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High-Temperature Aluminum Alloys

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Project ID# PM044

Outline

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- Project Overview
- Relevance
- Milestones
- Technical Approach
- Results and Accomplishments
- Summary
- Publications/Presentations

Project Overview

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Project Timeline

- Start: May 2011 (CRADA)
- Finish: May 2014 (delayed because of subcontractor's equipment problem)

Budget

- Total project funding
  - DOE – $1,115K
    - FY11 Funding - $300K
    - FY12 Funding - $395K
    - FY13 Funding - $300K
    - FY14 Funding - $120K
- Cummins and commercial participants providing $1115K cost share as in-kind materials and effort

Barriers

- Lack of suitable aluminum alloys meeting elevated temperature strength and durability requirements for heavy duty diesel propulsion applications
- High temperature and high strength aluminum alloys that exist have been produced by expensive processing methods (high energy ball milling)
- Material processing requires scale-up and development of supplier base

Partners

- Cummins, Inc.
- Transmet Corporation

Relevance

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Objectives: Develop and demonstrate aluminum alloys having high temperature tensile and fatigue strengths that can facilitate applications in heavy duty diesel engine and air-handling components

- Aluminum alloys capable of higher elevated temperature strength and fatigue properties can increase performance and efficiency of heavy duty diesel engine components through lower weight and higher operating temperatures

- Cost-effective processing methods for producing rapidly solidified (RS) high temperature aluminum alloys will allow the materials to compete with more expensive titanium and nickel-based alloys in selected applications

- Previously developed high temperature aluminum alloys were processed by Mechanical Alloying which is too expensive for large-scale commercial applications

Approach/Strategy

- Evaluate candidate high temperature and high strength aluminum-based alloys processed using rapid solidification methods
- Establish cost-effective processing methods that can preserve the desired microstructure and properties through the consolidation and forming steps
- Evaluate the elevated temperature properties and performance of the selected alloys and optimize for engine and powertrain applications
- Compare the cost and performance of the high strength/high temperature aluminum alloys with competing materials (high temperature steels, nickel alloys, titanium)

Milestones – FY 2014

Complete engine or rig testing of high strength, high temperature aluminum propulsion component demonstrating Cummins required B10 service life.

Note: This milestone has been delayed. Transmet Corporation produced 500 lb. of RS aluminum flake, as required. However, the consolidation subcontractor experienced delays due to mechanical problems in the extrusion press. The problems have been resolved and extruded and forged material was delivered to PNNL in April, 2014. If the mechanical properties are favorable, forgings will be provided to Cummins for further evaluation.

Milestones – FY2014

Evaluate elevated temperature mechanical properties in commercially-produced components, with the goal of achieving elevated-temperature tensile strength of 300 MPa at 300°C

This milestone has been delayed due to mechanical problems associated with the consolidation process. The problems have been resolved and extruded and forged material was delivered to PNNL in April, 2014. Mechanical property tests are underway.

Task Plan

- Evaluate candidate high temperature RS aluminum alloys and select alloy systems for evaluation that meet Cummins strength and fatigue property goals
- Produce RS flake materials for selected alloy systems and consolidate/extrude to test rod configuration
- Evaluate elevated temperature tensile strength properties and microstructure to determine which can meet property requirements
- Down-select candidate high temperature aluminum alloys and scale-up flake processing and consolidation methods
- Demonstrate hot forging process step to produce suitable forged alloy preform
- Select component(s) for demonstration of RS flake and consolidation/extrusion forming process
- Perform full-scale engine component demonstration using optimized high temperature aluminum alloy

