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

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ABSTRACT

Nickel-base alloys are required for many of the components in advanced supercritical CO_2 power systems operating at temperatures and pressures exceeding 700°C and 25 MPa. Age-hardened alloys offer a distinct advantage over traditional solid solution strengthened alloys by virtue of their significantly higher creep strength. This makes it possible to reduce wall thickness and, thereby reduce total materials cost. INCONEL® alloy 740H® is an age-hardened alloy that was developed and extensively characterized for Advanced-Ultrasupercritical steam boilers. Material testing by the A-USC Consortium and US Department of Energy led to ASME Code Case 2702 covering UNS N07740. Alloy 740H is the first age-hardened, nickel-base alloy permitted for welded construction for use in the creep limited temperature regime. More recent development work on the alloy has focused on product forms and environments relevant to supercritical CO_2 systems. Various laboratories have reported on oxidation properties of the alloy under simulated operating conditions. This paper focuses on the manufacturing and properties of tubing and fittings that are being applied for the various sCO_2 projects, planned or now underway. As many of the structures are constructed by welding, a review of welding practices and experiences is presented with reference to dissimilar metal welds.

INTRODUCTION

Many of the advanced supercritical CO_2 (sCO_2) energy conversion systems are projected to operate at temperatures above 700°C. This exceeds the temperature capability of ferritic stainless steels. Austenitic steels have greatly reduced strength that would require impractical tube wall thickness to contain high pressure fluids. Solid solution strengthened nickel-base alloys such as 800HT (UNS N08011), 230 (UNS N06230) and 617 (UNS N06617) have been used successfully as tubular materials in chemical process and energy applications for many years, but they also have relatively low strength, so extra heavy-wall tubing would be required [1]. For this reason, high strength age-hardened alloys were evaluated for service, initially in the European THERMIE program, then by the US Advanced-Ultrasupercritical (A-USC) Consortium and later by advanced energy programs in Asia. Alloy 740 (UNS N07740) was originally intended for boiler tube for coal fired power plants [2]. The alloy features high strength, sufficient ductility for fabrication into tube, weldability and resistance to oxidation and coal ash corrosion. Later the US A-USC program also considered the alloy for use in headers and reheater pipes. For these applications, better microstructural stability and resistance to liquation cracking in heavy section welds was needed. The alloy composition was subsequently adjusted to improve these properties [3]. The modified alloy, called 740H, fell within the original broad UNS alloy definition. The composition of the modified alloy is shown in Table I.

Table I. Nominal composition of alloy 740H and limiting composition of UNS N07740 (wt. %).

Alloy	Max/Min	Ni	Fe	Cr	Co	Mo	Al	Ti	Nb	C
740H	Nominal	Bal	0.25	24.5	20	0.5	1.4	1.4	1.5	0.03
UNS N07740	Max		3.0	25.5	22	2.0	2.0	2.5	2.5	0.08
	Min		-	23.5	15	-	0.2	0.5	0.5	0.005

During the period from 2002-2010 the US A-USC consortium conducted an extensive evaluation of mechanical properties and fabricability. This work has been documented in numerous technical publications [4-8] and culminated in submission of a data package that resulted in ASME Code Case 2702 [9]. Alloy 740H is the first age-hardened alloy to be accepted for welded pressure piping under Division 1. The design stress advantage for alloy 740H is evident from Figure 1. Within the temperature range of interest, alloy 740H has a significant strength advantage over alloy 617. For example, using the ASME BPV Code Section 1 methodology, for a 2.5 in (63.5 mm) OD tube and conditions of 1292°F (700°C) and 300 bar (30 MPa) the minimum wall thickness would be 0.256 in (6.5 mm) for 740H and 0.419 in (10.6 mm) for 617. Consequently, for similar OD pipes, one of 740H would be able to transmit 43% more fluid than one of 617. This advantage disappears at temperatures above 800°C (1472°F) because γ' in 740H goes back into solution. The code requirements were intentionally designed to be conservative because of the lack of experience with age hardened alloys in the power industry. Since its original issue in 2011, it has been modified three times to clarify and expand its applicability. The process rules of the current code case (now Rev 3) as they apply to fabrication of complex systems will be discussed later in this paper. Following Code approval, the consortium members, suppliers and selected fabricators began an extensive program to determine the limits of mill product dimensions, manufacture of fittings, and welding using a variety of processes, materials and configurations. This work has been reported in numerous venues [10-13].

