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

Project ID: PM060

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June 19, 2014

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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 FY13
  - $138K
- Funding for FY14
  - $1.2M

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

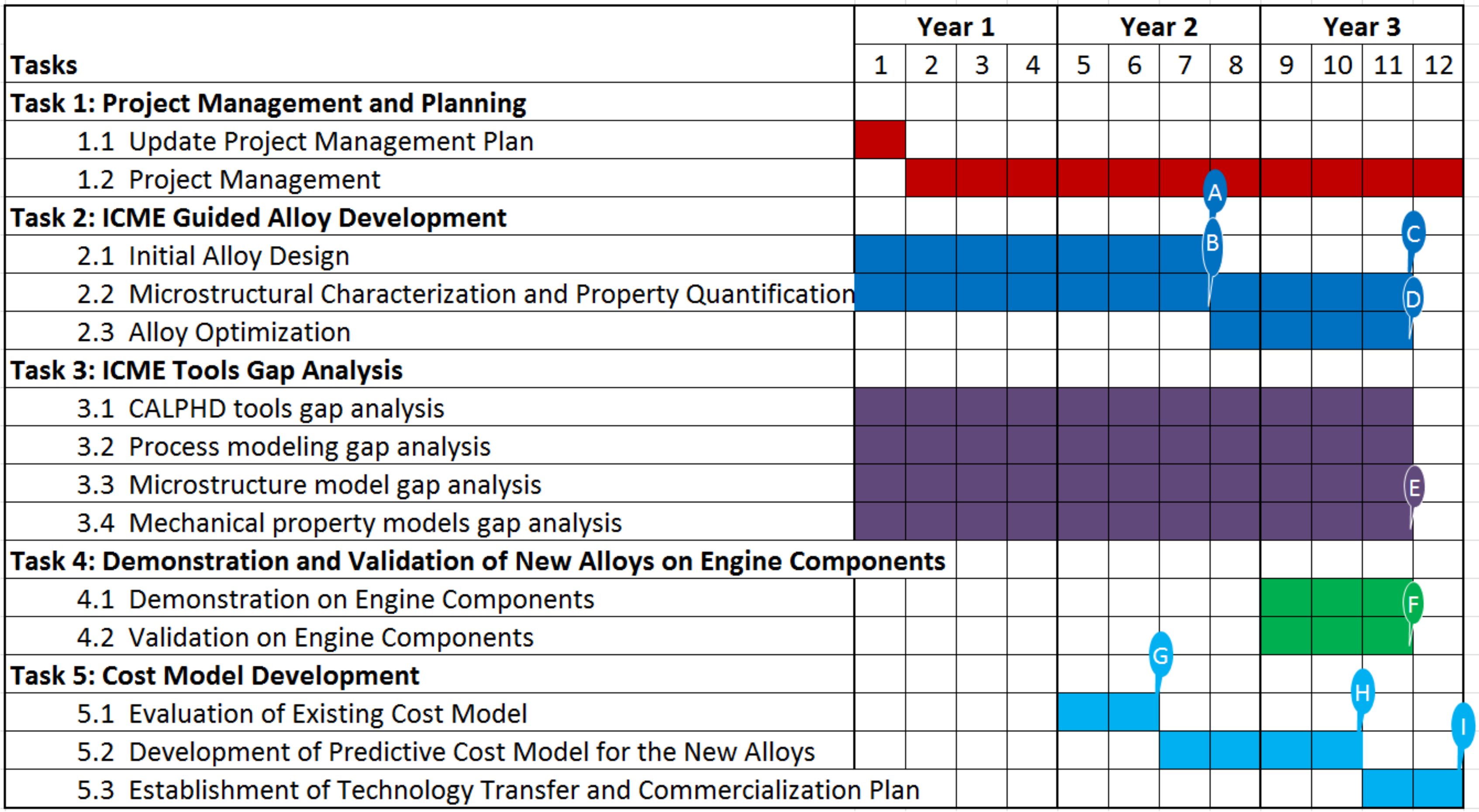
Task 2.0 – ICME Guided Alloy Development

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	

Background

- **Effect of Alloy Elements on Mechanical Properties Based on A356 Alloy**

Alloy	RT Tensile Properties			at 250C (after 100hrs-250C holding)				at 300C (after 100hrs-300C holding)			
	0.2% YS (MPa)	**UTS** (MPa)	**E %**	**0.2% YS** (MPa)	**UTS** (MPa)	**E %**	**Creep õ0.1-100h**	**0.2% YS** (MPa)	**UTS** (MPa)	**E %**	**Creep õ0.1-100h**
A356 T7	257	299	9.9	55	61	34.5	38.8	40	43	34.5	21.7
A356+Cu 0.50% T7	275	327	9.8	66	73	34.5	39.5	40	44	34.6	21.8
A356+Cu 0.50%+Zr 0.14%+Mn0.15% T7	264	319	11.3	65	76	37	41	44	51	46	22.5
AlSi7Cu3.3 MnVZrTi T7	195	335	8	95	124	19	tbm	66	75	26	tbm
AlSi7Cu3.8 MnVZrTi T7	234	368	6	102	133	19		63	77	26	31.8

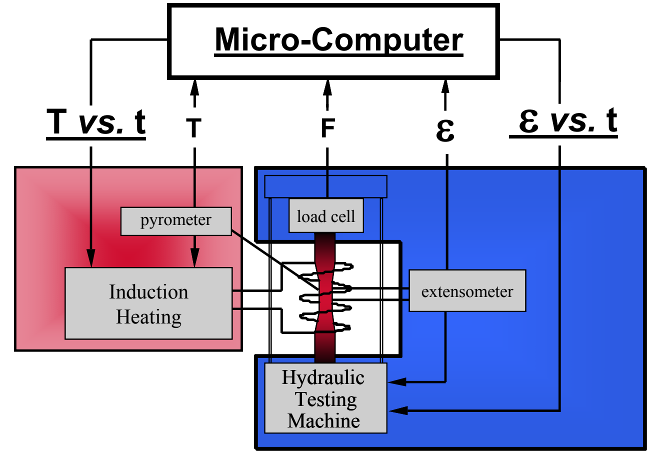
Background

- **Improved Mechanical Properties at Room Temperature and 150°C**

Alloy	Room Temperature(22C)			High Temperature(150C)		
	YS(MPa)	UTS(MPa)	E(%)	YS(MPa)	UTS(MPa)	E(%)
5Si1Cu0.6Mg	337.27	369.99	2.8	307.98	325.9	6
7Si1Cu0.5Mg	338.76	385.38	5.5	305.23	328.65	10
7Si1Cu0.5Mg3Zn	346.45	392.39	4.7	310.74	332.79	7.7
5Si1Cu0.5Mg	332.79	368.96	3.2	307.98	325.9	6
5Si3Cu0.5Mg	373.09	404.33	2	334.17	361.73	4
5Si3Cu0.5Mg3Zn	372.63	391.35	2	328.65	345.88	2
5Si1Cu0.6Mg	335.31	373.09	3.2	307.98	325.9	6
5Si1Cu0.6Mg3Zn	346.45	328.05	2.2	314.87	334.17	5.7
5Si1Cu0.6Mg	329.34	371.03	4	307.98	325.9	6
7Si3Cu0.6Mg	376.65	407.31	2	337.61	368.62	4.3
7Si3Cu0.6MgZn	379.06	401.34	2	333.48	352.77	5
5Si1Cu0.6Mg	329.92	368.84	3.2	307.98	325.9	6

