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

Paper #144

John Shingledecker, Eeva Griscom, Alex Bridges
Electric Power Research Institute

Jack deBarbadillo, Brian Baker
Special Metals Corporation

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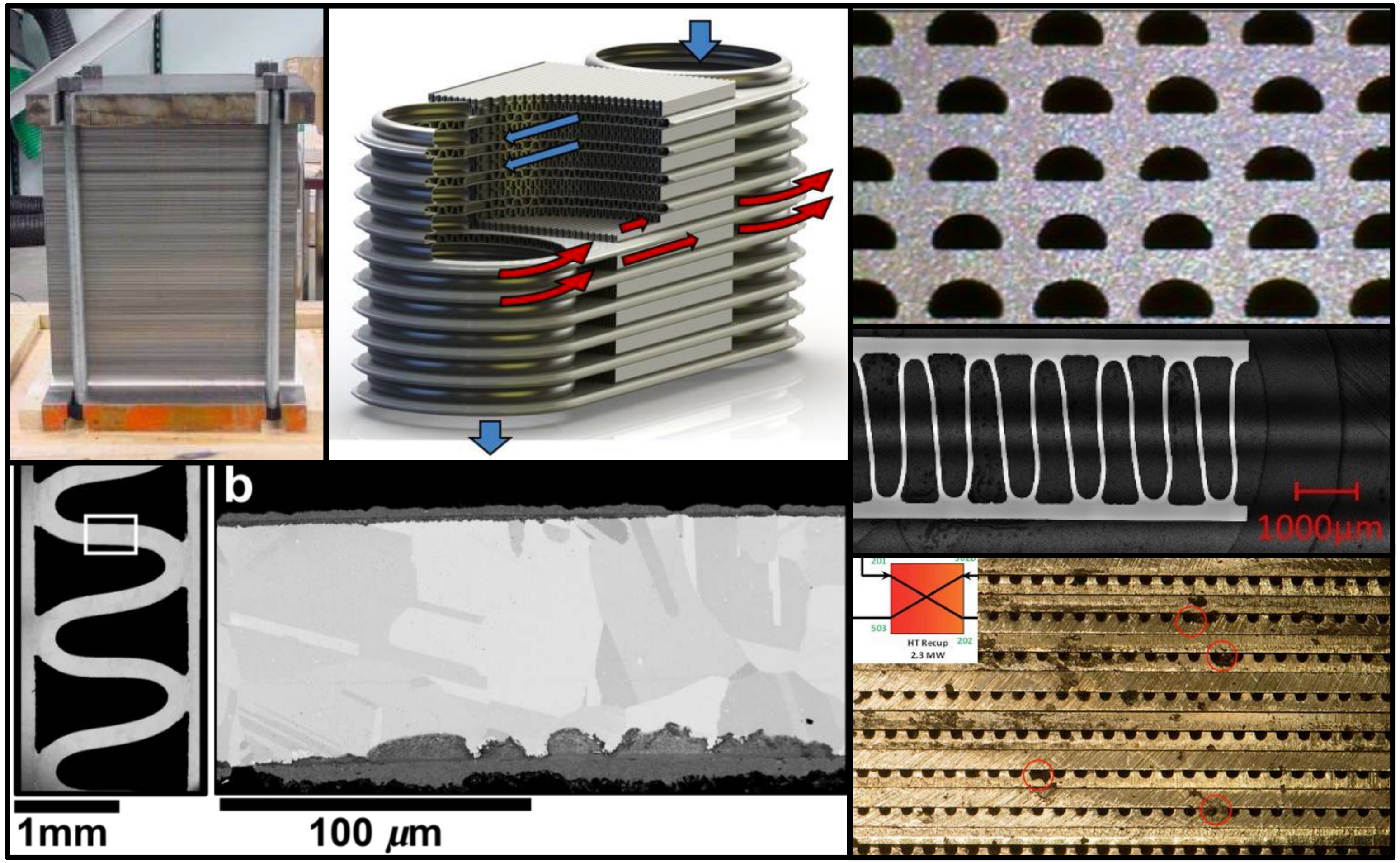
Compact Heat Exchangers

- Key component for sCO2 power cycles
- Multiple manufacturing routes
- Questions still remain on long-term high-temperature performance



Most larger-scale compact heat-exchangers start as metallic sheets and foils

Images taken from EPRI research & publicly available resources:NETL Cross-Cutting Reviews, NETL UTSR Reviews, sCO2 Symposiums

Processing of metallic sheets & foils

- Annealing times and temperatures may vary from traditional wrought processing
- Rapid heating and cooling may effect:
  - Grain size
  - Precipitate dissolution, size, and composition

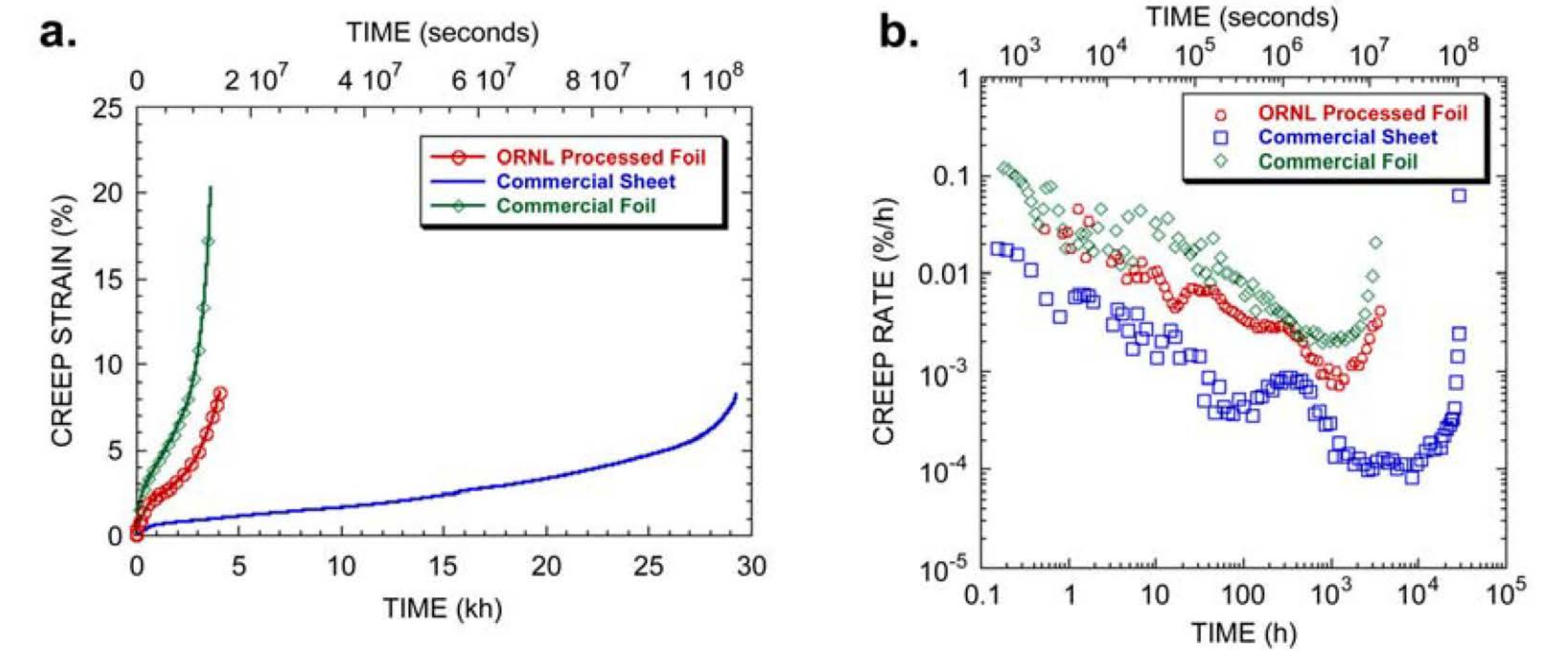


Figure 2. Thin section alloy 625 foils and sheets tested at 750°C, 100MPa a.) rupture life and b.) creep rates are functions of specimen thickness.