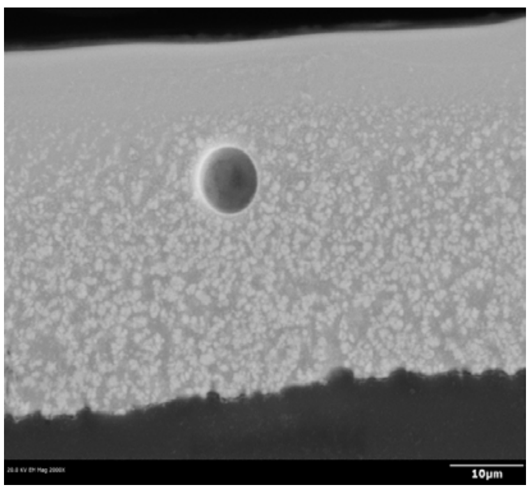
Nominal Compositions for Phase 2 High Strength Aluminum Alloys Prepared by Melt Spinning

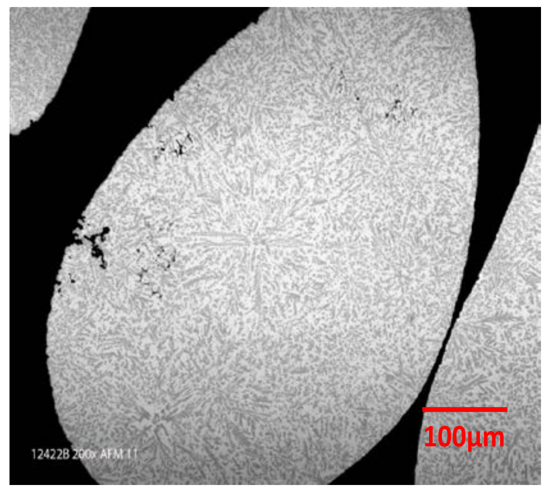
Alloy Designation	Fe (w/%)	Si	V	Ti/Cr	Mn
AL8.5Fe	8.5	1.7	1.3		
AL12Fe	12.4	2.3	1.2		
AFCT	5.8			3.3/3.6	
AFM - 11	11.4	1.8	1.6		0.9
AFM - 13	13.2	2.7	1.6		0.9

AFCT = Al-Fe-Cr/Ti AFM = Al-Fe-Mn

Evaluation of Melt Spinning vs. Spin Casting Technologies

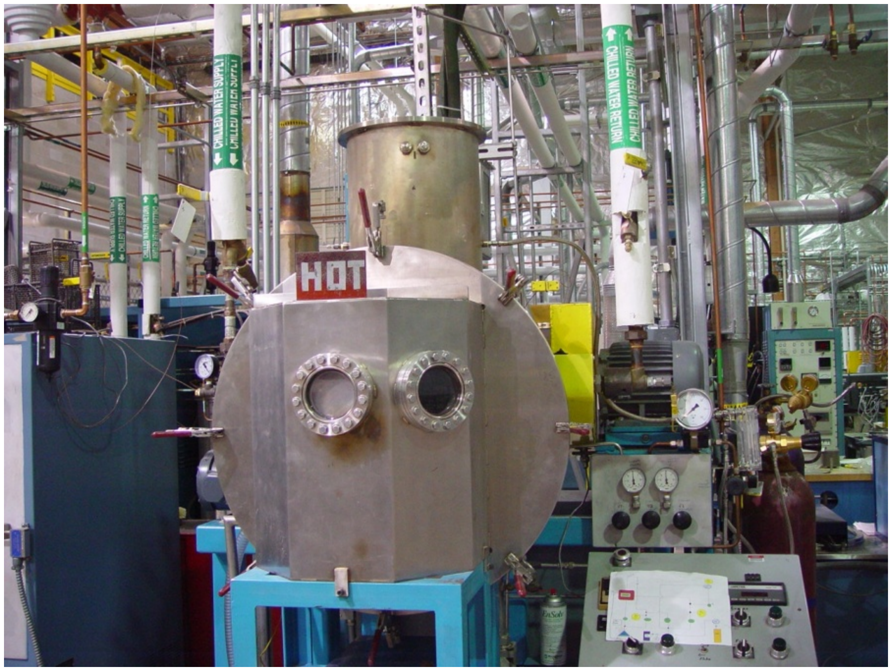
- The two methods have solidification rates that differ by several orders of magnitude; 10^6 ǺC/s for RS flake, and 10^2 ǺC/s for rotating cup process.
- The rotating cup RS method was being evaluated, in spite of the lower solidification rate, because it is established as one of the high-volume RS processes, and because the shot particulate has some advantages in handling and consolidation. The rotating cup process resulted in coarser grain size. Extrusions made from AFM-11 shot have lower strength and ductility than those made from AFM-11 flake.

