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Effect of Processing on the Microstructure and Creep Performance of INCONEL® Alloy 740H® Sheet

John Shingledecker, Ph.D., FASM
Senior Technical Executive
Electric Power Research Institute
Charlotte, NC USA

Dr. Shingledecker, is a Sr. Tech. Executive in Generation research area with responsibility for Technology Innovation, strategic planning, and technical leadership of collaborative projects focused on advanced manufacturing methods and materials. His research in the high-temperature behavior of engineering materials includes over 200 publications and multiple awards for technology transfer.

Eeva Griscom
Electric Power Research Institute
Charlotte, NC USA

John (Jack) deBarbadillo
Special Metals Corporation
Huntington, WV USA

Alex Bridges
Electric Power Research Institute
Charlotte, NC USA

Brian Baker
Special Metals Corporation
Huntington, WV USA

ABSTRACT

Heat exchangers (HXs) are a critical component in the supercritical CO_2 (sCO_2) power cycles for both heat recuperation and heating the sCO_2 in indirect cycles. One key candidate alloy for the highest temperature HXs, INCONEL ® Alloy 740H ® (alloy 740H), has been extensively tested and characterized in traditional wrought forms including piping, tubing, plate, and forgings. However, in many compact HX designs, thin sheets and foil (<2mm in thickness) are utilized. The processing of sheet and foil can differ substantially from other wrought products, such as rapid annealing cycles during roll processing, and the manufacturing of HXs can involve long heat-treatment cycles. Both of these extremes can change the grain size and precipitate character of the material. Subtle changes in microstructure can have a significant impact on high-temperature mechanical properties. In this study, commercially produced alloy 740H sheet was subject to a variety of heat-treatments and microstructural investigations were conducted. Selected heat-treatments were performed on three different sheet products and creep-rupture testing was initiated. This paper provides the details of the heat-treatment studies, and the creep-rupture and microstructure results which show that alloy 740H sheet can show inferior creep resistance and/or ductility compared to wrought under specific combinations of thickness and heat-treatment. Implications for HX manufacturing are discussed.

INTRODUCTION

Heat exchangers (HXs) are a critical component in the supercritical CO_2 (sCO_2) power cycles for both heat recuperation and heating the sCO_2 in indirect cycles. In future Generation 3 (Gen3) concentrated solar power (CSP) plants, direct heating of the sCO_2 as well as indirect heating using molten salts or solid particles as the primary heat-transfer media are being considered in order to achieve desired efficiencies with the goal of a 700ºC+ sCO_2 power cycle [1]. In order to control costs of expensive nickel-based alloys (which are specified for this application due to the need to withstand high pressure, high temperature, and corrosion), compact HXs (which use less material than traditional tube and shell designs) are being designed and fabricated for operation up to ~750ºC. One key candidate alloy for these HXs is INCONEL ® Alloy 740H ® (alloy 740H) which has been extensively tested and characterized in traditional wrought forms including piping, tubing, plate, and forgings [2-4]. However, in many compact HX designs, thin sheets and foil (<2mm in thickness) are utilized and few data exist about the performance of alloy 740H in this product form.

The processing of sheet and foil can differ substantially from other wrought products, such as rapid annealing cycles during roll processing, and the manufacturing of HXs can involve long heat-treatment cycles (such as vacuum heat-treatments in diffusion bonding) [5]. Both of these extremes can change the grain size and precipitate character (type, size, and distribution) of the material. A number of studies on the high-temperature performance (tensile, creep, oxidation, and corrosion) of stainless steels and nickel-based alloy sheets and foils supporting the development of microturbine recuperators have shown that these subtle processing changes can lead to inferior high-temperature creep performance [6-8]. In one study on nickel-based alloy 625, commercially produced 0.102mm thick foils showed a 6.5 to 8X reduction in time to rupture compared to thicker sheet [8]. Current studies on diffusion bonding of heat-exchangers has focused on 'weld qualification,' bonding optimization, and general microstructure of the bond joint with heat-treatment times at solution annealing temperatures in excess of 10 hours, which may be much longer than standard wrought product final anneals.

Research on wrought alloy 740H has shown that minor heat-to-heat variations in creep rupture strength were due primarily to grain size variations, where finer grain size material had lower than average scatterband rupture strength, and that compositional variations leading to changes in precipitates (such as the formation of eta phase during high-temperature exposure) may reduce creep ductility above 800ºC [9]. Therefore, to confidently optimize the design and manufacture of high-temperature HXs for all sCO_2 power systems using alloy 740H (or any other alloy) proper understanding of the processing, microstructure, and property relationships is needed in these alternative heat-treatment and processing regimes.

MATERIAL & EXPERIMENTAL PROCEDURE

The material used for the study was a 1.65mm (0.065") thick sheet supplied in the Mill Annealed (MA) condition with a composition shown in Table 1. The manufacturing route was Vacuum Induction Melting followed by Electroslag Remelting (VIM/ESR), forging into a slab and rolling to 6.4mm (0.25") thick hotband, and then successive rolling reductions and anneals to the desired thickness. The final continuous anneal was 1107ºC for approximately 5 minutes followed by a spray quench and stretcher leveled in coil as an outwork step. This material was produced as an 'intermediate product form' with a reported grain size of ASTM #7 (28.3 μm) and has been used as starting stock for thinner gauge sheet used in this study as well as welded tubing [10]. The thinner sheets produced from the starting sheet were 0.94 mm (0.037") and 0.46mm (0.018") in thickness and also provided in the MA condition as describe..