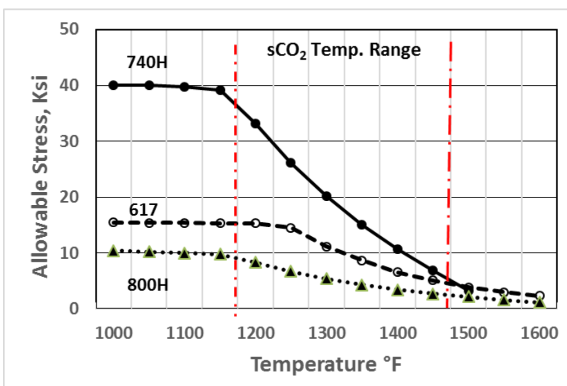

Figure 1. ASME allowable design stress for welded tube and pipe for alloys 740H, 617 and 800HT.

Although alloy 740H was initially characterized under A-USC programs, in recent years it has been considered for sCO_2 service as well. Although A-USC in-plant test loops designed to gain fabrication and operating experience have been built and operated [14], full operating systems have yet to be constructed. In the interim, sCO_2 programs system demonstration programs have advanced very rapidly; including DOE Sunshot [15], Supercritical Transformational Electric

Power (STEP) [16], Net Power [17] and new Concentrating Solar Power (CSP) Gen 3 initiative [18]. This work has provided invaluable experience in advancing the manufacturing of alloy 740H mill product forms to Technology Readiness Level (TRL) 8 [19]. This paper summarizes tube, pipe and fittings manufacturing status and presents new work on welded tube and comments on fabrication experiences and recommendations.

RESULTS AND DISCUSSION

<u>Seamless Tube and Pipe Capability</u>

Tube and pipe are the primary product forms used in advanced energy systems and hence have been the focus of much of the development work. Although there is no clear distinction between tube and pipe, for the purpose of this paper, tube will be defined as extruded, cold worked, annealed and aged product whereas pipe is defined as extruded and directly annealed and aged product. While there is considerable size overlap between the two products, tube tends to lie at smaller diameters and thinner walls. There is an inherent grain size difference between tube and pipe due to the different recrystallization conditions. Tube has a much wider possible ASTM grain size range of 3-8 with 5 being typical. In the case of pipe, the grain size may be 0-3 depending on pipe wall thickness. Grain size in as-extruded pipe is difficult to refine due to the relatively high temperatures required for the extrusion operation. The combinations of tube and pipe wall dimensions produced to date are shown in Figures 2 and 3. Approximate limits for nickel-base alloy tube and pipe are also shown. Generally, alloy 740H can be produced over the standard size and dimensional tolerance range of nickel alloys. Tube has been produced by the drawing, pilgering and roll forming processes. Roll forming provides an option for making large-diameter, thin-wall tubes. Pipe has been produced by extrusion on four different extrusion presses at Special Metals (Huntington, WV, Hereford, UK), and Wyman-Gordon (Houston, TX and Livingston, UK) facilities or by roll forming at PCC Rollmet, Irvine, CA.

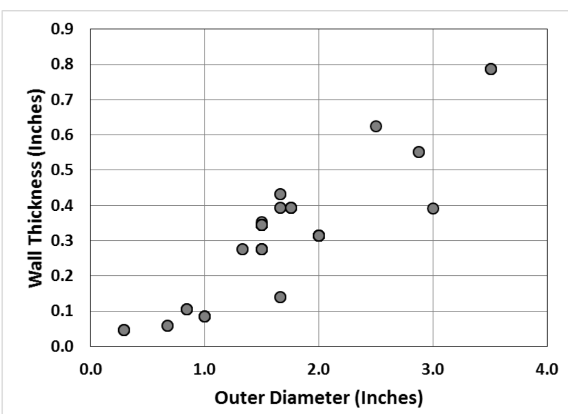

Figure 2. Range of tube OD and wall produced (drawn or pilgered).

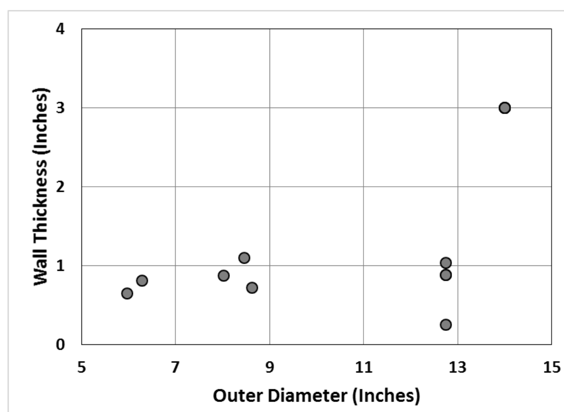

Figure 3 Range of pipe OD and wall produced (extruded or roll formed).

