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DEVELOPMENT AND APPLICATION OF INCONEL® ALLOY 740H IN USCO2 POWER SYSTEMS

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ABSTRACT

Nickel-base alloys are required for many of the high pressure components in advanced ultra-supercritical steam and CO_2 power systems operating at temperatures and pressures exceeding 650°C and 25 MPa. Age-hardened alloys offer a distinct advantage over traditional solid solution strengthened Nickel alloys and stainless steels by virtue of their significantly higher creep strength. This makes it possible to reduce wall thickness and thereby minimize total construction cost. INCONEL® alloy 740H (UNS N07740) is an age-hardened alloy that was developed and extensively characterized for advanced ultra-supercritical steam boilers. Extensive material testing 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 applications for supercritical CO_2 systems. Various laboratories have reported on oxidation properties of the alloy under simulated operating conditions. This paper reviews the mechanical and corrosion properties of the candidate materials and focuses on the manufacturing and properties of piping products that are being applied for the various advanced ultra-supercritical steam and supercritical CO_2 projects now planned or underway. As many of the structures are constructed by welding, a review of welding practices is presented, including dissimilar welds and their properties.

INTRODUCTION

Many of the planned advanced sCO_2 energy conversion systems are projected to operate at temperatures above 700°C. This is above the temperature capability of ferritic stainless steel and austenitic steels that have greatly reduced strength that would require impractical wall thickness to contain high pressure fluids. Solid solution strengthened nickel-base alloys such as 800HT, 230 and 617 have been used successfully in chemical process, energy and aerospace industries for many years; however, at the high pressures projected for many applications, impractically thick walls would be required for these materials as well [1]. For this reason, high strength age hardened alloys were evaluated for service, initially in a succession of European programs, then the US Advanced - Ultra Supercritical (A-USC) Consortium and then by advanced energy programs around the world. Alloy 740 (UNS N07740) was specifically developed under the THERMIE program for boiler tube for coal fired power plants [2]. The alloy featured high strength, sufficient ductility for fabrication into tube, weldability and resistance to oxidation and coal ash corrosion. Later the US program considered it for use in headers and reheat pipes. For this application better microstructure stability and heavy section weldability was needed. The alloy composition was subsequently optimized to improve these properties [3]. The optimized alloy, called 740H, fell within the original broad alloy definition. The composition of the optimized alloy is shown in Table 1.

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 [4-6] and culminated in submission of a data package that led to the ASME Code case 2702 [7]. Alloy 740H is the first age-hardened alloy to be accepted for fabrication of pressurized equipment. The advantage for alloy 740H in the temperature range of current

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TABLE I. MAXIMUM, MINIMUM AND NOMINAL OF PRIMARY COMPOSITIONAL ELEMENTS OF ALLOY 740H.

Max/Min/Nominal	Ni	Fe	Cr	Co	Mo
Max	Bal	3.0	25.5	22	2.0
Min	Bal	---	23.5	15	---
Nominal	Bsl	0.25	24.5	20	0.5
Max/Min/Nominal	**Al**	**Ti**	**Nb**	**Si**	**C**
Max	2.0	2.5	2.5	1.0	0.08
Min	0.2	0.5	0.5	---	0.01
Nominal	1.4	1.4	1.5	0.15	0.03

interest for advanced power plants is shown in Figure 1 (values for alloys 617 and 800HT from ASME BPVC Section II, Materials, Part D, Properties, Table 1B; values for alloy 740H from ASME code case 2702). The rules of the current code as they apply to fabrication of complex systems will be discussed in this paper. Following Code approval, Special Metals working with 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 [8-9].

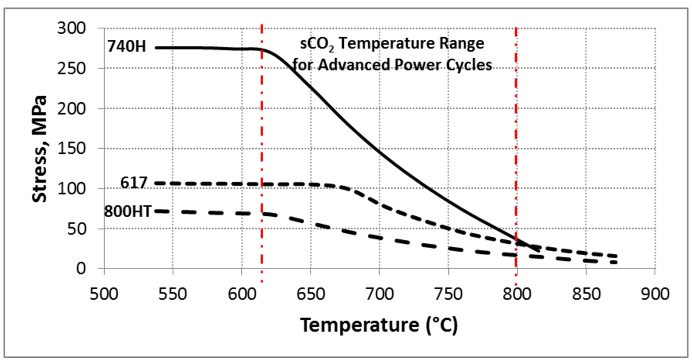

FIGURE 1. ASME MAXIMUM ALLOWABLE STRESS FOR ALLOYS 740H, 617 AND 800HT.

