High Performance Cast Aluminum Alloys for Next Generation Passenger Vehicle Engines

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Oak Ridge National Laboratory
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Annual Merit Review

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Overview

Timeline

- Start: November 2012
- *CRADA* Executed: Nov 2013
- End: December 2017
- 93% Complete

Budget

- Total project funding.
  - DOE-$3500 K
  - Cost share ~$2000 K+
- FY16 DOE Funding - $700 K
- FY17 DOE Funding - $250 K
  - Project leadership transition to industry in Year 4, as-planned

Barriers

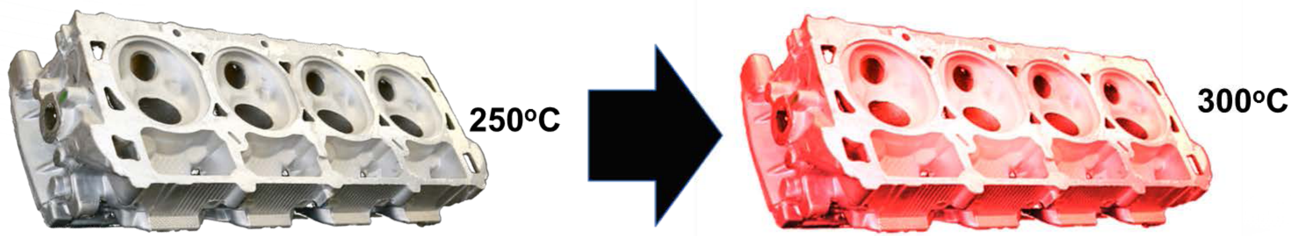
- Absence of ***economical*** lightweight materials with improved castability, high temperature strength and fatigue performance.
- A major barrier to the development of new alloys is the time-intensive trial and error approach applied to these complex systems. ***Integrated computational materials engineering*** (ICME) approach to accelerate the development and deployment of new cast aluminum alloys.

Partners

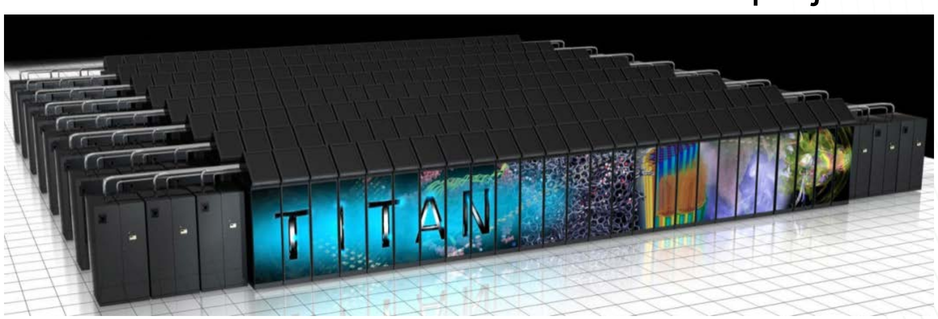
- CRADA Partners: Fiat Chrysler Automobiles (FCA US LLC), ORNL, Nemak USA.
- Collaborators: WPI, Element, Granta MI, ESI North America, Flow Science, Magma Foundry Technologies, Minco Inc.
- Project lead – *ORNL*

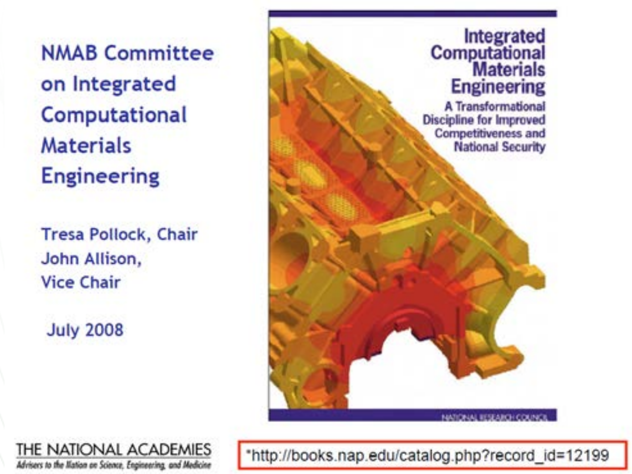
Relevance

- Objectives
  - Develop high performance cast aluminum alloys that have following characteristics
    - improved castability, high temperature strength and fatigue performance.
    - engine cylinder heads fabricated with new alloy will have ***> 25% strength improvement (at 300°C compared to baseline properties at 250°C)*** and will ***cost £ 10% more*** than heads manufactured by 319 or 356.



  - Evaluate the adequacy of existing ICME models and codes for the prediction of properties and development of cast aluminum alloys
    - A ***gap analysis report*** for existing ICME codes for cast aluminum alloy development will be submitted at the end of the project





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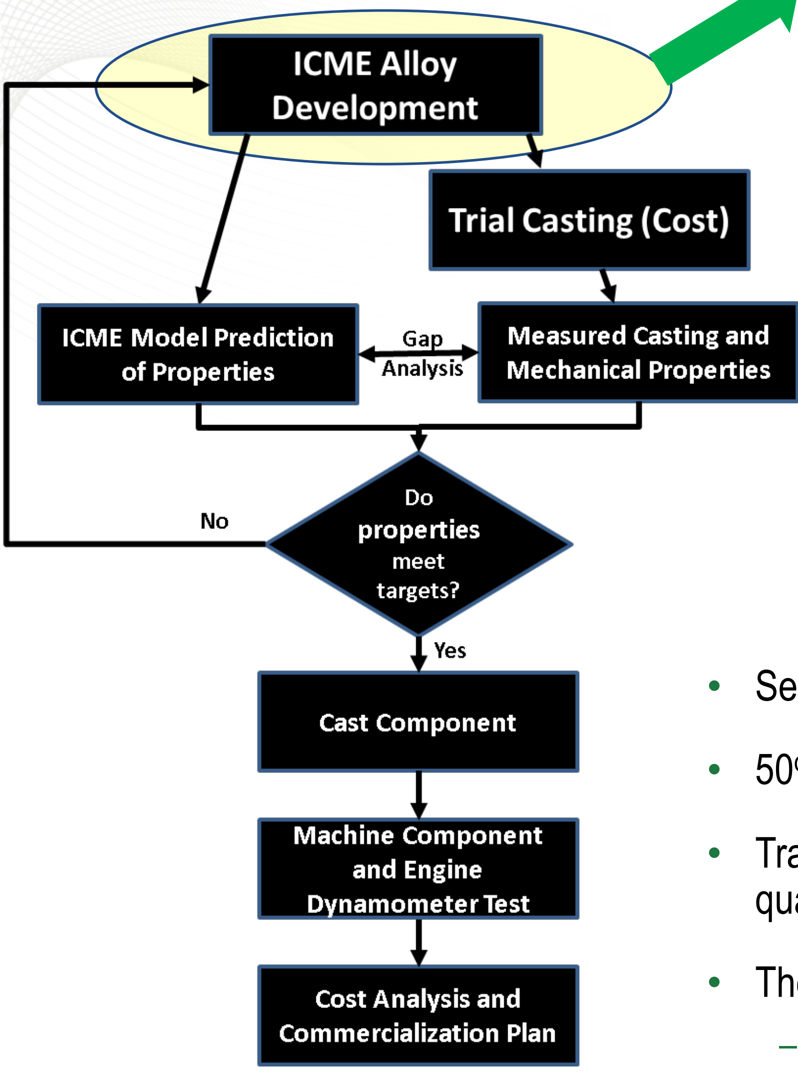
Project Milestones

