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: February 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 FY14
  - ➢ $579K
- Funding for FY15
  - ➢ $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.

Approach

Task 1.0 – Project Management and Planning

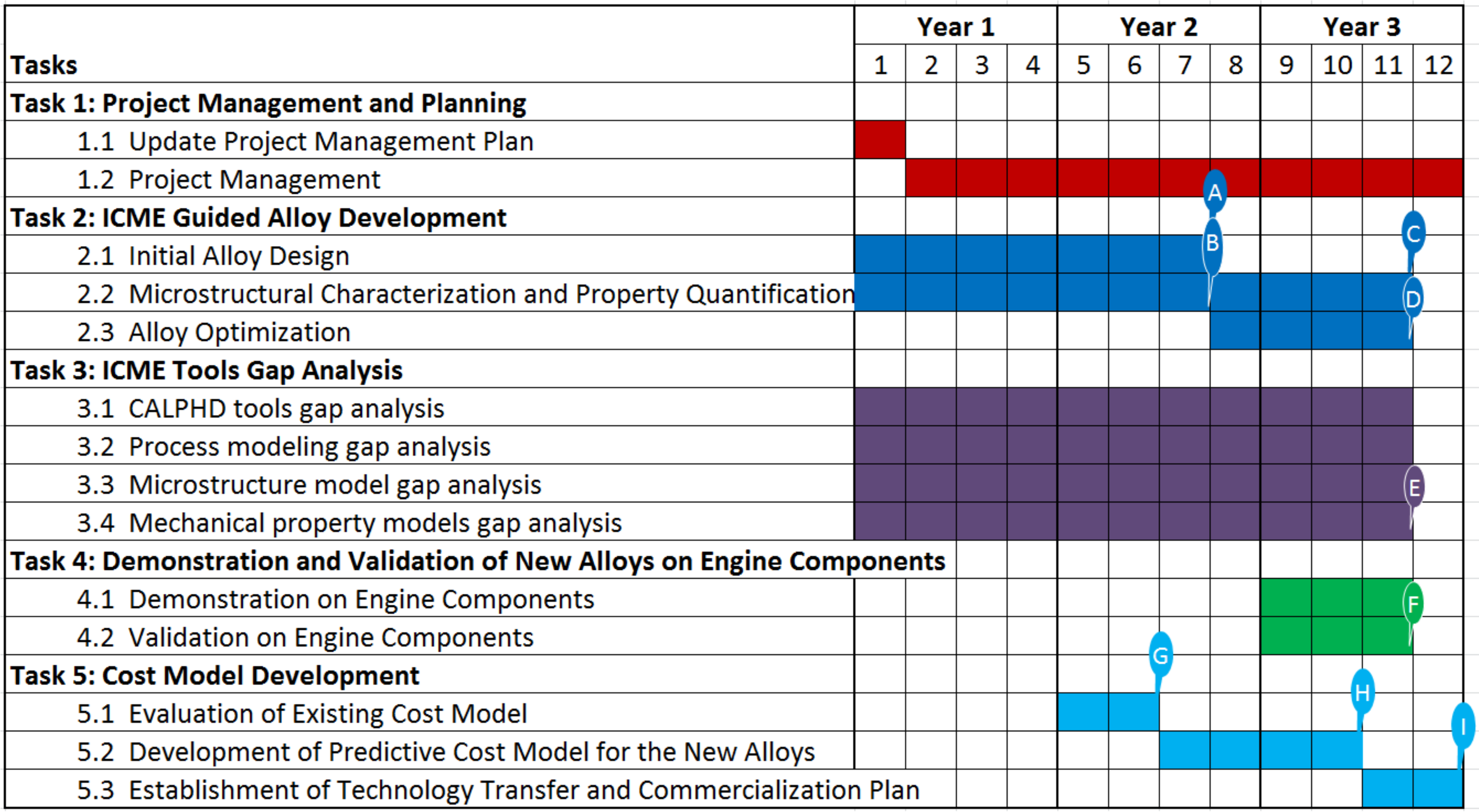
Task 2.0 – ICME Guided Alloy Development

Task 3.0 – ICME Tools Gap Analysis

Task 4.0 – Demonstration and Validation of New Alloys on Engine Components

Task 5.0 – Cost Model Development and Planning

Deliverables and Timeline

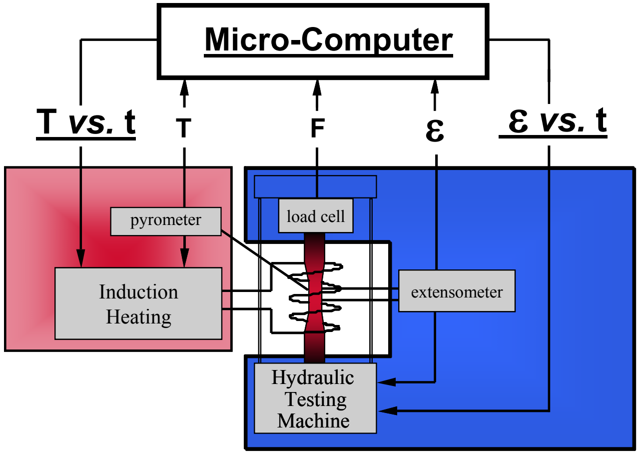


Targeted Properties

Property	Cast Aluminum Baseline	Cast Lightweight Alloy Targets	Key Properties
Tensile Strength (Ksi)	33 KSI	40 KSI	Key
Yield Strength (Ksi)	24 KSI	30 KSI	Key
Density	2.7 g/cm^3	< 6.4 g/cm^3	Key
Elongation (%)	3.50%	3.50%	
Shear Strength	26 KSI	30 KSI	
Endurance Limit	8.5 KSI	11 KSI	
Fluidity (Die Filling Capacity/Spiral Test)	Excellent	Excellent	Key
Hot Tearing Resistance	Excellent	Excellent	Key
High Temperature Performance	@ 250C	@ 300 C	
Tensile Strength (KSI)	7.5KSI @ 250 C	9.5 KSI @ 300 C	Key
Yield Strength (KSI)	5 KSI @ 250 C	6.5 KSI @ 300 C	Key
Elongation in 2”	20% @ 250 C	< 20% @ 300 C	

Casting and Testing Facility

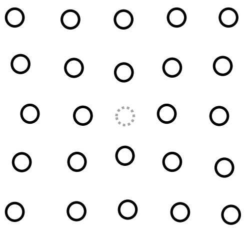
Electric melting furnaces and flux unit
Sand mixer and sand mold

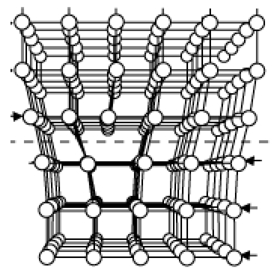


Schematic representation of the TMF test setup implemented at Ford R&A

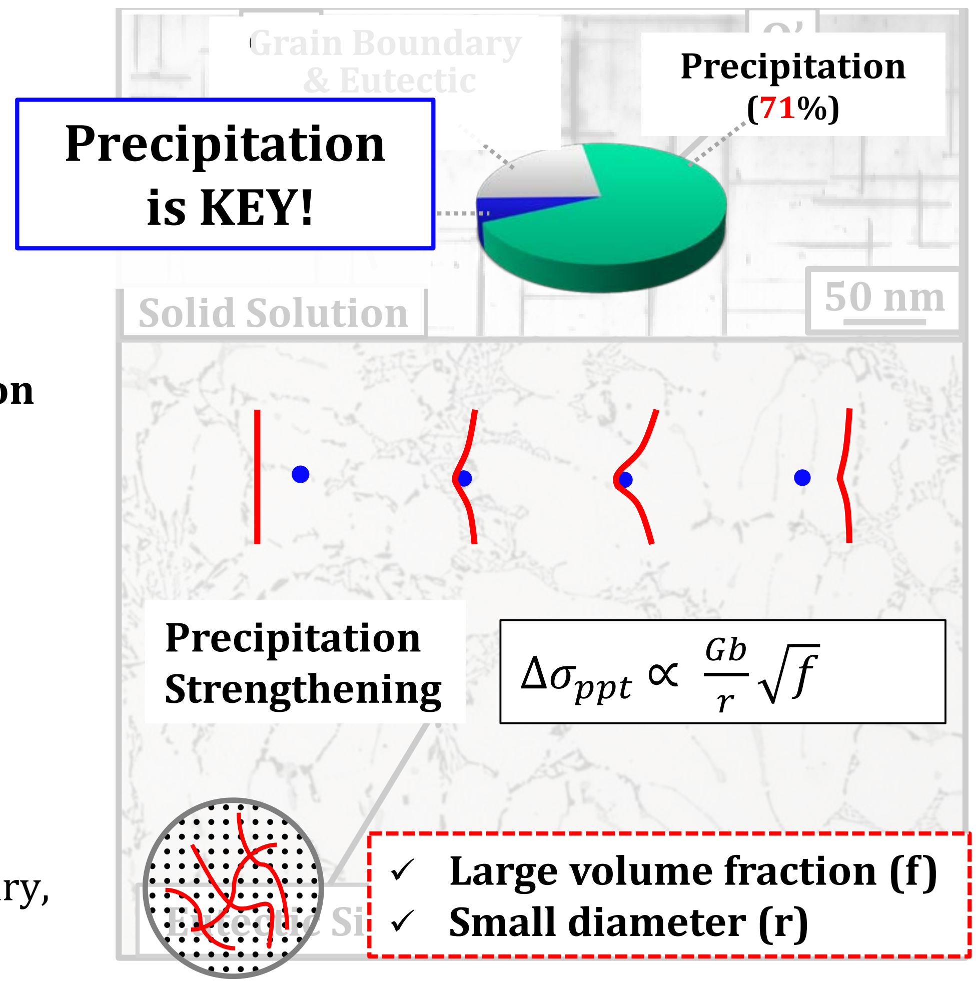
Drop bottom HT furnace and Quenching basket