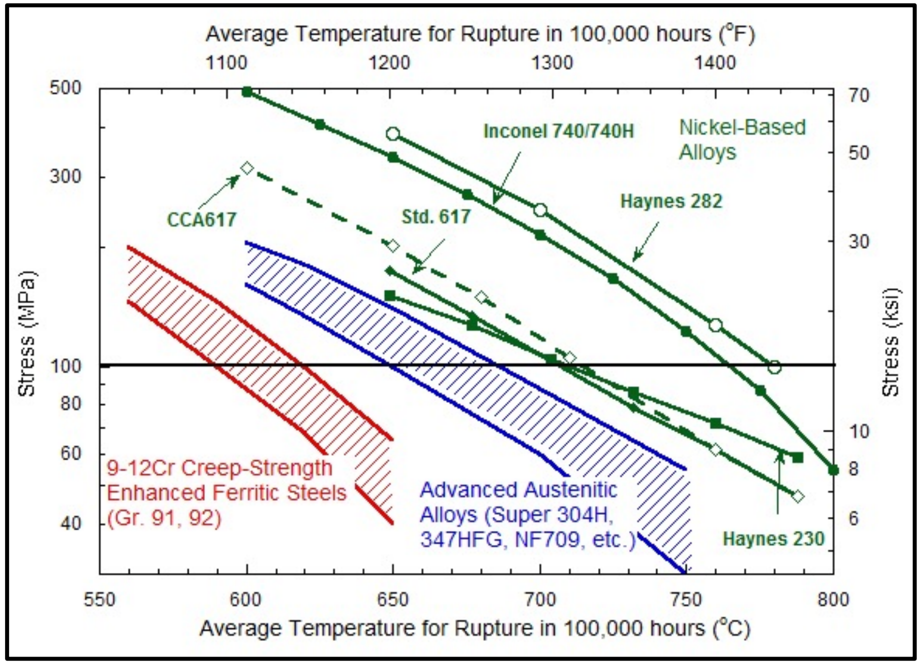
Ni-based alloy 625

Evans et. al., *Candidate Alloys for Cost-Effective, High-Efficiency, High-Temperature Compact/Foil Heat-Exchangers, MS&T, 2007*

High-temperature behavior of sheets and foils may depend on specific alloys and processing

Material: Inconel® Alloy 740H®

- Age-hardenable Ni-based alloy for application to 800°C
- 3 Sheet thickness obtained from the same heat
- Industrial process – Mill Annealed (MA) Condition
  - VIM/ESR → slab → 6.4mm thick hotband
  - Rolling reductions to target thickness
  - Final continuous anneal of 1107C for ~5min, spray water quench



Sheet Thicknesses	
1.65mm	0.065”
0.94mm	0.037”
0.46mm	0.018”

Composition (wt%)

C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti
0.0035	0.3	0.2	0.0002	0.15	0.016	Bal	24.55	1.37	1.47
Co	**Mo**	**Nb**	**Ta**	**P**	**B**	**V**	**W**	**Zr**	
20.01	0.503	1.52	0.011	0.004	0.002	0.01	0.046	0.018	

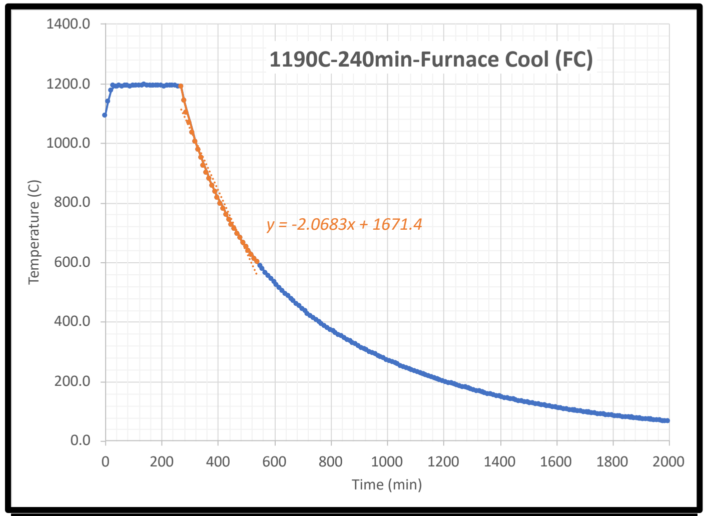
Sheet is an ‘intermediate’ product form (suitable for additional processing, heat-treatment, and final aging heat-treatment)

Heat-Treatment Study Matrix

1.65mm sheet

Solution Annealing Temperature (°C) & Cooling Method*							Target Condition
Time	1135		1150		1190		
(min)	AC	FC	AC	FC	AC	FC	
2					x		Simulate Foil Processing
10			x		x		
30			x		x		
30-50			x		x		Typical processing for wrought
240	x	x	x	x	x	x	Desired times for HX manufacturing
480	x	x	x	x	x	x	
840	x		x		x		Maximum diffusion bond cycle time

