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

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Dr. deBarbadillo is located at the Special Metals Huntington, WV plant. He has a wide range of experience in product and process development of nickel-base alloys. He has been directly involved in programs to develop, qualify, and manufacture 740H products for advanced energy applications.

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Abstract

Age-hardened nickel-base alloys have been evaluated over the past 25 years for pipe, fittings and heat exchangers for advanced energy systems operating in the time dependent property temperature regime. While the early material development and characterization was directed to advanced supercritical steam power boilers, more recent studies and pilot scale demonstrations have involved either direct containment of supercritical CO_2 or supporting heat transfer media such as molten salt. INCONEL alloy 740H has been the most widely evaluated of these alloys, and it has now undergone intensive scrutiny for its material properties, for its capability of being manufactured in the myriad of product shapes and sizes needed by the industry, and for its ability to be field fabricated and inspected. Much of this material evaluation work has been published in DOE reports as well as general literature. The alloy has been successfully employed in several demonstration projects and has generally performed as expected; however, “first of a kind” efforts have an associated learning curve. The ability to achieve nominal levels of mechanical properties has been demonstrated for a wide range of material section sizes and configurations. Although the alloy has excellent weldability in at least 100 mm section in controlled qualification tests, production of a sound weld in the shop or plant site with space limits, environmental issues and physical constraints requires strict adherence to procedure. The possibility of strain age cracking must be considered in pipe bending, weld joint design, weld bead management and post fabrication heat treatment. This paper focusses on experiences gained to date, especially on fabrication and joining, and identifies areas where further insight is needed.

INTRODUCTION

Alloy 740H is an age-hardened nickel-base alloy designed for use in power plants operating the 650-800°C temperature regime. The initial intended application was for boiler tube for coal-fired steam power plants (AUSC) and the composition was tailored to optimize creep strength, microstructure stability and resistance to hot corrosion under coal ash deposits. The development and properties for this application are detailed in Ref. [1]. Simultaneous programs in USA, Europe, Japan, Korea, China, and India produced a large body of literature, primarily characterizing properties of boiler tube. The work on AUSC spanned 25-years and culminated in the United States with the DOE funded AUSC ComTest demonstration of manufacturing capability for full-scale power plant components. The 740H components included boiler tubes, heavy-wall header and reheater pipes and a 13.6 MT wye block forging. Technical detail is contained in the final DOE project reports [2,3]. About ten years ago the technology being developed for AUSC began to be leveraged to advanced energy applications involving supercritical CO_2 (sCO_2) containment, sCO_2 turbines and solar thermal energy receivers. The DOE Office of Energy Efficiency and Renewable Energy, Solar Energy Technology Office funded several complementary projects designed to develop an optimum pathway for an advanced solar thermal receiver (Gen 3) that would operate above 700°C. This program considered solar receivers, energy storage and heat exchangers coupled with an sCO_2 turbine. Alloy 740H was the primary material for many of the components including new product forms such as seam welded tube and pipe and thin sheet for compact microchannel heat exchangers. This program contributed a great deal of new information [4]. Together these DOE funded programs generated the test data needed for ASME code cases CC 2702 for Section 1 which has subsequently been amended numerous times [5] and CC 3056 for Section VIII [6].

Although these material assessment and component demonstration programs were critical in establishing the capability of alloy 740H for use in advanced energy systems, additional hurdles remain. The first two: demonstration of manufacturing capability to deliver quantities of material to commercial specifications and the ability to shop fabricate and field erect pilot or full-scale power plants have now been underway for several years. The SunShot and STEP projects at Southwest Research Institute and the NET Power project at LaPorte TX have been the key drivers for manufacturing development. Inevitably, unanticipated challenges arise when technology moves from a controlled R&D environment to real world manufacturing. The experiences and learnings derived from this effort are the primary focus of this paper. All commercial activity to date has been “make to order” with the material package managed by the alloy developer. Additional issues will come up when there are multiple international materials and component suppliers and distributor stocks. The final phase in the qualification of age hardened alloys for advanced power applications is a critical assessment of long-time performance under commercial plant operating loads and conditions. This phase lies over the horizon.

RESULTS AND DISCUSSION

Composition**: The original al**loy 740 aim composition (UNS N07740) was optimized for creep strength and coal ash corrosion resistance based on heat treated section thickness of less than 25 mm. The composition was later adjusted to improve microstructure stability (increased Al/Ti ratio) and reduce sensitivity to liquation cracking in thick section welds (reduce Si, Nb, B). The adjusted composition aim shown in Table 1 was designated 740H. While much of the data contained in the initial ASME code case submission was generated on the 740 composition, later tensile and creep-rupture testing showed that there is negligible difference between the two variants [7]. All material produced since about 2010 has been to the 740H composition.

Table 1. Composition limits for UNS N07740 and nominal 740H composition.

