ICME Guided Development of Advanced Cast Aluminum Alloys For Automotive Engine Applications

Project ID: PM060

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Ford Motor Company
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Overview

Timeline

- Project start date: February 2013
- Project end date: November 2016
- Percent complete: 30%

Barrier

- High temperature performance
- Design data & modeling tools
- Manufacturability
- Cost

Budget

- Total project funding
  - ➢ DOE share: $3.24M
  - ➢ Contractor share: $1.39M
- Funding received in FY15
  - ➢ $860K
- Funding for FY16
  - ➢ $1.3M

Partners

- Alcoa Inc.
- Nemak
- MAGMA Foundry Technologies, Inc.
- University of Michigan

Project Objectives

- To develop a new class of advanced, cost competitive aluminum casting alloys providing a 25% improvement in component strength relative to components made with A319 or A356 alloys for high-performance engine applications.
- To demonstrate the power of Integrated Computational Materials Engineering (ICME) tools for accelerating the development of new materials and processing techniques, as well as to identify the gaps in ICME capabilities.
- To develop comprehensive cost models to ensure that components manufactured with these new alloys do not exceed 110% of the cost using incumbent alloys A319 or A356.
- To develop a technology transfer and commercialization plan for deployment of these new alloys in automotive engine applications.

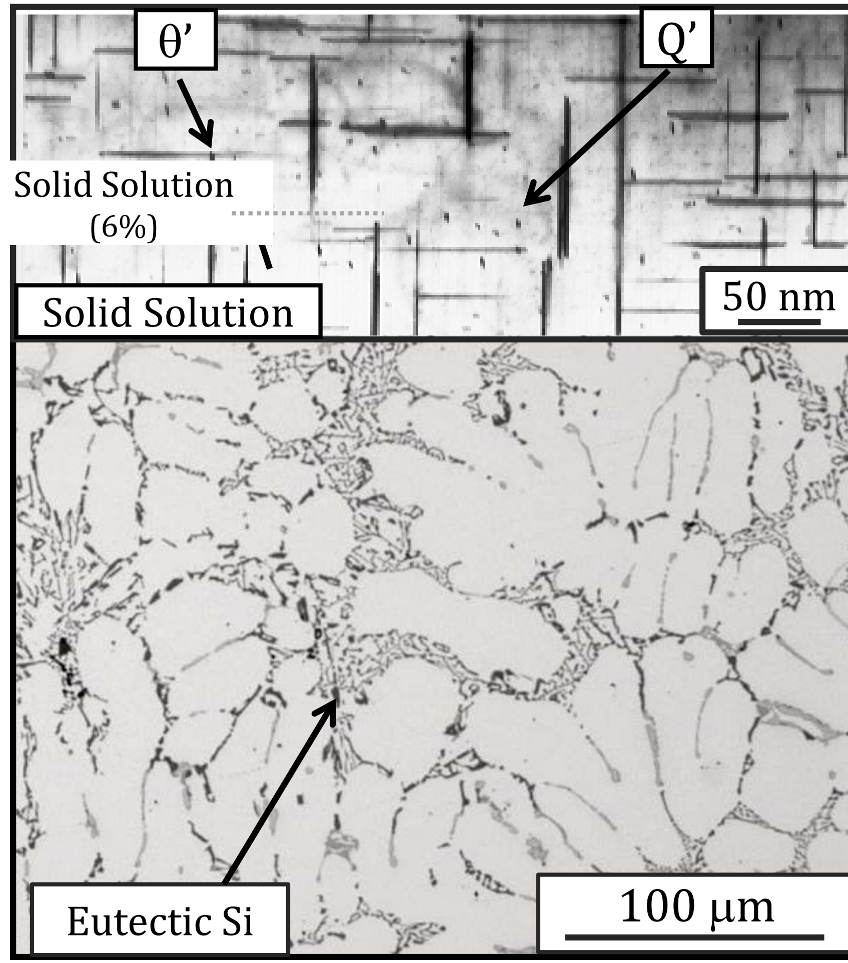
Baseline and Targeted Properties

Property	Cast Aluminum Baseline	Cast Lightweight Alloy Targets	Key Properties (must meet)
Tensile Strength	33 KSI (228 MPa)	40 KSI (276 MPa)	Key
Yield Strength	24 KSI (166 MPa)	30 KSI (207 MPa)	Key
Density	2.7 g/cm3	< 6.4 g/cm3	Key
Elongation (%)	0.035	0.035	
Shear Strength	26 KSI (179 MPa)	30 KSI (207 MPa)	
Endurance Limit	8.5 KSI (59 MPa)	11 KSI (76 MPa)	
Fluidity (Die Filling Capacity/Spiral Test)	Excellent	Excellent	Key
Hot Tearing Resistance	Excellent	Excellent	Key
High Temperature Performance	@250C	@300C	
Tensile Strength	7.5 KSI (52 MPa)	9.5 KSI (66 MPa)	Key
Yield Strength	5 KSI (35 MPa)	6.5 KSI (45 MPa)	Key
Elongation (%)	0.2	<20%	
Thermal Mechanical Fatigue (TMF)*	0.72% @ 1000 cycles	No requirements	

Alloy Design Approach: Engineering Microstructures

- Room temperature:
  - Precipitation strengthening (>70%)
  - Grain boundary strengthening (~20%)
  - Solute strengthening (<10%)

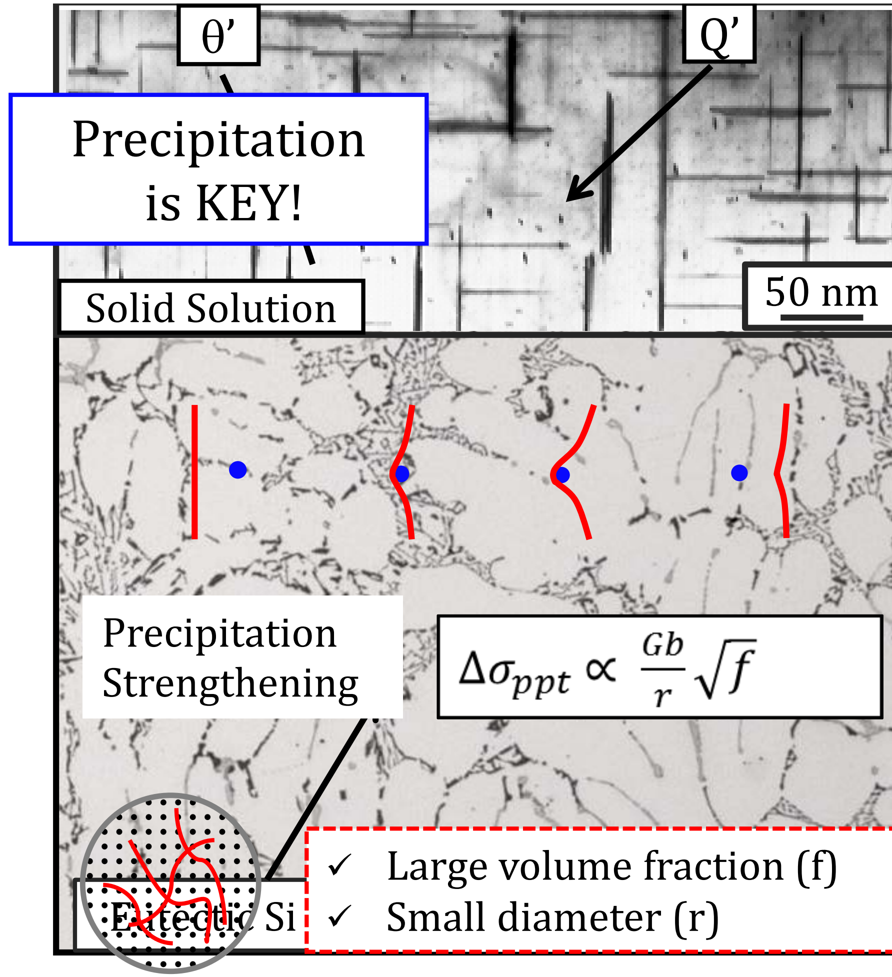
W319 (T7)



Alloy Design Approach: Engineering Microstructures

- Room temperature:
  - Precipitation strengthening (>70%)
  - Grain boundary strengthening (~20%)
  - Solute strengthening (<10%)

Yield Strength of W319 (230°C10hr): 310 MPa



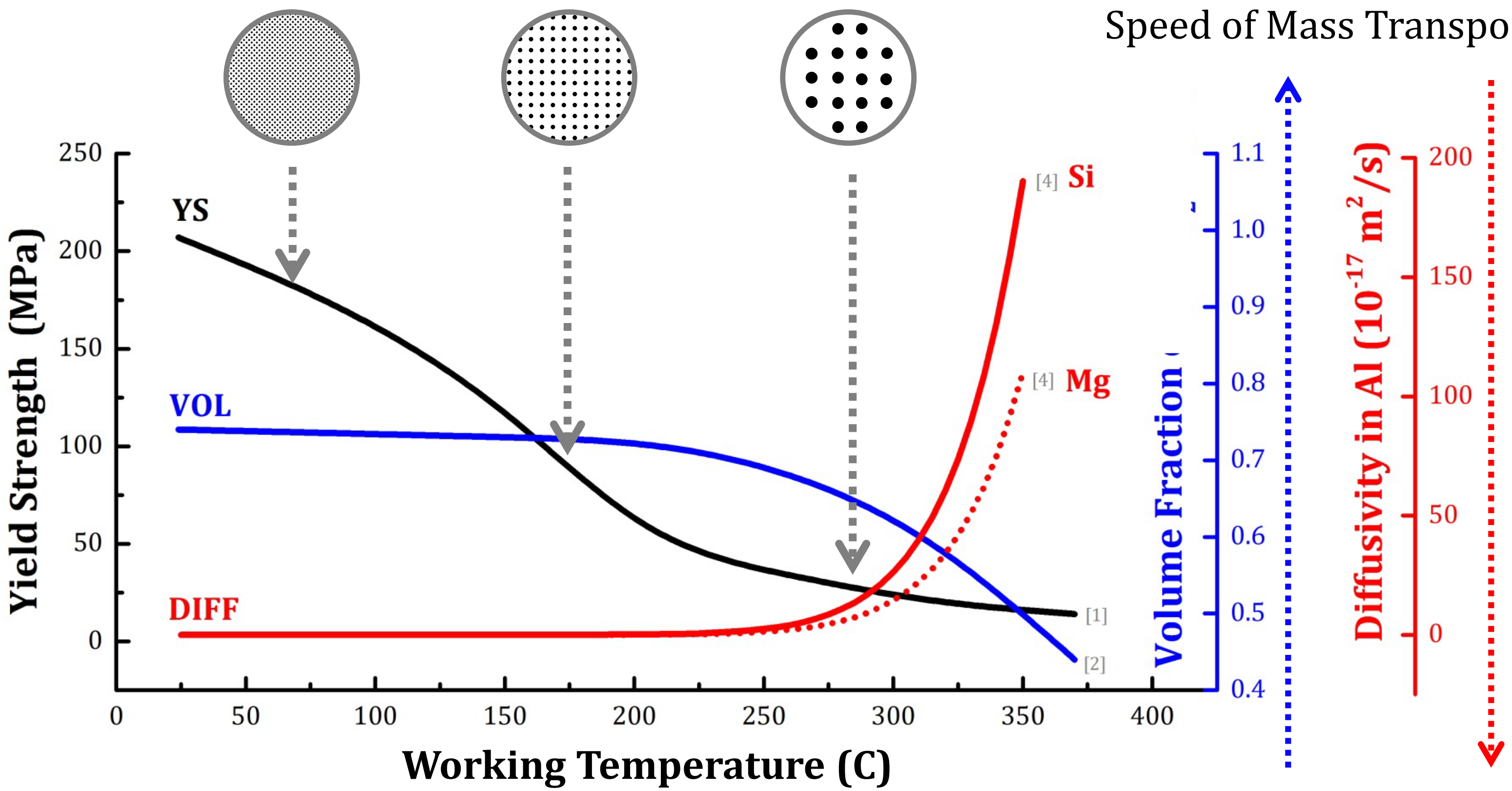
The Problem: High Temperature Property (300ºC)