Table 1. Composition (wt%) of Alloy 740H used in this study (Heat-Lot: HT6306JK T19M)

C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti
0.0035	0.3	0.2		0.15	0.016	Bal	24.55	1.37	1.47
Co	Mo	Nb	Ta	P	B	V	W	Zr	
20.01	0.0503	1.52	0.011	0.004	0.002	0.01	0.046	0.018	

Heat-treatment studies, Table 2, were conducted in air furnaces using small coupons (approx. 6mm x 6mm) removed from the 1.65mm thick sheet. Test conditions were chosen based on the author's knowledge of typical materials processing and discussions with HX manufacturers. For the long-term heat-treatments (>= 240min) samples were placed in a pre-heated box furnace, thermocouples were attached to the coupons or coupon holders and used to monitor temperature; in 20 min the samples reached within 20ºC of the desired temperature and in 30 min reached the set temperature. For short-term (<60min) heat-treatments, an open tube furnace was used to quickly slide the sample in and out of the hot-zone. For furnace cooled (FC) samples, the furnace was shut-down and the sample was allowed to cool to at least 500ºC before removal. Cooling rates from the target solution annealing temperature to 600ºC were measured to be approximately 2ºC/min. Air cooling (AC) was extremely fast with cooling from temperature to 100ºC in <10min.

Table 2. Heat-Treatment Matrix (AC=Air Cool, FC=Furnace Cool)

Solution Annealing Temperature (C) & Cooling Method							Notes
Time	1135		1150		1190		
(min)	AC	FC	AC	FC	AC	FC	
2					x		Simulate Foil Processing
10			x		x		Simulate Foil Processing
30			x		x		Simulate Foil Processing
30-50			x		x		Similar to Welded Tube Studies [10] slower heating to temperature
240	x	x	x	x	x	x	Desired time for HX manufacturing
480	x	x	x	x	x	x	Desired time for HX manufacturing
840	x		x		x		Maximum diffusion bond cycle time

Following the heat-treatment study, selected heat-treatment conditions were applied to materials for creep testing. Sheets of varying thickness were either tested in the MA condition, the MA+aged condition (aging was conducted at 800C for 4 hours in air), or in the solution annealed (SA)+aged condition. For solution annealing, sheet sections were placed within stainless steel bags to minimize oxidation and heat-treated in a box furnace with the same control and loading conditions as the heat-treatment study. Pin-loaded sheet-type creep specimens, Figure 1, with a 31.8mm (1.25 in) gauge length were extracted from the sheets using wire electro-discharge machining (EDM). Creep testing was conducted in accordance with ASTM E139 at constant load in dead weight or lever-arm creep machines with continuous strain monitoring attached to the specimen shoulders outside the gauge (see figure 1). It is important to note that per the ASTM standard all samples received a minimum 1 hour soak at the testing temperature (in this case 750ºC) prior to starting the test so the MA test condition has some prior aging in the creep frame before testing.

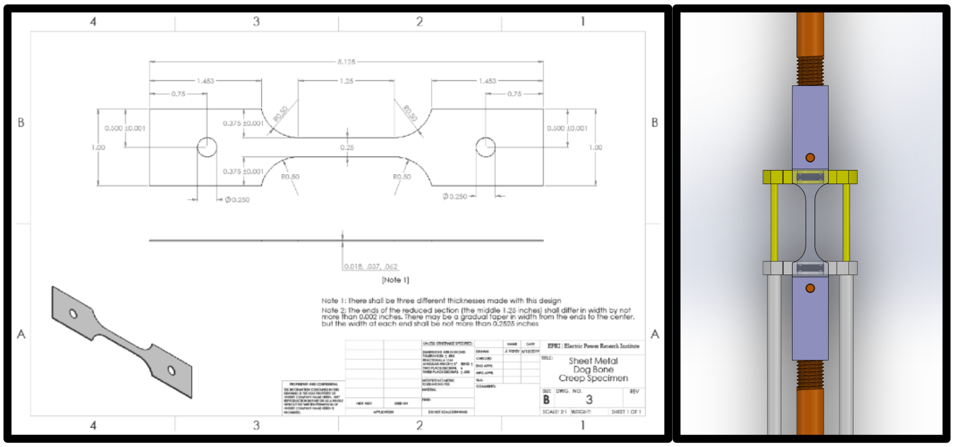

Figure 1. Creep specimen and arrangement of extensometer on sample shoulders

Samples from sheets and tested specimens were mounted in cross-section parallel to the rolling and creep testing direction (so the through thickness microstructure could be observed) and prepared using standard metallographic procedures with a final polish of 0.4μm colloidal silica with additional vibratory methods employed for advanced characterization on selected samples. Etching for grain size was performed with electrolytic nital (2% Nital@6V for 20-30 seconds) to preferentially attack grain boundaries and for microstructure analysis used Kallings No. 2 (5g CuCl2, 100ml HCl, 100ml; swab). Automated microhardness (Struers DuraScan) was performed on unetched samples. 20 indents were taken using a 300 gram load and a spacing of 0.25mm well away from the edges of the sample. Optical metallography was performed using a high resolution digital microscope (Keyence model VK-X). Automated image analysis for grain size was conducted using MIPAR Version 3.0.4 [11], and manual grain size measurements used traditional lineal intercept procedures in accordance with ASTM E112 for equiaxed grains. Scanning electron microscopy was performed on a FEI Tenero equipped with EDAX EBSD and EDS detectors.

RESULTS

Heat-treatment study

The starting material microstructure for the 740H mill annealed (MA) 1.65mm sheet is shown in figure 2 and characterized by equiaxed grains (ASTM 6.5-7.0) with extensive twinning and 'stringers' aligned along the sheet rolling direction (horizontal). A representative heat-treatment time/temperature curve is shown in Figure 3 for a longer-term heat-treatment followed by furnace cooling (FC). Heat-up was relatively rapid reaching the target temperatures in 20 to 30 min and a cooling rate of approximately 2ºC/min was measured. For the short-term heat-treatments using a different furnace configuration, more rapid heating allowed samples to reach temperature in approximately 1 min. Figure 3 shows the progression of the microstructure from no heat-treatment to the maximum time and temperature. The stringer's size and distribution do not change with heat-treatment but grain size increases notably.

