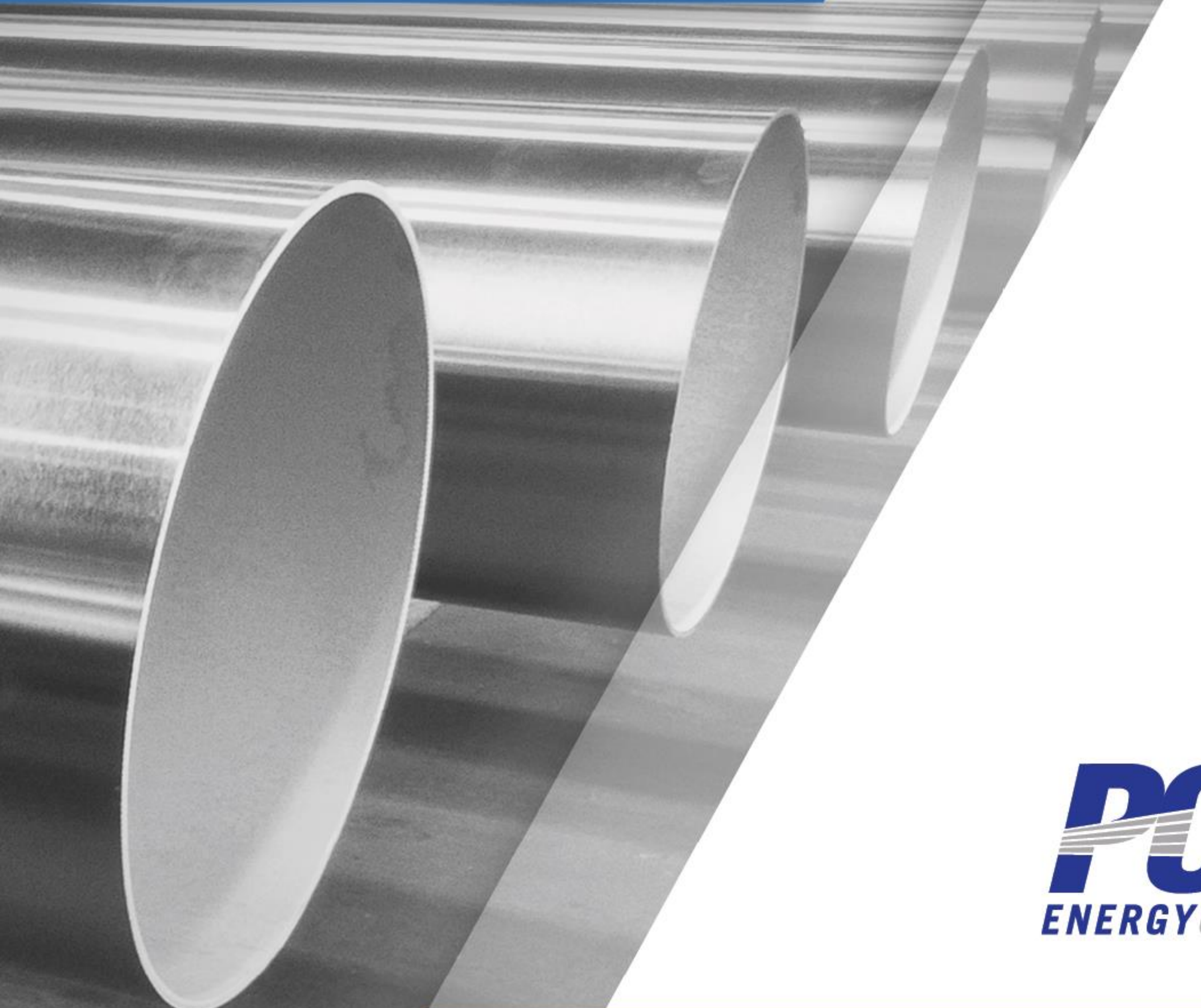
INCONEL® ALLOY 740H ®

A Superalloy Specifically Designed

For Advanced Ultra Supercritical

Power Generation



CONTENTS

Introduction

As the world's demand for electrical power increases, governments also demand that emissions be strictly controlled to minimize the greenhouse effects of society's carbon footprint. Despite that situation, coal, oil and gas continue to be the major fuels for power generation facilities. While nuclear, gas turbine, solar and wind generation are expected to increase, coal is still predicted to fuel 37% of the world's electrical generating capacity in 2035.[1] Thus, there is a strong impetus for development of cleaner, more efficient power generation. The efficiency of fossil fuel-fired boilers increases with operating temperature and pressure. There have been progressive increases in these conditions for boiler design culminating in advanced ultra-supercritical (A-USC) technology. A-USC boilers are expected to offer levels of generation efficiency over 50%(HHV) and their operation is such that carbon-base emissions can be readily collected and sequestered.

Programs to develop A-USC capability are currently active around the world. Since A-USC plants will operate at higher temperatures (700° to 760°C) and pressures (up to 35 MPa), nickel-base superalloys are required to meet the rigors of strength and corrosion resistance. INCONEL® alloy 740H® was developed specifically to operate under these demanding service conditions.

Applications

INCONEL alloy 740H is a nickel-base, precipitation hardenable superalloy that offers a unique combination of high strength and creep resistance at elevated temperatures along with resistance to coal ash corrosion. The alloy was originally targeted for use as A-USC boiler tubes in the superheater sections of these plants but was then adapted for application as a material for the steam headers to which the boiler tubes are connected. A-USC boiler tubes are conventional sizes [typically 1.5 to 3 inch (38 to 76 mm) outside diameter]. Main steam header pipe sizes occupy a much larger size range, with outer diameter greater than 12 inches (305 mm) and wall thickness likely exceeding 1.5 inches (38 mm). Seamless steam reheat piping, at up to 30 inch (760 mm) outer diameter, is also a feasible product line with INCONEL alloy 740H.

Chemical Composition

INCONEL alloy 740H (UNS N07740) is derivation of NIMONIC alloy 263. With its higher content of chromium (24.5%), alloy 740H offers a significant improvement is resistance to high temperature corrosion mechanisms. Alloy 740H is age hardened by the precipitation of a second phase, gamma prime (γ'). By balancing the hardener content (niobium, aluminum and titanium), alloy 740H exhibits good thermal stability in addition to high strength.

Nominal and limiting chemical composition ranges for alloy 740H are reported in Table 1.

Table 1
INCONEL alloy 740H
Limiting Chemical Composition Limits

Element	Cr	Co	Al	Ti	Nb*	Fe	C	Mn	Mo	Si	Cu	P	S	B	Ni
Min.	23.5	15.0	0.2	0.5	0.5	---	0.005	---	---	---	---	---	---	0.0006	Bal
Nom.	24.5	20	1.35	1.35	1.5		0.03		0.1	0.15					
Max.	25.5	22.0	2.0	2.5	2.5	3.0	0.08	1.0	2.0	1.0	0.50	0.03	0.03	0.006	---

Metallurgy & Microstructure

Alloy 740H exhibits an austenitic structure and is age hardened by the precipitation of a gamma prime (γ') $Ni_3(Al,Ti,Nb)$ phase. During heat treatment, niobium, aluminum, and titanium form the gamma prime precipitates required for strengthening. The microstructure of alloy 740H extruded pipe in the solution annealed and aged condition is seen in Figure 1. Second phases observed in this condition include primary carbo-nitrides of the (Nb,Ti)(C,N) type, $Cr_{23}C_6$ type carbides, and gamma prime. Additional exposure across the temperature range anticipated for A-USC service serves simply to modify the relative amounts of these same phases. Figure 2 shows an SEM image of the microstructure of INCONEL alloy 740H after solution annealing followed by exposure for 5,000 hours at 1380°F (750°C).

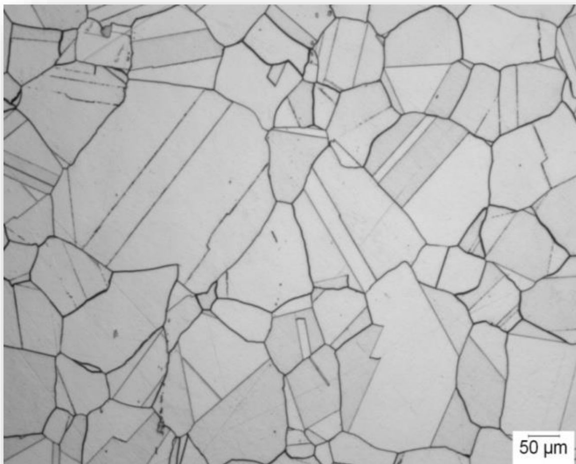


Figure 1 – Microstructure of solution annealed and aged INCONEL alloy 740H pipe. ASTM No. 3 Grain Size - 200X magnification – Kallings reagent etch.