	C	Cr	Co	Mo	Fe	Al	Ti	Nb	Si	Mn	Cu	P	S	B
UNS N07740 Max	**0.08**	**25.5**	**22.0**	**2.0**	**3.0**	**2.0**	**2.5**	**2.5**	**1.0**	**1.0**	**0.5**	**0.030**	**0.030**	**0.006**
740H Nominal	**0.03**	**24.5**	**20.0**	**0.5**	**0.5**	**1.45**	**1.45**	**1.5**	**0.15**	**0.3**	**0.02**	**0.005**	**0.001**	**0.002**
UNS N07740 Min	**0.005**	**23.5**	**15.0**	**0**	**0**	**0.2**	**0.5**	**0.5**	**0**	**0**	**0**	**0**	**0**	**0.0006**

Microstructure: The microstructure of heat treated thin and moderate section 740H has been extensively studied and reported [8-10]. The typical microstructure consists of spherical γ' evolving to a more cuboidal form during exposure at elevated temperature. This phase is not resolvable in the optical microscope until over-aging occurs in service. Some coarse γ' forms at the grain boundaries in addition to a semi-continuous network of $M_{23}C_6$ carbide. Isolated MC, TiN and M_6C are dispersed in the grains or occur as stringers. Eta phase (η) which formed extensively in the 740 formulation has only been observed as a minor isolated particles in 740H during exposure below 800°C. Sigma phase (σ) is predicted to be thermodynamically stable at 650°C by JMatPro, but it has not been identified in exposed test samples. To date, there have not been any assessments of the microstructure for very heavy section components.

Mechanical Properties: Only one heat treatment is currently specified for alloy 740H: Solution anneal 1100°C minimum for ½ hr. per 25 mm thickness but not less than 5 min., water quench or rapid air cool, age 760-816°C for 4 hr. minimum, air cool. Minimum room temperature tensile properties are 620 MPa yield strength, 1035 MPa tensile strength and 20% elongation. All tests conducted on mill produced cold drawn tube, extruded pipe, plate, sheet, bar and forged parts have met those requirements. A comparison of properties for selected commercial scale components is shown in Figure 1. The variation is attributed to differences in grain size, cooling rate and aging time. There is some evidence that regardless of initial heat-treated yield strength, creep rupture properties converge to a common level. This is because the only microstructure change that occurs in the service temperature range following precipitation of $M_{23}C_6$ is growth of γ' precipitates over time.

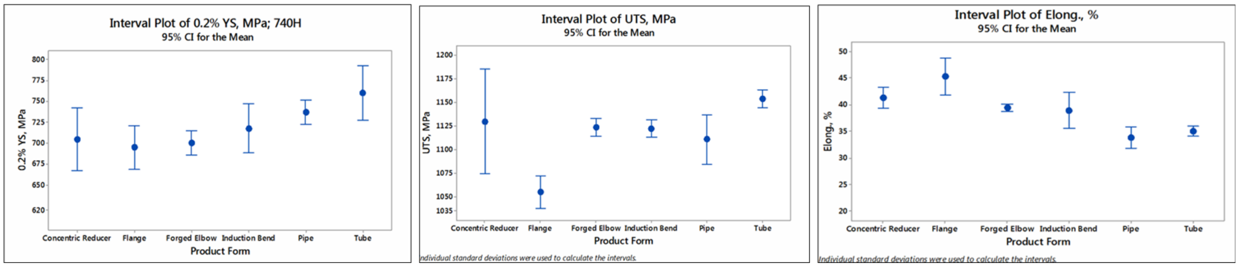

Figure 1. Room temperature tensile properties for various product forms: Left yield strength, Center tensile strength, Right elongation.

Extensive creep-rupture testing of boiler tube and plate and welded joints was conducted under the AUSC Phase 1 project [2]. This data formed the basis for the initial ASME code case including a defined weld strength reduction factor of 0.70 that applies to seam welds. Subsequent testing conducted on solution annealed and aged welds showed weld strength of approximately 90% of base metal strength (Figure 2) [4]. All of the creep testing conducted to date has been on cold drawn and heat-treated seamless boiler tube, welded solar receiver tube and thin sheet and plate. No testing has been done on heavy wall pipe, pipe bends or any of the fabricated components described in this paper. All tube testing has been longitudinal. This represents a significant data gap, especially for advanced energy systems that incorporate heavy section components.

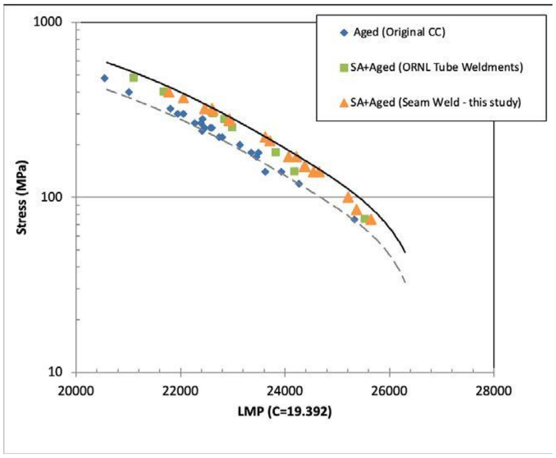

Figure 2. Larson-Miller curve for annealed and aged 740/740H base metal and welds. Orange triangles represent base metal, blue diamonds direct aged cross-welds, green squares solution annealed and aged cross-welds (Shingledecker).

