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CREEP-RUPTURE PERFORMANCE OF INCONEL ALLOY 740 AND WELDS

J.P. Shingledecker
Electric Power Research Institute, Charlotte, NC USA

ABSTRACT

Inconel alloy 740/740H (ASME Code Case 2702) is an age-hardenable nickel-based alloy designed for advanced ultrasupercritical (A-USC) steam boiler components (superheaters, reheaters, piping, etc.). In this work, creep testing, beyond 40,000 hours was conducted a series of alloy 740 heats of varying product form, chemistry, and grain size. Long-term creep-rupture strength was found to be weakly dependent on grain size. Analysis of the time-to-rupture data was conducted to ensure long-term strength projections and development of ASME stress-allowables. Testing was also conducted on welded joints in alloy 740 with different filler metal and heat-treatment combinations. This analysis shows the current weld strength reduction factor of 30% (Weld Strength Factor of 0.70) mandated by ASME Code Case 2702 is appropriate for 740 filler metal but other options exist to improve strength. Based on these results, it was found that alloy 740 has the highest strength and temperature capability of all the potential A-USC alloys available today.

INTRODUCTION & BACKGROUND

INCONEL® alloy 740/740H (ASME Boiler & Pressure Vessel Code Section I Code Case 2702 [1]), hereafter referred to as alloy 740, is an age-hardenable nickel-based superalloy which is purposely designed for advanced ultrasupercritical (A-USC) steam boiler applications at high-stress and temperatures where creep will be the dominate deformation mode [2]. Figure 1 shows that alloy 740 has the highest allowable stress (highest strength) of any section I alloy at 700 to 800°C. Code Case 2702 limits alloy 740 to a maximum use temperature of 800°C, but additional testing is underway to extend this limit to 850°C.

A-USC steam boilers with operating temperatures up to 760°C will help to increase efficiency and decrease emissions of all effluents, including CO_2, in coal-fired power plants by up to 25% in comparison to current technology [3,4]. The typical microstructure of alloy 740 is a gamma matrix containing gamma prime precipitates and very little precipitation at the grain boundaries. After high-temperature aging, the gamma prime coarsens, and grain boundary $M_{23}C_6$ carbides, G-phase (a complex silicide), and the plate-like eta phase forms [5,6]. Studies on alloy 740 have shown that this microstructure, and in particular the formation of eta phase, is sensitive to alloy chemistry [7].

Early research on alloy 740 showed that the formation of a small amount of eta phase, which grows by consuming gamma prime precipitates, is not detrimental to the creep strength or ductility at 750°C [8].Later work suggested the alloy's creep strength and ductility over a larger range of temperatures was relatively insensitive to chemical compositional differences, but grain size did have some notable effect on creep-rupture strength [9]. Successful welding of the alloy in thin and thick sections has been accomplished [10, 11], but the current code case applies a weld strength reduction factor (WSRF) or weld strength factor (WSF) of 0.70 [1] for seam-welded components. A reduction in creep strength of nickel-based alloys has been observed for other A-USC nickel-based alloys including Haynes 230 [12] and alloy 617 [13], but a thorough analysis of the available cross-weld creep-rupture data on alloy 740 is required. This paper provides an up-to-date analysis of some of the research first reported in [9] with additional analysis of cross-weld creep-rupture data for multiple filler metals and welding processes.

