Project No. 18518, Agreement No. 24034

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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

Budget

- Total project funding
  - DOE – $1,115K
    - FY11 Funding - $300K
    - FY12 Funding - $395K
    - FY13 Funding - $420K
- 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
- Producer/Processing Company

Relevance

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 high temperature aluminum alloys will allow the materials to compete with more expensive titanium and nickel-based alloys in selected applications
  - Previously developed alloys were processed by Mechanical Alloying.

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 – FY2012

Demonstrate that the rapidly solidified Al-Fe alloy consolidated by extrusion has a yield strength in excess of 300 MPa at 300°C. (Due 8/22/2012)

Note: This milestone is on track.

Initial testing of Al-8Fe-Si-V alloy has demonstrated 300°C yield strength of >225 MPa, which compares favorably with Allied Signal alloy results.

Higher Fe content and optimized processing should produce material with target 300 MPa yield strength.

Task Plan

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- Evaluate candidate high temperature rapidly solidified (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 and fatigue properties 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 High Strength Aluminum Alloys Prepared by Melt Spinning

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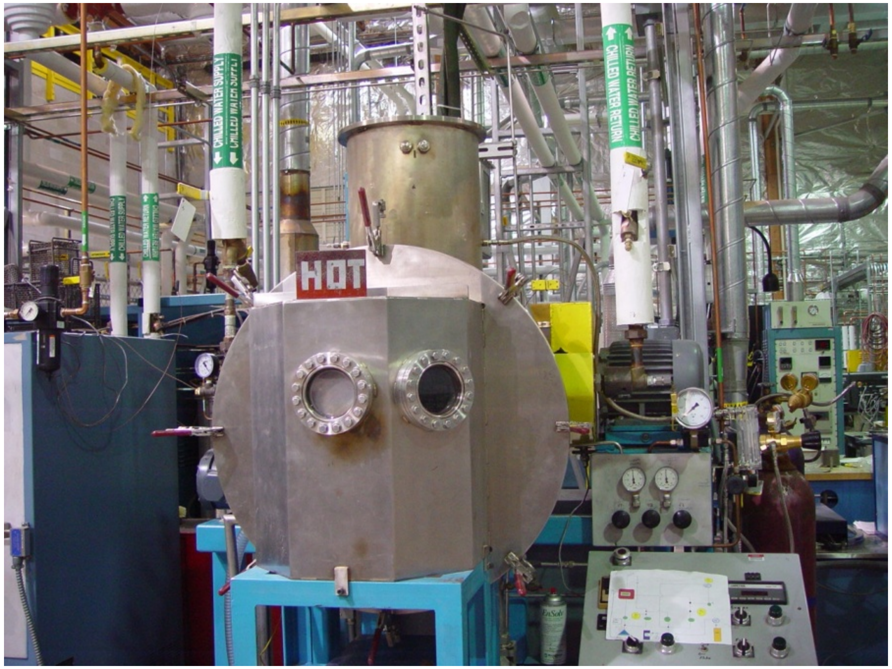
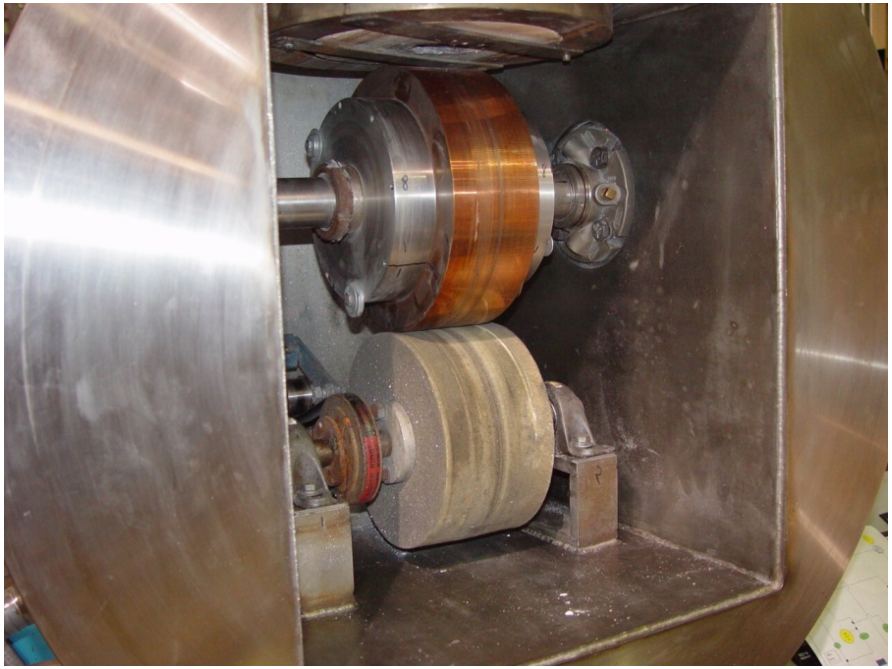
Alloy Designation	Fe (w/%)	Si	V	Ti/Cr	Mn
AL8Fe	8.5	1.7	1.3		
AL12Fe	12.4	2.3	1.2		
UConn	5.8			3.3/3.6	
AFM	11.4	1.77	1.63		0.9