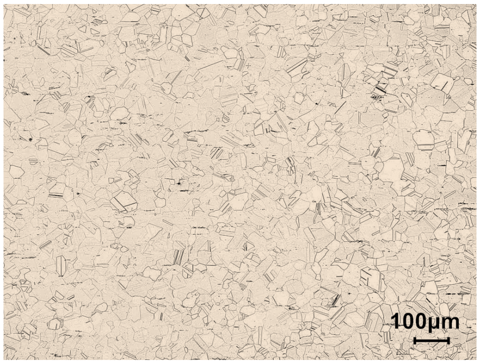

Figure 2. Microstructure of as-received mill annealed (MA) sheet [Kallings 2 etch]

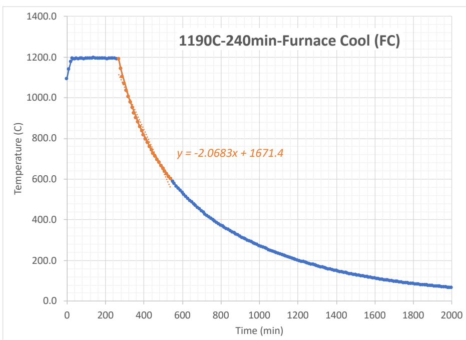

Figure 3. Characteristic time-temperature plot for longer-term heat-treatments (furnace cooling)

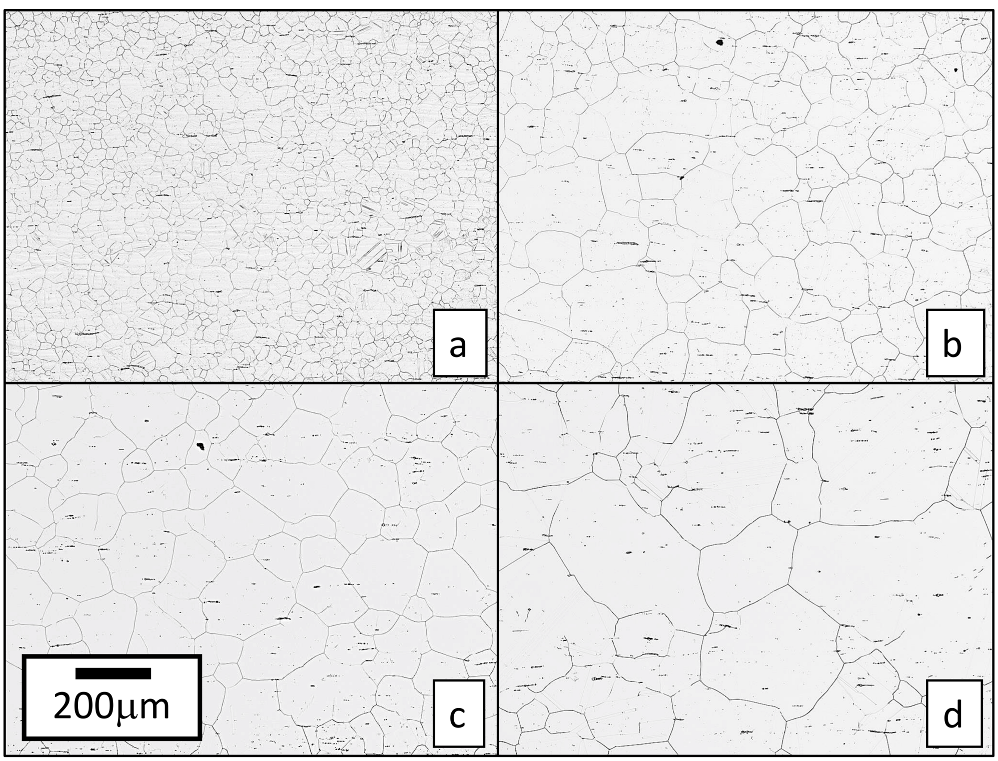

Figure 4. Examples of grain size for (a) MA, (b) 1135C-240min-AC, (c) 1150C-480min-AC, and (d) 1190C-840min-AC [electrolytic nital etch]

Grain sizes were measured for all of the AC samples. Using automated image capture and analysis, a cross-section of the entire sample through the thickness (approximately 6mm by 1.65mm) was analyzed. To eliminate stringers from the analysis, measurements less than 15 microns were screened. The results are reported in Table 3 for the manually determined grain size (ASTM) and the average result from the automated analysis. The automated routine could not distinguish between twins and grain boundaries for some etched conditions precluding its use on all samples. Figure 5 is a box and whisker plot for the measurements taken on each sample to more thoroughly describe the data (see appendix for definition of box and whisker plot). The ASTM values are plotted for comparison. Inspection shows that the average grain size is not a good quantitative measure of the material because there are large quartiles and multiple grain measurements which are statistical 'outliers.' Overall, the trend as a function of time and temperature was replicated by the manual and automated methods, but mean values for grain size statistics were clearly different than the ASTM measurements. Inspection of the table and plots show that even at very short-times and/or lower temperatures, the grain size increased rapidly from ~30μm to 110-150μm. At longer-times, 240 minutes and longer irrespective of temperature, caused even greater grain growth to 200μm or greater (ASTM 1.0 to 1.5) in most cases.