- Milestone 1: Selection of the cast aluminum alloy family for further development to refine alloy development path.
  - Planned Date: 11/30/14 (completed)
- Milestone 2: Finish implementation of ICME models that could be iterated to accelerate the alloy development.
  - Planned Date: 11/30/15 (completed)
- Milestone 3: Finish identification of new alloy composition(s) with improved properties.
  - Planned Date: 11/30/16 (completed)
- Milestone 4: Complete cost model for component fabrication with new alloy.
  - Planned Date: 7/31/17 (on track)
- Milestone 5: Finish commercialization plan for the new alloy.
  - Planned Date: 11/30/17 (on track)

Approach/Strategy

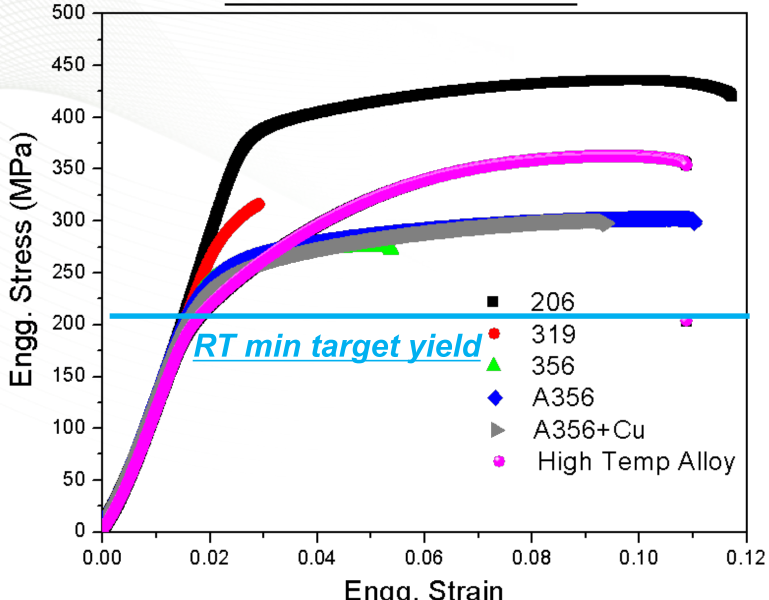


Key Properties	Cast Al Alloy Baseline	DOE Targets For Cast Alloys
Tensile Strength @ 25°C	228 MPa	276 MPa
Yield Strength @ 25°C	165 MPa	207 MPa
Peak Temperature	250°C	300°C
Tensile Strength @ peak T	52 MPa @ 250°C	66 MPa @ 300°C
Yield Strength @ peak T	35 MPa @ 250°C	45 MPa @ 300°C
Fluidity (Spiral Test)	Excellent	Excellent
Hot Tear Resistance	Excellent	Excellent
Cost	$x/lb	$1.1x/lb

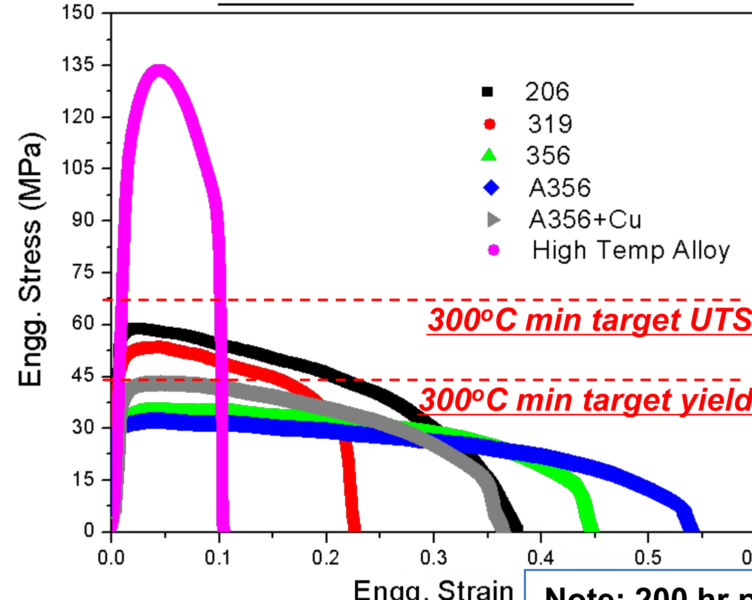
- Several properties need to be satisfied simultaneously
- 50°C increase in temperature was a very challenging target
- Tradeoffs need to be performed. These tradeoffs can be performed quantitatively with the ICME approach.
- The two key technical targets are related to:
  - **Elevated temperature mechanical properties**
  - **Castability and hot tear resistance**

Technical Accomplishments (previous)