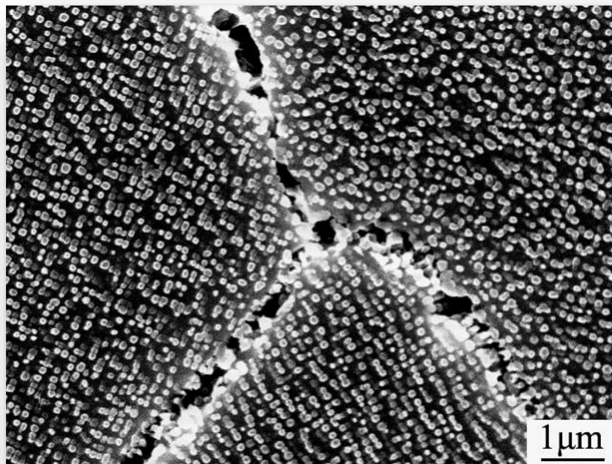


Figure 2 – Microstructure of INCONEL alloy 740H after 5000 hours at 1380°F (750°C). SEM analysis reveals individual gamma prime particles and grain boundary carbides.

Physical Properties

Some physical constants for INCONEL alloy 740H are listed in Table 2. Values for modulus of elasticity for annealed and aged material at various temperatures are shown in Table 3. Thermal properties of annealed material are given for a range of temperatures in Table 4.

Table 2 – Physical Constants

Density, g/cm^3	8.05
lb/in^3	0.291
Melting Range, °C	1288-1362
°F	2350-2484
Electrical Resistivity, Ω-circ mil/ft	702.7
µ Ω -m	1.168

Table 3 – Modulus of Elasticity

Temperature, °F	Modulus of Elasticity, Tension, 10^3 ksi
72	32.0
200	31.6
400	31.9
600	29.8
800	28.7
1000	27.7
1200	26.4
1400	25.1
1600	23.4
°C	**GPa**
22	221
100	218
200	212
300	206
400	200
500	193
600	186
700	178
800	169
900	158*

*Extrapolated value.

Table 4 – Thermal Properties

Temp.	Thermal Conductivity	Coefficient of Expansion[a]	Specific Heat
°F	Btu-in./ft^2-h-°F	10^{-6}in./in./ °F	Btu/in-°F
73	72.9	-	0.108
200	79.9	6.84	0.112
400	90.9	7.25	0.117
600	102.0	7.53	0.119
800	113.3	7.80	0.120
1000	124.9	7.96	0.121
1200	136.9	8.24	0.126
1400	149.3	8.61	0.133
1600	162.1	8.88	0.143
1800	175.6	-	0.152
2000	189.6	-	0.155
2100	196.9	-	0.152
°C	**W/m-°C**	**µm/m °C**	**J/kg-°C**
23	10.2	-	449
100	11.7	12.38	476
200	13.0	13.04	489
300	14.5	13.50	496
400	15.7	13.93	503
500	17.1	14.27	513
600	18.4	14.57	519
700	20.2	15.03	542
800	22.1	15.72	573
900	23.8	15.81*	635
1000	25.4	-	656
1100	27.3	-	669
1150	27.9	-	669

[a]Mean coefficient of linear expansion between 73°F (23°C) and temperature shown.
*Extrapolated value

Mechanical Properties & High Temperature Strength

INCONEL alloy 740H exhibits high strength and metallurgical stability at elevated temperatures. Tensile properties of extruded, solution annealed and aged piping in the transverse and longitudinal orientations are shown in Table 5. Table 6 shows the effects of aging temperature and time upon the room-temperature tensile properties of hot-rolled and solution annealed plate.

Table 5
Tensile Properties of Extruded, Solution Annealed and Aged 8.071" (205mm) ID, 2.854" (72.5mm) Minimum Wall Pipe

Test Temperature °F (°C)	0.2% Yield Strength, Ksi (MPa)	Ultimate Tensile Strength, Ksi (MPa)	Elongation %	Reduction of Area %
Transverse Orientation				
Room Temp.	105.0 (724)	154.6 (1066)	23.7	28.1
1292°F (700°C)	82.2 (567)	124.9 (861)	17.0	23.1
1337°F (725°C)	85.4 (589)	125.0 (862)	22.8	37.4
1382°F (750°C)	86.4 (596)	118.6 (818)	23.9	28.7
1424°F (775°C)	80.8 (557)	110.1 (759)	22.1	30.7
1472°F (800°C)	86.2 (594)	100.2 (691)	23.5	31.2
Longitudinal Orientation				
Room Temp.	107.7 (742)	164.4 (1133)	24.3	39.8
1292°F (700°C)	88.2 (608)	132.3 (912)	31.9	35.7
1337°F (725°C)	87.0 (560)	126.3 (871)	28.4	34.4
1382°F (750°C)	83.5 (576)	118.2 (815)	22.9	24.0
1424°F (775°C)	81.8 (564)	111.1 (766)	27.9	37.1
1472°F (800°C)	79.3 (547)	100.0 (689)	31.5	40.9

Note: All specimens were tested in the solution annealed + aged condition.
Solution Anneal = 2050°F/WQ; Age = 1472°F/5hrs/AC

Tensile properties at ambient and elevated temperatures of cold drawn, annealed and aged boiler tubes were determined. The tubes were annealed at 2125°F (1120°C) and aged at 1472°F (800°C) for 4 hours. Results are seen in Figure 3.

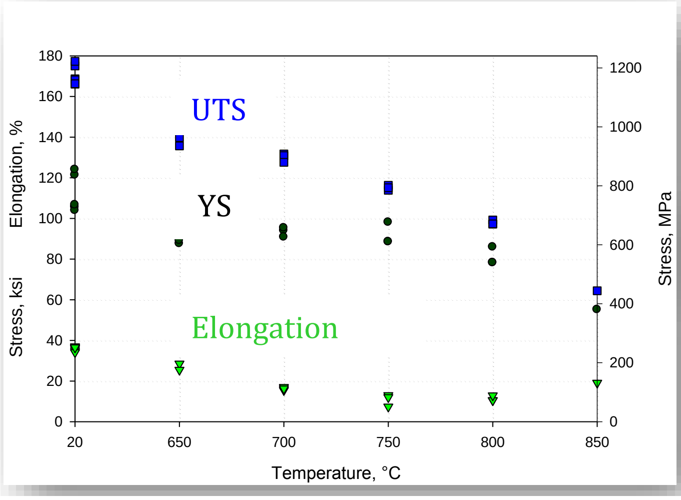


Figure 3 – Tensile Properties of cold drawn, solution annealed, and aged INCONEL alloy 740H boiler tubing.

Table 6 **Aging Response of Hot-Rolled/Solution Annealed Plate Room Temperature Tensile Properties**				
0.2% YS, ksi	**UTS, Ksi**	**Elongation %**	**Red of Area, %**	**Aging**
107.0	160.0	35.3	40.8	760°C/4hr/AC
113.4	165.1	32.8	36.7	760°C/8hr/AC
109.0	167.5	30.4	36.9	760°C/16hr/AC
111.6	163.7	32.5	38.7	800°C/4hr/AC
109.5	168.0	30.4	36.3	800°C/8hr/AC
110.6	165.1	27.4	27.6	800°C/16hr/AC

Stress rupture plots for alloy 740H between 1290°F (650°C) and 1427°F (850°C) are seen in Figure 4. Trend lines through the data were generated using the following polynomial equation published by J. P. Shingledecker[2]:

$$\log(t_r) = -C + \frac{A_1}{T} + \frac{A_2 \log(\sigma)}{T} + \frac{A_3 \log(\sigma)^2}{T} + \frac{A_4 \log(\sigma)^3}{T}$$

Having the following constants:

C	19.392
A1	23360
A2	5532
A3	-2065
A4	-102.7

Data represented include cold-worked solution annealed and aged superheater tubing as well as hot-extruded solution annealed and aged steam header piping, forged, solution annealed and aged bar, and hot-rolled, solution annealed and aged plate.

Codes and Specifications

INCONEL alloy 740H is designated UNS No. N07740 which also defines its chemical composition limits. Properties of seamless tubular products are specified in ASTM B983.

Alloy 740H is approved by the ASME Boiler and Pressure Vessel Code for Section I construction (Power Boilers) by Code Case 2702, and for construction under ASME B31.1 by Code Case 190. Allowable stresses are defined for operating temperatures from ambient to 800°C (1472°F). The allowable stresses for alloy 740H are compared to those for alloy 617 in Figure 5.

Figure 6 shows a piping size comparison between alloys 617 and 740H, showing the material savings that can be gained, firstly for a system having two main steam and reheat lines, whereby the quantity of alloy 740H required to construct these pipes is one-half of that required for alloy 617. In addition, the flow stress of alloy 740H is significantly lower at extrusion temperatures (Figure 9) and therefore a single pipe system for a plant size in the range of 600 MW would be feasible for alloy 740H, but not for alloy 617.

