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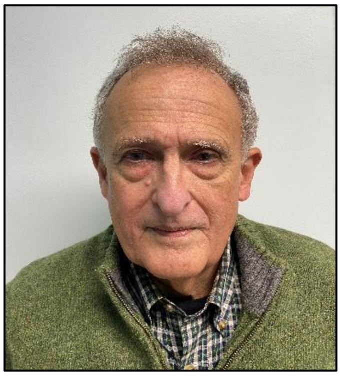
# Recent Developments in Manufacturing and Fabrication of Alloy 740H Components for $sCO_2$ Applications



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## Abstract

INCONEL® alloy 740H® (UNS N07740) is a gamma prime strengthened nickel-base superalloy that was initially developed for seamless boiler tube for Advanced Ultra-supercritical steam boilers for service in the 700-800°C temperature range. The alloy has been extensively evaluated under a series of projects funded by the US Department of Energy. It has been approved for use in welded construction in the ASME Boiler and Pressure Vessel Code. In recent years, alloy 740H has been considered for applications for supercritical $CO_2$ including turbines, heat exchangers and solar thermal receivers. A recent DOE focus has been to validate manufacturing methods that would lower the installed cost of systems utilizing this alloy. The work reported in this paper covers the development, testing and qualification of seam welded tube and pipe under the sponsorship of DOE EERE Solar Energy Technology Office. For this project, autogenous laser welded tube was made on a commercial tube mill from coiled strip. Tubes were also drawn to smaller diameter to refine the weld structure. Pipe was made from plate, also on a commercial line. A unique pressurized creep-rupture apparatus was constructed to determine creep properties of small diameter tubes. Current design stress allowables in the ASME Code case 2702 are based on properties of welds made with a post weld stress relief treatment. With seam welded tube and pipe, a higher temperature solution anneal that can improve creep strength is applied. Data is being generated to support higher stress allowables for solution annealed welds.

## Introduction

Many advanced energy systems have been designed to operate with temperature, pressure, and corrosive environment that are too severe for use of conventional ferritic and austenitic steels for pressure containing components. Age-hardened nickel-base alloys have been under development and testing for over twenty years for boiler and receiver tubing, heat exchangers, valves, fluid transfer piping, fittings, and turbine components [1-4]. One of these alloys, INCONEL alloy 740H, has been extensively tested by the US Department of Energy and approved for use in the ASME Boiler and Pressure Vessel Code for welded pressure applications in 2011 [5]. The original code case has been revised multiple times as more data have become available. The alloy has been used for several pilot demonstration facilities including the DOE funded STEP facility now under construction at Southwest Research Institute. While alloy 740H meets industrial design strength and fabricability requirements, by virtue of its composition, it is inherently very expensive, roughly ten times the cost of stainless steel. One manufacturing approach to significantly lower the cost of tubular components is to make them by seam welding sheet or plate. These processes are commonly used for solid solution strengthened nickel-base alloys but have rarely been used for age-hardened alloys and never for alloys used at temperatures where time-dependent properties are controlling.

Seam welded tubing is generally made on a semicontinuous basis where a long coil of thin strip is passed through a series of forming rolls designed to fold the flat strip into a tube. It is then welded, annealed, and inspected in-line before either coiling or cutting to specified length. In the case of age hardened alloys, the tube would have to be off-line aged in a batch due to the length of the age hardening cycle. In the present work autogenous laser welds were made. Welded pipe is made from plate that is bent into a tubular shape using a press brake. Pipe lengths for nickel alloys are typically much shorter and a weld filler metal is required. Weld bead mechanical conditioning or cold working (drawing or pilgering) are often done for the purpose of refining the cast weld structure.

A major departure from earlier applications of alloy 740H is the introduction of solution annealing of welds. The early work on which the original code case was based, used a post weld stress relief treatment temperature that corresponded to the age-hardening treatment. The welded and aged creep strength of alloy 740H is lower than that of the solution annealed and aged base metal. While the creep strength is also dependent on the specific welding process and conditions, a single strength reduction factor of 0.70 was assigned for all temperatures in the creep range where 740H is currently qualified for use (1202-1517°F, 650- 825°C). This penalty is not a concern for butt welds, but it would require a proportionally thicker wall for seam welded tubulars. Previous work had shown that annealing or homogenizing the weld could significantly increase creep strength of alloy 740H [6,7]. Bechetti studied the effect of temperature on the chemical homogenization and carbide dissolution in weld structures [8]. This work found that while inter-dendritic segregation could be essentially eliminated by use of a homogenizing anneal, MC carbide that restricted grain growth was stable at all temperatures below the solidus. Accordingly, a theme of the present work became an assessment of the effect of processing variables on the weld structure and creep properties.

Cross-weld creep testing of large diameter pipe is relatively straight-forward, but conventional testing procedures cannot be used for tube. In the present work, tube diameters varied from 2 in (50 mm) OD down to 3/8 in (9.5 mm) OD. To overcome this problem, an internally gas pressurized creep test was devised. The test used short sections of tube welded with a cap on one end and to a port to a high-pressure gas line on the other end. The assembly was contained within a small box furnace. The test equipment and procedure is described in greater detail in reference [9].

In a fabricated structure, the tubes and pipes will be incorporated into a more complex structure with bends, fittings, and attachments. Limited work was done under this project to simulate some of these processes. This work included hot induction bending of the pipe, cold bending of tube and automated welding of tube. In work to be published elsewhere alloy 740H welded tube was tested for corrosion resistance in various solar receiver salts and supercritical $CO_2$ and for erosion resistance by ceramic particles.

## Procedures

The materials used in this work were produced from vacuum induction melted (VIM) and remelted ingot and processed on mill equipment. The compositions of the starting stock (sheet, plate and welding wire) are shown in Table 1 along with the limiting composition for UNS N07740. Sheet and plate came from two electroslag remelted (ESR) ingots made from the same master VIM heat. Weld wire was made from a vacuum arc remelted (VAR) ingot from a different master VIM heat.