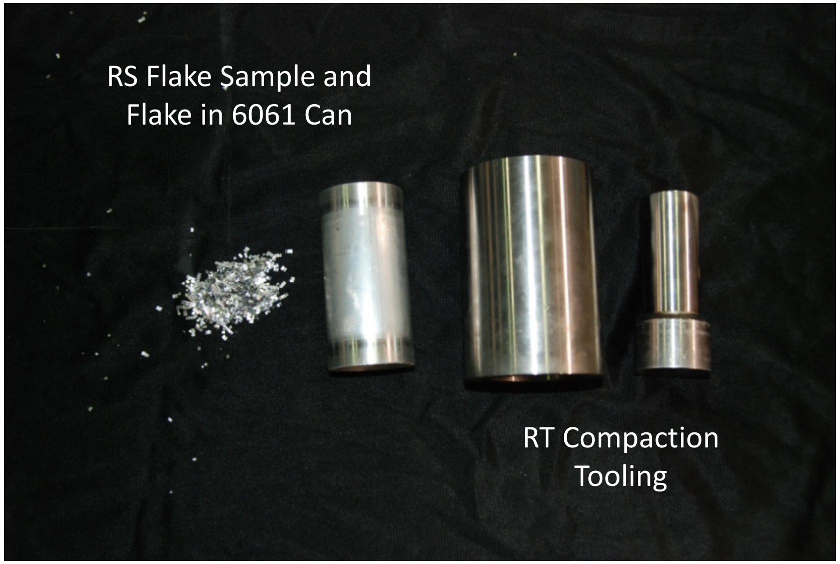
PNNL Rapid Solidification Flake Melt Spinning Machine