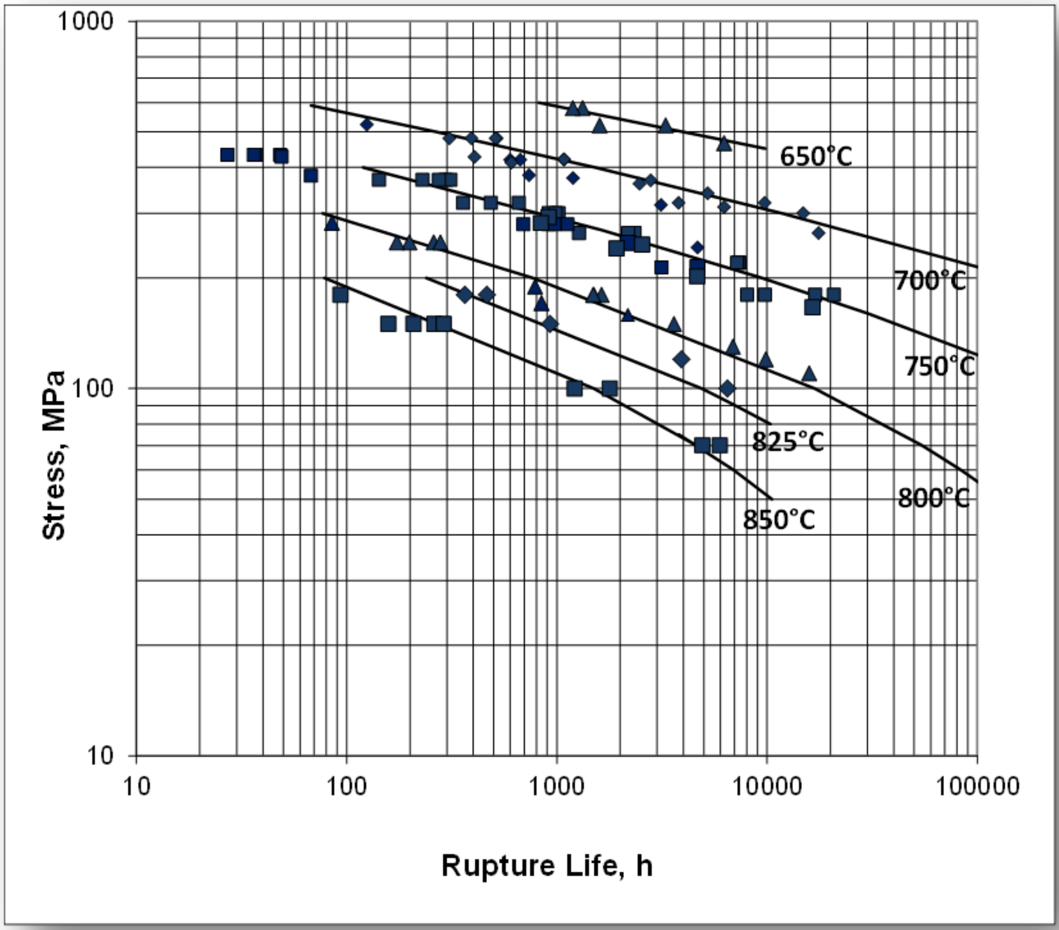


Figure 4 – Stress rupture properties of solution annealed and aged INCONEL alloy 740H. Data shown are from multiple heats and product forms, generated by ORNL for the United States A-USC Consortium and by Special Metals.

Thermal Stability

INCONEL alloy 740H products maintain their properties well during high temperature service. The effect of long term stress-free exposure on the impact strength of alloy 740H is seen in Figures 7 and 8.

Corrosion and Heat Resistance

With its high content of chromium, alloy 740H offers excellent resistance to corrosion at elevated temperatures. This is especially important for boiler tubes as they are exposed to fireside corrosion on the exterior and steamside corrosion on the interior. Alloy 740H has been extensively evaluated under both sets of conditions.

Fireside Corrosion

Key to the adoption of advanced ultra-supercritical (A-USC) boiler technology is assurance that the fireside corrosion resistance of the selected boiler tube alloy(s) will guarantee less than 2 mm metal loss in 200,000 hours at the operating steam temperature (700ºC in Europe and Asia and 760ºC in the U.S.). Of particular importance is the fact

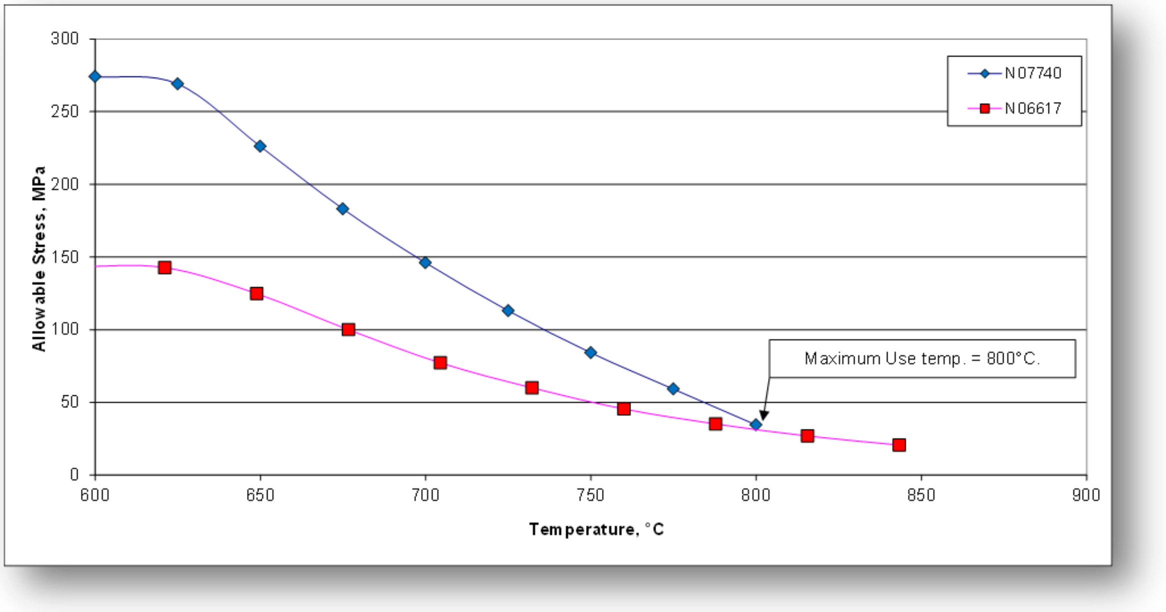


Figure 5. Comparison of ASME section I allowable stresses for INCONEL alloy 617 and INCONEL alloy 740H.

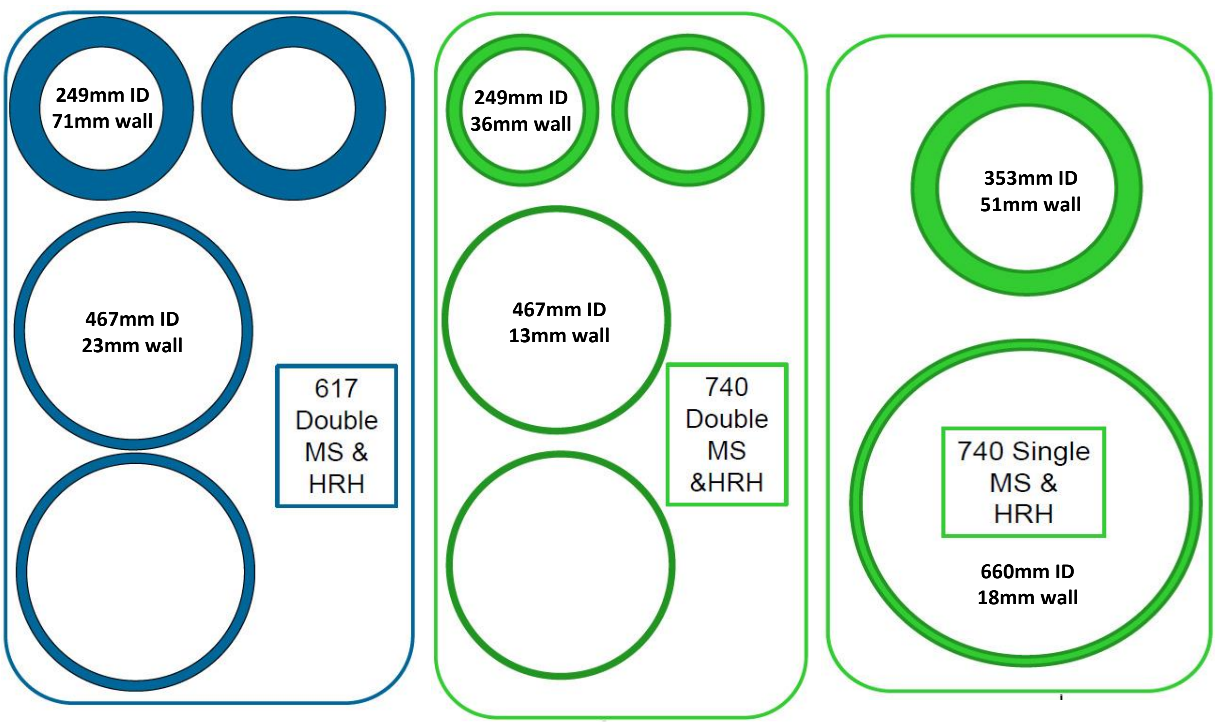


Figure 6. Piping size comparison between alloys 617 and 740H, for two options: a.) double main steam (MS) and hot re-heat (HRH) b.) single MS and HRH; the alloy 740H options comprise one-half the weight of the alloy 617 option, and alloy 740H is the only option for single MS and HRH.[3]

