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 2017
- Percent complete: 90%

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 FY16
  - $799K
- Funding for FY17
  - $716K

Partners

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

Project Objectives

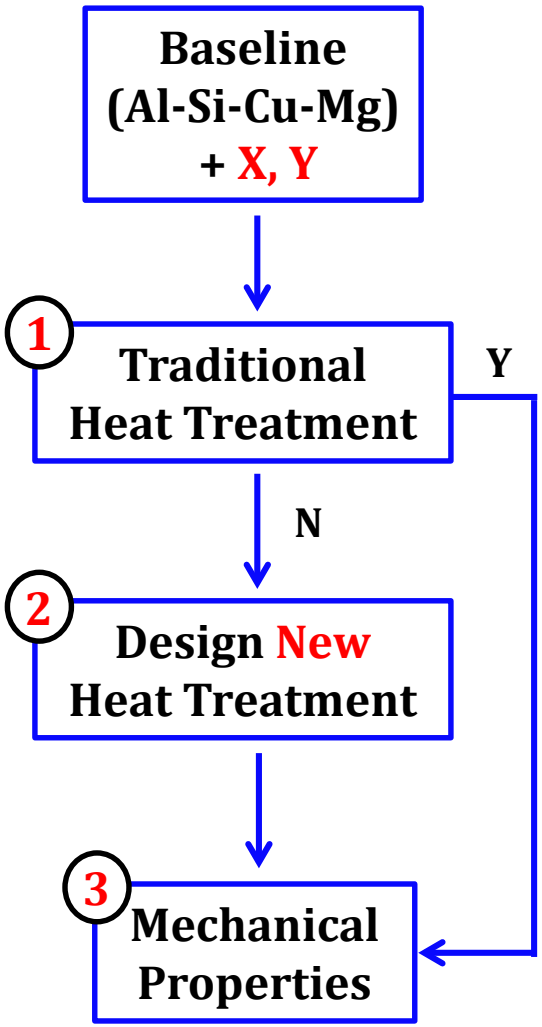
- To develop a new class of advanced, cost competitive aluminum casting alloys providing a 25% improvement in component strength relative to components made with A319 or A356 alloys for high-performance engine applications.
- To demonstrate the power of Integrated Computational Materials Engineering (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

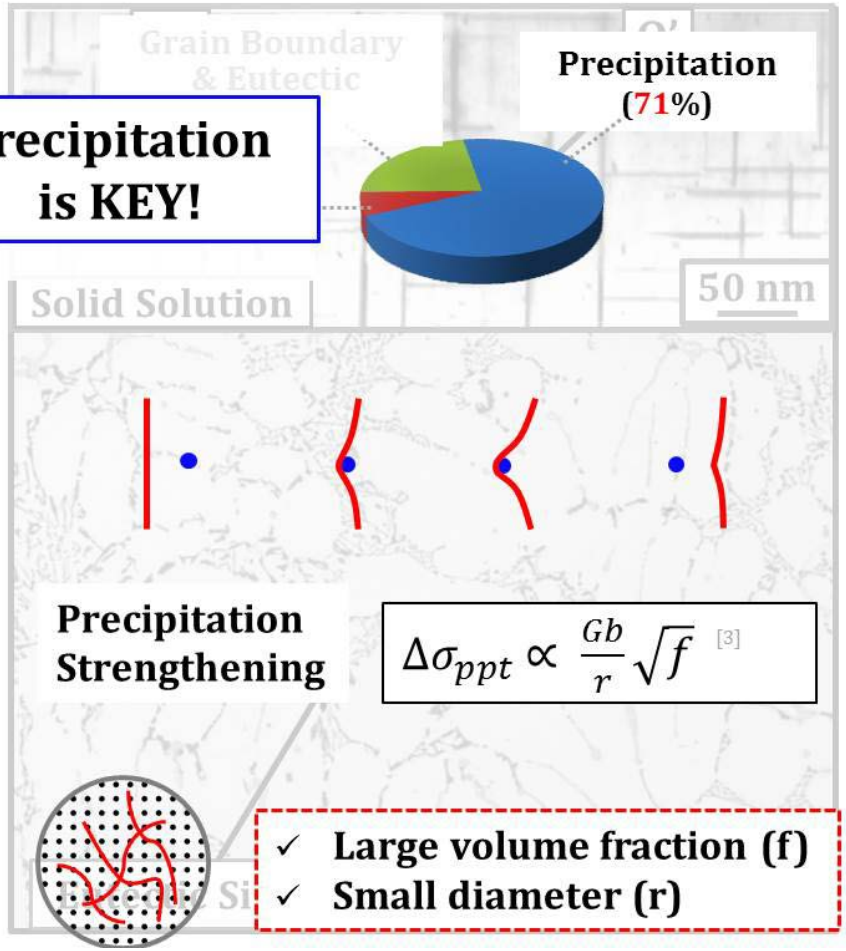
Property	Cast Aluminum Baseline	Cast Lightweight Alloy Targets	Key Properties (must meet)
Tensile Strength	33 KSI (228 MPa)	40 KSI (276 MPa)	Key
Yield Strength	24 KSI (166 MPa)	30 KSI (207 MPa)	Key
Density	2.7 g/cm3	< 6.4 g/cm3	Key
Elongation (%)	0.035	0.035	
Shear Strength	26 KSI (179 MPa)	30 KSI (207 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

Baseline:
W319, Al-Si-Cu-Mg
Heat 16

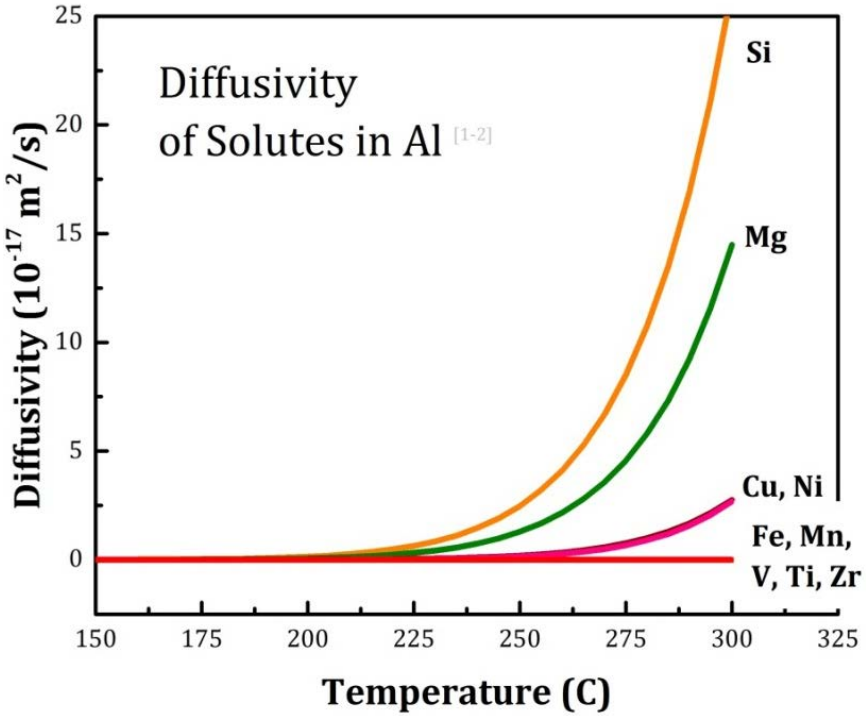


Precipitation is KEY!



Alloy Design Approach: Engineering Microstructures

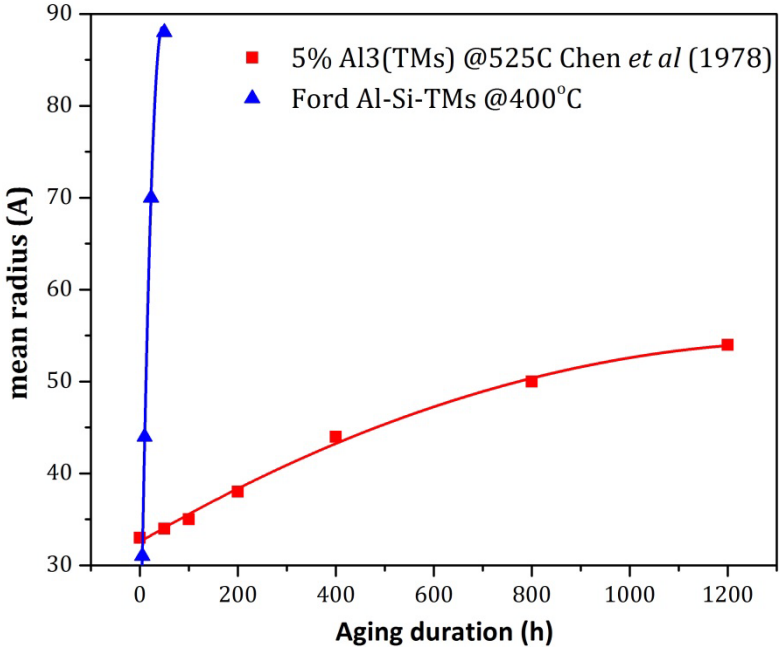
Simple Model Alloys
Al-Zr-TMs and Al-Si-TMs



Volume fraction of TM-contain precipitates is too **low**

Maximum solubility in Al-Matrix (wt%)				
wide used elements		Transition Metals		
Cu	Mg	Ti	Zr	V
5.7	14.9	1	0.6	0.28

Kinetics of TM-contain precipitates is **changed by Si**



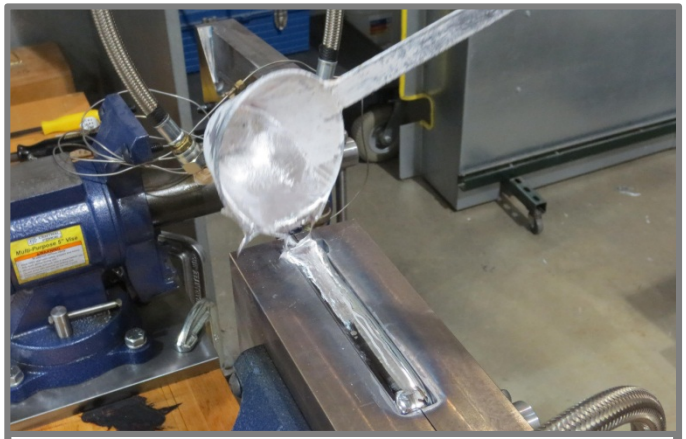
Design alloys:
Al-Si-Cu-Mg-TMs
Heat 17
With Ford Proposed Heat Treatment

Alloy Design Approach: Engineering Microstructures

Small Batch

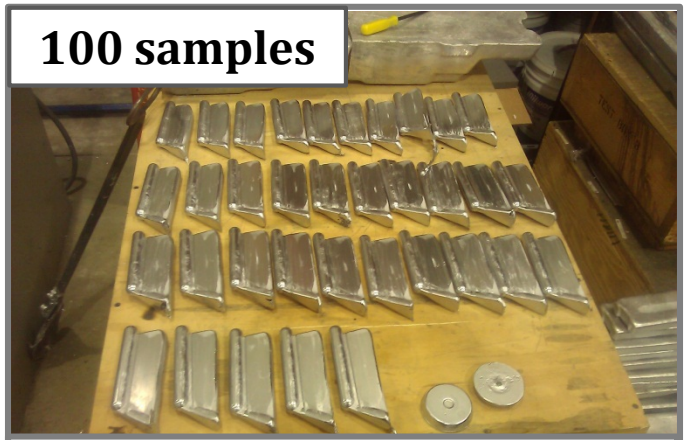
(a) Melting raw materials @ 750 C.

(b) Pouring spectrometer disk.



(c) Pouring torpedo shape sample.

100 samples



(d) Torpedo samples for analysis.