✓ **Large volume fraction (f) + Small diameter (r)**

$$r^3 = k \cdot t$$

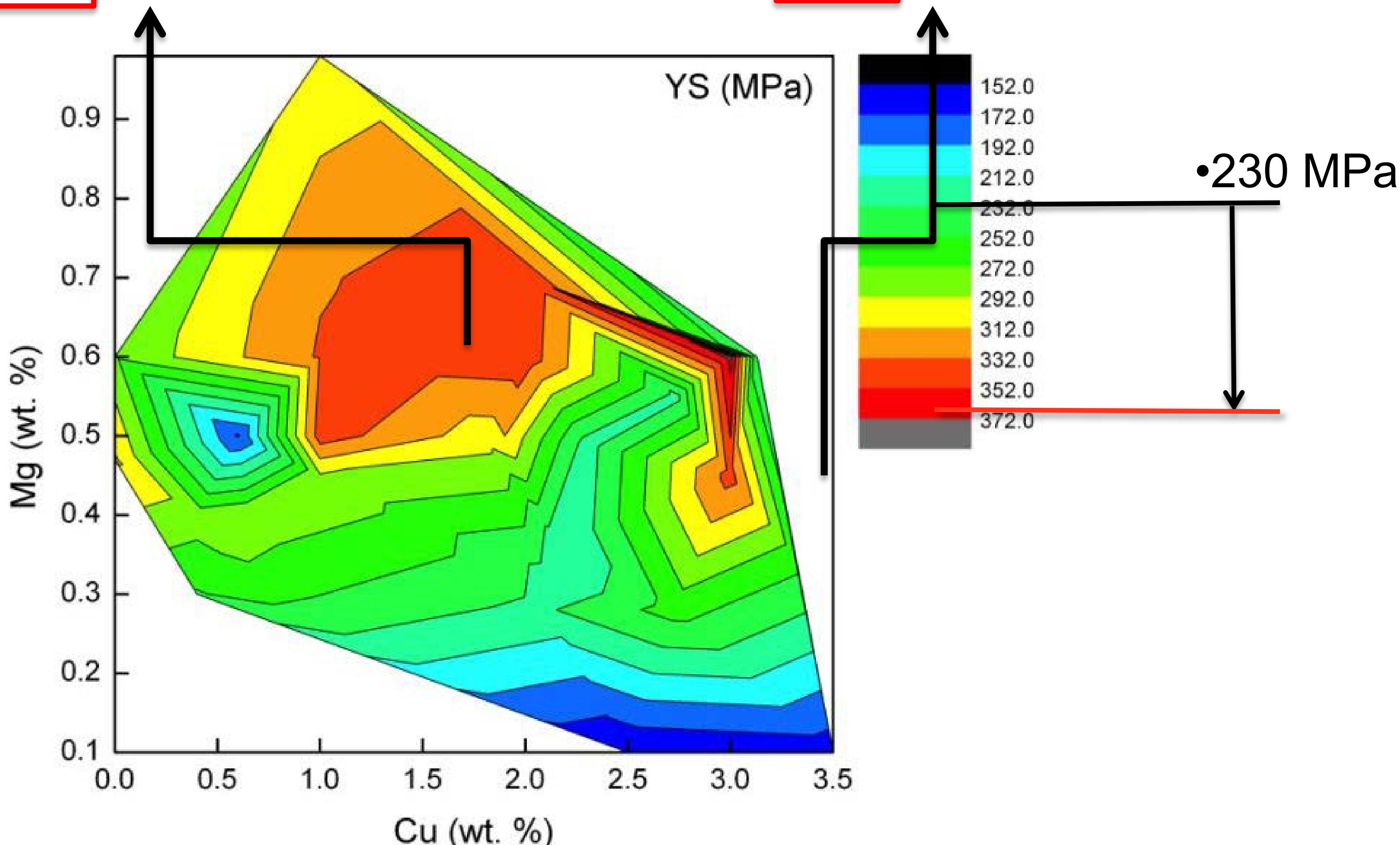
$$k \propto D\gamma C_e$$

Diffusivity:
Speed of Mass Transportation



Candidate Baseline Compositions for RT Property

- Batter corrosion resistant
  - 1-2Cu0.5-0.8Mg (Si: 7-11wt%)
- Better high temp strength
  - 3Cu0.4-0.6Mg (Si: 7-11wt%)



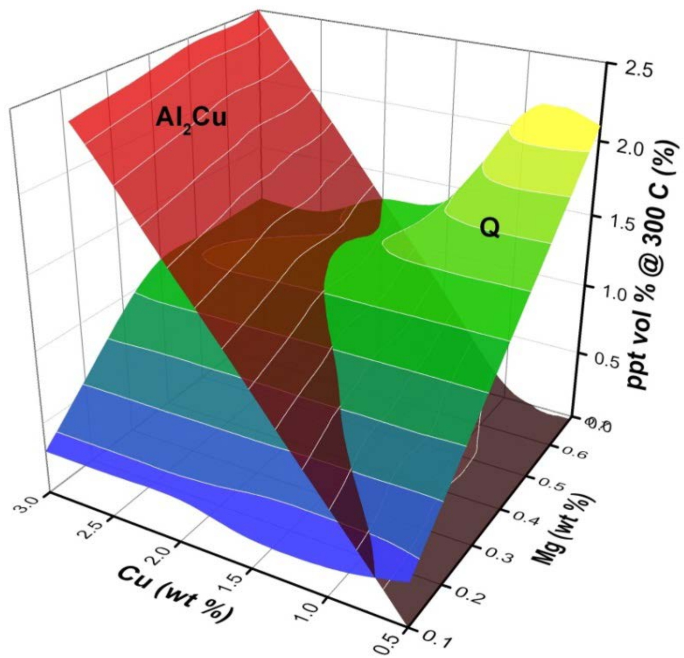
Alloy Design for Combined RT and HT Properties

Matrix:

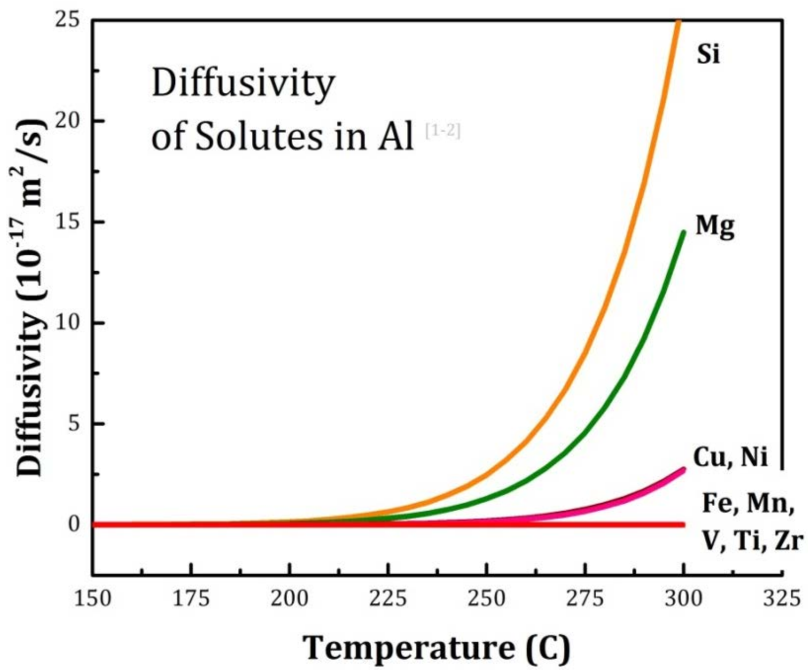
Al5.0-10.0Si0-4.0Cu0-0.4Mg was chosen as the baseline because of its good castability and strength.

Precipitates:

Optimize volume fraction of (θ'+Q')



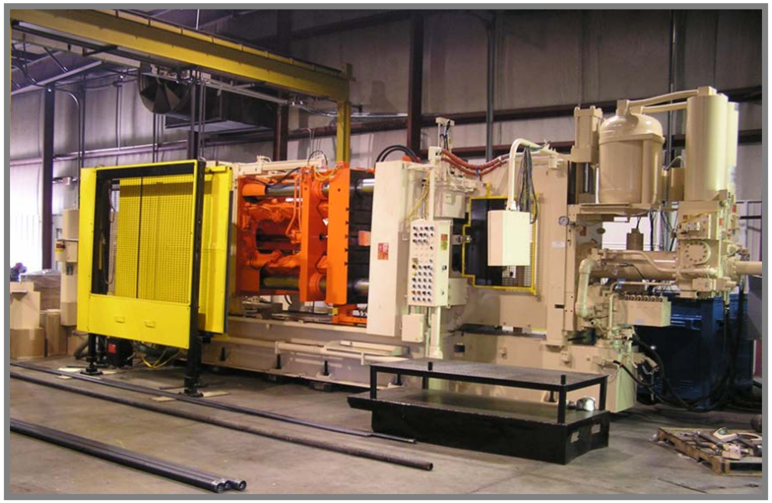
Introduce Heat-resistant Precipitates



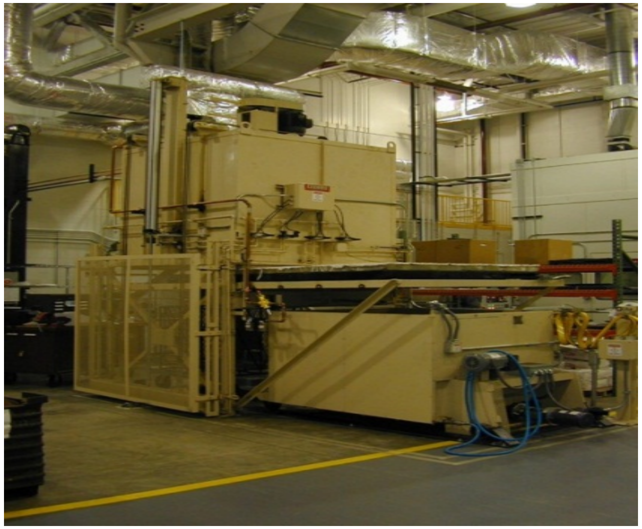
19 different heats of alloys were proposed to pursue the optimal alloy composition.

Casting and Heat Treatment Facility

Electric melting furnaces



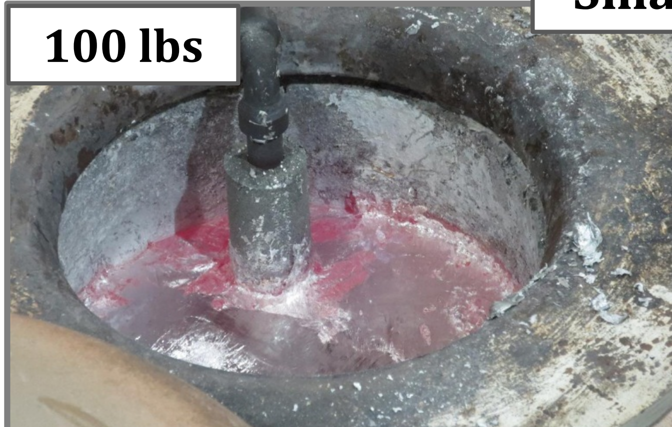
900 ton Prince cold-chamber HPDC



Drop bottom HT furnace and quenching basket

Experiment: Casting

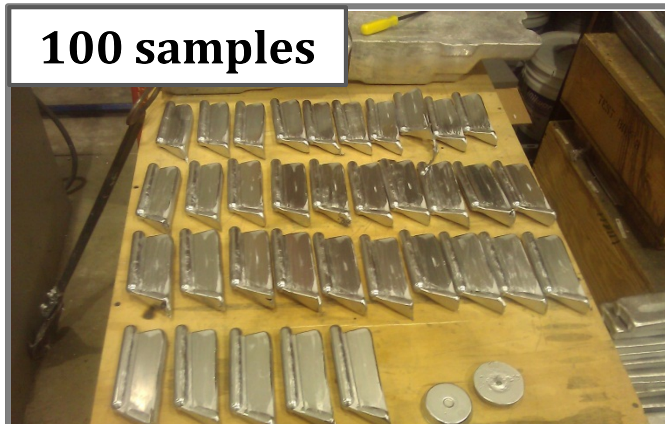
Small Batch



(a) Melting raw materials @ 750 C.


(b) Pouring spectrometer disk.


(c) Pouring torpedo shape sample.



(d) Torpedo samples for analysis.

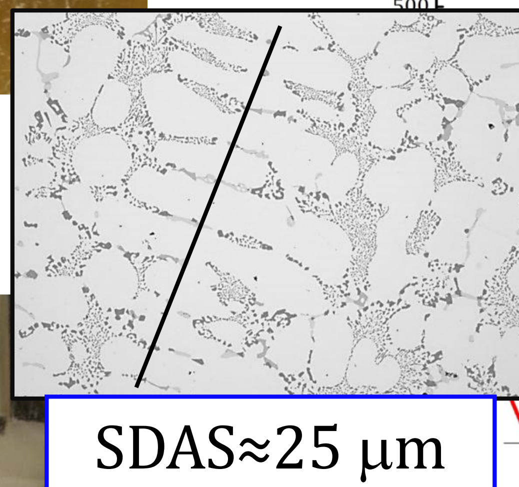
Experiment: Cooling Rate Control

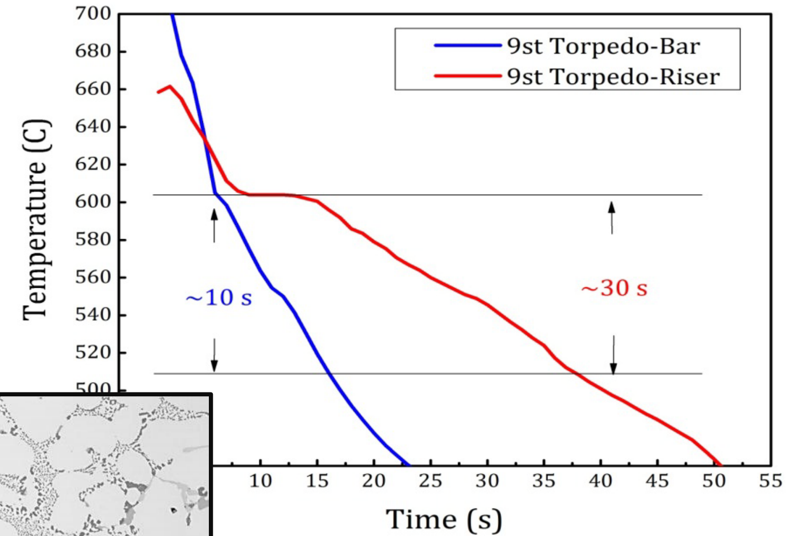
Without Coating (all our alloys)

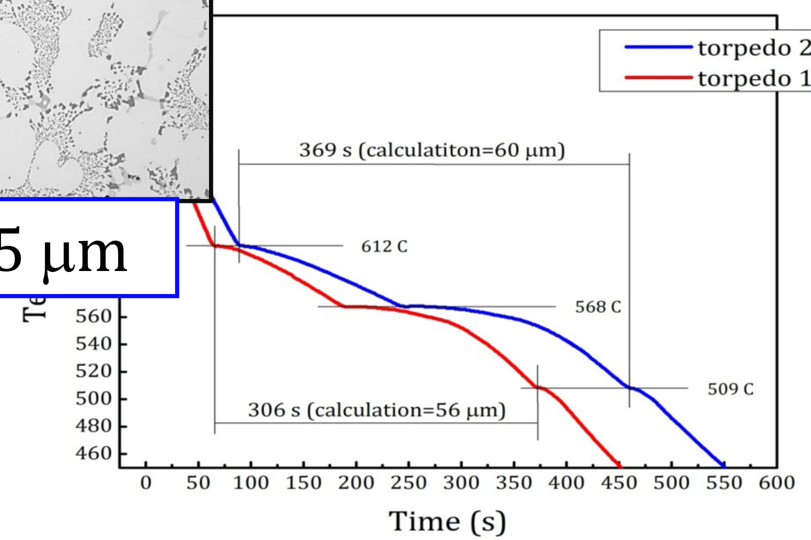
Secondary Dendrite Arm Spacing
≈ 15 ± 5μm