The initial AUSC testing program for 740H did not consider other mechanical properties such as impact toughness, plane strain fracture toughness or fatigue resistance. As interest grew in the use of coal-fired power plants for peaking service some basic fatigue data was generated as shown in Figure 3. More recently the Gen 3 CSP program raised the need for fatigue and creep-fatigue data to simulate daily cycling of receiver tubing. A recently completed project at Idaho National Lab has generated a substantial body of data for this application [11]. Additional fatigue crack growth and fracture toughness data will be needed to support interest in 740H for sCO_2 turbine rotor applications.

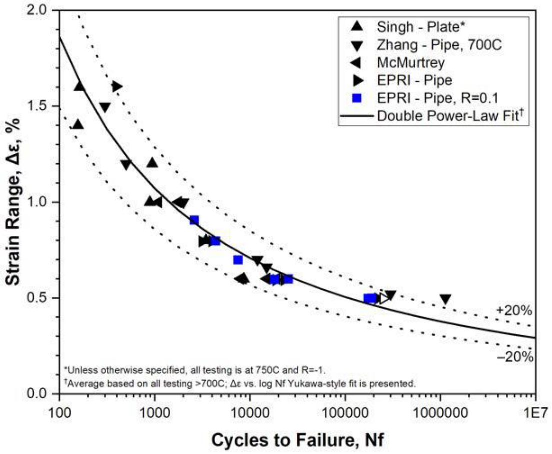

Figure 3. Fatigue properties from various published sources [4].

<u>Mill Product Forms</u>: All mill product forms including forged and rolled bar, plate, sheet and weld wire as well as tube and pipe have been produced to commercial specifications. Alloy 740H, despite being an age-hardened alloy, is more production friendly than some more widely used

nickel-base alloys such as 617, 625 and 718. Never-the-less there are practical weight, dimension and tube OD/wall limits that are both material and facility related. Currently the largest cropped and ground ingot size is roughly 14 MT. Ingots of this size were made and converted to pipe and forgings in the AUSC ComTest program [3]. Representative examples of some seamless and welded tube and extruded pipe produced for DOE projects are shown in Figure 4. Mill produced sheet and plate were the starting form for autogenously welded tube and GTAW welded pipe [12]. Figure 5 shows the distribution of OD and wall dimensions for 740H cold drawn tube and cold drawn or extruded pipe that have been produced to date. Also shown are the approximate limits of mill capability. A techno-economic study for use of 740H in advanced power systems is reported in ref [4]. The conclusion of this study was that 740H offers an economical alternative to the carbide-strengthened alloy 230 alloy over a wide range of temperature up to about 800°C due to its higher strength and lower density.

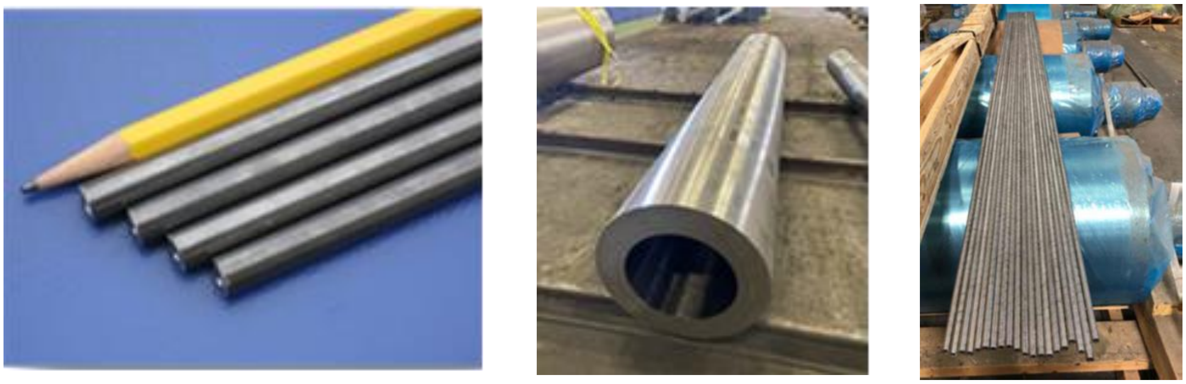

Figure 4. Left cold drawn seamless tube for SunShot (7.4 mm OD x 1.1 mm W)), Center extruded pipe for AUSC ComTest (560 mm OD x 100 mm W), Right welded and redrawn tube for Gen 3 CSP (9.5 mm OD x 2 mm W))

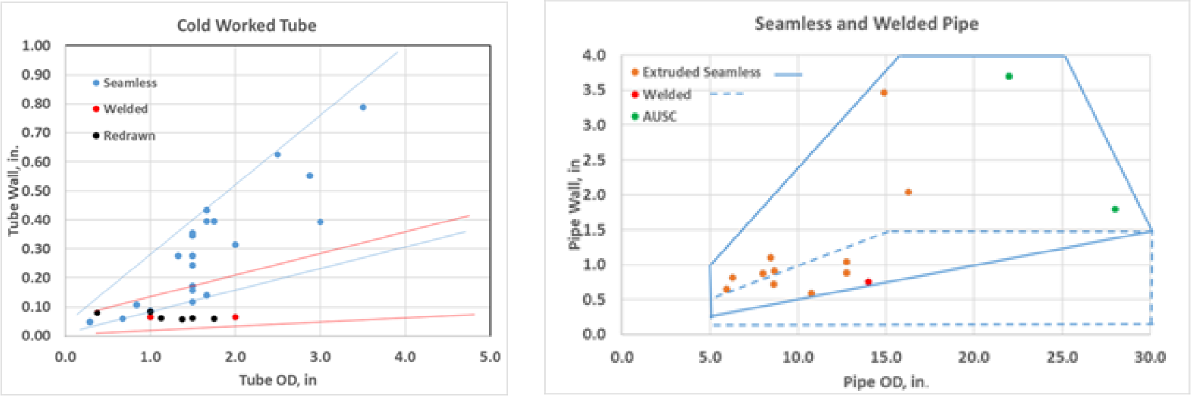

Figure 5. OD and Wall for tubular products made to date.