Table 1. Chemical composition of materials used in this project.

| Heat No. | Product | C | Mn | Fe | S | Si | Ni | Cr | Al | Ti | Co | Mo | Nb | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HT6306JK | Sheet | 0.036 | 0.30 | 0.20 | 0.0005 | 0.15 | 49.79 | 24.56 | 1.37 | 1.47 | 20.02 | 0.50 | 1.52 | 0.004 |
| HT6309JK | Plate | 0.033 | 0.29 | 0.17 | 0.0005 | 0.15 | 49.73 | 24.59 | 1.40 | 1.48 | 20.03 | 0.49 | 1.51 | 0.007 |
| HT5502JY | Wire | 0.034 | 0.24 | 0.17 | 0.0010 | 0.15 | 49.48 | 24.56 | 1.45 | 1.46 | 20.35 | 0.48 | 1.48 | 0.008 |
| UNS N07740 | Max | 0.08 | 1.0 | 3.0 | 0.03 | 1.0 | Bal | 25.5 | 2.0 | 2.5 | 22.0 | 2.0 | 2.5 | 0.03 |
|  | Min | 0.005 |  |  |  |  |  | 23.5 | 0.2 | 0.5 | 15.0 |  | 0.5 |  |

<u>Manufacture of welded tube</u>: A complete description of the welded tube manufacturing process used in this program is contained in Reference [10]. Briefly 0.065 in (1.65mm) thick coiled strip in widths 3.02 in. (76.7 mm) and 6.19 in. (157.2 mm) was supplied to RathGibson in Janesville, WI. This strip was formed into tubes of 1 in (25 mm) and 2 in (50 mm) outside diameter (OD) and autogenously welded with a $CO_2$ laser on a continuous tube mill. The welded tube was in-line annealed, bead conditioned, eddy current tested and cut into 20 ft (6.1 m) lengths. Tubes were re-solution annealed at 2075°F (1135°C) in a continuous anneal furnace and then batch aged for 4 hours at 1472°F (800°C). Standard quality tests such as bend, flare, flange and flattening tests were done. Entire tubes were tensile tested at room and elevated temperature. Creep testing was conducted using the internally pressurized creep test at EPRI. The details of this test are described in reference [6]. Room temperature hydrostatic burst tests were conducted at RathGibson. This test is described in reference [11]. Cold tube bending trials were conducted on 2 in (50 mm) OD tubes at Tebunus Tube Bending B.V. in Netherlands. Automated tube butt welds were made on 2 in (50 mm) OD tubes using a Liburdi Diametrics P300 power supply with an L2000 orbital tube weld head. Autogenous gas-tungsten arc welds were made using Argon or Argon + 25% Helium shielding gas. Selected samples were used for weld procedure qualification testing.

<u>Manufacture of Welded and Redrawn Tube</u>: Three separate redrawing trials were conducted. The starting stock was 1 in (25 mm) OD or 2 in (50 mm) OD welded tube in the solution annealed condition. The drawing was conducted at Greenville Tube in Clarksville AK with final solution anneal at RathGibson. The first trial consisted two sink drawing passes from 2 in (50 mm) OD to 1 in (25 mm) OD. These tubes were honed before testing because the ID surface was quite rough. A second set of tubes was redrawn from 1in (25 mm) OD to 0.375 in (9.5 mm) OD by a

combination of sink and plug drawing for supply to another SETO project. A third trial was undertaken to determine the minimum cold reduction needed to refine the weld grain structure and improve the creep rupture strength. This trial used 2 in (50 mm) OD tube as starting stock and a combination of drawing procedures and incorporated an intermediate continuous anneal. The trial matrix is shown in Table 2. Testing procedures were the same as those used for the as-welded tubes.

Table 2. Cold tube drawing matrix used for trial 3.

| Pass | Start OD, in. | Start Wall, in. | Finish OD, in. | Finish Wall, in. | Finish ID, in. | Mandrel | Pass Red. % | Total Red. % | Notes |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 0.063 | 1.75 | 0.058 | 1.634 | Yes | 19.6 | 19.6 | |
| 2 | 1.75 | 0.058 | 1.5 | 0.06 | 1.38 | No | 12 | 29.2 | No pre-draw anneal |
| 3 | 1.5 | 0.06 | 1.375 | 0.055 | 1.265 | Yes | 16 | 40.5 | Pre-draw anneal |
| 4 | 1.375 | 0.055 | 1.125 | 0.057 | 1.011 | No | 16.1 | 50.1 | No pre-draw anneal |

Manufacture of Welded Pipe: Welded pipe was fabricated from a hot rolled and mill annealed 0.75 in (19 mm) thick plate 48 in (1219 mm) wide by 240 in (6096 mm) long. The plate was formed on a press brake into a nominal 14 in (356 mm) OD pipe at Swepco Tube LLC in Clifton, NJ. The tube was welded using automated gas-tungsten-arc process that used 10 passes including a root cap pass. The procedure used a “V’ groove with a 60° bevel, a 0.0625 in (1.6 mm) root gap and a 0.0625 in (1.6 mm) land. Commercial 0.062 in (1.6 mm) diameter 740H (ERNiCrCo-1) spooled filler wire was used. Argon/Helium was used for shielding gas. Specific welding parameters are proprietary to Swepco. The welded pipe was solution annealed at 2025°F (1107°C), water quenched and cut into two pieces. One half was aged at 1472°F (800°C) for 4 hr. NDT included radiography and sonic testing to a 10% wall notch standard. Tensile and side bend testing were done at Swepco and additional tensile, impact and creep testing were conducted at Special Metals and EPRI. A picture of the pipe on the welding stand is shown in Figure 1.

Figure 1. Welded pipe at welding station

Figure 2. Induction bending of welded pipe

Welded Pipe Bending: The half of the pipe in the solution annealed condition was sent to McDermott in Clearfield, UT (now Shaw Clearfield, LLC) for bending. Hydraulic bending of large diameter pipe is done with a hydraulic clamp at one end that moves along track that controls the bend radius. The other end is pushed through the induction coil. The external induction heating coil is tuned to locally heat the pipe into the hot working range. The coil may be followed by a ring quench although in this case a quench was not used. A more detailed description of the process is contained in reference [12]. In the present work a 90° bend with a 42 in (1067 mm) radius was produced. The trial was conducted with the weld at the neutral axis. Specific bending parameters used in this work are proprietary to Shaw. After bending the pipe was solution annealed at 2050°F (1121°C), water quenched and aged at 1472°F (800°C) for 4 hr. Liquid penetrant and sonic testing were performed after heat treatment. The pipe was returned to Special Metals where radiography of the weld seam was done. The pipe was then sectioned for tensile and impact testing of the extrados, intrados, and weld seam.

## Results

Welded Tube Testing: In addition to the in-line eddy current test which checks for weld cracks and seams, welded tube may be subjected to a variety of destructive quality tests such as flare, flange, flattening and bend tests. These and mechanical property testing such as longitudinal tensile, hydrostatic pressure and burst tests are called out in ASTM B 1007 [13]. The details of these tests are contained in ASTM B 751 [14]. All samples of both welded tube sizes passed these tests in the annealed condition with no indications reported. These tests are designed to test the quality of the as-produced welded tube which would normally be in the solution annealed condition, with the expectation that the customer would apply fabrication operations such as bending and then resolution anneal the tubes. These tests would not be applied to age hardened tubes. Examples of these tests were shown in reference [11]. The pressure or leak test is an optional customer requirement identified in the ASTM general specification. Leak testing can be either hydrostatic or pneumatic. The former was used by RathGibson for this project. Tubes were subjected to an internal pressure of 1000 psi (6.9 MPa) for 5 seconds. This is a straightforward pass/fail test and all samples passed. The test is designed to detect through-wall imperfections that are not visually observable or detected by eddy current test.