With Coating

Secondary Dendrite Arm Spacing
≈ 35 ± 5μm

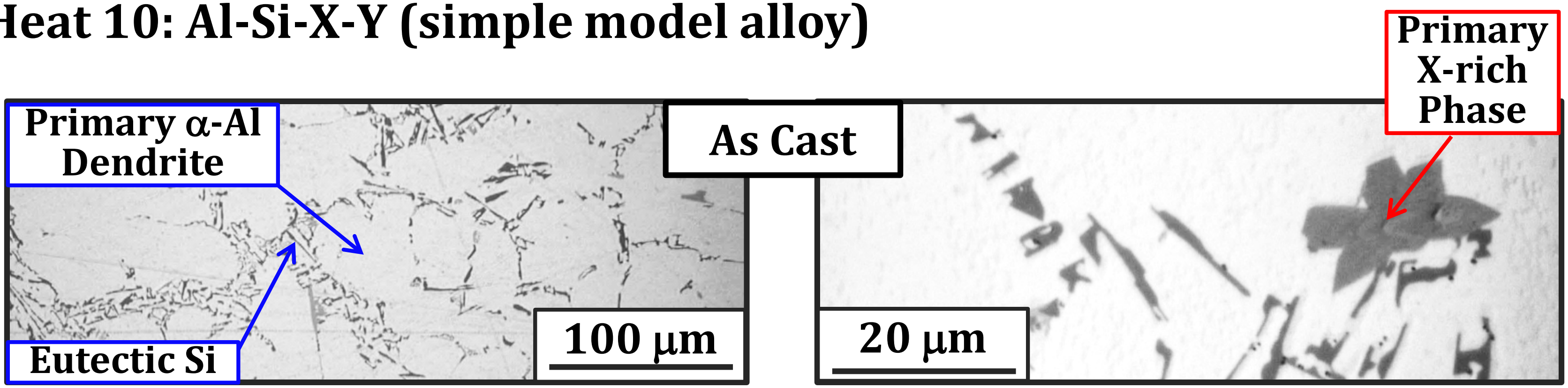


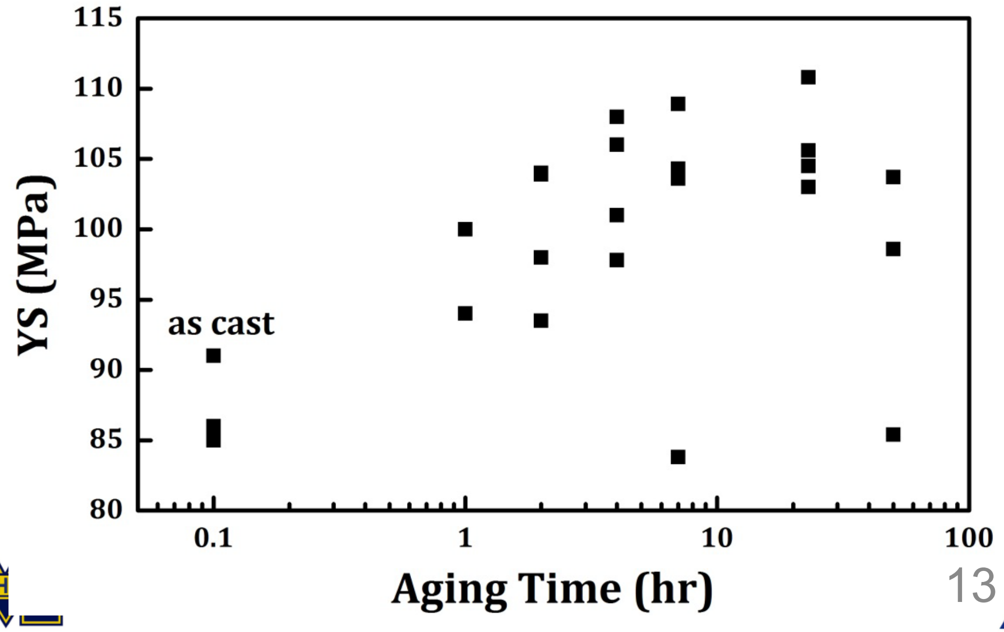




Experiment: New Heat Treatment

Heat 10: Al-Si-X-Y (simple model alloy)





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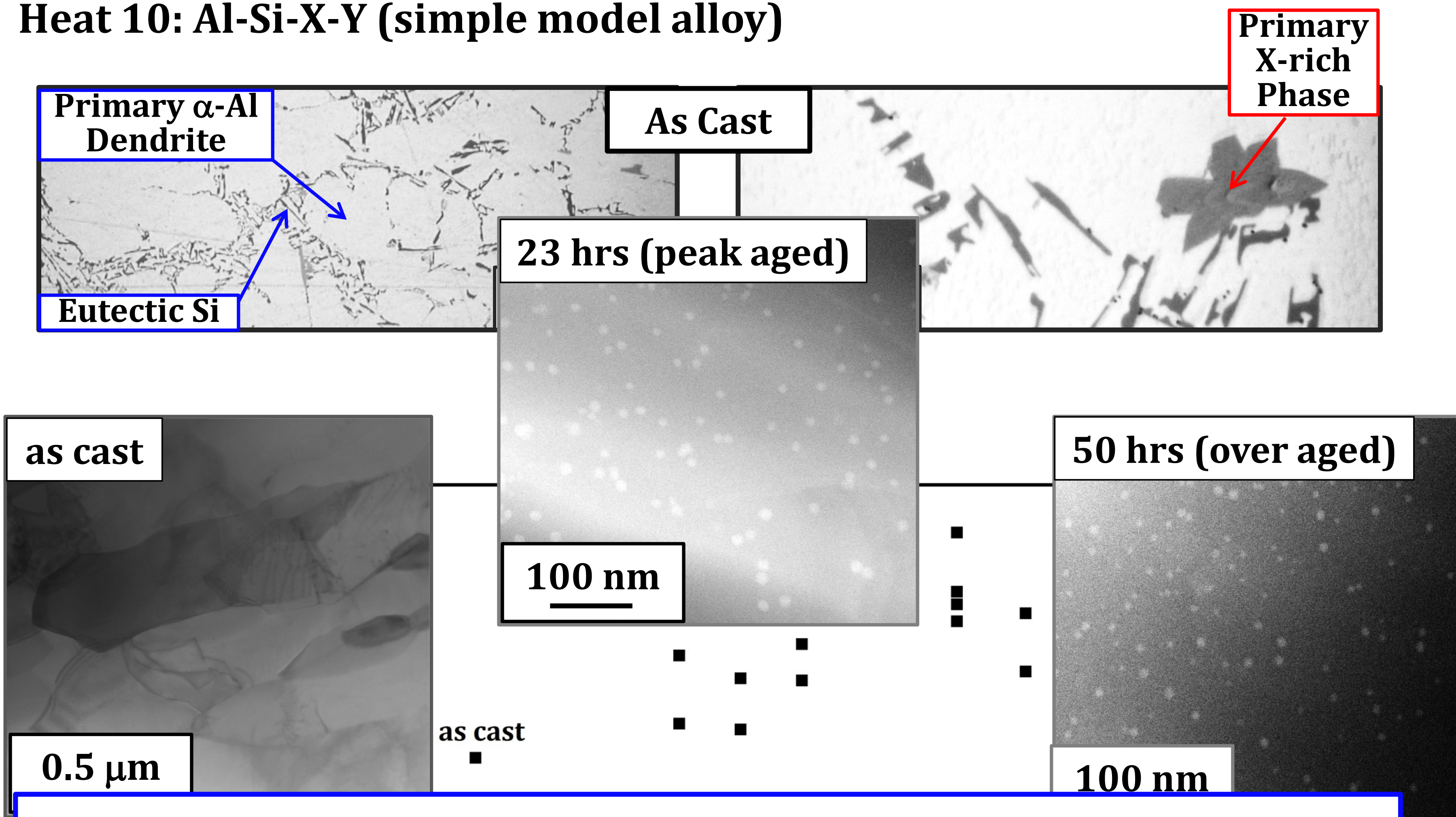
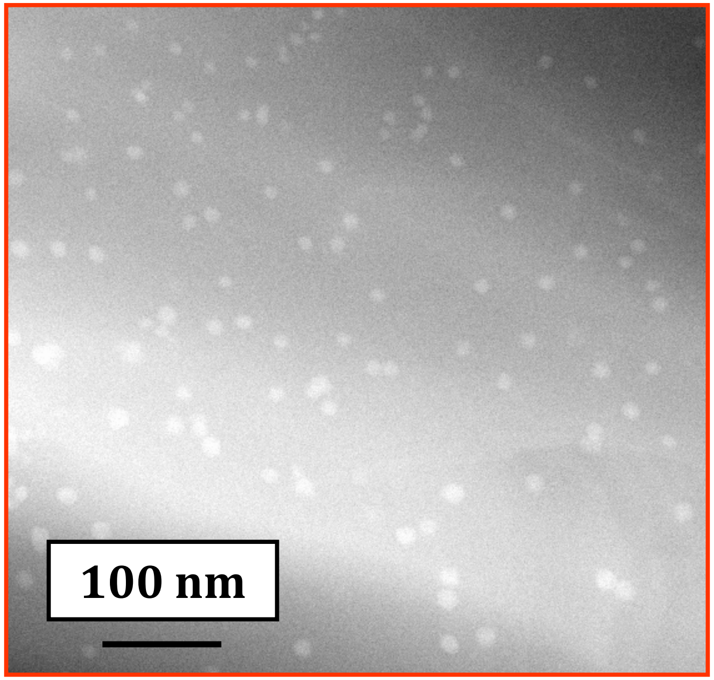


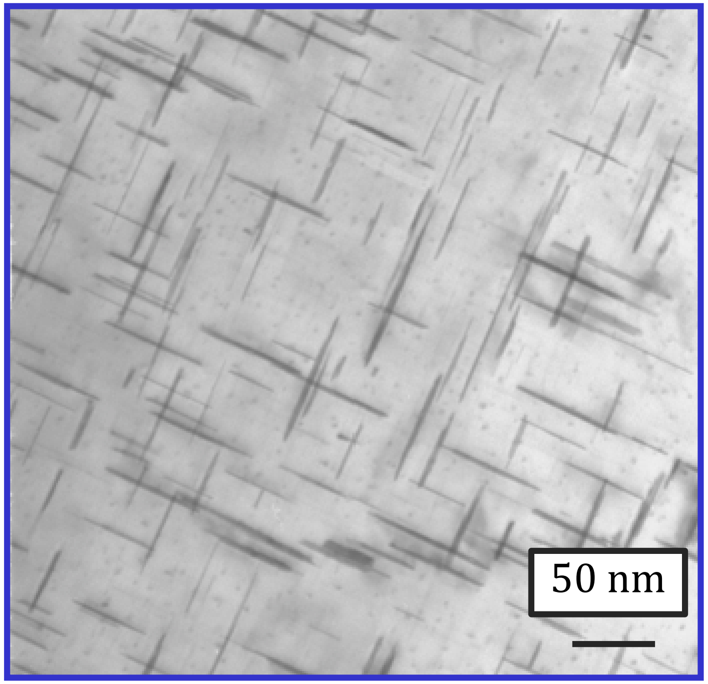
Aging generates nano-scale precipitates that ↑ RT YS by ~20 MPa and are coarsening resistant at this temperature.