Table 3. Grain Size Measurement Results

Temp	Time	Linear Intercept Grain Size (microns)	ASTM GS	Average Diameter – Automated (microns)
Mill Anneal		31.2	6.5-7.0	
1135	240	131	2.5	101
1135	480	201	1.0-1.5	134
1135	840			
1150	10	129	2.5	
1150	30	145	2.0-2.5	
1150	40	201	1.0-1.5	
1150	240	202	1.0-1.5	147
1150	480	187	1.5	120
1150	840	179	1.5	
1190	2	113	3.0	
1190	10	149	2.0-2.5	
1190	30	178	1.5	
1190	40	175	1.5	124
1190	240	214	1.0-1.5	218
1190	480	193	1.0-1.5	164
1190	840	210	1.0-1.5	204

Figure 5. Grain size measurements on AC samples. Open circles are outliers while the solid squares are the standard ASTM measurements.

Hardness test results for all samples are plotted in figure 6. The furnace cooled samples all exhibited higher hardness values from approximately 310 to 350HV without any trend with time and temperature. Conversely for the air cooled samples the trends were more complex with short-term heat-treatments causing a drop in hardness compared to the starting Mill Annealed (MA) material but with prolonged solution annealing temperatures hardness increased above the starting condition.

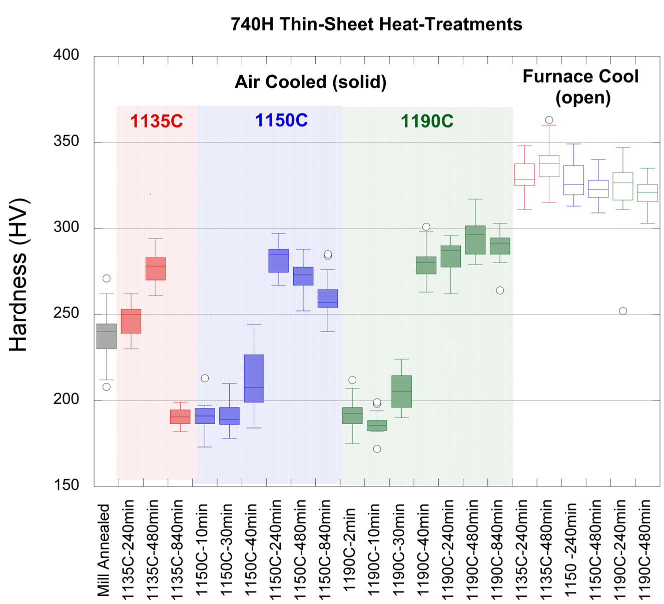

Figure 6. Microhardness results; box and whisker plot with outliers (open circle)

Heat-Treatment of Sheets & Creep Testing

Based on the heat-treatment study results, full sheets of 740H were selected for testing in the MA, MA+Aged, SA at 1150C-30min-AC+Age, or the SA 1190C-840min-AC+Age conditions. Table 3 shows the selected sheet thickness and heat-treatment conditions, the grain size measurements conducted on the sheets after heat-treatment, and the status of the ongoing creep-rupture testing. The table shows that while all the MA material had nominally the same finishing heat-treatment, the resultant grain size changes with thickness with the thinnest sheets have a larger average grain size compared to the thicker sheets. This trend persists with the 1150C heat-treat coarsening the grain sizes with the 1.65mm and 0.94mm sheets having similar grain size but the 0.46mm grain size being slightly coarser. Figure 7 are SEM images using EBSD highlighting the differences in grain sizes for the different sheet thicknesses and heat-treatments. For creep testing a total 14 of the 18 planned tests are complete with the final four ongoing. All testing is at 750C, and the time-to-rupture results are plotted in Figure 8 which also includes the standard 740/740H wrought database [9].

Table 3. Alloy 740H Full Sheet Grain Size Measurements and Creep Test Status

Sheet Thickness mm (inch)	**Heat-Treatment** (Age = 800C-4hrs)	Linear Intercept Grain Size (microns)	ASTM GS	**Creep Test Status** complete/planned (longest test time)
1.65 mm (0.065")	MA	32	6.5-7.0	3/3 (~1,200hrs)
	MA+Age			1/1 (~1,200hrs)
	1150C-30min-AC+Age	108	3.0-3.5	3/3 (~7,000hrs)
	1190C-840min-AC+Age	197	1.0-1.5	3/3 (~3,600hrs)
0.94 mm (0.037")	MA	38	6.0-6.5	1/2 (~1,300hrs)
	1150C-30min-AC+Age	96	3.0-3.5	1/2 (~1,700hrs)
0.46 mm (0.018")	MA	51	5.0-5.5	1/2 (~1,100hrs)
	1150C-30min-AC+Age	123	2.5-3.0	1/2 (~2,800hrs)