Room temperature tensile tests were conducted on tubes in three conditions: 1) In-line continuous anneal, 2) off-line static anneal, and 3) static anneal and static age. These tests were performed on full tubes in the longitudinal (tube axis) orientation. The results are shown in Table 3.

Table 3. Room temperature tensile test results

| Item | Size (OD x W)(mm, in) | Heat Treatment, °C (°F) | N | 0.2% Offset YS, MPa(ksi) | UTS, MPa(ksi) | % Elongation |
|---|---|---|---|---|---|---|
| Welded Tube | 25.4 (1) x 1.65(0.065) | In-line anneal 1066(1950) | 2 | 475.5(69.0) | 865.5(125.5) | 55 |
| " | " | Cont. Reanneal 1135(2075) | 3 | 512.3(74.3) | 921.3(133.6) | 54 |
| " | " | Reanneal + Static Age | 3 | 779.0(113.0) | 1172.0(170.0) | 37 |
| " | 50.8(2) x 1.60(0.063) | In-line anneal 1066(1950) | 2 | 479.5(69.5) | 883(128.1) | 56 |
| " | " | Cont. Reanneal 1135(2075) | 3 | 528.3(76.6) | 935.7(135.7) | 54 |
| " | " | Reanneal + Static Age | 4 | 884.5(128.3) | 1098.3(159.3) | 38.5* |
| Seamless Tube‡ | 21.3(0.84) x 2.79(0.11) | Cont. Ann 1135(2075) | 1 | 512(73) | 943(137) | 56 |
| " | " | Cont. Ann + Static Age | 1 | 746(108) | 1163(169) | 43 |
| Sheet | 1.65(0.065) | Continuous Ann 1107(2025) | 1 | 496(72) | 958(139) | 47 |
| " | " | Cont. Ann + Static Age | 1 | 855(124) | 1220(177) | 30 |
| ASME Min | | | | 621(90) | 1034(150) | 20 |
| * One test bar broke outside gauge mark ‡ Reference [2] | | | | | | |
| Age hardening treatment 4 hr at 800°C(1472°F) | | | | | | |

Data for the parent sheet coil and prior production of seamless thin-wall tube are provided for comparison. The tube properties are well in excess of the ASME minima. The welded tubes had slightly lower yield and tensile strength than the seamless tube, but the differences are not considered significant. Note that the relatively high yield strength of the as annealed product indicates that some γ' is present; either because it was not fully solutioned or that some auto - aging occurred during quenching. A limited number of tensile tests were conducted at 1292°F (700°C) and 1382°F (750°C). This data is presented in Table 4. The yield and tensile strength are comparable to previously tested seamless tube; however, the elongation is lower. Since the tubes were tested by different laboratories, it is difficult to judge the significance of this difference.

Table 4 Elevated temperature tensile test results

| Item | Size (OD x W)(mm, in) | Heat Treatment, °C (°F) | Temp., °C (°F) | 0.2% Offset Yield Strength, MPa(ksi) | Tensile Strength, MPa(ksi) | % Elongation |
|---|---|---|---|---|---|---|
| Welded Tube | 25.4 (1) x 1.65(0.065) | In-line anneal 1066(1950) | 700 (1292) | 628 (91.1) | 912 (132.4) | 13 |
| " | " | " | 750 (1382) | 635 (92.2) | 813 (118.6) | 10 |
| Welded & Redrawn Tube | 25.4(1) x 2.03(0.080) | Cont. Reanneal 1121(2050) | 700 (1292) | * | 868 (126) | 8.5 |
| " | " | Reanneal + Static Age | 750 (1382) | 679 (98.5) | 798 (115.8) | 8 |
| Seamless Tube‡ | 21.3(0.84) x 2.79(0.11) | Cont. Ann 1135(2075) | 700 (1292) | 682 (99) | 964 (140) | 23.2 |
| " | " | Cont. Ann + Static Age | 750 (1382) | 621 (90) | 845 (123) | 17.4 |
| * Extensometer slipped ‡ Reference [2] | | | | | | |
| Age hardening treatment 4 hr at 800°C (1472°F) | | | | | | |

Due to the difficulty of obtaining small transverse tensile samples, a direct comparison with longitudinal tensile strength was not possible. Instead, the tubes were subjected to a hydrostatic burst test. In this test, the hydrostatic pressure is progressively increased until the tube wall yields and then fractures. This test is described in ASTM B 353 [15]. However, this test is not required for acceptance of alloy 740H welded tube and some aspects of the test were not compliant with B 353. It should be noted that B 353 specifies Barlow's formula for stress calculation. Duplicate or triplicate tests were conducted. A typical fractured test specimen is shown in Figure 3. In the welded tubes the fracture initiated in the base metal away from the weld. All of the fractures showed a ductile shear mode. The test data are shown in Table 5.

Figure 3. Burst test specimen. Location of the weld seam indicated by arrow.

Table 5. Burst test results

| Item | OD, in. | Wall,in. | Draw Sequence | Total Rd., % | Final Anneal °C(°F) | N | Burst Stress, MPa(ksi) | Failure Loc. |
|---|---|---|---|---|---|---|---|---|
| Welded | 1.000 | 0.065 | None | 0 | 1121(2050) | 3 | 1199(174.0) | Base Metal |
| " | 2.000 | 0.063 | None | 0 | 1121(2050) | 3 | 1053(152.8) | " |
| Redrawn | 1.000 | 0.080 | Sink | 42.5 | 1121(2050) | 2 | 1286(186.6) | Weld |
| Age hardening treatment 4 hr at 800°C(1472°F); Stress calculated using Lamé equation. | | | | | | | | |

Redrawn Tube Testing: As noted previously there were three different redrawing trial at Greenville Tubes with final annealing at RathGibson. Since the tube sizes and drawing methods varied, one can only draw general conclusions from the data reported in Table 6. All tubes met the ASME room temperature strength requirements, although the 0.375 in (9.5 mm) tubes had very high yield strength, and all of them passed destructive tests. Some tubes failed eddy current testing due to chatter marks from the drawing operation. No weld related defects were observed. After redrawing, the weld seam was no longer visible externally.