Alloy Design Strengthening Mechanism

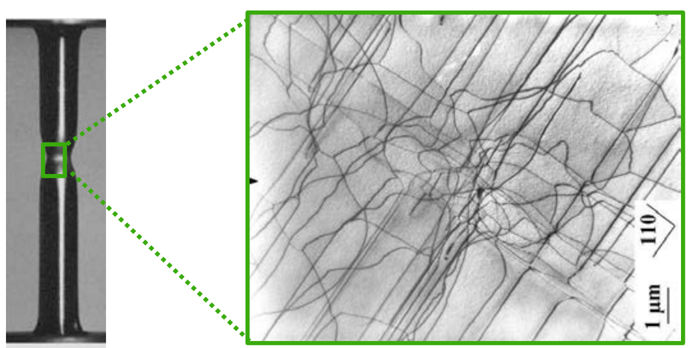




Yield Strength of W319 (230°C10hr): 310 MPa



Plastic Deformation: Motion of Dislocation



Strengthening Mechanism: Grain Boundary, Eutectic, Precipitation, Solid Solution…

Alloy Design The Problem

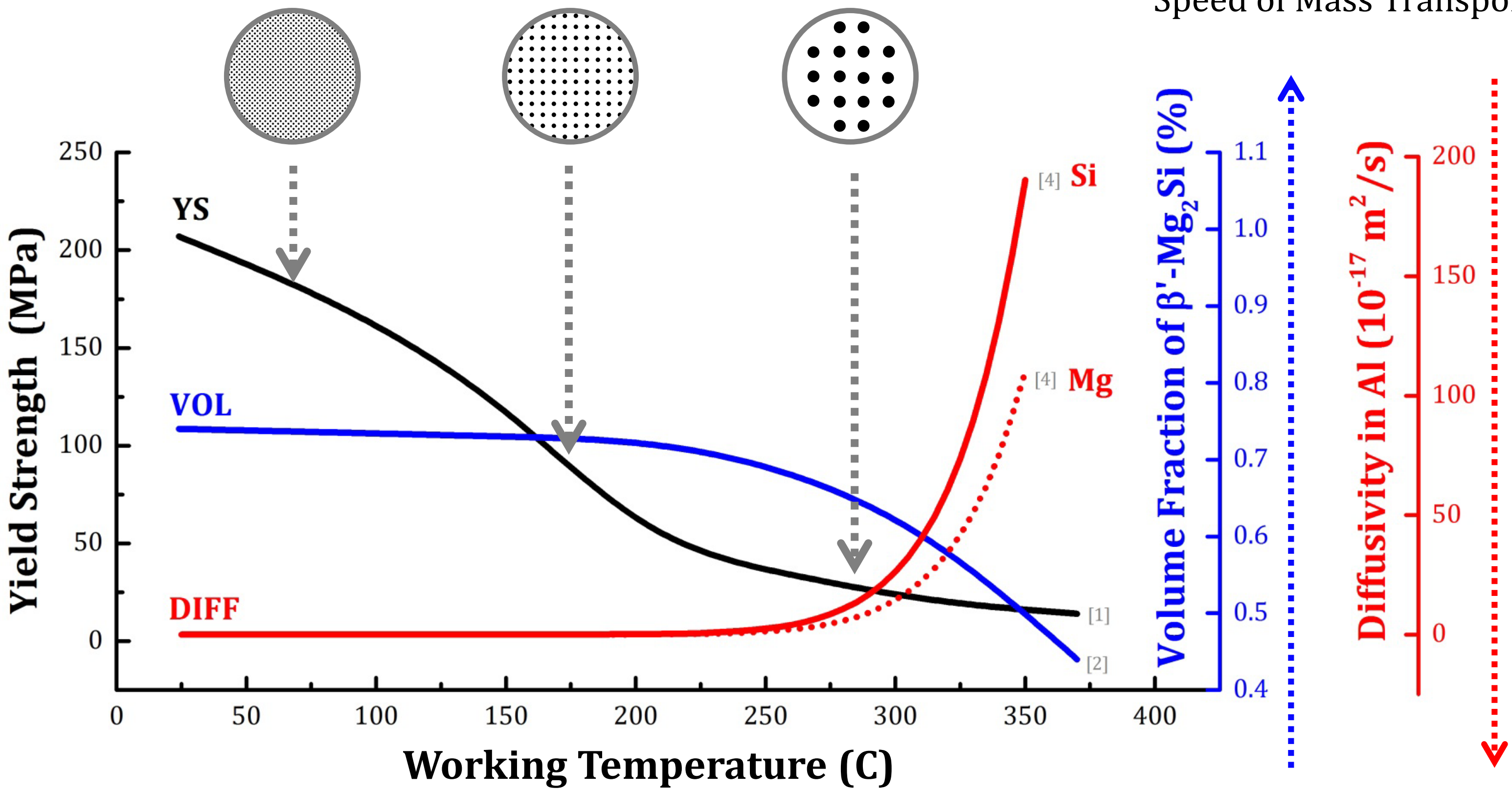
(A356-T61 Permanent Mold)

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

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

$$k \propto D\gamma C_e$$

Diffusivity:
Speed of Mass Transportation



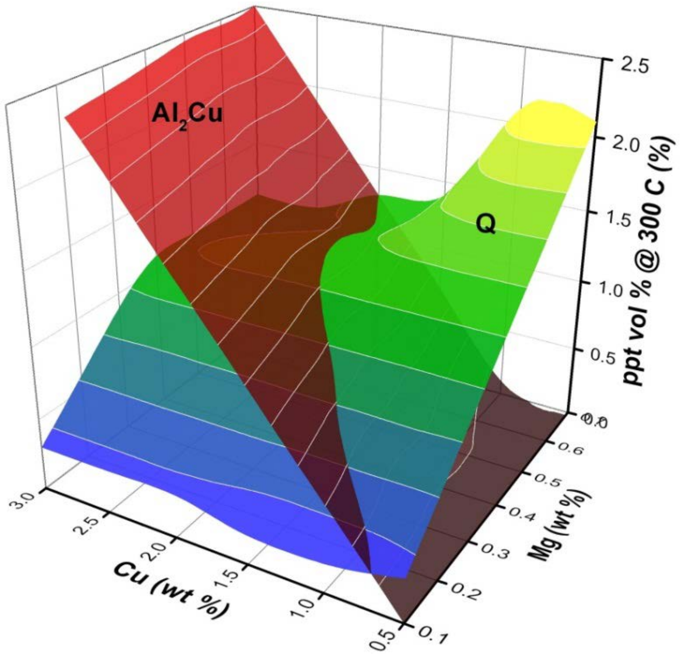
Composition

Matrix:

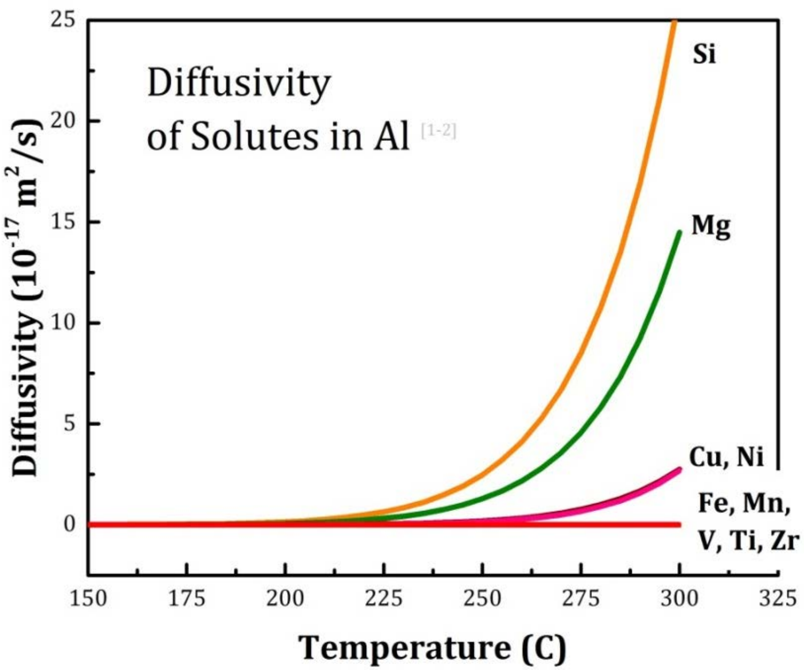
Al5.0-10.0Si0-4.0Cu0-0.4Mg was chosen as the baseline because of its good castability and strength.