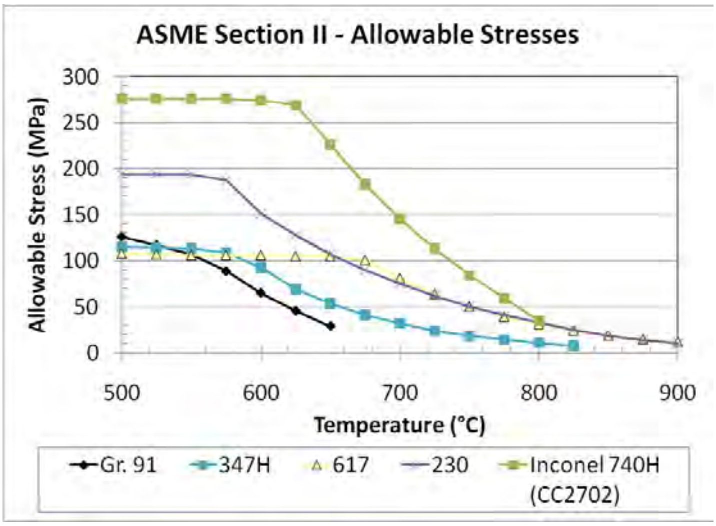

Figure 1. ASME Section I Allowable Stress Values for Code Case 2702 (Inconel 740/740H) Compared to Other Nickel-based Alloys (617 and 230), 347H stainless steel, and grade 91

EXPERIMENTAL PROCEDURE

Various heats of alloy 740 were evaluated representing a range of chemistries and product forms as shown in Table 1. In some cases, the solution annealing (SA) heat-treatment temperature was varied to modify the grain size of the alloy. All base materials were given the standard aging heat-treatment of 760 to 800°C for 4 to 16 hours per code case 2702. Welds were made and supplied by Babcock & Wilcox, Barberton, OH USA, using gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and hot-wire narrow groove GTAW (hot-wire TIG). Table 2 provides the relevant welding details and post-weld heat-treatments given to the weldments. Smooth bar creep rupture specimens with a 6.35mm diameter and a 31.75mm gauge length were utilized for the non-welded base material tests, and specimens with a 6.35mm diameter and a 57.15mm gauge length with the weld centered in the specimen gauge length were utilized for cross-weld creep rupture testing. Testing was performed at temperatures from 600 to 875°C in accordance with ASTM E139 in lever-arm type creep machines with most test run until failure. At the time of writing this paper, the longest failure durations exceeded 20,000 hours for base metal and 15,000 hours for cross-weldments with base metal specimens still running beyond 45,000 hours.

Microstructural analysis was conducted using light optical microscopy (OM) on etched samples using a solution of 40 ml H_20, 40 ml $HN0_3$, and 20 ml HF. Grain size was determined by the manual mean lineal intercept method in ASTM E112. Failure location was evaluated by specimen observation and in some cases through OM of polished metallurgical mounts of specimens after testing.

Table 1. Alloy 740 Heat Descriptions

Heat (SA Temp, C)	Grain Size (μm)	C	Mn	Fe	S	Si	Cr	Al	Ti	Co	Mo	Nb	P	B
		Composition wt% (Ni balance)												
A (1120)	82.4	0.03	0.28	0.42	0.0010	0.54	24.43	0.94	1.81	20.00	0.55	1.98	0.005	0.0030
A (1190)	165													
B (1120)	188	0.03	0.26	0.46	0.0010	0.53	24.38	0.98	1.77	19.90	0.50	1.97	0.005	0.0043
C (1120)	127	0.03	0.26	0.46	0.0010	0.54	24.34	0.97	1.78	19.80	0.50	1.99	0.005	0.0037
D (1200)	169	0.03	0.27	1.02	0.0002	0.45	24.31	0.75	1.58	19.63	0.52	1.83	0.003	0.0006
E* (1190)	89.6	0.06	0.30	0.69	0.0060	0.48	24.86	1.20	1.41	19.90	0.53	2.05	0.004	0.0010
E (1120)	**113													
F (1121)	-	0.04	0.31	1.05	0.0100	0.30	24.28	1.30	1.50	19.88	0.53	1.57	0.002	0.0007
G	-	-	0.30	1.07	-	0.20	24.35	1.28	1.45	20.08	0.53	1.53	0.002	-

*Material furnished in hot-rolled condition
** Bimodal grain size distribution, average grain size reported (center region grain size = 92.4 and outer sample region grain size = 145.1)