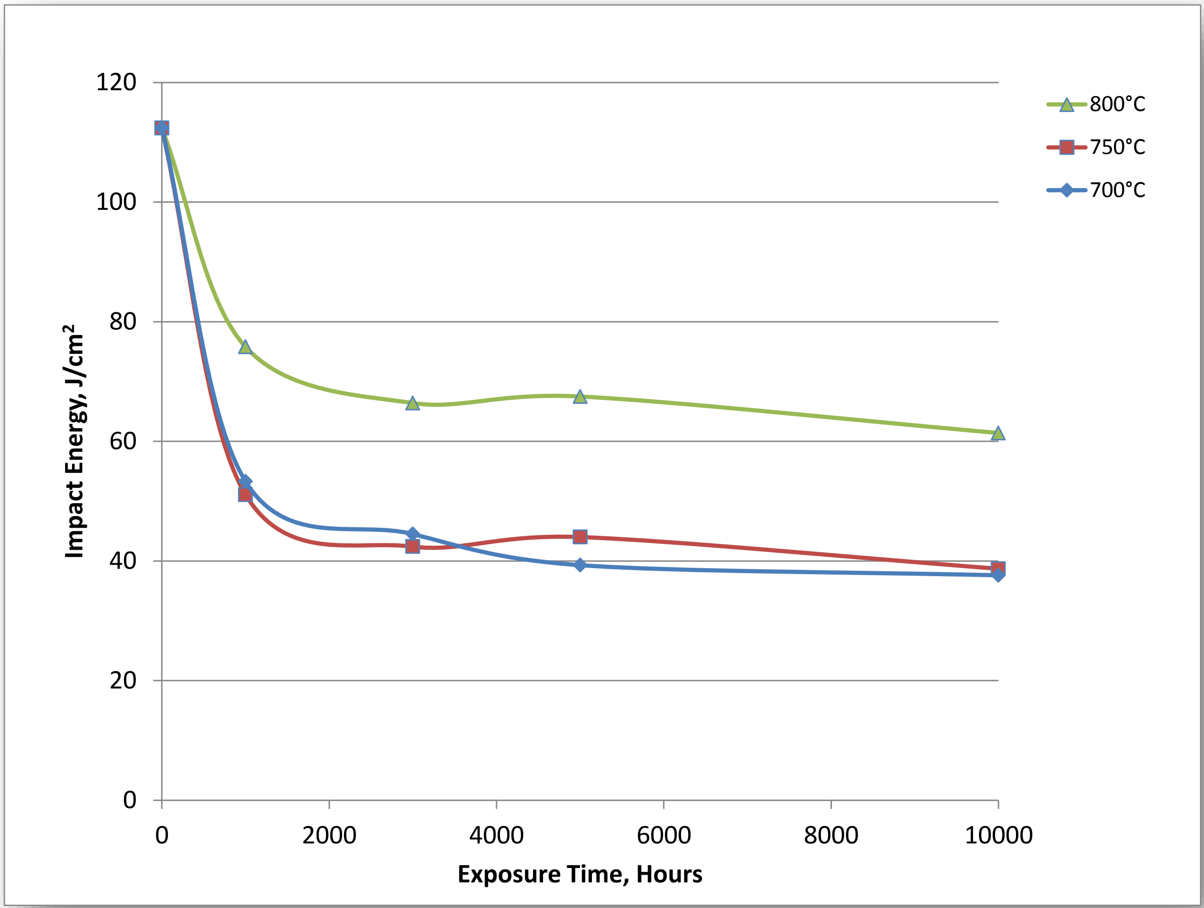


Figure 7 – Room temperature impact strength values for aged INCONEL 740H Superheater Tubing after exposure at 700, 750 and 800°C.

that coal-ash corrosion is a function not only of alloy composition but of the boiler environment in terms of the coal chemistry and the boiler operating conditions. Coal composition as it influences the boiler environment is of primary consideration. Unfortunately, coal compositions vary widely even within the recognized four primary coal types making absolute, real world, corrosion rate predictions difficult if not impossible.

Coal typically contains a significant amount of sulfur that as Kung has shown[4] evolves into H_2S, S_2, SO_2, SO_3 and COS during combustion. Other coal constituents, such as chlorides, alkali and alkaline earths, water content and total ash content likewise play an important role in fireside corrosion. Boiler operating conditions, such as the operating steam temperature, oxy-fuel (low NO_x) and strategies to lower emissions, for example washing the coal to reduce pyritic sulfur (FeS) or use of fluidized bed combustion using limestone to ameliorate SO_2 formation during coal combustion likewise influence alloy corrosion rates.

INCONEL alloy 740H test specimens were exposed at Special Metals Corporation at 750°C (1292°F) for times to 500 hours in a synthetic flue gas composition of 15 Vol. % CO_2 + 5.0% Vol. % H_2O - 3.5 Vol. % O_2 + 0.25 Vol. % SO_2 + Bal. N_2 and a specimen coating of synthetic coal ash consisting of 2.5% Na_2SO_4-2.5% K_2SO_4-95% (Fe_2O_3-Al_2O_3-SiO_2 in 1:1:1 Ratio).

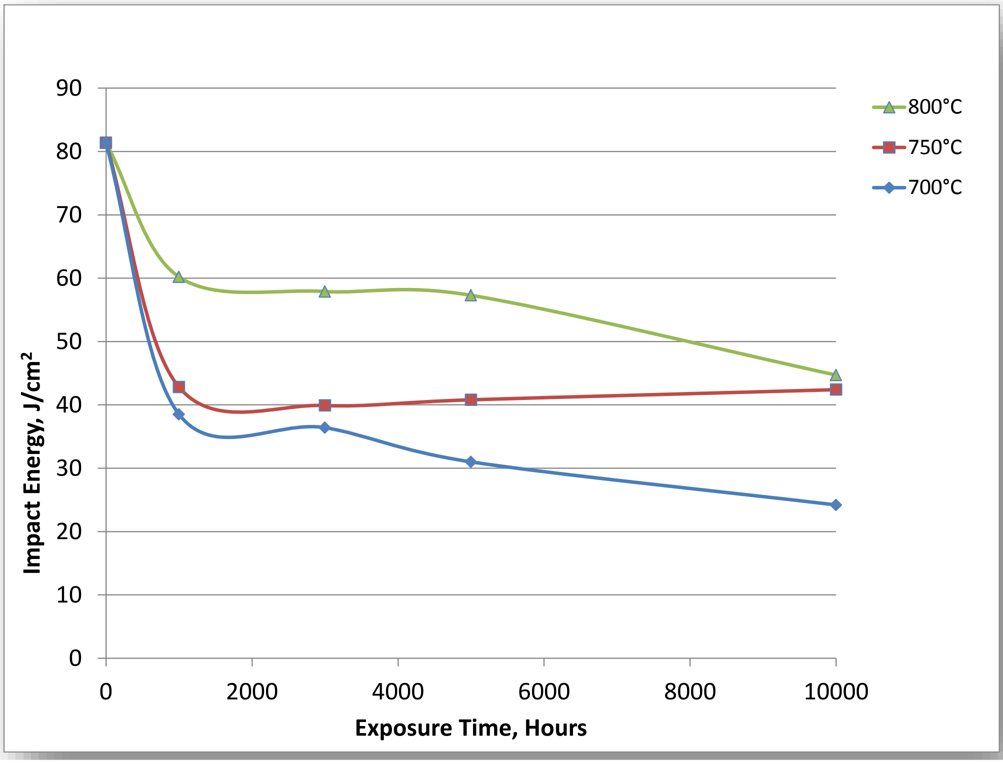


Figure 8 – Room temperature impact strength values for extruded, solution annealed and aged 8.071” (205mm) ID, 2.854” (72.5mm) minimum wall pipe after exposure at 700°, 750° and 800°C.

Samples were cycled to room temperature at the intervals shown, and re-coated. Figure 9 shows corrosion depth measurements with reference to the original sample surface as a function of time. Extrapolation of the last three data points using a linear fit, produces a predicted 347 microns of attack depth (0.35 mm).

INCONEL alloy 740H, alloy N06230, NIMONIC alloy 263 and INCONEL alloy 617 test specimens (base metal samples denoted with ‘B’ and matching all-weld metal samples denoted with ‘W’ were exposed at Special Metals Corporation at 750ºC (1292ºF) for times to 1000 hours in a synthetic flue gas composition of 15 Vol. % CO_2 + 5.0% Vol. % H_2O - 3.5 Vol. % O_2 + 0.1 Vol. % SO_2 + Bal. N_2 and a specimen coating of synthetic coal ash consisting of 6% Fe_2O_3-29% $CaSO_4$-1.9% Na_2SO_4-1.9% K_2SO_4-39% SiO_2-22% Al_2O_3-0.05% KCl-0.05% NaCl. Samples were cycled to room temperature at weekly intervals, and re-coated. Figure 10 shows corrosion depth measurements with reference to the original sample surface after 1000 hours of testing. Photomicrographs of sample cross sections are shown in Figure 11. Significant pitting corrosion is evident in the alloy 617 sample; incipient pit formation was noted in the alloy 263 sample as well.