AC=Air Cool, FC=Furnace Cool

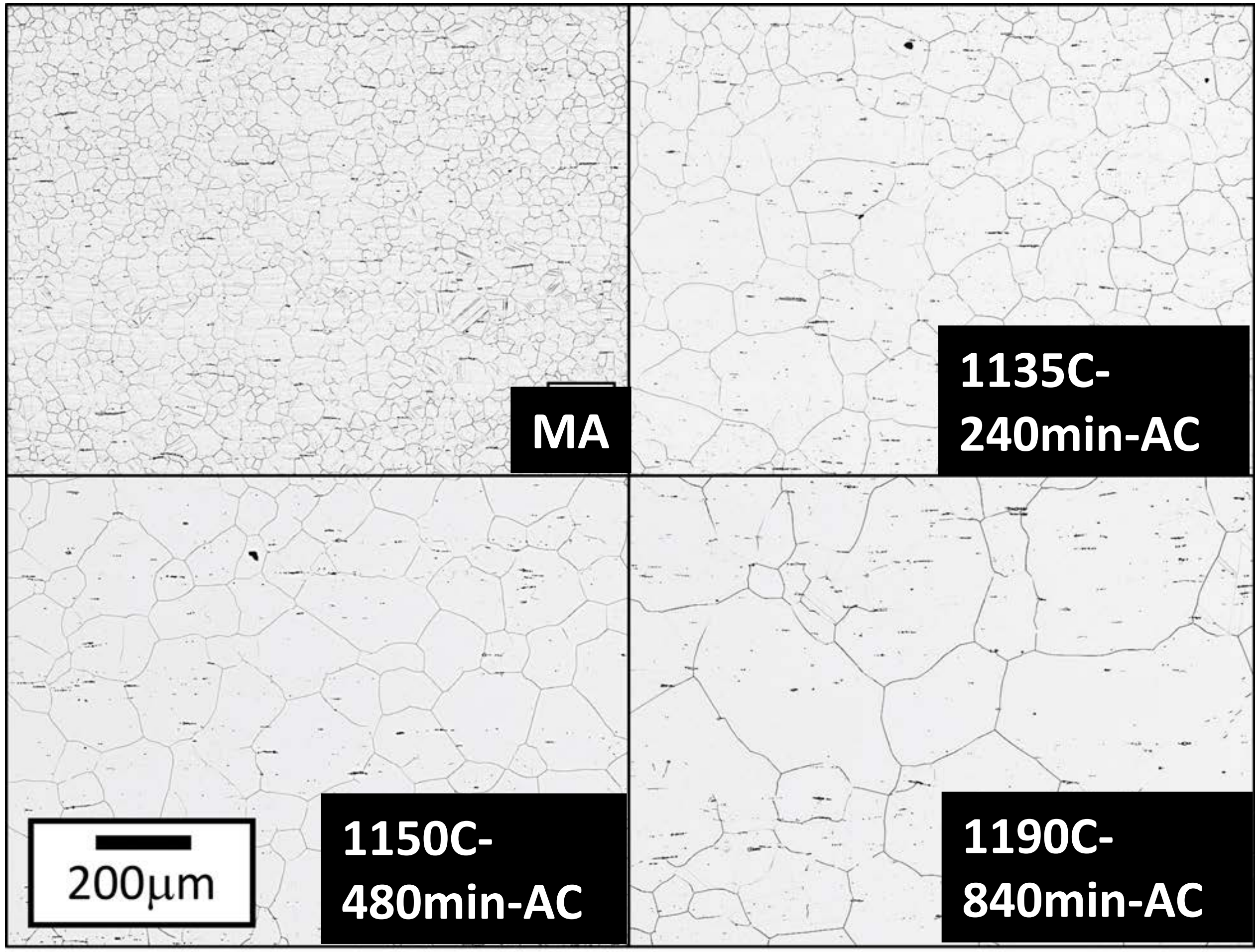


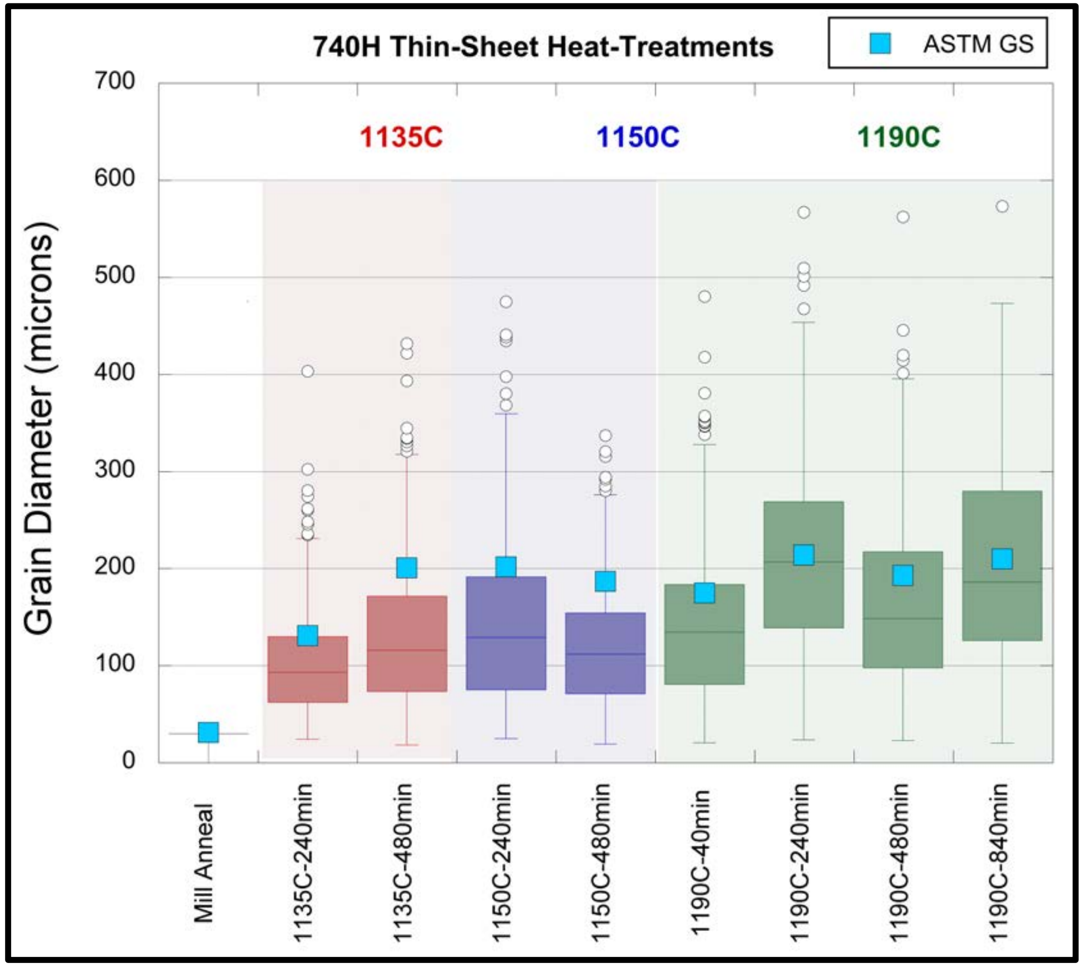
Example of heat-treatment record

Matrix developed with input from various developers and literature to represent a range of potential processing conditions

Microstructural Results – Grain Size

1.65mm sheet





Grain size can affect creep behavior, but what is appropriate measure of grain size?

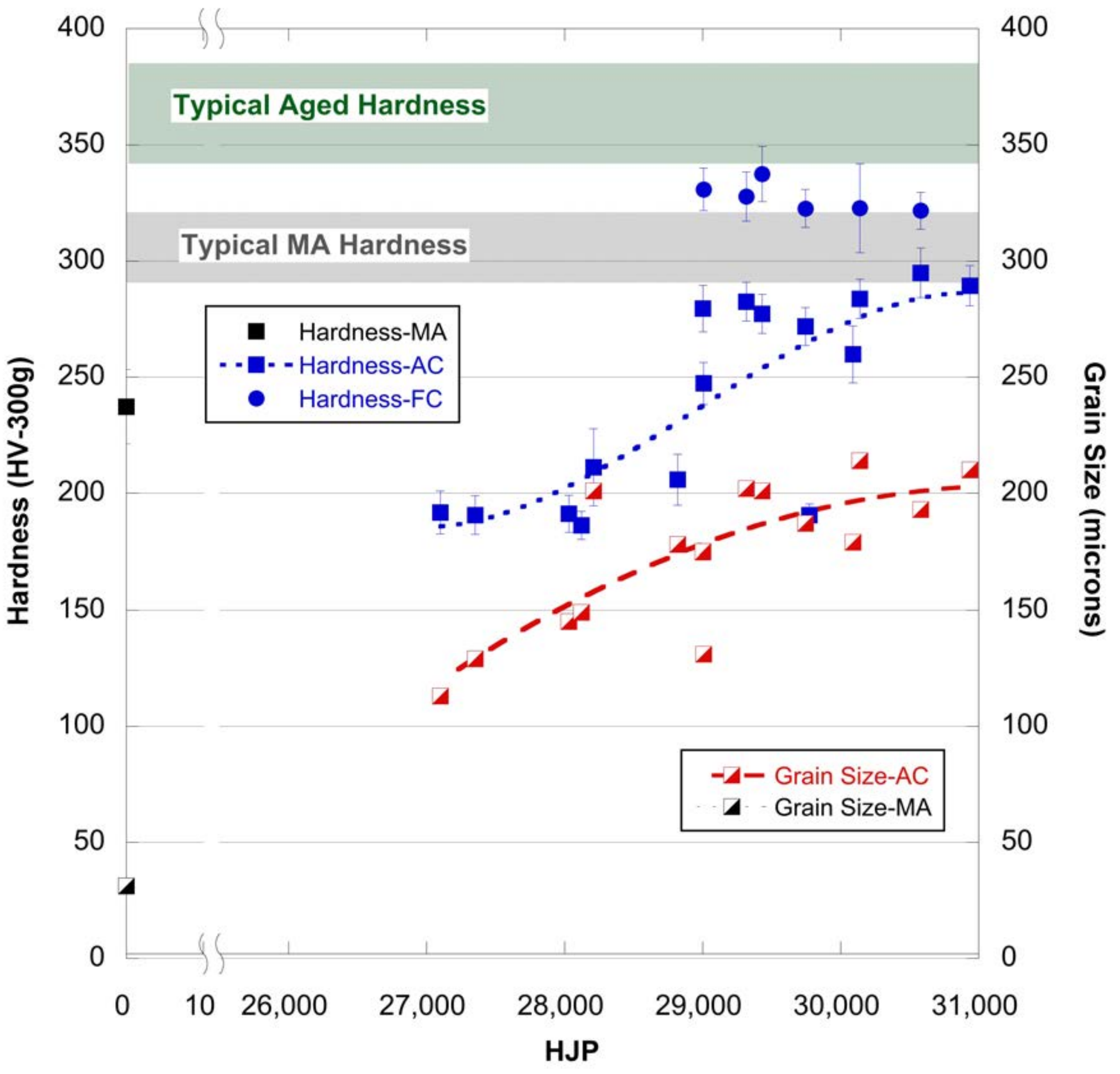
ASTM Average GS and GS distribution including outlier grains approaching sheet thicknesses