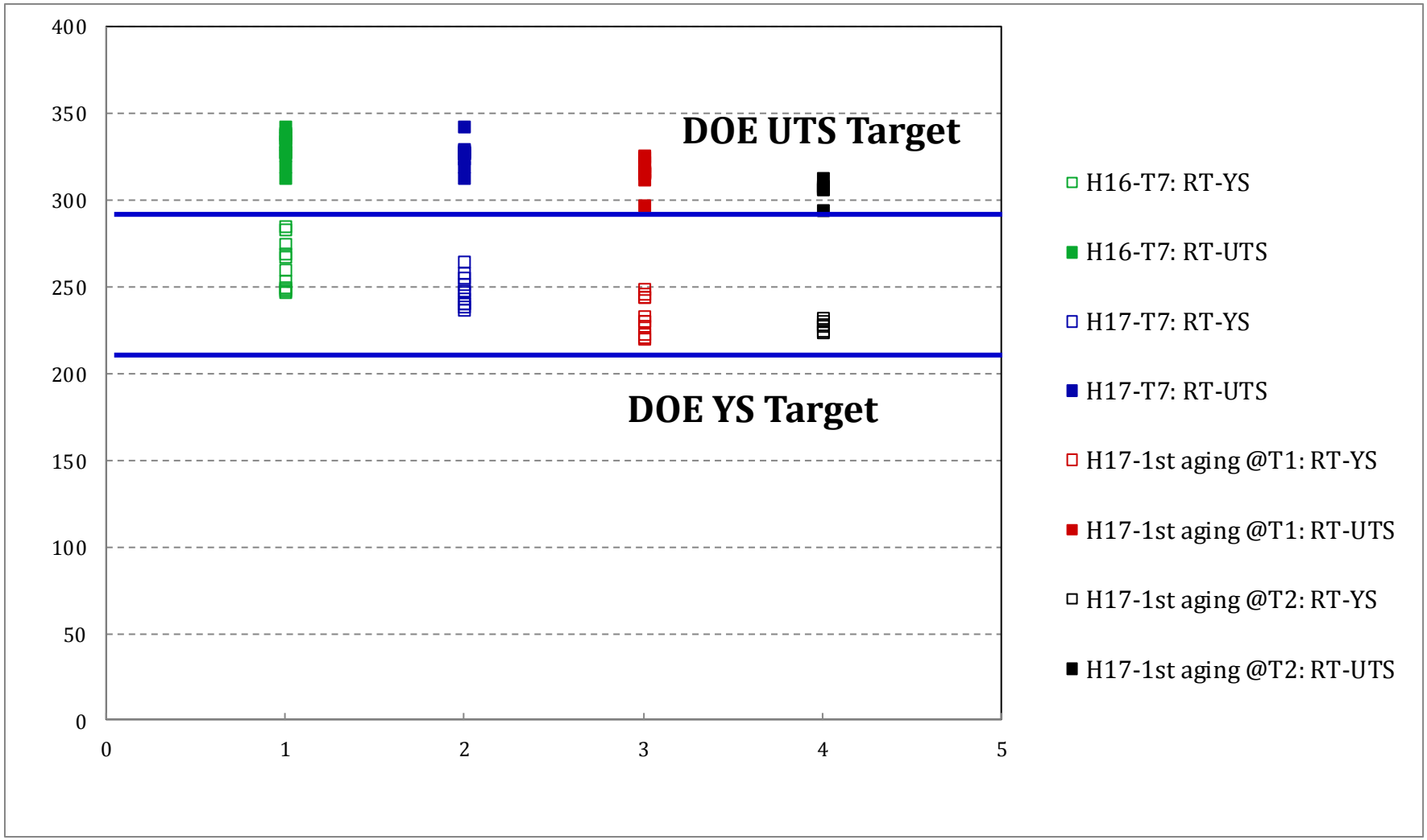
Alloy Design Approach: Engineering Microstructures

	Designation	Component	Heat Treatment
Baseline alloys	Heat 16-T7	Al-Si-Cu-Mg-Fe-Ti	T7
	Heat 16-w/o Sr-T7	Al-Si-Cu-Mg-Fe-Ti	T7
Semi-Permanent alloys for cylinder head	Heat 17-T7	Al-Si-Cu-Mg-TMs-Fe-Ti	T7
	Heat 17-w/o Sr-T7	Al-Si-Cu-Mg-TMs-Fe-Ti	T7
	Heat 17-T_1	Al-Si-Cu-Mg-TMs-Fe-Ti	Novel Heat Treatment 1
	Heat 17-T_2	Al-Si-Cu-Mg-TMs-Fe-Ti	Novel Heat Treatment 2
	Heat 17-w/o Sr-T_1	Al-Si-Cu-Mg-TMs-Fe-Ti	Novel Heat Treatment 1
High pressure die cast alloys for engine block	Heat 26-T5	Al-Si-Cu-Mg-TMs-Mn-Fe-Ti	T5

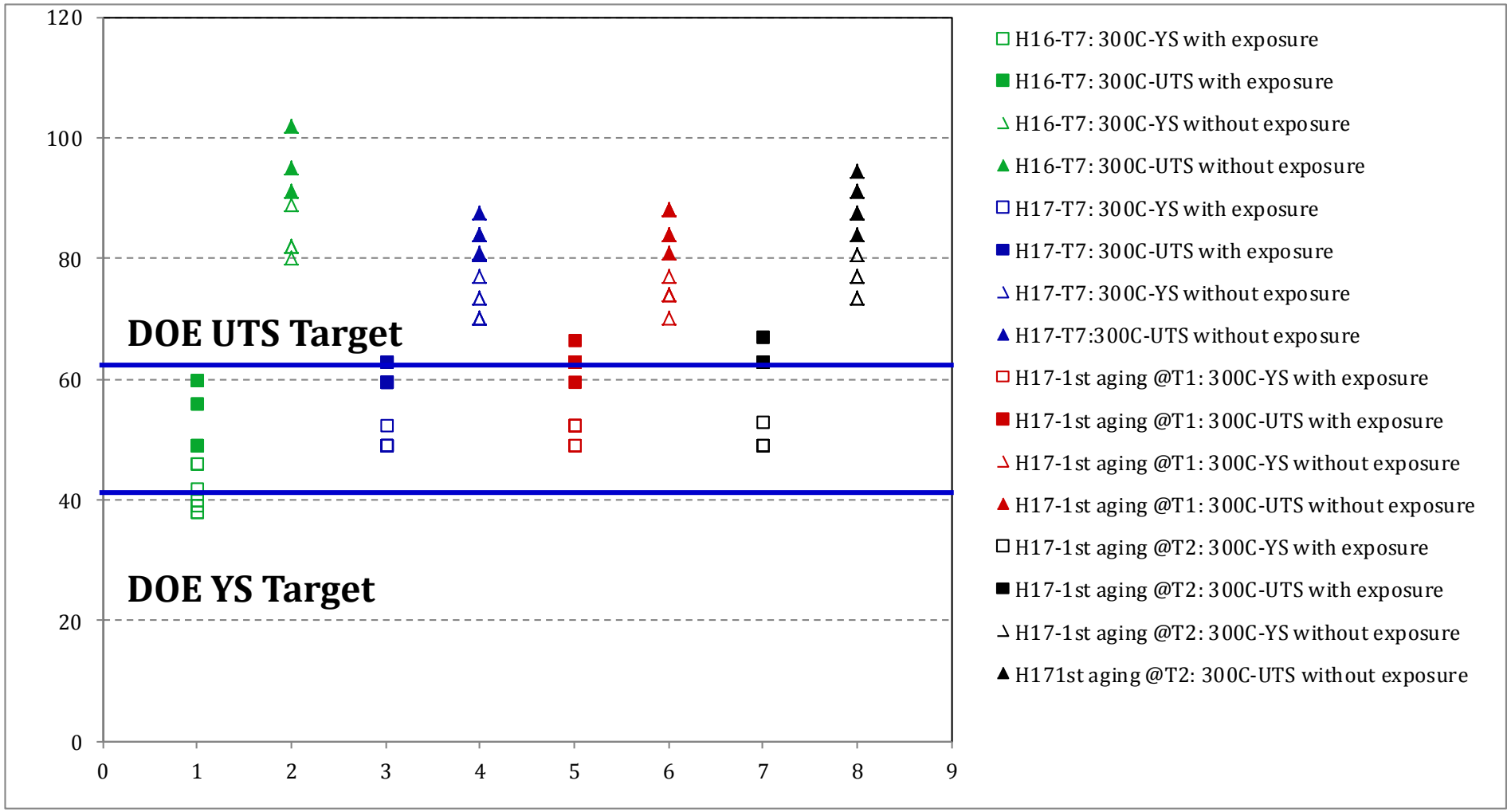
Alloy Design Approach: Engineering Microstructures

Designation	Mechanical test				
	Tensile at different temperatures	RT Endurance Limit	Elevated Temperature Endurance Limit	Thermal Fatigue	Thermal Mechanical Fatigue
H16-T7	✓	✓	✓	✓	✓
H16-w/oSr-T7			✓		
H17-T7		✓	✓	✓	✓
H17-T_1	✓	✓	✓	✓	✓
H17-T_2		✓	✓	✓	✓
H17-w/oSr-T7			✓		
H17-w/oSr-T_1			✓		
H26-T5	✓		✓		

