Supercritical CO_2 Power Cycles Symposium

Experience in Manufacturing Pipe and Fittings from INCONEL® alloy 740H® for Demonstration Facilities for sCO_2 Service

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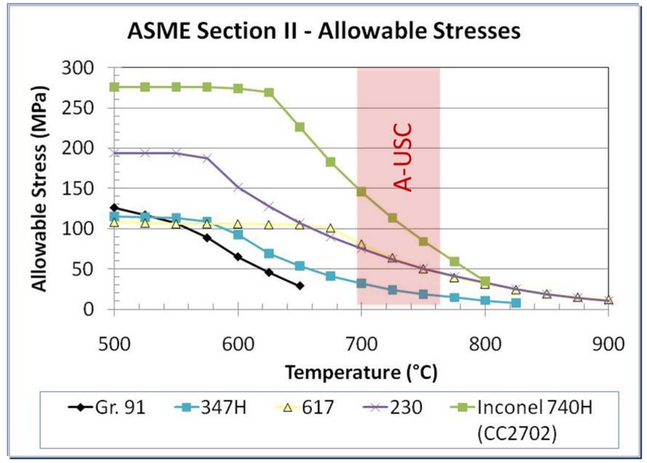
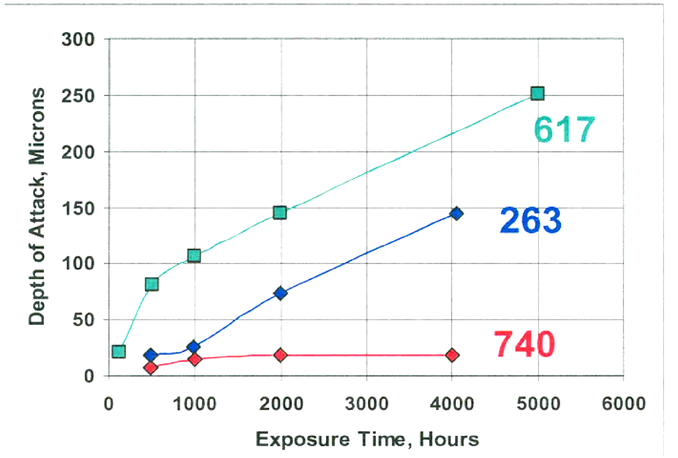
740H Background

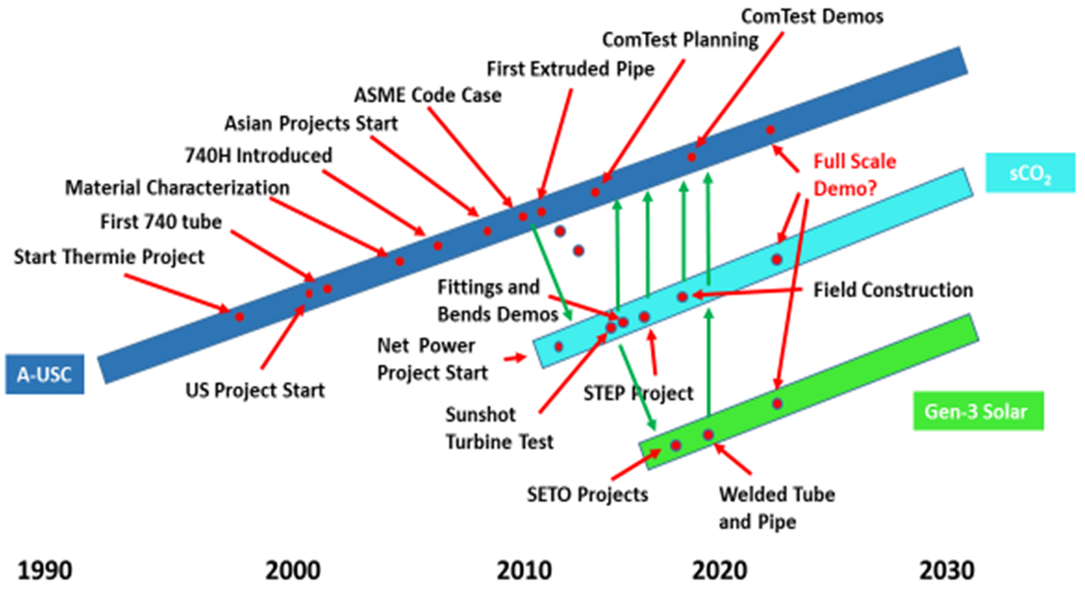
- **Age-hardened Ni-base alloy initially designed for boiler tube**
  - **Creep strength, microstructure stability and hot corrosion resistance**
- **Characterized through many DOE programs**
- **ASME Code Case 2702 (2011)**
- **Coal to sCO_2 and Solar**
- **Manufacturing capability facilitated through Demos**



Allowable stress for various alloys



Simulated coal ash corrosion test at 700°C



Synergy between DoE programs

Reference: ASME Case 2702-8, Sec. 1, Ni-25Cr-20Co Material, UNS N07740, 2023; ASME Case 3056, Sec VIII, 2022.