Microstructural Results – Hardness & Grain Size

1.65mm sheet

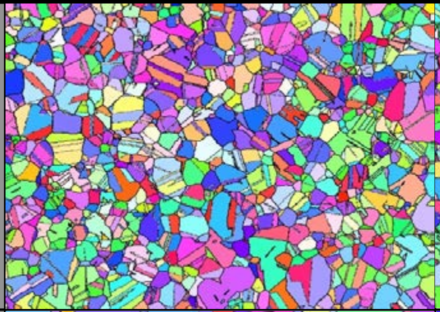
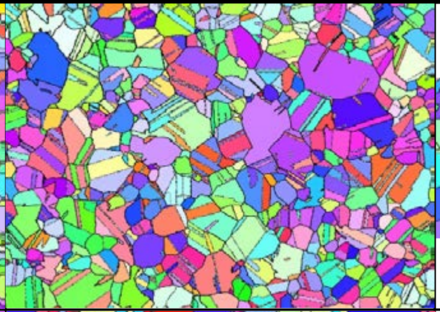
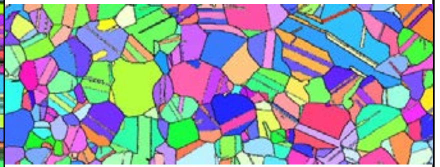
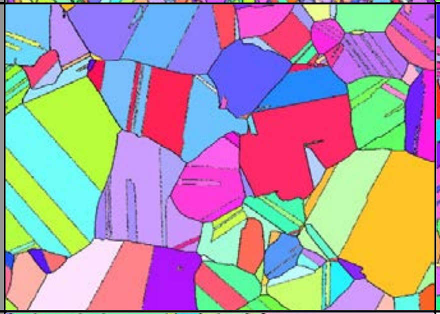
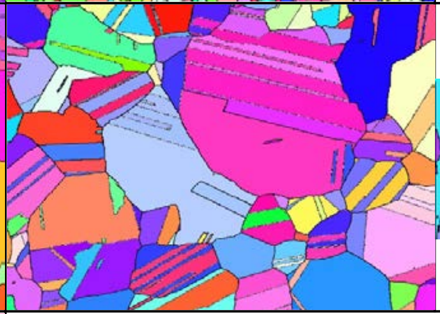
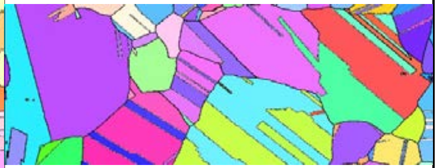
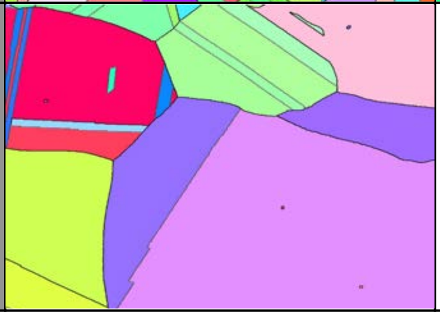
- Furnace cooling (slow cooling) results in hardness similar to other wrought products
- Grain size generally follows traditional time-temperature relationships

Based on grain size and hardness results and sheet thicknesses, multiple heat-treatments were conducted on full-sheets for assessment of high-temperature performance



HJP = (T°C+273) x Log[time(hrs)+20]

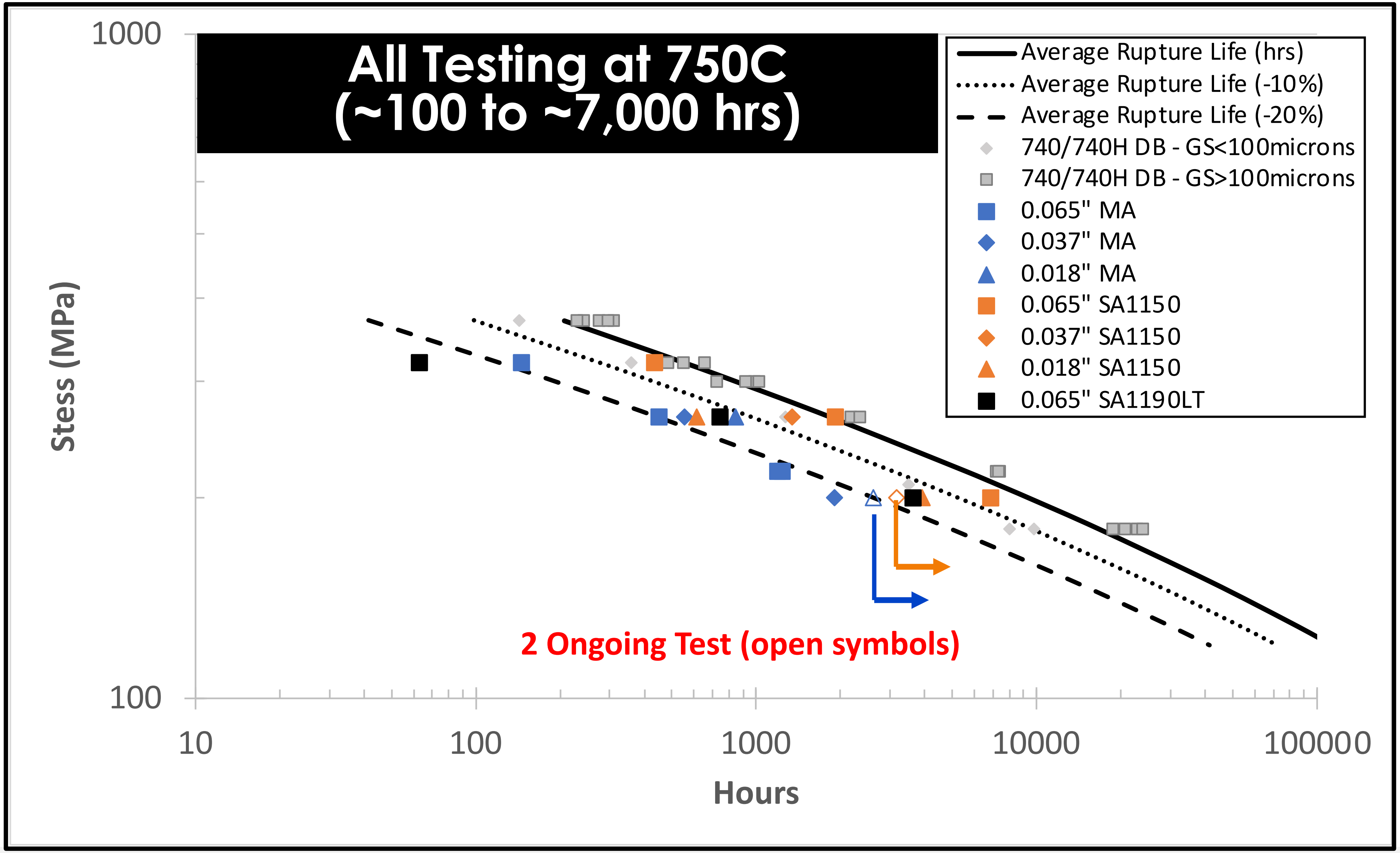
Microstructures for 740H Sheet Creep Testing

Heat Treat./thickness	1.65mm (0.065”)	0.94mm (0.037”)	0.46mm (0.018”)
Mill Annealed			
Solution Annealed: 1150C-30minAirCool+Age			
Solution Annealed: 1190C-840minAirCool+Age			100 um

Sheet Thickness mm (inch)	Heat-Treatment (Age = 800C-4hrs)	Linear Intercept GS (μm)	ASTM GS
1.65 mm (0.065”)	MA	32	6.5-7.0
	MA+Age		
	1150C-30min-AC+Age	108	3.0-3.5
	1190C-840min-AC+Age	197	1.0-1.5
0.94 mm (0.037”)	MA	38	6.0-6.5
	1150C-30min-AC+Age	96	3.0-3.5
0.46 mm (0.018”)	MA	51	5.0-5.5
	1150C-30min-AC+Age	123	2.5-3.0