<u>Pipe Bends</u>: Cold worked and solution annealed tube can be readily cold bent using conventional equipment, but these bends must be solution annealed and aged before being placed in service [4,12]. Due to the high strength of the alloy pipe must be bent hot. This process is generally done commercially on an induction bending machine. Pipes ranging in size from 73 mm OD x 14 mm W to 710 mm OD x 38 mm W have been bent under various DoE research projects and plant demonstrations. Figure 6 shows a seam welded pipe that was given a 90-degree 3D bend at Shaw Clearfield, UT. The seam weld was located at the neutral axis. Also shown is a plot of wall thickness around the circumference at the apex of the bend. The

wall thinning conforms to standard pipe bending limits. Tensile and impact toughness properties at extrados and intrados of all bent pipes tested have met the ASME code minima and no microstructural damage such as intergranular cavitation has been detected [3,4,12]. Through wall tensile tests on heavy pipe showed lower but acceptable elongation. No creep-rupture testing has been conducted.

Although most induction pipe bends of alloy 740H have been crack-free, certain OD/W combinations have experienced both ID and OD cracking some of which could be attributed to surface condition and operational issues [13]. Specifically, it was found that long heat up time prior to the start of bending could result in a low ductility microstructure. Grinding marks or surface indications of a size that would be acceptable in commercial extruded pipe specifications may risk cracking of this alloy. Consequently, ID conditioning such as honing and full OD liquid penetrant inspection may be needed, especially for very large thin-wall pipes. These problems can be avoided through machine adjustments and more robust inspection and surface preparation. More concerning is cracking that was seen at the neutral axis or sometimes around the entire circumference at the bend stop location in pipes with an OD/W ratio of greater than 10. This cracking, which was detected by radiography has been attributed to strain age cracking during heating of the bent pipe for the solution anneal [4]. An image of the crack is shown in Figure 7. It was determined to have initiated on the pipe ID at a location well away from the weld and have grown approximately half-way through the pipe wall. Metallographic analysis showed profuse secondary grain boundary cracking of the type that is commonly seen near primary strain age cracks. The crack location corresponded to an area of high stress as predicted in a thermal stress model of induction bending by Ding [14].

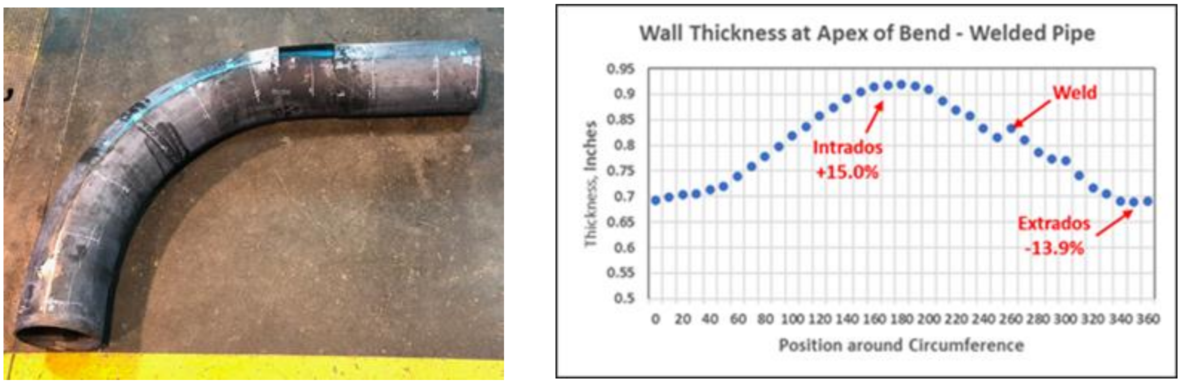

Figure 6. Left: 356 mm OD x 19 mm W welded pipe after bending, Right: Variation of wall thickness around circumference at apex of the bend.