Desired Microstructures for Both RT and HT

- **Al-Si-Cu-Mg-Fe-X-Y alloy system**

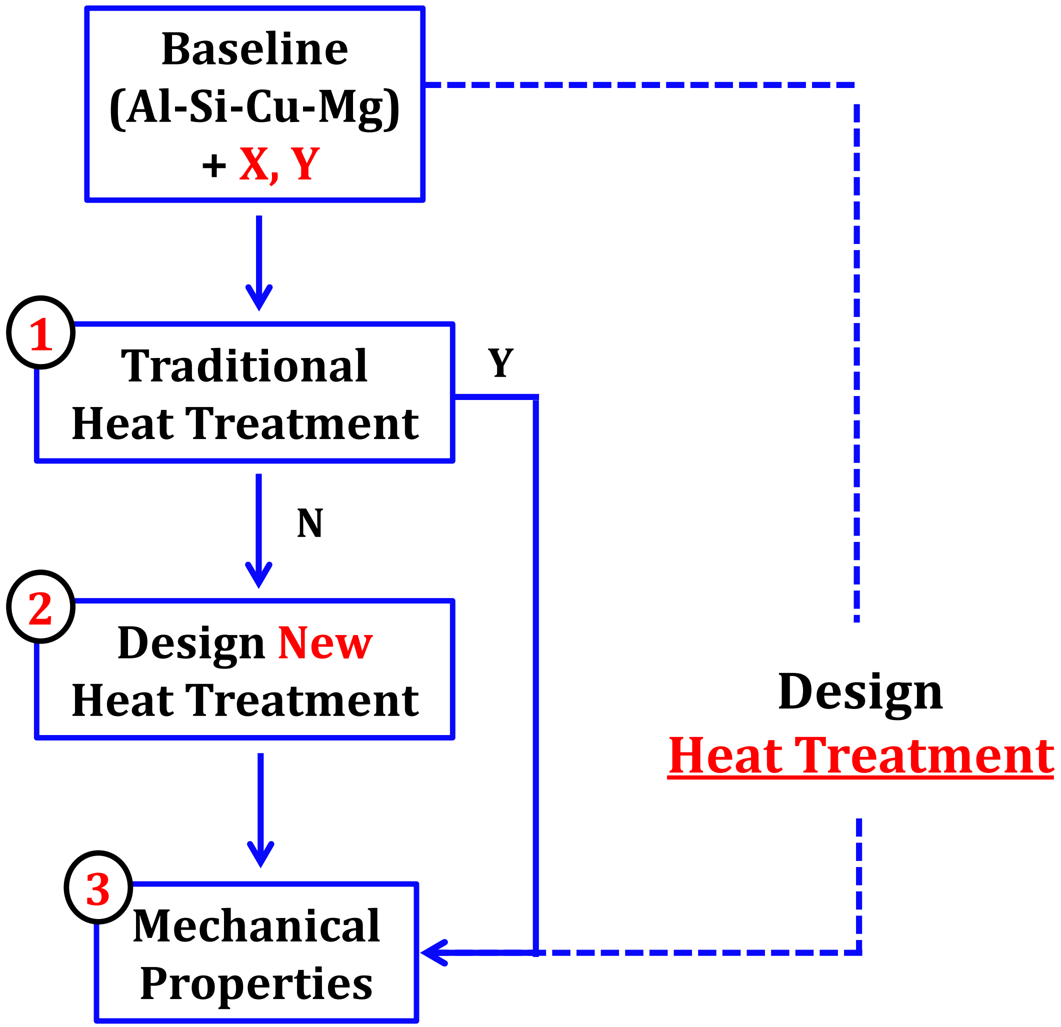


Fine HT stable precipitates

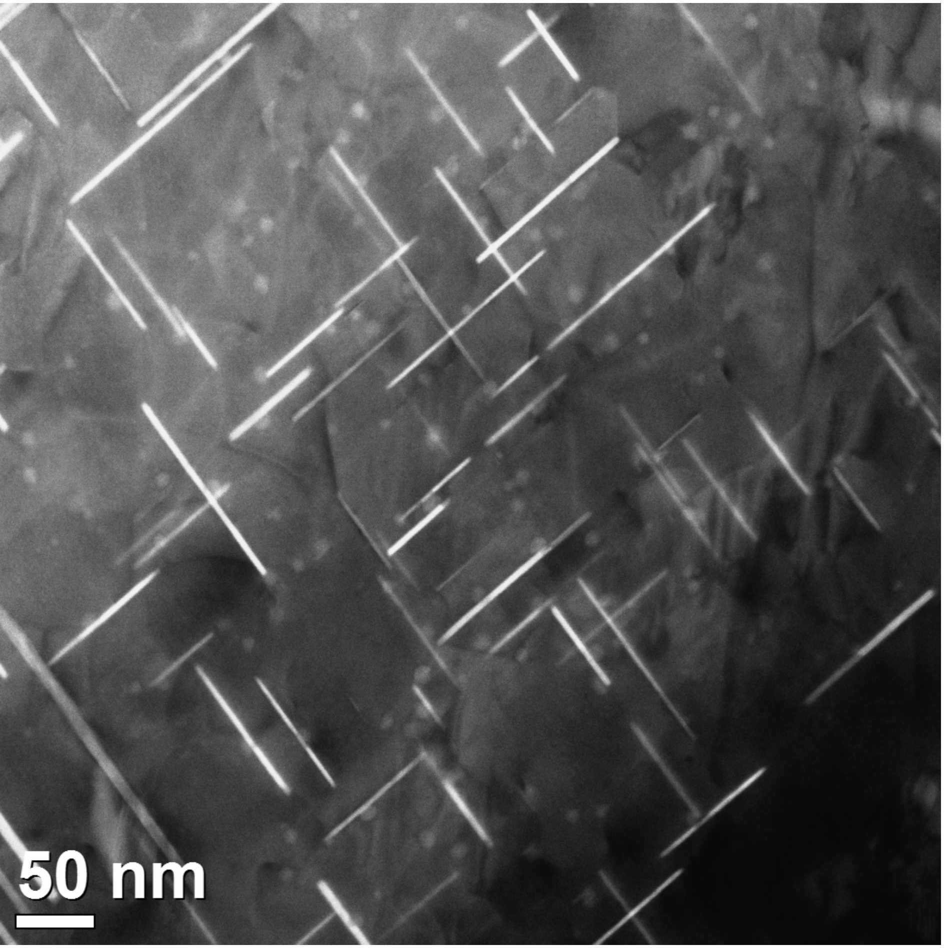


Fine Al_2Cu θ' precipitates

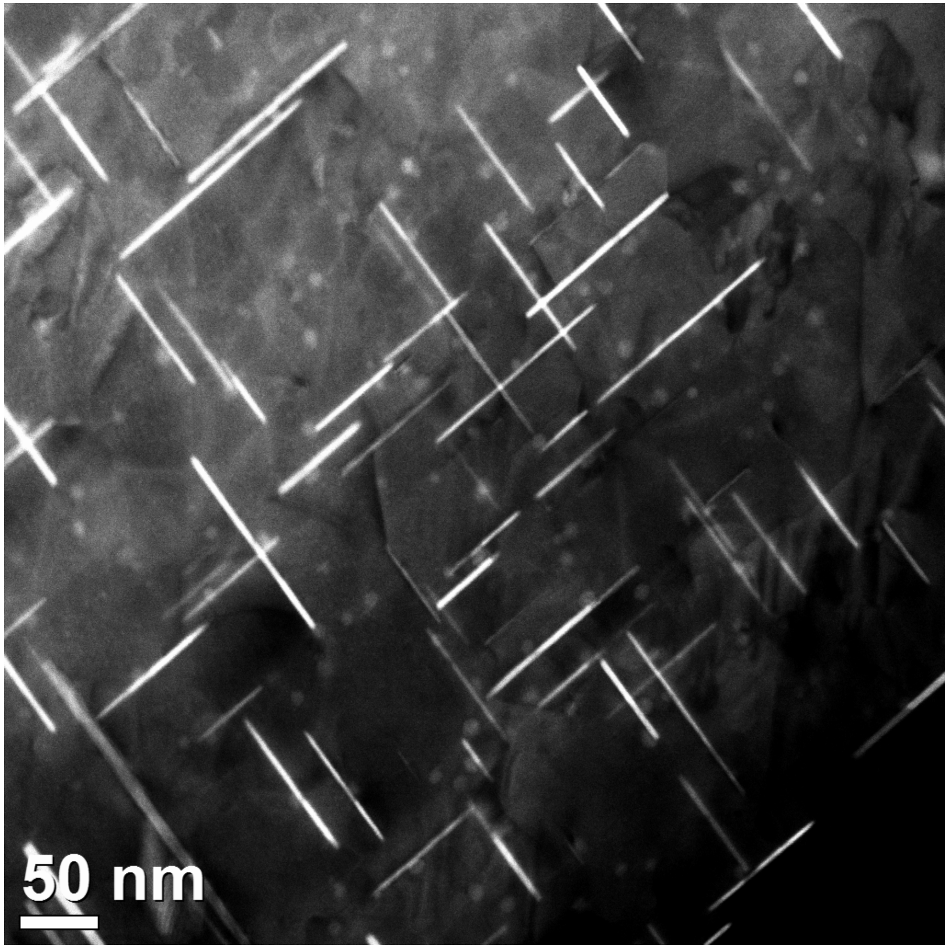
Heat Treatment Development



Fine HT stable precipitates and θ'-Al_2Cu



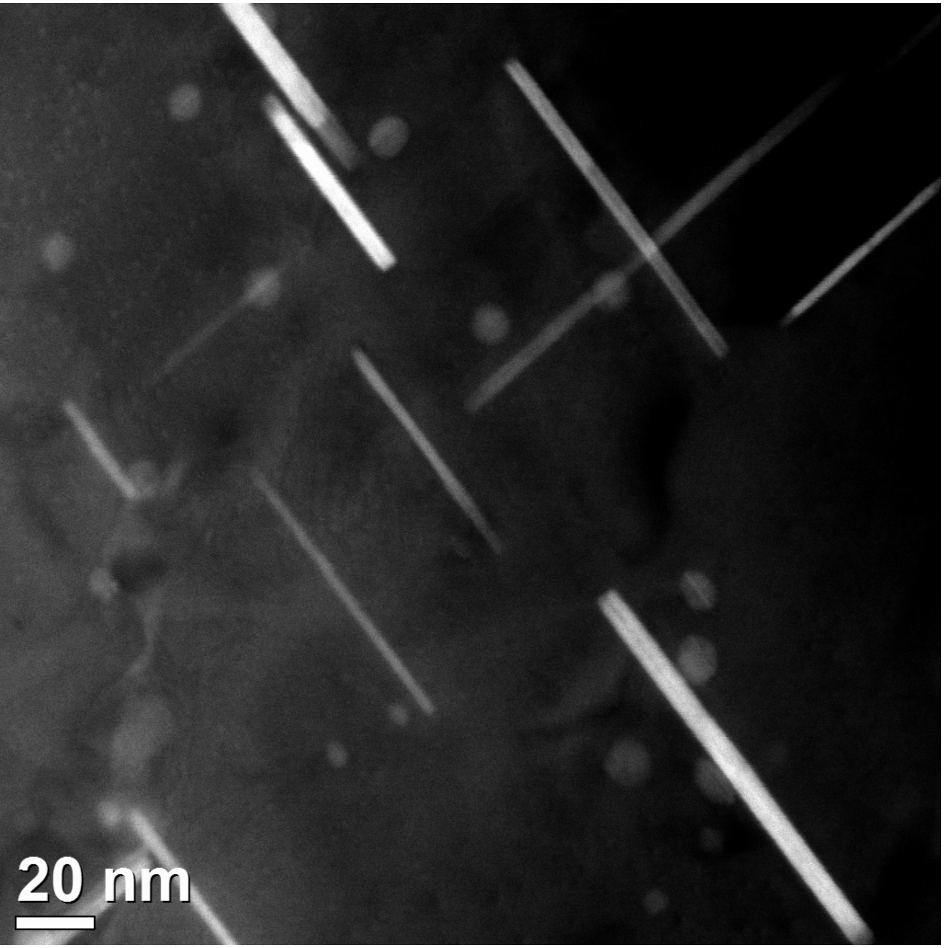
ADF-STEM



ADF-STEM

Beam direction =Al [001]

Fine HT stable precipitates and θ'-Al_2Cu



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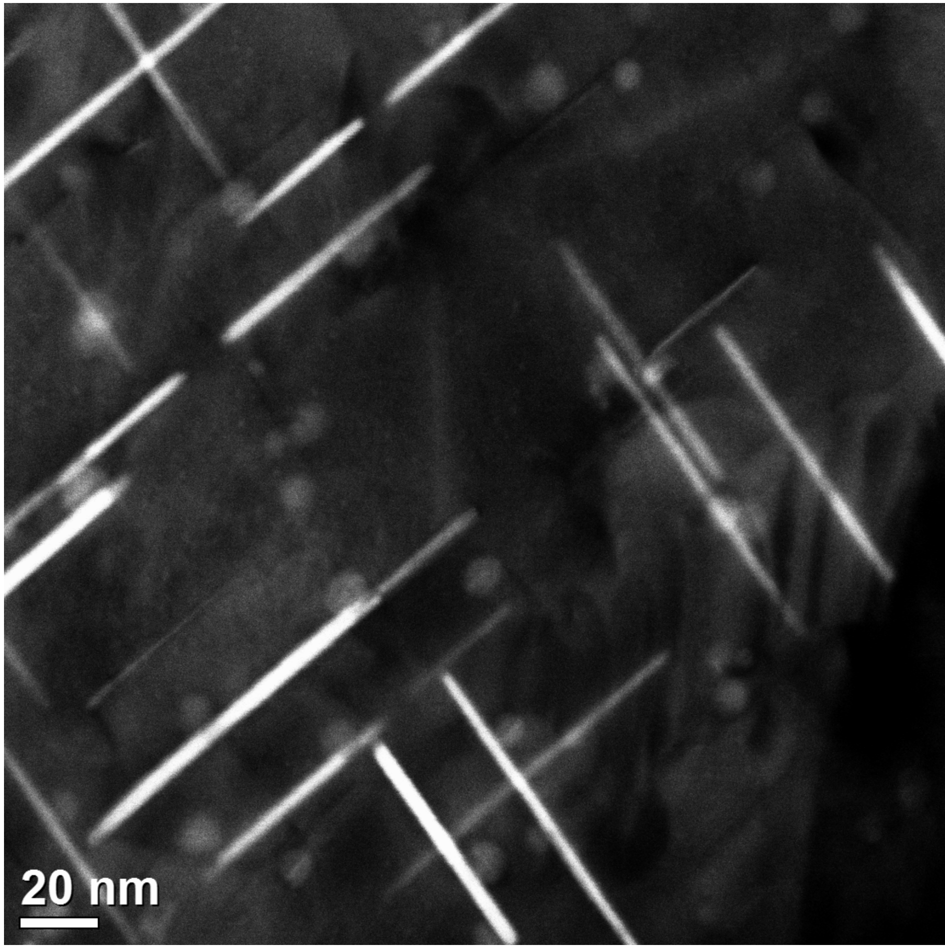
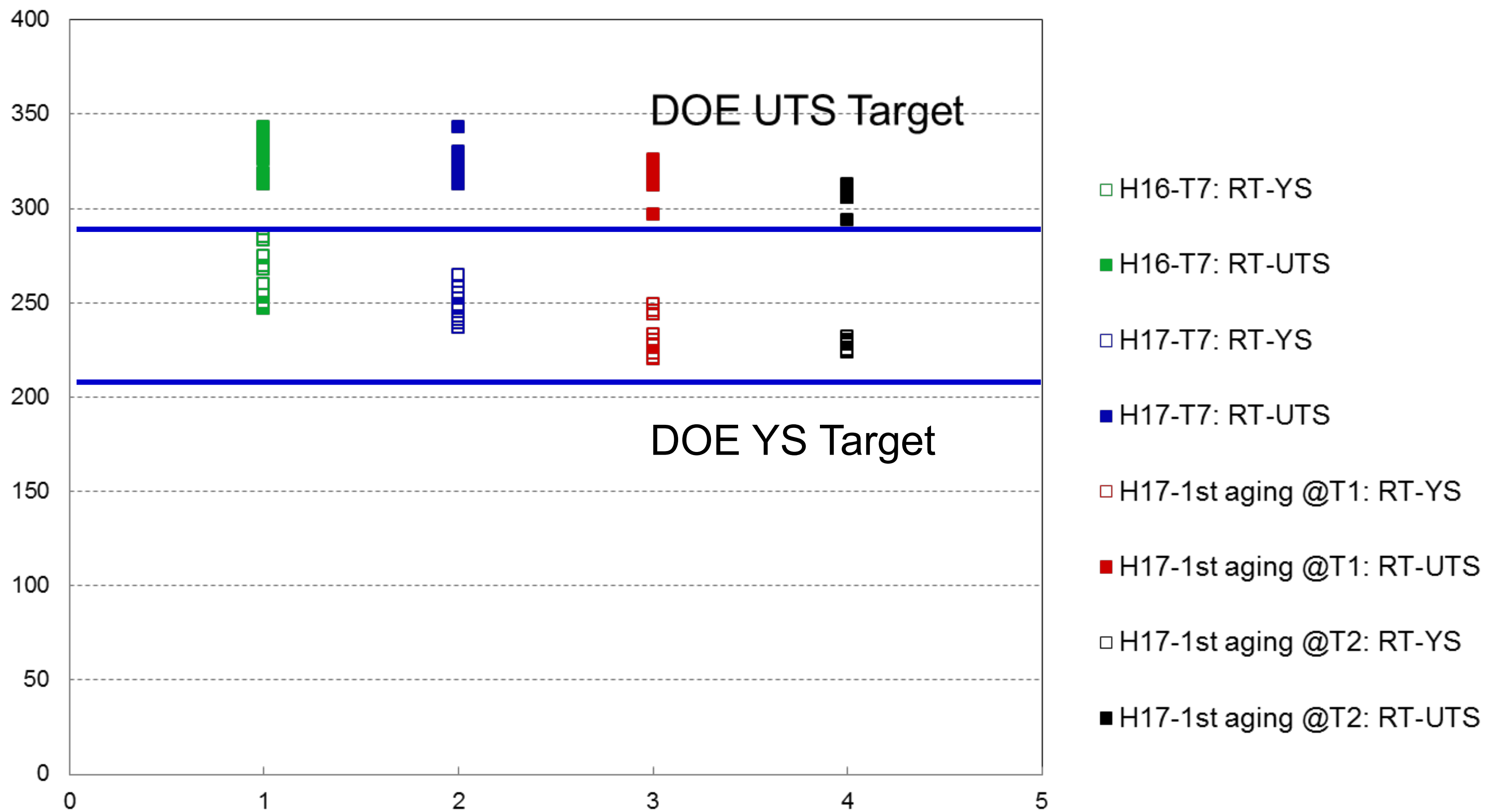