RT tensile curves



300°C tensile curves

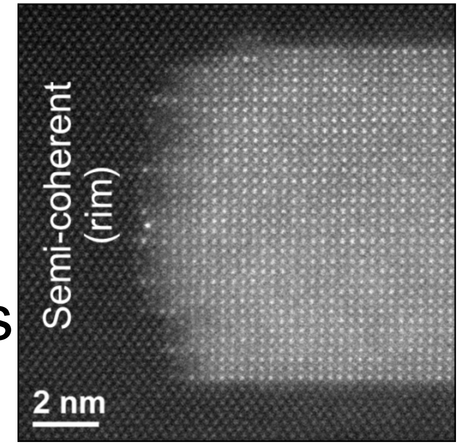


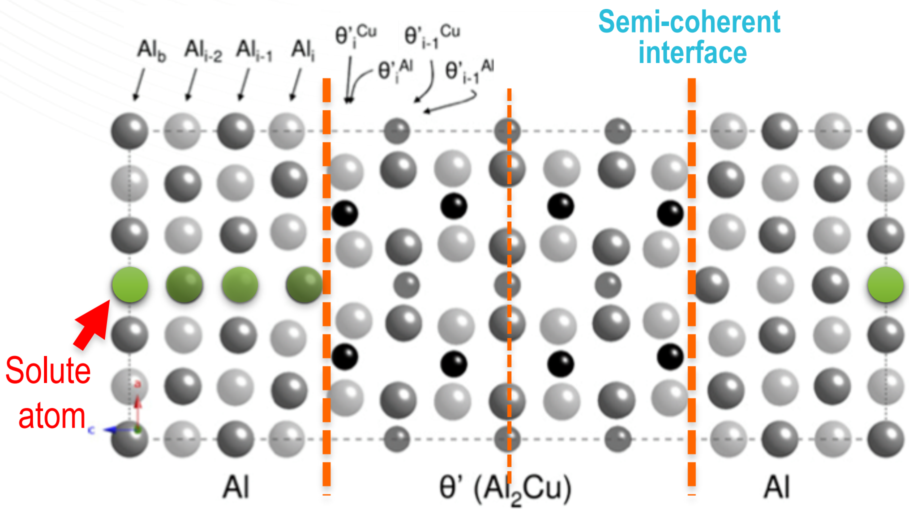
Note: 200 hr preexposure prior to 300°C tensile testing

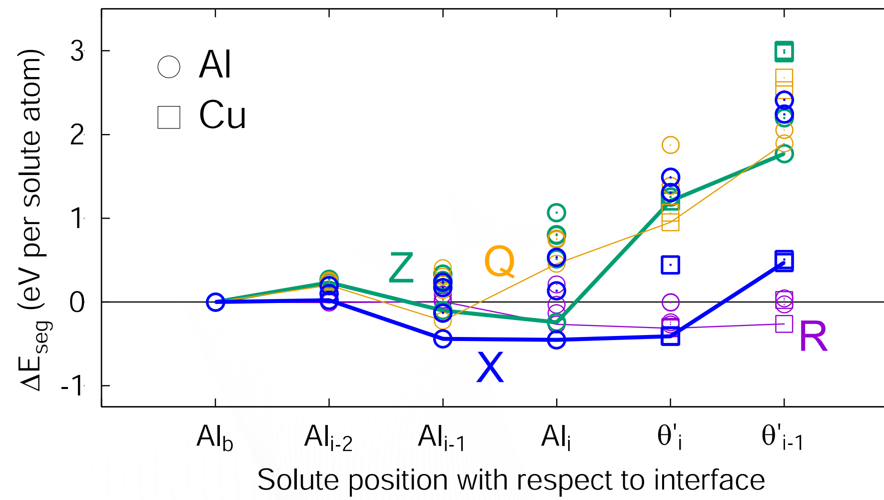
- Cylinder head materials supplied by Nemak
  - 319-T7; 356-T6; A356-T6; A356+0.5Cu-T6; 206-T6; High Temp Alloy (AlCuEx)
  - All materials have grain size/secondary dendrite arm spacing (SDAS) of ~ 30 μm
- **High temperature alloy exceeds 300°C technical target by >2X**
- Alloy is in Al-Cu family (AlCuEx) and has ***exceptionally stable microstructure*** after sustained elevated temperature exposure
- Two patent applications filed

Technical Accomplishments

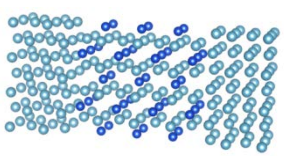
- ICME approach with modeling and characterization has enabled rapid understanding and development of new alloys







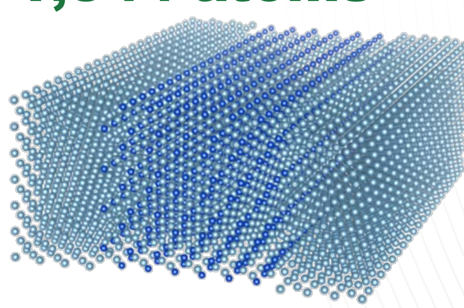
168 atoms

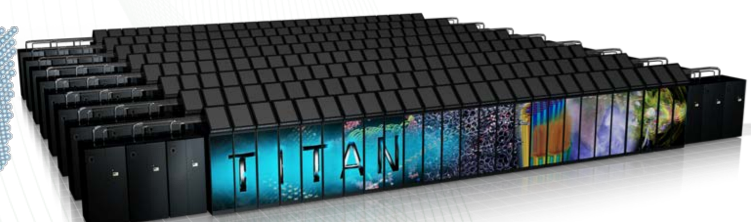


32 cores × 48 hours
~ 1,500 CPU hours per supercell
(hundreds of serial calculations)

~30 nodes
(~400 cores)

1,544 atoms





~20,000 nodes
(~300,000 cores)