Oxidation

The steam oxidation resistance of candidate alloys for an A-USC is a further consideration in selecting an alloy for the boiler, superheater and reheater tubing, the header and transfer piping. The concern is that steamside oxidation could potentially lead to wall loss compromising structural integrity as well as act as an insulating barrier to heat transfer. Loose scale can also lead to clogging of the tubes.

Figure 12 shows oxidation depth results from exposure of coupons of alloy INCONEL 740H and NIMONIC alloy 263 in air + 10% water vapor at 800°C (1470°F) for 3077 hours. Samples were cycled to room temperature once per week.

Steam oxidation resistance of various nickel-base A-USC candidate materials is summarized in the work of Sarver and Tanzosh.[5]

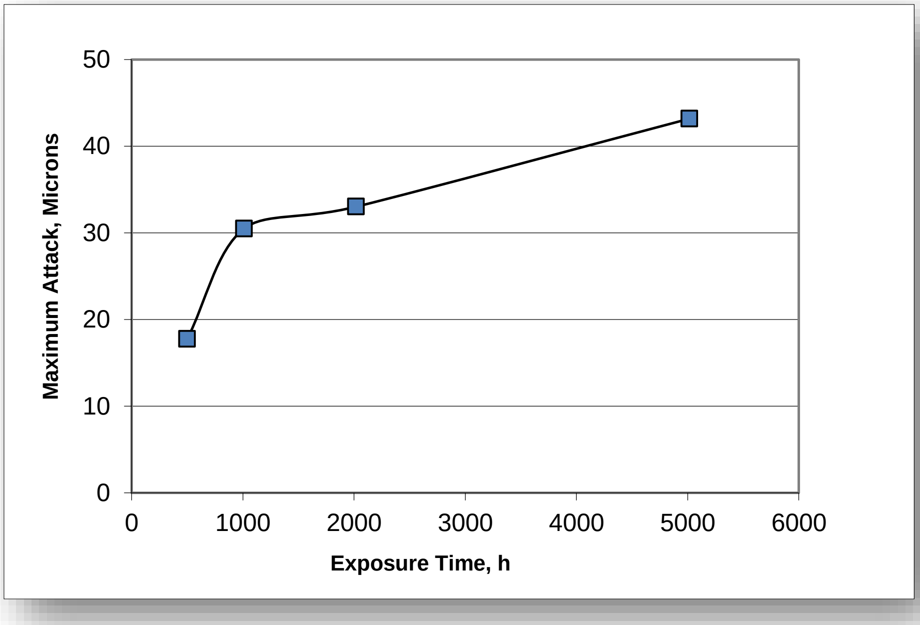


Figure 9 – Attack depth after simulated coal ash corrosion exposure of INCONEL alloy 740H sample at 750°C (1382°F).

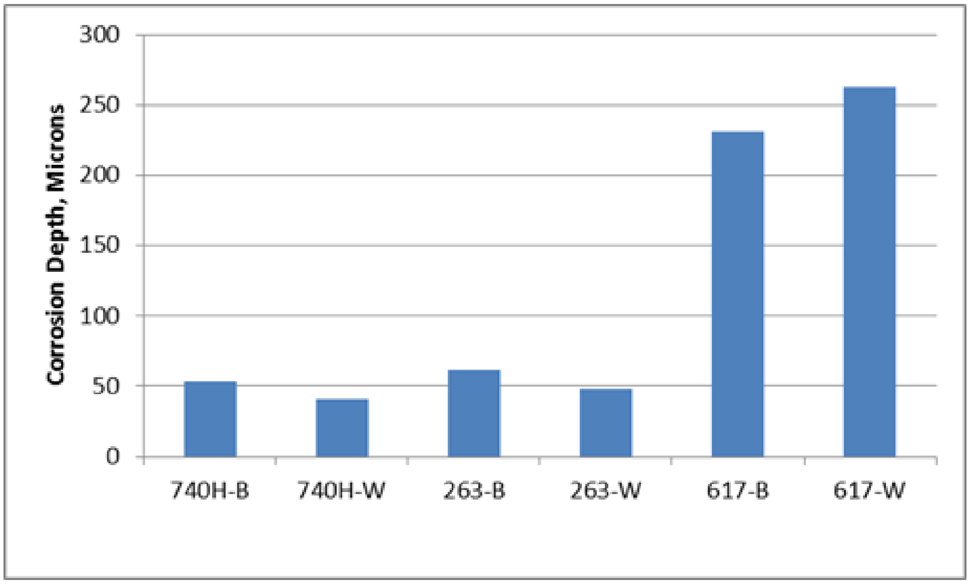


Figure 10 – Attack depth after simulated coal ash corrosion exposure at 750°C (1382°F) for 1000 hours. Base metal = "B"; all weld metal = "W".

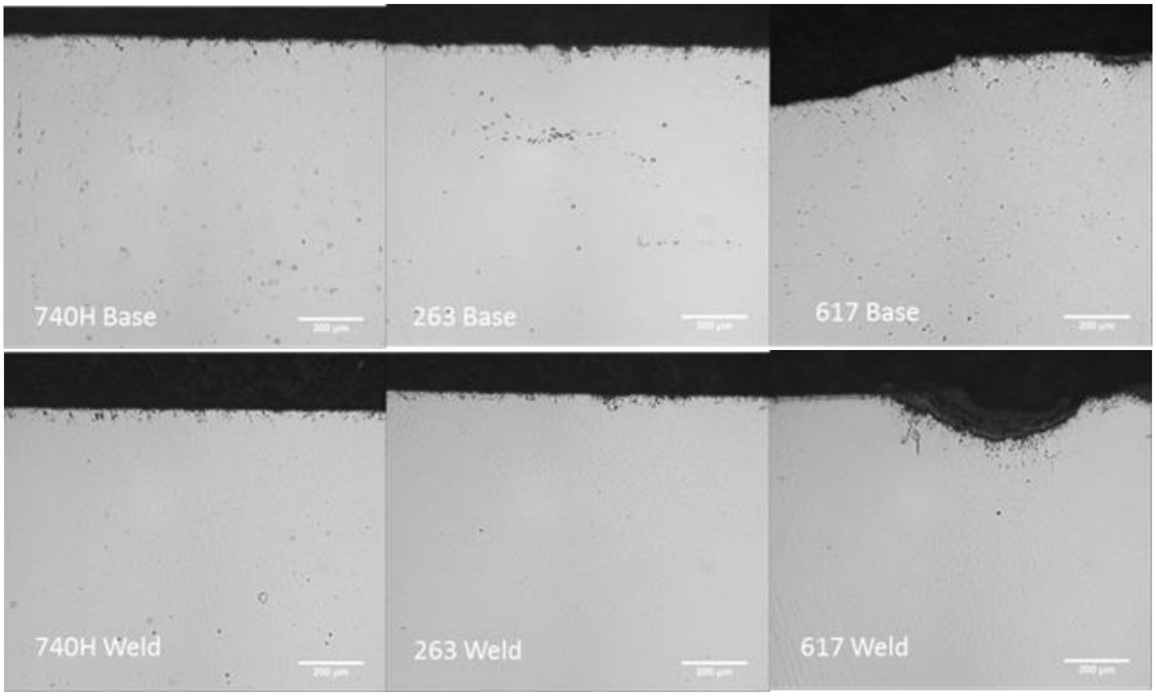


Figure 11. Photomicrographs of cross sections from samples of alloys 740H, 263 and 617 after simulated coal ash corrosion exposure at 750°C (1382°F) for 1000 hours.