ADF-STEM

Beam direction =Al [001]

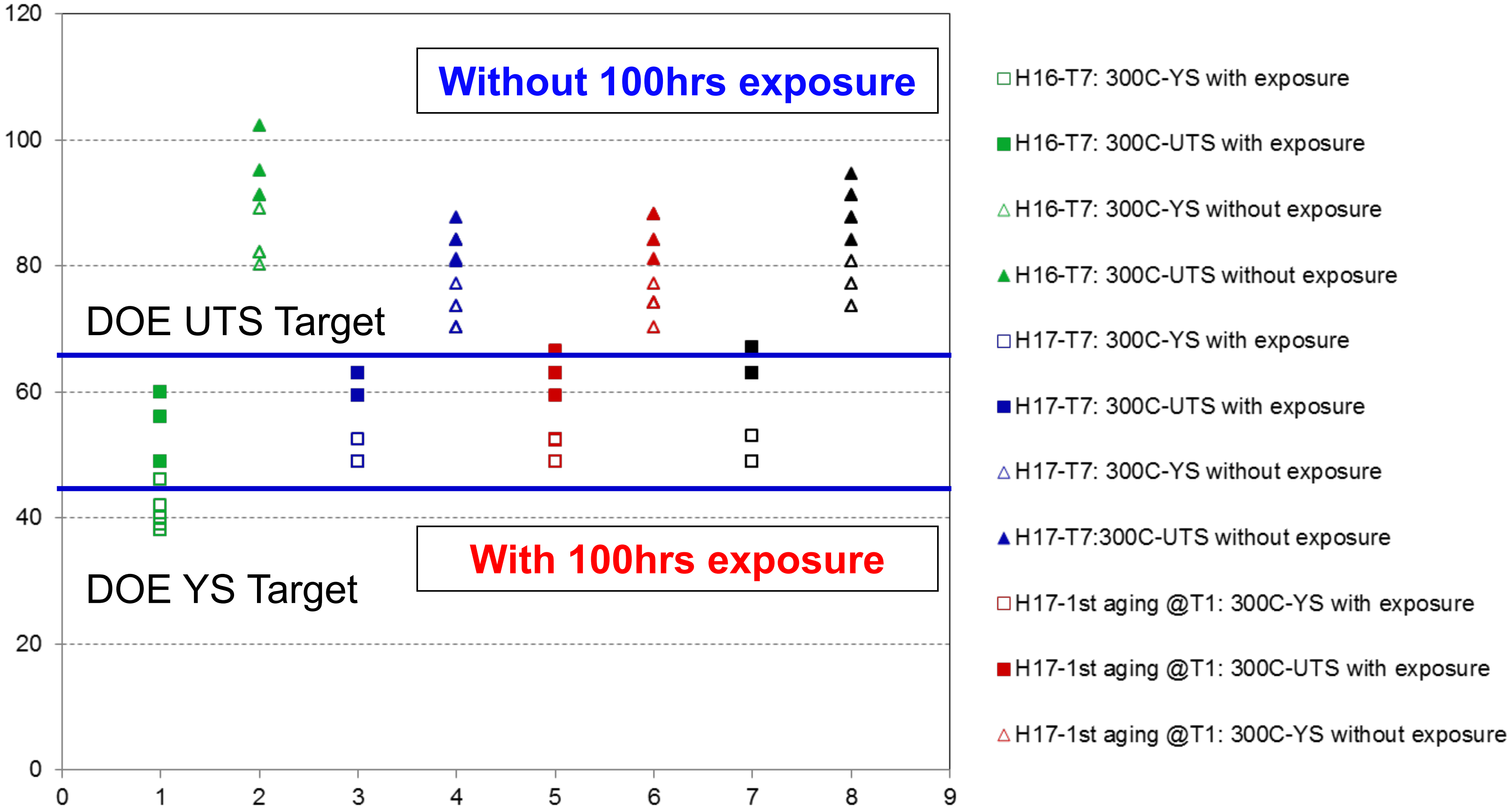
Results: Tensile for H16 and H17 at RT

H16: Al-Si-Cu-Mg (T7)
H17: Al-Si-Cu-Mg-X-Y (T7 and two-stage HT@T1 and @T2)



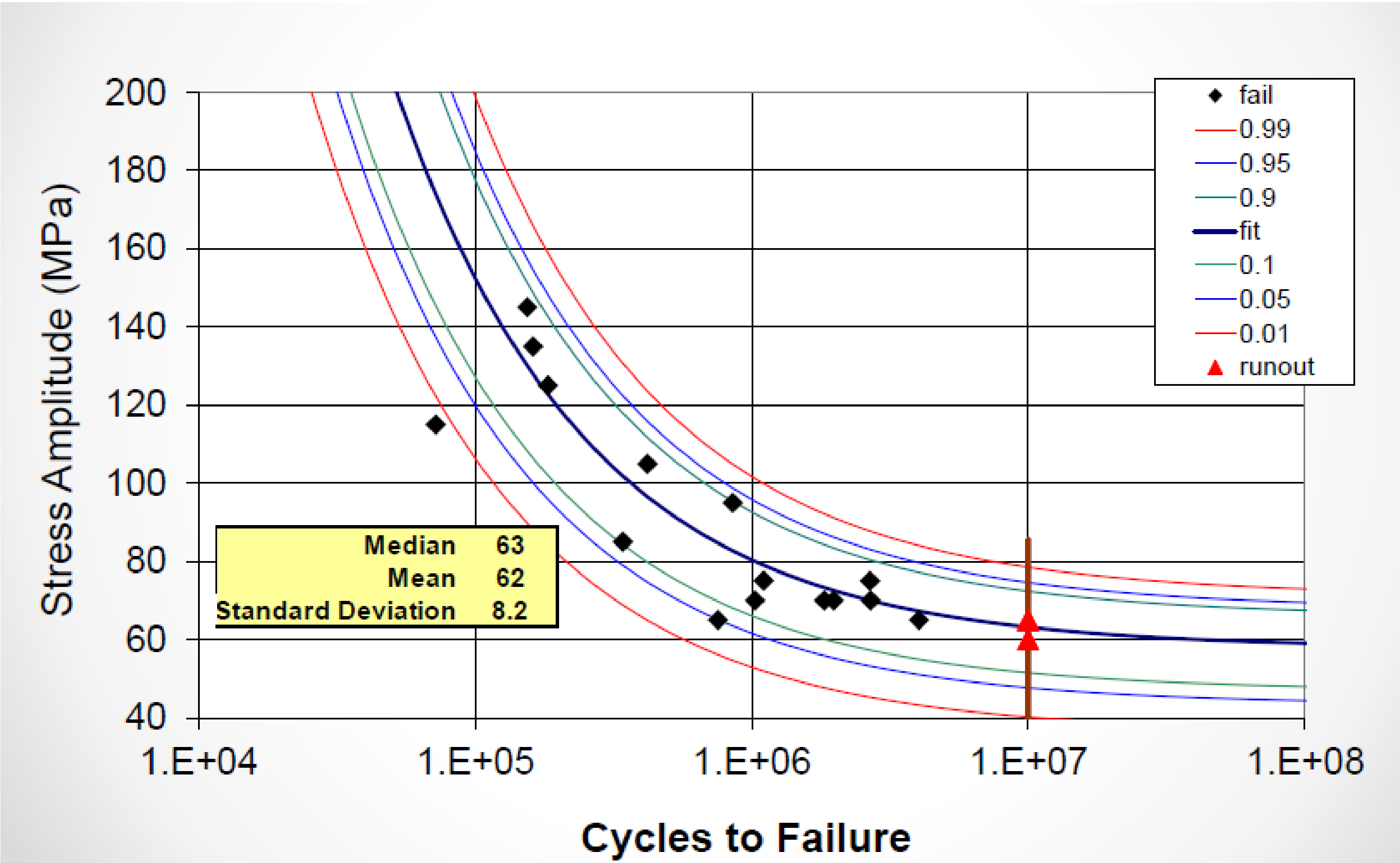
Results: Tensile for H16 and H17 at 300˚C

H16: Al-Si-Cu-Mg (T7)
H17: Al-Si-Cu-Mg-X-Y (T7 and two-stage HT@T1 and @T2)



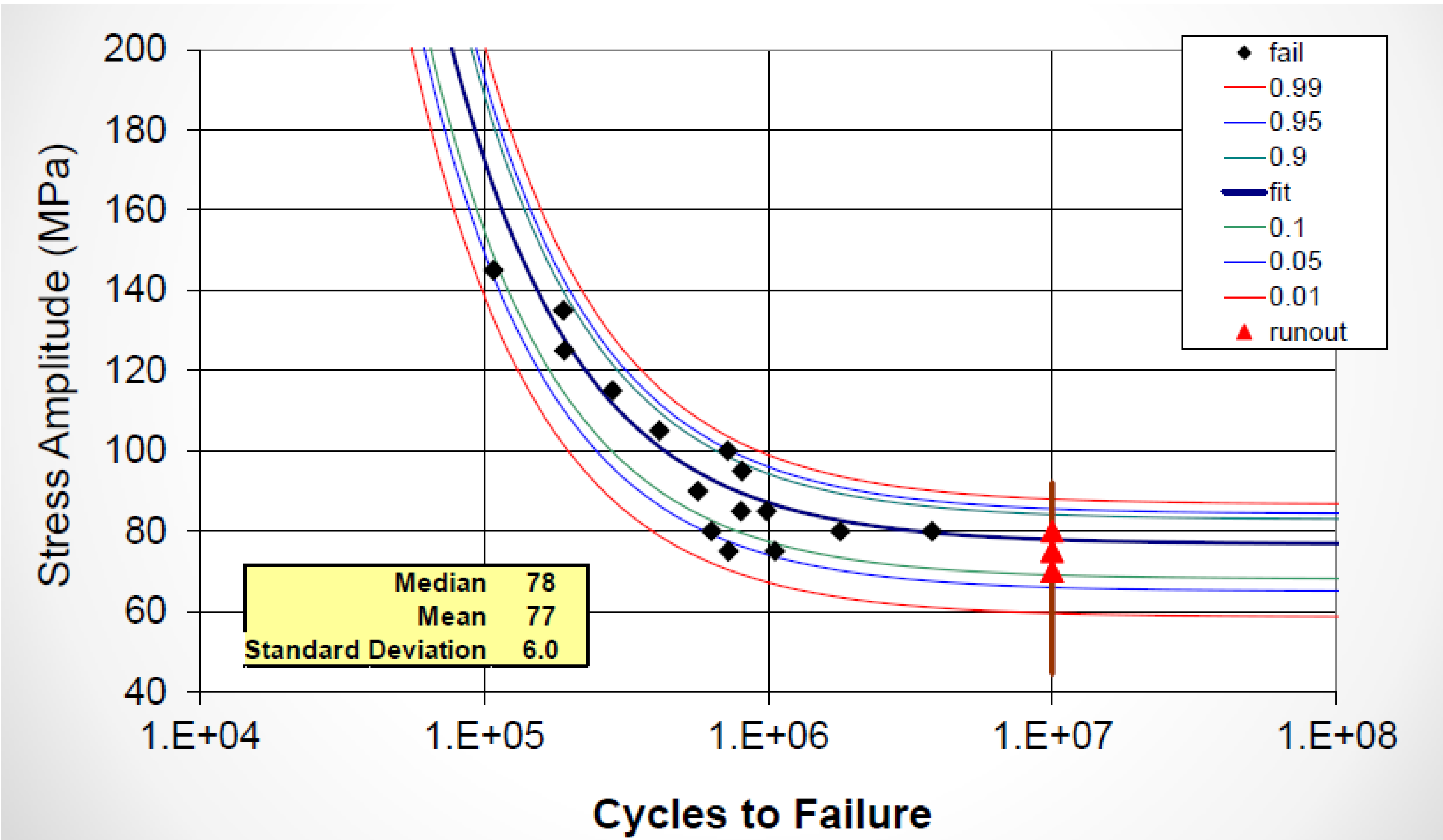
Results: Fatigue Strength at 120ºC (H16)