Age-hardened alloys have characteristics that are very desirable for power plant use. They are relatively soft and formable in the solution treated condition. In this condition they can be rolled and drawn to form sheet and tube, and tube can be cold formed by bending. Subsequently the components are again solution treated and aged. Direct aging of cold formed parts is restricted due to a loss of creep strength. Alloys of this type can be welded successfully although strict protocols must be followed and high energy processes cannot be used. Concerns about use of age-hardened alloys in this application include long time microstructure stability (> 100,000 h. at temperature), impact toughness, creep, creep-fatigue, over temperature damage tolerance and strain-aging and stress relaxation cracking of welds. Understanding of the issues is being developed through continued laboratory work, component manufacture, and in-plant test loops and pilot plants. The following discussion presents recent developments using alloy 740H.

Although alloy 740H was developed under A-USC programs, in recent years it has been considered for sCO_2 service as well. Although A-USC in-plant test loops to gain fabrication and operating experience have been installed [10] to date a full operating system has not yet been constructed. In the interim sCO_2 programs have advanced including Sunshot [11] and Supercritical Transformational Electric Power (STEP) [12].

RESULTS AND DISCUSSION

Mechanical properties

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 in codes between tube and pipe on the basis of fabrication methods, for 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. While there is considerable size overlap between the two products, tube tends to lie at smaller diameters and thinner wall product. There also is an inherent grain size difference between tube and pipe with tube having a much wider possible range of ASTM #3-8. In the case of pipe the grain size may be ASTM #1-5 depending on pipe size. Grain size in as extruded pipe can be more difficult to refine due to the relatively high temperatures required for the extrusion operation. Generally alloy 740H will be producible over the standard range of nickel alloys. Tube has been produced by both drawing, pilgering and roll forming processes. Pipe has all been produced by extrusion on presses at Special Metals (Huntington, WV and Hereford, UK) and Wyman-Gordon (Houston, TX and Livingston, UK)

TABLE 2. TYPICAL ROOM TEMPERATURE MECHANICAL PROPERTIES FOR VARIOUS SOLUTION ANNEALED AND AGED PRODUCT FORMS OF ALLOY 740H.

Product Form	0.2% PS MPa	TS, MPa	El. %
Pipe	728 - 741	1083 - 1094	31 - 34
Tube	731 - 769	1153 - 1174	33- 42
ASME 2702	**620 min.**	**1035 min.**	**El. 20 % min**

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Mechanical properties have been extensively evaluated and documented in the literature (3-7, 10). Generally additional production has confirmed the data used in the data package submitted for ASME code approval. The ASME specified heat treatment for 740H is a solution anneal at (1100°C) (2010°F) minimum and aging at 760-816°C (1400-1500°F).

Microstructure and stability

Many superalloys undergo microstructural changes if they are held for long periods of time at elevated temperatures. These changes may include formation of complex carbides, growth of γ′ and the formation of a variety of topological close-packed (TCP) phases including Laves and sigma. These phases may form undesirable morphologies that reduce ductility and toughness. In the application of superalloys for power plant use it is necessary to demonstrate that they will be stable for the design lifetime of the plant. To evaluate the microstructural stability of 740H, material obtained from commercially produced pipe was exposed stress-free for times up to 10,000 h at 700°C (1292°F), 750°C (1382°F) and 800°C (1472°F). Longitudinal Charpy V-notch impact tests were conducted and the microstructure was analyzed in detail. The results of this investigation reported by deBarbadillo [13], are shown below in Figure 2. This high temperature exposure study demonstrate the material shows some loss of ductility as carbides form on the grain boundaries, however the material retains an adequate level of impact strength after 10,000hrs.