The mechanical properties of alloy 740H have been extensively evaluated and documented [3-7, 10]. Production of tube and pipe for prototype facilities has confirmed the initial results used in the data package submitted for ASME code approval. The ASME specified heat treatment for 740H is solution anneal at a minimum temperature of 2010°F (1100°C) and age 1400-1500°F (760-816°C). Much of the variation in room temperature properties is the result of different heat treatment combinations within the specified ranges. Limited data has shown that the property variation diminishes, after exposure of a few hundred hours at the operating temperature, to a narrower range as the γ' volume fraction reaches an equilibrium value. Room temperature tensile properties to 95% confidence intervals for tube and pipe are shown in Figures 4-6.

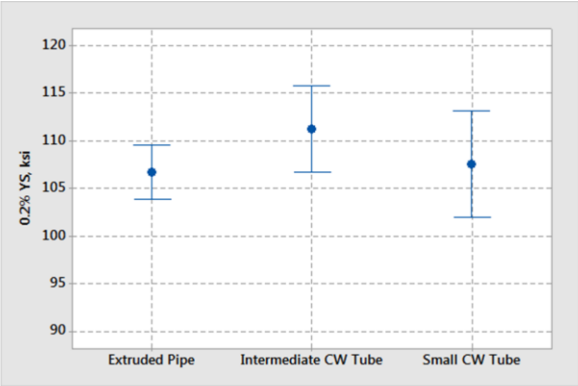

Figure 4. Room temperature 0.2% offset yield strength range of tube and pipe. ASME min. 90 ksi.

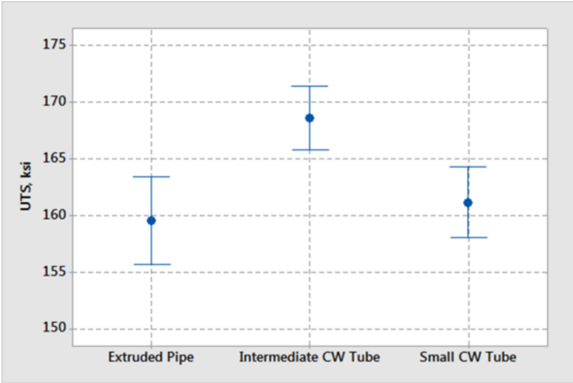

Figure 5. Tensile strength range of tube and pipe. ASME min. 150 ksi.

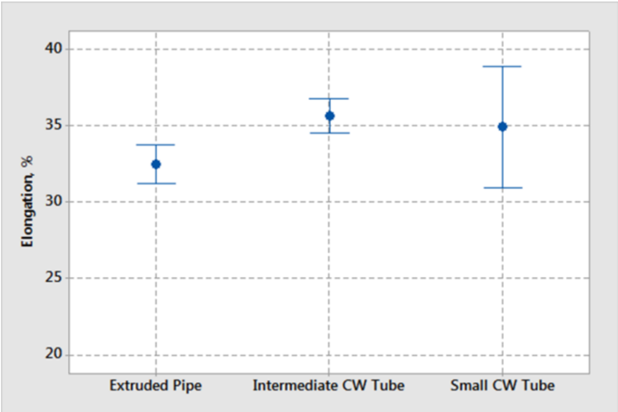

Figure 6 Tensile elongation range of tube and pipe. ASME min. 20%

<u>Welded Tube</u>

A more economical method for manufacturing tube and pipe is through longitudinal welding of continuous strip or plate. By this means, a much longer thin-wall tube can be produced than can be made by cold draw, pilger, extrusion, or roll pierce/expansion methods. This process is widely used for the manufacture of solution strengthened nickel-base alloy products. The process also offers higher productivity and superior dimensional tolerances. A schematic drawing comparing the two production routes is shown in Figure 7. While the extrude/draw process looks relatively straightforward, it becomes increasingly complex as the tube diameter and wall thickness decrease. This is because additional cold work, anneal and pickle cycles are required with their adverse effects on productivity and product yield. Very small diameter tubes may require five or more draw/anneal cycles to reach final size.