Casting and Testing Facility

Electric melting furnaces and flux unit
Sand mixer and sand mold

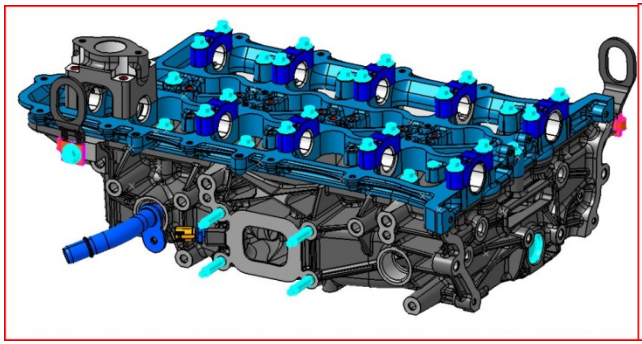


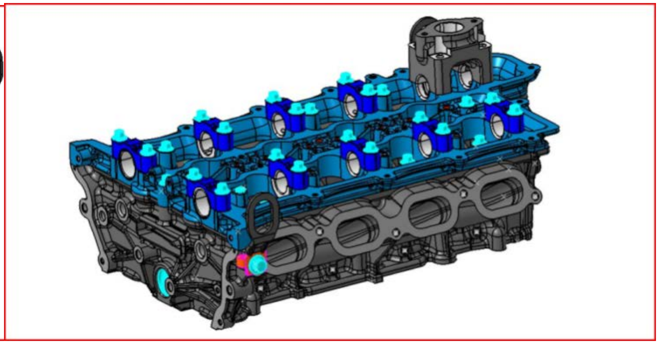
Schematic representation of the TMF test setup implemented at Ford R&A

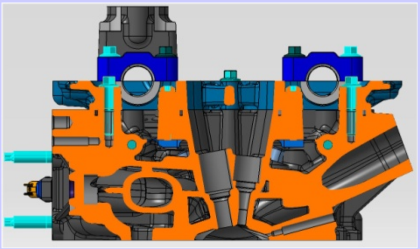
Drop bottom HT furnace and
Quenching basket

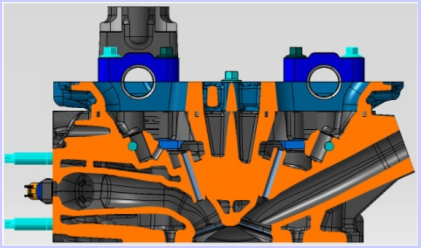
Demonstration on Ford GTDI Engine Program