Precipitates:

Optimize volume fraction of (θ'+Q')



Introduce Heat-resistant Precipitates



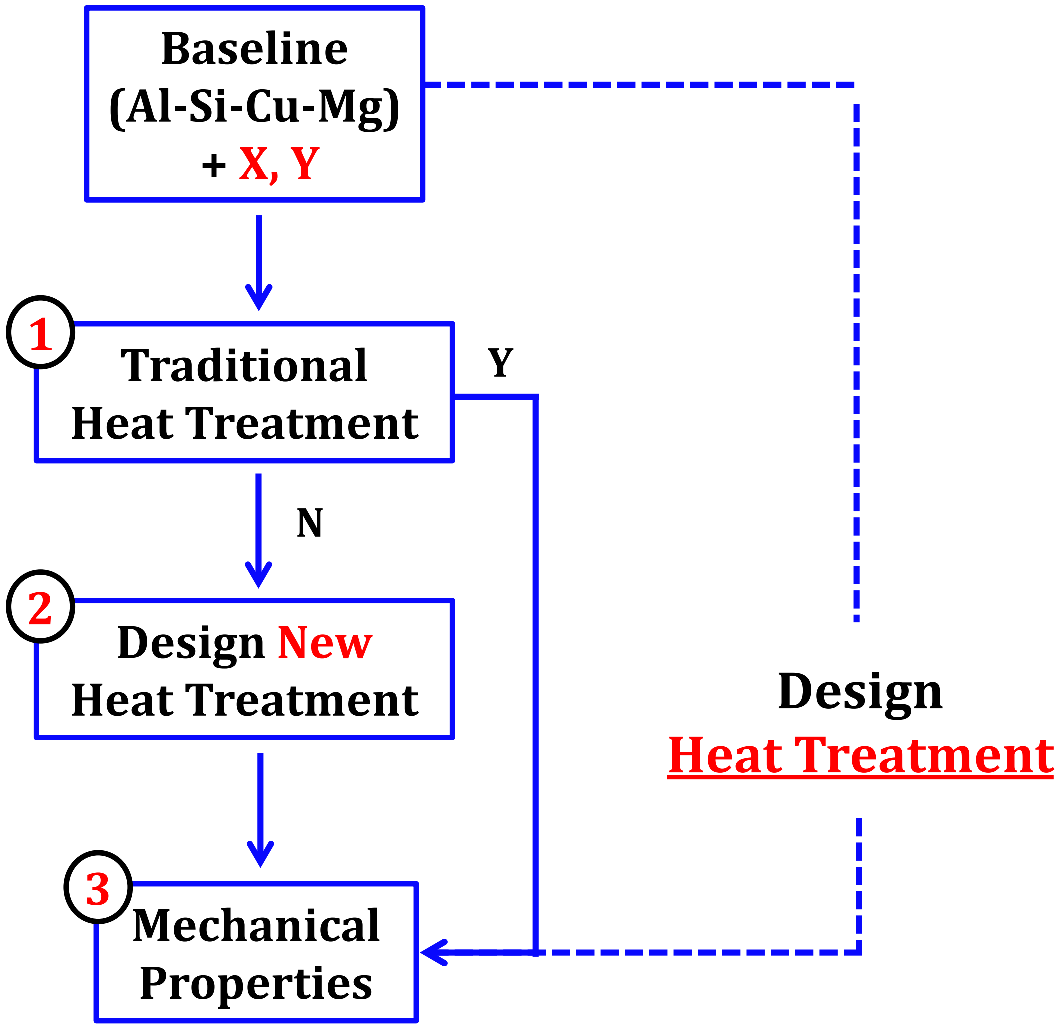
15 different heats of alloys were proposed to pursue the optimal alloy composition.

Alloy Design Heat Treatment

AS7GU-based
Al-Si-Cu-Mg-X-Y
Heat 1-7

Simple Model Alloys
Al-Si-X-Y
Heat 8-13

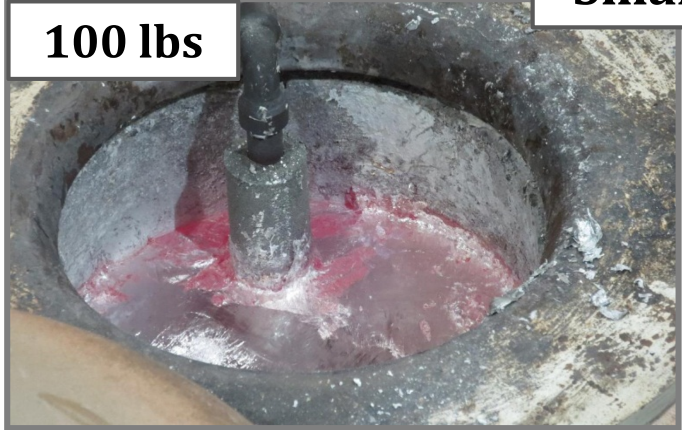
319-based
Al-Si-Cu-Mg-X-Y
Heat 14-15



Experiment Casting

Small Batch

100 lbs

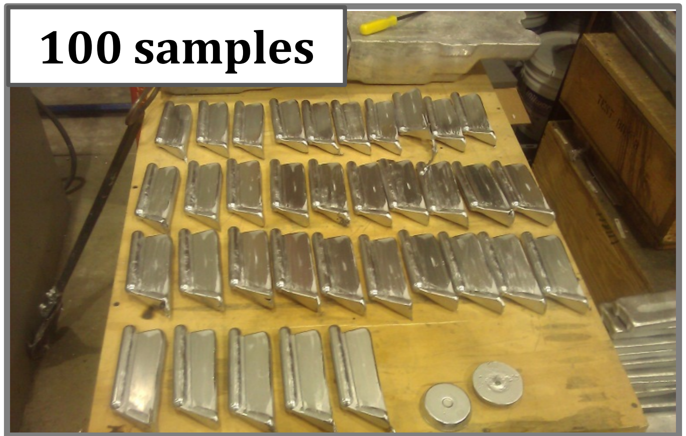


(a) Melting raw materials @ 750 C.

(b) Pouring spectrometer disk.

(c) Pouring torpedo shape sample.

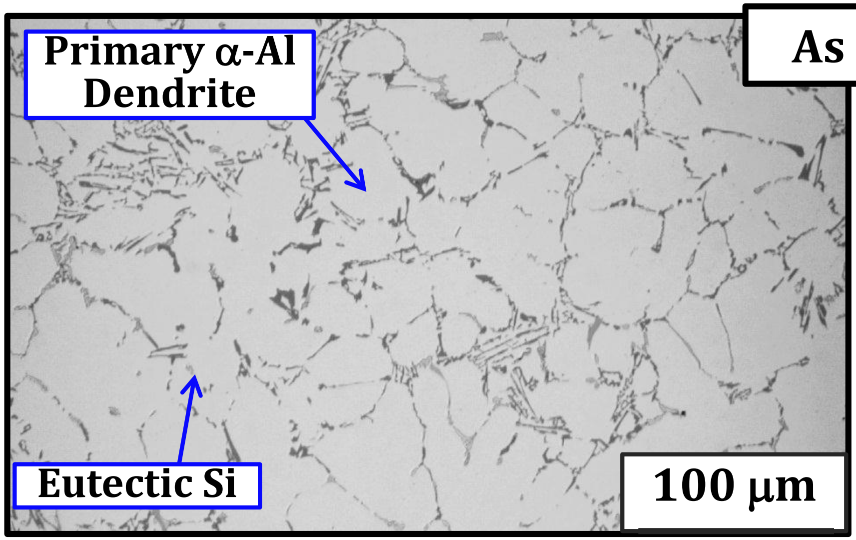
100 samples

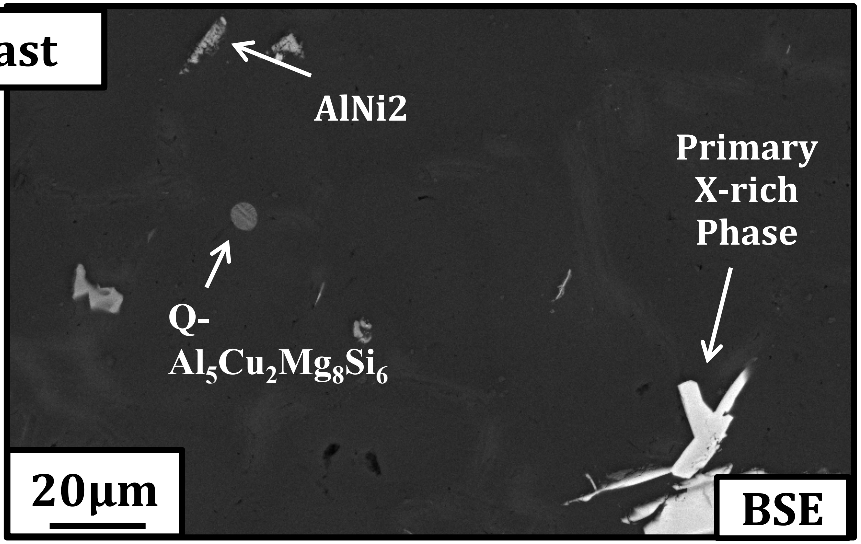


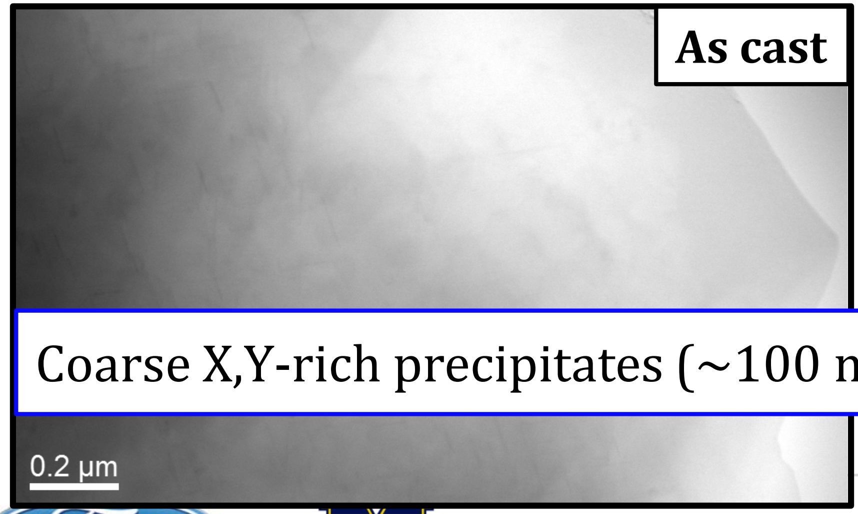
(d) Torpedo samples for analysis.