Results: Yield Strength and Ultimate Tensile Strength at RT

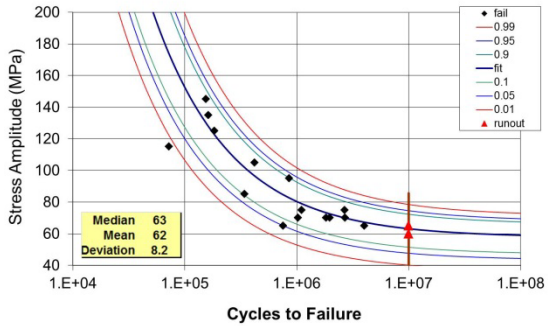


Results: Yield Strength and Ultimate Tensile Strength at 300˚C

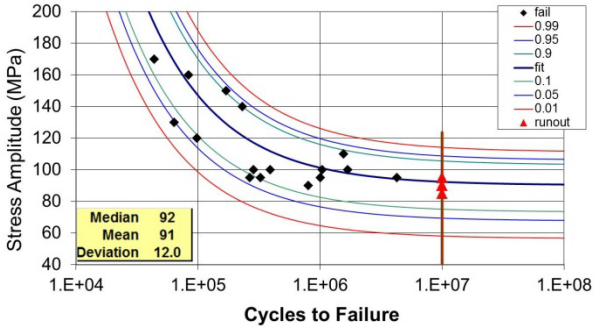


Results: Endurance Limit at RT and Elevated Temperatures

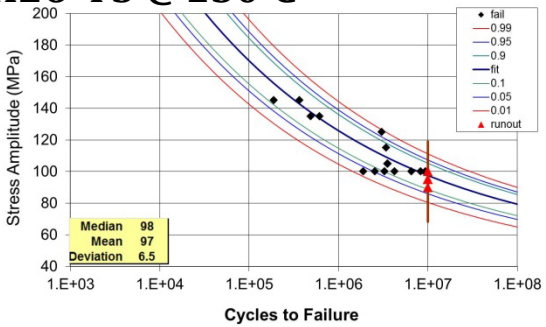
H16-T7 @120˚C

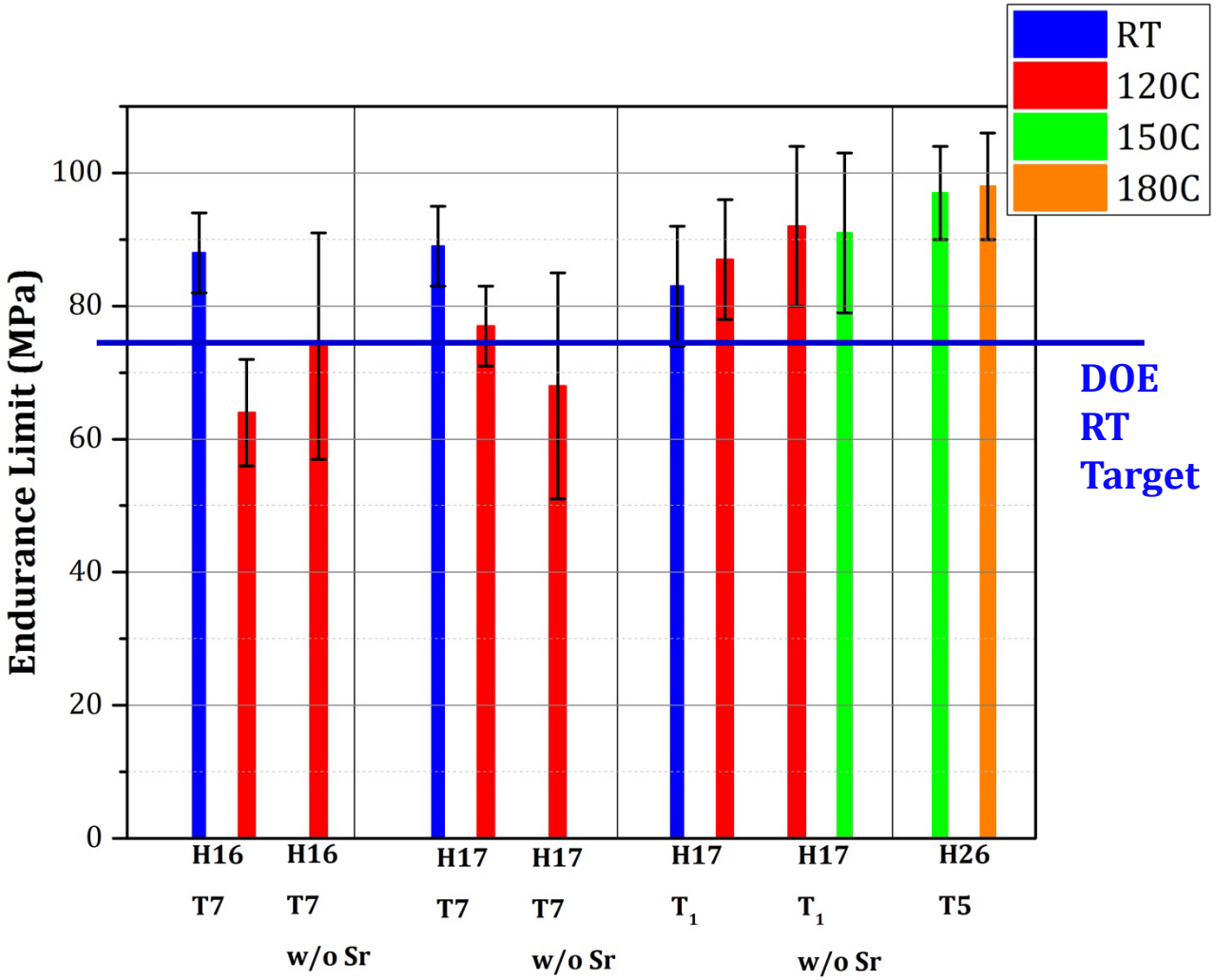


H17-w/oSr-T_1 @150˚C

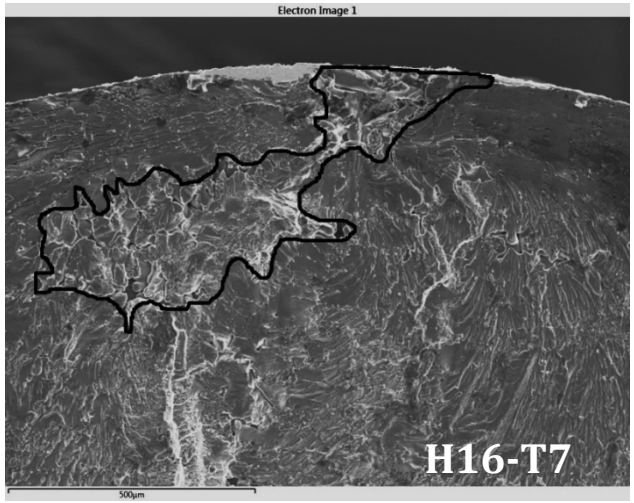


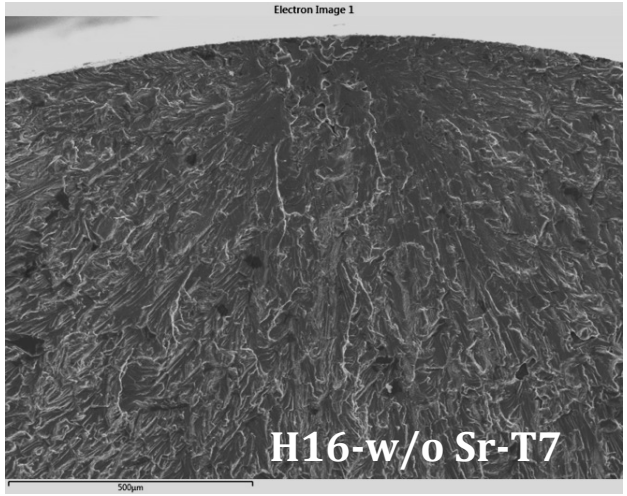
H26-T5 @150˚C

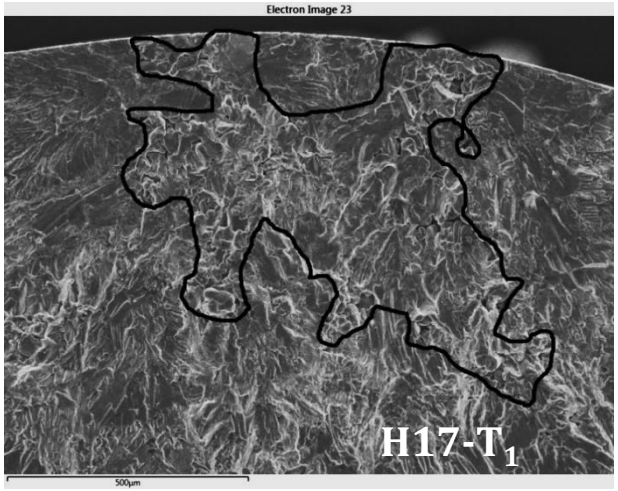


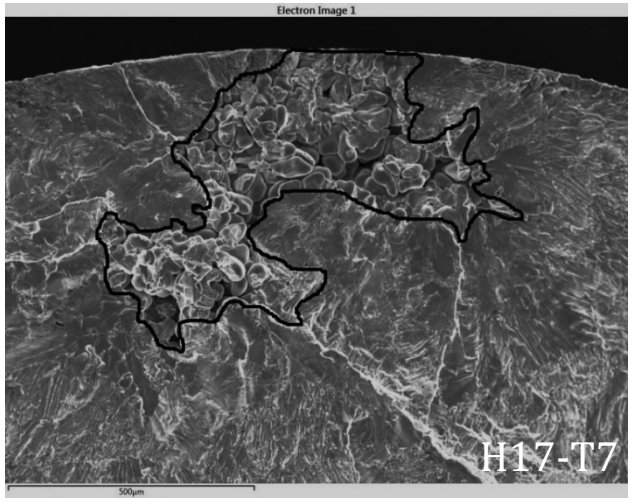


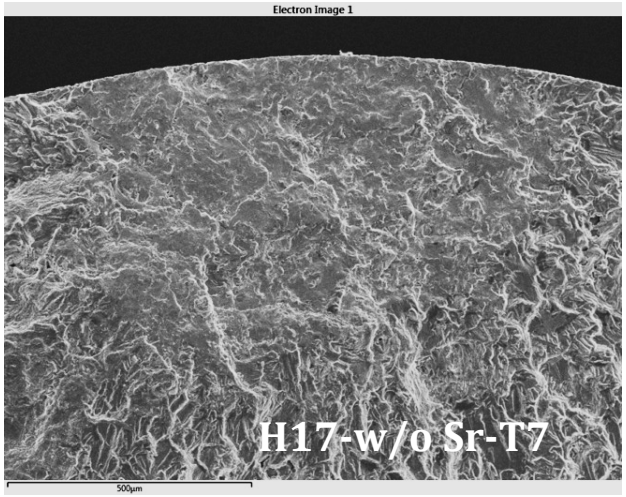
Results: Initiation Sites Characterization

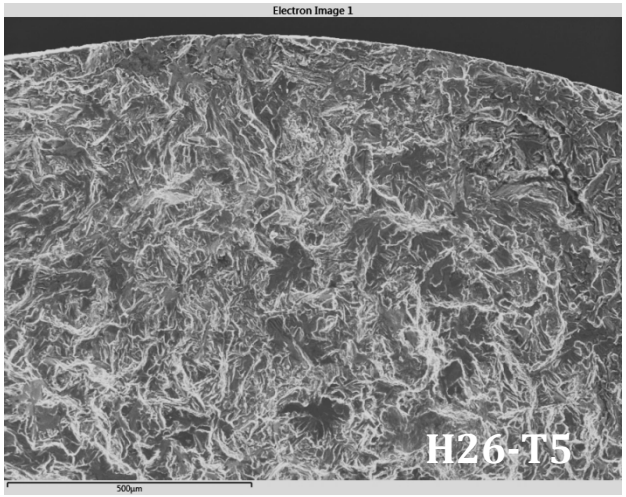






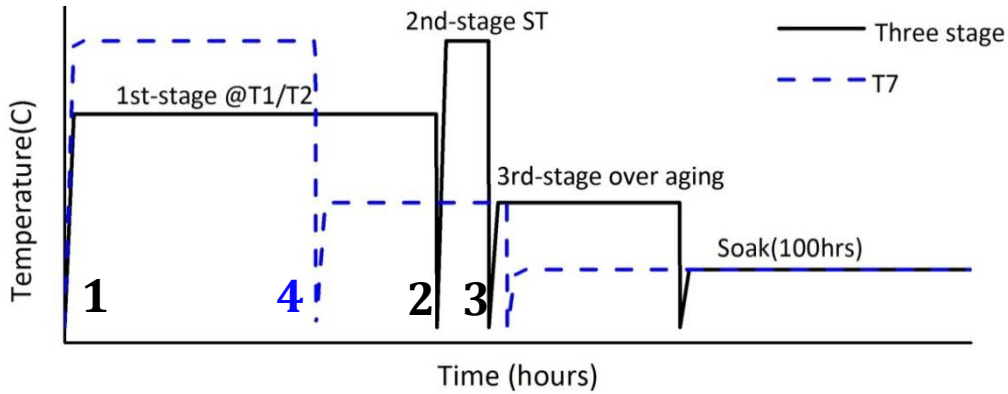






Results: Microstructure Characterization

- **Back-Scatter Imaging and EDS mapping of Heat 17**



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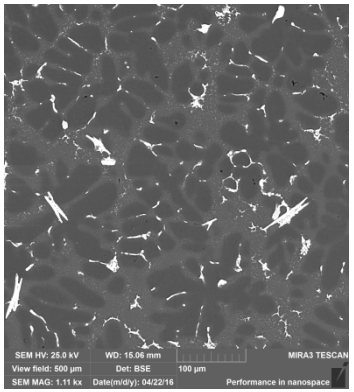

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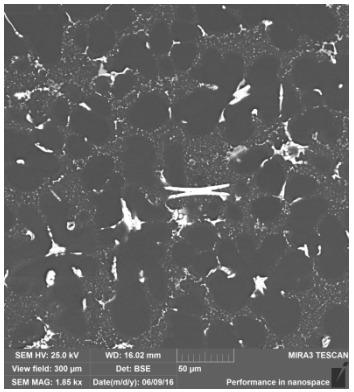

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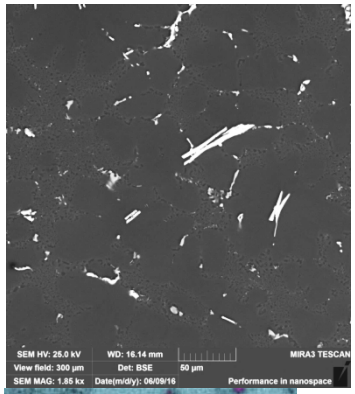