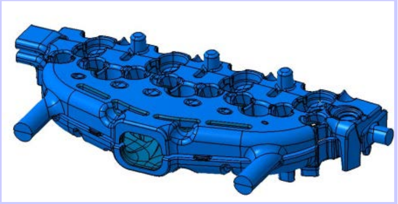
Under DOE Contract DE-EE0003332











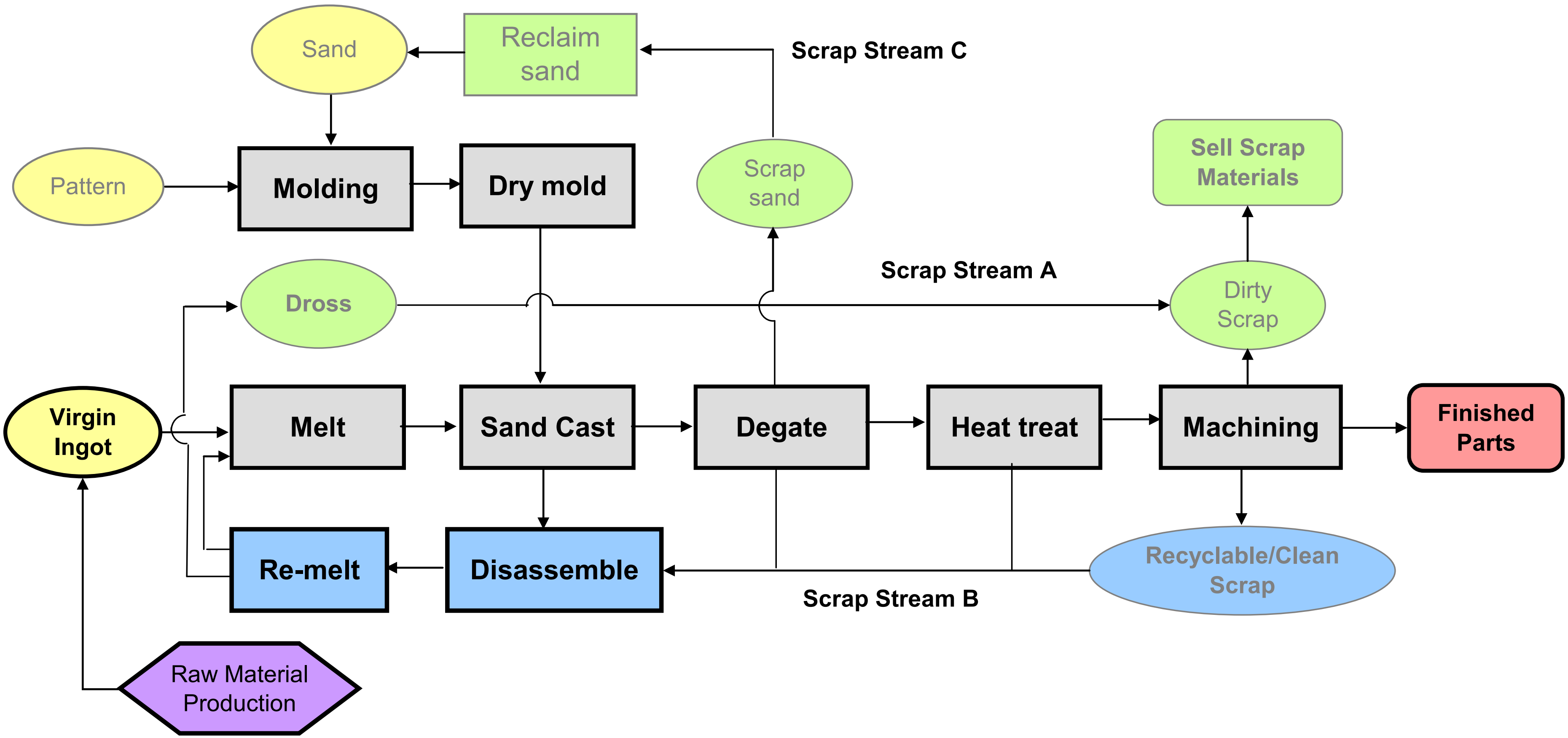
Design Requirements

- 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

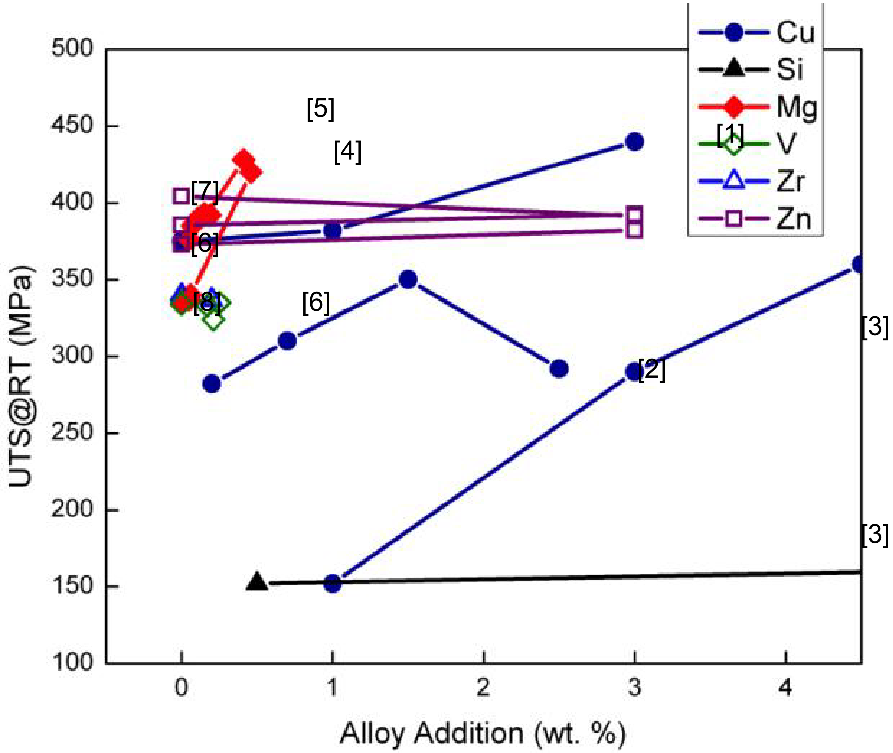
Cost Modeling

Technical Cost Model - Sand Casting Process Flow Diagram Assumption

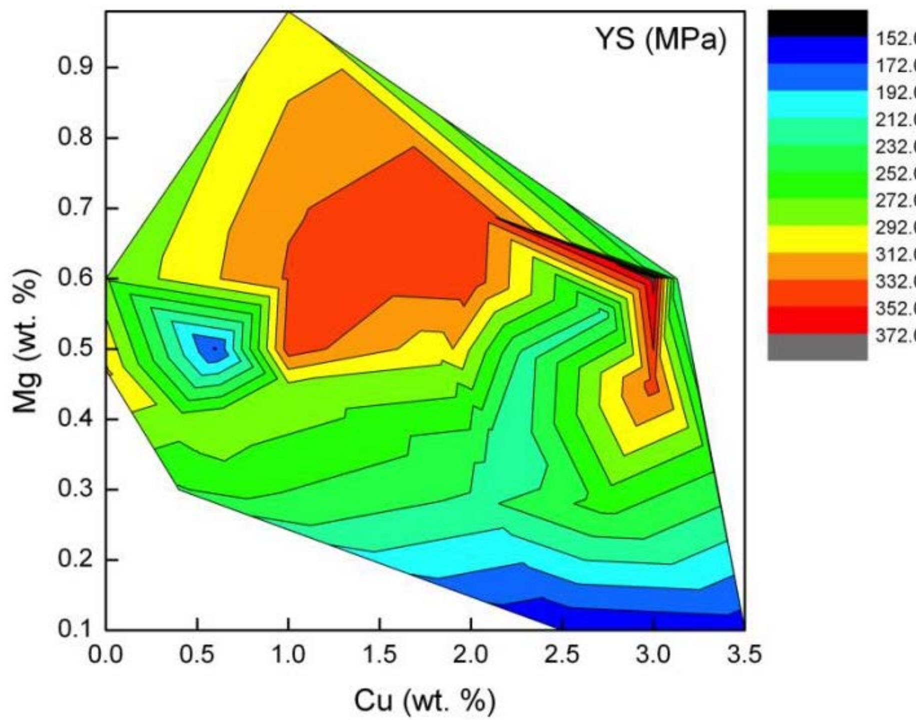


Initial Alloy Design

Effectiveness of Alloying Additions



Yield Strength Contour Map



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[2] S G Shabestari and H Moemeni, J Mater Process Technol, 153-154 (2004) 193-198.

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[4] P Ouellet and F H Samuel, J Mater Sci, 34 (1999) 4671-4697.

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[6] M Garat, US20110126947, 2011.

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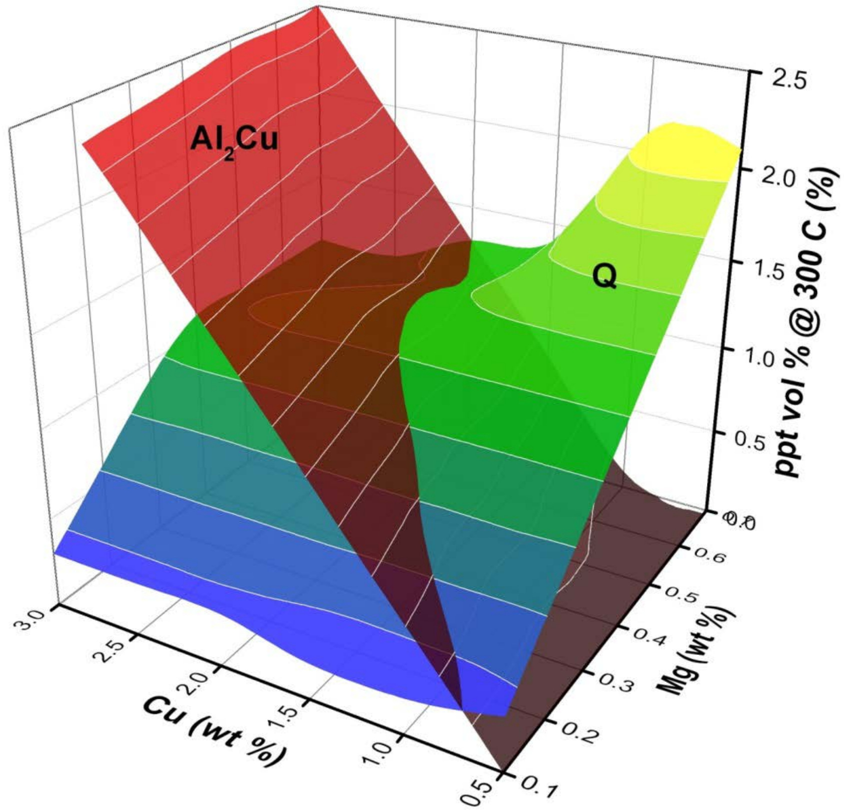
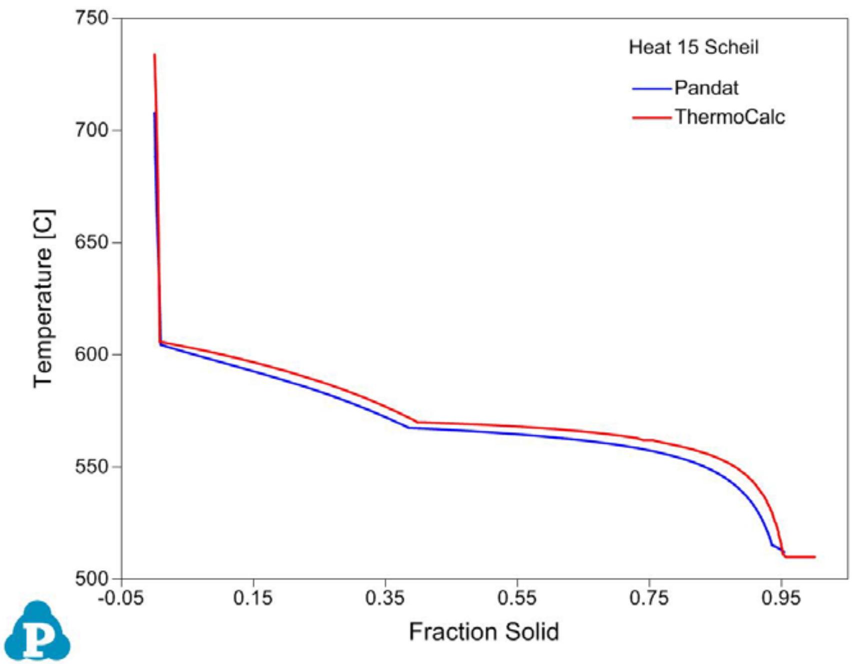
[8] H A Elhadari, H A Patel, D L Chen and W Kasprzak, Mater Sci Eng, 528 (2011) 8128-8138.