Table 2. Alloy 740 Weld Descriptions

ID	Base Metal	Product Form	Welding Process	Filler Metal	Post Weld Heat Treatment
740GMAW	B	15.9mm plate	GMA	740	4hrs-800C
263GMAW	B	15.9mm plate	GMA	263	4hrs-800C
740GTAW	A (1120)	50.8mmOD 10mm WT tube	GTA	740	4hrs-800C
740GTAW-SA					1hr-1120C air cool, 4hrs-800C
282GTAW	G	38.1mm plate	Hot-Wire TIG (GTA)	Haynes 282	4hrs-800C

RESULTS

Base metal rupture data and analysis

To evaluate the large range of times and temperatures, and to provide an estimate of long-term rupture life, the base metal creep-rupture data were analyzed using the Larson Miller Parameter (LMP). To find a best fit to the data, a regression to minimize the error in time to rupture (t_r) was performed using the following:

$$\log(t_r) = -C + \frac{A_1}{T} + \frac{A_2 \log(\sigma)}{T} + \frac{A_3 \log(\sigma)^2}{T} + \frac{A_4 \log(\sigma)^3}{T} \qquad \text{equation 1}$$

where C is the LMP constant, A_x are the regression coefficients, σ is stress (MPa), and T is temperature in K. Figure 1 is a Larson-Miller (LMP) plot for all the base metal creep-rupture data including ongoing tests (open symbols) using the best fit LMP constant of 19.392. Table 3 provides the regression coefficients. Inspection of the figure shows the data are tightly grouped and fall within a +/- 20% scatterband on stress. The only exceptions are two data points which are short-term tests at 875°C. To analyze the goodness of the fit and its ability to accurately predict long-term behavior, the rupture data are plotted as actual versus predicted life (equation 1) in Figure 2. The figure shows excellent agreement and all the data fall within a factor of +/-2 on life. Inspection of the ongoing test data (open symbols) show the prediction of long-term performance is very good with all tests exceeding 30,000 hours meeting or exceeding predicted life. A fit to the rupture data gives a slope of 0.93 which is close to unity (perfect fit) but is slightly conservative for long-term strength predictions. Based on these results, the equation was found to be accurate in the assessment of long-term material performance. Earlier research [8,9] found that alloy 740 was insensitive to microstructural variation due to chemistry, but some effect of grain size was noted. Figure 3 segments the heats of tested material by grain size. The figure clearly confirms the trend that the lower scatterband of creep strength is occupied by heats with finer grain size while slightly coarser grain sizes results in average or above average life with long-term tests exceeding the average prediction.

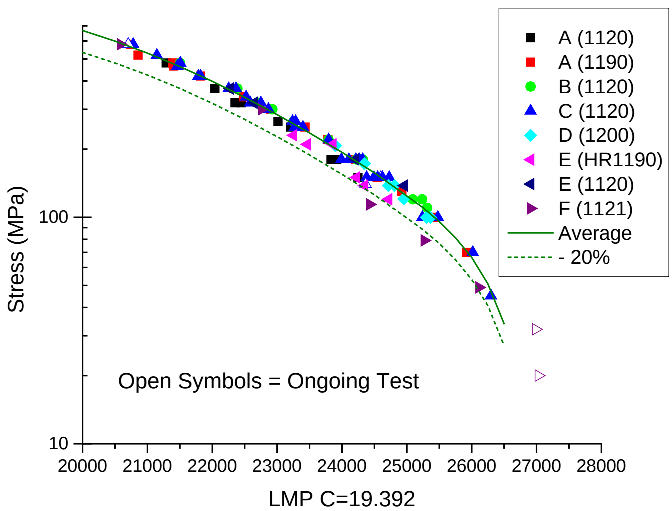

Figure 2. Optimized Larson-Miller-Parameter (LMP) plot for Inconel 740/740H creep-rupture test data segmented by heat. Open symbols on ongoing (not ruptured) tests.