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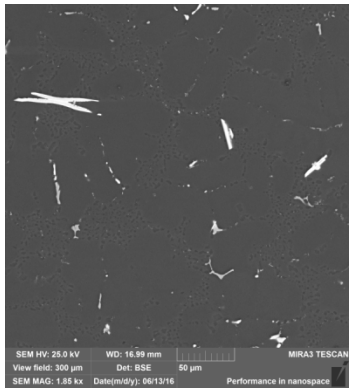
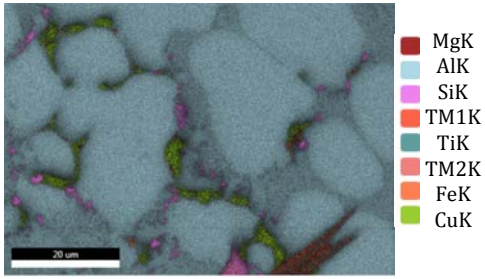
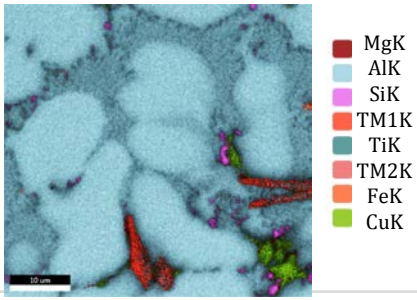
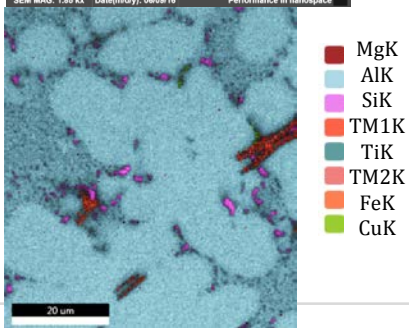
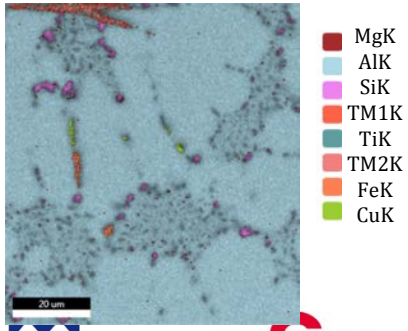




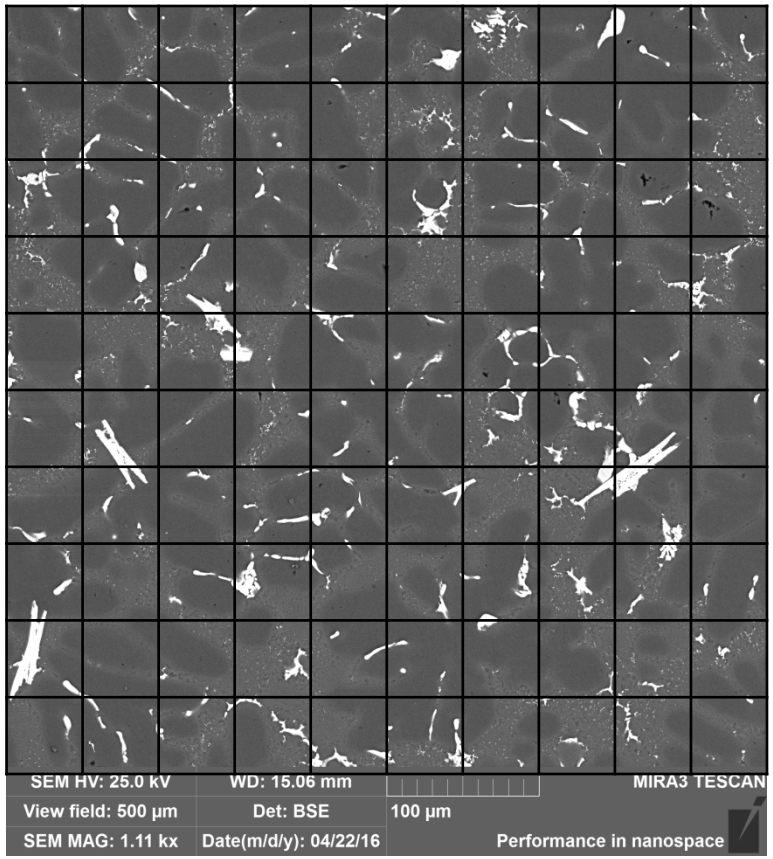


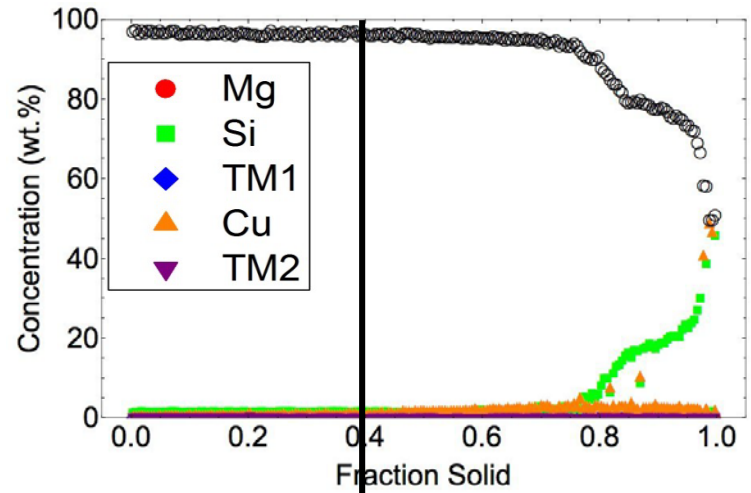


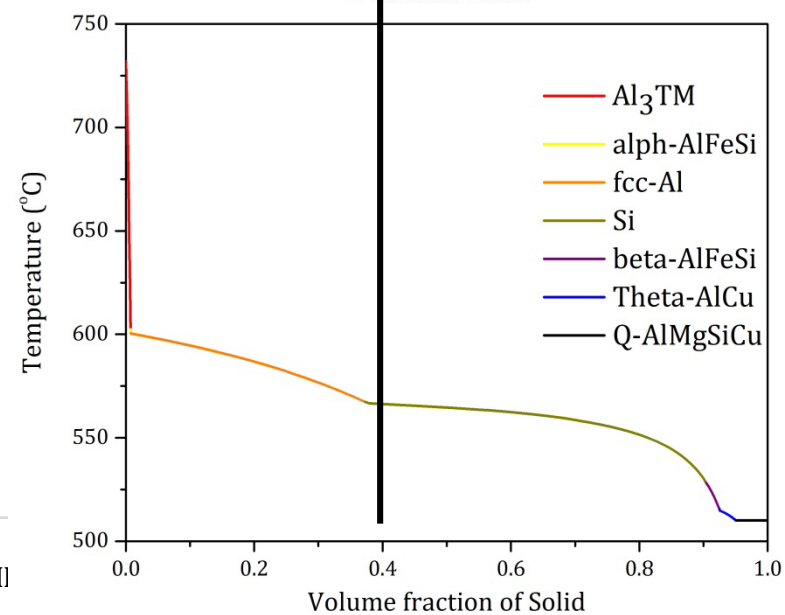


Results: Microstructure Characterization

- **EPMA measured matrix composition**
  - Gird measurement: two12*12 grids with 50μm spacing

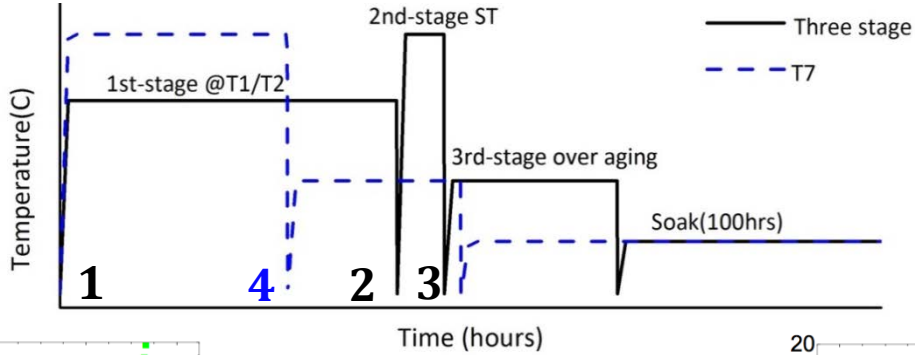


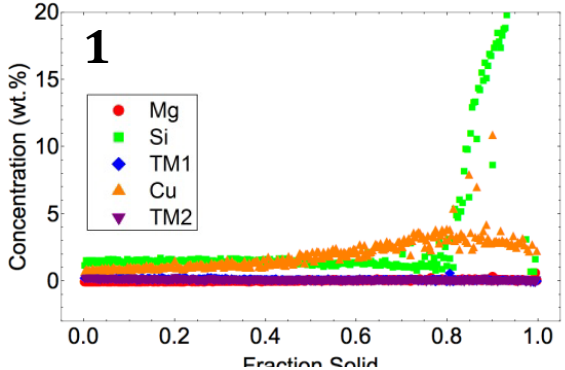




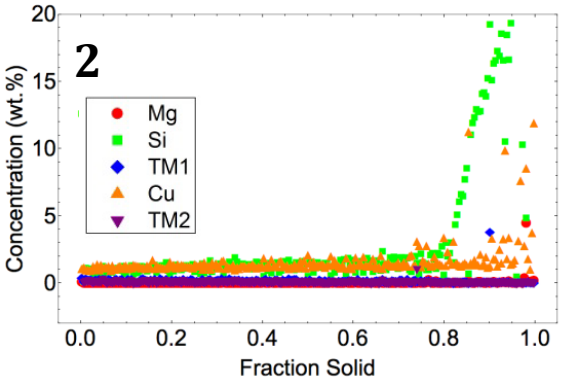
Results: Microstructure Characterization

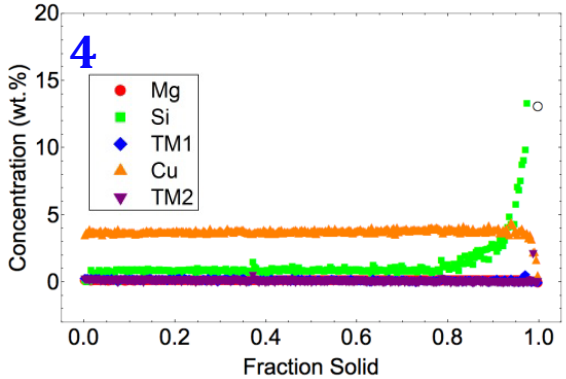
- **Matrix composition measurement by EPMA of Heat 17**





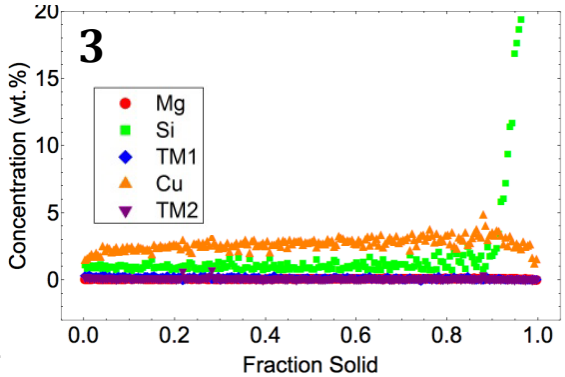
Macro-segregation alleviates
Minor increasing of Cu/Mg