A concern about welded tube has traditionally been the possibility of “unzipping” a linear continuous weld seam. However, improvements in welding and post processing have alleviated these concerns. In addition a factor of 0.85 is applied to the allowed design stress to account for the weld. Today this process is widely used to manufacture carbon, stainless steel and nickel alloy tubes. In particular, it has been used successfully in the production of N06230 alloy for the receiver portion of CSP solar plants. For Gen 3 systems higher temperatures will require the use of stronger alloys such as alloy 740H. However this process has seen very limited use for age hardened alloys and has not been accepted for use in high temperature creep limited applications. Accordingly, a project was initiated with the aim of developing, testing and qualifying alloy 740H welded tube.

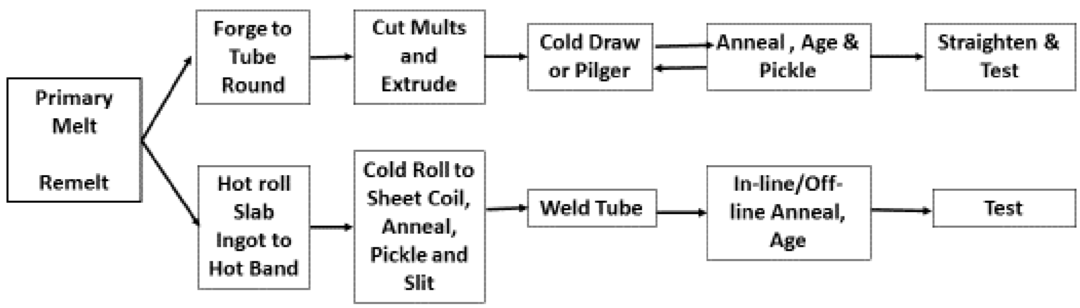

Figure 7. Comparison of seamless and welded tube processes.

Although alloy 740H sheet was not considered a priority in early A-USC development work, more recent design concepts in sCO_2 heat exchangers require sheet. In the course of the sheet process development, 0.065 in (1.65 mm) thick sheet became available for use to make welded tube. The results of a 1 in (25 mm) tube manufacturing trial are presented in this paper. Future trials will include 2 in (50 mm) tube and redrawn tubes.

There are a wide variety of commercial welded tube mills. The one used in this work at the RathGibson facility in Janesville, WI is a straight-line feed mill in which the mill-annealed strip is continuously fed from a coil and folded through a series of rollers to the tube shape. A general view of the entry side of the tube mill is shown in Figure 8. A 275 lb (125 kg) coil of 0.065 in (1.65 mm) thick x 3.02 in (76.7 mm) wide strip was used. The strip was autogenously welded using a CO_2 laser, mechanically worked on line and continuously annealed using an induction coil. Resistance welding is also commonly used on small diameter tubes while heavier wall tube and pipe may require a filler metal applied with GTAW or GMAW processes. The specific welding parameters are typically determined experimentally for each alloy, thickness, diameter combination and in this case are proprietary to RathGibson. The annealed and cut finished tubes are shown in Figure 9.

Relatively little adjustment was needed to produce acceptable alloy 740H tube. In-line NDT testing with an eddy current coil was conducted. Off-line tests include flare, flattening and bend tests. Two material conditions were examined: in-line continuous anneal at 1950°F (1066°C) and an off-line continuous anneal at 2075°F (1135°C). Flare and flattening tests for these two conditions are illustrated in Figures 10 and 11. No failures were found in these tests or in the longitudinal bend and eddy current tests.

Representative microstructures are shown for the two annealed conditions in Figures 12 and 13. The starting strip grain size of ASTM 7 did not grow appreciably during the in-line anneal. After the continuous reanneal the grains grew to ASTM 3. There was no sign of lack of fusion, fissures or porosity associated with the weld. The in-line annealed tube shows a columnar weld grain structure. The off-line annealed weld nugget has substantially recrystallized.

Figure 8. Entry end of tube welding line

Figure 9. Finished tubes

Figure 10. Flare/Flattening Test, welded with flash 1950°F (1066°C) on-line anneal.

Figure 11. Flare/Flattening Test, after 2075°F (1135°C) off-line anneal.

The room temperature tensile properties are shown in Table II. The tubes were tested whole with the applied tensile stress parallel to the weld. The mechanical properties of a similar sized seamless tube and the precurser sheet are also shown in the table. The annealed and aged welded tube tensile properties exceed ASTM/ASME code minima and are reasonably consistent with sheet and seemless tube properties. Much more detailed mechanical property testing will be conducted in the future to support a code case. These tests will include internally pressurized creep tests as well as tube bending and similar and dissimilar metal butt welding for attachment.