Table 3. Regression coefficients determined for equation 1

Regression Constants	740 BM	740 WM (GTAW & GMAW Aged)	740WM (WM failures only)
C	19.392	16.513	17.0245
A_1	2.336e-4	6.044e4	4.478e4
A_2	5.532e3	-4.612e4	-2.457e4
A_3	-2.0.65e-3	1.9481e4	1.005e4
A_4	-1.027e2	-3.066e3	-1.709e3

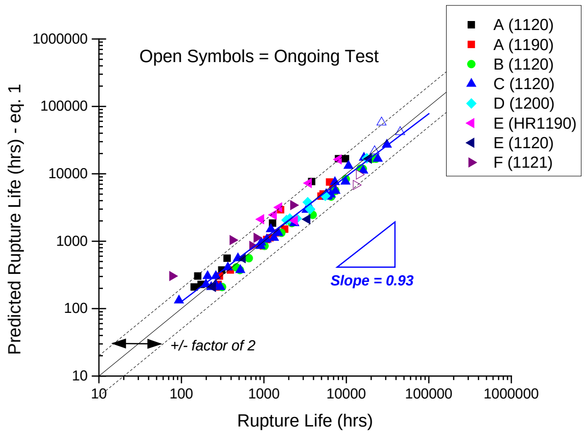

Figure 3. Predicted (equation 1) versus actual rupture life for alloy 740. Note, the predicted life is based off an earlier assessment of the data. All non-ruptured specimens (open symbols) are within a +/-2 scatterband on expected life with most ongoing tests (including those over 30,000 hours) exceeding predicted life.

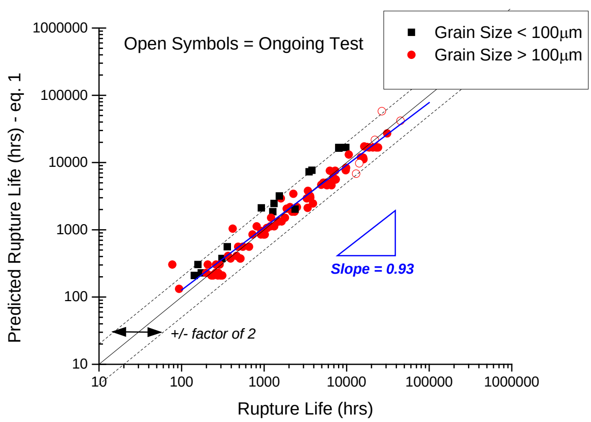

Figure 4. Predicted versus actual failure life segmented by grain size

Cross-weld testing results and analysis

All the cross-weld time to rupture results for the welds in Table 2 are plotted against the average alloy 740 base metal (BM) behavior in Figure 4. All but one data point (black square at LMP = ~23,500) for a variety of weld filler metals and heat-treatment conditions fall between the average expected behavior and -30% on stress. A 30% reduction in stress is equivalent to a WSF of 0.70.

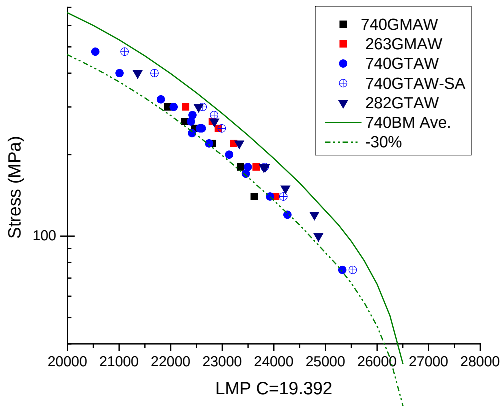

Figure 5. Alloy 740 Cross-Weld Rupture Results

Using the LMP of 19.392 and the base metal fit (Table 3), the stress for rupture (σ_r) data in Figure 4 were analyzed to determine the specific WSF for each data point. These data are plotted as a function of rupture time in Figure 5 and Table 4 provides the average of the measured WSFs for each weldments. The data show that the 740GMAW and 740GTAW specimens had a WSF of slightly greater than 0.70, but that the application of a solution annealing heat-treatment after welding and prior to aging improved this to close to 0.90. The use of alternate filler metals, alloy 263 and Haynes 282, also improved the strength of the welded joint to 0.82 and 0.85, respectively.