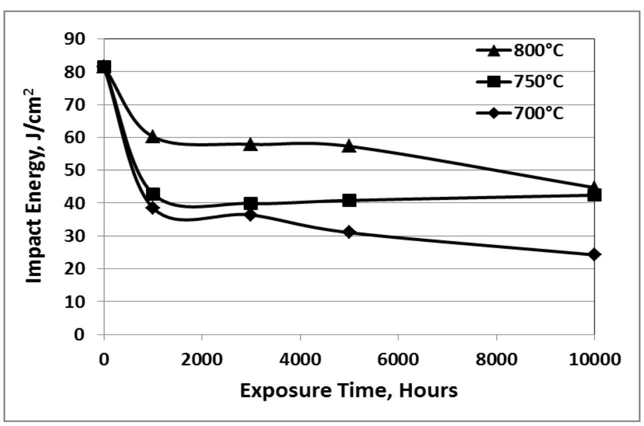

FIGURE 2. CHARPY IMPACT TOUGHNESS AFTER HIGH TEMPERATURE EXPOSURE FOR TIMES UP TO 10,000 HOURS

A representative scanning electron micrograph (SEM) of material in the as heat treated condition is shown in Figure 3. The grain interiors show a uniform fine γ′ precipitate. The grain boundaries are almost completely covered with $M_{23}C_6$ and coarse γ′. Material exposed for 5,000 h at 750°C (1382°F) is shown in Figure 4. Note that the γ′ has grown significantly, but it continues to maintain a generally cubic morphology. Larger chunky γ′ decorates the grain boundaries. Most of the remaining grain boundary area is covered by $M_{23}C_6$ carbide. No evidence of η or G phase. Sigma phase is predicted by Thermo-Calc to form at 650°C (1202°F) in this alloy at very long exposure times, but to date, it has not been reported. Creep deformation sometimes accelerates microstructural changes by providing enhanced diffusion and nucleation sites. Based on limited observations this does not seem to be the case for 740H. Figure 5 shows the structure near the fracture surface of a specimen tested at 750°C (1382°F) with an initial applied stress of 280 MPa (40.6 ksi) that broke in 1087.4 h. The structure is similar to the starting structure, but a chain of grain boundary voids is visible. Test bar fracture occurs by linking of these voids. There was no sign of a precipitate-free zone adjacent to the grain boundary although this feature has been observed in welds of 740H.

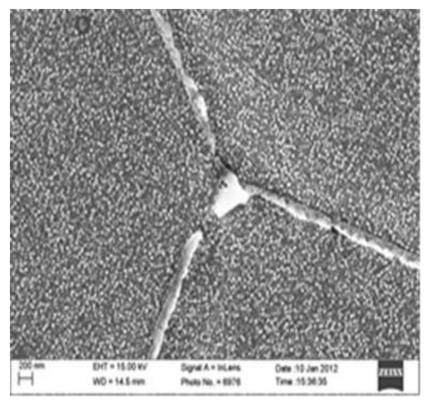

FIGURE 3. SEM MICROGRAPH SHOWING SOLUTION ANNEALED AND AGED MATERIAL

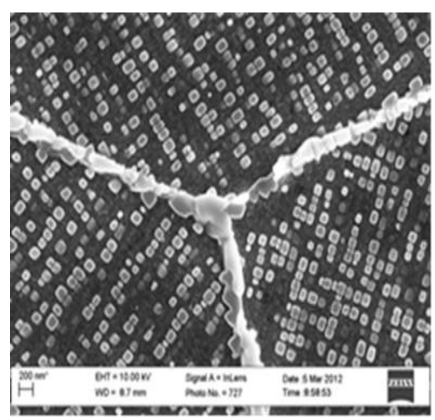

FIGURE 4. SEM MICROGRAPH SHOWING SOLUTION ANNEALED AND AGED MATERIAL AFTER 5000HRS EXPOSURE AT 750C

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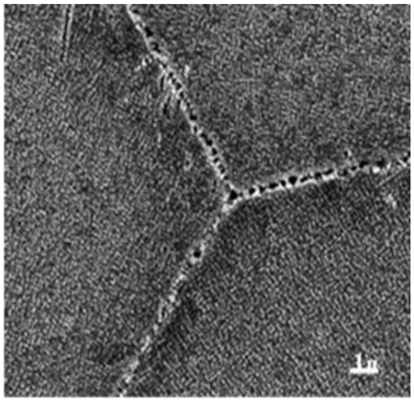

FIGURE 5. SEM MICROGRAPH SHOWING REGION NEAR FRACTURE FACE OF A CREEP RUPTURE SPECIMEN FAILED AT 1087.4 H AT 750C AND 280 MPA

Corrosion in supercritical carbon dioxide

The Brayton cycle system, using supercritical carbon dioxide as the working fluid, is being used and developed for use in various power generation systems, including nuclear, solar, and fossil/biofuel. This system provides a means of achieving very high levels of efficiency when compared with using a steam power cycle. The University of Wisconsin-Madison has devised an apparatus to evaluate the corrosion behavior of metal samples in high high-pressure carbon dioxide at temperatures up to 650°C(1202°F) [14]. The results indicate that 740H has a very low rate of mass gain at temperatures up to 650°C. More recent work by Kung et al at EPRI at 700°C and 200 bar on alloy 740H has shown only very thin oxide scales of 1 um develop after exposures of up to 5000 hours in CO2 containing 3.6% vol O2 and 5.3% vol H2O [15].