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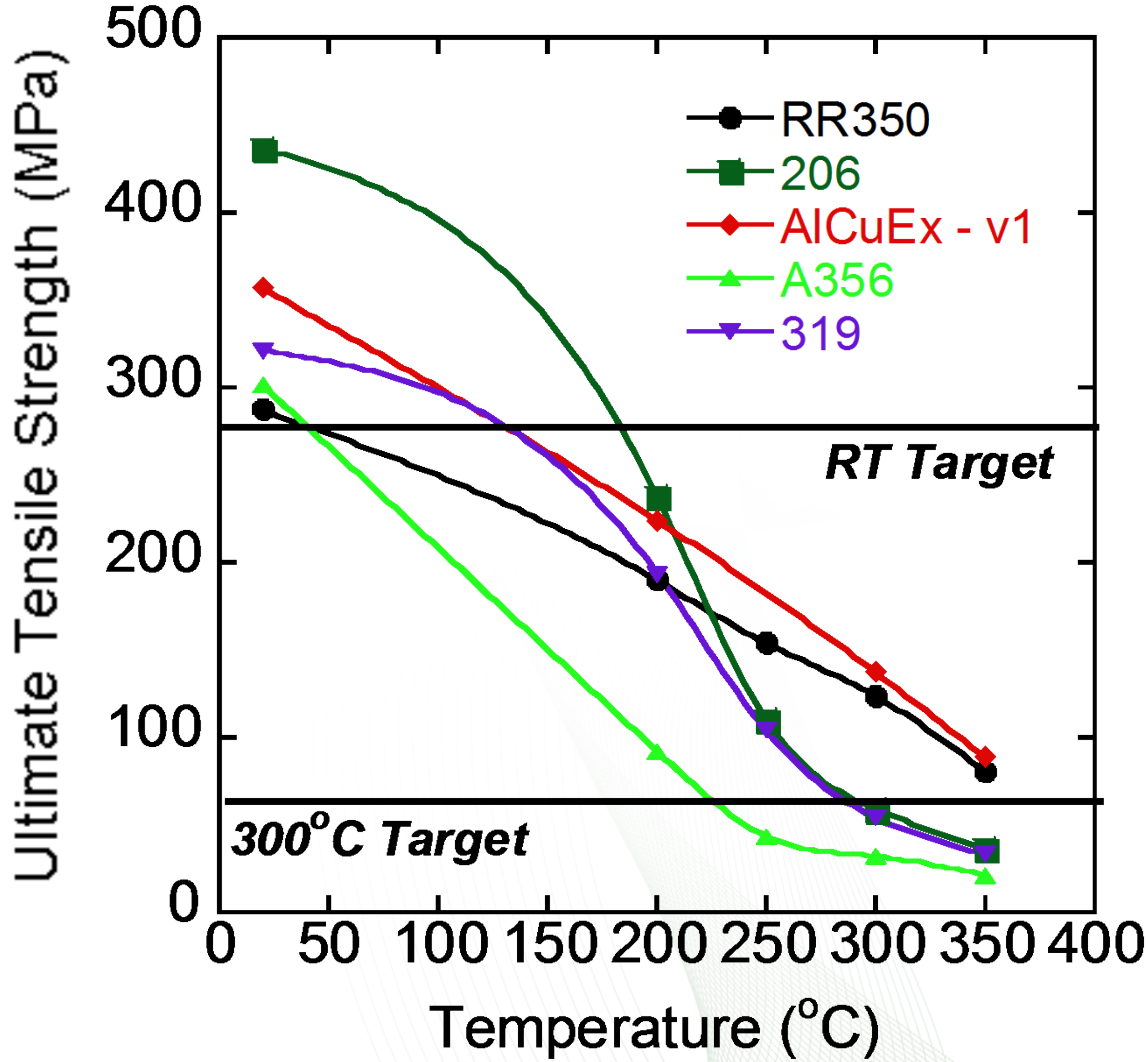
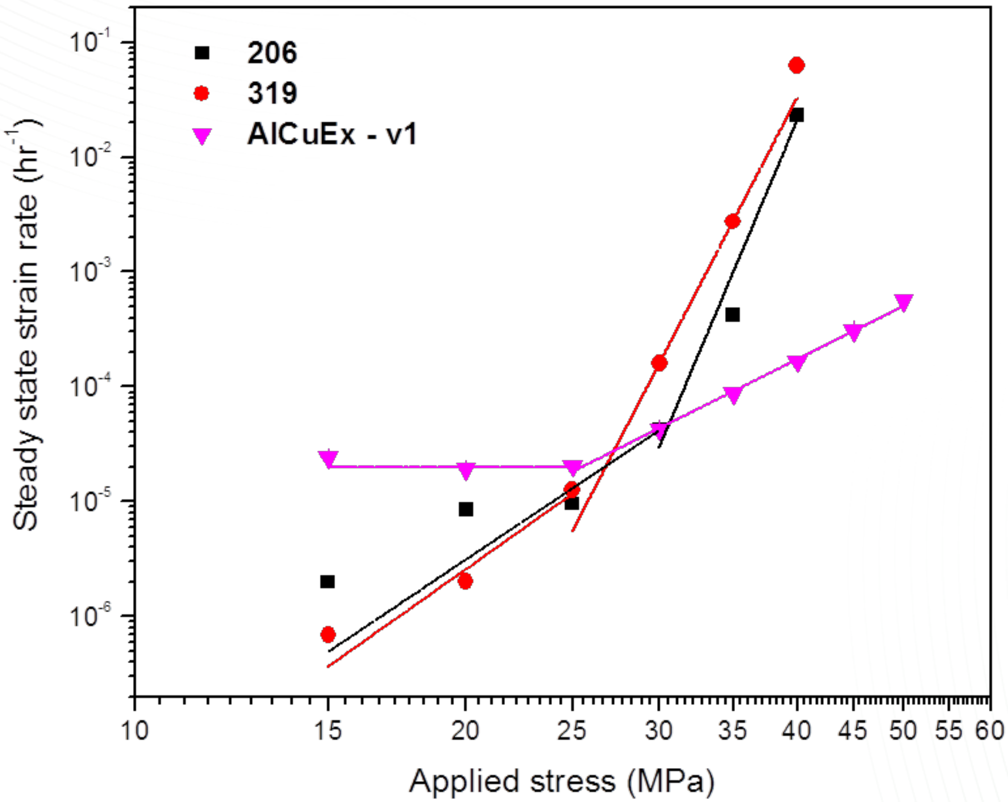
Technical Accomplishments