T7 Heat Treatment



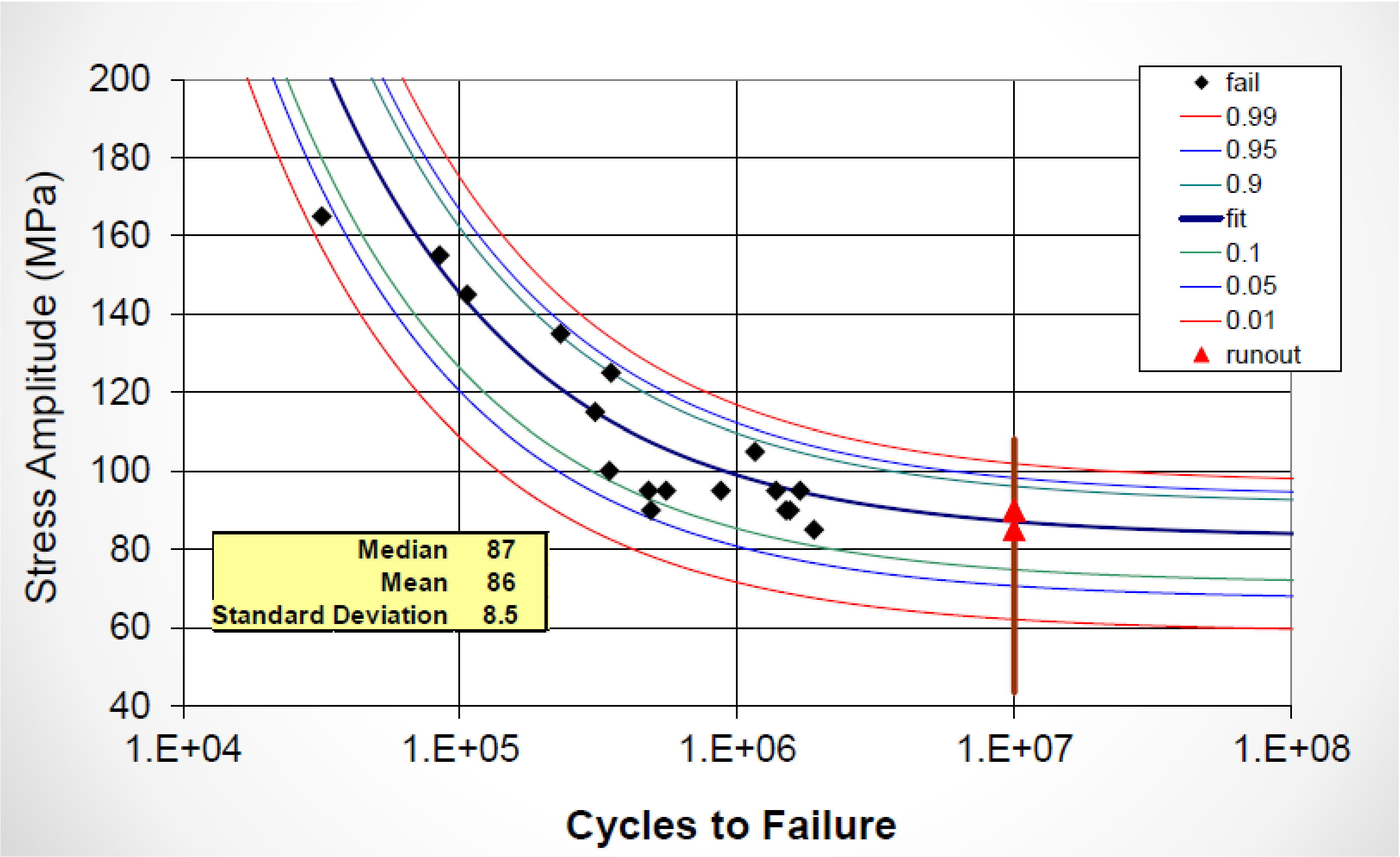
Results: Fatigue Strength at 120ºC (H17)

T7 Heat Treatment

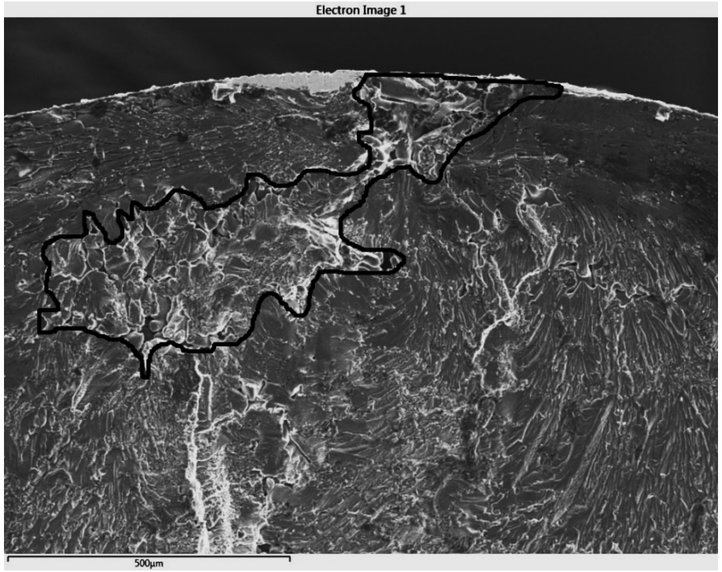


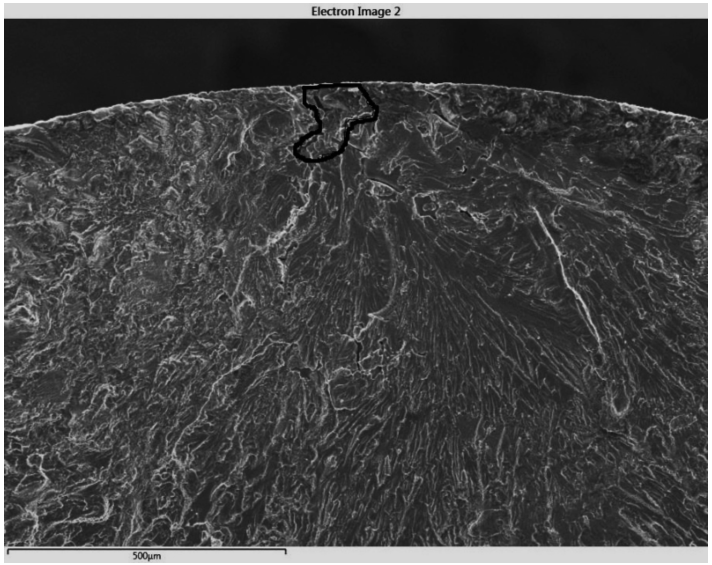
Results: Fatigue Strength at 120^{o}C (H17)

Two-stage Heat Treatment



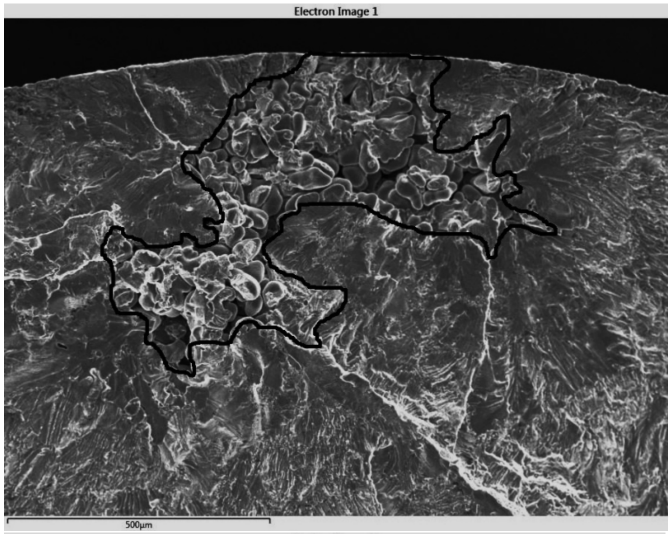
Results: Initiation sites on 120°C Fatigue for H16-T7

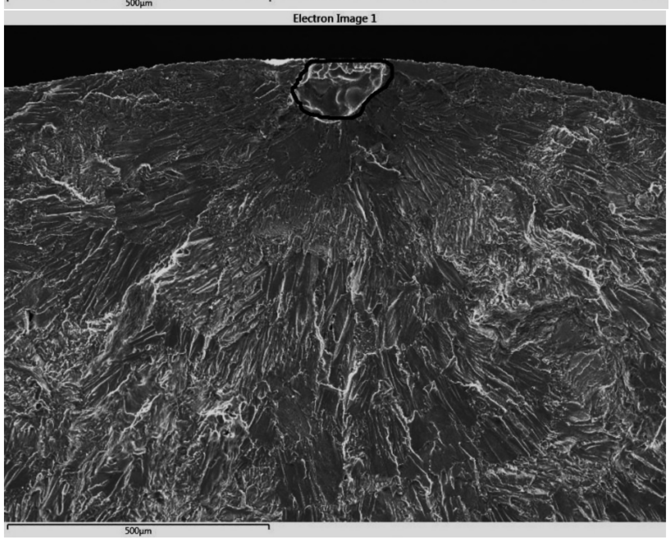




Sample ID	Number of pores at initiation site	Area (mm^3)	ECD (um)	L max(um)	Type of Pore
15-3196	1	0.166	459.7	1010	Shrink
15-3197	1	0.0118	122.6	176	shrink
15-3199	1	0.015	138.2	270	shrink
15-3203	1	0.0781	315.4	690	shrink
15-3204	1	0.0328	204.4	411	shrink
15-3207	1	0.0105	115.6	216	shrink
15-3208	1	0.0822	323.5	444	shrink
15-3209	1	0.0324	203.1	412	shrink
15-3210	1	0.0643	286.1	571	shrink
15-3212	2	0.0214	165.1	278	shrink
		0.00958	110.4	218	shrink
15-3213	1	0.0366	215.9	555	shrink
15-3215	1	0.0345	214.0	267	shrink
15-3217	1	0.213	520.8	847	shrink
15-3218	1	0.0615	279.8	541	shrink
	Shrink average	**0.0580**	**277.4**	**477.7**	

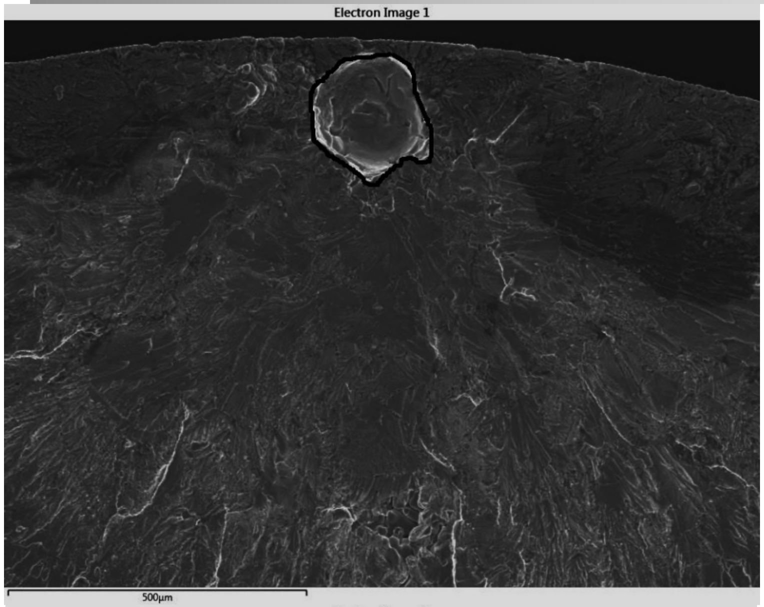
Result Initiation sites on 120˚C Fatigue for H17-T7