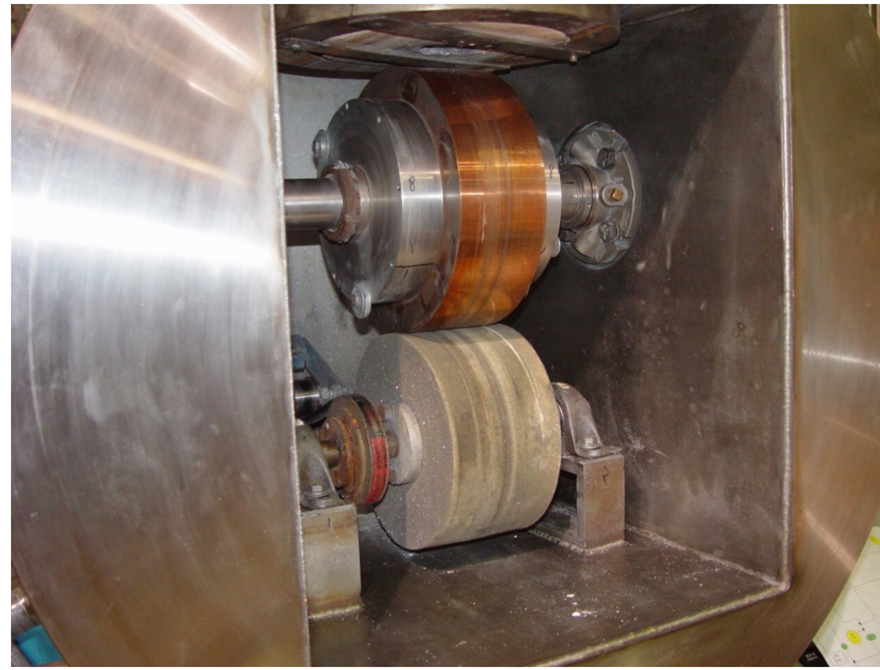




As-received AFM-11 RS flake, left, and AFM-11 rotating cup shot (right), with coarser grain size.

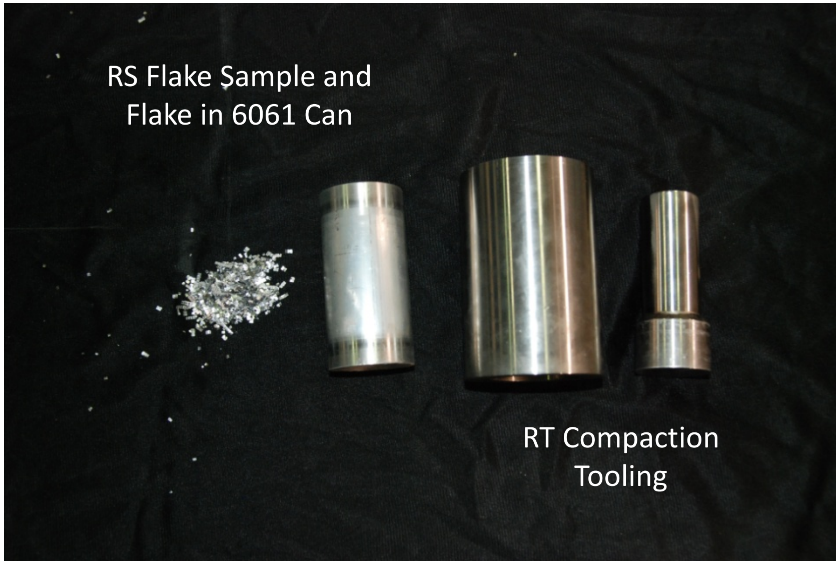
PNNL Rapid Solidification Flake Melt Spinning Machine