Manufacturing Capabilities and Limits

- VIM/ESR, VIM/VAR
- Cropped and conditioned ingot weight max 30,000 lb
- All mill product forms have been made in commercial quantities
- Welding products available
- Product size limits for forgings, pipes and fittings are similar to other “hard” nickel alloys such as 625
- Currently product melted to order – long lead times for fittings
- Competition with aerospace and oil and gas markets for production capacity
- Cost is subject to raw material variability
- Numerous nickel alloy mills are capable of making the alloy

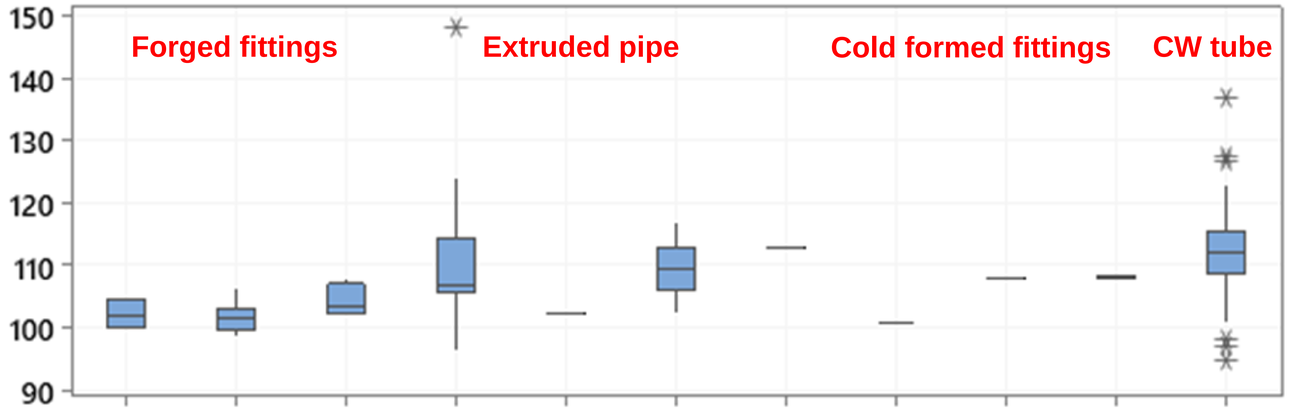
Largest 740H ingot produced by Special Metals in Huntington WV

22” OD x 3.7” W pipe extruded at Wyman-Gordon, Houston TX

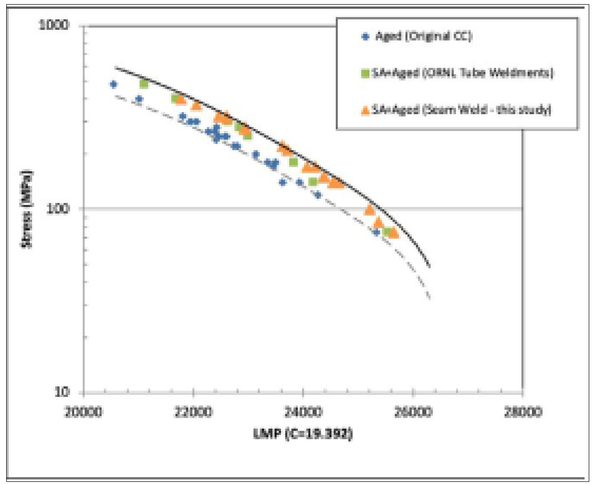
Reference: Purgert et al, Materials for Advanced Ultra-Supercritical Steam Turbines, Final Report, https://doi.org/10.2172/1875111