Table 6 Room temperature tensile properties of redrawn tubes.

| Trial / Pass | Method | Actual OD, in | Actual Wall, in. | Total Red. % | Final Anneal °C(°F) | N | 0.2% Offset YS, MPa(ksi) | UTS, MPa(ksi) | Elong., % |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Sink* | 1.0000 | 0.0800 | 42.5 | 1121(2050) | 2 | 696(101) | 1093(158.5) | 45 |
| 2 | Sink/Mandrel | 0.3750 | 0.0800 | 60.8 | 1148(2100) | 1 | 931(135) | 1144(166) | 35 |
| 3/1 | Sink | 1.7500 | 0.0590 | 19.6 | 1200(2192) | 2 | 696(101) | 1097(156) | 45.5 |
| 3/2 | Sink/Mandrel | 1.5000 | 0.0620 | 29.2 | " | 2 | 689(100) | 1093(158.5) | 46 |
| 3/3 | Sink/Mandrel | 1.3750 | 0.0560 | 40.5 | " | 2 | 679(98.5) | 1051(152.5) | 41 |
| 3/4 | Sink/Mandrel | 1.1250 | 0.0600 | 50.1 | " | 2 | 679(98.5) | 1075(156) | 42 |
| * ID honed | | | | | | | | | |
| Age hardening treatment 4 hr at 800°C(1472°F) | | | | | | | | | |

The microstructure of the 1 in (25 mm) welded tube in the in-line and off-line annealed conditions is shown in Figure 4a-b. The base metal grain size coarsened slightly from ASTM 7 in the starting strip to 6-7 in the in-line anneal and 2-3 in the off-line anneal. The weld metal grain structure is columnar after the in-line anneal, but substantially recrystallized after the off-line anneal. The 2 in (50 mm) tube had a similar weld structure and recrystallization response. The weld sound with no lack of fusion defects, porosity or liquation cracking. The weld nugget in the redrawn tube (Figure 4c) was compressed but still readily visible. There was little grain growth which is attributed to the presence of very fine carbides. These carbides and the grain structure could not be changed in laboratory higher temperature solution annealing heat treatments.

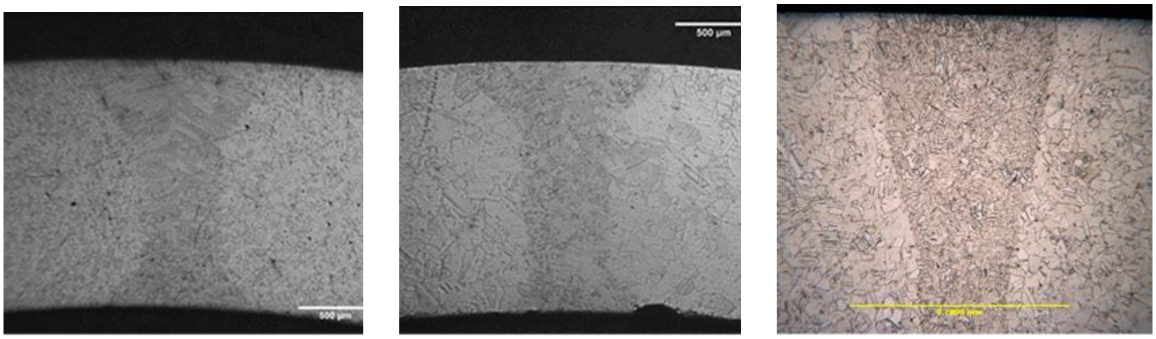

Figure 4. a) In-line anneal, b) Off-line anneal, c) Redrawn and off-line anneal

The weld hardness was explored with micro-hardness distribution maps shown in Figure 5a-b. These maps were created with a 2D grid of micro-hardness indentations using an automated micro-hardness machine with a 500 g load, 100 µm spacing and an indentation dwell time of 13 s. The data are plotted as a 2D color matrix using Origin software. The welded and off-line annealed tube showed an unusual hardness peak near the toe and toward one side of the weld. This may reflect higher residual stress due to closure pressure in the small diameter tube. The map for the redrawn and annealed tube discussed below shows a much more uniform hardness pattern in the weld although it was slightly elevated over that of the base metal.

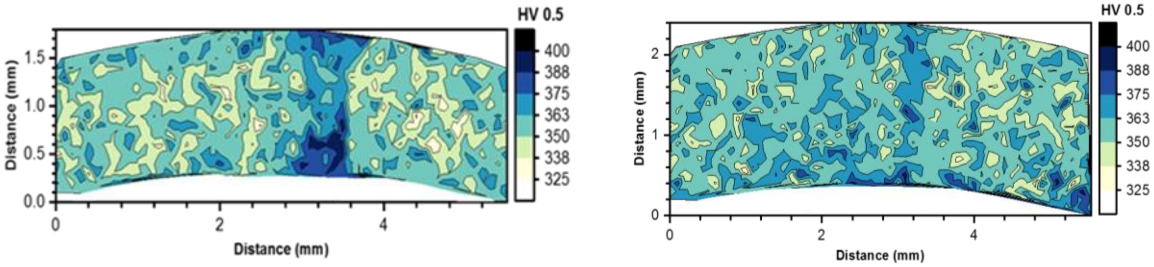

Figure 5. a) Welded plus off-line anneal, b) redrawn plus off-line anneal.

<u>Creep Rupture Testing</u>: As described previously, all creep testing on welded tube was done as pressurized tube tests. While these tests are on-going, the initial test results, presented in Figure 6, provide insight into the critical issues. The data for both welded and redrawn tubes fall short of the median composite data for 740H (tube, plate, and bar products). Both the 1in (25 mm) and 2 in (50 mm) tubes failed at the weld with relatively short life. A typical ruptured test piece is shown in Figure 7. Test completion was signaled by a loss of internal pressure. The crack in the view from the OD surface runs linearly along the fusion line. A cross-section of this crack along with higher magnification photographs is shown in Figure 8. While the through wall crack ran along the fusion boundary, small voids linking to cracks also formed on the opposite side of the weld nugget. This failure location may be associated with the sharp hardness change across the fusion line as shown in Figure 5. A few voids also formed in the weld metal. Only a few tests on the redrawn tubes have been completed to date. However, it is clear that redrawing does significantly improve creep strength. The failure location appears to be in the weld metal, but a detailed metallographic analysis has not been completed.