Melt spinning flake machine with controlled atmosphere chamber closed (left) and open (right)

Rapidly Solidified Flake & Cold Compaction



Melt spun rapidly solidified Al-8.5Fe alloy flake

Room temperature compaction tooling with sample of RS flake and flake compacted in a 6061 aluminum can for extrusion or vacuum hot pressing

Technical Accomplishments and Progress – Alloy Processing

- Completed melt spinning flake runs for the Al-8.5Fe, Al-12Fe, AFCT Alloy, AFM – 11 and AFM-13 alloys during Phase 2.
- Evaluated rotating cup vs melt spinning methods, and found that both strength and ductility were higher for extrusions made of RS flake.
- Melt spinning sufficient flake for extrusion of 3 billets each of the Al-8.5Fe, Al-12Fe alloys, and 2 each of AFCT and AFM alloys.
- Due to high temperature strength of the alloys, Al-12Fe and AFM-13 billets exceeded the load capacity of the extrusion equipment and did not extrude.
- Commercial source for commercial-scale melt spinning of materials was identified (Transmet Corporation).
- Transmet produced ~500 pounds of RS flake, and subcontracted the consolidation work (canning, extrusion, and forging). Forgings were delivered to PNNL in April, 2014.

PNNL Extrusion and Consolidation Tooling

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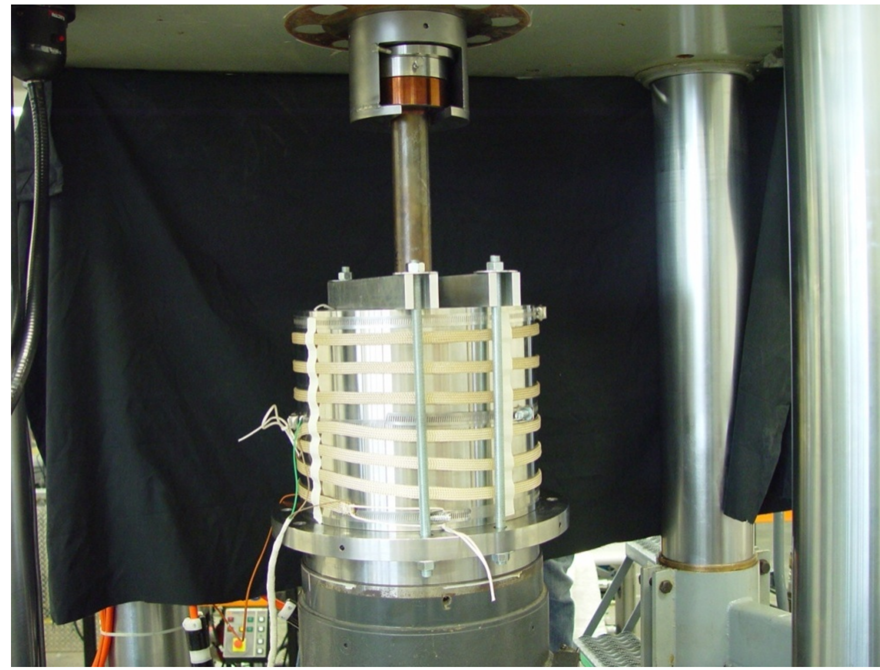
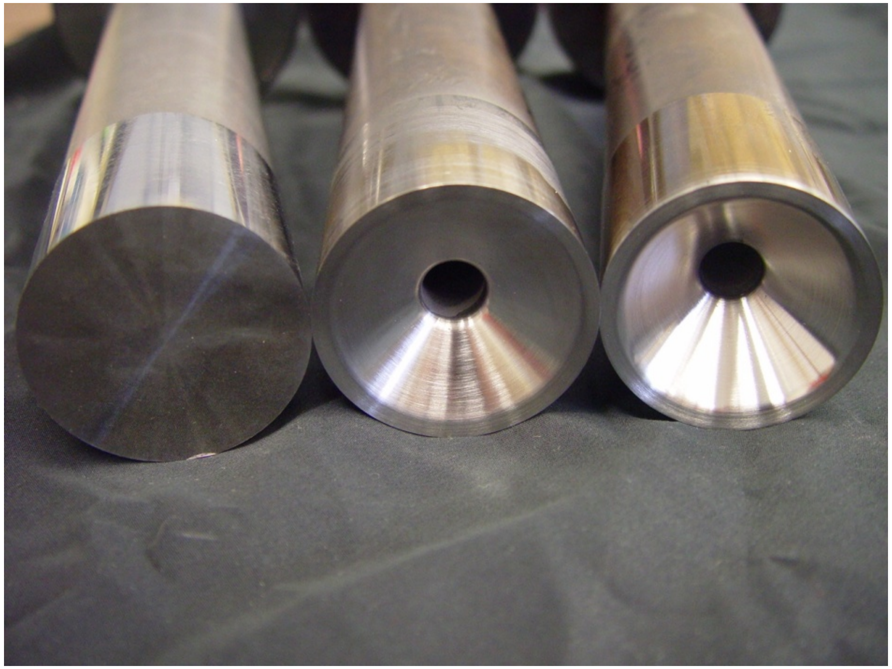
Four-post MTS 500,000-lb.load frame shown with extrusion tooling