Mechanical Properties

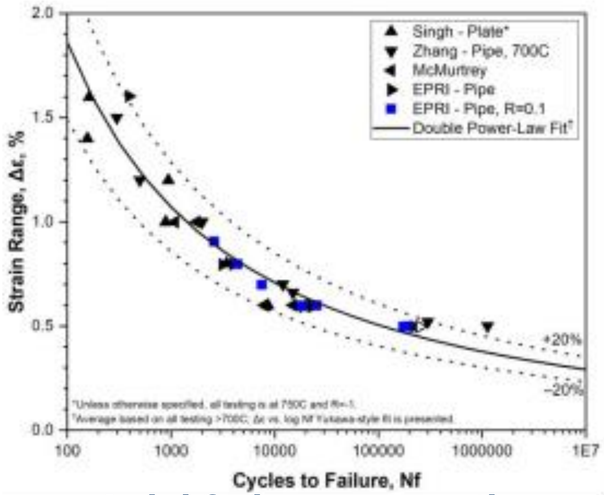
- Mill and fabricated products
- Property variability
  - Annealed grain size (SA ≥ 2010°F) Batch vs continuous
  - Aging time, temperature (4-16 hr 1400-1500°F)
  - Test orientation
  - Cooling rate and auto-aging
- Long time static aging
- Creep strength convergence?
- Weld strength reduction
- Gaps:
  - Fatigue, fracture toughness, creep on components
  - Environmental effects
  - Residual properties



0.2% YS (ksi) for selected fully heat-treated product forms. ASME min 90 ksi (Baker)



Creep strength showing weld reduction (Shingledecker)

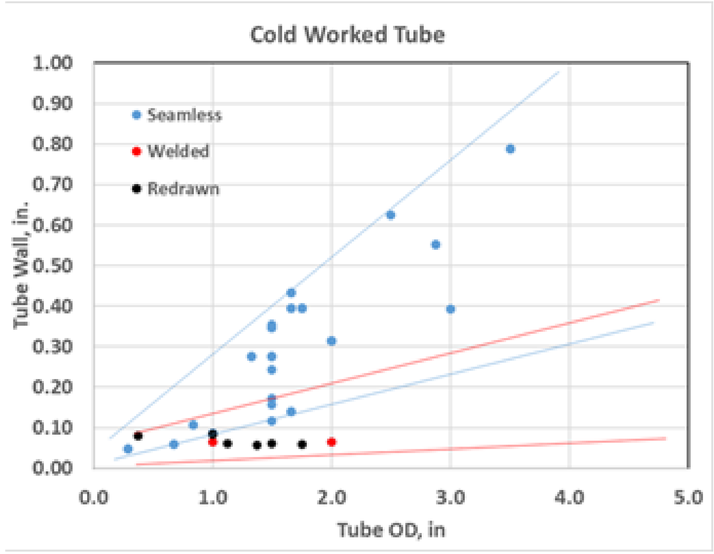


Axial fatigue properties (Shingledecker)

References: Shingledecker, “Improving Economics of Generation 3 CSP System Components…”, Final Technical Report, to be published by OSTI; McMurtrey, “Creep-fatigue Behavior and Damage Accumulation of Candidate Materials, Final Technical Report, https://doi.org/10.2172/1797935

Seamless and Welded Tube

- **Seamless tube process**
  - Forged bar, extruded shell
  - Cold drawn or pilgered
  - Continuous or batch anneal
  - Processing similar to alloy 625
- **Welded tube**
  - Autogenous welded strip
  - Semi-continuous process
  - 30-40% reduction in cost
  - Direct or redrawn
  - Weld strength issues
- **Gaps**
  - Limited characterization of hoop properties
  - Min % reduction for redrawn tube