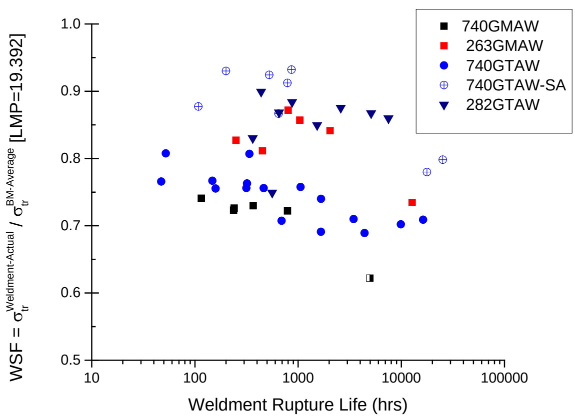

Figure 6. Inconel 740 measured cross-weld Weld Strength Factors (WSF) as a function of test time using average Inconel 740 base metal

To examine the behavior of the 740 filler metal welds in more detail, the data are plotted in Figure 6 along with information on the failure location. The weld given the solution annealing heat-treatment failed in the base metal outside the weld. Because these solution-anneal weldments were made in heat A with the finer grain size, a WSF of ~0.90 is equivalent to base material heats in the lower scatterband of the data. In contrast, the GMAW and GTAW welds all failed in the weld metal with the exception of one test which had a reported heat affected zone (HAZ) failure. This location was reported based on visual observation and detailed OM was not complete at the time of writing this paper. Based on these findings, the 740GMAW and GTAW data (note these data were aged following welding) were combined and analyzed in same manner as the base metal to determine optimized LMP fits. Table 3 provides the results of this analysis for all the data and with the HAZ data removed because a different failure mechanism or failure due to a welding defect may be influencing results. Tables 5 and 6 compare the predicted stress to produce a rupture in the base metal and a 740 weld metal for various times up to 100,000 hours based on the LMP constants in Table 3. The optimized fits of the data show, in some cases, a slightly more pessimistic value for the WSFs compared to the average data in Table 4 since the LMP constants and equations vary between the base metal and the weldments data. However, the values do not show any consistent trend with temperature or test time. The values of the WSF calculated from optimized fits and reported in Table 6 are 0.70+/-0.3 which suggests the value of 0.70 is appropriate.

Table 4. Average of measured WSFs (Figure 5) for Inconel 740/740H

ID	WSF
740GMAW	**0.71**
263GMAW	**0.82**
740GTAW	**0.74**
740GTAW-SA	**0.88**
282GTAW	**0.85**

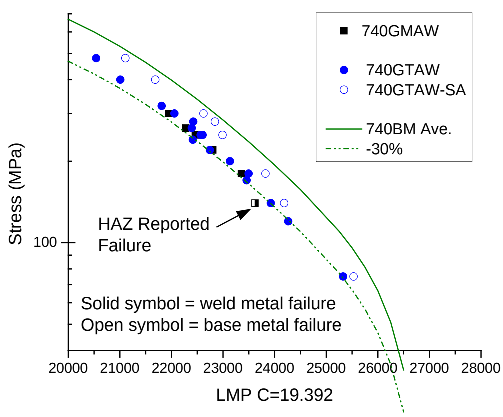

Figure 7. Inconel 740 Cross-Weld Rupture Results for 740 Filler Metals and Failure Locations

Table 5. Comparisons between average Inconel 740 data and an optimized fit to a combined dataset of cross-weld data on 740GMAW and 740GTAW (aged condition, all failure modes)

Time to Rupture	10,000 hours (MPa)			30,000hours (MPa)			100,000 hours (MPa)		
Temp. (C)	BM	Weldment	WSF	BM	Weldment	WSF	BM	Weldment	WSF
700	307.5	211.6	0.69	260.5	171.8	0.66	214.1	134.4	0.63
750	197.9	132.1	0.67	160.3	105	0.66	123.7	82.4	0.67
800	114.6	82.3	0.72	84.8	66.3	0.78	84.8	-	-