Initial Alloy Design

- Precipitation Vol. % @ 300 C (Al7Si): (ThermoCalc)



- Scheil Solidification Simulation
- (ThermoCalc & Pandat)



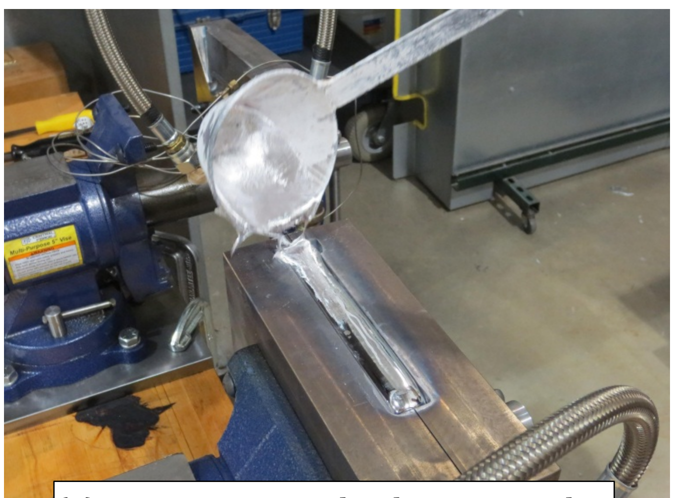
Initial Alloy Design: Heat 1-13

- ✓ **13 alloy compositions have been proposed and cast.**
- ✓ **Heat 1-7**
  - Si-Fe-Cu-Mg-V-Zr-Ni.
  - To compare the mechanical properties of these alloys with DOE criteria.
- ✓ **Heat 8-13**
  - Si-Ti-V-Zr-Ni
  - To investigate the effect of Ti, V, Zr and Ni.

Alloy Fabrication- Permanent Mold Gravity Cast

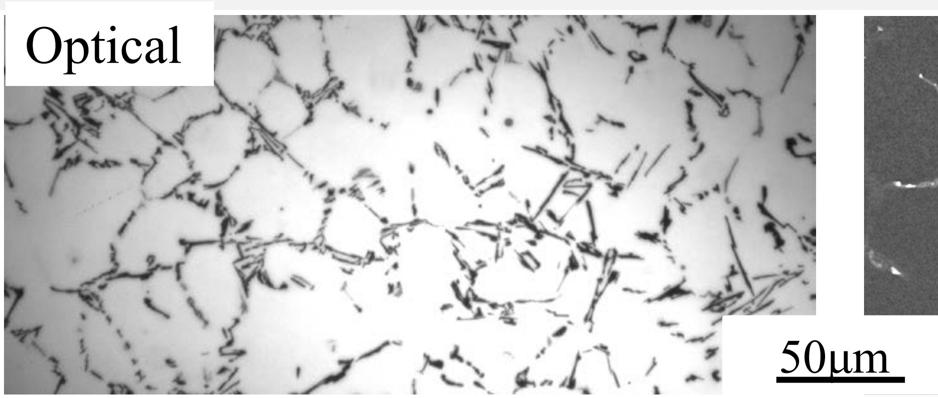

(a) Melting raw materials @ 750 C.

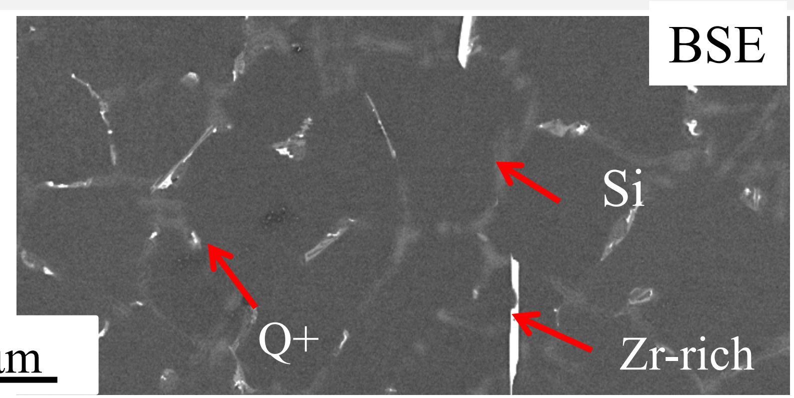

(b) Pouring spectrometer standard disk to control melt composition.


(c) Pouring torpedo shape sample.

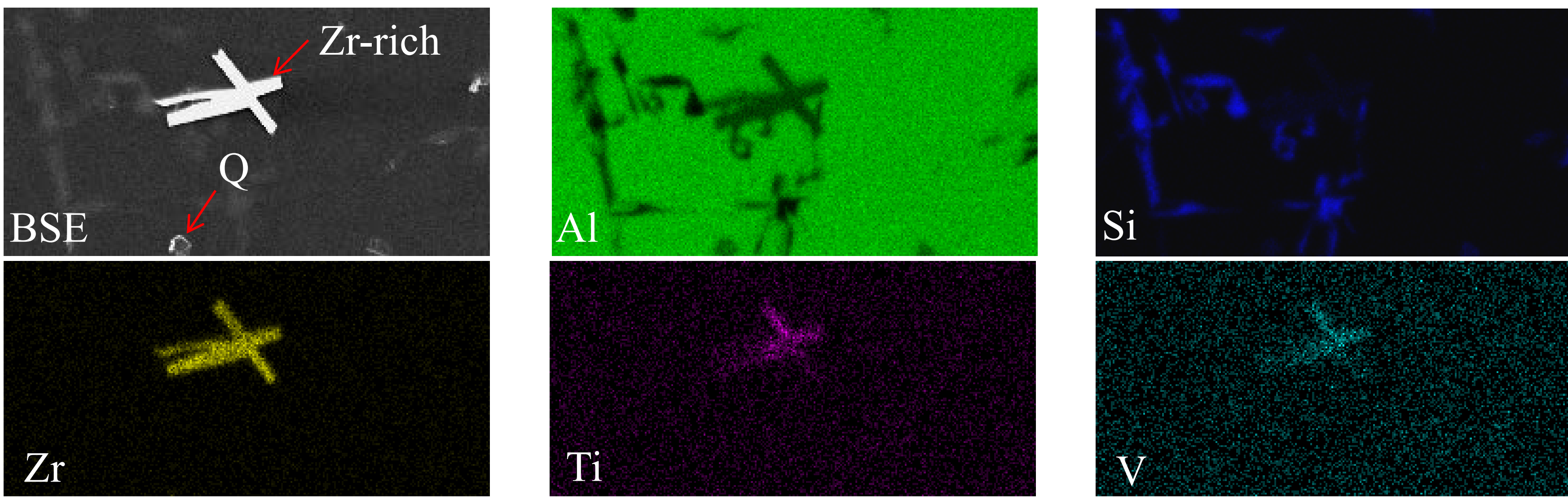

(d) Torpedo samples ready for analysis.