Cold worked tube sizes made to date

HX tube with spiral fins

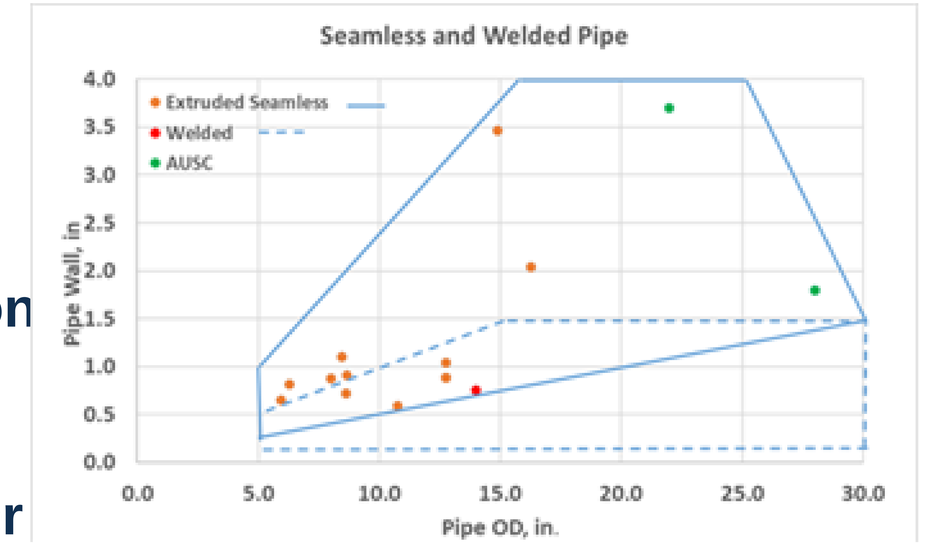
Seamless HX tube:
0.29” OD x 0.043” W

Welded and redrawn,
0.375” OD x 0.080” W

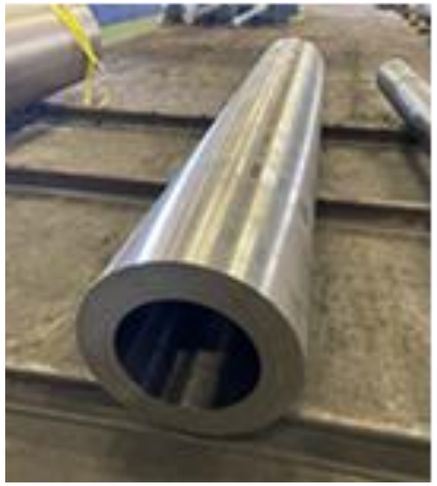
References: Seamless Tube - Purgert, et al. AUSC Final Technical Report, https://www.osti.gov/scitech/biblio/1346714 and Welded Tube - Shingledecker, et al., Final Technical Report OSTI report (XXX)

Seamless and Welded Pipe

- **Seamless pipe process**
  - Extrude as ingot or billet
  - Condition OD & ID
  - Heat treat and inspect
  - Large pipes made at Wyman Gordon
- **Welded pipe**
  - Start with annealed plate
  - Bend and weld using matching filler
  - Heat treat and inspect
  - Weld creep strength penalty
- **Gaps**
  - Dimensional control and cracking on large thin-wall pipes
  - Limited property assessment on large pipes



Pipe sizes made to date



Extruded seamless pipe
22” OD x 3.7” W

Welded pipe – 14” OD x 0.75” W x 20’

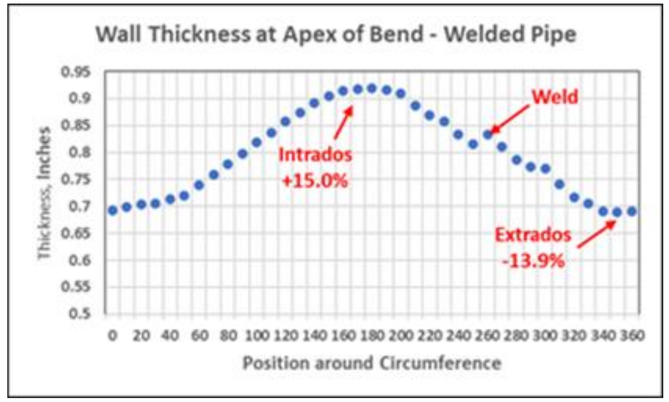
References: Seamless - Purgert et al., AUSC ComTest Final Report, https://doi.org/10.2172/1875111;
Welded – Shingledecker…XXX

Tube and Pipe Bends

- Small tube cold bends
  - Similar to alloy 230 or 625
- Pipe induction bends
  - Bends made on 4” to 28” OD pipes
  - Process parameter optimization
  - Good shape response
  - Surface condition
  - No degradation of properties
- Gaps
  - Start and stop strain-age cracking during reheating of thin-wall pipes with OD > 10”
  - Robust bending model for age-hardened alloys