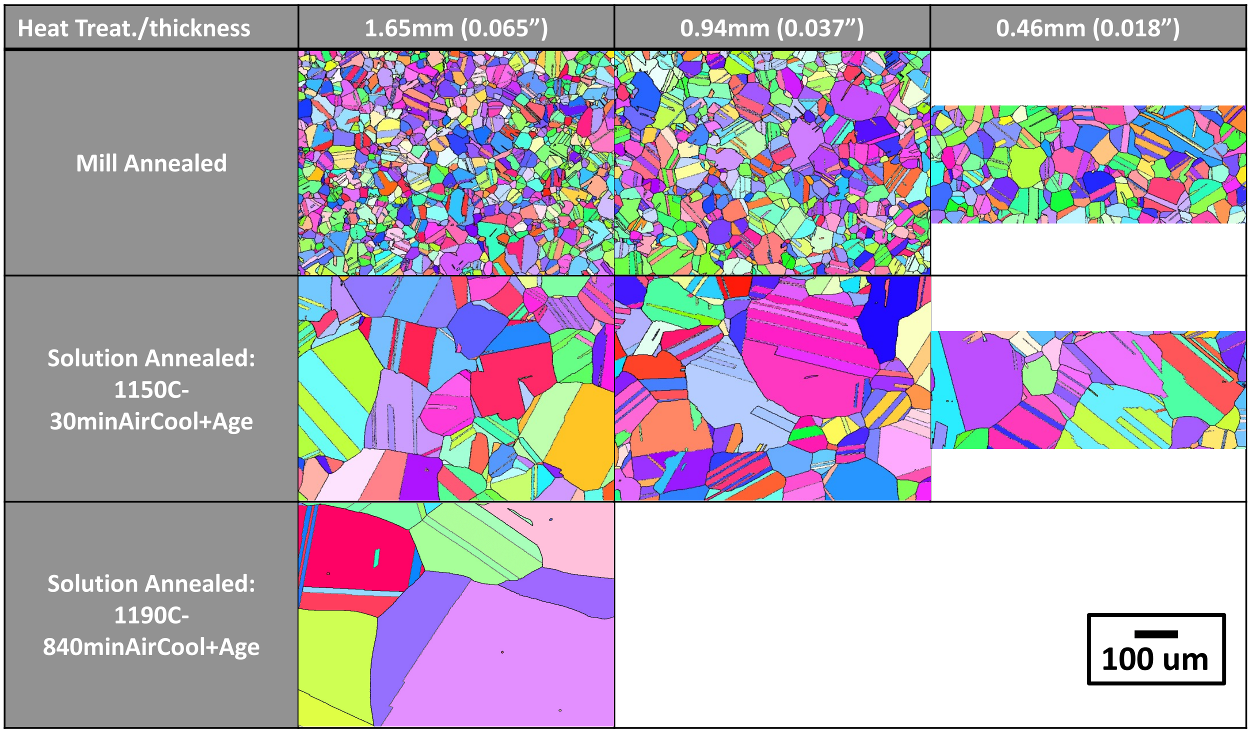

Figure 7. EBSD maps showing the relative grain sizes of the starting sheets

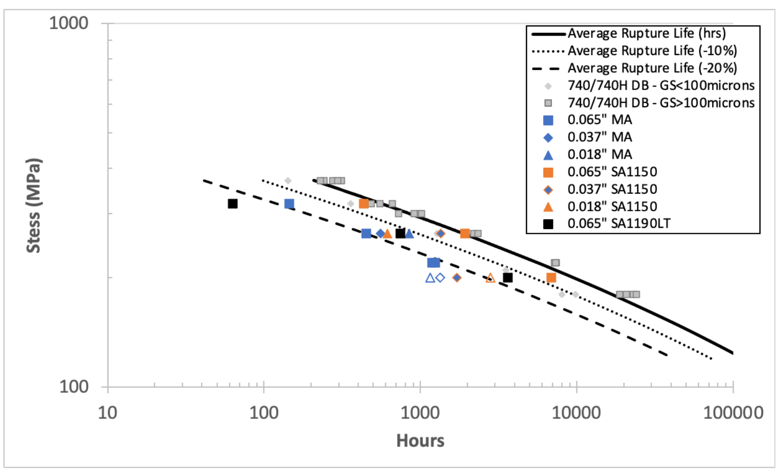

Figure 8. Time-to-rupture for alloy 740H sheet creep tests at 750C, ongoing tests are open symbols. Gray 740/740H DB (wrought data base) points are included from Ref [9].

DISCUSSION

Heat-treatment study

Initial inspection of the grain size results in Table 3, show that the grain size coarsen quickly at all the heat-treatment times and temperatures rapidly, going from an ASTM 6.5 to 7.0 to a 2.0-2.5. For all the heat-treatments which exceeded 30 minutes, irrespective of temperature, the average grain size became ASTM 1.0 to 1.5. However, closer inspection of the data in Figure 5 shows that while the average grain size was 'equivalent' on the standardized ASTM scale, the actual data was different as a function of temperature. The statistical box plots show that the average values are inflated from the mean due to outliers, i.e. individual large grain(s). Thus, there are clear differences in the maximum size of outliers with the 1135 and 1150ºC long-term aged samples having grains as large as 300 to 500 μm and the 1190ºC samples having individual grains between 500 and 600 μm. Considering the overall thickness of the sheets is between ~1650 and ~460μm, the longer heat treatments may result in samples with locations where there may only be a few grains across the entire sample thickness. The EBSD images in Figure 7 clearly show this effect for the thinner sheets which only have a few grains through the thickness after heat-treatment. When only a few grains are aligned across a sample thickness, there is the potential for high variability in creep strength due to changes in creep mechanisms [12] as well as loss of creep ductility because the sample behavior is controlled by a few local grain boundaries. Furthermore, effects of grain size and creep need to account for the variability in the microstructure and the ASTM grain size may not be the best measure. Additional measurements of grain boundary length, for example, may be used in the future to clarify grain boundary effects with greater accuracy. Also, measuring maximum grain size (either outliers or 95% confidence interval) may be more important to the controlling creep mechanism when testing sheets and foils.

Since the optical metallography precluded full statistical analysis for grain size for all samples, the average grain size was plotted against the average hardness data from Figure 6 in Figure 9 using the Holoman Jaffe Parameter (HJP) using a generalized constant of 20 (no attempt to optimize the parameter was undertaken) as follows:

$$HJP = (T^{o}C+273) \times \text{Log}[\text{time(hrs)}+20] \qquad \text{(equation 1)}$$

which allows the data from different times and temperatures to be compared to each other. The mill annealed starting material is plotted for comparison along with the typical hardness measurements for wrought alloy 740H in the mill annealed and aged condition. While the material shows a general trend to higher grain sizes with increasing HJP, the hardness behaves differently. For the furnace cooled samples, hardness is high, presumably due to precipitation and growth of gamma prime precipitates (auto-aging phenomenon). The hardness values in all these samples which all had the similar furnace cooling profiles were very similar indicating the heat-treatment time and grain size had essentially no effect on the hardness. However, the actual hardness values, about 325HV, were still lower than fully solution treated and aged 740H which will hardness values of approximately 375HV depending on the specific aging heat-treatment given (typically 4+ hours at 760-800ºC). Based on the author's knowledge of 740H behavior in typical wrought processing, at cooling rates of ~2ºC/min, up to 10vol% gamma prime is expected to form which is about 50% the amount of gamma prime in the standard aged conditions. Thus, the results for the furnace cooling are well in-line with expectations.