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 hot pressing

Metallography of Al-8Fe flakes exposed to elevated temperatures for 3 hours

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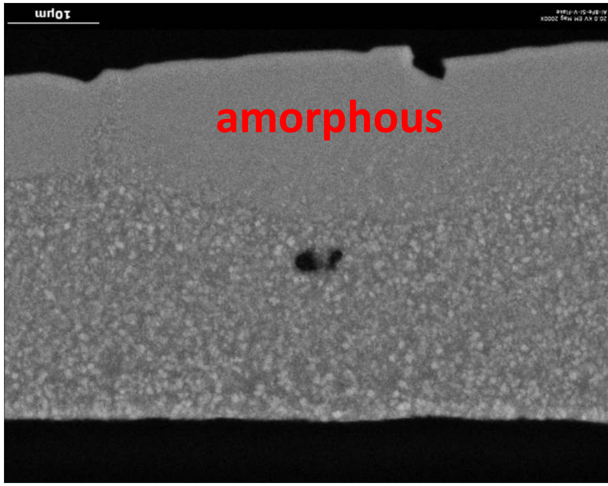
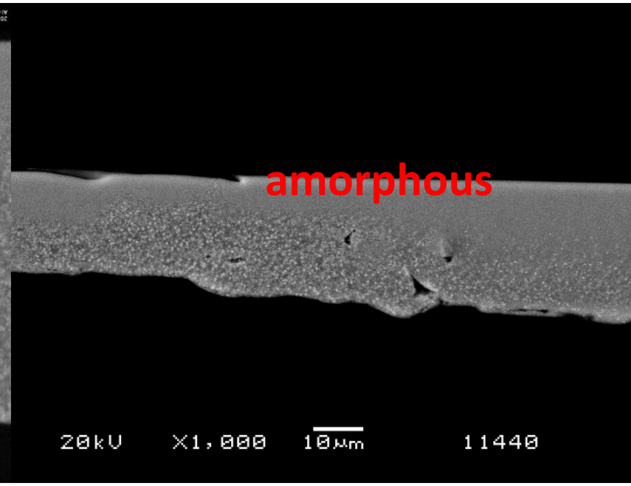
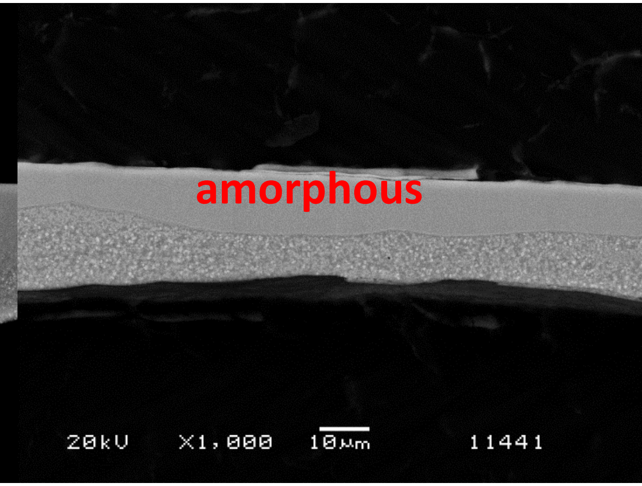