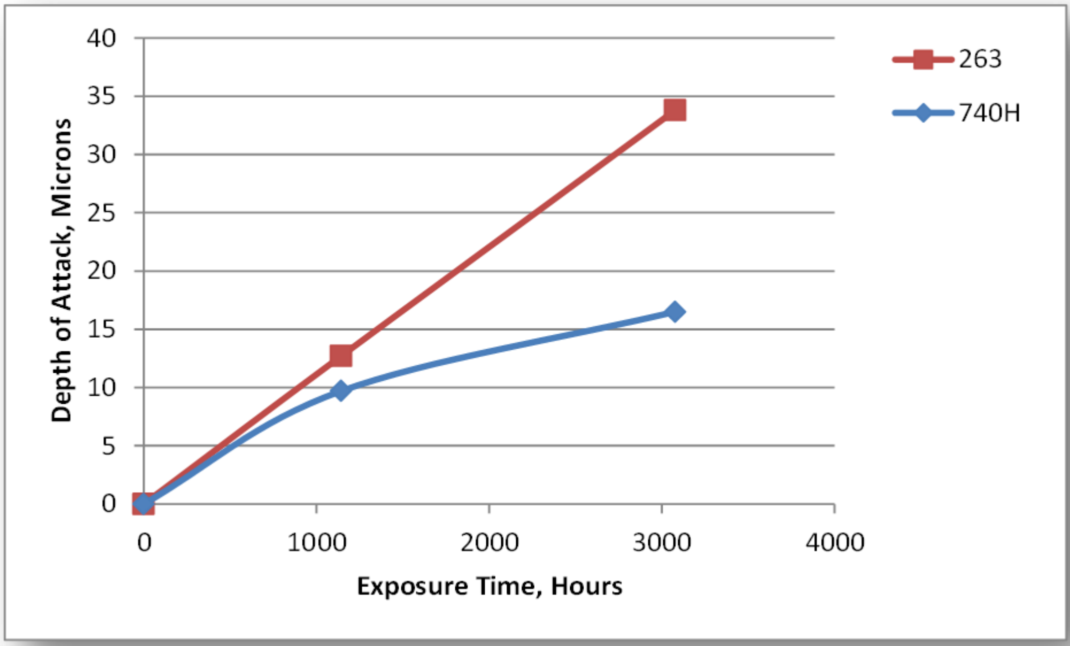


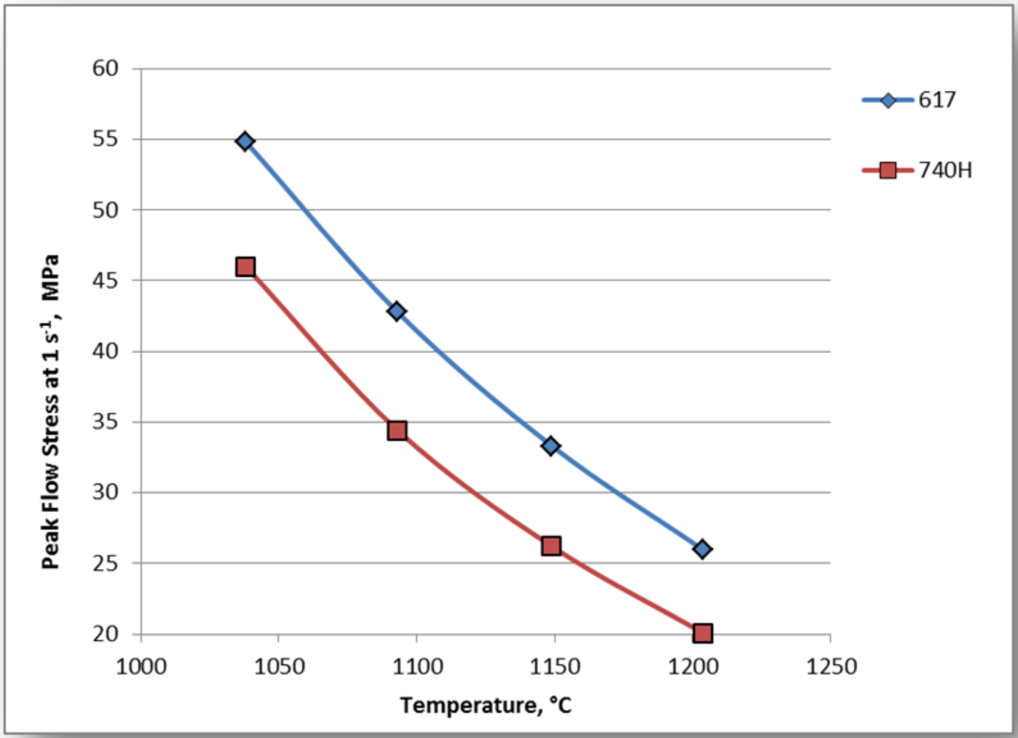
Figure 12. Depth of oxidation results for alloys 263 and 740H after 3077 hours of exposure in air + 10% water vapor at 800°C (1470°F).

Processing and Heat Treatment Considerations

INCONEL alloy 740H is an age-hardened superalloy typically supplied in the solution annealed and age-hardened condition. The recommended temperature range for hot-forming operations such as forging or hot-rolling is between 870°C (1600°F) and 1190°C (2175°F). Figure 13 shows the ratio of peak compressive flow stress at a strain rate of $1s^{-1}$a for INCONEL alloy 617 to that of INCONEL alloy 740H. With the peak flow stress of INCONEL alloy 617 at nearly 30% higher at extrusion temperatures, a comparatively larger pipe can be extruded from INCONEL alloy 740H.

Annealing practices are described in ASME code case 2702, which specifies a temperature of 1100°C (2010°F) minimum, for 1 hour per one inch (25.4mm) of thickness but not less than 30 minutes. The annealing range may extend as high as 1160°C (2125°F). Specific annealing conditions will be dependent upon the product form and intended application. Consult the manufacturer. Water quenching is recommended after solution annealing,
ASME code case 2702 also specifies the age-hardening practice for INCONEL alloy 740H. Aging shall be performed at temperature between 760°C (1400°F) and 815°C (1500°F), for a minimum of 4 hours. The minimum aging time shall be increased for thicknesses above 2 inches (50.8 mm) in thickness at a rate of ½ hour per inch of additional thickness. Aging shall be followed by air cooling. These same instructions for age-hardening must be followed for post-weld heat treatment.

Figure 14 shows Rockwell C hardness as a function of cold deformation percentage for cold-rolled plates in the solution annealed condition. ASME code case 2702 mandates that after cold-forming in excess of 5%, after any swages, upsets or flares, or after any hot-forming, the material shall be solution annealed in accordance with the provided instructions. No local solution annealing may be performed. The entire part or component that includes the deformed area must be included in the solution annealing treatment.



.

Figure 13. Ratio of peak compressive flow stress for INCONEL alloy 617 to that of INCONEL alloy 740H as a function of temperature.

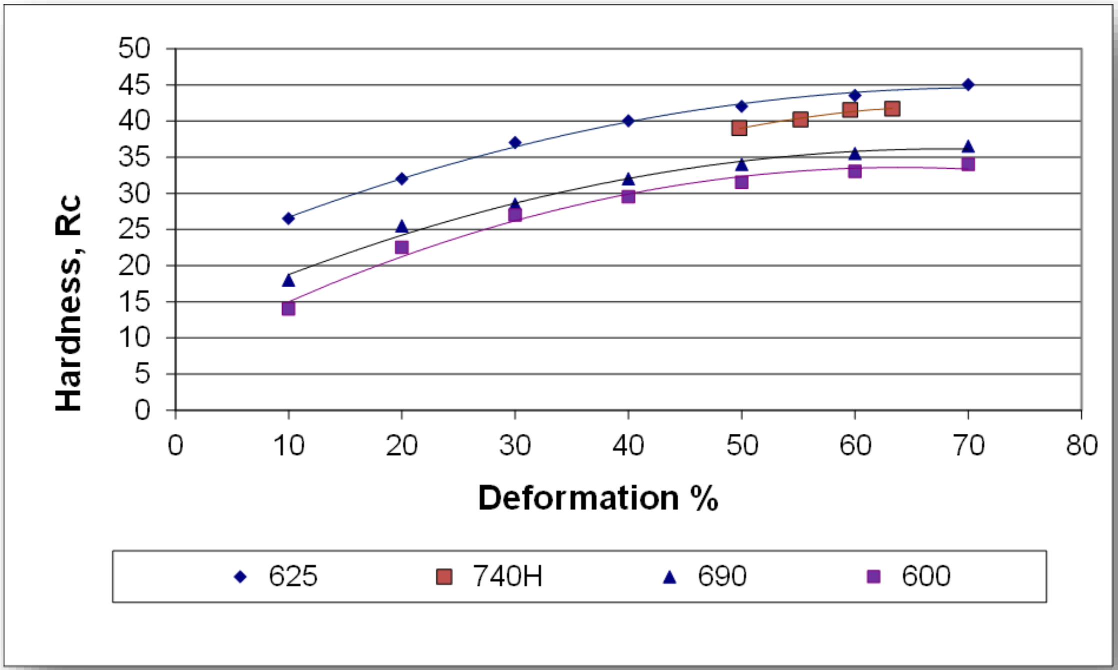


Figure 14. Rockwell C hardness for cold-rolled plate samples starting in the solution annealed condition, as a function of cold deformation percentage.

Welding

For A-USC applications, INCONEL alloy 740H products are normally welded in the solution annealed and aged condition. This is a requirement of the ASME Code Case 2702 which sets forth Section I requirements for fabricating alloy 740H components for power boiler service. Currently, as spelled out in the code case, all similar metal weldments must be joined with matching alloy 740H filler metals utilizing the GTA or GMA welding process. However, this does not imply that the use of other processes cannot be used for joining alloy 740H to other materials. Multiple dissimilar weldments have been fabricated utilizing the Shielded Metal Arc Welding (SMAW) process with INCONEL 182 welding electrodes and have produced code quality welds, meeting the requirements of ASME section IX.