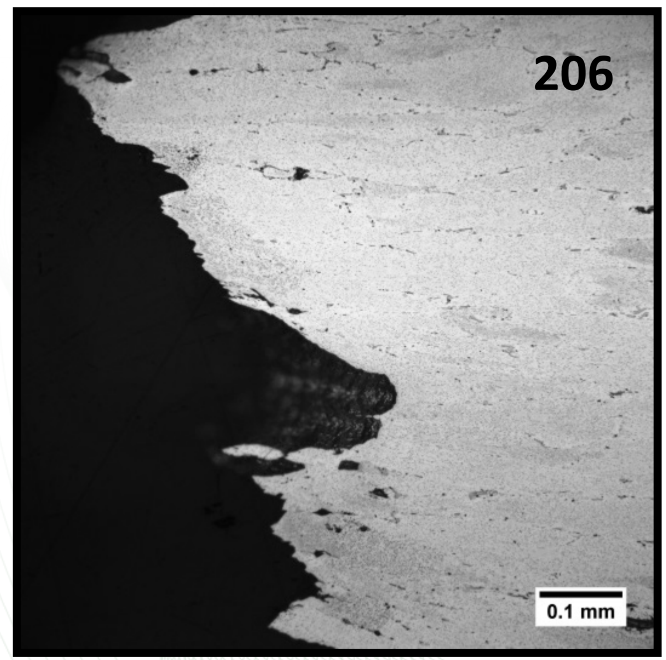
- High temperature properties remain exceptional due to the microstructural stability of the elevated temperature AlCuEx alloys
- 350°C properties exceed 300°C DOE target properties (350°C properties also measured after 200 hr exposure)



Technical Accomplishments

- Understanding creep mechanisms allows us to tailor creep resistance (already better than most Al-Sc alloys)





- Grain boundary deformation mechanisms kick-in once interior regions are strengthened

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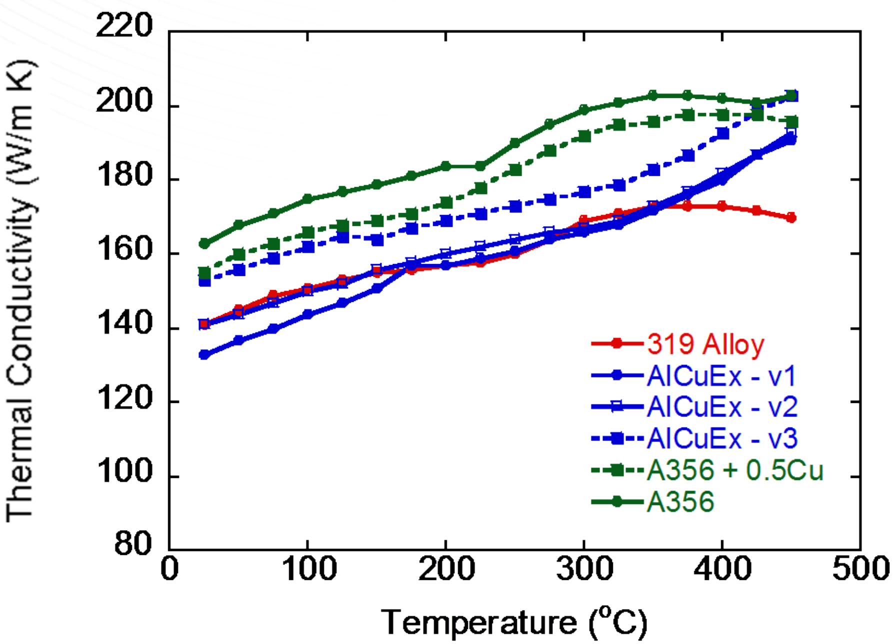
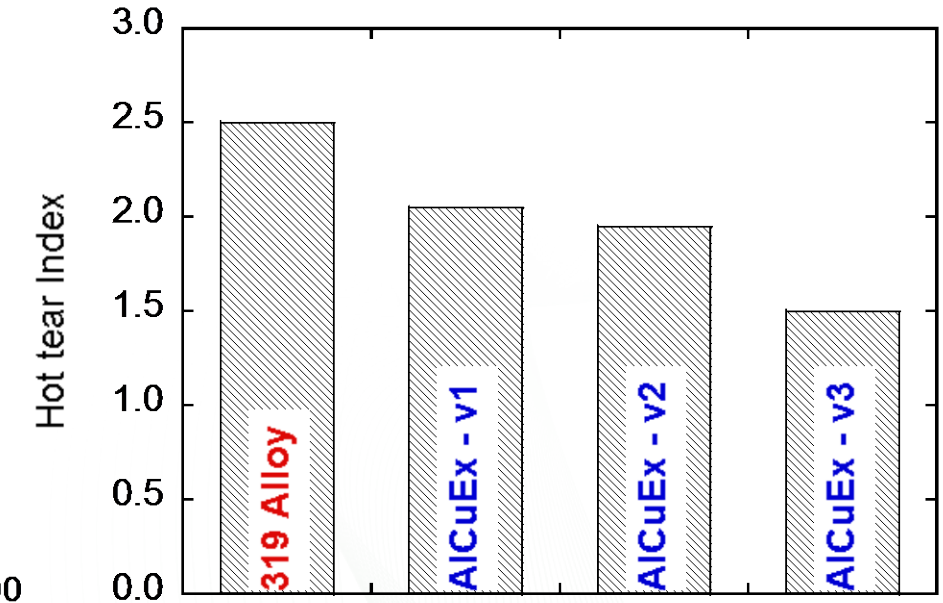
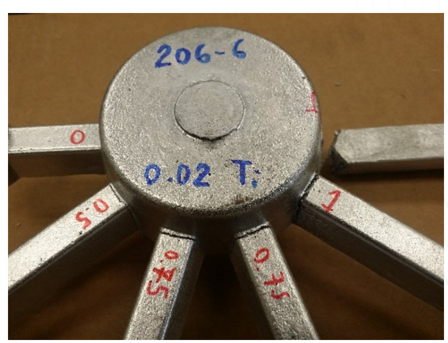
Technical Accomplishments

- Thermal conductivity and hot tear index are comparable or superior compared to 319 aluminum alloy
- Flexibility of alloy selection within alloy family