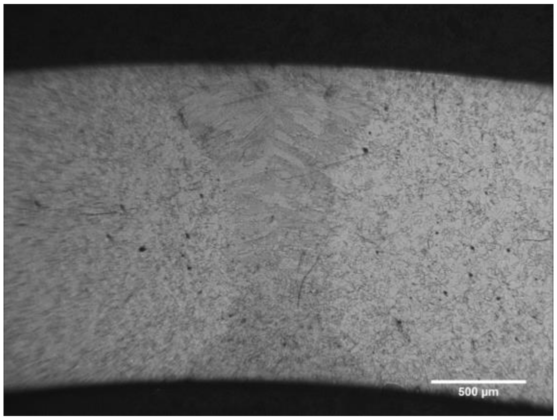

Figure 12. Weld microstructure, In-line continuous anneal.

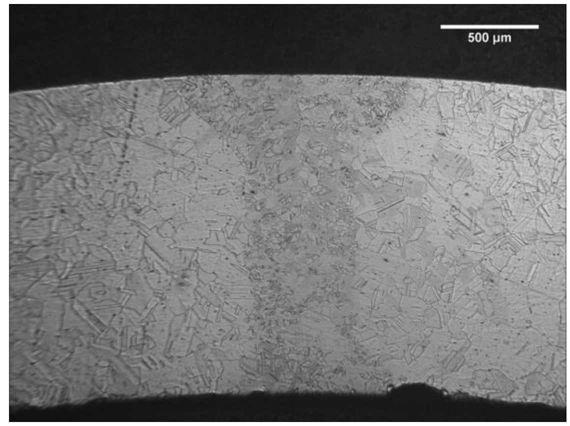

Figure 13. Weld microstructure, off-line continuous anneal

Table II. Room Temperature Tensile properties of welded and seamless tubes tubes and annealed strip.

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)					

Tube and Pipe Bends

For the past five years Special Metals has pursued a program to demonstrate the ability to fabricate the various components required for A-USC and sCO_2 plants. This work included cold and hot tube and pipe bending. The A-USC consortium initially conducted a series of cold bending experiments on boiler tubes of 2 in (50 mm) OD x 0.400 in (10.2 mm) wall to define practical bending limits. These tubes were bent in the solution annealed condition and demonstrated the ability to make bend radii as tight as 2D [8]. Subsequently, Shingledecker conducted a detailed microstructure analysis of tube bends that had been subjected to an internally pressurized creep test [20]. This was a very significant program of work, in that it established that bends meeting code mechanical property requirements could be produced. It also helped to establish rules for heat treatment of cold formed components. Specifically, any cold work operation that generates a plastic strain exceeding 5% must be followed by a full solution anneal.

Induction bending is commonly used for making pipe bends for power plants. Successful induction bends have been reported for alloy 617, but no γ' strengthened alloy pipe bending trials had been previously reported. 3D radius bends were made on three sizes of pipe at Chicago Bridge & Iron (CB&I) Alloy Piping Products (APP) plant in Clearfield, UT (6.6 in (168 mm) OD x 0.55 in (14 mm) W, roll-formed pipe, 5.25 in (133) mm OD x 0.75 in (19 mm) W extruded pipe, and 4.5 in (114 mm) OD x 0.5 in (12.5 mm) W pilgered pipe) using a mid-range 500 KW machine [16]. Process variables included temperature, cooling method and feed rate. Some optimization was required to achieve the desired shape and surface quality. A cross section of the tube made at the apex of the bend showed a thickness of 0.85 in (21.8 mm) at the intrados and 0.70 in (17.7 mm) at the extrados compared with an original wall thickness of).75 in (19.05 mm). Figure 14 shows the induction bending operation. Figure 15 shows a fabricated pipe section in which three 90° bend segments are butt welded to straight sections of pipe. Tensile properties shown in Table III are comparable to the original pipe properties. A 3D radius bend was also made at Induction Pipe Bending UK, Ltd., Washington, Tyne and Wear, UK in a 2.87 in (73 mm) OD x 0.55 in (14 mm) W pilgered pipe.

Figure 14. Induction bending at CB&I APP, Clearfield, UT.

Figure 15 Pipe bends assembled with butt welds.

Table III Properties of induction bent pipe.