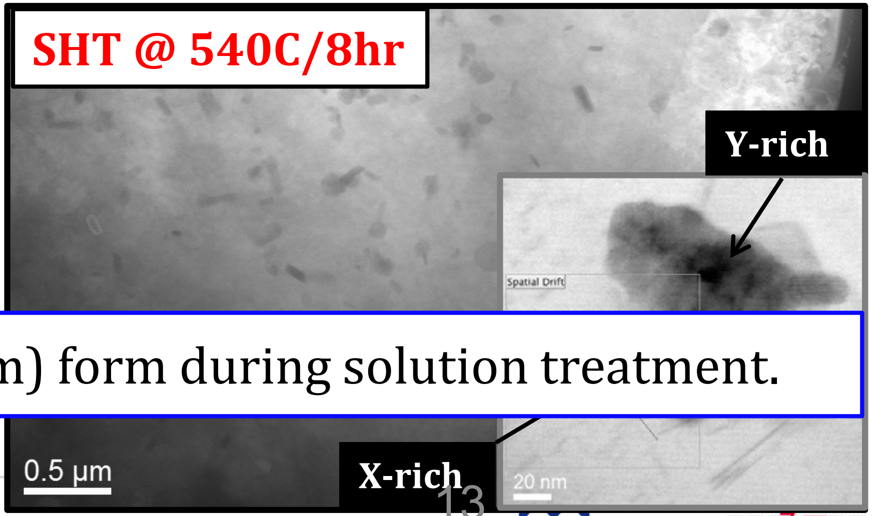
Step 1: Traditional Heat Treatment

Heat 7H: Al-Si-Cu-Mg-X-Y (AS7GU based)





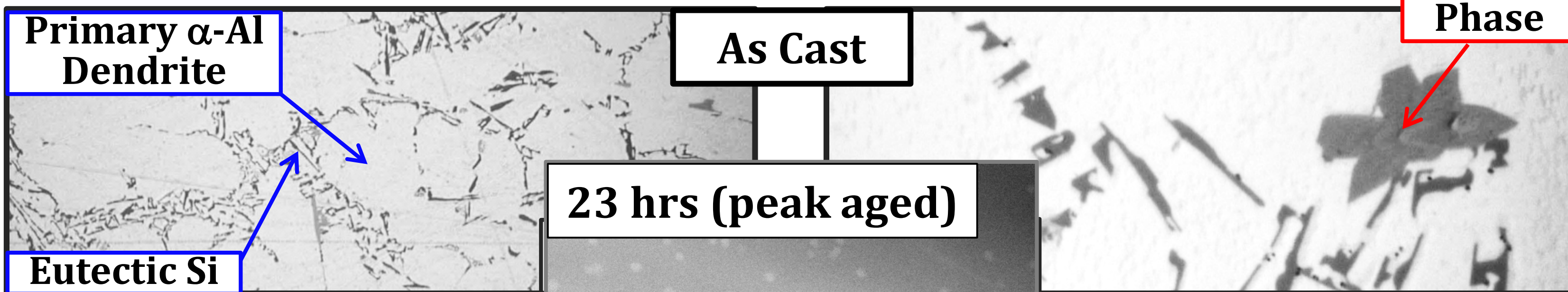


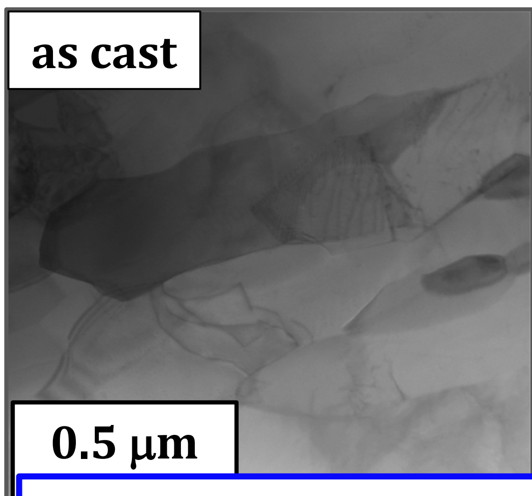


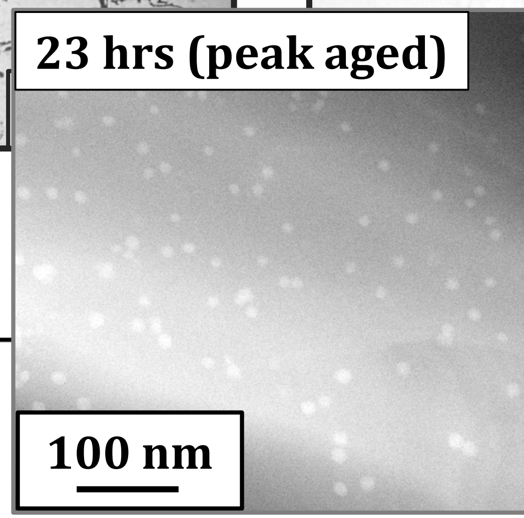
Coarse X,Y-rich precipitates (~100 nm) form during solution treatment.

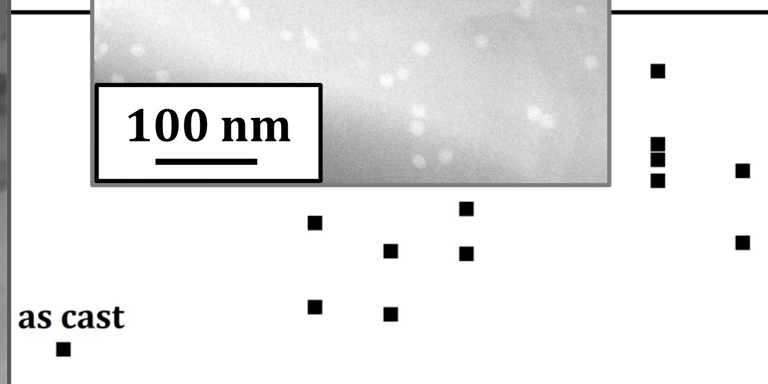
Step 2 New Heat Treatment

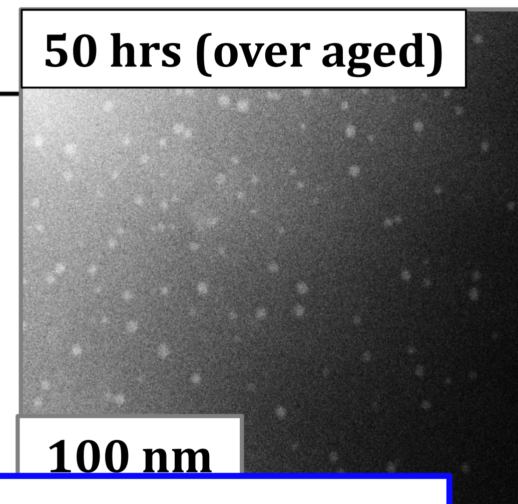
Heat 10: Al-Si-X-Y (simple model alloy)