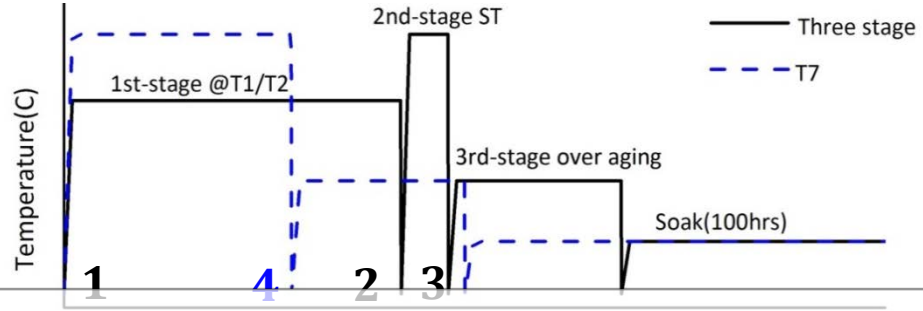
significant increasing of Cu/Mg

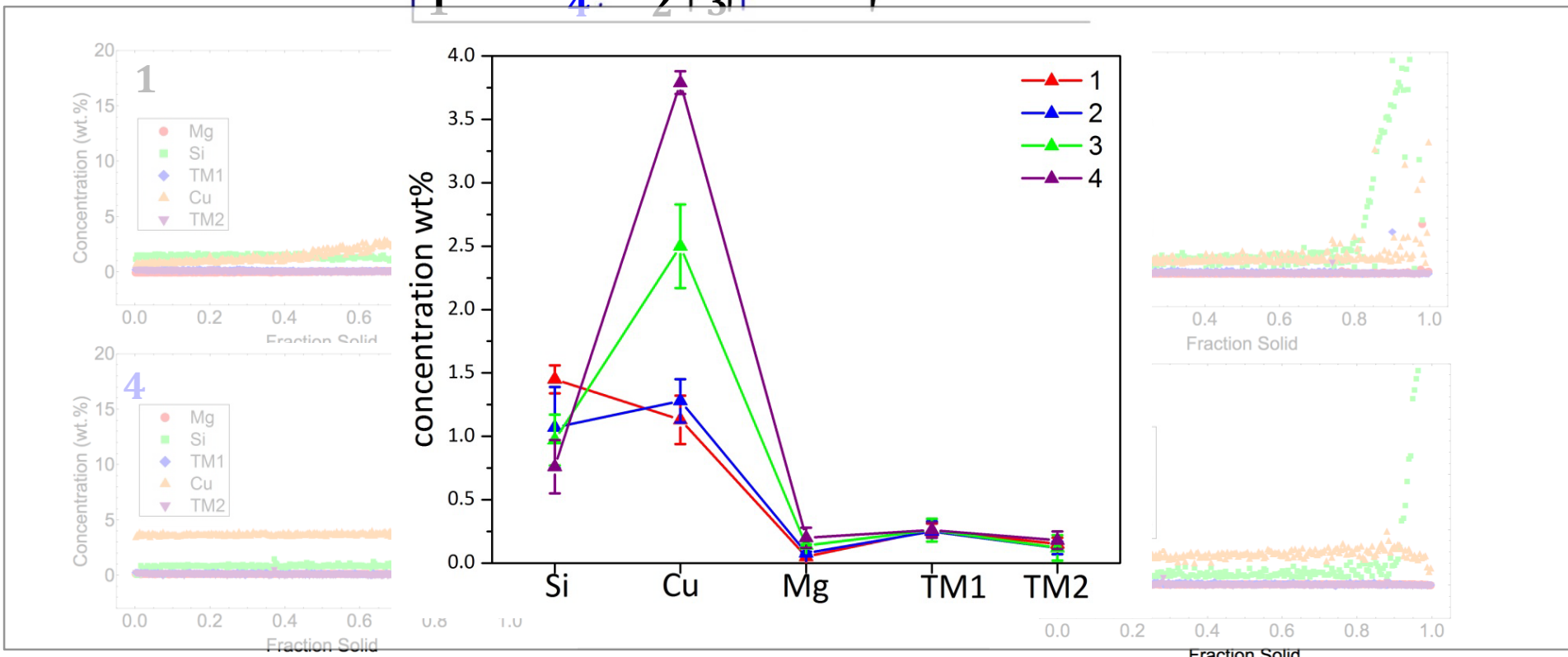
further increasing of Cu/Mg



Results: Microstructure Characterization

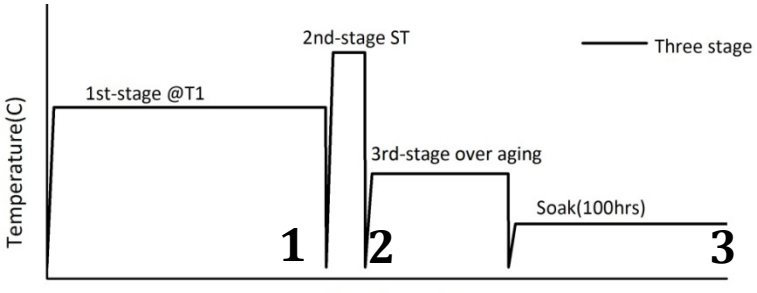
- **Matrix composition measurement by EPMA of Heat 17**





Results: Microstructure Characterization

- **Transmission Electron Microscope of Heat 17-T_1**



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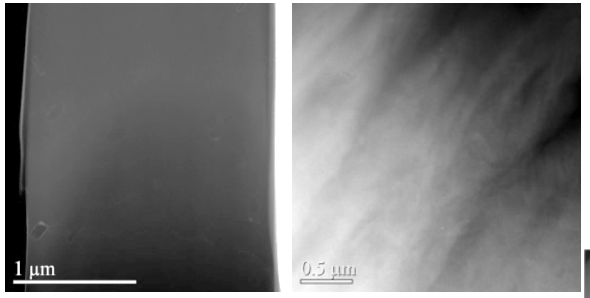

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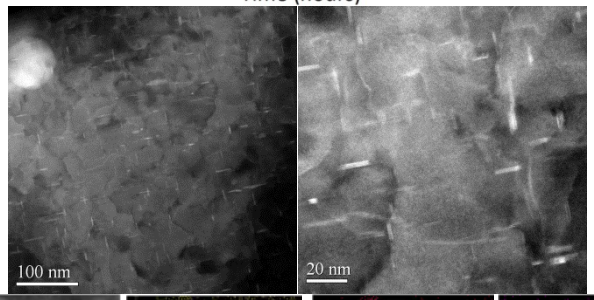

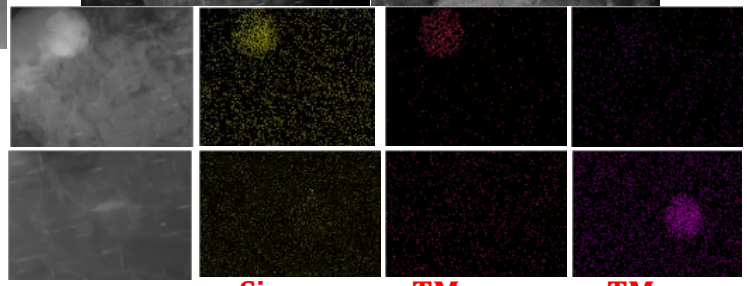

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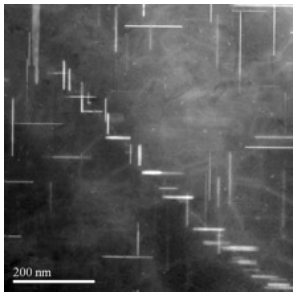
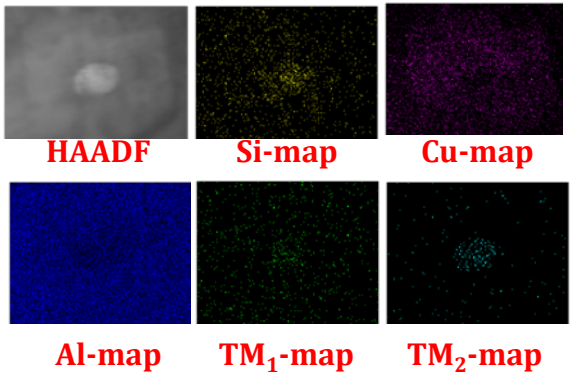
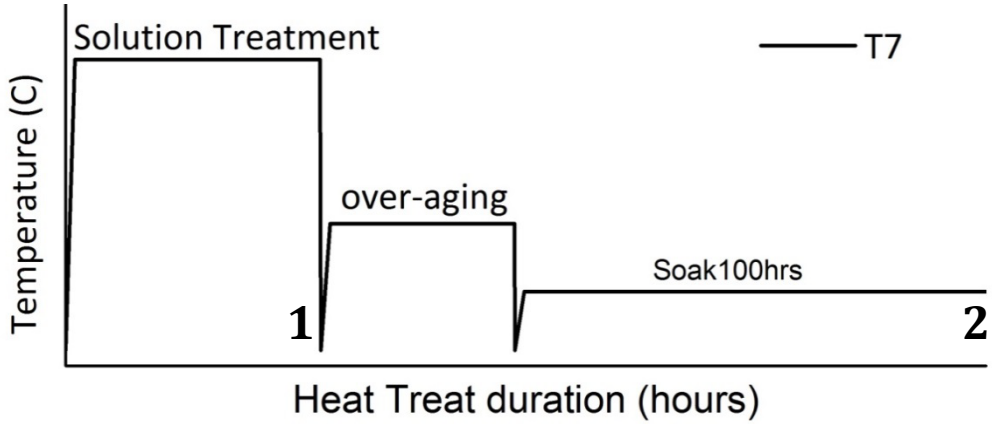


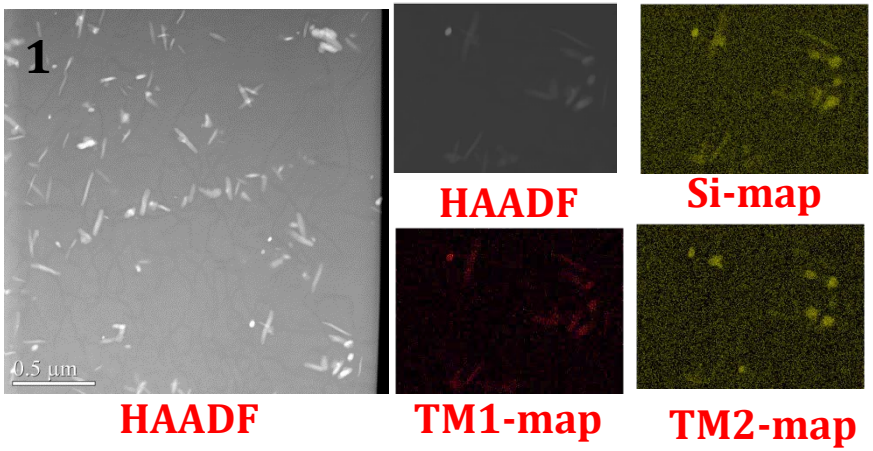


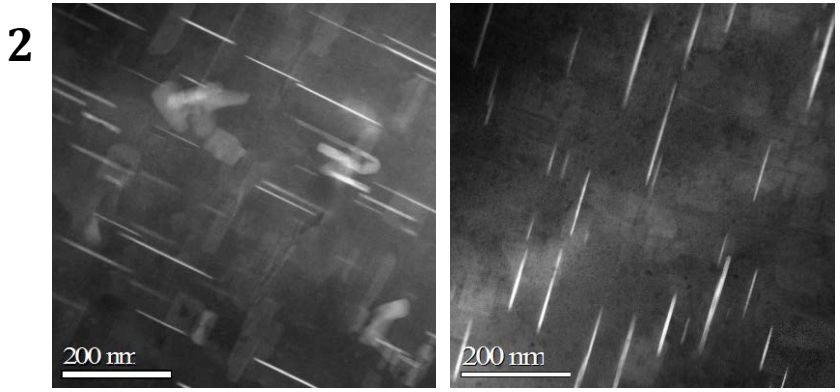
No.1: TMs in Al-Matix	No.2: Spherical TMs precipitates theta'-Al2Cu from natural aging	No. 3: Al2Cu (7.5e21/m^3 and 90±18nm) Very rare TMs precipitates

Results: Microstructure Characterization

- **Transmission Electron Microscope of Heat 17-T7**



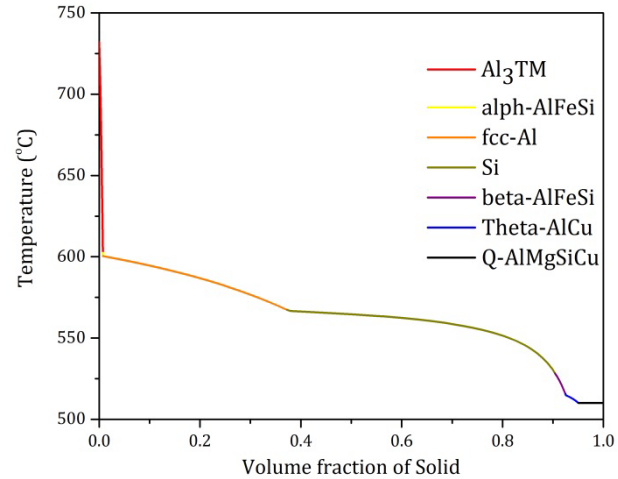


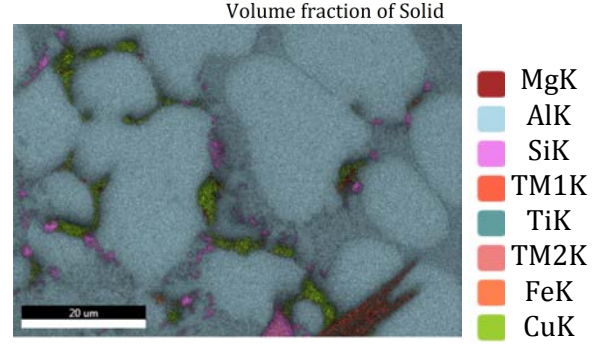


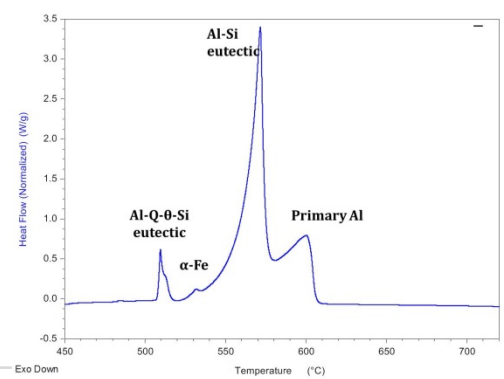
No.1 :Very coarsen TMs-contain precipitates	**No.2: Al2Cu precipitates (1.3 X $10^{21}/m^3$ and 135 ± 23 nm) Very coarsen TMs-contain precipitates**