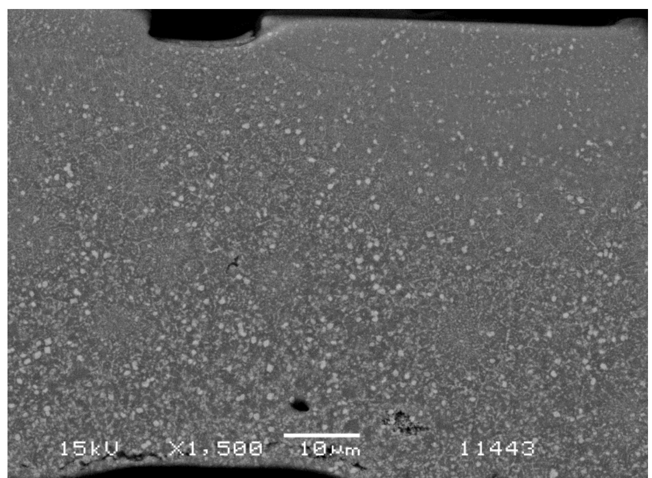
As Melt Spun



350°C



400°C



500°C

Note: Magnification is the same for all samples – thickness of flake varies

Technical Accomplishments and Progress – Alloy Processing

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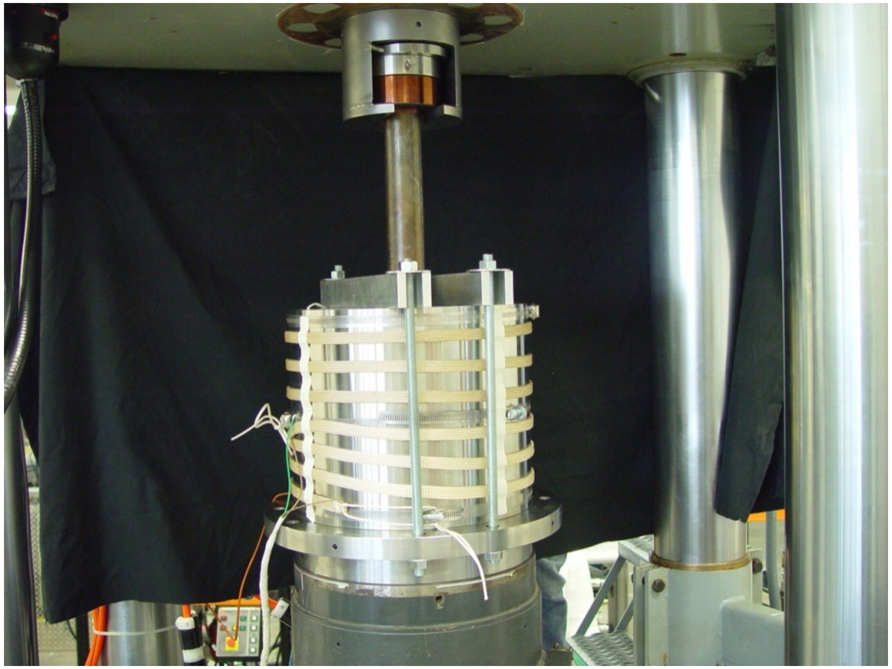
- Completed melt spinning flake runs for the Allied Signal Al-8%Fe, Al-12%Fe alloys, and the University Of Connecticut Alloy (Al-Fe-Cr-Ti)
- Developed new Al-Fe-V-Mn alloy (AFM) and melt spun flake
- Melt spinning sufficient flake for extrusion of 3 billets each of the Al-8%Fe, Al-12%Fe alloys, and 2 each of UConn and AFM alloys
- Have developed melt spinning parameters for higher melting point Al-Fe alloys which results in >90% yields
- Commercial source for commercial-scale melt spinning of materials has been identified (Transmet Corporation)

PNNL Extrusion and Consolidation Tooling

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

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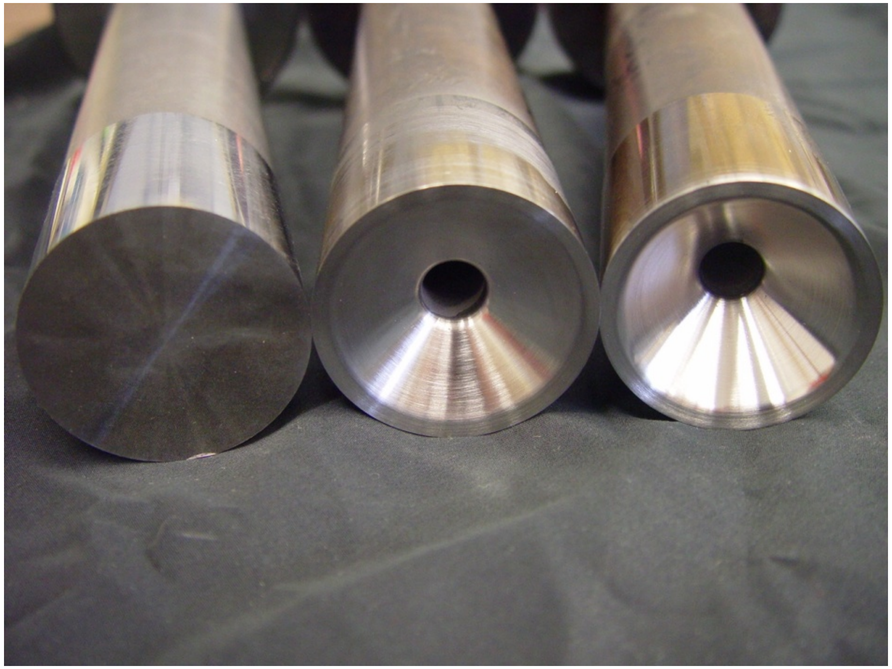