Extrusion die/container with external heating in 4-post 500,000-lb.load frame. Shown with indirect extrusion stem

PNNL Extrusion and Consolidation Tooling



Extrusion stems for indirect extrusion, showing (left to right) spare blank, 30° and 45° dies

Phase 2 Metallography of Extruded Alloys

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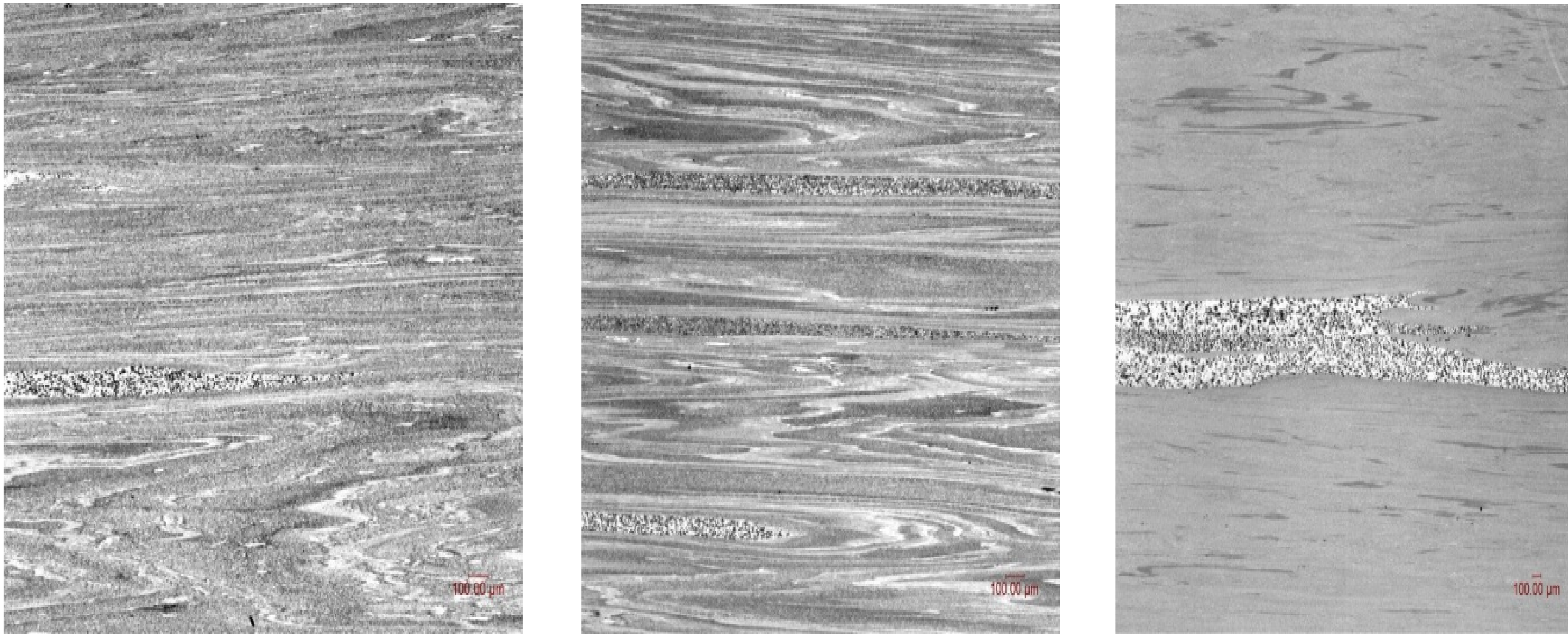