INCONEL alloy 740H is normally joined with a matching composition welding product designated as INCONEL filler metal 740H. Welding techniques used for alloy 740H have been developed with emphasis on the procedures and processes that will be employed for fabrication of piping systems for A-USC boilers. While the Hot-Wire Gas Tungsten-Arc Welding process (HWGTAW) is a common process for the heavy section header pipe welds, manual Gas Tungsten-Arc Welding (GTAW) may be required for field welding of superheater tubes. Pulsed Gas Metal-Arc Welding (p-GMAW) was also evaluated with the idea that it would be a good process for general construction and dissimilar welding.

A welding program was undertaken to develop welding procedures for alloy 740H products. The study showed that when welded utilizing the welding processes noted above, sound, quality welds could be produced that were free from detrimental heat affected zone (HAZ) / weld metal micro-fissuring. Welding parameters developed are seen in Table 7.

Table 7
INCONEL alloy 740H Welding Parameters

Parameter	Manual GTAW	Manual p-GMAW	Hot-Wire GTAW*
Power Source	Miller Dynasty DX-300	Miller Axcess 350	AMI Model 415
Process	Manual GTAW	Manual PGMAW	Hot-Wire GTAW
Amperage	180 ±5	130 ±5	*
Voltage	15.0 ±.75	27.0 ±1	*
Shielding Gas Flow Rate	75 Argon / 25 Helium 30 cfh	75 Argon / 25 Helium 40 cfh	75 Argon / 25 Helium 40 cfh
Electrode or Wire Feed Speed (ipm)	2% Thoriated Tungsten 1/8" Ø	250 ipm with 0.045"Ø filler metal	*
Travel Speed (ipm)	~8.0	~10.0	*
Heat Input (kJ/in)	36	58.5	23.1
Interpass Temp.	<350°F	<350°F	<350°F

*Welding parameters for this process are proprietary to the Babcock & Wilcox Company

Using these Hot-Wire GTAW welding parameters, a full-section circumferential narrow-groove weld was made in a solution annealed [1120°C (2050°F)] and aged [800°C (1472°F)] INCONEL alloy 740H header pipe with 8.071" (205 mm) ID and 2.854" (72.5 mm) minimum wall thickness, using filler metal 740H, with a 5° bevel . Figure 15 shows a photograph of the 75% completed narrow groove header pipe weld. Figure 16 shows a photograph of a polished and etched cross section of the completed weldment, after application of a simulated field aging treatment after welding. The field heat treatment was accomplished utilizing ceramic heating pads, with a heating rate of 150°C (300°F) per hour to 425°C (800°F), then 40°C (100°F) per hour to the targeted aging temperature of 800°C (1472°F). After 5 hours at 800°C (1472°F), the sample was cooled at 65°C (150°F) per hour to 425°C (800°F), after which the thermal blanket was removed and the sample was air cooled.[6] Table 8 shows the acquired room temperature tensile properties obtained from transverse samples across the aged weld. Figure 17 shows a photomicrograph of the fusion zone from the aged weldment.

Figure 15. HWGTA weld in progress in large diameter, heavy wall INCONEL alloy 740H tube to simulate fabrication of an A-USC boiler steam header.

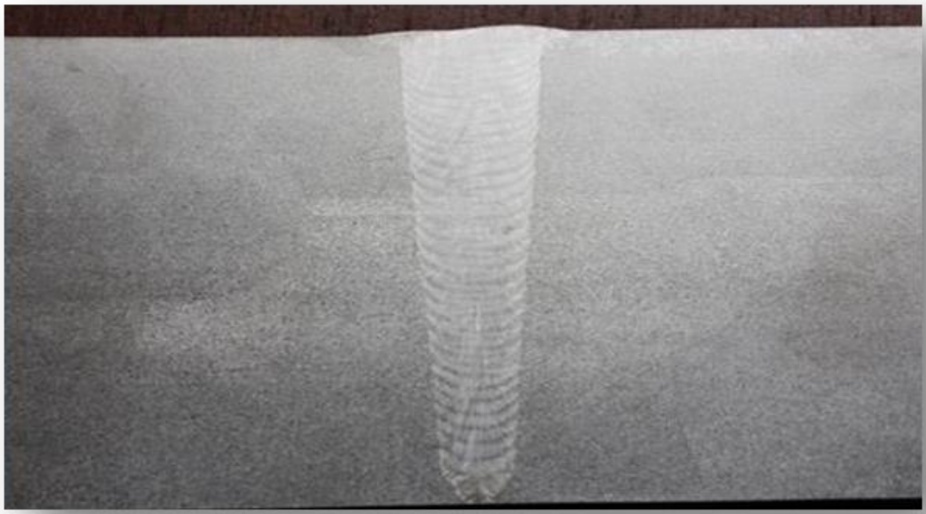


Figure 16. Etched cross section of a HWGTA weldment in 3” wall INCONEL alloy 740H steam header tube weldment showing bead sequence.

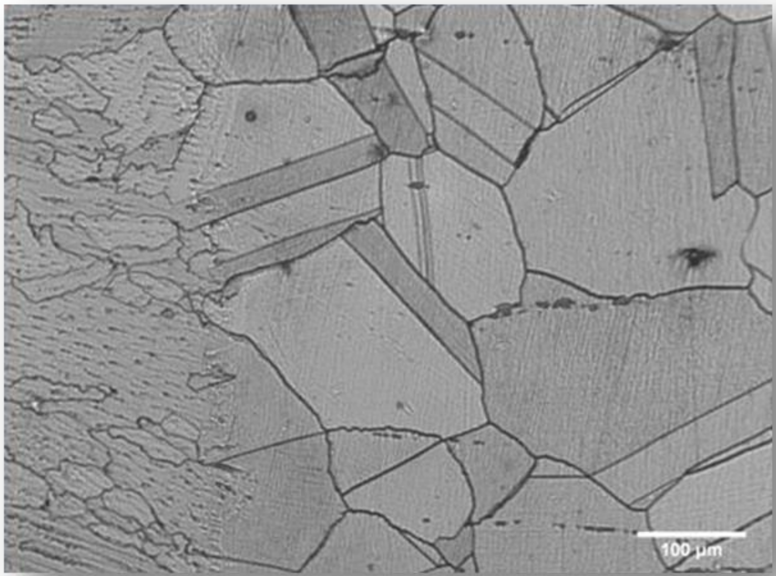


Figure 17. Photomicrograph of the fusion and heat affected zones of the hot-wire GTA weld seen in Figure 12. No fissuring is seen in the weld metal or adjacent base metal.

Table 8.
Room Temperature Tensile Properties of the Full Section HWGTA INCONEL filler metal 740H Weldment 8.071" (205 mm) ID x 2.854" (72.5 mm) Minimum Wall Steam Header Pipe

Sample Location	0.2% YS		UTS		Elong. %	R of A %	Failure Location
	ksi	MPa	ksi	MPa			
OD	118.2	815	164.6	1134.9	21.3	22.8	Weld
OD	116.4	802.6	162.8	1122.5	21.2	24.9	Weld
Mid-Wall	110.6	762.6	159.3	1098.4	24.6	22.3	Base
Mid-Wall	109.9	757.8	158	1089.4	20.6	21	Base
ID	108.8	750.2	156.8	1081.1	21.4	22.9	Base
ID	109.7	756.4	157.7	1087.3	24.4	24.5	Base

Four full section 4T side bend specimens were also tested following the field-simulated aging treatment at 1472°F (800°C) for 5 hours. All four passed ASME Section IX requirements with no visible indications noted. Figure 18 shows the acceptable bends as well as a room temperature tensile specimen used in the qualification.

Table 9 shows impact results acquired from the base material before and after the field-simulated post-weld aging treatment; results after the post-weld age are shown from within and adjacent to the region to which the ceramic heating pad was applied. In addition, impact results from the weld center and heat-affected-zone HAZ are shown, obtained after the field-simulated aging treatment.

Figure 18. Full-section, direct-aged 4T side bend test specimens from the HWGTAW steam header tube weldment. The room temperature tensile specimen fractured in the base metal away from the weld.

Table 9
INCONEL Alloy 740H Room Temperature Impact Properties for the As-Supplied and HWGTAW Welded Steam Header Tube

Heat Treatment*	Location	Base/Weld	Orientation	ft. lbs.	J	J/sq.cm.
I	Pipe Ctr	Base	L	48	65.1	81.4
II	Pipe Ctr	WC	T	49.8	67.5	84.4
II	Pipe Ctr	HAZ	T	39.4	53.4	66.8
II	Outside Pad	Base	L	43.1	58.5	73.1
II	Adjacent To Weld	Base	L	31.6	42.8	53.6

Note: All values are from an average of three tests

* I = 2050°F(1121°C) Anneal + 1472°F(800°C)/5h/AC; II = 2050°F(1121°C) Anneal + 1472°F(800°C)/5h/AC + Weld +1472°F(800°C)/5h/AC

A 2 inch (50.8mm) thick pulsed GMA weldment was tested in accordance to ASME section IX requirements in the direct-aged condition. Room temperature tensile properties are seen in Table 10. Ultimate tensile values exceeded Section IX requirements. Four- full section 2T side bend specimens were tested in the direct aged condition. The 2T bend radius equates to about 20% elongation. All four bend tests successfully met the requirements of ASME Section IX. The full section side bend tests are seen in Figure 19.