Extrusion stems for indirect extrusion, showing (left to right) spare blank, 30° and 45° dies

Extrusion Billets

Extrusion billets showing partially extruded 6061 (left), canned billet of 6061 flake (center) and canned billet of Al-8.5%Fe-Si-V alloy flake (right)

Extrusion Billet and Extruded Rod Samples

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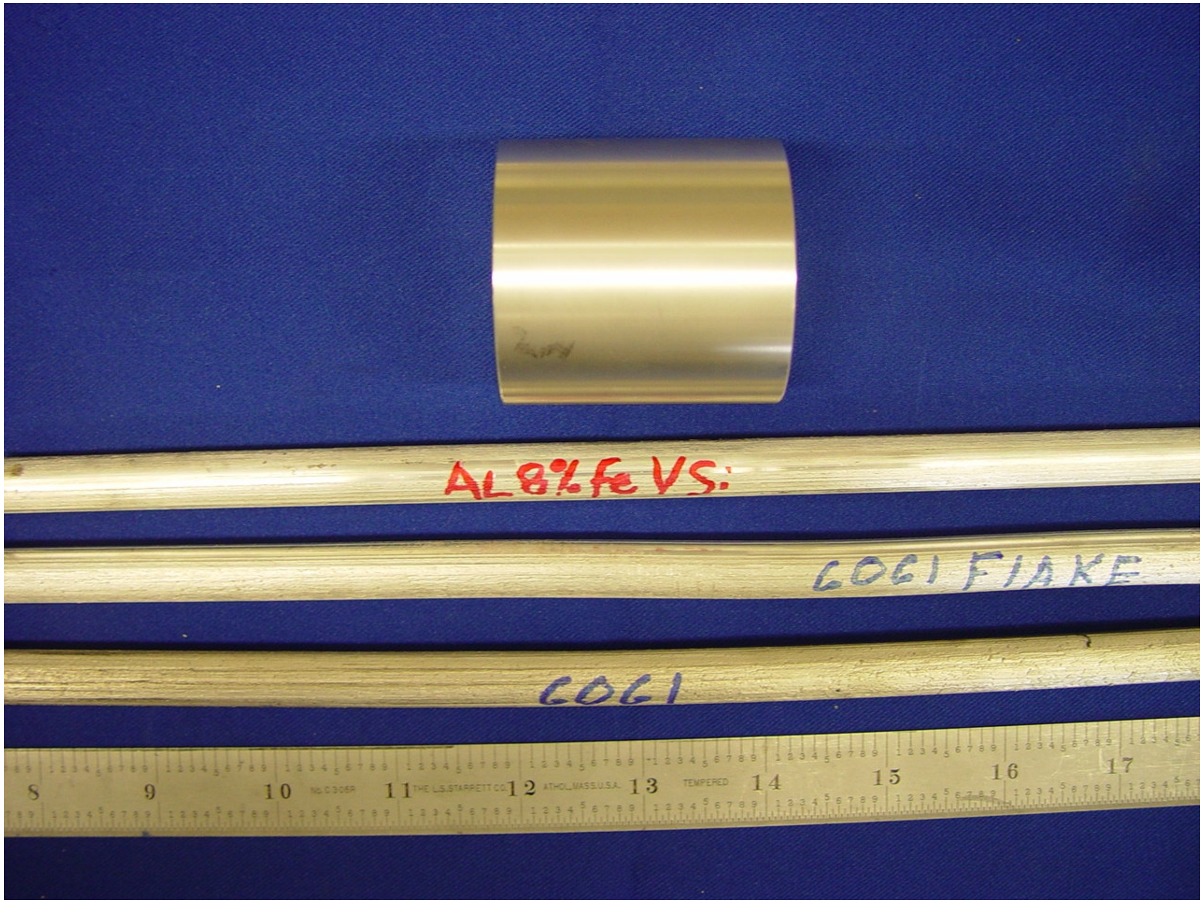
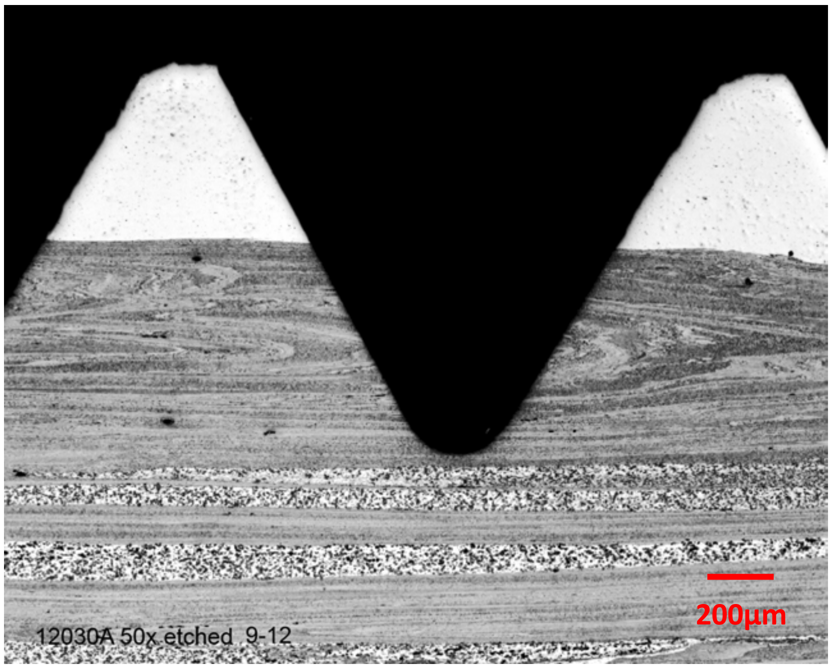
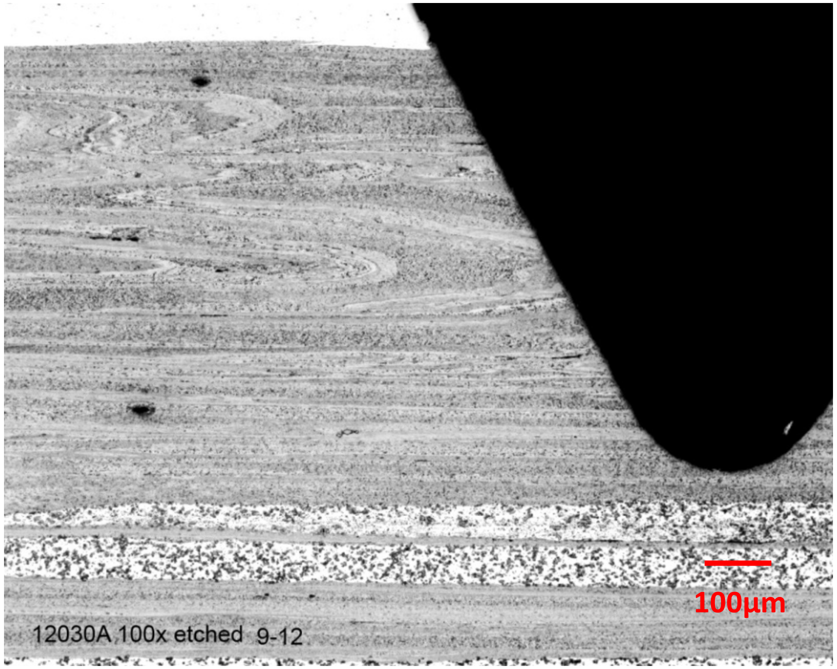


Extrusion billet (top, 50 mm diameter) shown with extruded rods of 6061 and Al-8Fe aluminum (11 mm diameter). Extrusion ratio of approximately 20:1