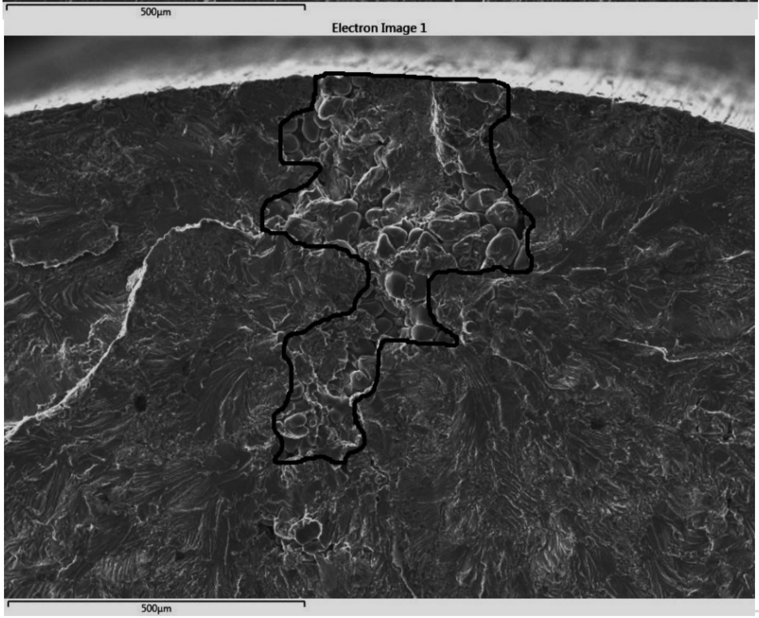




Sample ID	Number of pores at initiation site	Area (mm^3)	ECD (um)	L max(um)	Type of Pore
15-2913	1	0.0836	326.3	538	shrink
15-2914	1	0.0458	246.5	407	shrink
15-2915	1	0.0665	291.0	587	shrink
15-2916	1	0.197	500.5	788	shrink
15-2917	1	0.05	252.3	282	gas
15-2918	1	0.232	543.5	868	shrink
15-2919	1	0.016	142.7	190	gas
15-2920	2	0.142	425.5	687	shrink
		0.048	247.2	428	shrink
15-2921	1	0.238	550.5	814	shrink
15-2924	1	0.161	452.8	647	shrink
15-2928	2	0.061	278.6	370	shrink
		0.02	159.6	225	gas
15-2932	2	0.122	394.1	585	shrink
		0.144	428.2	588	shrink
15-2933	2	0.0586	273.2	419	shrink
		0.0222	168.1	262	gas
15-2935	1	0.373	689.2	1257	shrink
	Shrink average	**0.150**	**417**	**664**	12/14
	Gas average	**0.0271**	**180**	**239**	4/14

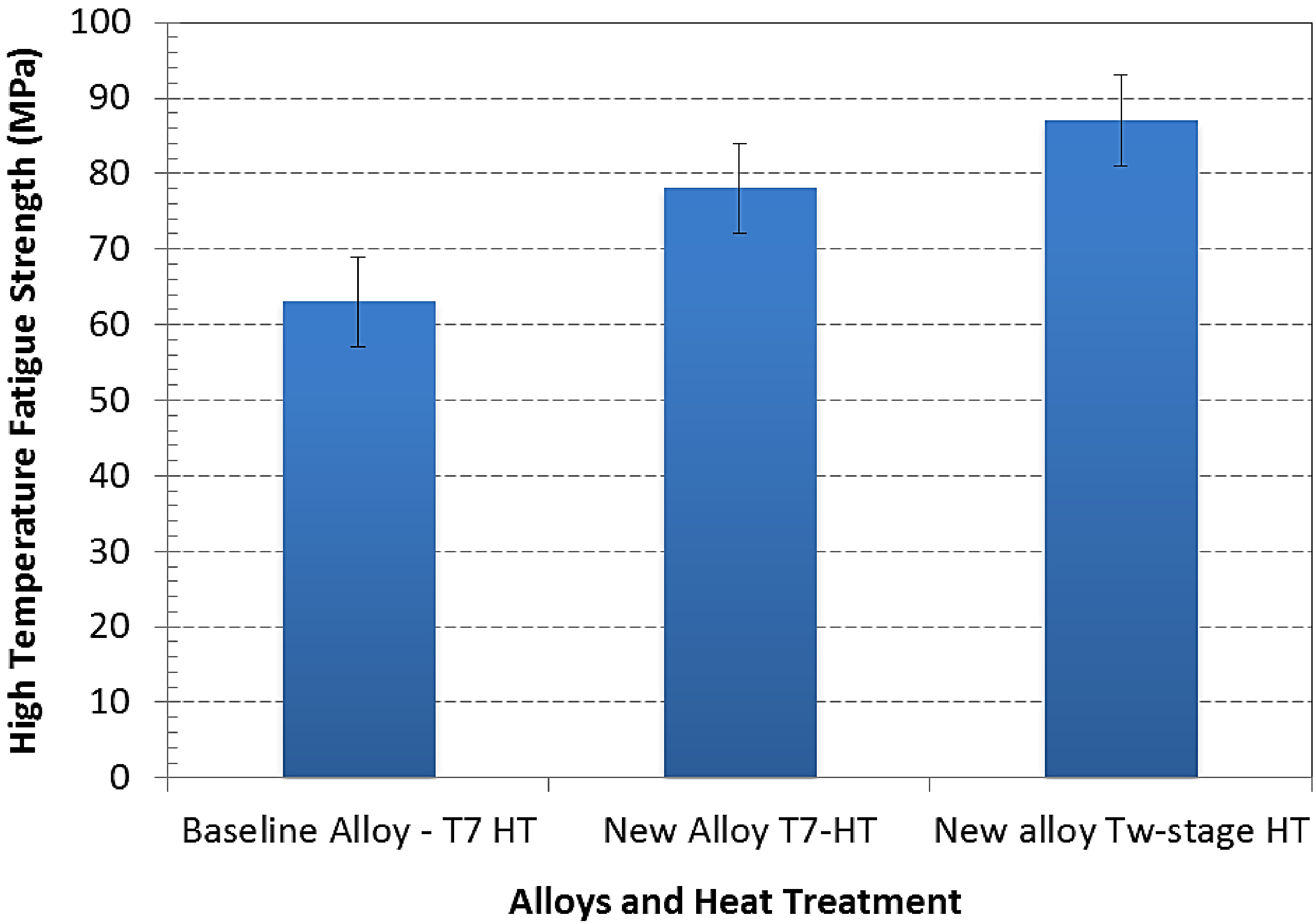
Results: Initiation sites on 120°C Fatigue for H17-two stage





Sample ID	Number of pores at initiation site	Area (mm^3)	ECD (mm)	L max(mm)	Type of Pore
15-2942	1	0.0289	191.8	532	gas
15-2943	1	0.0488	249.3	608	shrink
15-2945	2	0.113	379.3	689	shrink
		0.415	733.0	1040	shrink
15-2946	1	0.0432	234.5	305	shrink
15-2947	1	0.0409	228.2	314	gas
15-2949	1	0.163	455.6	743	shrink
15-2950	2	0.0417	230.4	280	gas
		0.279	596.0	834	shrink
15-2953	1	0.0096	110.6	180	gas
15-2954	2	0.0454	240.4	284	gas
		0.0405	227.1	287	gas
15-2955	1	0.0789	317.0	479	shrink
15-2956	2	0.156	445.7	648	shrink
		0.0331	205.3	250	gas
15-2957	1	0.0285	190.5	234	gas
15-2958	1	0.0405	227.1	291	gas
15-2960	2	0.0405	227.1	291	gas
		0.0348	210.5	261	gas
	Gas average	**0.0342**	**205**	**296**	10/14
	Shrink average	**0.169**	**433**	**665**	7/14

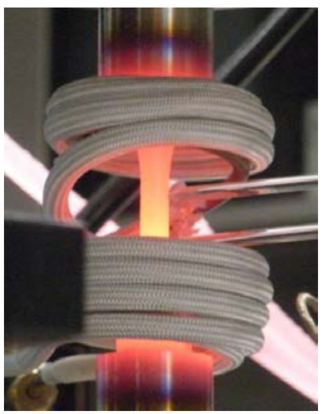
Results: Comparison of Fatigue Strength at 120^{o}C

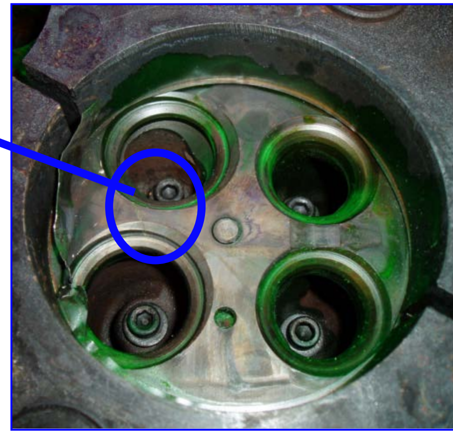


Thermal Mechanical Fatigue

TMF

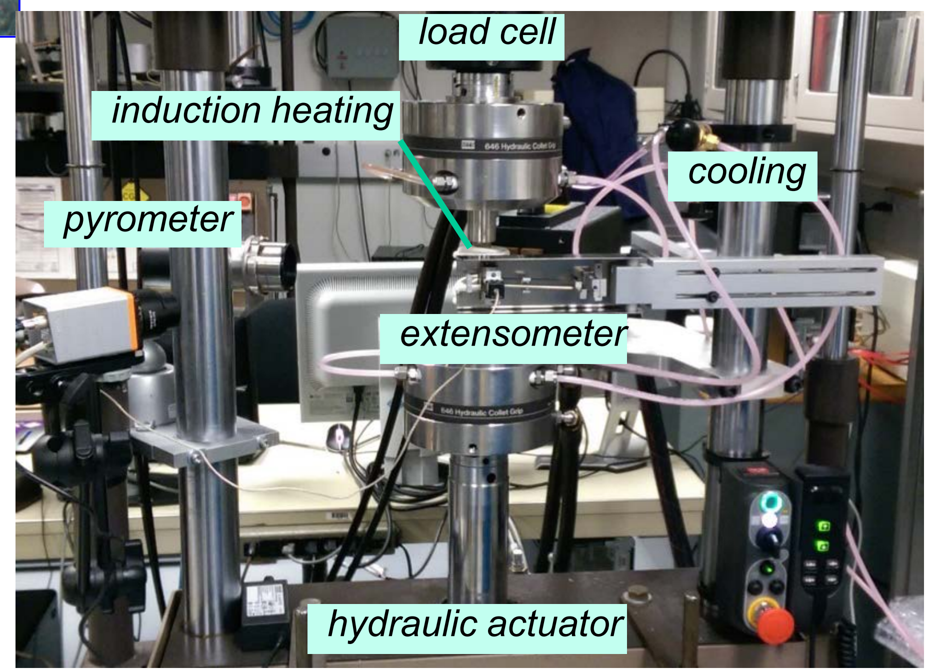
Material Test



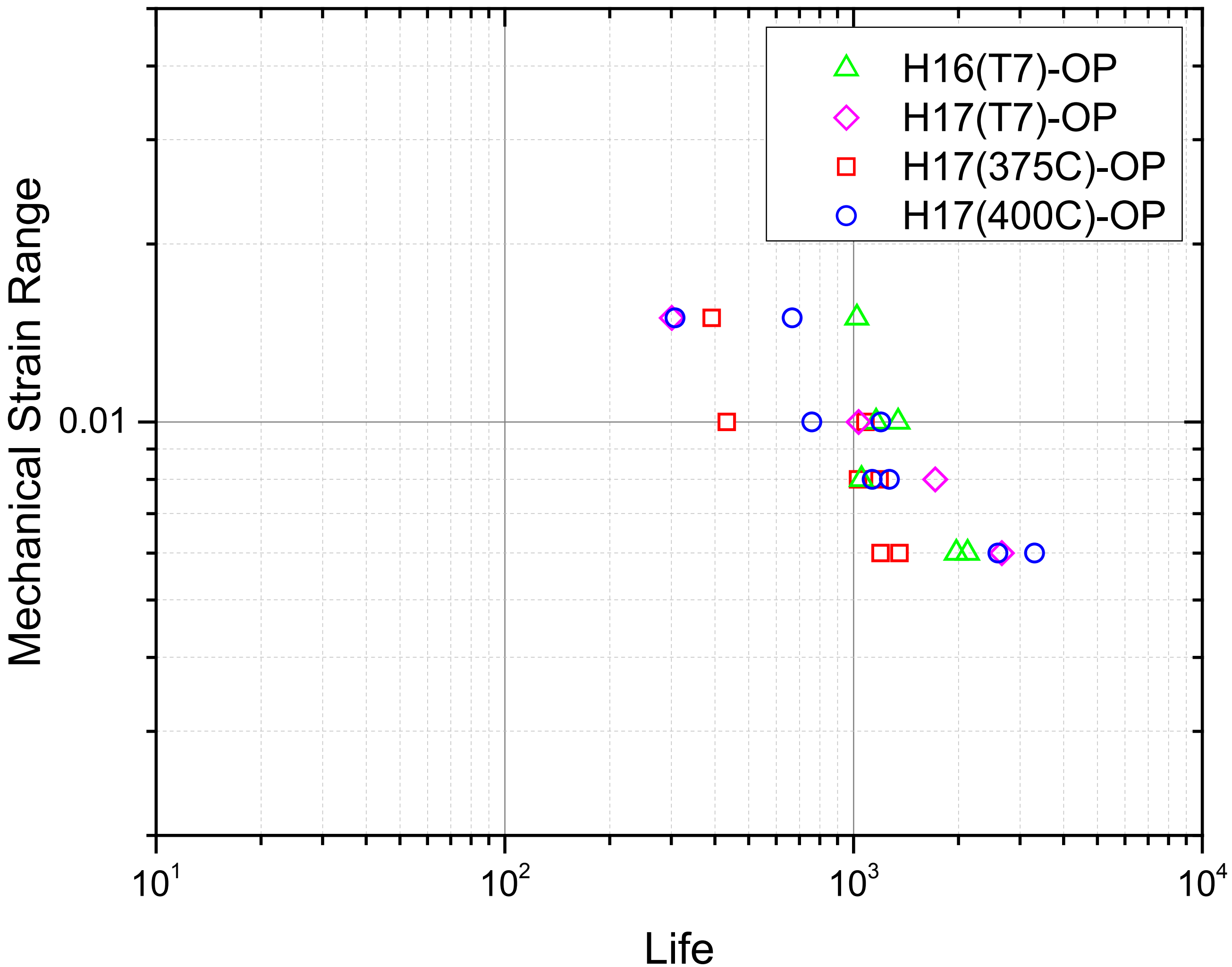


- External strains and stresses (no thermal gradient)
- Essential for assessing intrinsic fatigue properties