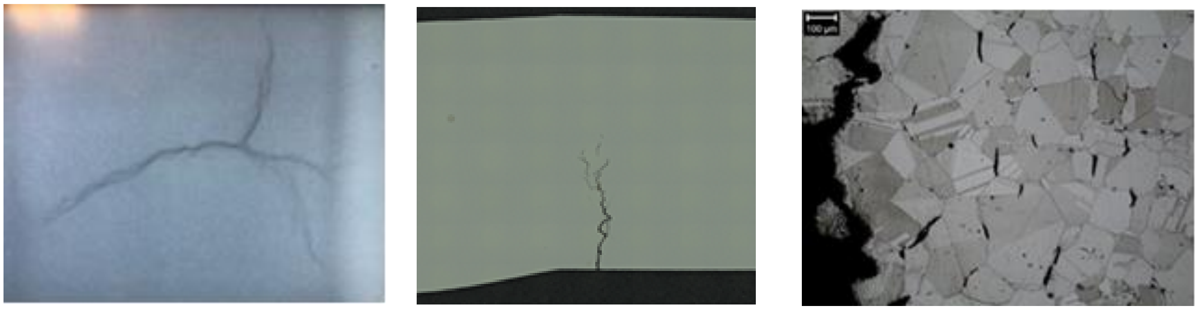

Figure 7. Left: Radiograph showing branching ID crack on neutral axis at bend stop, Center: Macrograph of crack, Right: Micrograph showing grain boundary voids near the primary crack.

While bending machine adjustments have mitigated the stop location cracking to some degree, cracking was still observed during bending of 710 mm OD x 38 mm W alloy 740H pipes (OD/W = 18.7) [3,13]. This continued cracking was used to justify new model development activity based at Argonne National Lab under the High-Performance Computing for Energy Applications Program [15]. The first phase of the project that was recently completed resulted in a beta version of a thermal stress model. A proposed extension will include microstructure simulations. To support this activity, DOE released a pipe made through the AUSC ComTest project for use in an instrumented bending test at Tulsa Tube Bending Co. To support the trial, 80 thermocouples were attached on OD and ID around the circumference and length of the pipe. Images from the start and steady state portion of the bending trial along with some sample data are shown in Figure 8. The data from this trial is still being analyzed and will be reported later. While this work is still incomplete, induction bending and subsequent reheating of high OD/W ratio 740H pipes must be done carefully to avoid strain age cracking.

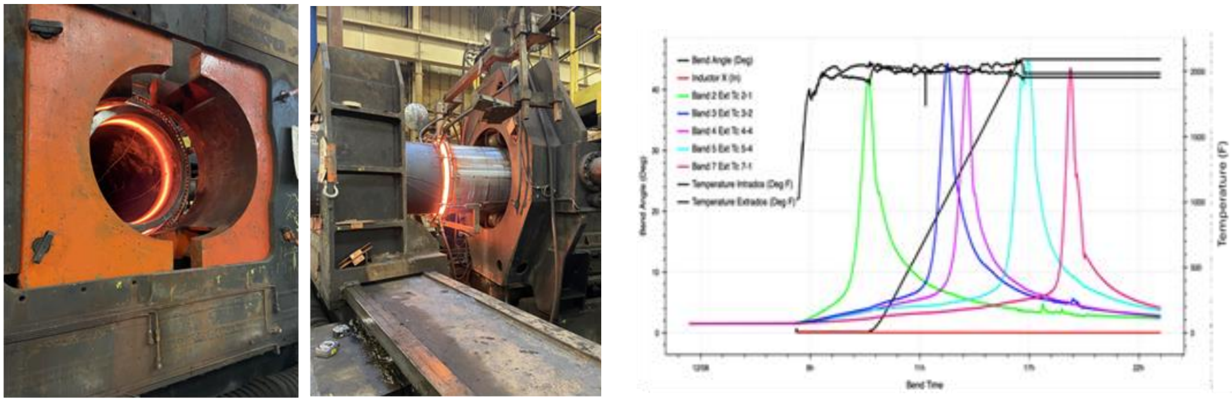

Figure 8. Instrumented bending trial at Tulsa Tube Bending Inc. Left: Set-up during heating prior to clamping, Center: Bending underway, Right: Example of thermocouple traces.

<u>Fittings</u>: The supply of pipe fittings and valves of an age hardened alloy for power systems poses a significant challenge because this supply chain is unfamiliar with its process requirements and initially must deal with very small volumes. Special Metals took the initial step of making trial fittings of 740H in 2013 when it supported fabrication of flanges, concentric reducers, elbows, and tees at selected forge shops. A detailed report of processing and properties has been published [16]. An example, shown in Figure 9, is a weld neck flange that was made by hammer forging a cylindrical block at Maass Flange Co. A cut cross-section of one forged part along with grain size and hardness maps is shown in Figure 10. Tensile properties of the solution annealed and aged part met ASME requirements. The elbows were hot forged from pipe while the tee was hydroformed in multiple steps from a similar size pipe. No cracking was encountered in any of this work and all properties were satisfactory. Subsequently, tees, elbows and Grayloc® fittings have been fabricated by other forge houses for the NET Power and STEP projects. This demonstrated the capability of the supply chain to provide the required components to drawing and specification. Sporadic cracking in elbow forgings has shown the need to have good surface integrity in the starting stock. Alloy 740H has a much lower flow stress than alloy 625 or 718, but also has a narrower hot working range with the possibility of edge cracking if the piece gets too cold. Currently alloy 740H fittings are made to order which implies relatively long delivery times.

Figure 9. Weld neck flange hammer forged at Maass Flange Corporation, Sealy TX, Left: as forged, Right: Machined flange.