Table 10
Room Temperature Tensile Properties
2 inch (50.8 mm) Thick Alloy 740H p-GMAW Weldment

0.2% YS		UTS		Elong. %	R of A %	Failure Location
ksi	MPa	ksi	MPa			
104.8	722.6	152.6	1052.2	21.2	22.3	Weld
111.2	766.7	153.3	1057	18.4	18	Weld
108.7	749.5	152.9	1054.2	19.6	22.6	Weld
112.6	776.4	154.7	1066.7	21.7	23.3	Weld

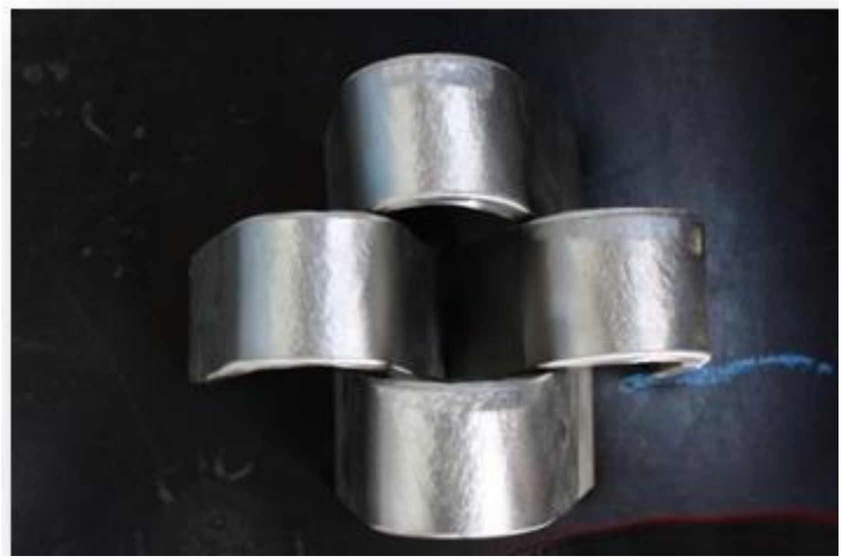


Figure 19. 2 inch (50.8mm) full section p-GMAW 2T side bend tests.

Stress rupture results from transverse weldments are shown in Figure 20. All samples were welded in the solution annealed and aged condition, with direct aging after welding, as prescribed by ASME code case 2702. The code requires application of a weld strength reduction factor of 0.7 for longitudinal seam welds at and above 650°C (1200°F).

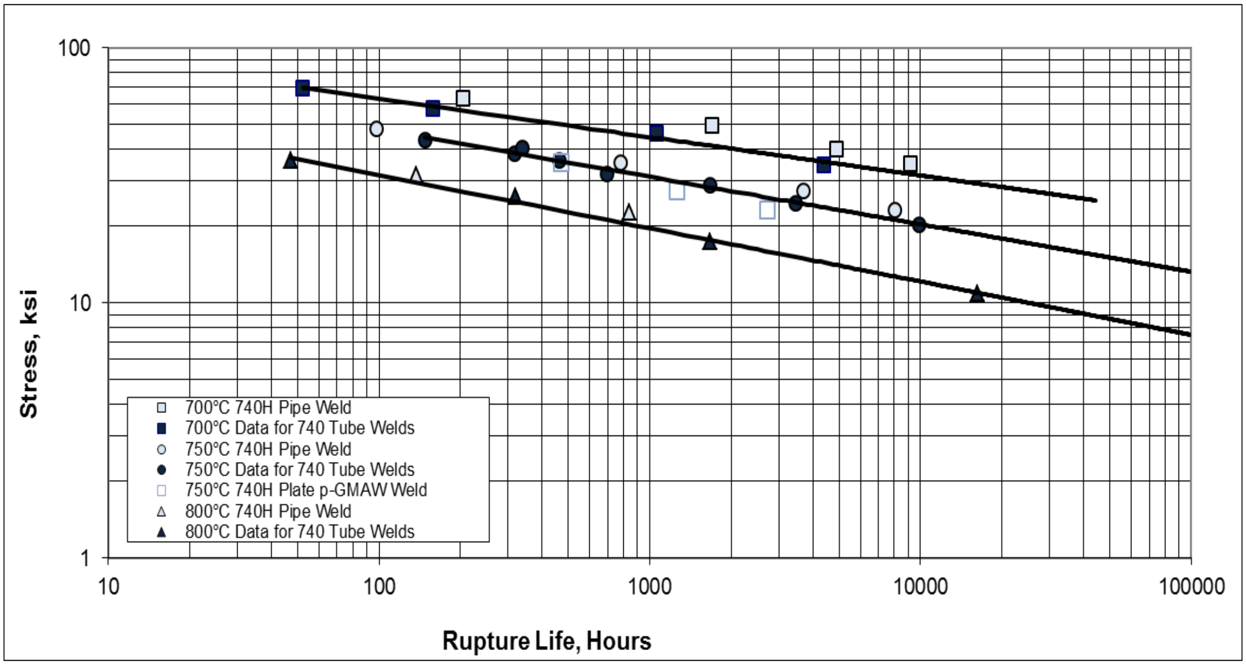


Figure 20. Stress rupture results for transverse weld samples, joined in the solution annealed and aged condition and direct aged after welding, in accordance with ASME code case 2702.

Dissimilar Welding

When using alloy 740H in dissimilar applications, care must be taken to ensure the material(s) being joined to alloy 740H will not have a detrimental effect on the mechanical and or physical properties. Utilizing the SMAW and GTAW processes, code quality weldments were produced by joining alloy 740H to P92 steel with INCONEL welding electrodes (WE) 182 and filler metal 82. Welding Electrode182 and filler metal 82 have a long history of being used for dissimilar applications, especially with alloy to steel combinations.

At no time during the fabrication of the dissimilar weldments did the filler materials exhibit any type of questionable performance. Both the 182 WE and 82 FM fused with the P92 base material with no problem. The wetting and tie-in actions are as good as or even slightly better than that of a similar weldment using matching 740H filler. Table 11 shows the room temperature mechanical properties of both the SMA and GTA dissimilar weldments. Each weldment was given a post weld aging treatment of 1400°F/4hr/AC (760°C) to satisfy requirements of both alloy 740H and P92.

Table 11
Room Temperature Tensile Properties
1 inch (25.4 mm) Thick Alloy 740H to P92 Steel Dissimilar GTAW and SMAW Weldments

0.2% YS		UTS		Elong. %	R of A %	Failure Location
Ksi	MPa	Ksi	MPa			
GTAW						
60.6	417.8	97.4	671.5	23.3	64.4	P92
60.7	418.5	98.2	677	22.5	64.3	P92
SMAW						
59.4	409.5	98.2	677	23.6	63.2	P92
72.1	497.1	98.8	681.2	21.2	63.3	P92

Transverse side bends were sectioned from each dissimilar weldment and tested in accordance with ASTM section IX and AWS B4.0. Side bends were tested to a 2T radius which equates to ~20% elongation. To test a bend specimen at 2T, one would measure the bend test thickness, double it and that would be the radius of the plunger diameter. As shown in Figures 21 and 22, both the SMAW and GTAW direct aged dissimilar side bend tests met requirements.

Figure 21. Photograph Illustrating Acceptable Direct Aged 2T Side Bends Utilizing SMAW to Join Alloy 740H to P92 Steel with INCONEL 182 Welding Electrodes.

Figure 22. Photograph Illustrating Acceptable Direct Aged 2T Side Bends Utilizing GTAW to Join Alloy 740H to P92 Steel with INCONEL 82 Filler Metal.

References

1. International Energy Outlook (IEO2013), U. S. Energy Information Administration, U. S. Department of Energy, July 25, 2013.
2. Shingledecker, John P., “Metallurgical Effects of Long-Term Stress Rupture in a New Nickel-Base Alloy,” Doctoral Dissertation, University of Tennessee, Knoxville, May, 2012.
3. Shingledecker, J., et al., IEA Clean Coal Centre Workshop: Advanced Ultrasupercritical Coal-Fired Power Plants, Vienna, Austria: 19-20 September 2012.
4. S.C. Kung, “Online Gas Measurements in a Pilot-Scale Combustion Facility for Fireside Corrosion Study”, Presented at Advances in Materials Technology for Fossil Power Plants, Proceedings from the Sixth International Conference, August 31 – September 3, 2010, Santa Fe, NM.
5. M. Sarver, J.M. Tanzosh, "Characterization of Steam-Formed Oxides on Candidate Materials for USC Boilers", Presented at Advances in Materials Technology for Fossil Power Plants - Proceedings from the Sixth International Conference, August 31 - September 3, 2010, Santa Fe, NM.
6. Baker, B. A., Gollihue, R. D., and deBarbadillo, J. J., “Fabrication and Heat Treatment of Weld Joints in INCONEL alloy 740H Superalloy Steam Header Pipe and Superheater Tubing,” Conference Proceedings of 10th Annual Conference on Welding and Repair Technology for Power Plants, Electrical Power Research Institute (EPRI), Marco Island, FL, June 2012.