Grain size varies for sheet thickness & heat-treatment

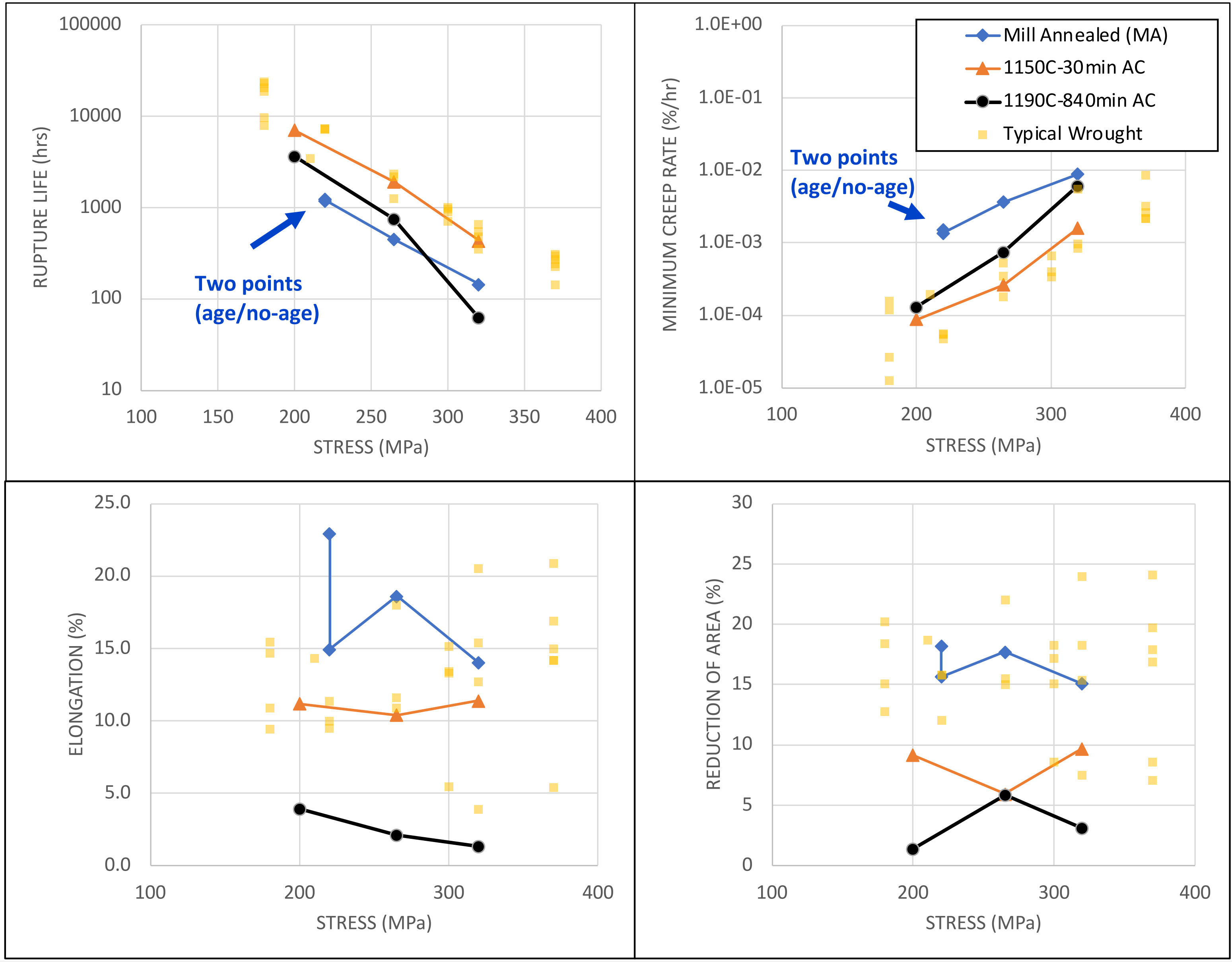
Creep-rupture testing



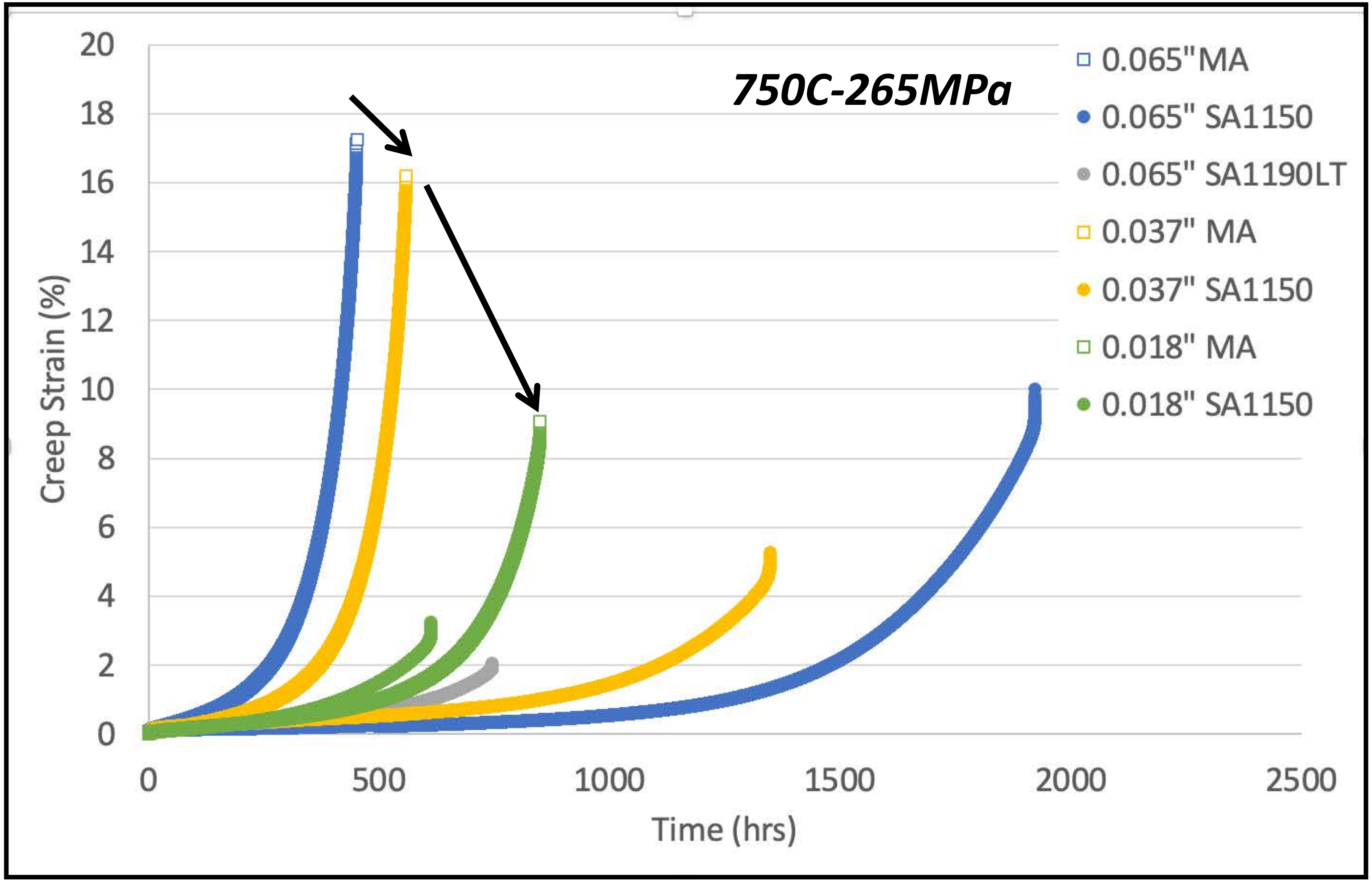
Creep-Rupture Testing

1.65mm sheet

- MA:
  - No effect of aging
  - Lower rupture life and creep resistance with average ductility
- 1150C-30min
  - similar to wrought (lower in-scatterband ductility)
- 1190C-840min
  - Average long-term rupture life and creep resistance
  - Poor creep ductility