Microstructure of Heat 4 (As Cast)





SEM-EDS Analysis of "Zr-rich Phase" in Heat 4 (As cast)



Zr-rich Phase– contains Zr, Ti, V.

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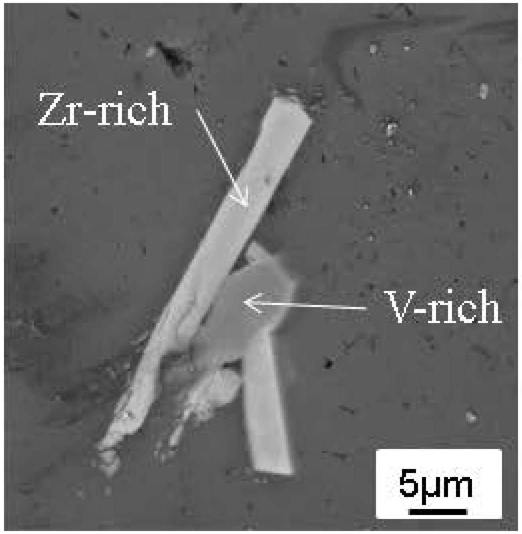
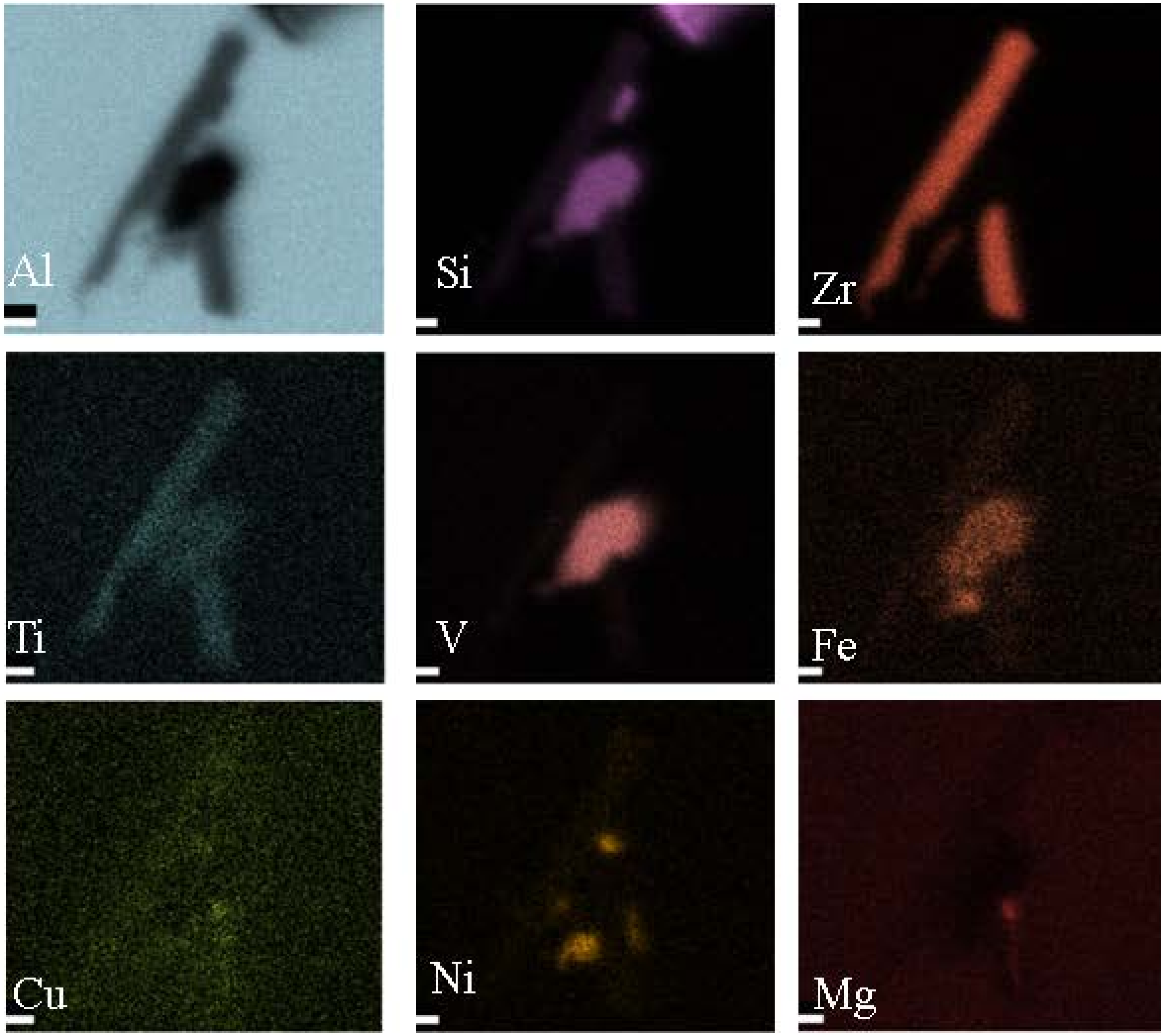
Microstructure of Heat 7 (As Cast)





In heat 7, two types of intermetallic phases were observed: Zr-rich and V-rich.