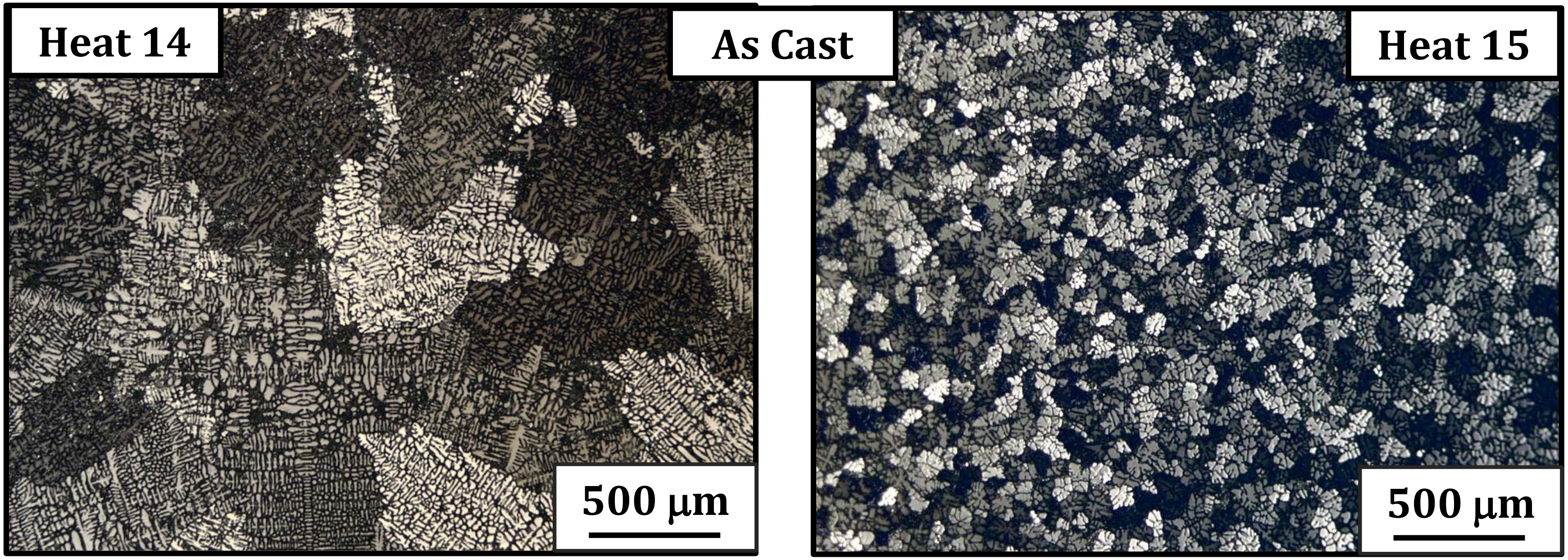


Aging generates nano-scale precipitates that ↑ RT YS by ~20 MPa and are coarsening resistant at this temperature.

Step 3 Multi-Step Heat Treatment

H14: Al-Si-Cu-Mg
H15: Al-Si-Cu-Mg-X-Y

Electrolytic Etching: 5 mL HBF4 (48%) + 200 mL water (Barker's) 20 V, 90 seconds. (polarized light)

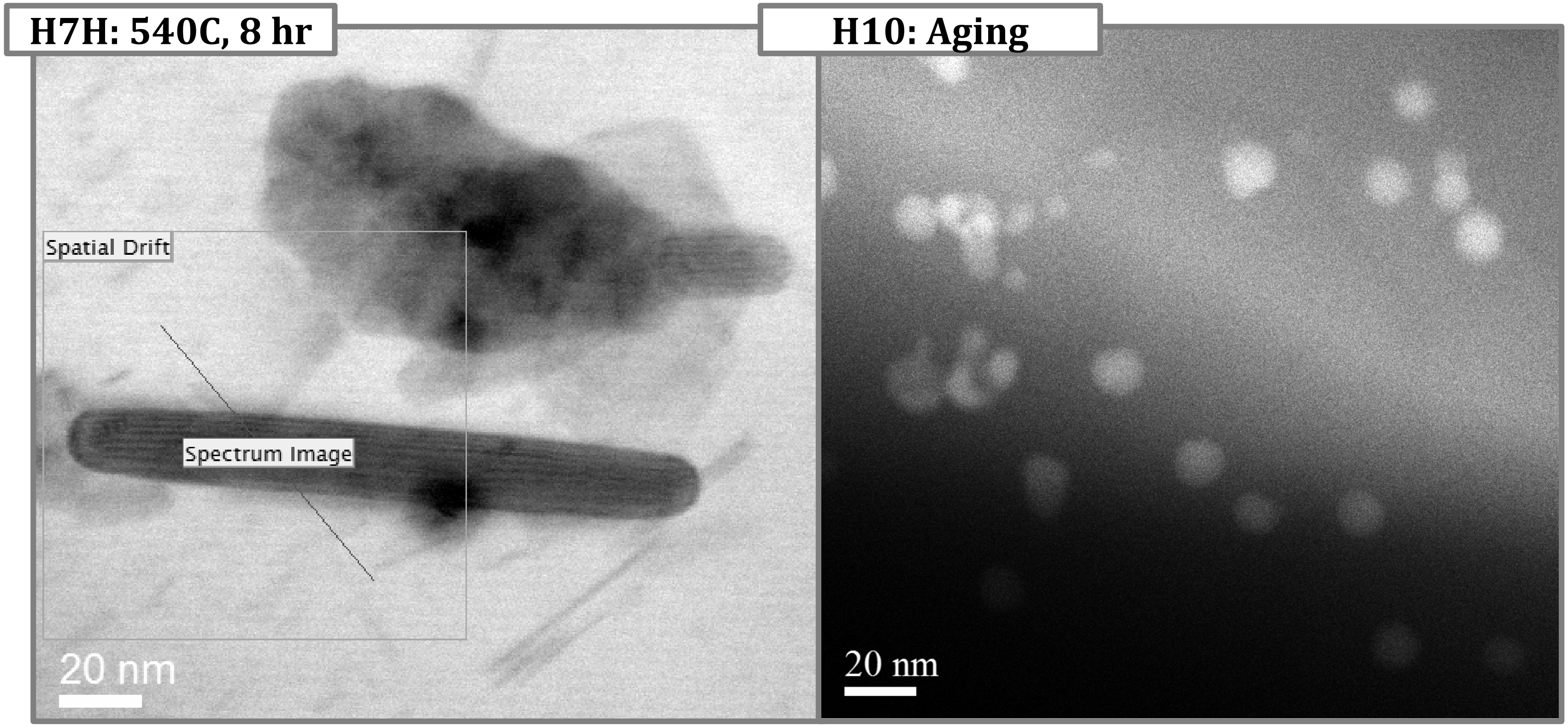


Grain Size: >500 µm | **Grain Size: 70 µm**

Significant grain refinement with X, Y additions !!

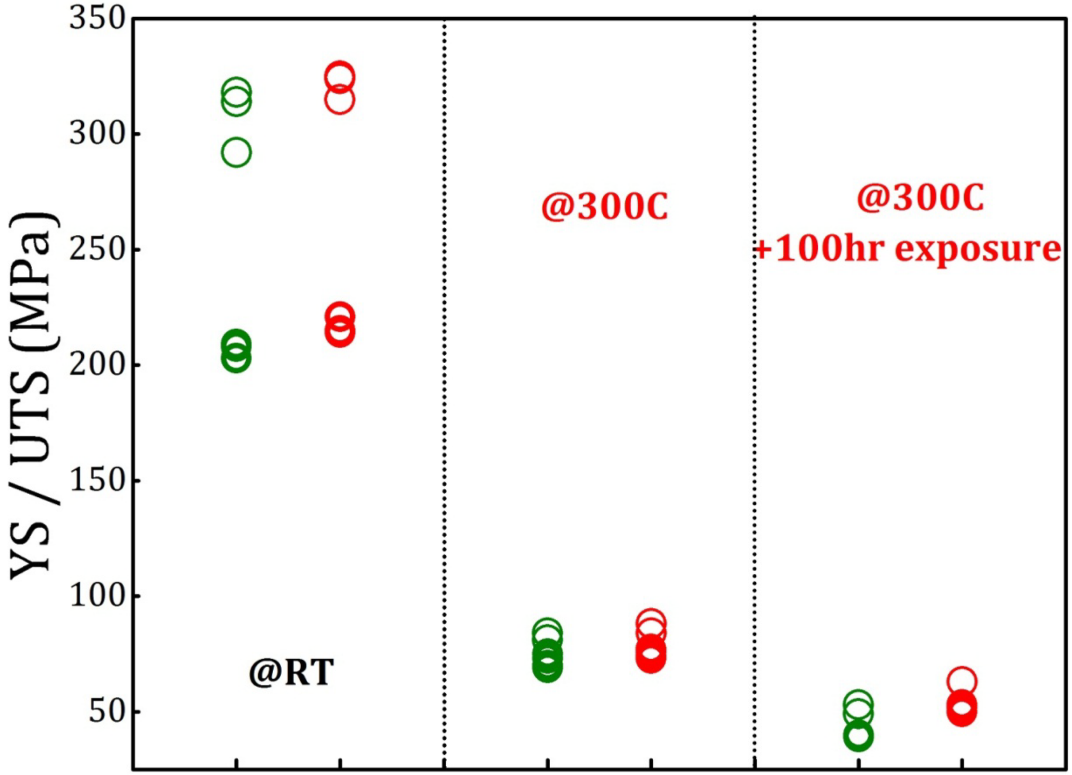
Step 3 New Heat Treatment

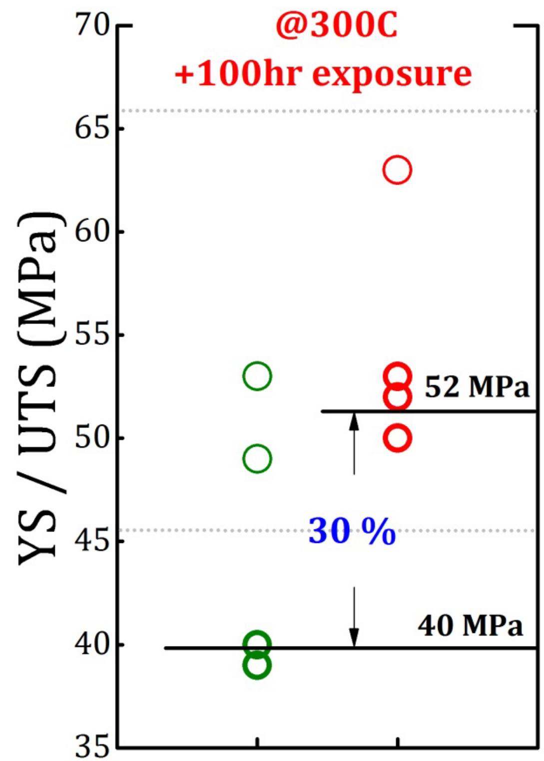
Apply the knowledge gained from Heat7H and Heat 10 on heat treatment to Heat 15 (Al-Si-Cu-Mg-X-Y, 319-based).