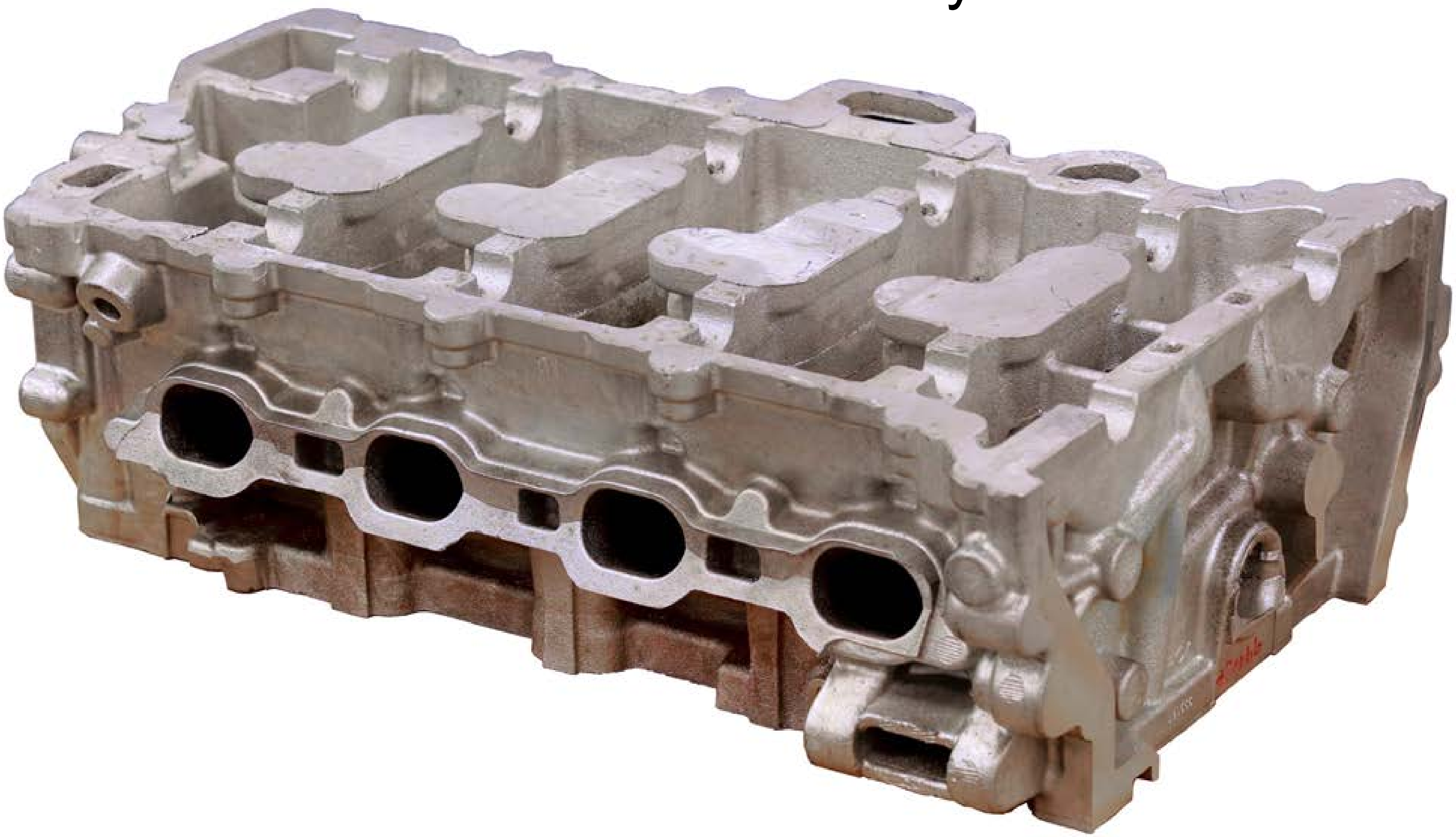




* Hot tear index – lower values are better

Technical Accomplishments

- Excellent hot tear resistance demonstrated on full scale components. Over 50 cylinder heads fabricated for casting trials to optimize process parameters. Cylinder head fabricated with AlCuEx-v3 alloy shown below.



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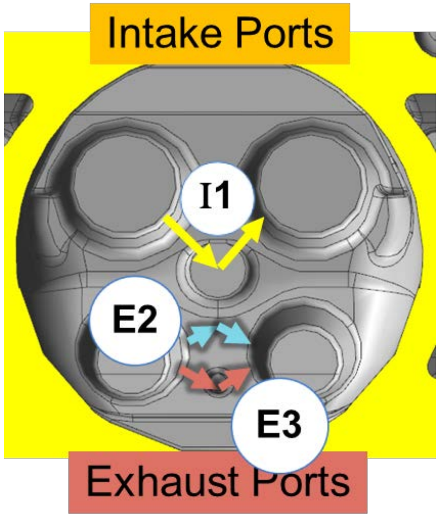
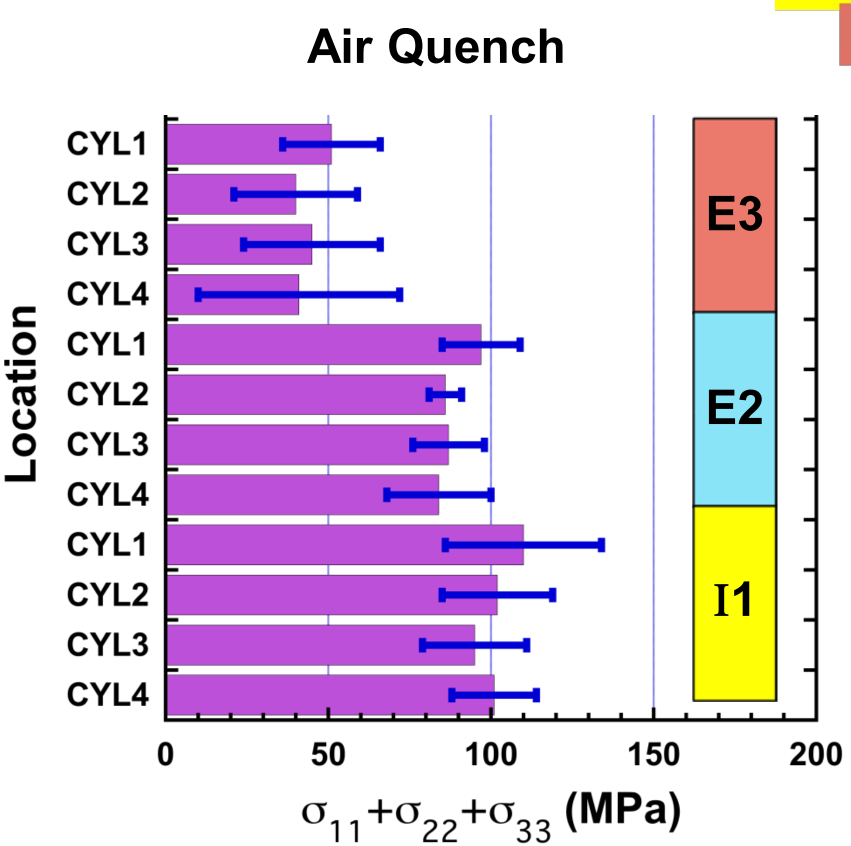
Technical Accomplishments