Computational Tools Development: Solidification

- **Scheil solidification model**
  - Assumption
    - no diffusion in solid phase
    - infinite diffusion in liquid phase
  - Qualitative agreement with experiments
  - Modified Scheil Model
    - Back diffusion in solid phases
    - Undercooling
    - dendrites arm coarsening
  - Quantitative comparison with Differential Scan Calorimeter
    - Phase transformation temperature
    - Fraction of each phases







Computational Tools Development: Precipitation

- **The concurrent nucleation, growth, and coarsening of dispersed phases**
  - Kampmann and Wagner numerical method to solve Langer-Schwartz problem:
    - $$\frac{\partial f(r,t)}{\partial t} = -\frac{\partial}{\partial r}[v(r)f(r,t)] + j(r,t)$$

1st stage: Classic Nucleation Theory-homogeneous or inhomogeneous

2nd stage : Diffusion controlled continuity equation: Binary model, PrecipiCalc model, *et al*

3rd stage: Coarsening after $j(r,t)$ disappears: LSW model

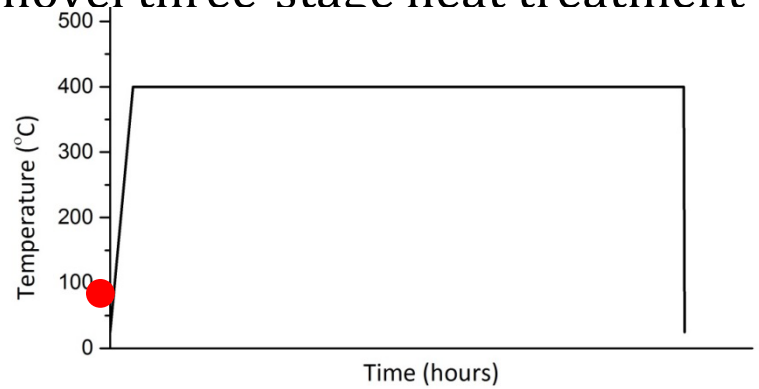
    - $$C_0^{\alpha} = C^{\alpha} + \left(C^{\beta} - C^{\alpha}\right)\int_0^{\infty}\frac{4\pi}{3}f(r,t)r^3dr$$

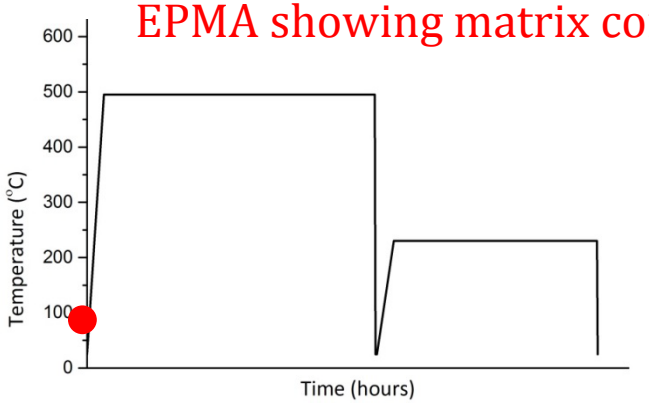
- **Commercial software for precipitation simulation**
  - PanPrecipitation from CompuTherm LLC
  - TC-PRISMA from Thermo-Calc

Computational Tools Development: Precipitation

- **Investigated alloys and Heat treatment condition**
  - Ford Heat 10: Al-Si-TMs simple quaternary system with aging at 400°C for different time
  - Ford Heat 16: W319 alloys with T7 condition
  - Ford Heat 17: Advance Al Alloys for automotive engine application with novel three-stage heat treatment

EPMA showing matrix composition



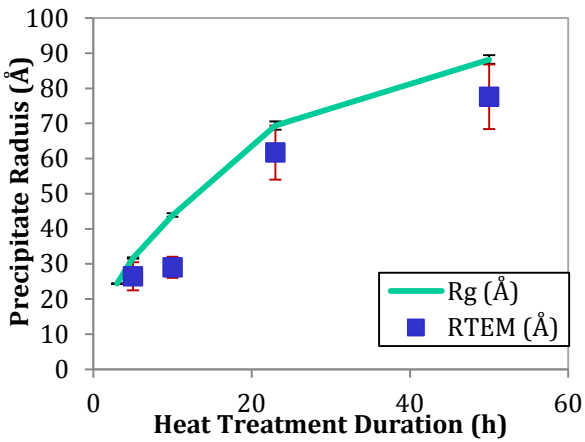


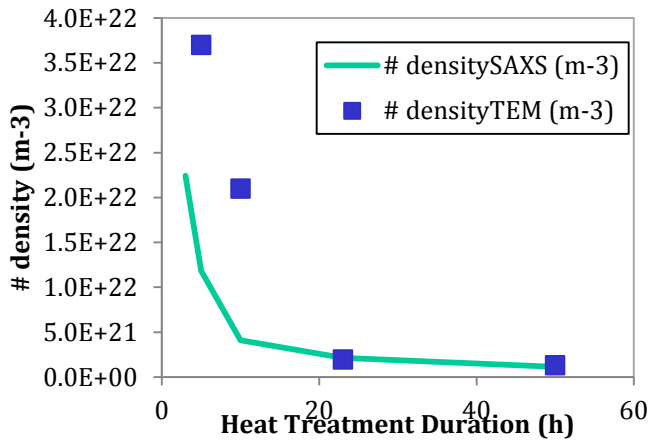
wt%	Al	Si	Cu	Mg	TM1	TM2
As-cast Heat 10	bal.	1.4	-	-	0.16	0.36
Heat 16 after solution treatment	bal.	0.7	3.8	0.2	-	-
As-cast Heat 17	bal.	1.4	1.1	0.03	0.16	0.24

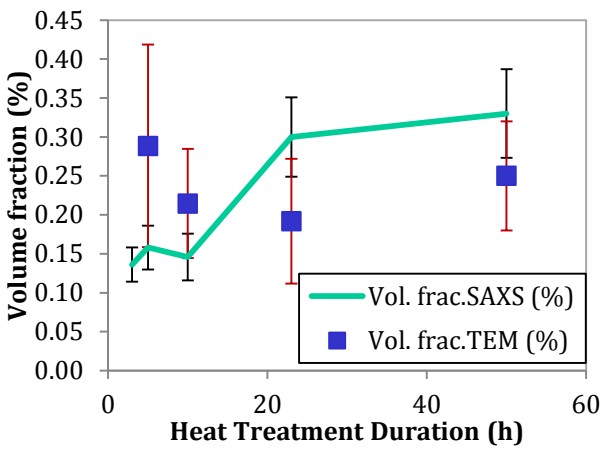
Computational Tools Development: Precipitation

- **Small-Angle X-ray Scattering & TEM for Al-Si-TMs at 400°C**

	Al-Si-TMs aging at 400°C											
	Small Angle X-ray Scatter (SAXS)						Transmission Electron Microscope (TEM)					
	R_{SAXS} (Å)		# density$_{SAXS}$ (m^{-3})		Vol. frac.$_{SAXS}$ (%)		R_{TEM} (Å)		# density$_{TEM}$ (m^{-3})		Vol. frac.$_{TEM}$ (%)	
H.T. (h)	Ave.	Error	Ave.	Error	Ave.	Error	Ave.	Error	Ave.	Error	Ave.	Error
3	24.4	0.1	2.24E+22	3.73E+21	0.14	0.02	-	-	-	-	-	-
5	31.7	0.2	1.19E+22	2.10E+21	0.16	0.03	26.5	4	3.70E+22	1.48E+22	0.29	0.13
10	43.9	0.5	4.11E+21	8.60E+20	0.15	0.03	29	3	2.10E+22	2.10E+21	0.21	0.07
23	69.4	1.2	2.14E+21	3.80E+20	0.30	0.05	61.7	7.7	1.95E+21	9.10E+20	0.19	0.08
50	88.2	1.2	1.15E+21	2.10E+20	0.33	0.06	77.6	9.2	1.30E+21	4.80E+20	0.25	0.07







Computational Tools Development: Precipitation

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H.T. (h)	Ave.	Error	Ave.	Error	Ave.	Error	Ave.	Error	Ave.	Error	Ave.	Error
3	24.4	0.1	2.24E+22	3.73E+21	0.14	0.02	-	-	-	-	-	-
5	31.7	0.2	1.19E+22	2.10E+21	0.16	0.03	26.5	4	3.70E+22	1.48E+22	0.29	0.13
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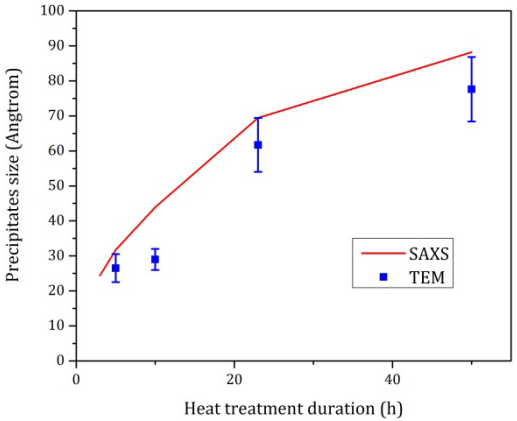
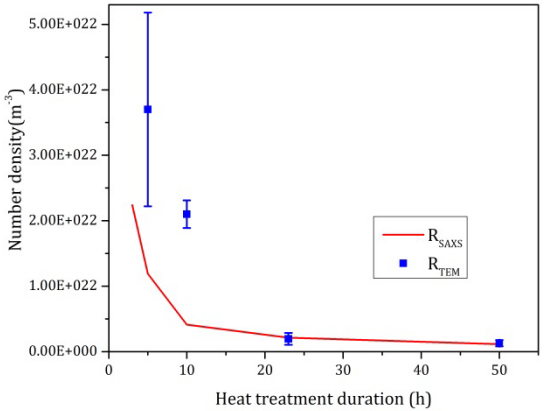
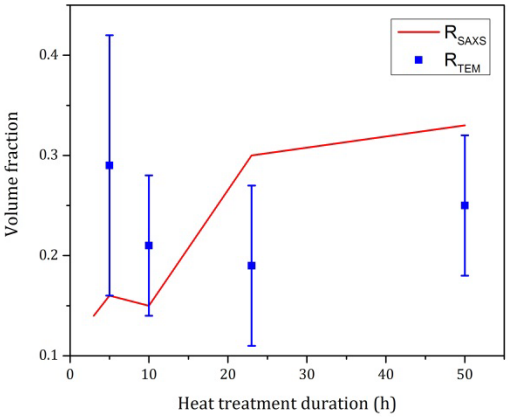
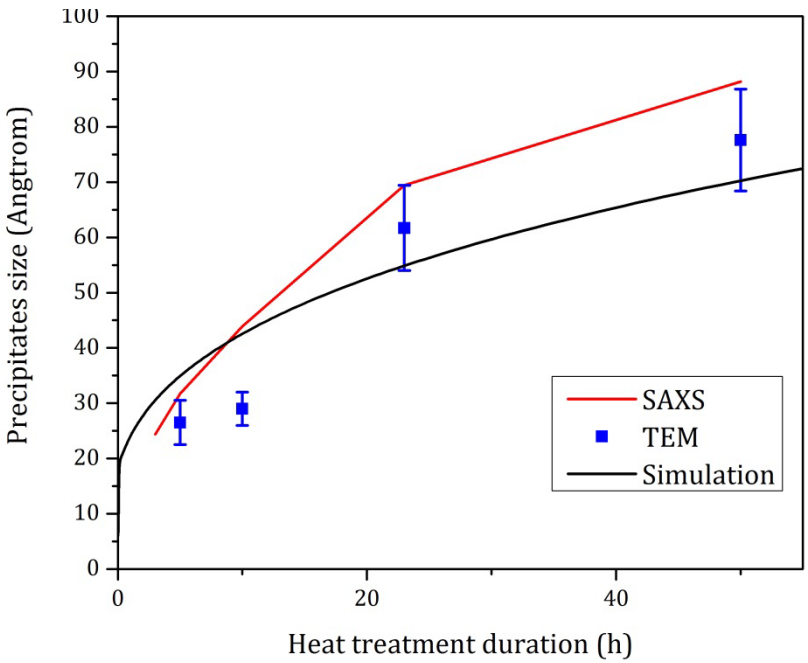