a b c

Longitudinal metallography of extruded a) Al-8.5Fe, b) AFN-11 and c) AFCT aluminum alloys showing lamellar structure with regions of larger intermetallics

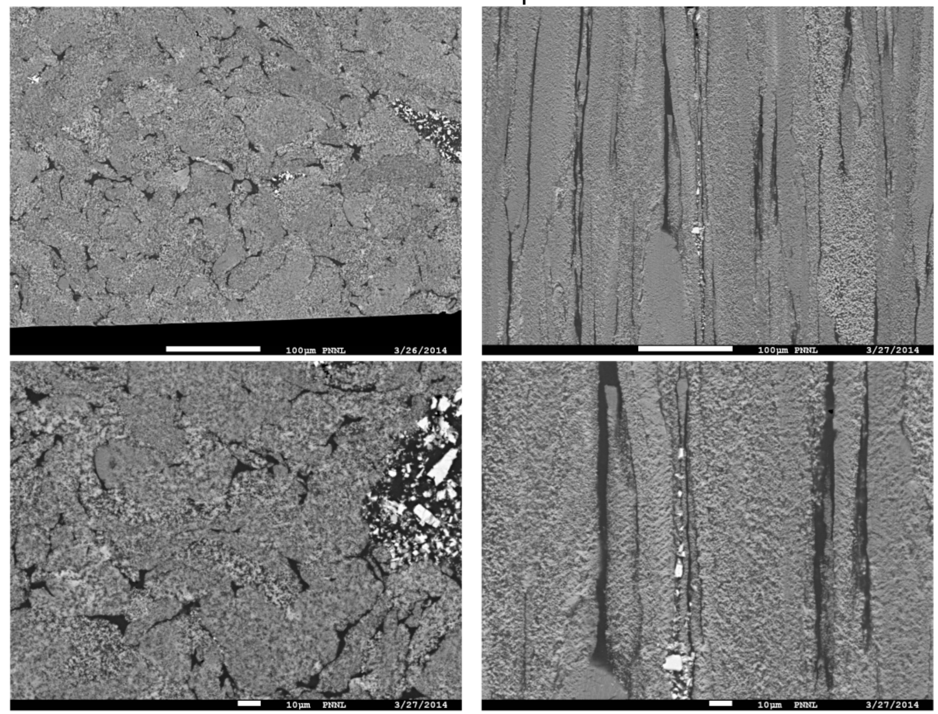
Metallography of Small-Scale and Large-Scale Extrusions

Longitudinal metallography of a) lab-scale (0.5-in.) AFM-11 extrusion and b) larger-scale (3.25-in.) AFM-11 extrusion showing lamellar structure with regions of larger intermetallics. The intermetallics are finer in the larger extrusion.