thermomechanical fatigue

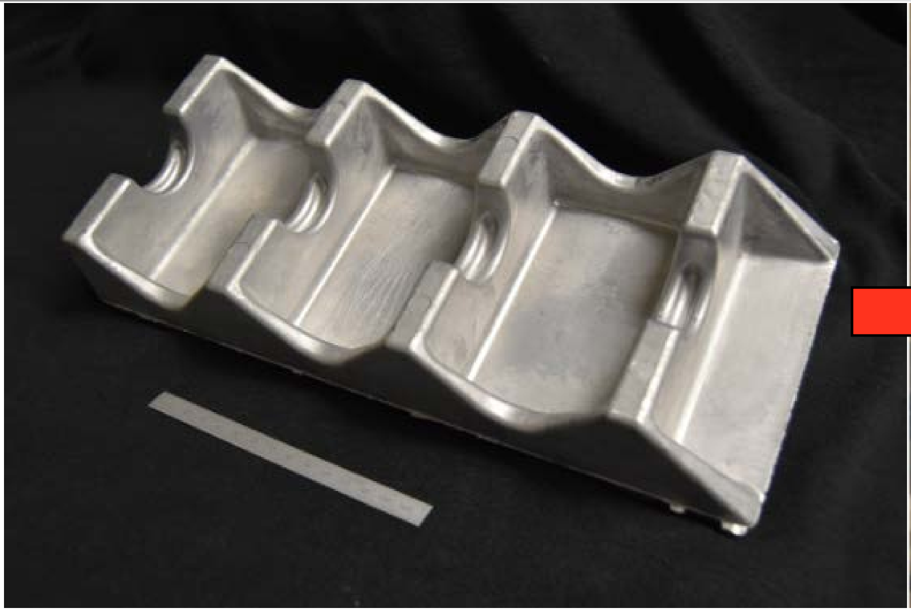


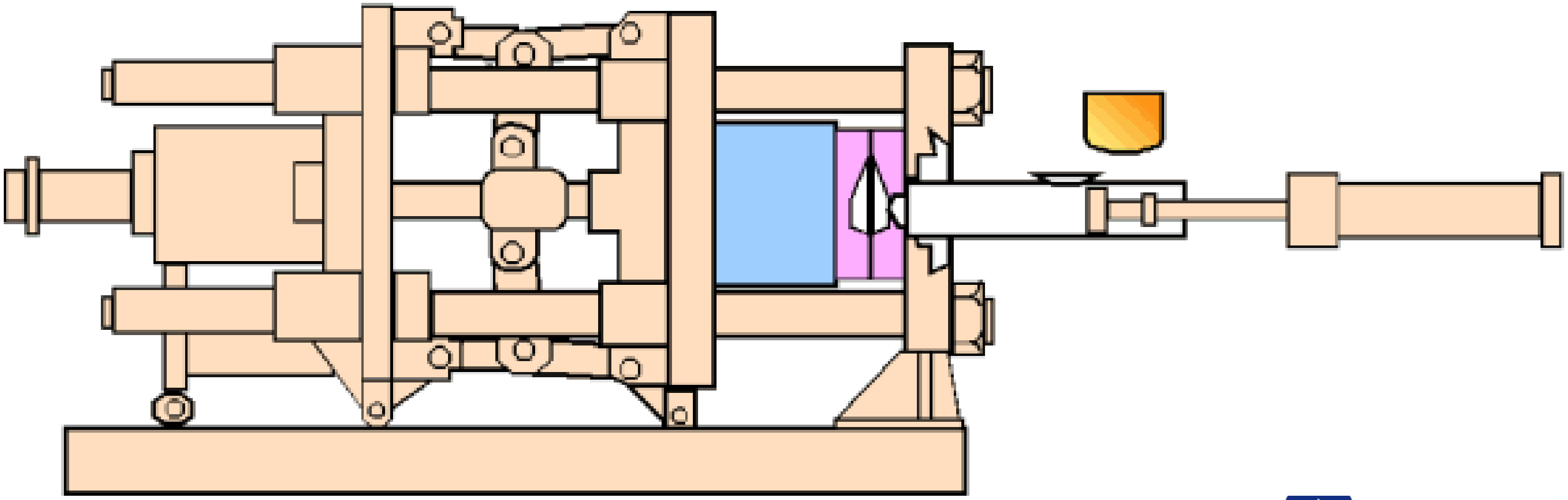
Results: Thermal Mechanical Fatigue for H16 and H17



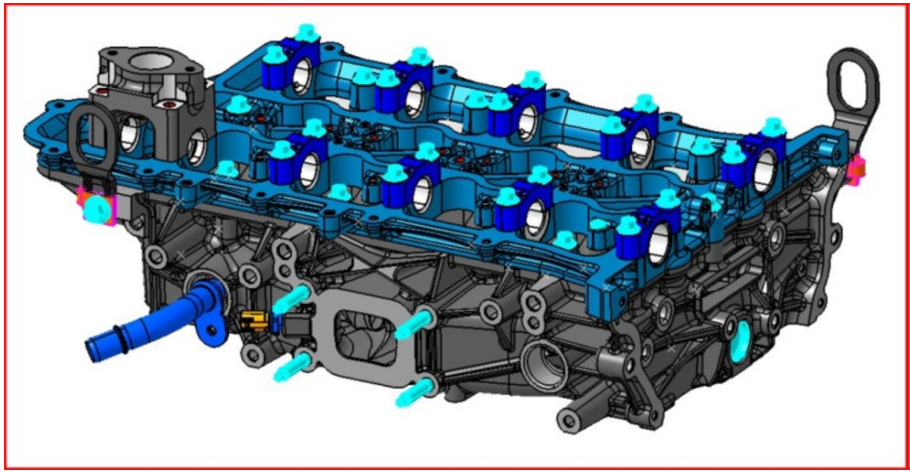
Temperature range: 100-300C out-of phase

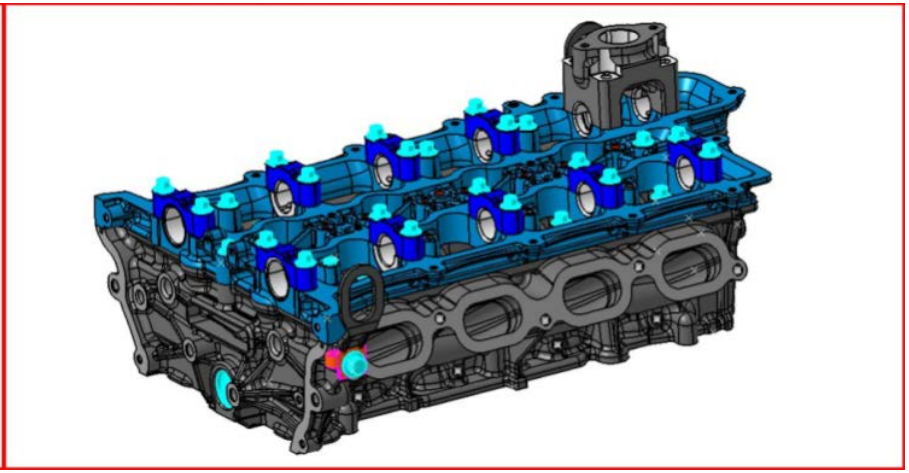
Demonstration on HPDC Block Bulkhead

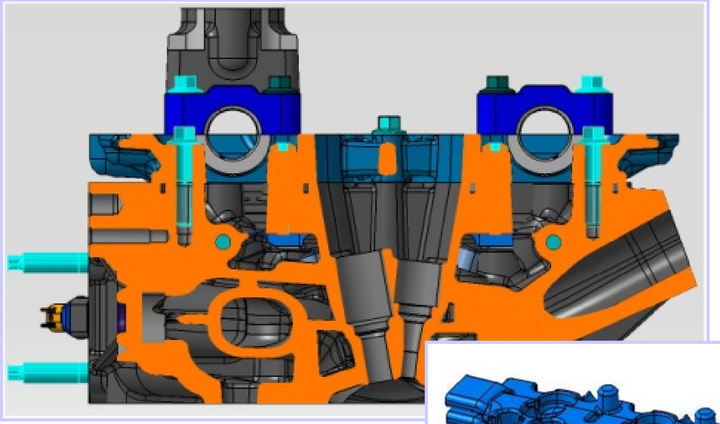


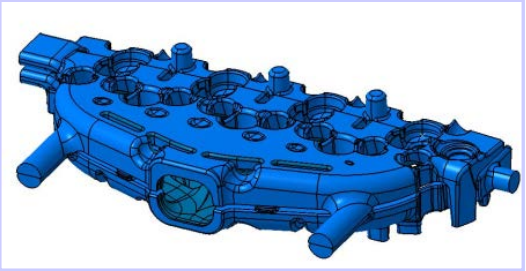


Demonstration on Ford GTDI Engine Program





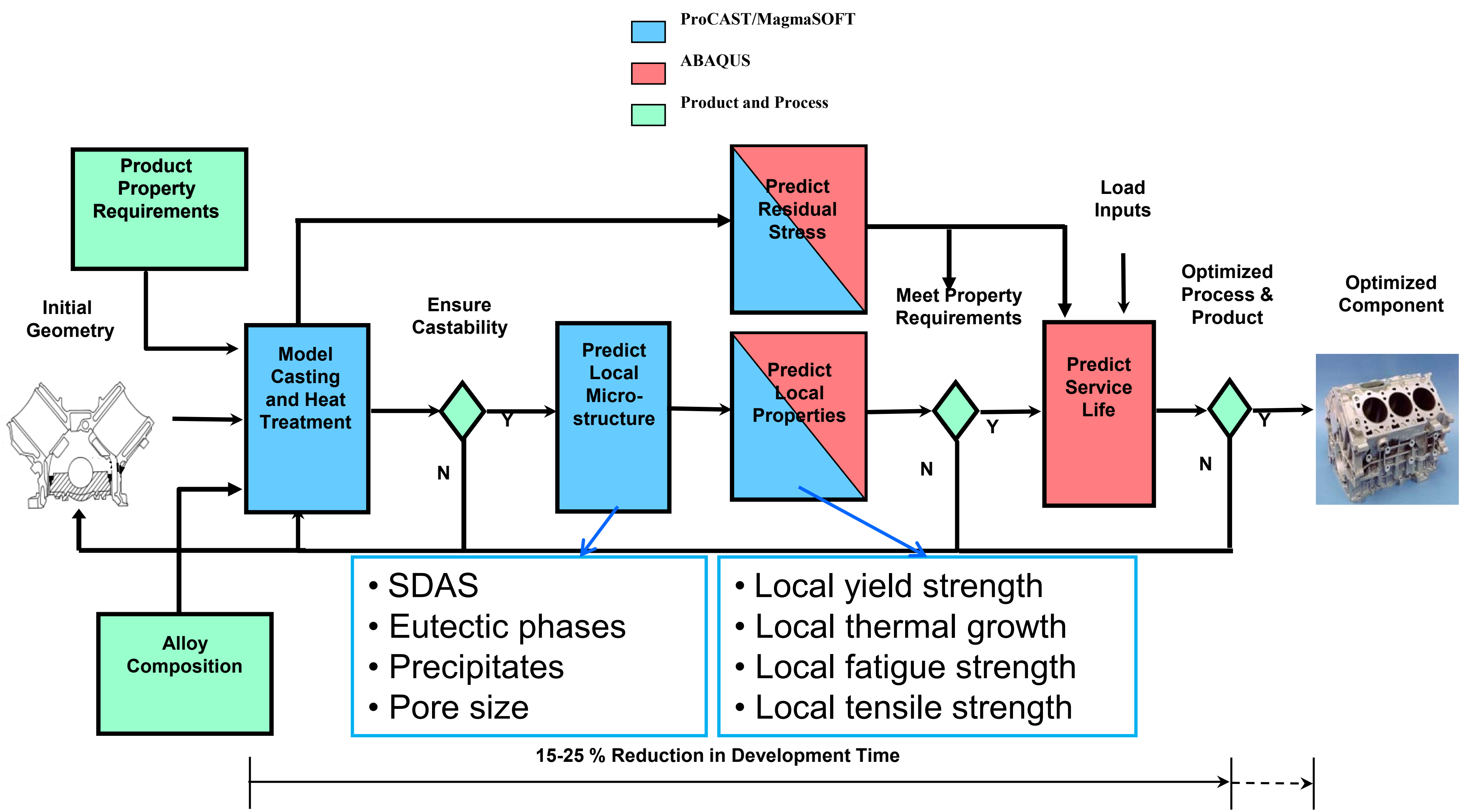




Under DOE Contract DE-EE0003332

- Based on Ford's large I4 Architecture
- Complete new Cylinder Head Design
- New Feature Content

ICME: Virtual Aluminum Castings



Accomplishments

- Completed the design of new cast aluminum alloys and the development of associated novel heat treatment process to achieve the heat resistant microstructures and enhanced high temperature mechanical properties.
- The new alloys met both the room temperature and high temperature tensile property DOE targets. Yield strength of the new alloys at 300^{o}C with 100 hours holding time is 52MPa, and the corresponding tensile properties without holding time are > 20 MPa above the targets.

Accomplishments

- Both room fatigue strength met the DOE targets. The new alloys with the optimum heat treatment process achieved > 20MPa fatigue testing above the baseline at 120^{o}C.
- Out-phase thermo-mechanical properties for temperature range of 100^{o}C-300^{o}C demonstrated thermal stability of the new alloys at low strain range and long life regime.
- Developed the demonstration plan on the HPDC block bulkhead and Ford GTDI cylinder head

Future Work

- Complete the quantification and modeling of phase transformation kinetics during casting, solution treatment and aging treatment
- Complete the quantification and modeling of mechanical properties including yield strength, fatigue strength and thermo-mechanical fatigue properties
- Validate and identify the gaps in microstructural and property models
- Refine the cost model to quantify the cost of new alloys compared with A319 and A356 alloys.
- Demonstrate the performance of the new alloys in block bulkhead and Ford GTDI cylinder head