Table 6. Comparisons between average Inconel 740 data and an optimized fit to a combined dataset on 740GMAW and 740GTAW weldments (aged condition, only weld metal failures)

Time to Rupture	10,000 hours (MPa)			30,000hours (MPa)			100,000 hours (MPa)		
Temp. (C)	BM	Weldment	WSF	BM	Weldment	WSF	BM	Weldment	WSF
700	307.5	215.5	**0.70**	260.5	177.1	**0.68**	214.1	141.1	**0.66**
750	197.9	136.1	**0.69**	160.3	108.5	**0.68**	123.7	84.3	**0.68**
800	114.6	83.2	**0.73**	84.8	65.5	**0.77**	84.8		

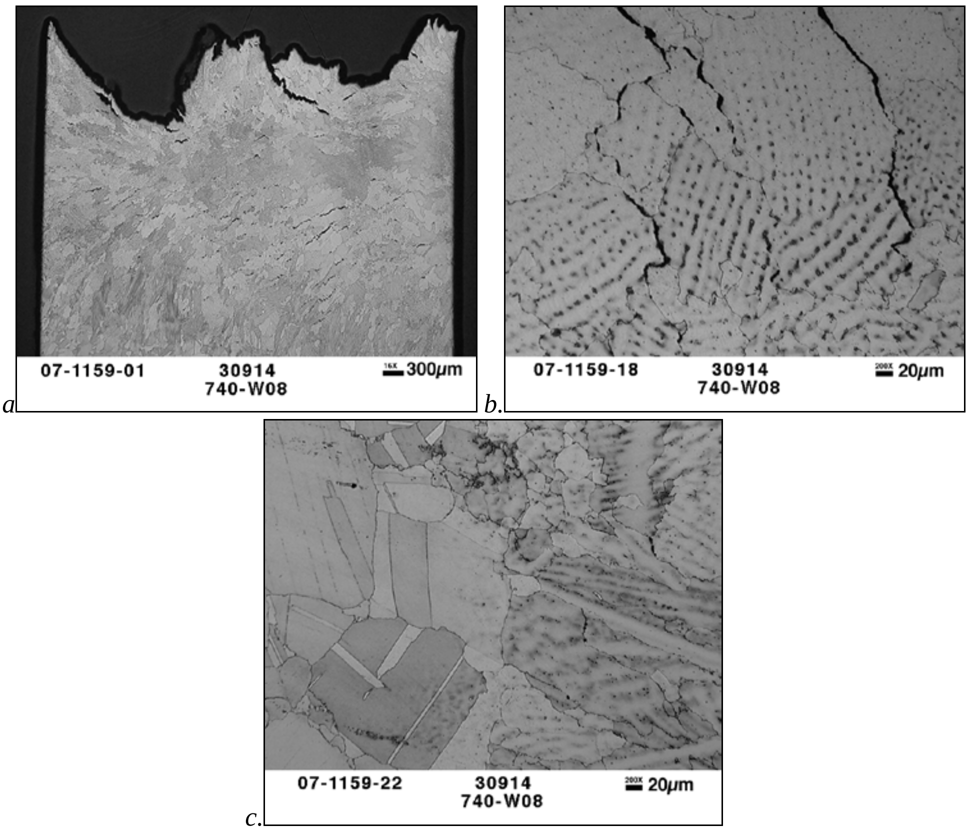

Figure 8. OM of failure (a, b) and fusion line (c) in 740GTAW after1668.9hours at 750°C

To examine failure modes in more detail, OM was conducted on cross-sections of failed samples. Figure 7 provides an overview of the typical failure mode observed in the 740 weld metal tests where creep failure occurred in the weld metal (a) with no evidence of distress in the HAZ (c). Higher magnification images suggest the interdendritic regions (final region to solidify) had a large population of creep cavities and microcracks (b). This is consistent with more detailed ongoing research which shows cavitation initiates in the interdendritic regions having large areas denuded in gamma prime [14] which is similar to reported initiation sites in base metal [9].