Microstructural Analysis of AFM-11 Extrusion

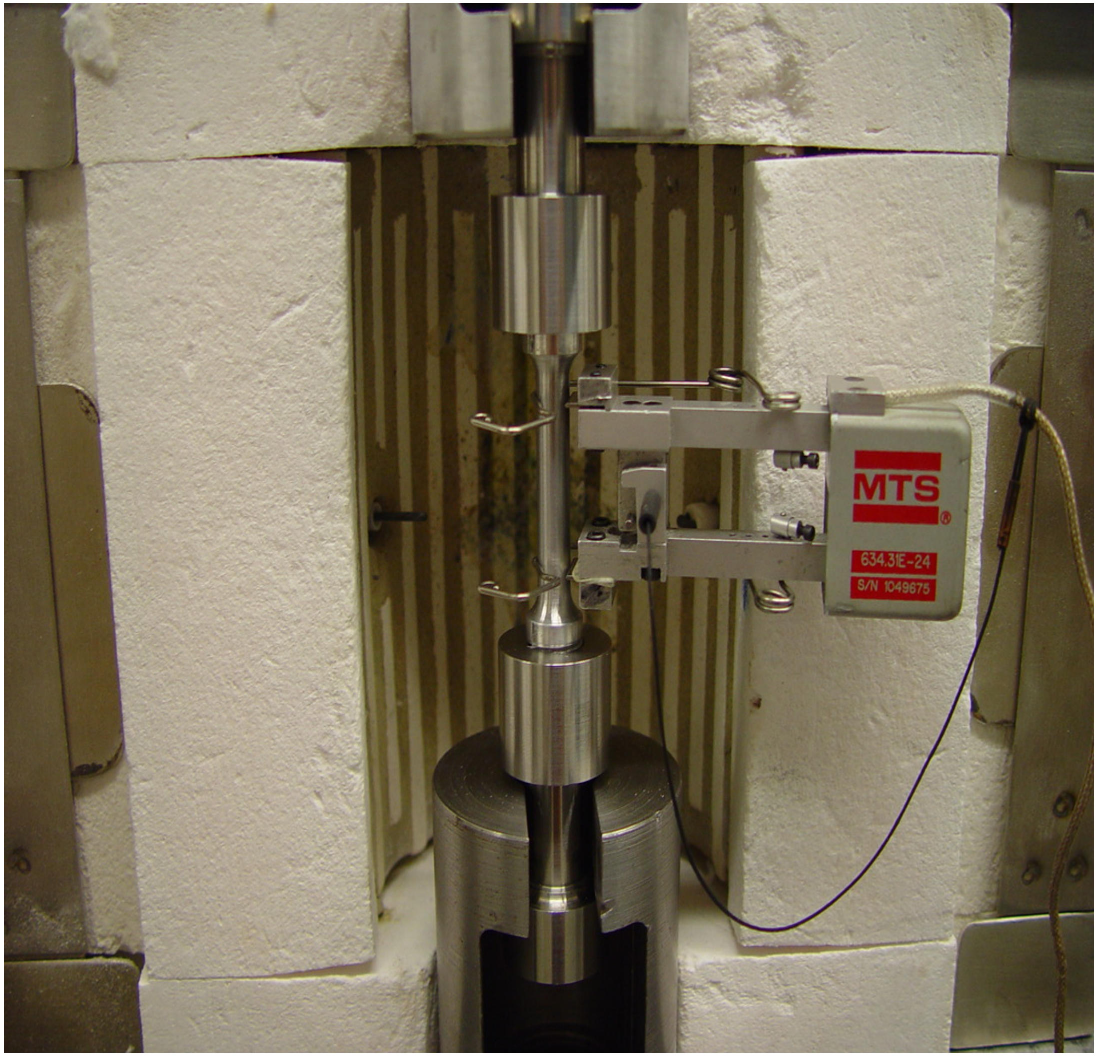
- Backscatter imaging showed a microstructure which had significant compositional variation in the form of Al-rich veins across the entire structure. Bright regions are Fe-rich and dark areas are Al-rich.

Parallel to Extrusion Direction | Perpendicular to Extrusion Direction



EBSD mapping showed that the Al rich regions exhibited a larger grain size than the surrounding matrix material. Additionally, the entire sample (both matrix and Al-rich veins) showed a preferential (111) orientation in the extrusion direction.