Result Yield Strength of Heat 14 & 15

H14: Al-Si-Cu-Mg (T7)
H15: Al-Si-Cu-Mg-X-Y (HT Aging + T7)

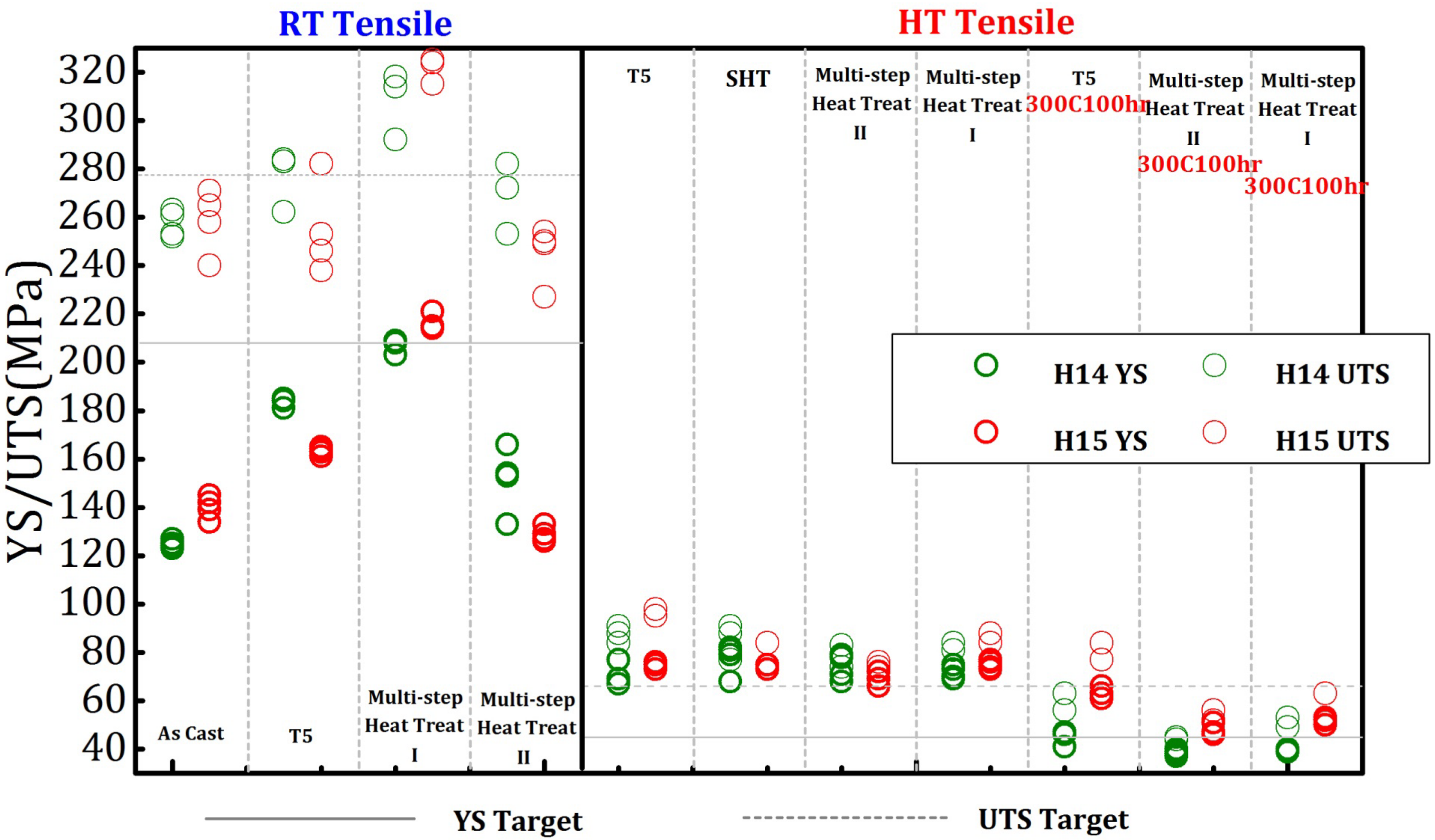




H15 exhibits superior YS @ 300 C than H14 !

Result Other Heat treatment of Heat 14 & 15

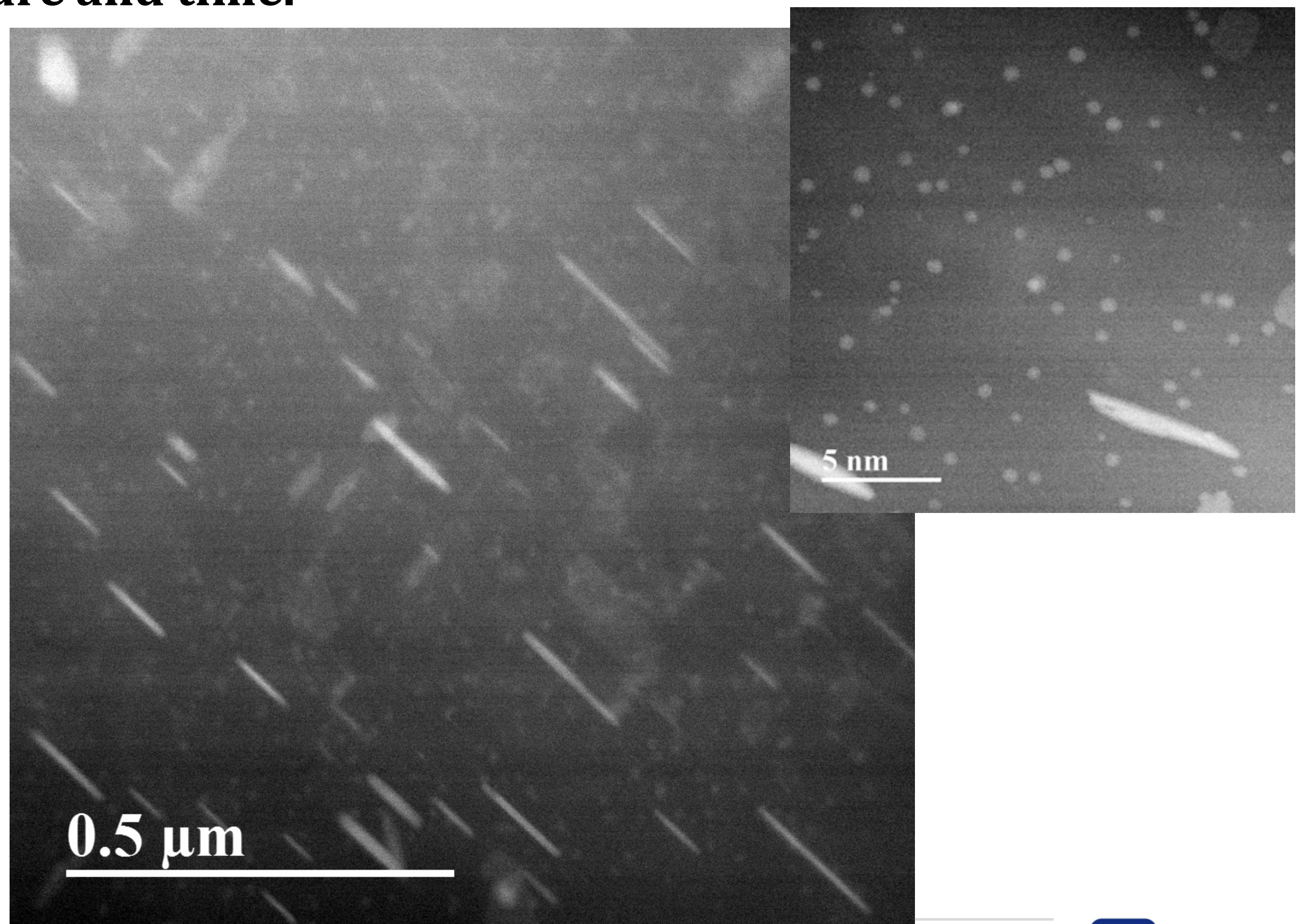
H14: Al-Si-Cu-Mg
H15: Al-Si-Cu-Mg-X-Y



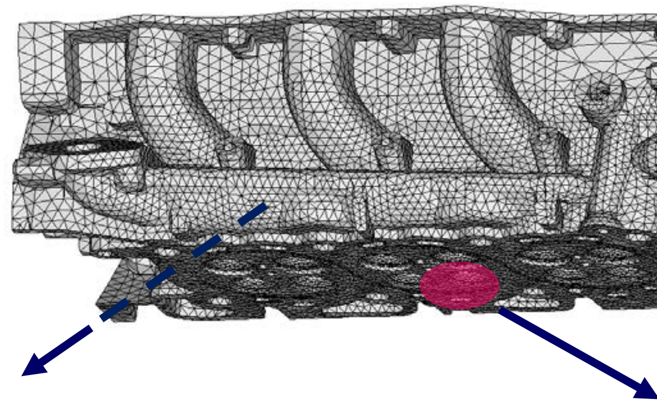
Result Heat Treatment Optimization

H15: Al-Si-Cu-Mg-X-Y

Duplex precipitation microstructure achieved by ↓ solution treatment temperature and time.