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)					

Fittings

Forged fittings such as flanges, saddles, elbows, concentric reducers, tees, wyes, rings and valve parts are required for plant piping design. For pilot plants, it may be faster and more economical to machine unique small parts from forged bar; but ultimately, components formed on dedicated tooling by the power industry supply chain will be required. Consequently, a series of trials on representative parts were conducted on available tooling by fabricators who had prior experience forming nickel-base alloys such as 625. The details of these trials including detailed hardness and microstructure maps were presented previously [21]. A summary is presented in this paper.

Four finished parts are depicted in Figures 16-19: 1) Cold hydro-formed “tee”, 2) Hot drop forged flange, 3) Cold formed concentric reducer, and 4) Hot forged elbow. Parts 1, 3 and 4 were made at CB&I APP in Shreveport, LA from 8 in (200 mm) schedule 120 pipe and Part 2 was made at Maass Flange in Houston, TX from 8 in (200 mm) mill forged bar. Alloy 740H has characteristics that are favorable for fabricated components such as low flow stress and good ductility at ambient and forging temperatures. However, die chill could result in tearing due to rapid precipitation of γ' and reduced ductility between 1000 and 1800F, Consequently, forging protocols for complex thin-wall parts should be carefully planned to account for material properties. Flow stress and ductility data for alloy 740H were presented previously [6]. No cracking was experienced in any of the parts shown, apart from a superficial end split on the forged elbow.
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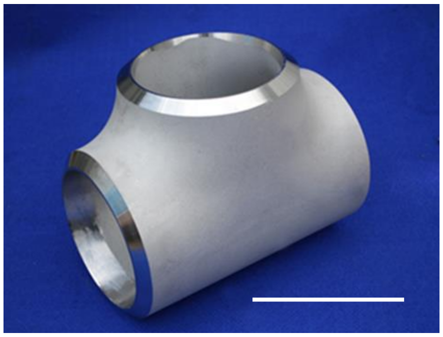

Figure 16. Cold formed “Tee” (8 in (200 mm) size bar)

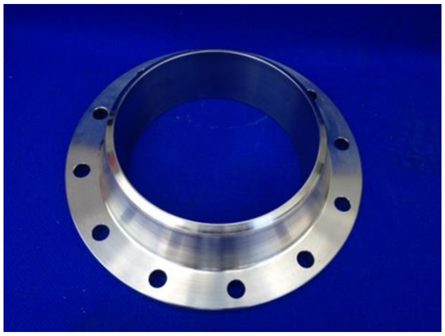

Figure 17. Hammer forged flange.

Figure 18. Cold formed concentric reducer.

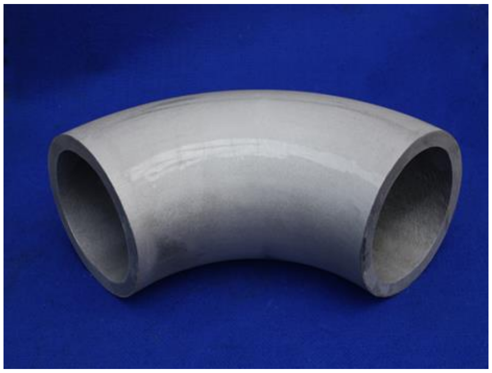

Figure 19. Hot forged elbow

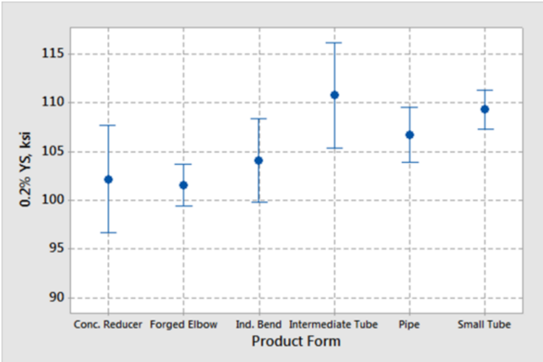

Figure 20. Room temperature 0.2% offset yield strength of heat-treated fittings. ASME min. 90 ksi.

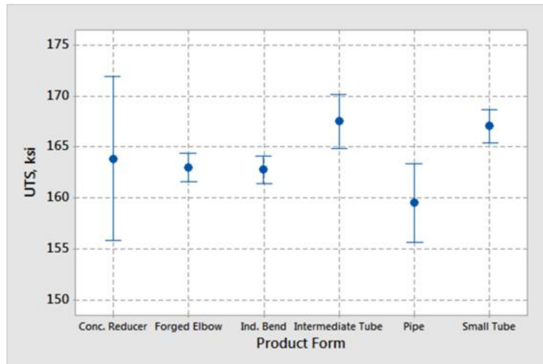

Figure 21. Room temperature tensile strength of heat-treated fittings. ASME min. 150 ksi.