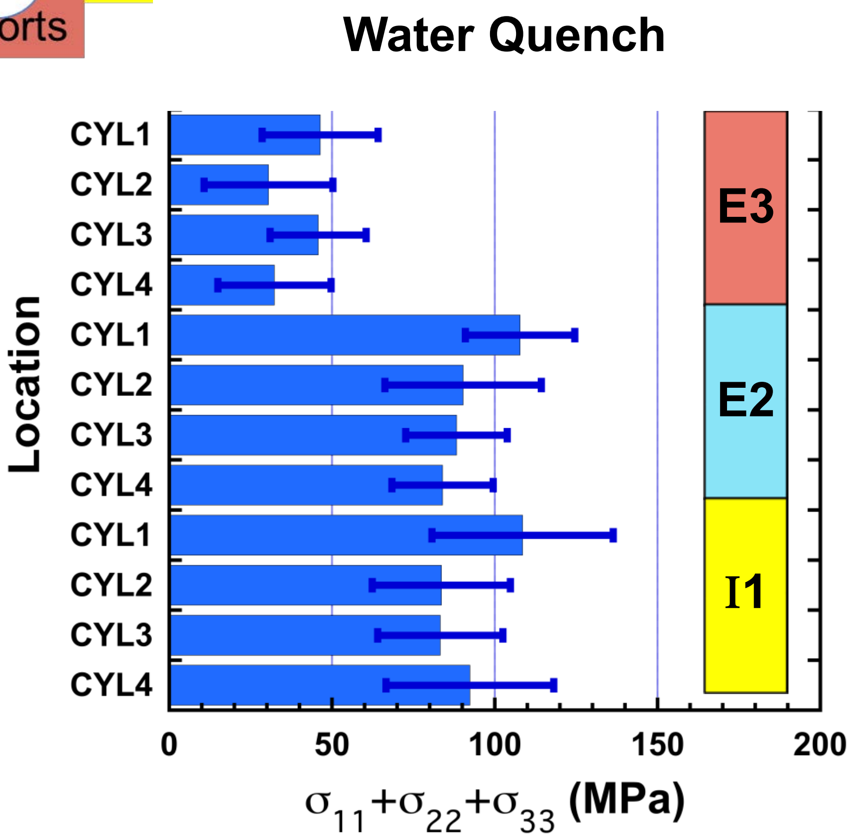
Average Residual stresses ($\sigma_{11}+\sigma_{22}+\sigma_{33}$) of paths=bridges in AlCuEx-v3 alloy cylinder head – Vulcan beamline at SNS - ORNL



TRENDS

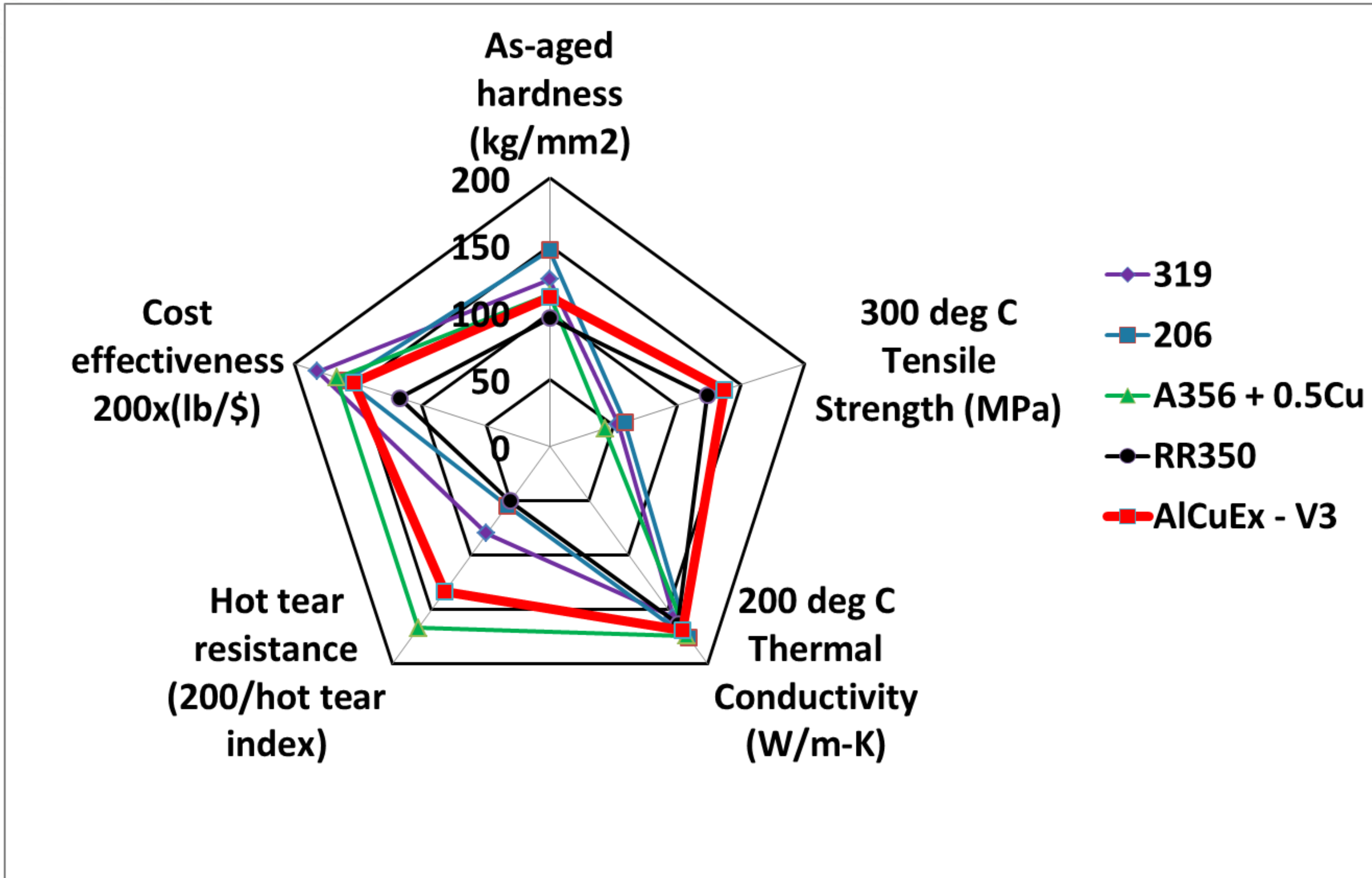
- Residual stresses in water and air quench very similar
- Residual stress less for path E3