The trend for hardness in the air cooled (AC) samples was not directly correlated to the grain size. This can be observed by the curve fits through the data in Figure 9. Grain size increases significantly from the starting MA material but grow slows with increasing HJP (decreasing rate). Conversely, the hardness for the shorter-times and temperatures (lower HJP) stay quite low (around 180HV) and then go through a 'step-change' to approximately 275HV. Since the grain size measurements were done using a 300g load, the size of the indents was much smaller than the size of the grains with the exception of the MA material, thus grain size, which generally has an inverse relationship with tensile strength and thus hardness, is likely to have no effect on the hardness which is borne out in the observed behavior. While all AC samples were air cooled in less than 10 minutes (on the order of a 100ºC/min), removal of the long-term samples from the aging furnaces did take a few minutes while the short-term samples (30minutes and less) were extracted instantaneously. Therefore, it is plausible that the variation in hardness is due to very fine nucleation of gamma prime during cooling of the longer-term aged samples. These samples had hardness values approaching those typically found in thicker wrought products which are given forced air or water quenching. SEM analysis for gamma prime and other precipitates could be used in the future to confirm the trends in the hardness data.

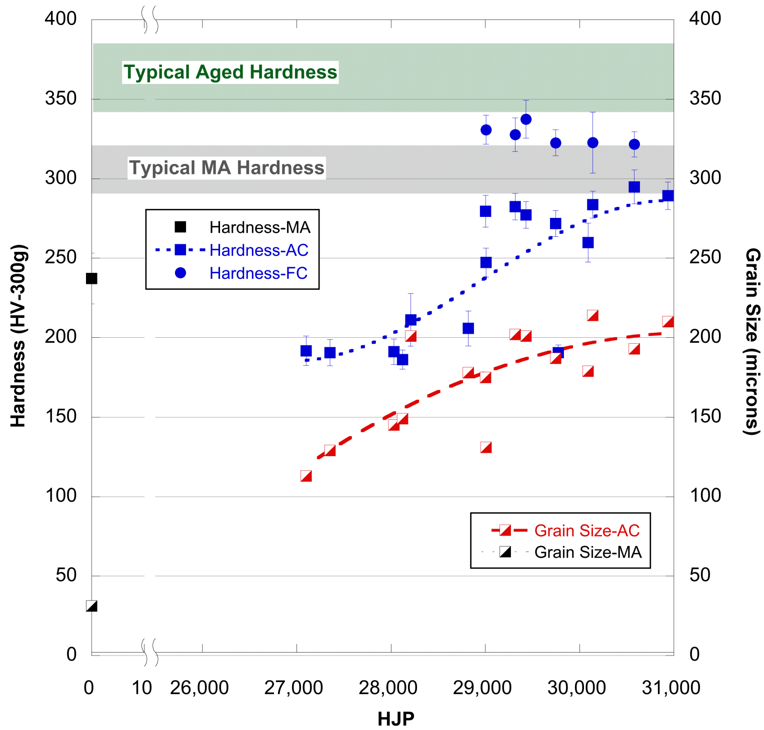

Figure 9. Average hardness and grain size using the HJP (equation 1, constant = 20) and compared to typical wrought hardness values

Heat-Treatment of Sheets & Creep Testing

Creep-rupture test data are plotted against the 740/740H database (DB) [9] in Figure 8. The expected 740H average rupture at 750ºC along with a -10% and -20% on stress lines are plotted for comparison of the data. The data clearly show the effect grain size has on the standard wrought products (gray datapoints) with grain sizes >100µm meeting or exceeding the average rupture life while lower grain sizes trend to -10% on stress from average. The current rupture life results show some interesting trends:

- All the MA materials have rupture lives around -20% except for the thinnest sheet which is close to -10%. Table 3 and Figure 7 both show coarser grain size for the thinnest MA sheet with average grain diameter of ~50µm whereas the other sheets are ~30µm. The wrought 740H database has grain sizes down to ~80µm which suggests that the grain size effect in standard wrought product continues to follow the same trend downward as grain size further decreases.

- To ensure no complication in the data, since the majority of the sheet was testing in the MA condition without a secondary age hardening heat-treatment, a duplicate longer-term test was conducted on the 1.65mm sheet in the MA+Age condition. The rupture life was 1239 hours compared to 1192 hours for the MA condition; so effectively aging was found to have no effect on rupture life for testing at 750ºC. It is important to note that per the

ASTM standard, the sheet will actually receive a minimum 1 hour 'heat-treatment' at the testing temperature which is close to the standard aging heat-treatment. Testing by others [13, 14] has confirmed that aging is not required at 750ºC and above to achieve equivalent creep strength and ductility to aged material. This is presumably because the material ages rapidly in the testing condition. Therefore, we do not believe there is an influence of not aging the MA material for these creep test conditions.

- For the SA heat treatments at 1150ºC, a significant change in performance was found as near average rupture life was obtained for the 1.65mm sheet, but the same heat-treatment on the thinner sheets resulted in rupture life between the MA and average wrought for the 0.94mm sheet and a small loss in creep life for the 0.46mm sheet. The thinner sheets creep testing continues to determine if this trend holds for multiple tests at different stress levels.

- The long-term 1190ºC SA heat-treatment on the 1.65mm sheet results in poor, near -20%, creep-rupture life despite having the largest grain size tested.