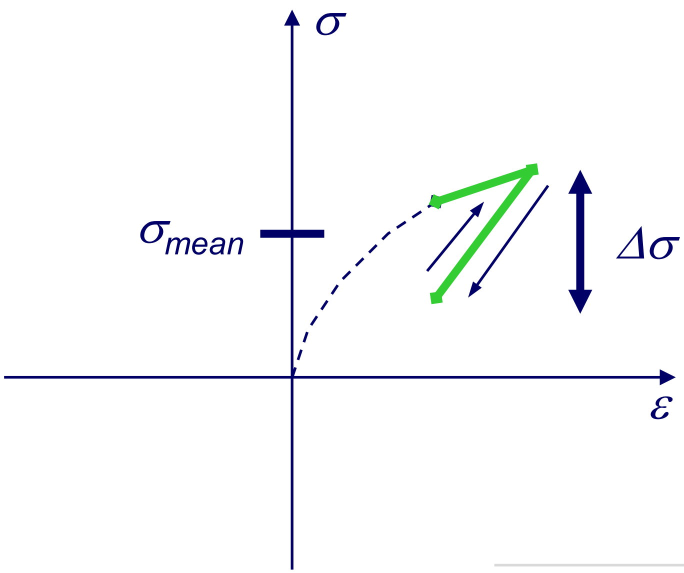


High-cycle Fatigue (HCF) vs. Low-cycle Fatigue (LCF)



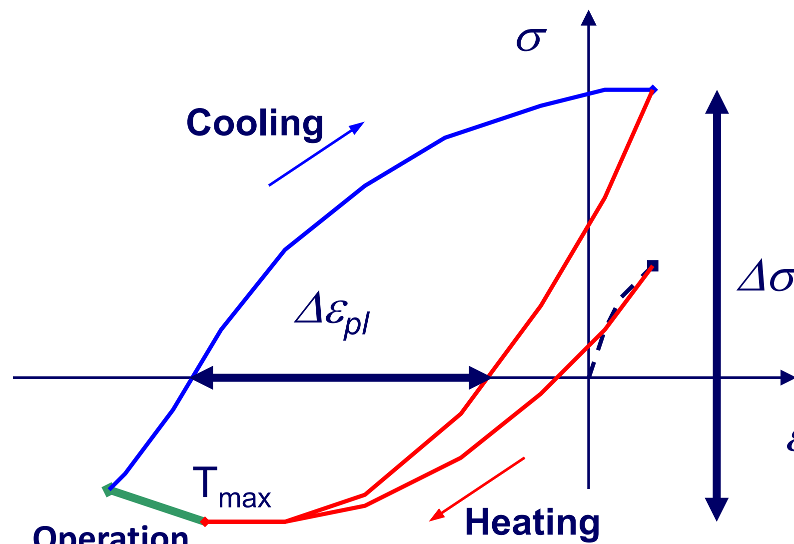
HCF

cracks initiate internally
usually from water jacket
infinite life (>10^7 cycles)
elastic strains and stresses
property: ***Fatigue Strength*** *(endurance limit)*



LCF/TMF

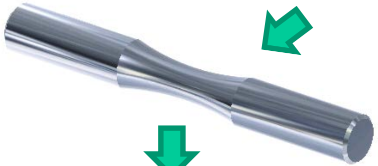
cracks usually from
combustion chamber
finite life (target is ~10,000)
plastic strains
Strain-Life curve

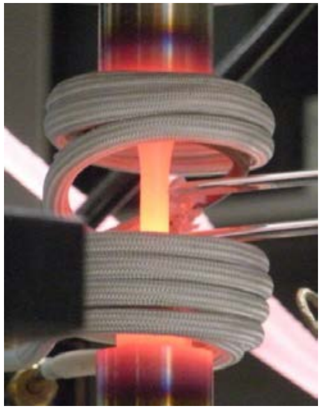


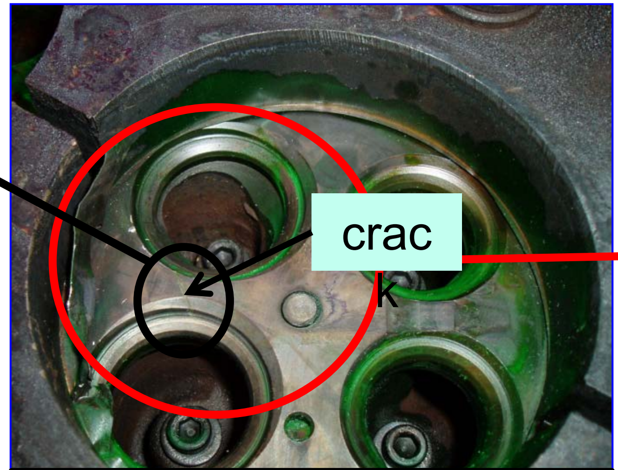
Testing: Thermomechanical vs. Thermal fatigue

TMF

Material Test



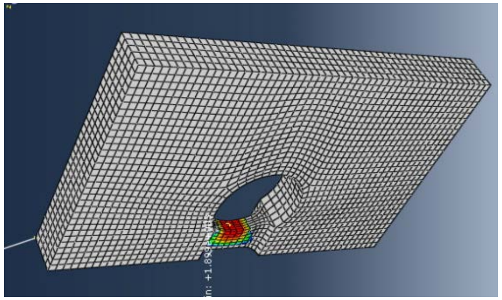




cylinder head thermal fatigue bench test

TF

Structural Test



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

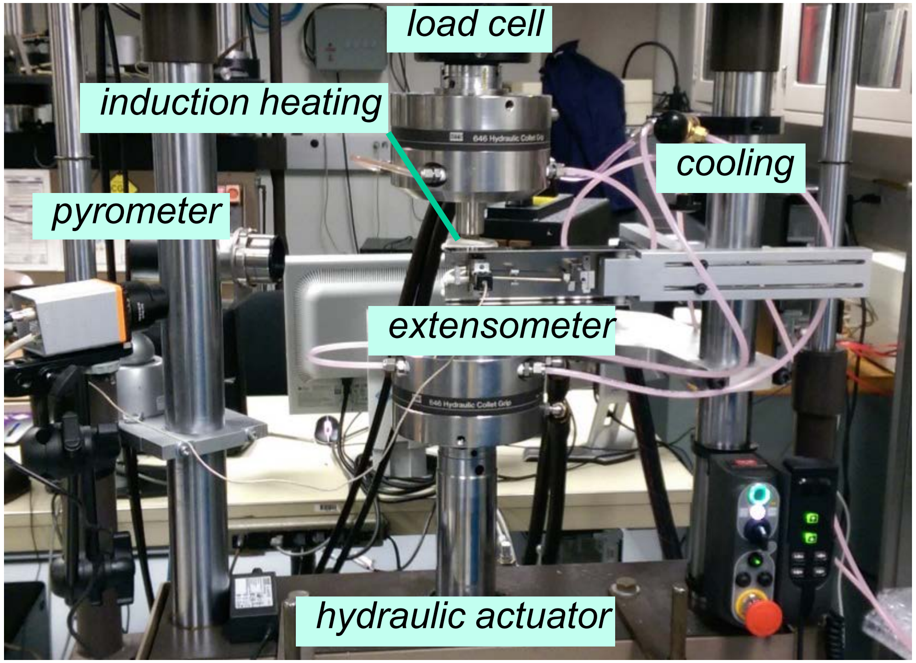
- Internal strains and stresses (due to thermal gradients)
- Ideal for comparing different materials (includes effects of other properties like stiffness, expansion, conductivity, etc.