Technical Accomplishments - Summary

- Comparison of AlCuEx alloys with commercial alloys indicates that the latter represent a ***superior new alloy family for elevated temperature automotive engine applications***



* Plot intended to show superior properties at greater values

Collaboration and co-ordination

- Weekly conference calls and biannual face-to-face all hands meeting
- *CRADA* partners with significant cost share
  - FCA US LLC - OEM automotive manufacturer
    - Provides technical guidance to the overall effort and leads tasks on Engine Testing, Thermomechanical fatigue evaluation, corrosion testing and machinability evaluation.
  - Nemak USA – Cylinder head supplier to FCA
    - Guides casting effort. Provides the cast specimen and cylinder heads to FCA and ORNL.
- Other partners
  - Granta MI – Data management partner
  - ESI North America, Flow Science, Magma Foundry Technologies – casting simulation software, Minco Inc – casting supplies
- Subcontractors
  - WPI – Hot tear evaluation
  - Element – Specimen preparation and some materials testing

Remaining challenges and barriers

- The technical targets have been achieved in several alloy variants. Developing cost model and commercialization plan are remaining activities.
- Cylinder heads can perform differently compared to laboratory scale castings. There are unknowns such as thermomechanical fatigue (TMF) response, corrosion resistance, machinability and engine testing response of alloy before the alloys can be commercialized.
- Several gaps exist in ICME models; for example those pertaining to microstructural evolution. These are barriers for future improvement of the alloy family and for cast aluminum alloys for engine applications, in general.

Future work

Cost Analysis

↓

Engine Testing (June ~ December 2017)

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Commercialization Plan

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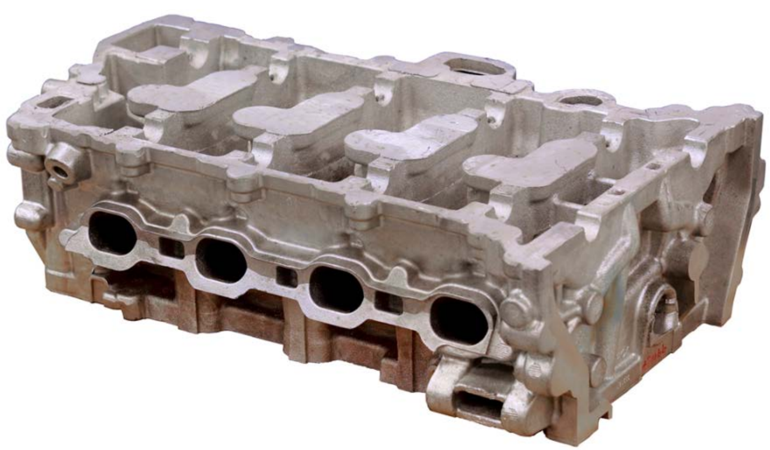
Commercialization of new Alloys (Beyond 2017)



- FY17 work (ongoing work led by industry partners)
  - Thermomechanical fatigue evaluation relevant for cylinder head application
  - Measurement of properties such as corrosion resistance and machinability
- FY17 future work
  - Industry partners will test new alloys on engine platform
  - Cost Analysis and Commercialization Plan
  - Publish gap analysis report
  - Alloy commercialization

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

Responses to Previous Year Reviewers' Comments

- All comments on Approach taken by our team were generally positive
- All reviewers appreciated the Technical Accomplishments of our team
- High level of Collaborations was also acknowledged by reviewers. One reviewer expressed slight concern for downselection of alloys since many choices were available and the cost analysis model was not complete
  - **Response:** Although cost analysis milestone is not due till FY17, our team has performed preliminary cost analysis to downselect the alloys for engine testing.
- Future work plans were appreciated by the reviewers. As one reviewer stated, "The reviewer enthusiastically looked forward to the results of the larger heats and component trials".
- Comments on petroleum displacement mission of DOE and availability of resources were also positive from the reviewers with no specific concerns relayed.

Summary

- **Relevance:** New alloys that can enable the development and implementation of higher efficiency passenger car engines.
- **Approach:** ICME approach used to accelerate the development of cast aluminum alloys. Partner with leaders in the area of Al castings and automotive engines.
- **Collaborations:** FCA, Nemak, WPI and smaller software cost-share partners
- **Technical Accomplishments:**
  - New higher temperature alloys developed that meet all technical criteria for the funding opportunity
  - Tensile properties exceed 300^{o}C targets by >2X.
  - Tensile property goals at 300^{o}C exceeded at 350^{o}C and alloys have stable microstructures up to 350^{o}C
  - >50 cylinder heads cast demonstrating the excellent hot tear resistance of new alloys at component scale
  - Pre-commercialization activities being completed
- **Future Work:**
  - Test new alloys on engine platform
  - ICME Gap Analysis; cost model and commercialization plan for new alloys

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