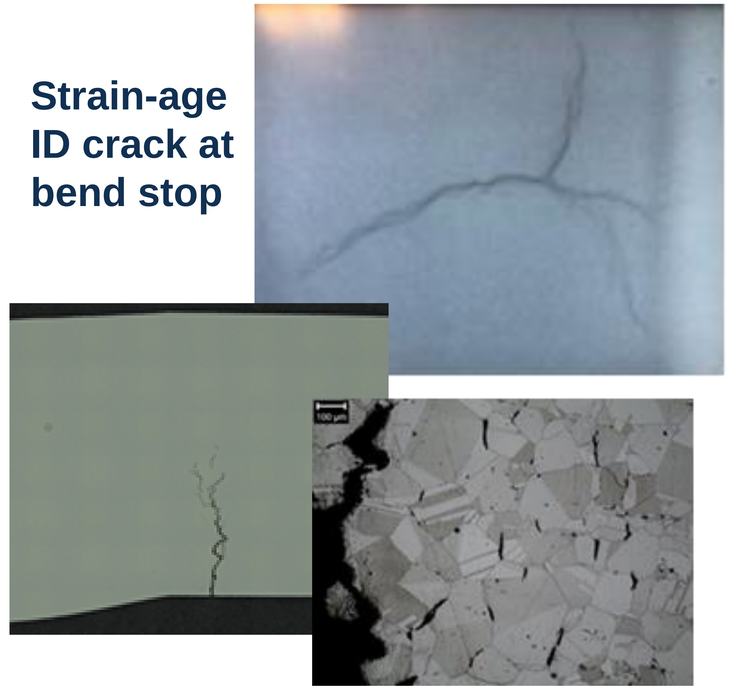
Start of bending

Steady state bending



Wall thickness around circumference

Strain-age ID crack at bend stop

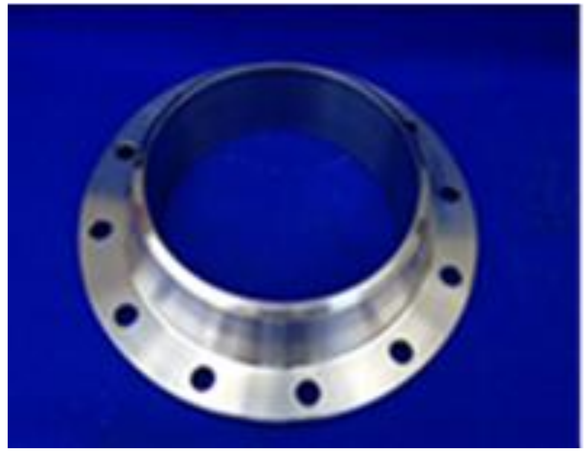


Reference: deBarbadillo et al., Mfg of Large Superalloy Pipe Bends, Superalloy 718 and Derivatives 2023, TMS.

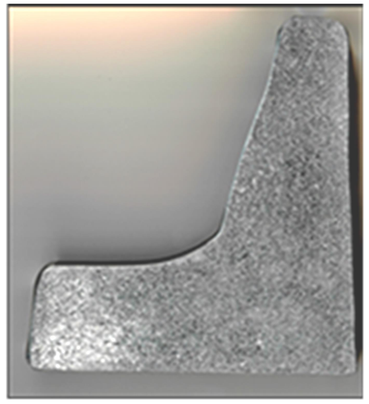
Forged Fittings

- **Small fittings**
  - Flanges, elbows, concentric reducers, wyes, tees, saddles, valve parts
  - Produced on conventional equipment
  - Narrow hot working range
- **Large fittings**
  - Few capable forgers
  - Large machining costs
- **Gaps**
  - Limited mechanical property testing
  - Few forge shops with experience
  - Long delivery time