Testing: Thermomechanical vs. Thermal fatigue

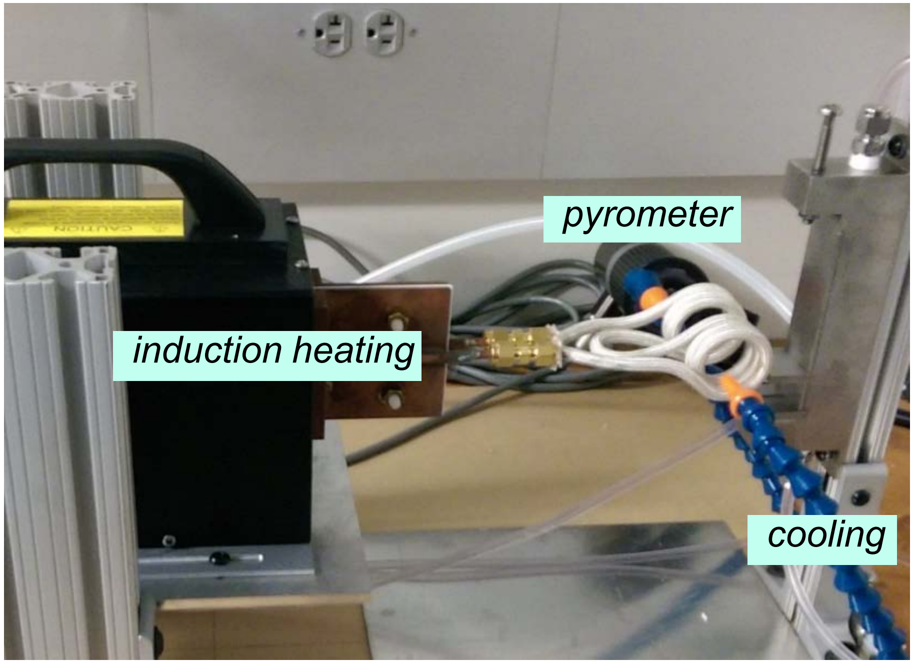
Customized testing systems at Ford Research & Innovation Center:

- Simulation of complex Thermal and Mechanical Fatigue loading
- Determination of properties under non-isothermal loading conditions (start-up / shut down)
- First in Industry (no other OEM has this capability)

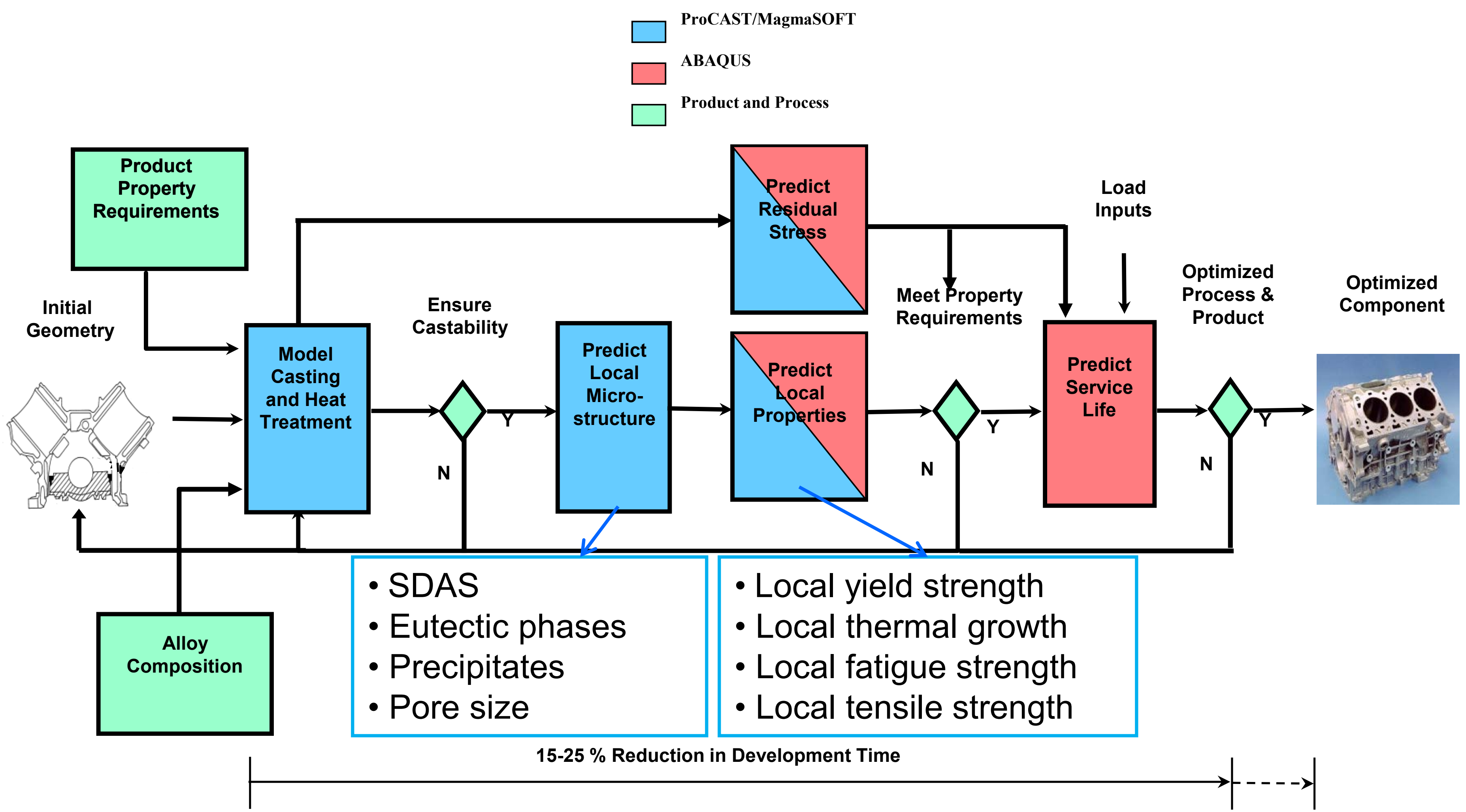
thermomechanical fatigue



thermal fatigue

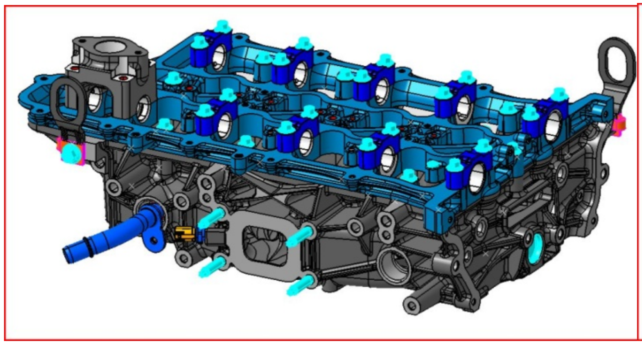


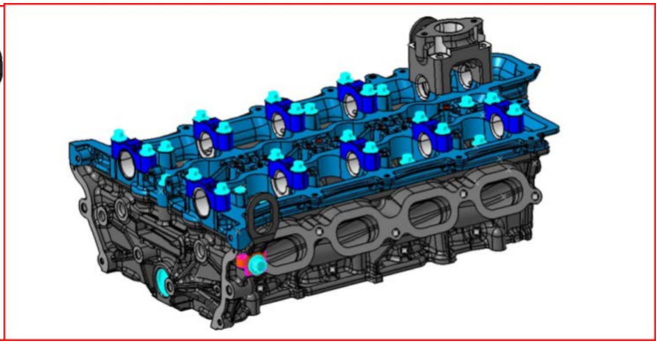
ICME Virtual Aluminum Castings

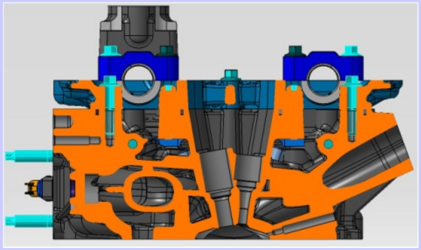


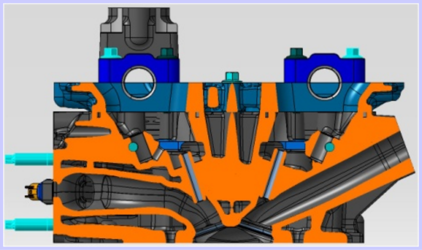
Demonstration on Ford GTDI Engine Program

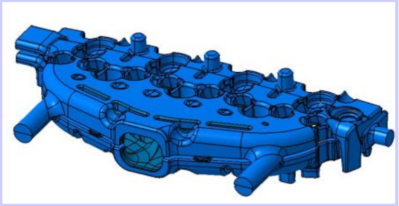
Under DOE Contract DE-EE0003332











Design Requirements

- 14 mm spark plug w/transverse fuel injector location
- Bosch and MM fuel injector (protect for both injectors)
- Two piece water jacket (cross / split cooling)
- Cross flow coolant path (lower jacket)
- Longitudinal coolant path (upper jacket)
- 8.5 mm chamber wall w/ additional IEM / chamber support
- AS7GU material
- 10° spark plug angle / 6° injector angle
- 31.8 mm (X2) intake valve diameter at a 18° angle
- 28.5 mm (X2) exhaust valve diameter at a 18.4° angle
- Outboard intake and exhaust HLA

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

Accomplishments

- Identified several key alloying elements that could potentially form heat resistant precipitates and enhance the high temperature mechanical properties.
- Designed novel multi-stage heat treatment procedure that generates complex nano-scale precipitation microstructure.
- Optimized alloy composition and heat treatment that could meet the room temperature and high temperature strength criteria.
- Thermo-mechanical fatigue testing frame set up has been completed and is ready for testing candidate alloys.

Accomplishments

- Customer designed a thermal fatigue rig and sample geometry compare candidate alloys under complex thermal and mechanical fatigue loading condition similar to engine working condition.
- Casting process simulation has completed on the selected engine component
- Thermop-hysical properties are being characterized for the new alloys
- Initial cost model has been accessed and the cost associated with the new heat treatment is being incorporated

Future Work

- Complete the design and optimization of the new alloys and the associated casting and heat treatment processes
- 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.