To clarify some of the effects of grain size and creep, Figure10 presents not only rupture life, but creep deformation resistance (minimum creep rate), and rupture ductility for all the tests conducted on the 1.65mm sheet against the 740H database. The MA material has lower rupture life, higher creep rates and generally middle of the scatterband creep ductility when compared to wrought. Interestingly, the slope of the minimum creep rate versus stress plot diverges from the slopes of the database and the other sheet samples suggesting a different creep mechanism. The 1150ºC SA has middle of the scatterband creep life, creep rate, and somewhat lower scatterband ductility. The 1190ºC long-term heat-treatment shows reduced rupture life which is more pronounced at high stresses, within scatterband minimum creep rates, but very low below scatterband ductility. Thus, it appears the long-term heat-treatment rupture life debit compared to wrought is principally due to loss of creep ductility, although the creep rate data is on the lower-end of the scatterband.

To clarify the failure modes, Figure 11 presents the cross-sectional metallography for all of the 1.65mm ruptured samples. Inspection of the figure shows some interesting trends. The creep damage in the MA material at high stress and short rupture times is dominated by surface and near-surface intergranular cracking. At longer times the damage becomes more uniform through the sample thickness, but in general is still non-uniform through the sample thickness. Microcracking and failure are perpendicular to the loading direction. For similar stress levels and failure times, the 1150ºC SA material shows relatively uniform and widespread intergranular wedge cracking, cracking at triple points, and grain boundary cavitation. The 1190ºC SA material showed fine grain boundary cavitation and limited large microcrack or grain boundary separation. There are relatively few cracks observed, and the failure locations show full grain boundary separation with little additional damage. In some cases (see the shortest and longest tests on the 1190ºC material), large grains on the order of ½ the sample thickness appear to be on the main failure crack path. Overall, while the fracture evaluation shows intergranular damage, the different locations and types of damage clearly indicate differing failure modes directly related to both the grain size and sheet thickness.

Putting the creep data and metallographic evaluation together for the 1.65mm sheet, it appears that the fine grain MA material has a different operative creep mechanism compared to all the other 740H materials. The evidence for this is the differing slope of the minimum creep rate data combined with the surface dominated damage which suggest principle stress is not the only contributor to creep damage. In contrast, the 1150ºC SA material showed similar creep rates to wrought products and widespread intergranular creep damage similar to other wrought observations [15]. While the coarser grain 1190ºC SA material showed intergranular damage, the damage was not widespread, and it appears reduced resistance to creep crack growth due to large grains leads to the reduction in macroscopic ductility.

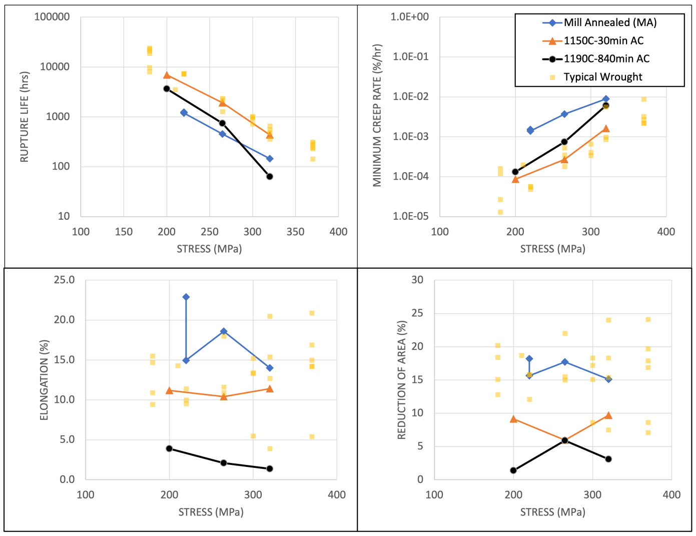

Figure 10. Comparison of creep-rupture results at 750ºC on the 1.65mm (0.065") sheet compared to the wrought database