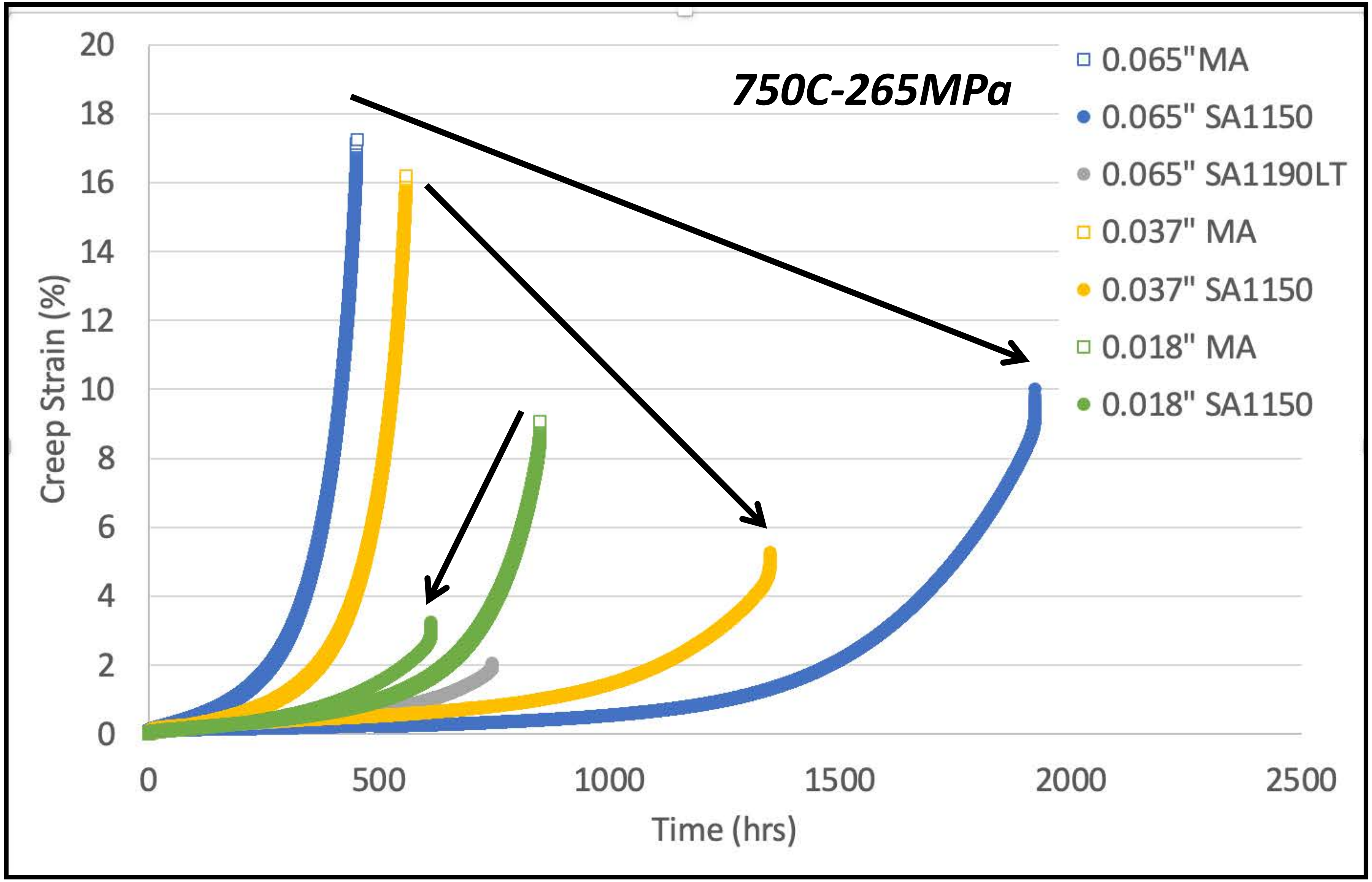
Creep behavior: All Sheets



Not all Mill Annealed Material Behaves the same

0.46mm shows improved life compared to thicker sheets

Creep behavior: All Sheets

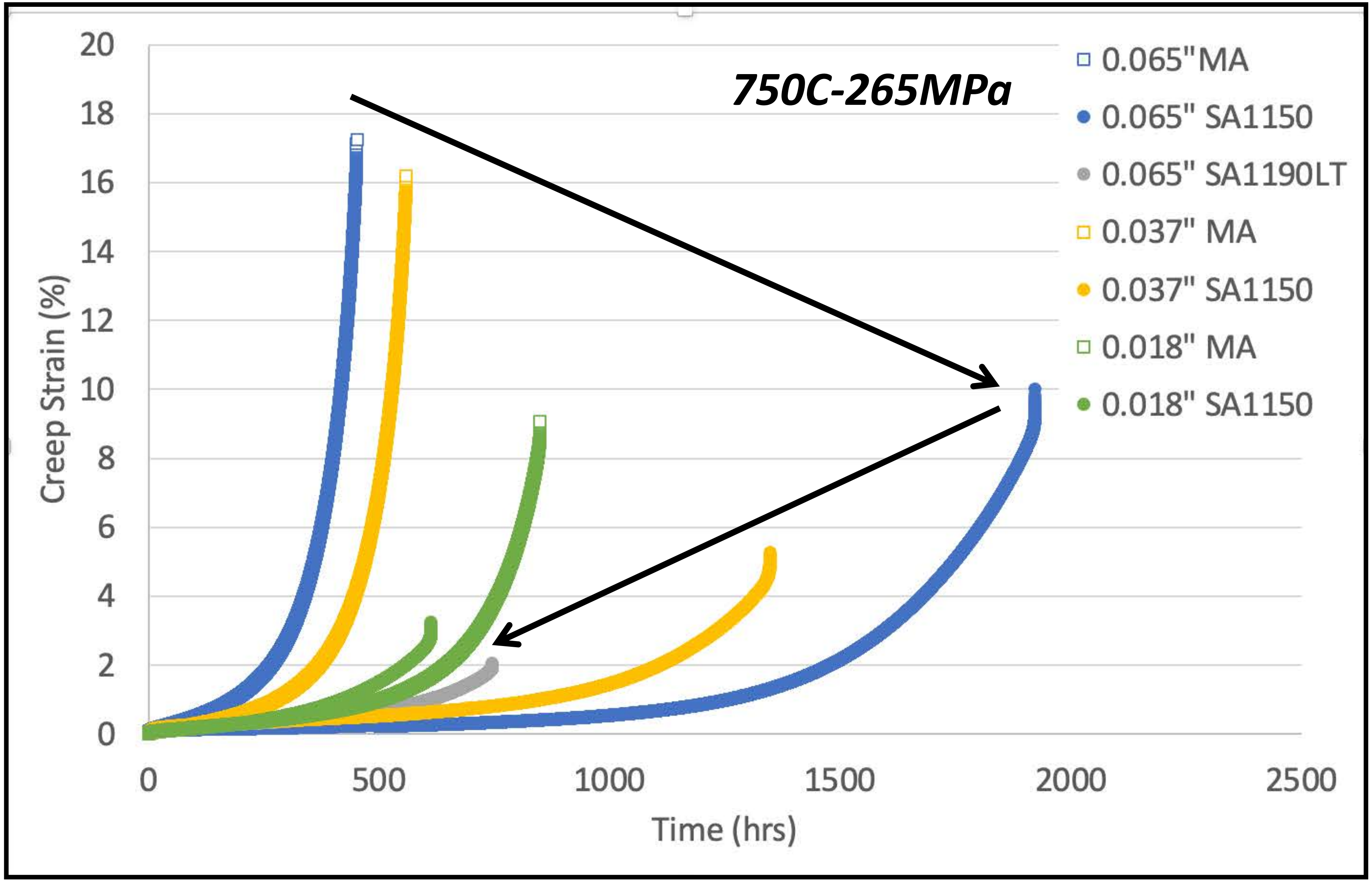


SA at 1150C can have different effects depending on sheet thickness

Thicker sheets show increased rupture life and modest ductility reduction

Thin sheets shows loss of ductility and minimal change in life

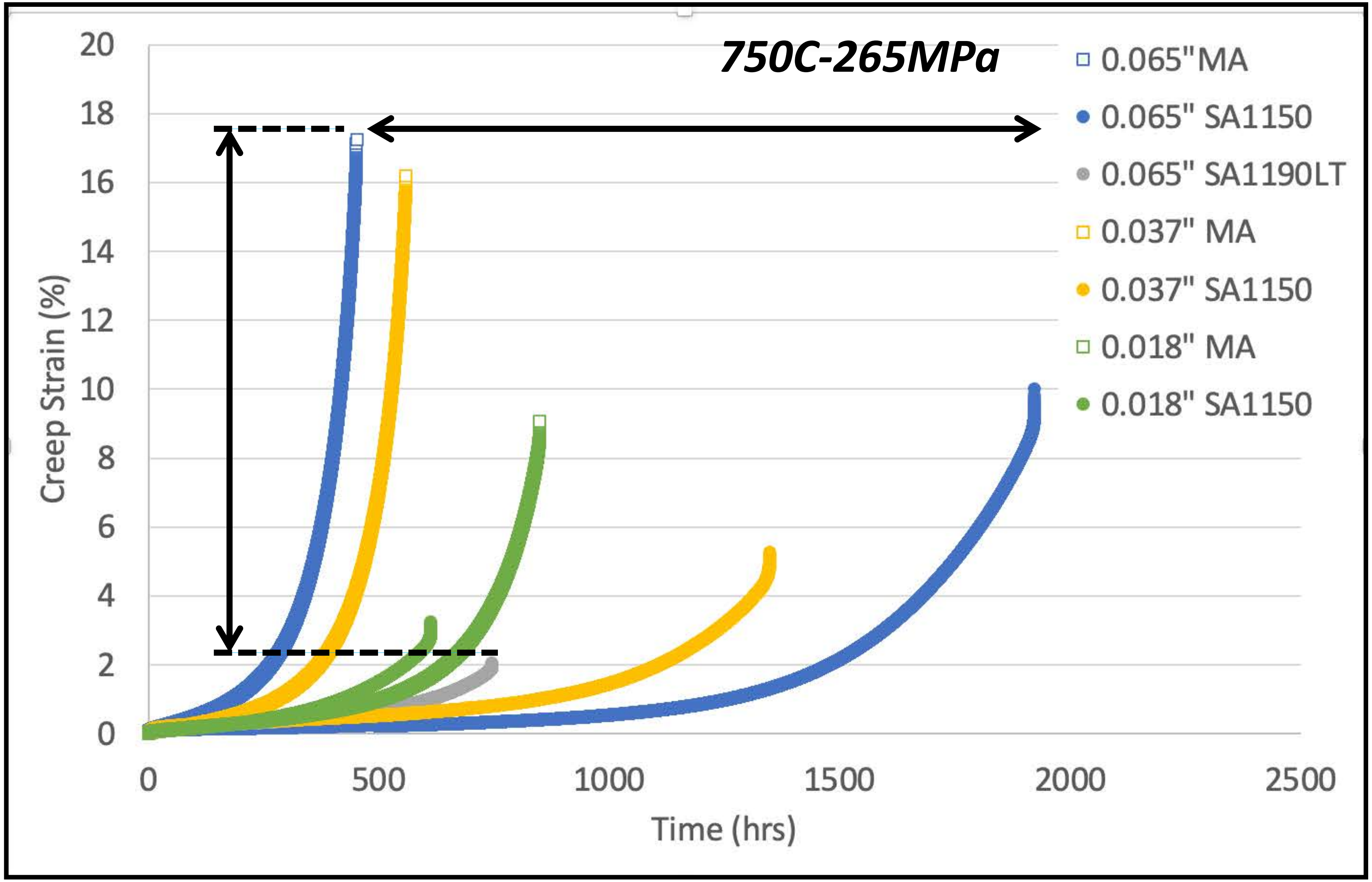
Creep behavior: All Sheets



Longer or higher temperature heat-treatments may 'short-circuit' improvements in creep from grain growth