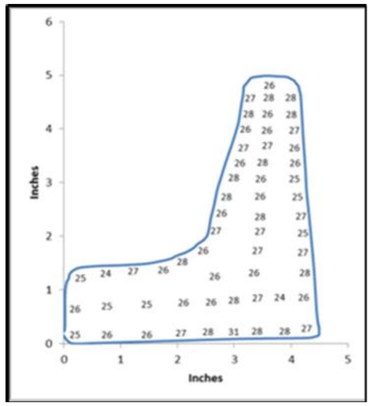
Hammer forged flange



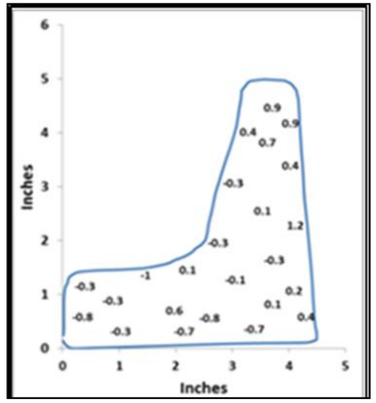
Machined flange



Etched cross-section



RC Hardness



Grain size

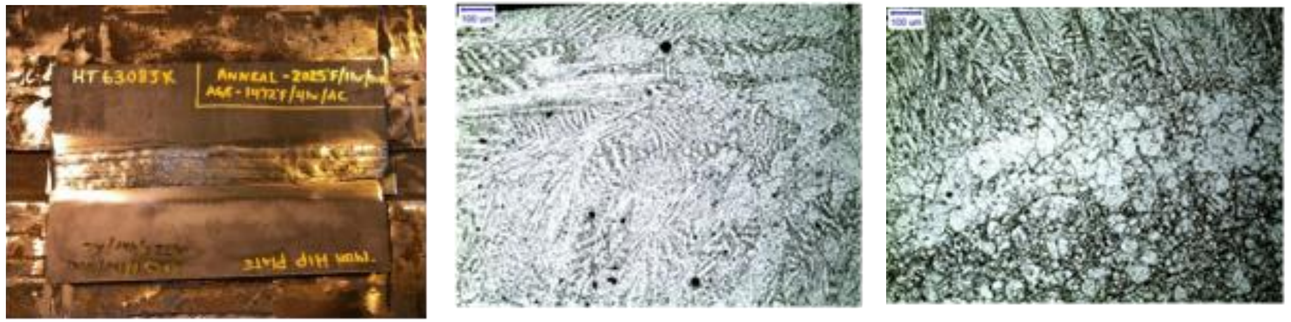
Reference: Small fittings – deBarbadillo et al., Development of Fittings Capability for AUSC applications, 8th EPRI Conf, ASM, 2016. Large fittings – Purgert et al. AUSC ComTest Final Technical Report https://doi.org/10.2172/1875111.

Process Alternatives

- Casting
  - Experimental, no commercial parts
- Cold Forming
  - Hydroformed tee (two suppliers)
  - Properties acceptable
- HIP Gas Atomized Powder
  - DOE FE funded project led by GE R&D
  - HIP and machined elbow
  - Weld joint porosity acceptable
  - Low creep strength due to residual PPB
  - Costing study showed significant savings
- Wire and Powder Additive
  - Limited experimental
  - No process issues

Steps in manufacturing hydroformed tee

Steps in manufacturing 740H HIP elbow

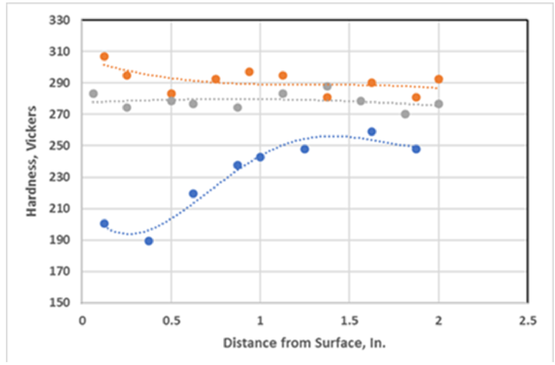


HIP 740H plate successfully welded to wrought 740H plate

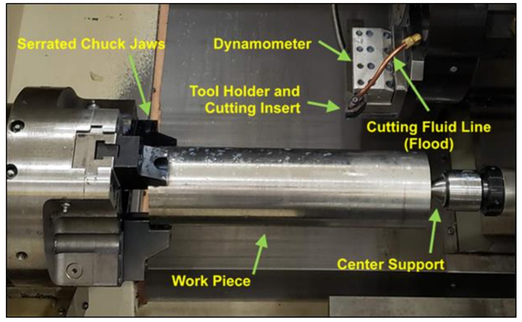
Reference: Huang et al., Low-cost HIP fabrication of Advanced Power Cycle Components, Final Technical Report, https://doi.org/10.2172/182264

Machining

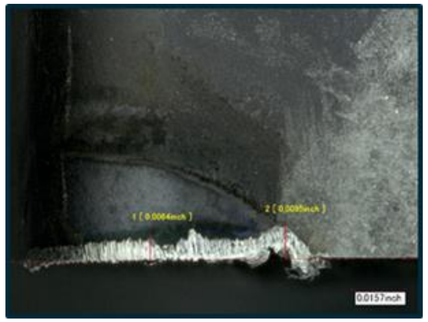
- Age hardened Ni-base alloys considered difficult to cut and machine
- High hardness, work hardening, abrasive, galling, distortion
- Variable hardness in thick section
- Carbide tools generally required
- Single point turning tests at TechSolve Inc
- Tested three heat treated conditions
- Kennametal KC5010-RP used on Sph and SA+A bars, Sandvik 1105-SM used on SA bar
- “Spheroidized” condition gave better tool life and lower machining cost compared to SA or SA+A Condition
- Properties recovered after final heat treatment
- Gaps
  - Needs validation for complex part with multiple operations