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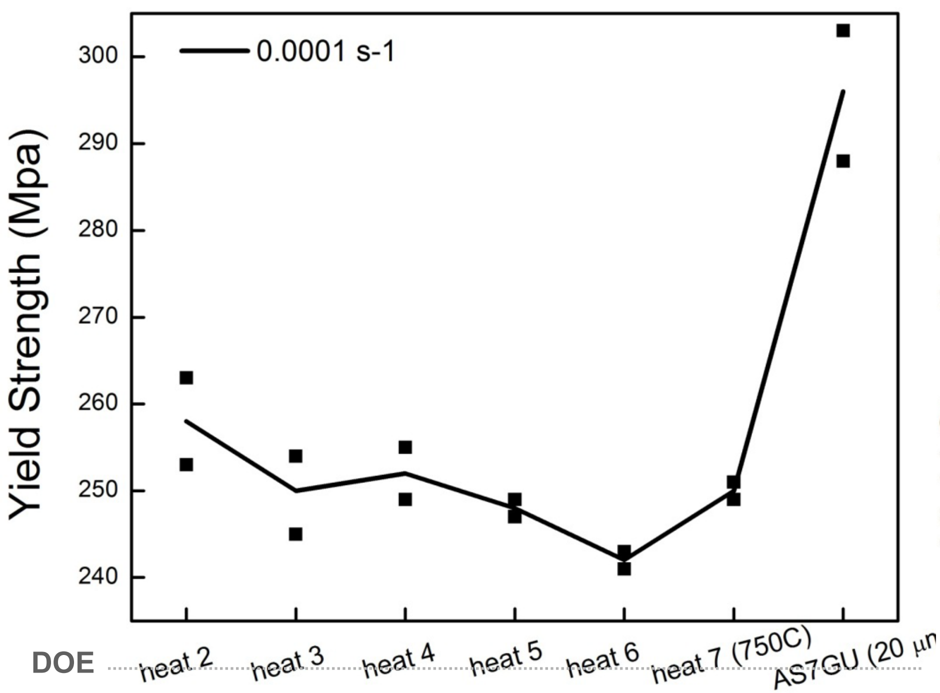
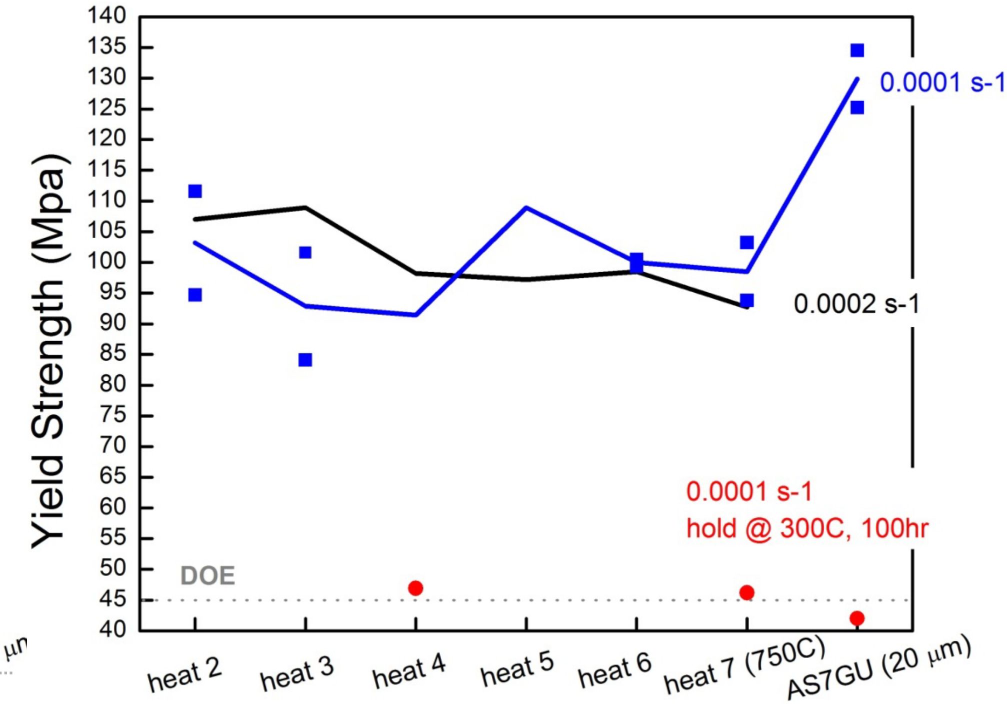
Tensile Testing of Heat 1-7 (T6)