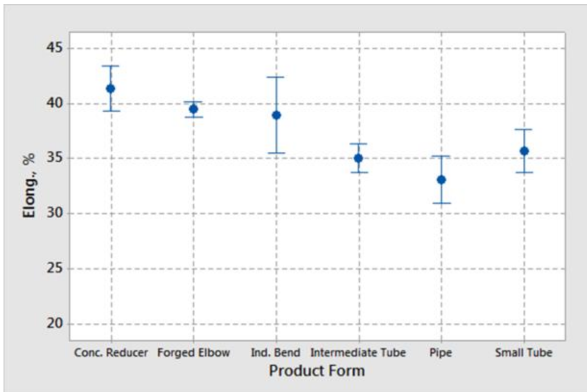

Figure 22. Room temperature tensile elongation of heat-treated fittings. ASME min. 20%.

The room temperature tensile properties of the trial fittings are shown in Figures 20-22. All parts were solution treated at 2075°F (1121°C) and aged for 4 h. at 1472°F (800°C) by the forger. The properties all exceed ASME minimum requirements, but they show some variability because these were one-off feasibility trials in which the process parameters were not optimized.

Welding Experience

Fusion welding is universally used to fabricate piping structures for power plant heaters, heat exchangers and piping systems. Accordingly, the alloy 740H development program has placed a heavy emphasis on demonstrating the weldability of the alloy [11, 12, 22] in various structural configurations. Nickel alloys can be welded by all fusion processes; but, in the case of alloy 740H, which contains the reactive elements Al and Ti, restrictions are needed to produce high quality welds. To provide guidance for welding engineers, a “Practical Guide to the Welding of alloy 740H” has been created [23]. Additional technical information pertaining to welding 740H and age hardened nickel alloys can be found in references [24, 25]. The following discussion provides an overview of some key requirements for welding 740H along with some learnings from recent demonstration projects.

a). The welding methods for alloy 740H that are permitted by Code Case 2702 are GTAW (TIG) and GMAW (MIG). These inert gas shielded processes can protect the Al and Ti from oxidation during arc transfer. However, the welder must verify shielding gas purity and flow rate and must scrupulously remove any oxide from the surface of the bead by grinding every few passes. The most common defect in welding alloy 740H is lack of fusion (LOF) due to inadequate removal of surface oxide or use of contaminated shielding gas.

b). Welding trials have shown that SMAW and SAW methods are not feasible for alloy 740H filler wire with existing commercial fluxes. The shortcomings are excessive loss of Al and Ti combined with slag entrapment and LOF. The use of a nickel-base alloy 263 coated electrode has shown promise in laboratory trials to produce high strength welds on alloy 740H [4]. DOE sponsored creep-rupture testing is now underway at Oak Ridge National Lab to develop a data base, but use of this electrode is not currently permitted by the code. If ultimately approved, this electrode would provide an alternative option to GTAW or GMAW for repair welding.

c). Good management of heat input when welding alloy 740H is essential. Unlike steel, a high preheat/inter-pass temperature is undesirable and leads to an excessively wide HAZ and cracking. Generally, no preheat is required for welding alloy 740H and the inter-pass temperature should be limited to about 350°F (177°C). A concave weld bead and abrupt weld termination should be avoided to prevent cracking.

d).The Code Case requires that all welding of 740H to itself be done with matching chemistry filler metal (chemistry within UNS N07740). Alloy 740H straight length and spooled wires are commercially available that have chemistry aims and limits identical to those of the base metal.

e). Dissimilar metal welds have been made between alloy 740H and P91, P92, 316H, 347 and 617 using filler metal 82 and welding electrode 182. No issues were encountered when making these welds; however, the post weld heat treatment conditions were adjusted within the ASME permitted range for alloy 740H to accommodate the ferritic materials. All cross-weld tensile test specimens failed in the lower strength non-740H member. This work is reported in reference [12]. The results of a heavy 740H pipe insert between P91 and 316H in a fossil-fired power plant has been reported [13]. In this work a filler metal 82 butter layer was placed on the steel before making the closure weld with the same product. FM82 is an ideal choice for dissimilar metal welds because of its tolerance for dilution from the disparate base metals.