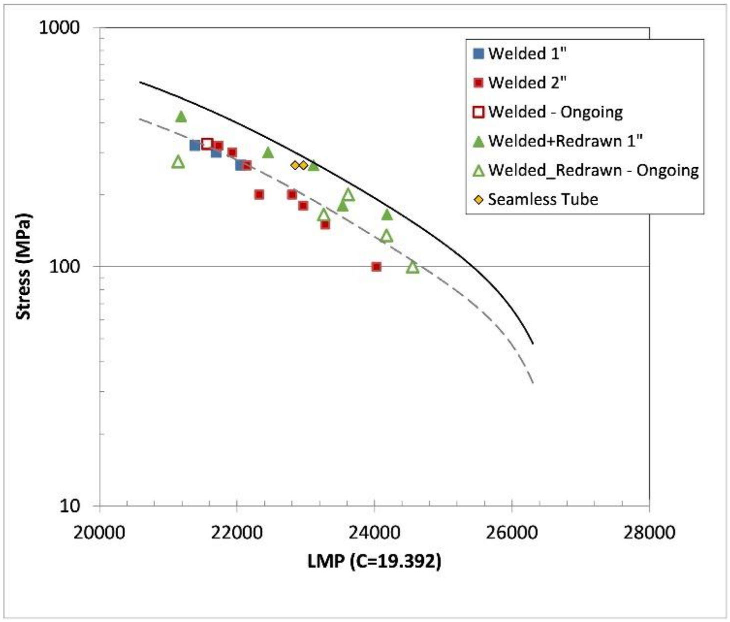

Figure 6. Creep rupture test data. Solid black line is median for base material.

Figure 7. Tube OD view of fractured creep specimen

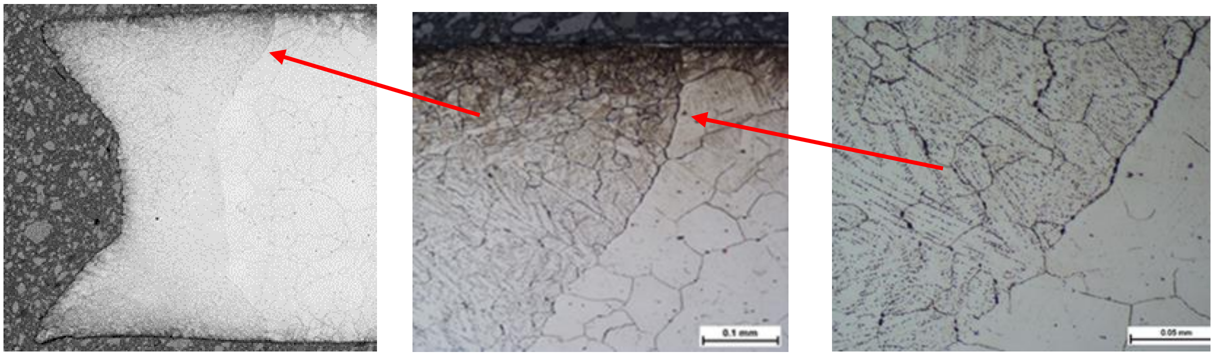

Figure 8. Three views of fusion line cracking opposite to creep rupture fracture plane.

Bending and fabrication: Most if not all CSP receiver system designs will require tube bending. Thin wall solar receiver tubes would generally be bent cold over a flexible insert. To test the cold bending of alloy 740H, four samples of 2 in (50 mm) diameter solution annealed tubes were supplied to Tebunus Tube Bending B.V. in Netherlands. This company has experience in bending alloy 230 which is commonly used for solar receivers. One tube was used to establish machine parameters. The bend radius was 6.7 in (170 mm) with an R/OD ratio of 3.35. Dimensional data provided by Tebunas are shown in Table 7. Tebunas reported that the material was harder to bend than alloy 230 but that after the initial test bend and machine parameter adjustments, it was not a problem for them. They further concluded that 740H could substitute for 230 without impact on the current design of the solar receiver. Selected photographs supplied by Tebunas are shown in Figure 9.

Figure 9. a) Bent tube samples, b) measurement fixture (Tibunas)

Table 7. Cold bending test data (Tibunas)

| Bend No | Item | Ovality, mm | | | Wall Thickness, mm | | |
|---|---|---|---|---|---|---|---|
| | | Max | Min | % | Straight | Extrados | Intrados |
| 1 | Trial | X | X | X | X | X | X |
| 2 | 90° | 50.85 | 49.68 | 2.33 | 1.63 | 1.5 | 1.79 |
| 3 | 90° | 50.53 | 49.63 | 1.8 | 1.62 | 1.46 | 1.78 |
| 4 | 90° | 50.89 | 49.61 | 2.55 | 1.62 | 1.48 | 1.8 |

Joining of thin-wall solar receiver tubing utilizes automated welding whenever possible. Automated welding has the advantages of repeatability and productivity along with the disadvantages of equipment cost and fit-up challenges. Autogenous automated butt welds had not been previously demonstrated on alloy 740H thin-wall welded tube. In this work, a Liburdi Dimetrics P300™ weld power supply with data logging was used with an L2000 orbital tube weld head. The welding head shown in Figure 10a can be adjusted to weld tube diameters of 0.25 in to 2.50 in.. Figure 10b shows one of over 50 tests conducted.

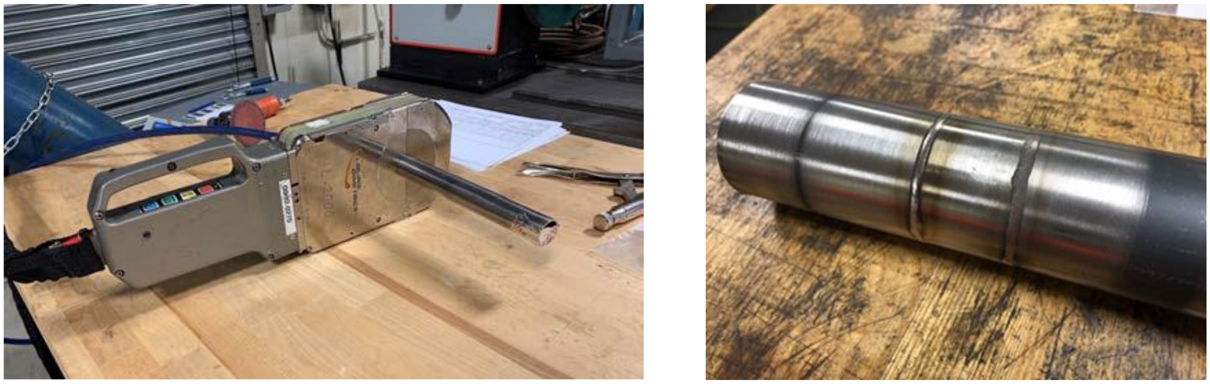

Figure 10. a) Welding head, b) Test specimen

Each weld was sectioned and viewed on a Keyence VHW-7000 digital microscope at 50X. Measurements included 1) OD reinforcement, 2) ID reinforcement, 3) width of weld bead cap, 4) undercut, 5) width of ID penetration, 6) depth of penetration, 7) OD surface misallignment, 8) ID surface misallignment, 9) axial misallignment. The welds were also rated for porosity and cracks. An image showing a typical test is shown in Figure 11.