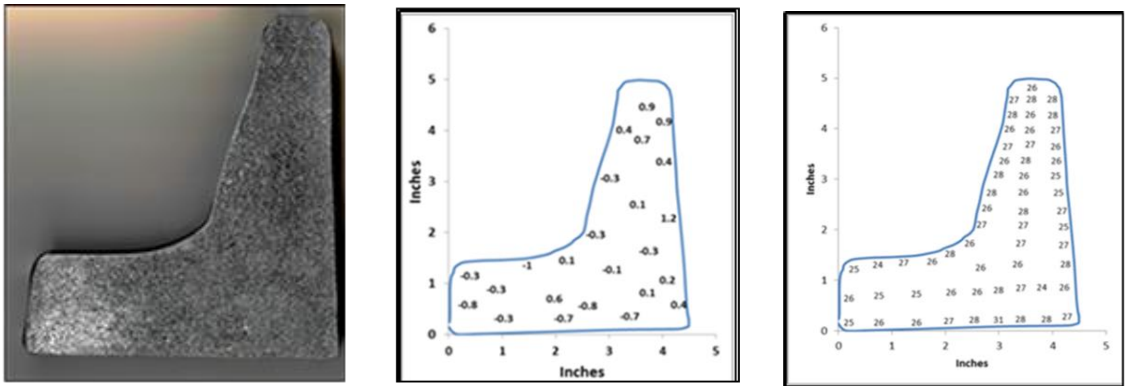

Figure 10. Left: Etched cross-section of weld neck flange, Center: Grain size map, Right: Hardness map.

Valves are also essential components for power systems. The US AUSC ComTest project collaborated with three major valve manufacturers to develop technology for operation above 700°C. The STEP project procured a valve from a European supplier. High temperature valves are complex with precision components that must function reliably in service for many years. A significant deliverable of the ComTest project was the design and qualification of a pressure relief valve (PRV) capable of operating up to 760°C and 34.47 MPa. Baker Hughes successfully manufactured a valve which received an ASME code stamp. In this work they were able to demonstrate machining and welding procedures for 740H that would be needed for a full-scale fossil fired power plant [3].

The unavailability of standard “off-the-shelf” forged or cast fittings for alloy 740H has generated interest in alternative manufacturing processes. One project supported by DOE Office of Fossil Energy explored the possibility of making near net shape hot isostatic pressed (HIP) argon gas atomized powder parts [17,18]. In this work powder was produced at Wyman-Gordon from cast/wrought bar made by Special Metals. A detailed study of powder size distribution, presoak, HIP and heat treatment temperature was conducted prior to selecting conditions for making a demonstration article. The complex geometry for the demonstration elbow tooling was designed and fabricated by Synertech PM Inc. in Garden Grove, CA. The tooling was designed to produce near net shape ID and minimal machining on the OD. The can was filled under argon atmosphere and then evacuated. HIP was performed at Bodycote in Princeton; KY. Figure 11 shows the assembled HIP can and the final machined elbow.

Figure 11. Left: Fabricated and filled can prior to HIP, Right: Machined and heat treated elbow.

The microstructure at various locations through the wall of the heat-treated part are shown in Figure 12. Recrystallized grains have grown across the original powder particle boundaries which are not visible in these photos. Yield and tensile properties were comparable to those of cast/wrought alloy 740H, however creep-rupture strength was 25-40% lower. Assessment of the microstructure of broken creep-rupture bars showed preferential void formation at prior powder particle boundaries. The best properties were obtained in material that had been presoaked prior to HIP. It is believed that the creep strength can be further improved relative to cast/wrought material properties [18].

In most cases HIP powder fittings would need to be fusion welded to cast/wrought pipe. A weldability study was performed on a separately processed 50 mm thick HIP plate. The solution annealed mother plate was band saw split into 25 mm thick plates for welding to cast/wrought plate of similar thickness. The plates were machined with a 25° V-groove and the set-up used a 740H backing plate with a 4 mm root gap. Gas tungsten arc welding using a matching 740H composition filler metal was used to join the plates. The weldments were then given the required post weld heat treatment. A photo of the completed weld is shown in Figure 13. Mechanical properties and bend tests were acceptable per ASME CC 2702. The microstructure of the weld deposit and fusion zone is shown in Figure 13. The possibility of porosity in the heat affected zone (HAZ) and weld metal due to argon entrained in the powder was a major concern for this project. Some porosity was observed, but the maximum pore size of 40 μm was well within the ASME Section IX rounded indication size limit for welds . No porosity was observed in the HAZ or on the fracture surface of transverse tensile test bars. Grain coarsening occurred near the fusion line.

Figure 12. Back scattered electron images of grain structure of solution annealed elbow. Magnification approximately 200X [18]

Figure 13. Left: Completed GTA weld of HIP plate to cast/wrought plate, Center: Fusion line showing coarse grain HAZ, Right: Weld deposit showing scattered argon gas porosity [18].

A techno-economic study for HIP powder fittings was conducted using the results of the testing program. The assessment included some specific items such as the turbine stop/control valve design from the STEP project, large elbows that do not have standard forge tooling and large tees and wyes. In each case, despite the high cost of powder and reduced creep strength, the HIP powder approach resulted in approximately 50% cost reduction compared to alternatives such as forgings or castings.