Tensile Test Set-up for Flake Extrusion



Room Temperature Tensile Test with Extensometer
(Note: Extensometer not used for elevated temp. tests)

Tensile Test Results for Phase 2 Flake Extrusion – Room Temperature

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Specimen Group ID	Extrusion Temperature (C)	Elastic Modulus (GPa)	Tensile YS Strength MPa	Tensile Strength (UTS) MPa	Strain at Failure, %
Al-8.5Fe	450	83.5	345	390.4	19.1
Al-8.5Fe	500	84.2	331.2	389.4	18.0
AFCT-1	500	95.9	400.2	448.6	12.2
AFM-11	500	95.9	427.8	493.6	7.2

Tensile Test Results for Phase 2 Flake Extrusion – 300 C

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Specimen Group ID	Extrusion Temperature (C)	Tensile YS Strength MPa	Tensile Strength (UTS) MPa	Failure Strain (extension) %
Al-8.5Fe	450	(1)	210.9	25.1
Al-8.5Fe	500	(1)	208.2	21.7
AFCT-1	500	(1)	226.7	18.8
AFM-11	500	(1)	256.8	17.0

Note(1): Yield stress and tensile stress consider equal at 300 C test temperature

Technical Accomplishments and Progress- Phase 2 Flake Extrusion

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- Tensile tests completed for RT and 300℃ for three Phase 2 alloys that were extruded (Al-12Fe and AFM-13 could not be extruded), with results showing improved strength at RT and 300°C.
- Completed metallography on the Phase 2 extruded materials.
- Metallography shows evidence of a coarser phase along with very fine sub-micron intermetallics. The coarser phase is believed to be from melt splats or flake that did not see as high a cooling rate.
- Vacuum hot pressing was used to pre-consolidate the extrusion billets. In commercial practice an extrusion upset step followed by direct extrusion could replace the hot press step.
- Although the Phase 2 300℃ tensile strengths did not reach 300 MPa, strength levels are attractive for potential Cummins applications.
- The AFM-11 alloy was selected for the next phase of scale-up; the processing of 500 lb. of RS flake using Transmet commercial flake melt spinner, followed by extrusion and forging to produce ~6-in. diameter disks.

HS/HT Aluminum Task Plan

Task Plan

- Completed visit to Transmet to discuss approaches for larger-scale flake melt spinning runs (Completed)
- Can, consolidate and extrude 2-3 billets of each alloy and characterize properties and microstructure (Completed)
- Contract with Transmet to process 500 lb. (net) of AFM-11 RS flake and consolidate and extrude to nominal 75 mm diameter rod (contract placed February 2013)
- Cummins to identify heavy duty engine component for prototype development and engine testing (Completed)
- Initiate cost analysis of RS flake- extrusion and forging process for commercial scale material production (Completed)
- Complete processing and machining of engine components manufactured from AFM-11 extruded material and initiate engine/component testing process (Delayed)
- Develop elevated temperature high-cycle fatigue data for commercial-scale RS flake materials (Delayed)

Summary and Conclusions

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- CRADA Project with Cummins, Inc., initiated May, 2011
- Second phase of the project focused on evaluation of candidate aluminum alloys with potential to meet 300 MPa strength at 300℃
- Rapidly solidified Al-Fe alloys have been successfully melt spun and flake materials characterized – properties of RS flake materials approaching properties of previous MA materials
- Phase 2 laboratory-scale consolidation and extrusion of 3 Al-Fe alloys has been completed and the AFM-11 alloy down selected for scale-up processing
- A commercial RS flake producer (Transmet Corp.) has been engaged in the scale-up phase to produce 500 lb. of RS flake and convert to 75 mm diameter extruded product
- Cost analysis of a commercial-scale RS flake/extrusion process has been initiated by Cummins and PNNL, and will use input from Transmet and aluminum producers
- A heavy duty diesel engine component has been selected, and material processed by Transmet will be used to manufacture prototype components and to develop a high temperature fatigue data base for the AFM-11 Al-Fe-Mn alloy

Collaboration

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- Cummins, Inc. - principal industry partner, CRADA partner
- Transmet Corporation - commercial melt spinning and processing of rapidly solidified flake and particulate
- Kaiser Aluminum – Potential consolidation and extrusion services and input to commercial-scale cost analysis