f). The current Code Case 2702 language stipulates that weld procedure qualification must be done with the 740H in the solution treated and aged condition. A procedure qualification issue that has been encountered is bend test failure. The code requires a 4T bend, however, several welding labs have reported failures when using a 1.5 in (37.5 mm) diameter tool as called out in QW-466-1 of ASME Section IX as being a 4T bend. As stated in Code Case 2702, a 4T minimum bend radius may be used for bend testing 740H welds. This equates to a 1.5 in (37.5 mm) radius or a 3.0 in (75 mm) diameter tool. Depending on bend specimen thickness, tool sizes will vary. The above mentioned sizes are for 0.375 in (9.5 mm) thick bend specimens.

g). Despite the preceding weld qualification rule, welding of 740H in the solution treated condition is widely interpreted as acceptable provided that the entire component is given the prescribed age hardening treatment.

h). The ASME Code Case mandates post-weld heat treatment (PWHT) for 740H welds. The treatment time and temperature corresponds to the aging treatment for the alloy. The code specifically prohibits the use of “local heat treatment”. This has been interpreted to mean “no local solution treatment”, a process that would produce a heat affected zone that spans the γ' resolution range. Local aging is allowed and is necessary for field erection. This local aging process was simulated on a 14.9 in (378 mm) OD x 3.46 in (88 mm) W pipe using a ceramic heating blanket. This work has been described in detail [11].

i). Stress relief/relaxation or strain-age cracking has been encountered in complex weld structures in a wide range of alloys including P22, P92, 347 and 617. Consequently there has been apprehension about 740H which is a much stronger material. Stress relief cracking has not been encountered under laboratory welding conditions, including the heavy pipe weld just mentioned. Circular patch (Borland [26]) tests have been conducted (10,000 hours exposure at 725°C) with no sign of cracking [7]. Ramirez used short time Gleeble tests to rate the susceptibility of alloy 740 to stress relief cracking as similar to alloy 718 [27]. These observations do not infer that under certain conditions, stress relief cracking cannot occur. Recently Kant and DuPont used a similar Gleeble test to develop a ranking system for high temperature structural alloys [28]. In this work, they were able to induce stress relief cracking in all of the test materials under restricted ranges of conditions. Alloy 740H was judged to be moderately susceptible and less susceptible than alloys such as P22 and 347 that are widely used in power plant construction. At this time very limited fabrication shop and field welding experience is available on 740H. Instances of cracking encountered in trial welds have been mitigated by minimization of residual stress, avoidance of crevices and laps, joint redesign and rapid heating to the stress relief temperature.

j).The code is ambiguous on the subject of solution annealing of alloy 740H welds. Solution annealing is not expressly permitted or prohibited. There is no technical problem associated with solution annealing welds, but when the code case was written, there was insufficient data to validate this process. Data reported by Shingledecker showed higher creep-rupture strength for solution treated and aged welds compared with direct aged welds [4]. Bechetti and DuPont reported both recrystallization and partial homogenization of the weld structure occurred during solution treatment [29]. Unpublished has also shown improved tensile, creep and impact properties [30]. This is an issue that will need additional creep-rupture testing to resolve, but is important to do so because the manufacture of valves, heat exchangers and seam welded pipe and elbows may require intermediate solution annealing.

CONCLUSIONS

Based on extensive experience in full-scale manufacturing of mill product forms used for component fabrication and pilot plant construction, it is considered that alloy 740H is now at technology readiness level (TRL) 8 [19]. This includes plate, sheet and heavy-section forged billet that were not discussed in this paper. A status of TRL 9 would require the long-run production experience associated with material supply for a full-scale power plant. Other age hardened alloys have been developed and are in various stages of qualification testing. The path for commercialization of these alloys has been paved by the work of the US A-USC Consortium and others on 740H.

Industrial use of alloy 740H in power plant systems is judged to be at TRL 6. This is based on construction and brief operation of test loops and pilot plants in relevant environments and temperatures. The level of understanding how plants respond to the use of the new age-hardened materials should advance rapidly over the next few years as more complex systems are constructed and tested. In the interest of avoiding repeating mistakes in design and fabrication of these unique materials, it would be beneficial to the industry if the fabrication experiences are shared freely; an example being the dissimilar welding results presented at a recent EPRI Conference [13]. The ultimate goal is to reach TRL 9 as quickly and painlessly as possible where utilities could routinely construct, operate and repair piping systems using age-hardened nickel alloys.

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