Additive manufacturing offers another approach to cost, availability and lead time for 740H components for advanced energy applications. Tests using laser powder bed process have been conducted by several laboratories. In one test an alloy 740H cylinder that was HIP'd, solution treated and aged had room temperature yield and tensile strength and ductility similar to cast/ wrought properties [19]. Given the similarity of 740H to other alloys that have been successfully printed, LPBF appears to be a viable manufacturing technique for small fittings. Wire arc additive manufacturing (WAAM) is facilitated by the relatively good weldability of alloy 740H. A study by Sridar [20] produced a sound crack-free vertical build with good mechanical properties. Short -time creep properties were comparable to cast/wrought properties. This work was exploratory and did not simulate an actual fitting design. Again, there do not appear to be any major hurdles for manufacture of small parts. Larger parts may be more difficult due to the need for repeated weld deposit conditioning (see discussion below).

Machining: Alloy 740H, along with similar low percent γ' strengthened alloys, has a reputation for being difficult to machine. This is because the alloy tends to form long chips which are strain hardened as they form thus causing excessive tool wear. Conventional wisdom calls for machining in the solution annealed (softest) condition; however, for high volume machining that may not be the best condition. One deliverable for the AUSC ComTest project was a machinability study which was conducted by TechSolve Inc., Cincinnati, OH. For this study, 100 mm diameter bars were supplied in three heat treated conditions: 1) Solution annealed and water quenched (HRA 63), 2) Solution annealed and standard aged at 800°C for 4 hr. (HRC 38) and 3) Solution annealed and spheroidize aged at 927°C for 24 hr. (HRC 33). A single point turning test using carbide inserts was conducted on an instrumented lathe. Extensive calibration trials were conducted to select insert type, depth of cut and lead angle that facilitated the best comparison between the three material conditions. Tool-life tests were then run as a function of turning speed. The results summarized in Figure 14 show a substantial improvement in tool life for spheroidized material over the other two conditions. A cost assessment that included machine power as well as machine time and tooling cost showed an approximately 50% cost reduction to remove a unit volume of material over a wide range of machining speeds. The full TechSolve report is appended to the AUSC ComTest final report [3]. A spheroidized test bar that was re-heat treated showed that the mechanical properties could be recovered [3].

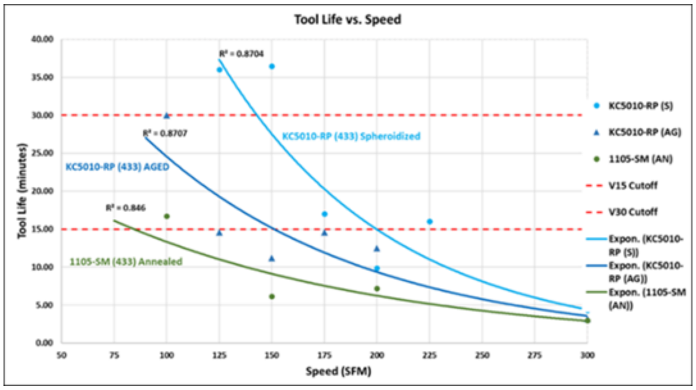

Figure 14. Plot of tool life versus cutting speed for alloy 740H bar in three heat-treated conditions: 1) solution annealed (green dots), 2) solution annealed and standard age (green triangles) and 3) solution annealed and spheroidize aged (blue dots) [3].

Welding: Since most advanced energy systems require welding for construction, characterization of alloy 740H weldability and development of guidelines and protocols has been a major part of technology development over the past 25 years. Viewed at a high level, this alloy has good weldability compared with many of the superalloys that are designed for aircraft engine applications. A substantial package of test data was generated for the initial ASME code case that was approved in 2011. That case was amended several times since that date as more information became available, but several unique rules remain: 1) Only GTAW and GMAW processes are permitted, 2) Matching composition filler metal is required for welding 740H to itself, 3) Post weld heat treatment is mandatory, 4) Solution annealing is required if cold strain exceeds 5%, 5) A non-standard rule for bend test radius applies and 6) a creep strength reduction factor apples for weld joints [5]. A welding procedure for use of a proprietary SMAW electrode based on another nickel-base alloy (263) has been incorporated into the code case. This process was intended to facilitate repair welding; however, the electrode currently has limited commercial availability. As a nickel-base alloy containing a substantial quantity of reactive elements, additional rules need to be followed as outlined in the Special Metals Practical Welding Guide [21]. These include 1) maintenance of a convex bead shape, 2) minimal preheat which affects pass schedule, 3) avoid abrupt arc stop, 4) rigorous use of inert cover gas, 5) internal pipe purging for closure welds and 5) frequent grinding to avoid build-up of oxide on the weld bead.

These practices were sufficient for successful qualification welds at laboratories and fabrication shops. New issues arose during shop and field fabrication for demonstration plants. Instances of random cracking and rework for manual welds were reported. An investigation led by EPRI that identified additional considerations needed to achieve sound welds [22,23]. Recommendations were developed following a detailed metallographic examination of cracked welds and laboratory simulation of crack sensitivity using a Gleeble-based controlled strain tensile test. This work demonstrated that the primary cause of weldment cracking was a strain-age or stress relief cracking phenomenon to which many age-hardened alloys are sensitive. Figure 15 shows the cross-section of two GTAW tube welds examined in this work. In each case the cracks initiated near the root of the weld and then progressed through successive weld beads. The cracks were found by liquid penetrant testing following post weld heat treatment. Optical microscopy revealed branching of the primary cracks and secondary cracks in weld metal and base metal. Closer examination (Figure 16) showed that cracking tended to originate at locations with high stress concentrations that induced creep strain during the PWHT cycle. The formation of precipitate free zones and discontinuous coarsening has been associated with stress relief cracking in alloy 740H [24].