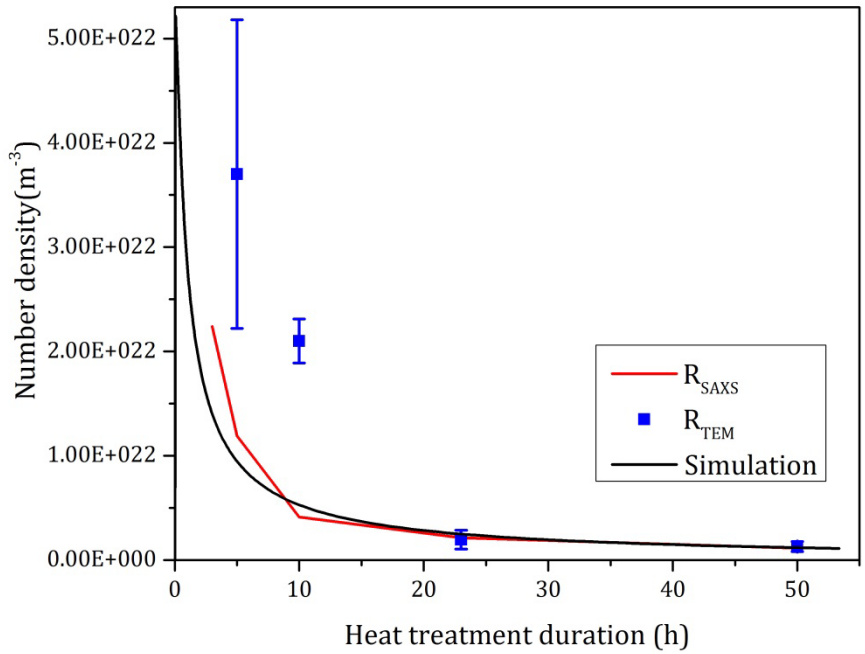




Computational Tools Development: Precipitation

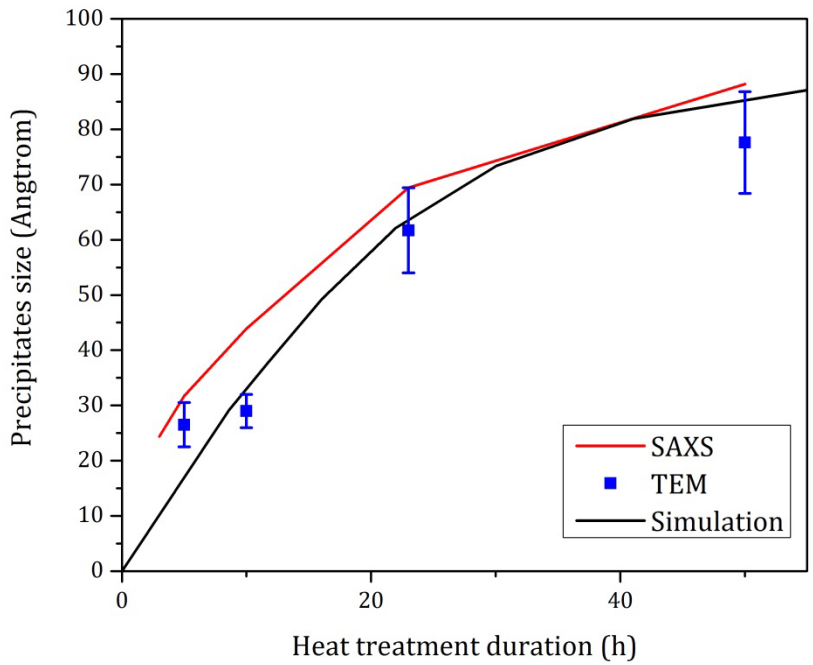
- **Kinetic Simulation on Precipitation: TC-PRISMA**
  - The diffusivity of TM1 in fcc Al with Si should be one or two order higher than that in fcc without Si according to experimental data from Al-Si-TMs and Al-TMs
  - TC-PRISMA with mobility factor shows good agreement

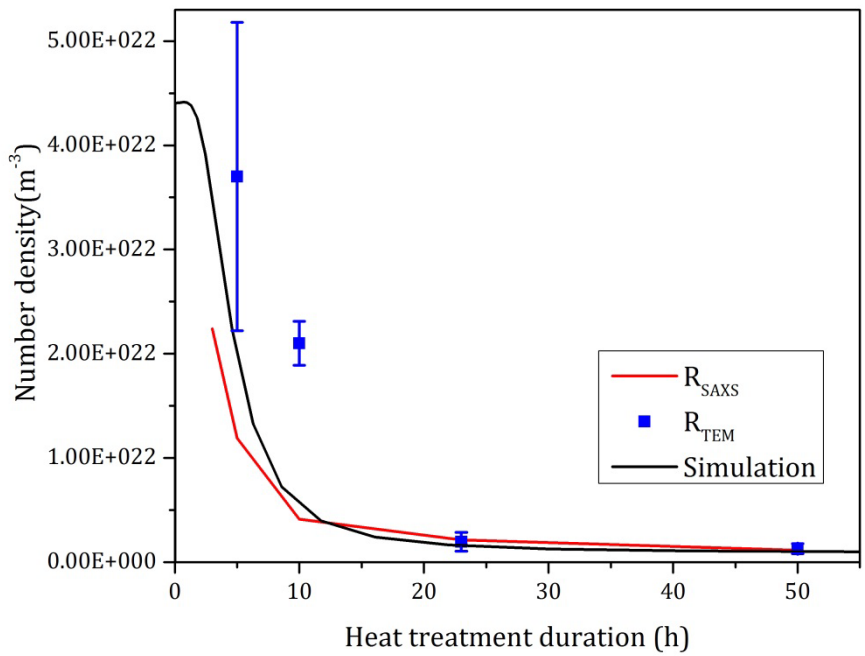




Computational Tools Development: Precipitation

- **Kinetic Simulation on Precipitation: PanPrecipitation**
  - Improve the PanPrecipitation module for better handling the growth/coarsening transition
  - Modify thermodynamic database to increase the equilibrium fraction of $L1_2$ precipitate from 0.18% to 0.31%
  - Adjust the mobility by adding a factor of 60