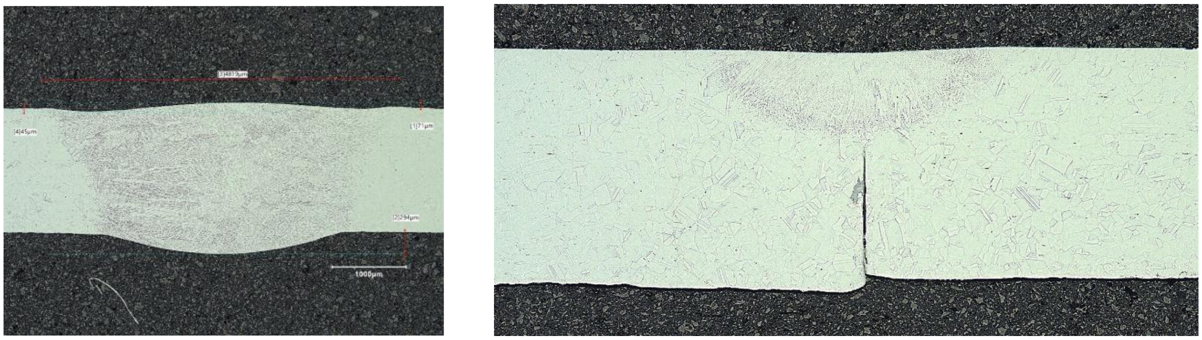

Figure 11. Automated tube welding test parameters recorded

Once the optimum parameters were selected, tubes were produced for destructive testing. Room temperature tensile tests included full size tests on 1 in OD tubes and cross-weld strips cut from the 2 in OD tubes. The test results are shown in Table 8. All of them exceeded the minimum properties for ASME Code Case 2702. Weld face bend tests also passed.

Table 8 Room temperature tensile test data

| Autogenous Gas Tungsten Arc Welded Tubes | | | | | | |
|---|---|---|---|---|---|---|
| **Test ID** | **Test Type** | **Test Temp** | **0.2% Yield, ksi** | **UTS, ksi** | **Elong., %** | **Failure Location** |
| **DOE503111001** | **1" Full size** | **Room** | **97.2** | **158.1** | **37.2** | **Fusion Line** |
| **DOE503111002** | **"** | **"** | **101.4** | **162.3** | **35.6** | **Fusion Line** |
| **DOE503011001** | **2" T-12** | **"** | **99** | **164.7** | **34.9** | **Base Metal** |
| **DOE503011002** | **"** | **"** | **94.4** | **154.7** | **30.8** | **Base Metal** |

<u>Welded Pipe Testing</u>: Swepco Tube performed both destructive (side bend and tensile) and non-destructive (sonic, radiographic and dimensional) testing on the pipe. Additional mechanical property and radiography testing were performed by Special Metals. Sonic testing was done by Inspection Services Group, Inc in Jackson N.J. to ASTM B 775, using a Sonatest Sitescan 350M unit. The reference standard containing U-notches of 10% of wall thickness was prepared by PH Tool Co in Pipersville PA. No rejectionable indications were found on sonic or radiographic testing; however, some centerline porosity was detected. Metallography showed these pores to be concentrated in the final weld layers and to be well within ASME porosity size limits. Photographs of the side bend specimens and weld cross section are shown in Figure 12.

Figure 12. a) Side bend test bars, b) Weld cross-section

Room temperature tensile and Charpy V-notch impact toughness properties were determined in the longitudinal and transverse directions in the base metal and the weld metal. All of properties met the ASME minimum requirements and were typical of alloy 740H bulk metal properties reported previously on plate and seamless pipe. These results are shown in Tables 9 and 10. No significant loss of toughness in the weld metal or heat affected zone was noted.

Table 9. Room temperature tensile properties

| Item | Location | Orientation | N | 0.2% Offset YS, MPa(ksi) | UTS, MPa(ksi) | Elong, % | RoA, % |
|---|---|---|---|---|---|---|---|
| Welded Pipe | Base Metal | Circumferential | 3 | 697(101.5) | 1114(161.5) | 40.4 | 40.2 |
| " | " | Longitudinal | 3 | 707(102.6) | 1117(162) | 39.6 | 39.5 |
| " | Weld | All Weld Metal | 3 | 743(107.9) | 1129(163.8) | 30.0 | 30.9 |
| " | " | Cross Weld | 3 | 702(101.9) | 1094(158.6) | 30.9 | 33.3 |
| Plate | Base Metal | Longitudinal | 1 | 731(106) | 1174(170.3) | 36.2 | 45.7 |
| Seamless Pipe* | Base Metal | Lonfitudinal | 1 | 786(114) | 1124(163.0) | NA | NA |
| * Seamless Pipe: 12.8 in* OD x 0.9 in. W, Solution Anneal 1121°C(2050°F), Age Harden 4 hr at 800°C (1472°F) | | | | | | | |
| Plate and Welded Pipe: Solution Anneal 1107°C(2025°F), Age Harden 4 hr at 800°C (1472°F) | | | | | | | |

Table 10. Charpy V-notch impact toughness test results.

| Location | Orientation | Ft. Lbs. | Joules | Jules/cm$^2$ |
|---|---|---|---|---|
| Base Metal | Longitudinal | 80 | 108.5 | 135.7 |
| " | Circumferential | 77.9 | 105.7 | 132.1 |
| Weld | Heat Affected Zone | 75.6 | 102.6 | 128.3 |
| " | Weld Center | 65.7 | 89.1 | 111.4 |
| Average of three tests | | | | |
| Solution Anneal 1107°C(2025°F), Age Harden 4 hr at 800°C(1472°F) | | | | |

The cross-weld stress rupture test results are presented in Figure 13. These tests are continuing, with some tests already exceeding 10,000 hours. The data are shown in Larson-Miller format in Figure 13a. The solid black line represents the mean of the base metal properties on which the ASME code case allowables were based. The dotted line represents the approximate creep strength of material in the welded and direct aged condition. The data show a clear benefit in creep strength provided by solution annealing after welding. The chart in Figure 13b shows that the solution annealed weld strength ratio is trending toward unity with increasing time. A more detailed assessment of this data will be made after the completion of the remaining tests. This analysis will form the basis of a new code case application.