Metallography of Al-8%Fe Extrusion

Section 9-12 Longitudinal



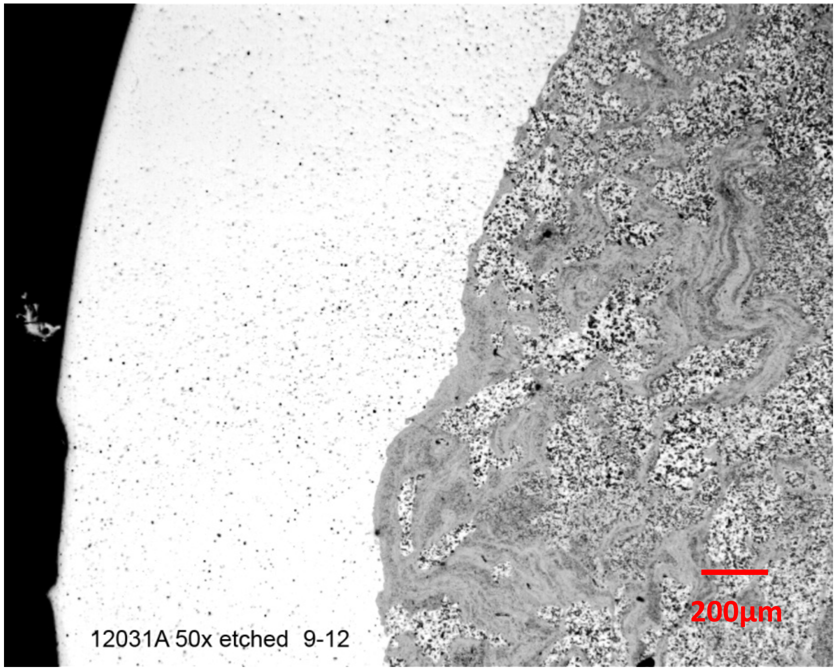


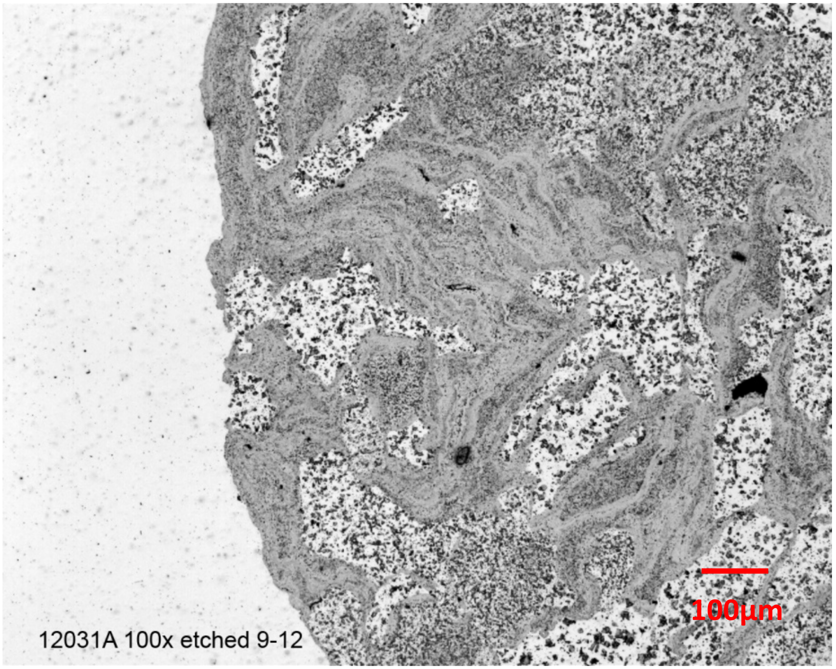
Longitudinal metallography of extrude Al-8Fe showing lamellar structure with regions of larger intermetallics