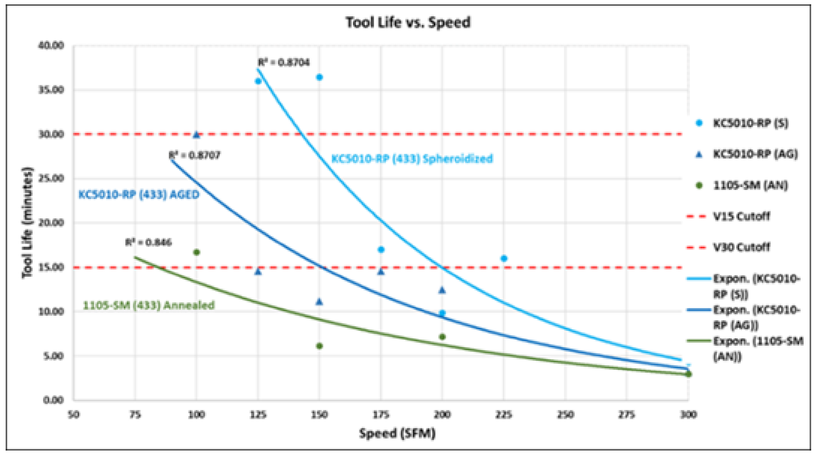
Hardness of trial bars



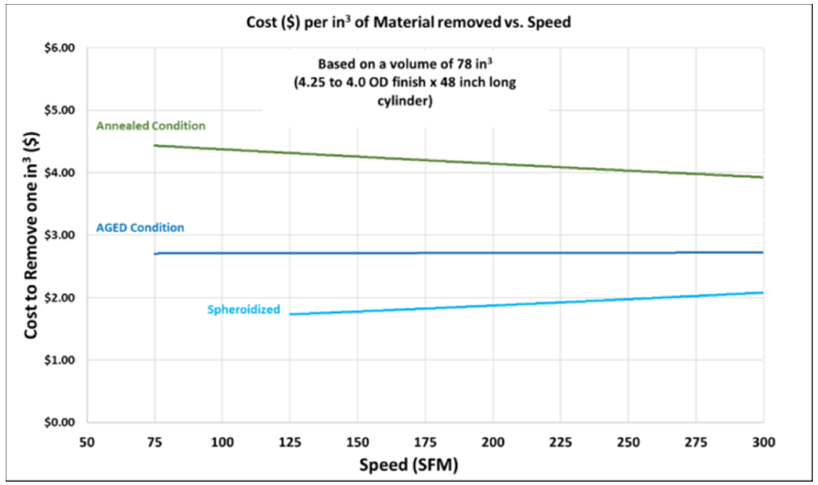
Cutting test



Criterion: 0.030” flank wear



Tool life vs cutting speed for 740H in three conditions



Cost for removal of cubic inch of material vs cutting speed

Reference: Adinamis, Appendix to AUSC Final Report, https://doi.org/10.2172/1875111.

Welding

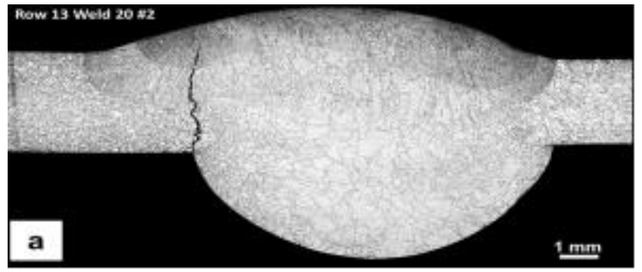
- 740H designed with weldability as key requirement
  - Nickel alloy welding
  - Superalloy welding
- ASME Case 2702 rules
  - PWHT mandatory
  - No local solution anneal
  - GTAW and GMAW only
  - Weld strength reduction factor
- Field fabrication experience
- Welder training, qualification and experience
- Gaps
  - Service experience
  - Repair

GE Power mockup for AUSC ComTest: Thick-wall girth welds, socket welds, butt welds, overlays, dissimilar metal welds