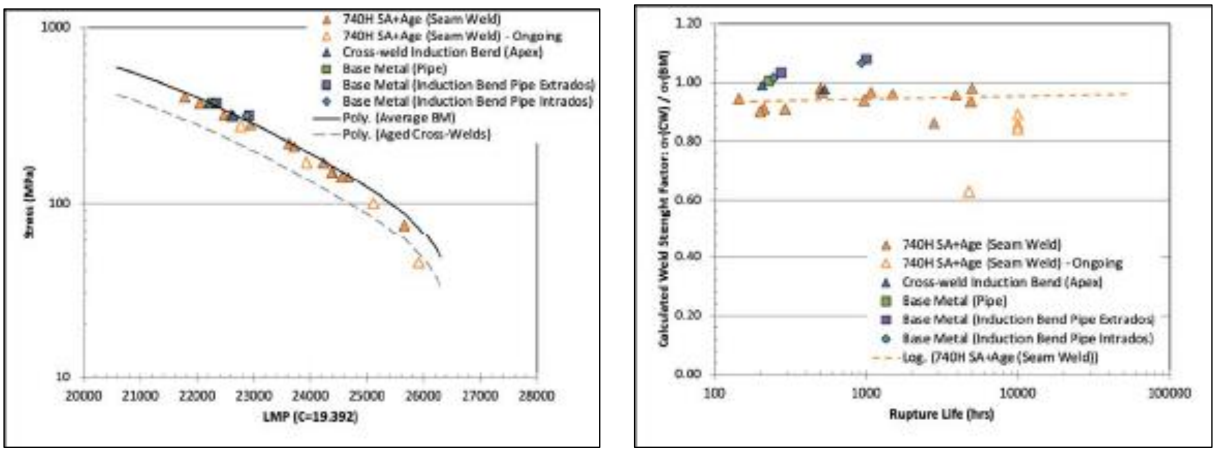

Figure 13. a) Creep rupture test results, solid line represents base metal properties; b) percent base metal strength as a function of rupture life.

The microstructure of the solution annealed and aged weld metal is shown in Figure 14 a,b. The weld metal was substantially recrystallized although it still retained the columnar solidification grain structure. No evidence of liquation cracking or lack of fusion was noted. A more detailed microstructure analysis of the fractured stress rupture samples will be conducted in the future.

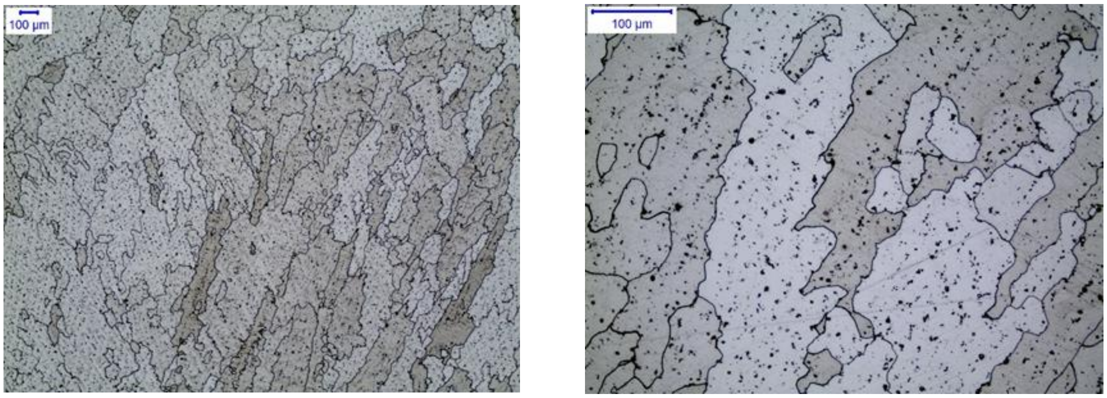

Figure 14. Microstructure of solution annealed and aged pipe weld.

Bend Testing: The induction bent pipe is shown is Figure 15a. The bend is smooth with no sign of buckling or external cracking. The extrados and intrados wall thicknesses were 0.709 in and 0.920 in respectively compared to the original pipe wall thickness of 0.800 in. No indications were visually noted. Since the weld was located at the neutral axis, it received a relatively small bending strain. However radiographic inspection revealed a branching crack on the ID surface that appeared to have initiated in the base metal and ran into the weld metal. The crack was located just after the stop of the bending process. This crack is shown in the radiographic image in Figure 15b. The initial metallographic investigation suggested that this crack was most likely a strain age crack that occurred during reheating of the pipe for solution annealing. The observation of cracking was unexpected since previous induction bends of seamless pipes exhibited no cracking [16]. This crack and potential causes and mitigation is being further investigated under a separate DOE funded program.

Figure 15. a) Completed pipe bend, b) radiographic image of ID crack.

The mechanical properties of the bent pipe are contained in Tables 11 (room temperature tensile), 12 (Elevated Temperature tensile), and 13 (Charpy V-notch impact). There is no significant difference between the properties in the three locations. Note that the strength is somewhat lower than that of the original pipe and plate. That difference is probably due to a difference in aging time and unrelated to the bending process itself.

Table 11. Room temperature tensile test data

| Location | Orientation | 0.2% Offset YS (MPa(ksi) | UTS, MPa(ksi) | Elong., % | R of A, % |
|---|---|---|---|---|---|
| Extrados | Longitudinal | 670(97.2) | 1104(160.2) | 40.2 | 42.8 |
| " | Circumferential | 659(95.6) | 1097(159.1) | 38.1 | 39.6 |
| Intrados | Longitudinal | 679(98.5) | 1102(159.8) | 39.8 | 38.3 |
| " | Circumferential | 685(99.3) | 1109(160.9) | 39.9 | 36.6 |
| Neutral/Weld | All Weld Metal | 722(104.7) | 1141(165.5) | 31.6 | 30.2 |
| " | Cross Weld | 686(99.5) | 1094(158.6) | 31.6 | 33.4 |
| Average of two tests | | | | | |
| Solution Anneal 1121°C(2050°F), Age Harden 788°C(1450°F) | | | | | |