1190C heat-treatment reduced rupture life and ductility

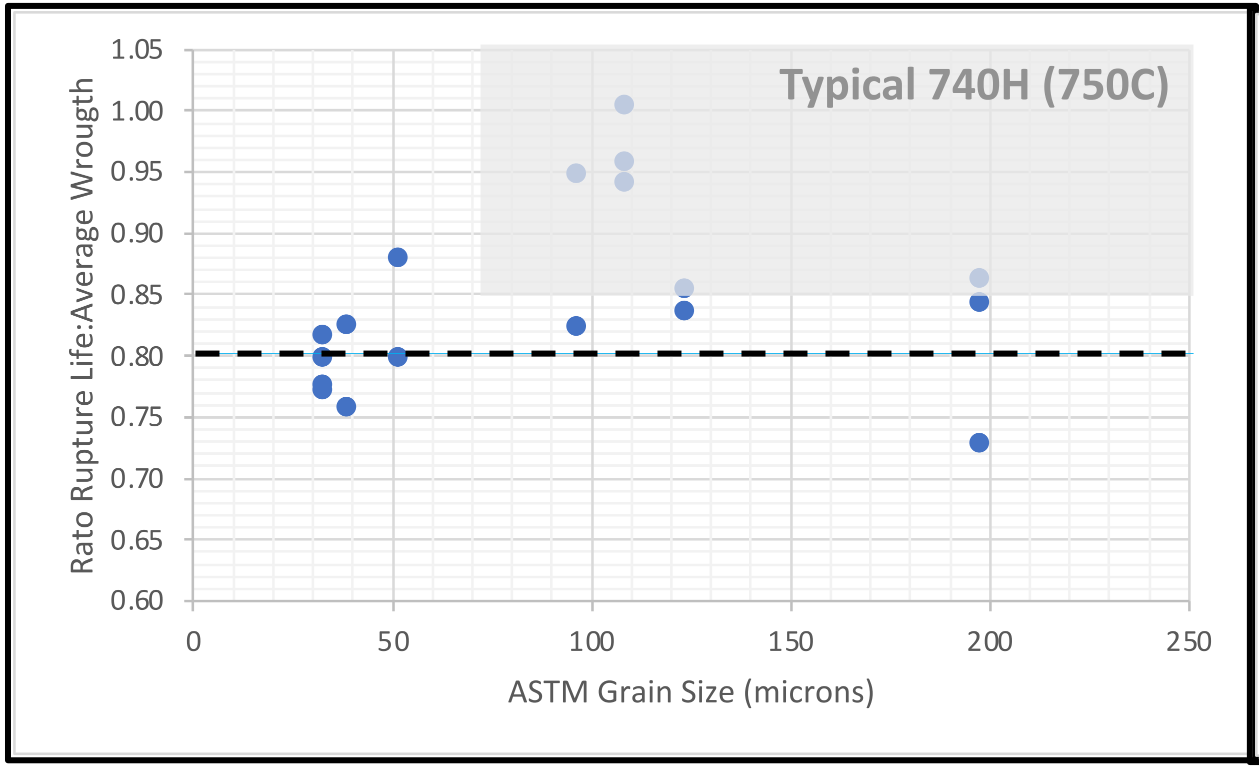
Creep behavior: All Sheets

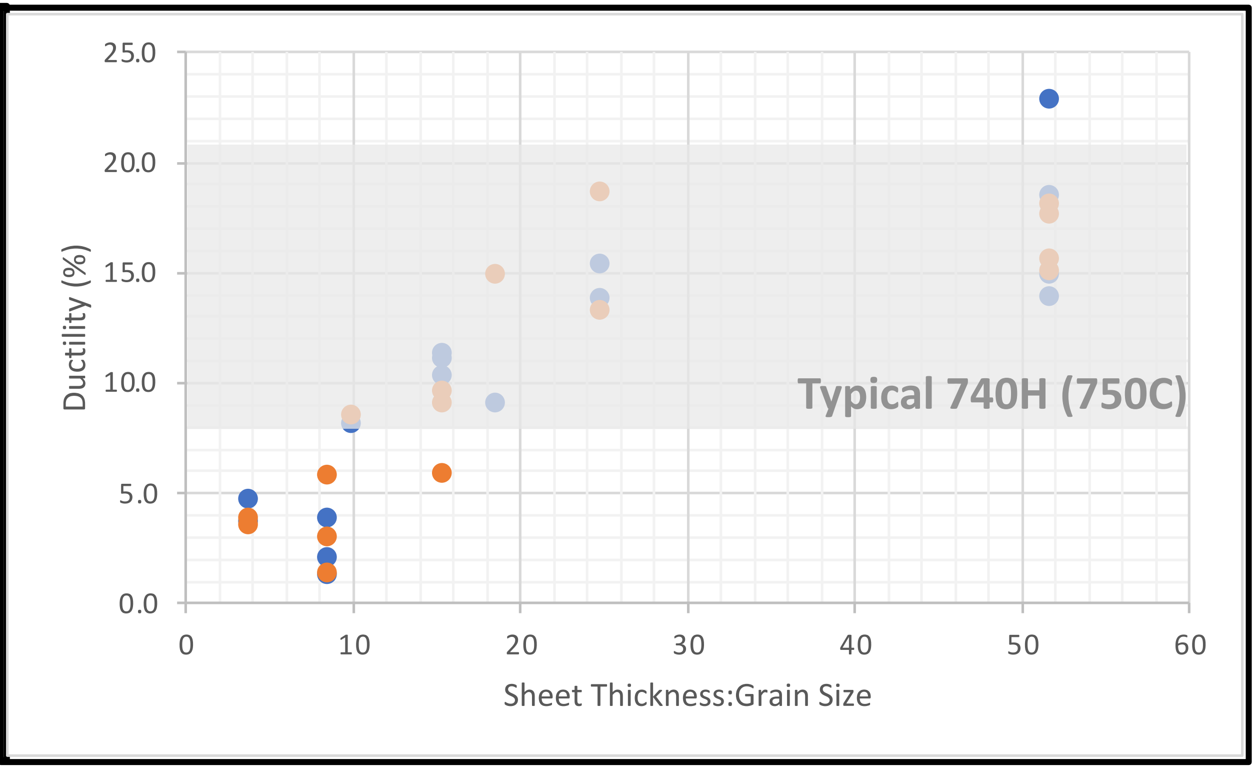


Rupture life can vary by a factor of ~6

Ductility can vary by a factor of ~10

Summary of creep performance



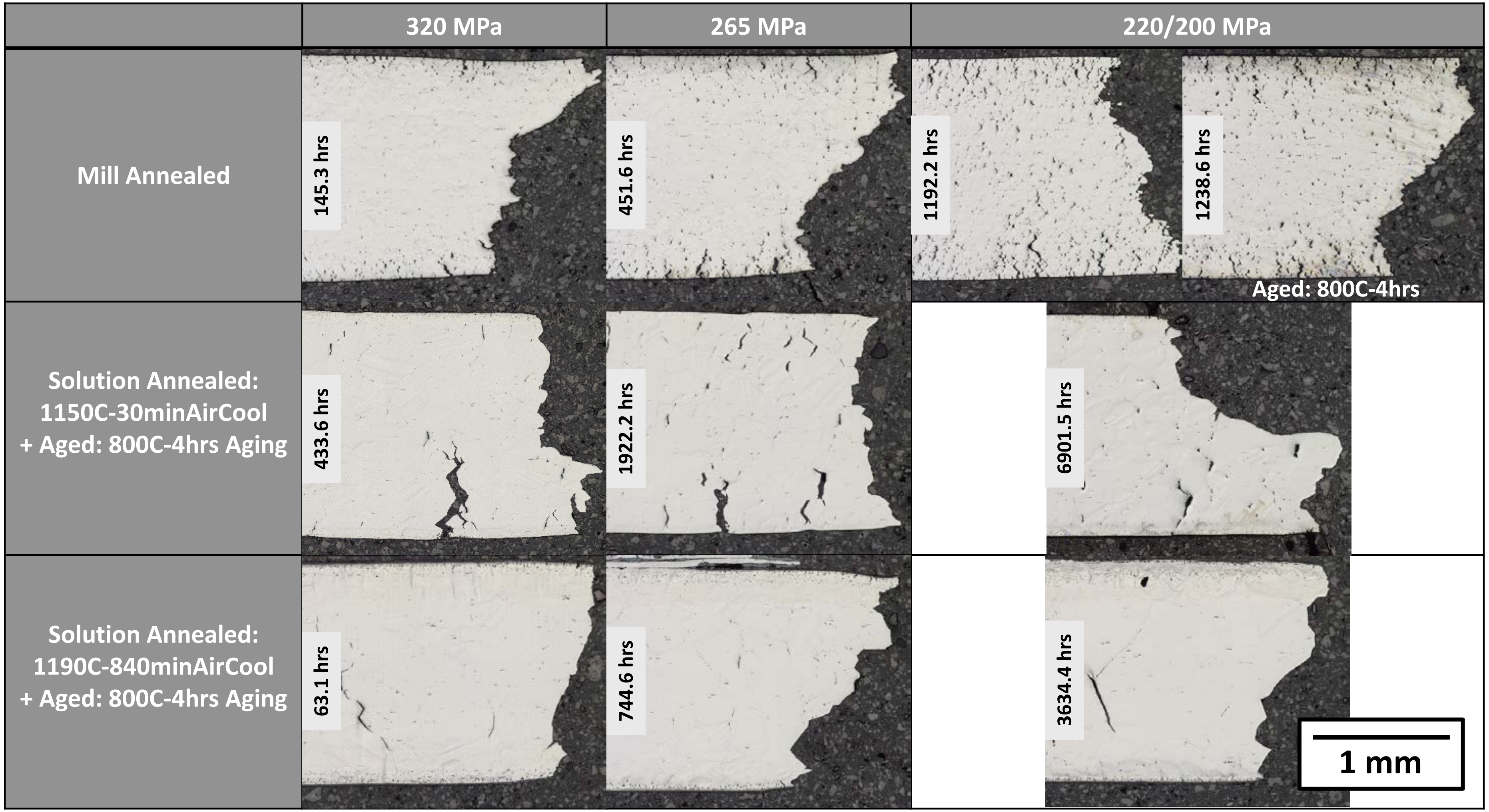


- ASTM GS < 50 microns (ASTM 6 or higher) may result in lower than scatterband (-20%) rupture life
- Sheet thickness to grain size ratios of <10 may result in low ductility

Complicated trends to interpret based on grain size alone

Post-Test Evaluation

1.65mm sheet



- MA
  - No effect of aging on creep at 750C
  - Surface cracking dominates
- SA+Age:
  - Grain boundary cavitation and cracking
  - Minimal secondary cracking for larger grain size

Confirms trend to lower-ductility failures at smaller sheet thickness to grain size ratios

Conclusions

- The following trends were observed for alloy 740H sheets tested at 750C
  - MA materials with finer grain sizes will have reduced rupture life at or below the wrought 740H scatterband
    - NOTE: not some MA material had slightly larger grain size resulting in improved creep resistance
  - SA at 1150C generally improves creep strength to expected properties but for thinner sheet it can reduce creep ductility
  - SA at 1190C results in larger grain size and larger ‘outlier’ grains which approach the sheet thickness, this results in poor creep ductility and loss of rupture life
- Practical considerations for heat-exchanger design & manufacturing:
  - Proper control of the heat-treatment cycle will produce material with anticipated creep performance
  - For long diffusion bonding cycles, some reduction in rupture ductility and possible rupture life may need to be considered in design
  - For direct use of MA sheet material, without any additional materials characterization or testing, assuming at 20% reduction in high-temperature long-term creep performance appears reasonable

First study to systematically evaluate grain size and sample thickness on industrially relevant alloys

Next Steps & Other Research

- Current Plan
  - Complete remaining tests on thinner sheets (2 creep tests)
  - Additional analysis of data
    - Statistical treatment of grain size distribution and outliers
      - Perhaps number density of very large grains ‘short circuits’ good behavior and is a better measure of grain size for thin sheet creep performance
    - Examination of creep-rate (deformation) data
    - Evaluation of other parameters (e.g. λ–creep ductility parameter & MG-relationships)
  - Produce a contour plot or failure diagram to show targeted regions performance
- Future research opportunities:
  - Compare findings to creep testing of diffusion bonded plates
  - Evaluate other materials (e.g. 617, 316/316H, 800H) to see if relationships developed are applicable to austenitic materials
  - Application and validation to channels in the diffusion bonded materials

This study provides a baseline to compare processing routes and build improved material models for advanced heat exchangers

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