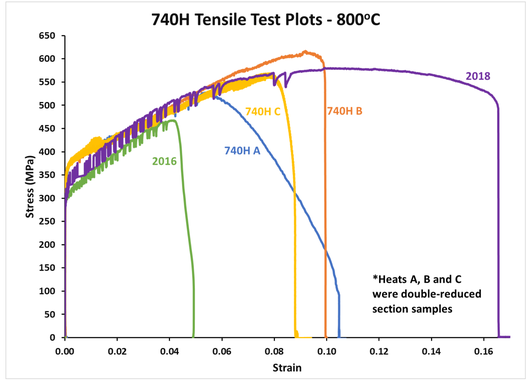
References: Purgert, et al. AUSC ComTest Final Report, https://doi.org/10.2172/1875111. Gollihue, et al. Practical Guide to Welding INCONEL alloy 740H, Proc. 7th EPRI Conf, ASM, 2013

Stress Relief Cracking

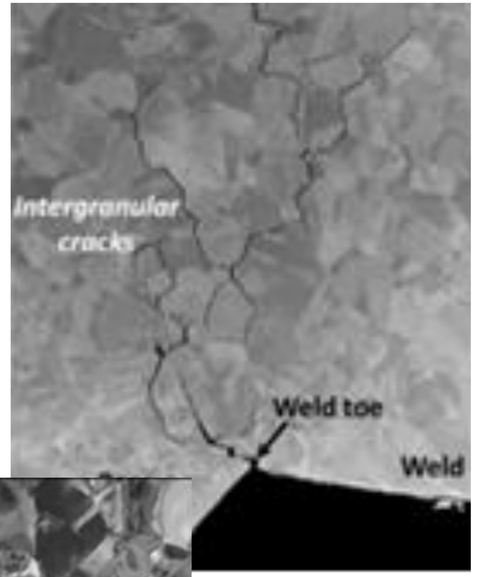
- Strain-age (SRC) cracking
  - Common in age-hardened alloys
  - Not limited to welding
  - Short term and long term
- Experience with 740H in STEP Heater
  - Weld cracks found in pressure testing
  - 3% of 1300 welds required repair
  - Metallographic evidence of SRC
  - Lehigh U testing identified critical variables
- Guidelines for successful welding
- Gaps
  - Many variables, no model
  - No single definitive test
  - No long-time service data

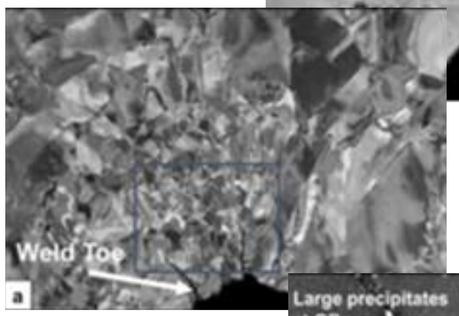


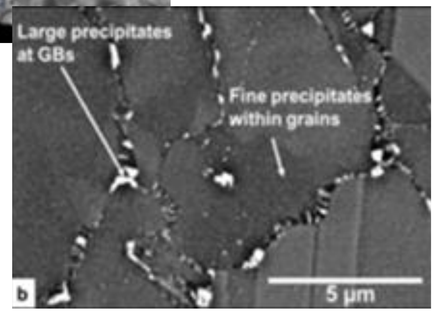
Example of SRC in tube weld



Tests showing micro-alloy effects on ductility







Recrystallization and precipitate-free zones in SRC region

Reference: Shingledecker, et al., Innovative Method for Welding…, SETO Final Technical Report, 2023, https://doi.org/10.1007/978-3-031-27447

740H – 25 Years

- Mill product forms
  - Tube, pipe, bar, welding products to commercial orders, sheet & plate demonstrated
  - Size limit capability demonstrated
  - All product to date from alloy developer
  - Capacity competition with aerospace
- Reprocessing
  - Large pipe extrusions to commercial orders
  - Welded tube and pipe demonstrated
- Fittings
  - Standard forged fittings capability demonstrated for various parts and vendors
  - Not stocked, currently long lead items
  - Machinability characterized
  - Alternative manufacturing methods need further validation
- Bends
  - Capability demonstrated
  - Some quality issues remain with thin wall induction bends

740H – 25 Years

- Welding
  - Alloy specific procedures developed
  - Welding guidance documents
  - Weld strength reduction factor, definition beyond base case
  - Guidelines for avoiding stress relief cracking
  - Stress relaxation cracking sensitivity not defined
- Properties
  - Excellent oxidation/hot corrosion resistance in most environments
  - Nominal tensile properties reproduced in all product forms
  - Limited data base for creep properties in commercial mill products and fabrications
  - Application specific properties on relevant product forms
  - Very limited characterization of service performance and repair
- Codes & Standards
  - Novelty of age hardened materials
  - Correspondence between ASME sections for enhancements

Acknowledgements

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