- @ RT

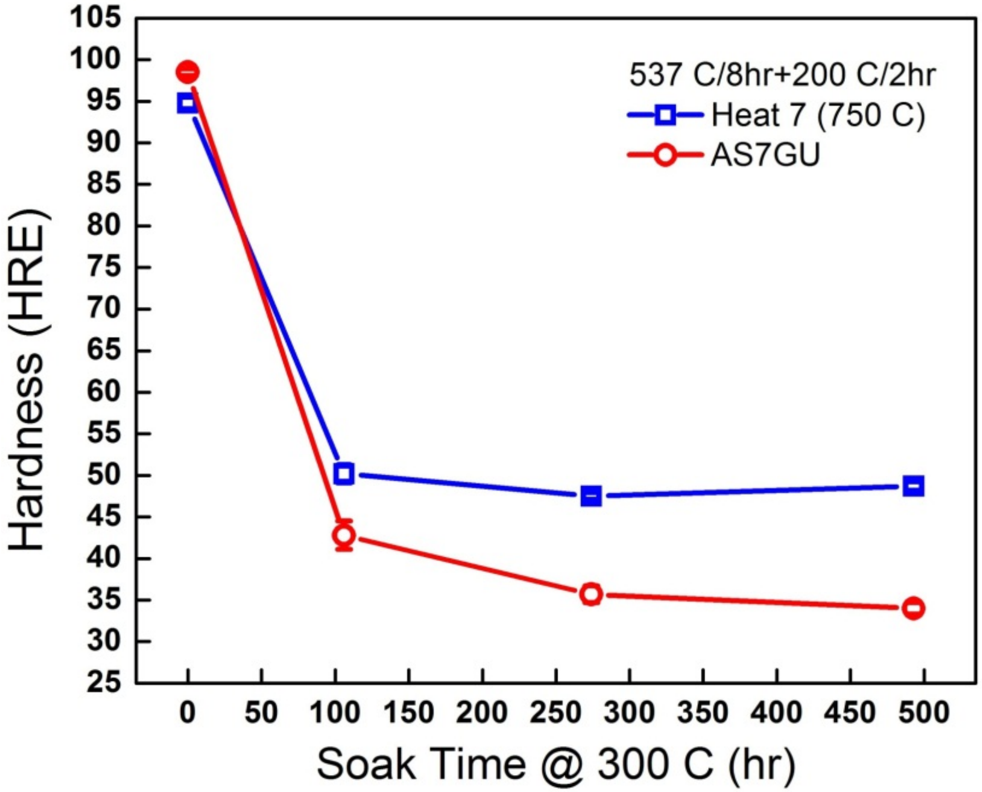


- @ 300 C



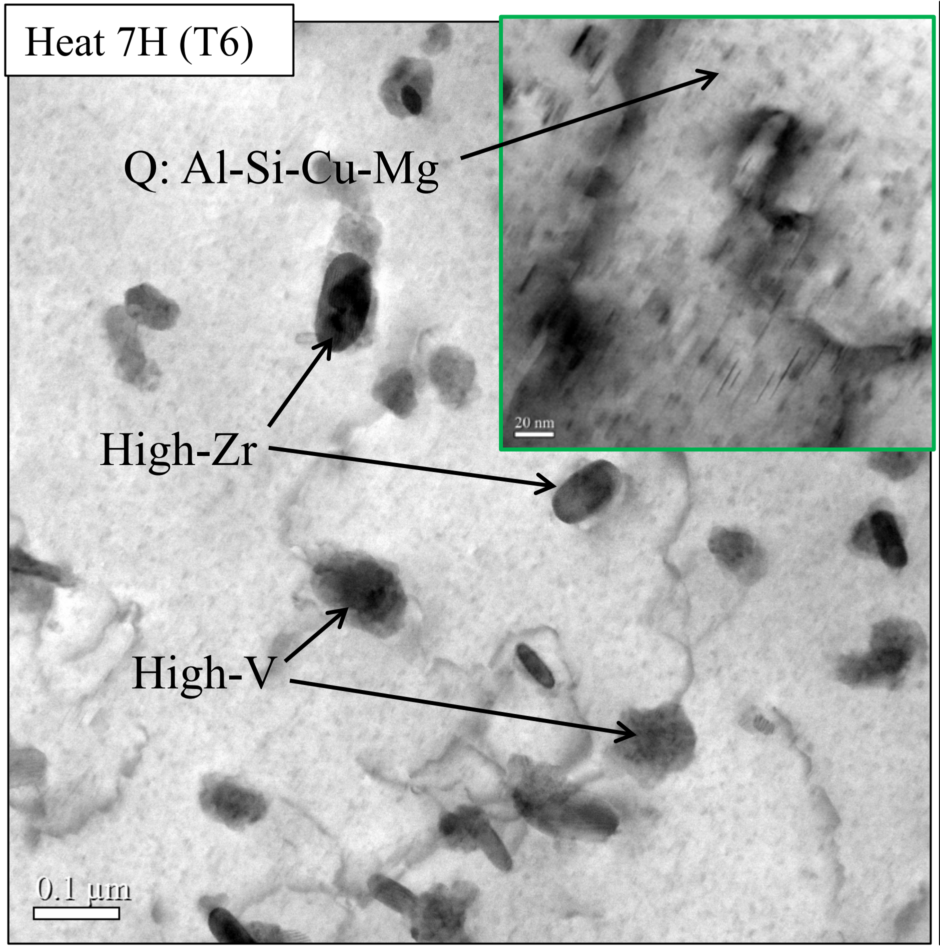
- **Heat 1-7 alloys fulfill DOE yield strength criteria at both RT and 300 C.**
- @ RT and 300 C, heat 1-7 alloys exhibit lower yield strength than AS7GU due to lower (Cu+Mg) levels.
- When tested @ 300 C after 100 hour thermal exposure, heat 7 alloy shows yield strength comparable to AS7GU (or better).

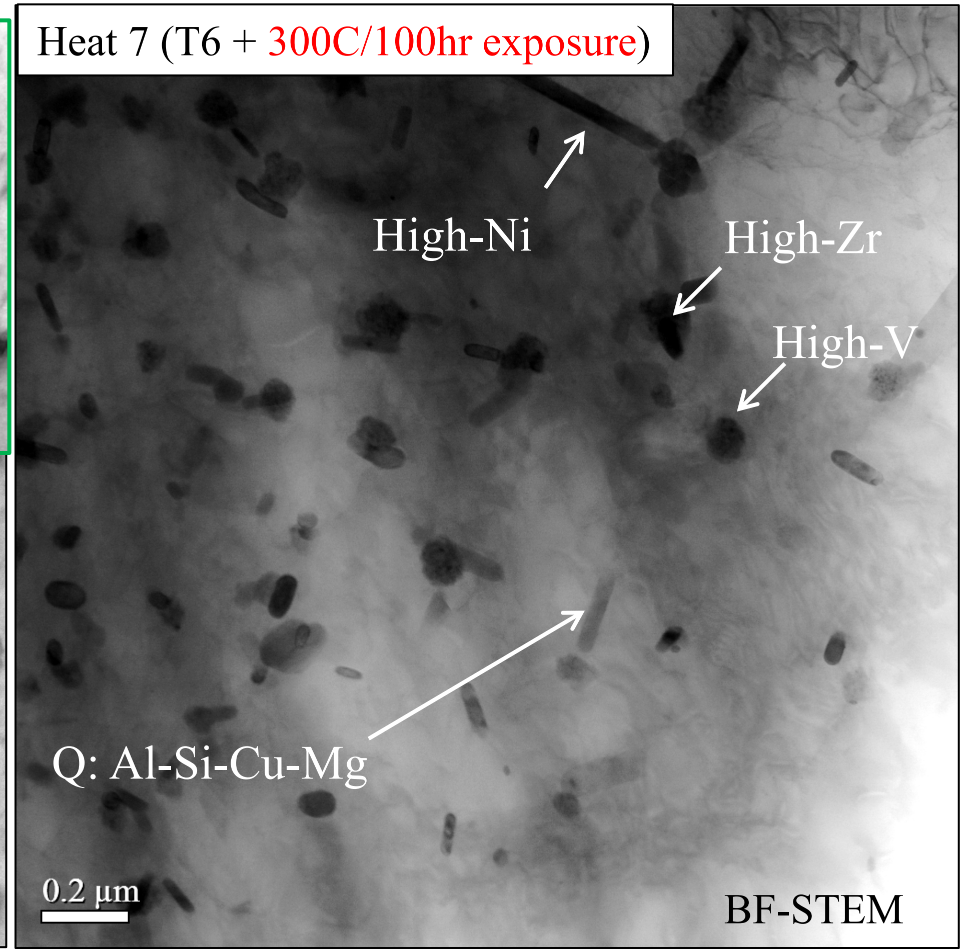
Hardness Comparison between Heat 7 & AS7GU (T6) after Thermal Exposure @ 300°C



- Difference in hardness between heat 7 and AS7GU is **reversed** after thermal exposure @ 300 C.
- Effect of V, Zr & Ni additions?

Morphology of Precipitates in Heat 7





A variety of precipitates with relatively fine size exist in heat 7, even after thermal exposure @ 300 C for 100 hours.