Solution annealing after welding restored base metal strength and moved the failure location from the weld metal to the base metal. Figure 8 shows the change in microstructure in the GTAW weldments after creep testing. In this case, it appears the large dendritic weld microstructure was completely recrystallized resulting in a 'wrought' weld structure after solution annealing. This suggests very high residual stresses in this tube to tube butt weld. Creep damage was not observed in the recrystallized weld metal which exhibited a coarser grain size than the base metal. This is again consistent with the base metal analysis which showed larger grains are beneficial for creep strength. This data also suggests that the welding processes utilized did not have significant defects and that they were controlled to minimize loss of specific strengthening elements. If weld quality were poor, strength restoration via solution annealing would not be possible.

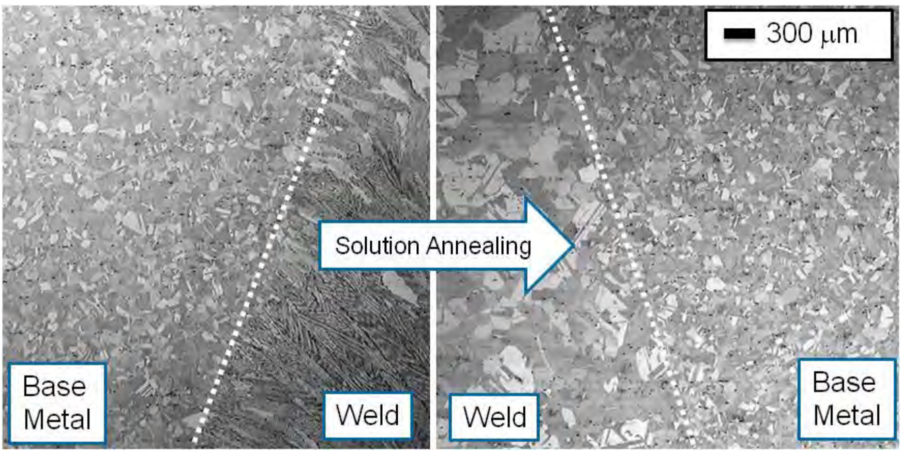

Figure 9. Change in microstructure of 740GTAW weld (left) with application of a solution annealing heat-treatment (right) after testing at 800°C and 180MPa for ~300-600hrs. Fusion line is indicated by dashed white line.

Alternative weld filler metals offer a second approach (compared to heat-treatment) to improve weldment strength because failure (see Figure 7) of 740 weldments are due to poor filler metal strength. The alloy filler 263 failures were all reported in the weld metal similar to the 740 filler metals, but overall strength was slightly better. Figure 9 is an OM of one of the 263 failures. Similar to the other 740 weldments, the base metal did not exhibit creep damage and cavitation was observed in the weld metal. However, a significant difference was noted. In the weld metal adjacent to the fusion line a region of finer grains/refinement compared to the rest of the weld metal (Figure 9 left) was intermittently observed. Creep damage was concentrated in these weld regions (Figure 9 right) suggesting the failure mechanism may be different for the examined filler materials and process improvements may increase the strength of the filler metal.

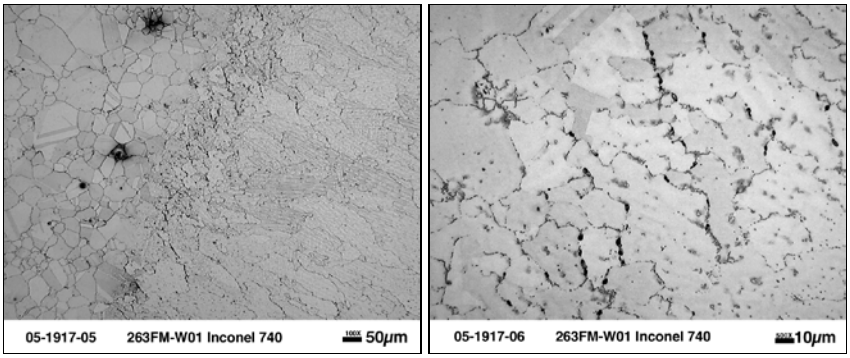

Figure 10. Cross-sectional micrographs for failure in 740 welded with 263 after 250.2hrs at 750°C. Cavitation is observed in a refined region of the weld metal near the fusion zone.