Table 12. Elevated Temperature tensile test data

| Location | Orientation | Temperature, °C(°F) | 0.2% Offset YS, MPa(ksi) | UTS, MPa(ksi) | Elong., % | R of A, % |
|---|---|---|---|---|---|---|
| Extrados | Longitudinal | 650(1202) | 558(80.9) | 948(137.5) | 32.8 | 33.3 |
| | | 750(1382) | 586(85) | 820(119) | 21.0 | 22.6 |
| | | 850(1562) | 453(65.7) | 523(75.8) | 20.9 | 38.4 |
| Intrados | Longitudinal | 650(1202) | 566(82.8) | 933(135.4) | 31.5 | 30.9 |
| | | 750(1382) | 570(82.6) | 788(114.3) | 17.2 | 20.5 |
| | | 850(1562) | 461(66.9) | 538(78.1) | 18.9 | 26.9 |
| Neutral | Cross Weld | 650(1202) | 568(82.4 | 906(131.4) | 23.2 | 15.2 |
| | | 750(1382) | 576(83.5) | 787(114.1) | 16.6 | 15.3 |
| | | 850(1562) | 440(63.8) | 440(63.8) | 20.6 | 25.0 |
| Single test | | | | | | |
| Solution Anneal 1121°C(2050°F), Age Harden 788°C(1450°F) | | | | | | |

Table 13. Charpy V-notch impact test data.

| Location | Orientation | Ft. Lbs. | Joules | Jules/cm$^2$ |
|---|---|---|---|---|
| Extrados | Longitudinal | 84.6 | 114.7 | 143.1 |
| " | Circumferential | 70.9 | 96.1 | 120.2 |
| Intrados | Longitudinal | 71.5 | 96.9 | 121.2 |
| " | Circumferential | 64.9 | 88.0 | 110.0 |
| Weld | Heat Affected Zone | 73.3 | 99.4 | 124.3 |
| " | Weld Center | 62 | 84.1 | 1.5.1 |
| Average of three tests | | | | |
| Solution Anneal 1107°C(2025°F), Age Harden 4 hr at 800°C(1472°F) | | | | |

## Discussion

Thin-wall autogenous laser-welded tubing was manufactured on a commercial tube mill, continuously annealed and batch aged. Based on advice from industry experts, we believe that other tube mills in the US could successfully manufacture the product. While these trials covered only two OD x Wall combinations, with some tuning, the process should be applicable to the range of combinations normally produced for nickel-base alloys. The process should also be applicable to autogenous and filler wire GTAW processes. Mill quality tests and mechanical properties met the requirements of ASTM B 1007 and ASME Code Case 2702. However, creep-rupture strength as determined in an internally pressurized test was less than 70% of the nominal base metal strength. Creep fracture was primarily along the fusion line. Despite the fact that the welds were solution annealed twice, this result is no improvement over the properties of direct aged 740H welds. Based on a limited number of experiments, thermal treatments were ineffective in improving the rupture strength. The reason is uncertain but may relate to the stability of the very fine carbide particles in the weld metal that generate a steep hardness gradient at the fusion line. Because of this deficiency, greater emphasis in the project was devoted to redrawing technology.

Welded tubes were drawn to smaller size to refine the weld structure and to promote grain growth across the fusion line. Based on initial tests, redrawing significantly improved the creep strength. The percentage of base metal creep strength achieved will be determined in ongoing testing. The degree of improvement may be influenced by the intermediate annealing temperature and wall thickness reduction. Current specifications provide no guidance for minimum redrawing reduction or distinguish between sink and mandrel drawing. Pure sink drawing actually thickens the tube wall resulting in redundant work which may be less effective in refining the weld structure. While a light reduction may provide acceptable results for non-time dependent mechanical properties a larger reduction is probably needed to improve creep-rupture properties. Work currently underway will provide guidance.

Limited work was done in this project to demonstrate fabrication capability for welded and welded and redrawn tube. These included cold bending and automated GTAW butt welds. Alloy 740H tubing was reported to have forming characteristics similar to those of other strong nickel-base alloys. Autogenous butt welds met ASME Section IX requirements. Some welded and redrawn tube from this project was successfully incorporated into demonstration articles in other SETO funded Gen 3 CSP projects. These results will be reported separately by the investigators.

Welded pipe was manufactured on a commercial line by a GTAW process using a matching filler wire. Mechanical properties of the solution annealed and aged pipe met the requirements of ASME Code Case 2702. Solution annealed and aged cross-weld creep strength as measured with conventional cylindrical test bars was approximately 90% of nominal base metal strength. Welding processes that can be used for manufacturing welded pipe are limited to GTAW and GMAW. Previous work had shown that SAW, a process used by some welded pipe manufacturers, is not suitable for welding alloy 740H due to the loss of strength. Possible welded pipe OD, Wall and length dimensions are limited by several factors. The forming ability of the press brake limits the wall thickness to between 1-1/2 and 2 in (38-50 mm) due to the high strength of annealed 740H plate. The pipe OD is limited to approximately 32 in (813 mm) by the maximum width alloy 740H plate can be rolled to on the Special Metals reversing mill. It may be possible to roll a wider plate at a steel mill. The maximum length of approximately 20 ft is set by the capability of the press brake at the welded pipe mill. Several welded pipe mills in the US have the capability to manufacture the product.

The welded pipe was bent 90° with 3D radius with the weld at the neutral axis using a conventional induction bending machine. Mechanical properties in the intrados and extrados of the bend met ASME code requirements. A crack on the ID surface originating away from the weld was found after heat treatment. This crack was located just outside the bend area. It is thought to have occurred during reheating of the pipe for the solution annealing operation. This is an area that is believed to have high biaxial residual stress. A second bend using the same process conditions did not reproduce the cracking. Based on experience, cracking is most likely to occur in pipes with large OD/W ratios or in very heavy wall pipes. A separate DOD funded project is developing a process model that will be able to simulate stresses in induction bending of age-hardened nickel-base alloys. Much larger and heavier wall 740H pipes have been induction bent under the DOE AUSC ComTest project. Based on this experience, it is concluded that any size of welded 740H pipe could be physically bent with the caveat that very thin wall pipes may be susceptible to strain age cracking. To date successful induction bends have been made in alloy 740H at four different companies. It is concluded that there is adequate bending capability to supply the power industry.

The project demonstrated that within the applicable size ranges, seam welded tube and pipe meeting spec and code requirements can be manufactured. The project was initiated on the premise of the industry rule of thumb that welded tube and pipe should be about 30-40% lower manufacturing cost compared to seamless tube and pipe. Even greater cost reductions would apply to very small diameter thin wall tubes. The results of this work show that to also be true for 740H. No manufacturing issues were encountered that indicate hidden cost factors specific to the alloy. The possible size ranges of seamless and welded tube and pipe do not perfectly overlap so comparing costs for a specific size can be misleading. For this reason, the project developed a cost model that incorporates the many factors that influence costing for piping applications. These include the cost of raw materials, tube processing, alloy density and design stress allowables which vary with service temperature. This model will be contained in the final publicly available DOE contract report.

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