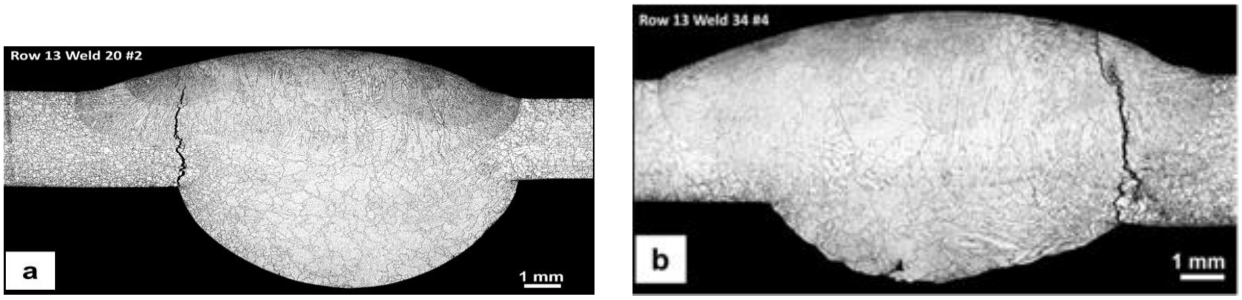

Figure 15. Cross-section of alloy 740H GTAW welds in post weld aged tubes of nominal dimension 38 mm OD x 5.5 mm W. OD of tube at top [22].

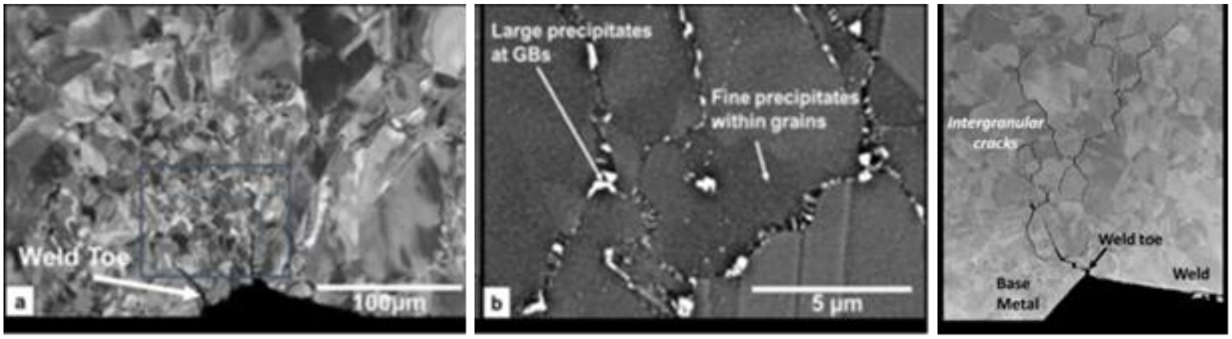

Figure 16. Left: Back scattered electron image of weld root showing indications of severe plastic strain and local recrystallization, Center, grain boundary migration and precipitate denuded zones and 3) Branching cracks at the weld root [22].

This study concluded with an expanded list of considerations for producing sound welds for plant construction [22]. Most important for engineers and welders alike, is the understanding that successful welding of alloy 740H or any age hardened nickel-base alloy requires a deeper understanding of the nature of these materials than is needed to simply pass a weld qualification test. From joint design to operations and inspection, situations where a high level of stress is present after welding is likely to lead to cracking must be avoided. These situations would include thin-to-thick section joints, excessive reinforcement and bending moments and care in heating for PWHT. When these considerations are followed it has been shown that complex structures of 740H including small diameter thin wall tubing and large thick wall pipes can be successfully welded.

CONCLUSIONS

1. Currently alloy 740H is available on order from one company at two producing locations. Additional companies have the capability to make the alloy as demand increases. The alloy has been manufactured in all product forms including welding wire.

2. Tensile properties of all product forms reliably meet ASME CC 2702 requirements. Creep-rupture test data currently available was generated on relatively thin section plate and tube product. A data gap remains for other product forms and heavy section products.

3. Induction bending of 740H can be done on commercial machines. Cracking can be avoided by surface quality and inspection and control of machine parameters. Pipes with an OD/W ratio >10 require special care.

4. A wide variety of fittings have been made by hot or cold forming on conventional equipment. Near net shape powder HIP and LPBF processes are potential ways to manufacture bespoke fittings, but they have yet to be qualified.

5. Alloy 740H machinability can be improved using a γ' spheroidizing heat-treatment.

6. Thousands of successful shop and field welds have been produced with a relatively small percentage of rework. Sound weld joints can be obtained if designers, engineers, and welders understand and respect the specific requirements of this alloy.

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