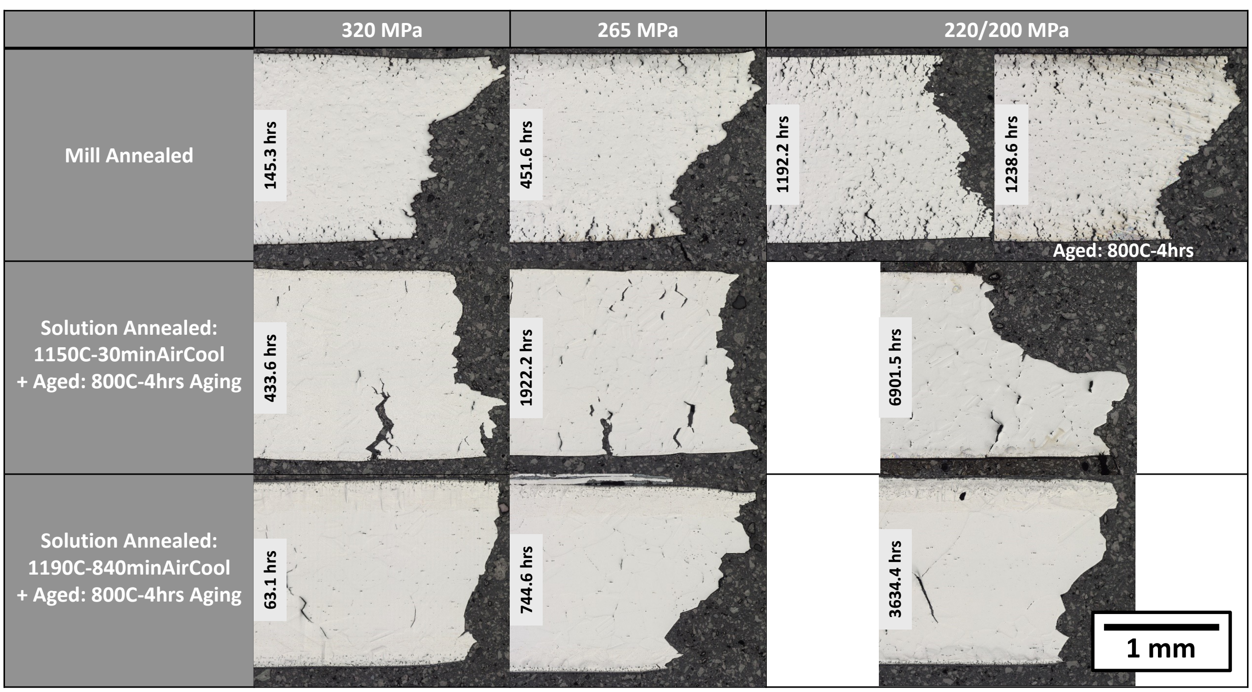

Figure 11. Polished (un-etched) optical images of 1.65mm ruptured sheet creep samples tested at 750ºC near the fracture location. Loading axis is horizontal.

CONCLUSIONS & FUTURE RESEARCH

A study was conducted to evaluate the fundamentals of heat-treatment, grain size, hardness, microstructure, and creep strength in alloy 740H sheets. The findings show that:

- Grain growth can be very rapid and that average grain size based on ASTM methods may not be the best measure for assessing the behavior of sheets and foils. This is because individual large grains may control the high-temperature behavior once there are only a few grains thick. Heat-treatments at 1190ºC for as little as 240minutes were sufficient to create large individual grains >500μm.

- Microhardness measurements confirmed auto aging in furnace cooled samples, but the absolute hardness values were still below standard aging heat-treatments.

- Microhardness and grain size effects appeared to be independent of one another

- Completed creep tests on the 1.65mm sheets showed clear influences of grain size and sheet thickness with fine grain MA material having higher creep rates leading to reduced rupture life. Conversely long-term 1190ºC heat-treatment resulted in reasonable creep resistance in comparison to wrought, but significant reductions in ductility with the metallography suggesting large grains are reducing the alloy's resistance to creep crack growth.

- Ongoing creep tests on thinner sheets show the 'not all MA material' behaves the same with some improvement in rupture life for 0.46mm thick sheet over other MA product thicknesses. Similarly, the 1150ºC heat-treatment, while beneficial to rupture performance for the thicker sheets was detrimental to rupture life of the 0.46mm sheet. This suggest a similar trend as the 1.65mm sheet where larger grains of similar size to the sheet thickness control failure and rupture life.

Based on these findings, it is clear that grain size, grain size distribution, and sheet thickness all must be considered in understanding the creep performance of alloy 740H sheet at 750ºC. The average grain size does not appear to be the best measure of performance when large individual grains approaching the thickness of the sheet reduce crack growth resistance and lead to shortened rupture life and ductility. Ongoing work including creep testing is aimed at:

- Using SEM EBSD techniques on limited samples to quantify overall grain boundary length as an alternative measurement of grain size.

- Detailed comparisons and analysis of the creep data using statistic measurements of grain size versus sheet thickness to determine an optimum window for sheet thickness and grain size. The goal is to provide a window of heat-treatment conditions and sheet thicknesses to keep creep strength within the expected base metal scatterband.

Overall, this work shows the importance of understanding the effect secondary processing will have on future compact heat-exchangers. In general, if a HX manufacturer utilizes 740H within the creep regime in the MA material, some reduction in creep life is likely, but the alloy will have high ductility making it damage tolerant. Conversely, when using very thin sheets or when subjecting thicker sheets to long-term high-temperature SA cycles, there appears to be combinations of grain size and thickness which results in significant reductions in creep ductility leading to reduced creep-rupture life. Thus, HX designers should be aware that the manufacturing procedures may influence long-term creep strength and should appreciate where these debits in strength and ductility may be considered in design.

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APPENDIX: Box Plot Definitions

Figure 5 and 6 utilizes a box plots to represent the data collected on grain size and hardness. Unlike Table 3 which reports average or mean size, the center line on the box plot is the median value of the dataset and the top and bottom of the box (upper and lower quartile) are halfway between the median and the largest or smallest dataset value. Outliers are individual datapoints which are greater than 1.5 times the interquartile distance. Figure A-1 describes the terminology and calculation method utilized.

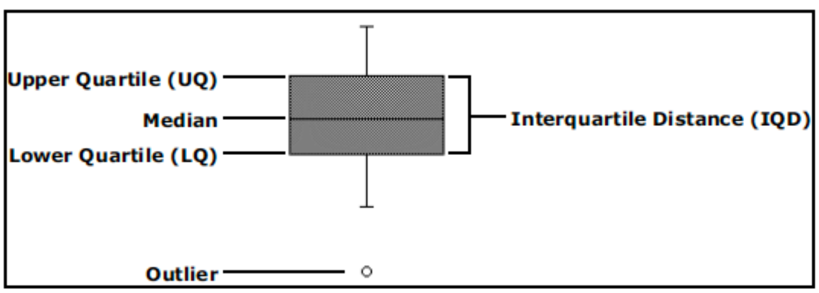

Figure C-1 Box plot terms

- **Median -** The data value located halfway between the smallest and largest values.
- **Upper Quartile (UQ)** - The data value located halfway between the median and the largest data value.
- **Lower Quartile (LQ) -** The data value located halfway between the median and the smallest data value.
- **Interquartile Distance (IQD) -** The distance between the Upper and Lower Quartiles (UQ - LQ).
- **Outliers -** Points whose value is either:

  greater than UQ + 1.5 * IQD or less than LQ - 1.5 * IQD

Figure A-1 Box Plot description and definitions