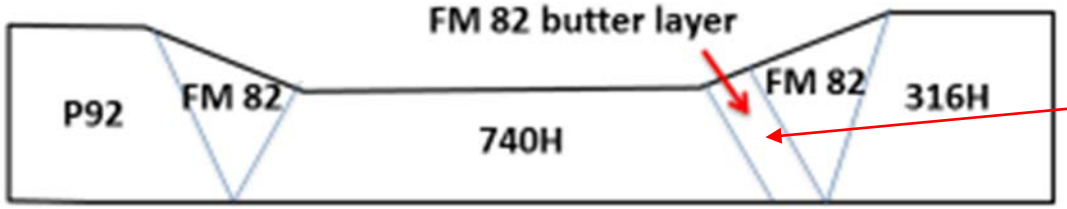


Header Mockup, Girth Welding done at Babcock & Wilcox

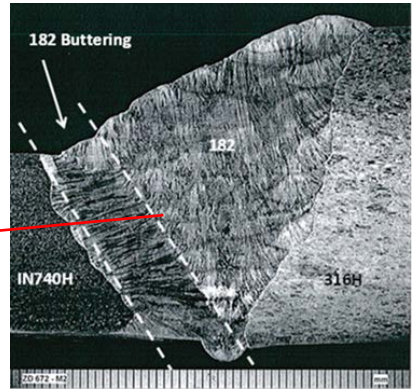
Welding 740H to Other Alloys

- 740H Used only where Essential
- Alloys Joined
  - P92, P92, 304, 316H, 347, 617, 282
- Filler Metals
  - FM82, WE 182 (Ni-Cr-Mn-Fe-Nb)
  - 617, 282
- Considerations
  - Design PWHT to match requirements of both alloys
- Doosan Experience

304 Fins resistance welded toon 740H, Optimus, Chanute, KA



Schematic of joint



Macro of weld joint

Where Are We Now: What remains to be Done

- Age-hardened nickel-base alloys are new to power piping industry but not to alloy producers
- Manufacturing Mill Products
  - All forms demonstrated and characterized
  - Some size limits
  - Currently TRL 8
  - Needs a full commercial plant order to bring to TRL 9
- Manufacturing Components and Fabricating Systems
  - Basic procedures demonstrated
  - Code enhancements needed for flexibility
  - All welding by specialists so far
  - Forging and machining experience is limited
  - Currently TRL 6
  - Projects underway will bring to TRL 8
- Systems
  - Very limited experience at pilot plant level
  - No experience with damage detection or repair
  - Currently TRL 4
- **Sharing of fabrication experiences and data will help to advance technology**

Acknowledgements

- Dave O'Donnell – RathGibson
- Kenny Rowley – PCC Energy, now CB&I APP
- Ken Doughty – CB&I APP
- Firdosh Kavarana – CB&I Bend Tech
- Alex Maass and Jerry Swenson – Maass Flange
- Jim Schaeffer, Bob Keener and Matt Reinhold – Carlton Forge

Blue Hole, Lighthouse Reef, Belize