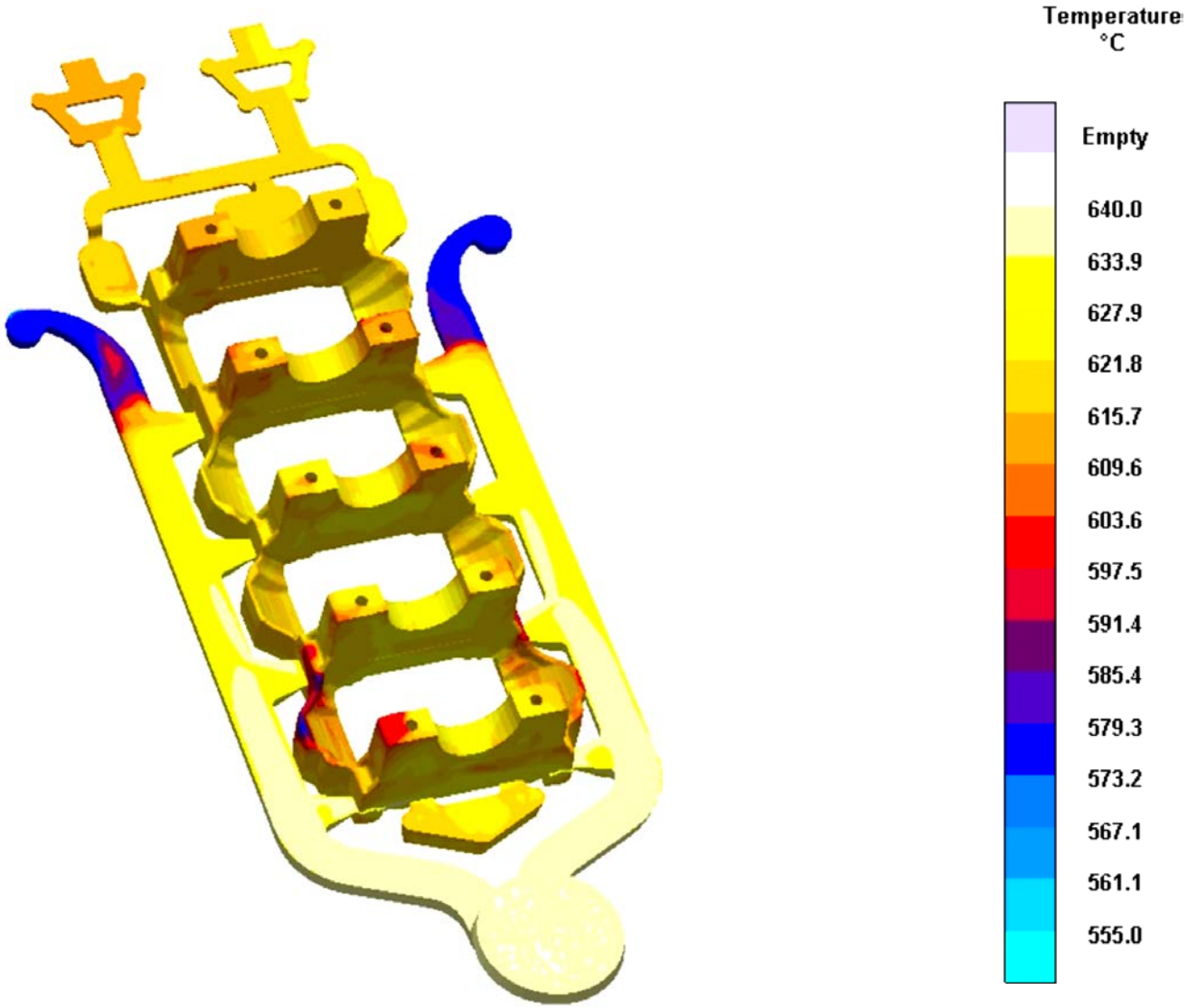


Computational Tools Development: Gap Analysis

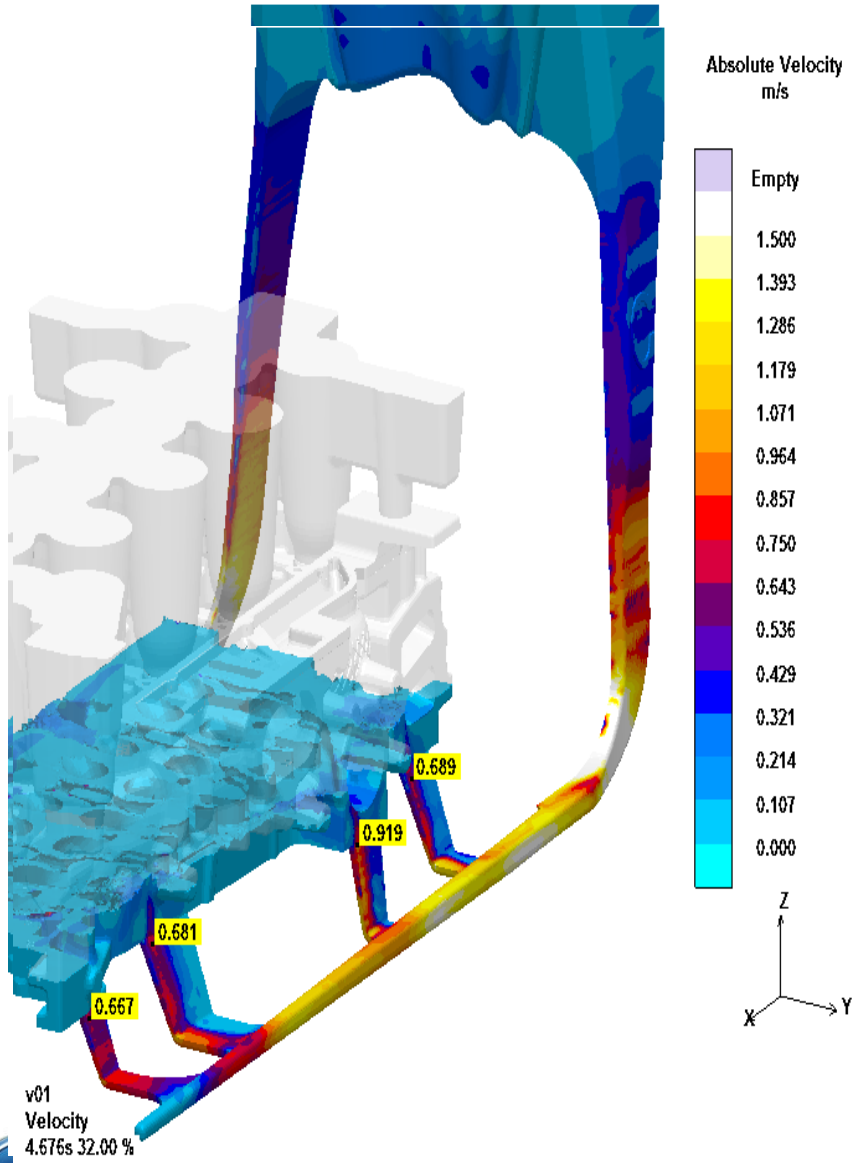
- **Thermodynamic simulation on solidification**
  - Quantitative comparison between DSC measurement and simulation
  - Modified Scheil model for solidification simulation: Back diffusion in solid phases, undercooling, and dendrites arm coarsening
- **Kinetic simulation on precipitation**
  - One dimension problem, spherical shape precipitates
  - Accurate and suitable thermodynamic/mobility data at low temperature/for metastable phases
  - Determination of kinetic parameters from experiment
  - Predication of dual precipitation microstructure

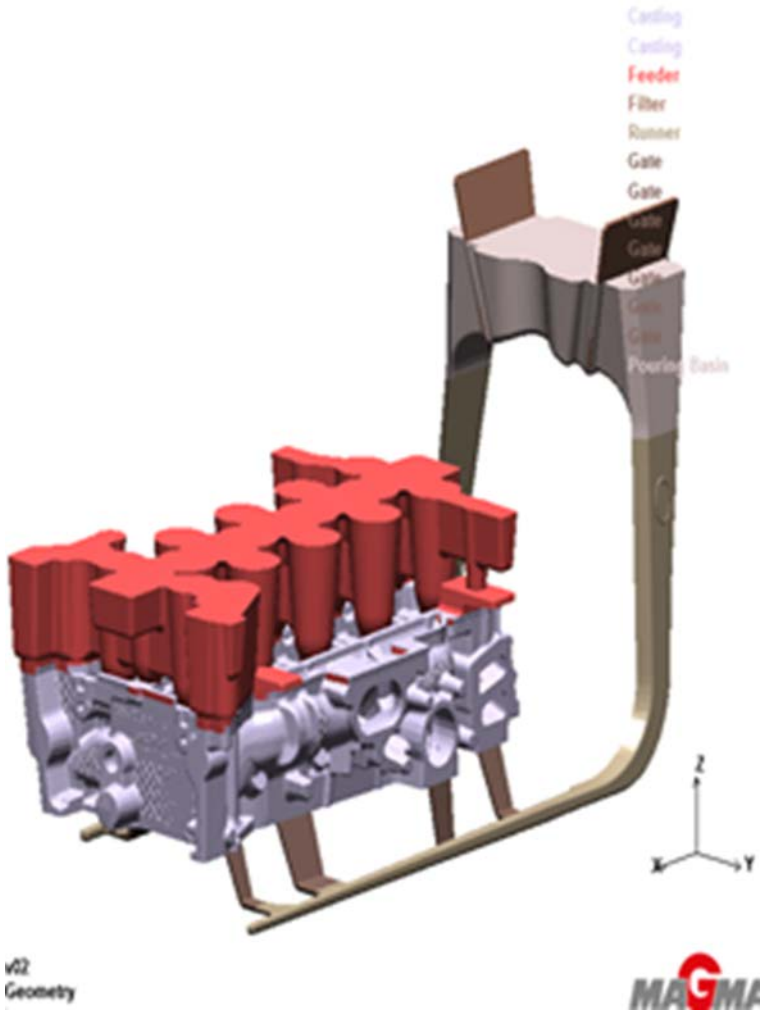
2019MY 2.0/2.3L I4 4V Duratec GTDI Maverick Ladder

Global Powertrain
Manufacturing Engineering
Manufacturing Excellence

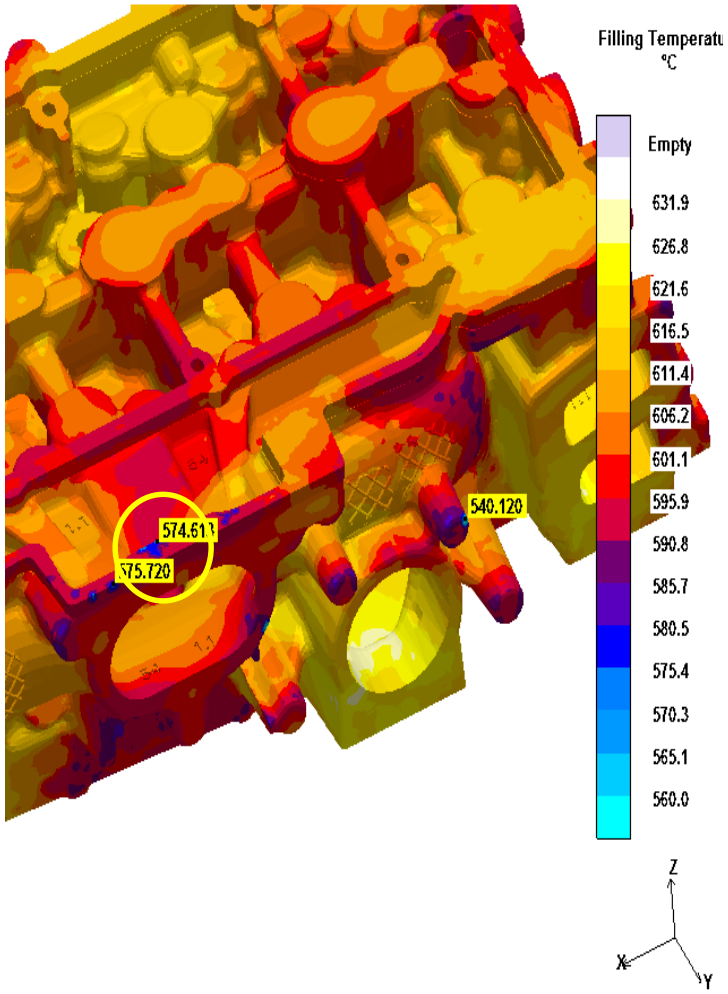


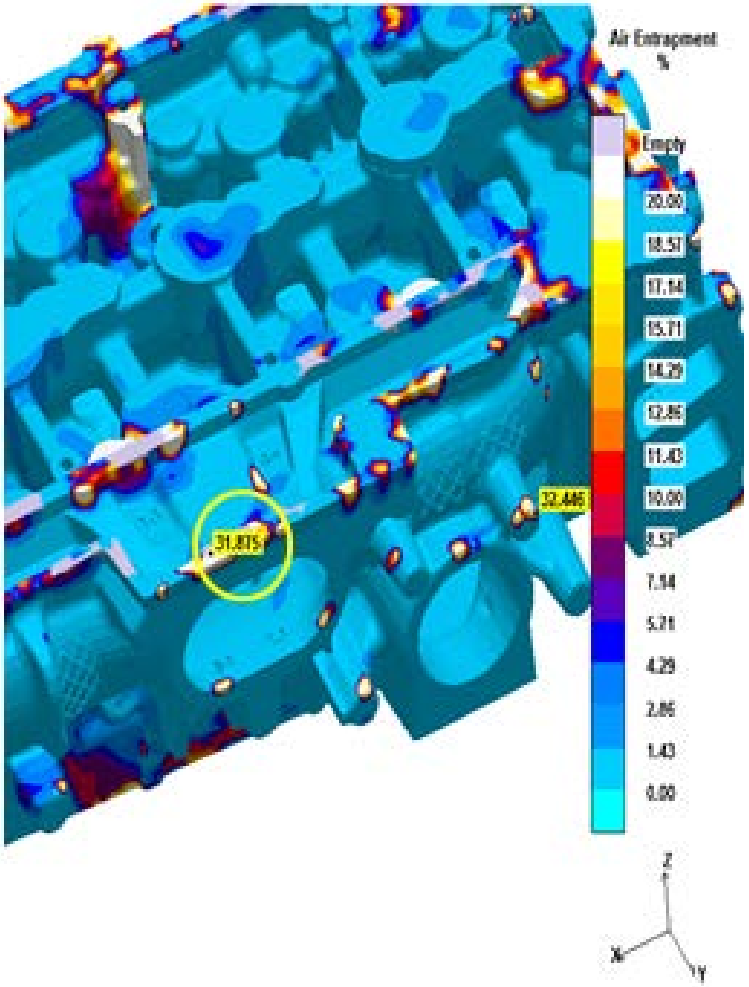
2.3/2.5L Small Diesel Panther Head





Temperature and Air Pressure



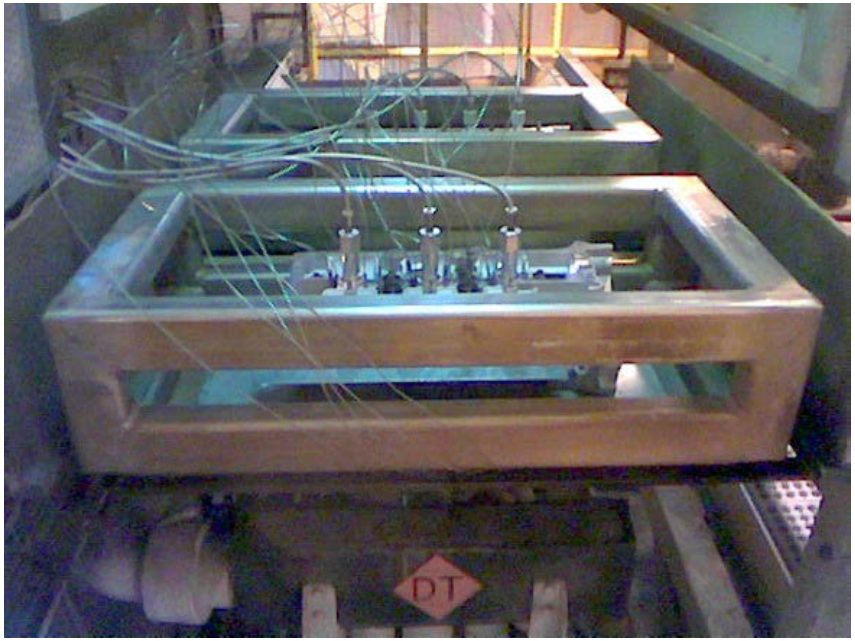


v01
Filling Temperature
22.825s

Demonstration on Ford GTDI Engine Program

- Testing and CAE analysis based on Ford Global Engine Engineering (GEE) guideline

Cylinder Head High Cycle Fatigue Bench Test Set Up



Thermal Fatigue Test Bench Set Up

Conclusion

Summary

I. Successfully developed *two* novel combined alloy-heat treatment procedures for high temperature powertrain applications.

II. All the targets set by DOE are met on the sample tests, and demonstration on the components are on the way

Future plan

I. Prototyping the new alloys for engine block cylinder head applications

II. ICME gap analysis on the microstructural and mechanical property predictions

Any proposed future work is subject to change based on funding levels