DISCUSSION

Analysis of the current base metal testing shows an optimized Larson Miller Parameter analysis can be used to accurately represent the data and to make extrapolations for longer life. Long-term ongoing tests, beyond 40,000 hours, suggest the equation provided in this paper will be slightly conservative for such purposes. At 750°C, the analysis shows the 100,000 hour rupture life on alloy 740 is greater than 120MPa which is in excess of the generally accepted criteria of 100MPa-100,000 hour rupture life needed for power steam boiler components [2]. At 700°C, the value is greater than 210MPa which confirms the stress allowable values (Figure 1). In the interest of A-USC powerplant construction, alloy 740 has the highest strength of any ASME-approved alloy for this application.

Cross-weld creep-rupture testing shows that 740 weldments generally have inferior creep strength to the base metal. For 740 matching filler metals given a standard aging heat-treatment after welding, a WSF of 0.7 was found, through multiple analysis methods, to be an accurate measure of long-term creep performance. No clear trend with test time or temperature was observed suggesting a single factor can be applied in the creep regime. Microscopy shows the interdendritic regions are prone to creep cavitation and microcracking and at failure no creep damage was observed in heat affected zone (HAZ) or base metal. More detailed microscopy is required to understand the failure mechanism in the weld metal and ultimately improve the strength of the 740 weld metal. Solution annealing offers one path for improved weld metal strength. This research shows that base metal strength can be achieved through application of a standard solution annealing heat-treatment which results in a stronger weld metal and moves the failure location to the base metal. A second option to improve the cross-weld strength of alloy 740 weldments is to use an alternative filler metal. In this work, both alloy 263 and Haynes 282 filler metals improved the strength of the welded joint to within an acceptable -20% scatterband of the base material. However, neither alloy 263 nor Haynes 282 restored cross-weld strength in alloy 740 to that of the base metal. Examination of the 263 joints revealed that creep cavitation was observed in fine grained regions (associated with weld metal refinement) in the weld metal suggesting process improvements may be warranted for this combination.

Currently, ASME only applies WSRF (WSF) to longitudinally seam welded components which are not envisaged for A-USC designs. A WSF less than 1.0 is standard for many power plant materials including extensively used ferritic steels such as grade 91 which has a WSF between 0.5 and 0.9 (due to the Type IV failure mechanism). Other studies of nickel-based alloys such as

Haynes 230 [12] and alloy 617 [13] show WSF around 0.8. Therefore, from a practical standpoint, a WSF of 0.7 can be successfully utilized in design by avoiding seam welded components. If seam welds are required, the data clearly indicate alternative filler metals or solution heat-treatment are viable options for improving weldments strength.

CONCLUSIONS

Analysis of a large set of creep-rupture data on Inconel alloy 740/740H of varying compositions showed the alloy has sufficient strength to achieve desired lifetimes for A-USC boiler components. Optimized time-temperature parameter analysis was shown to give accurate results for the base metal dataset and ongoing tests are meeting predictions. Extensive cross-weld rupture tests confirm the use of a 0.70 WSRF in the current ASME code case for matching filler metal made with various processes. Although not needed in most designs, if higher weldments strength is required, the data show alternate filler metals and solution heat-treatment are both options available to the end user and manufacturer. Microstructural analysis of failed cross-weld specimens showed different behavior for different filler metals and heat-treatments which illuminate the needs for further study. Future work should include microstructural analysis of weldments samples to understand the failure mechanisms, continued long-term base metal testing, and interrupted tests to improve understanding of damage development.

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