Manufacturing Demonstration

Tube has been made in alloy 740H by extruding billet, cut from forged bar, to tube shell and cold working to size using multiple cold work and anneal cycles. This tube process is similar to that used for other "hard" alloys such as 625 and 718.

Large pipe of 740H sections have been extruded at Wyman-Gordon Houston TX. This 378 mm OD x 88 mm W x 10.5 m L pipe is shown in Fig 6. A 762 mm diameter VIM/VAR Ingot was used for this extrusion. VAR was selected as the remelt step in order to minimize the risk of solidification segregation. Excellent chemistry uniformity and microstructure was obtained. The detail for this work has been reported previously [13].

FIGURE 6. HEAVY WALL 740H PIPE EXTRUSION.

Welding

Fusion welding is an essential joining method for power plant construction. Welding studies on alloy 740H showed that it could be readily welded by GTAW and GMAW processes with good operability, tensile and bend properties. Successful girth welds were made on superheater tubes. Alloy 740H has excellent resistance to liquation cracking while retaining the operability characteristics of the original alloy. An SMAW electrode is not currently available for alloy 740H due to the difficulty of transferring Al and Ti through the flux. Alloy 263 fluxes have been developed and it is expected that SMAW capability will be adopted into the ASME code case 2702.

Process parameters have been optimized by making butt welds on restrained 75 mm (3 in) thick plates and these parameters were then used to make circumferential welds on 378 mm (14.9) OD x 88 mm (3.46 in) wall extruded, solution annealed and aged pipe. The welds were made using a hot-wire narrow-groove GTAW process with a fixed torch and rotating work piece. Argon-25% He was used as the shielding gas for the matching composition filler wire. Welds were made with 5, 2, and 1 degree beveled V-grooves with a 1.57 mm (0.062 in) land. A cross-section of a weld with a 1 degree bevel is shown in Figure 7. Note that the entire weld of 33 passes is one bead wide. The full pipe section was aged per ASME code requirement for 5 h at 800°C (1472°F) using a ceramic tile heating blanket. This method is commonly used for post-weld heat-treatment of field welds. No fissures, porosity or cracking were detected with ultra-sonic, radiographic or microscopic examination. Details of microstructure and weld qualification properties have been previously been reported [16]. Key requirements for successful heavy section 740H welds are 1) use of proper shielding gas, 2) careful management of heat input and inter-pass temperature, 3) maintenance of correct bead geometry, and 4) frequent removal of residual surface oxides.

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FIGURE 7. MACROGRAPH OF 88MM THICK PIPE SECTION WELDED WITH HOT WIRE-GTAW.

FIGURE 8. SIMULATED FABRICATION OF A HEAVY WALL PIPE HEADER.

Once it was determined that sound welds could be made in heavy-wall pipe, a full scale header section was fabricated. For this simulated header, the nipples were inserted in predrilled holes and GTAW welded on the inside with a special rotary torch. The external welds were made manually by GTAW. This prototype header section is shown in Figure 8.

The alloy 740H will need to be joined to ferritic steels, austenitic stainless steel and other nickel alloys in various parts of the heaters, recuperators or to the turbine Work by several fabricators is underway to evaluate dissimilar metal welds. Work by Moody et al [17] and Baker et al [18] showed the development alloy 740H pipe welds to 316H and P92 steels. Restrained, V-groove plate welds were made using GTAW (FM 82, P87 and 617) and SMAW (WE 182 and P87). The 740H was in the aged condition and welds were stress relieved for 4 h at 775°C. All combinations produced sound welds and all except SMAW with WE P87 passed ASME tensile and bend qualification requirements with failure in the steel base metal. Creep, stress relaxation and fatigue tests were used to generate data for an FEA analysis of the high temperature joint design.

FIGURE 9. WELDING TRIAL DEMONSTRATING PIPE JOINT BETWEEN 316H, 740H AND P92.

NOMENCLATURE

A-USC = Advanced-Ultrasupercritical

EPRI = Electric Power Research Institute

ASME = American Society of Mechanical Engineers

ASTM = American Society for Testing and Materials

GTAW = Gas Tungsten Arc Welding

GMAW = Gas Metal Arc Welding

SMAW = Shielded Metal Arc Welding

UNS = Unified Numbering System

VIM = Vacuum Induction Melting

VAR = Vacuum Arc Remelting

ESR = Electro-slag Remelting

OD = Outside Diameter

ID = Inside diameter

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