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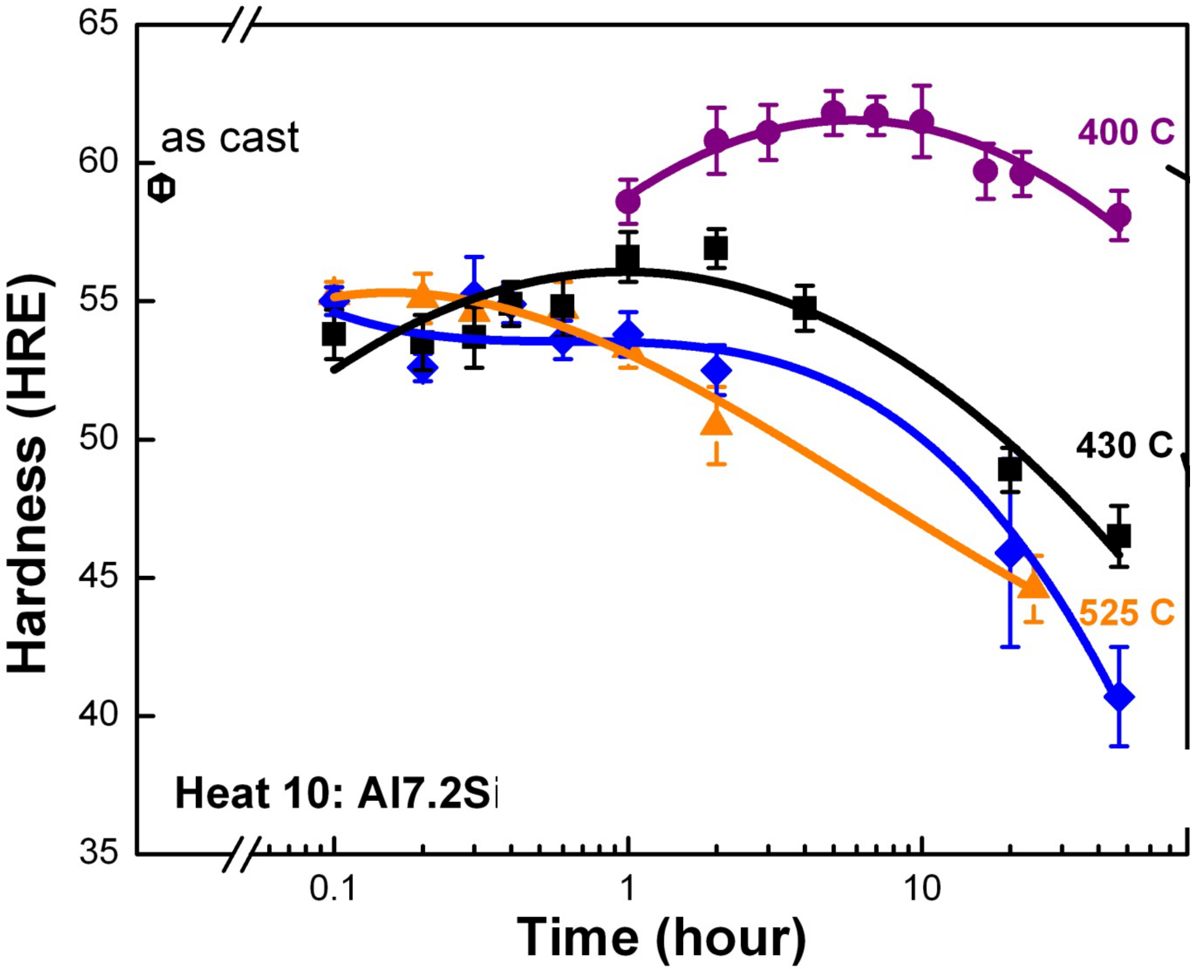
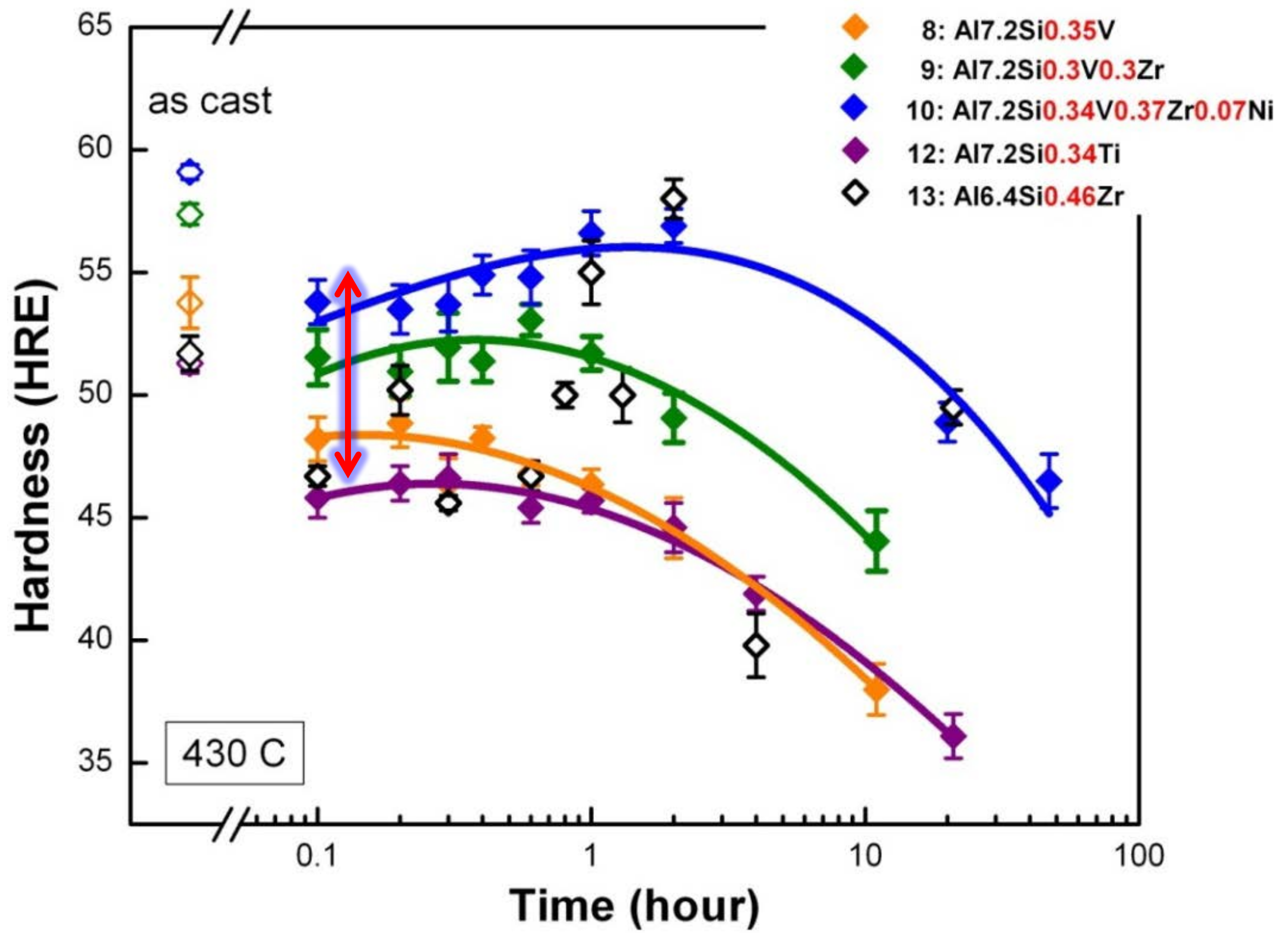
High Temperature Aging Response of Heat 10



Age hardening observed in heat 10 @ 430 & 400 C.

Comparison of Aging Response of Heat 8-13



Alloys with higher levels of V, Zr and Ni exhibit stronger aging response @ 430 C.

Summary

- The program was kicked off in February 2013.
- CALPHD method was applied to explore and determine the initial 13 alloy compositions.
- Heat 1-7 alloys meet DOE criteria on yield strength at RT and 300 C, even with 100 hour thermal exposure at testing temperature.
- (Cu+Mg) level is key to RT strength. Much higher RT strength could be attained by optimize the Al-Si-Cu-Mg baseline composition.
- V, Zr, Ni are beneficial for high temperature strength, particularly after long time thermal exposure. High temperature strength could be potentially improved by optimizing the aging heat treatment for these heat resistant precipitates.

Future Work

- Continue to investigate the strengthening mechanisms of Al-Cu-Mg-Si-V-Zr-Ni-Ti at room and high temperature using combined ICME and TEM approach.
- Optimize alloy compositions and heat treatment to achieve sufficient volume fraction and effective size and morphology for the heat resistant precipitates.
- Continue to investigate the fatigue and thermal mechanical fatigue performance of the new alloys.
- Continue to investigate the gaps of ICME models in modeling the casting process, microstructural evolution and mechanical properties.
- Continue to establish the cost model for these new alloys to ensure not to exceed 110% of the cost of incumbent alloys A319 or A356.