Note: White-colored material at tip of specimen thread is 6061can material

Metallography of Al-8%Fe Extrusion

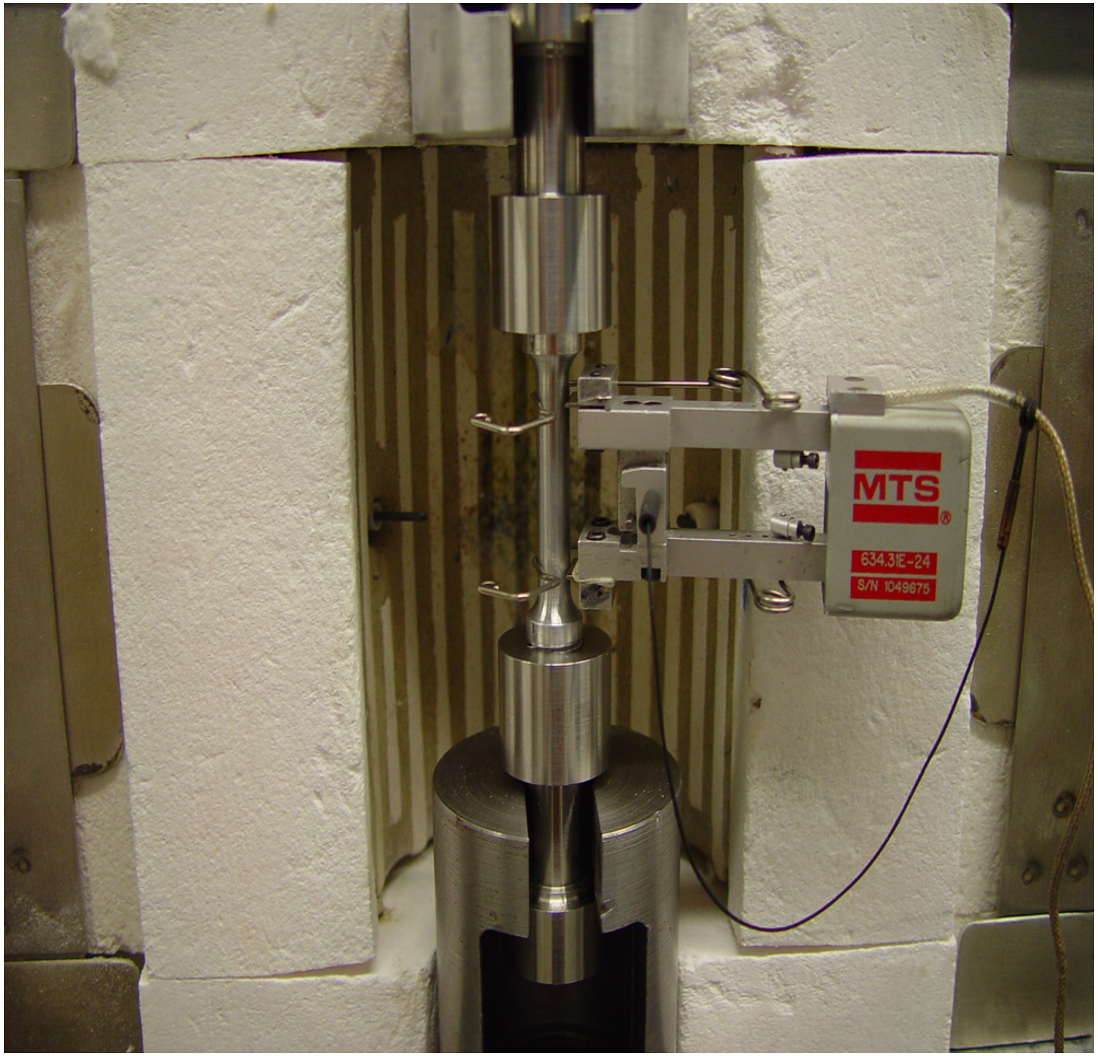
Section 9-12 Transverse





Transverse metallography showing interspersed regions of coarser intermetallics and porosity

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 Flake Extrusion Al8Fe-1 – Room Temp. Data

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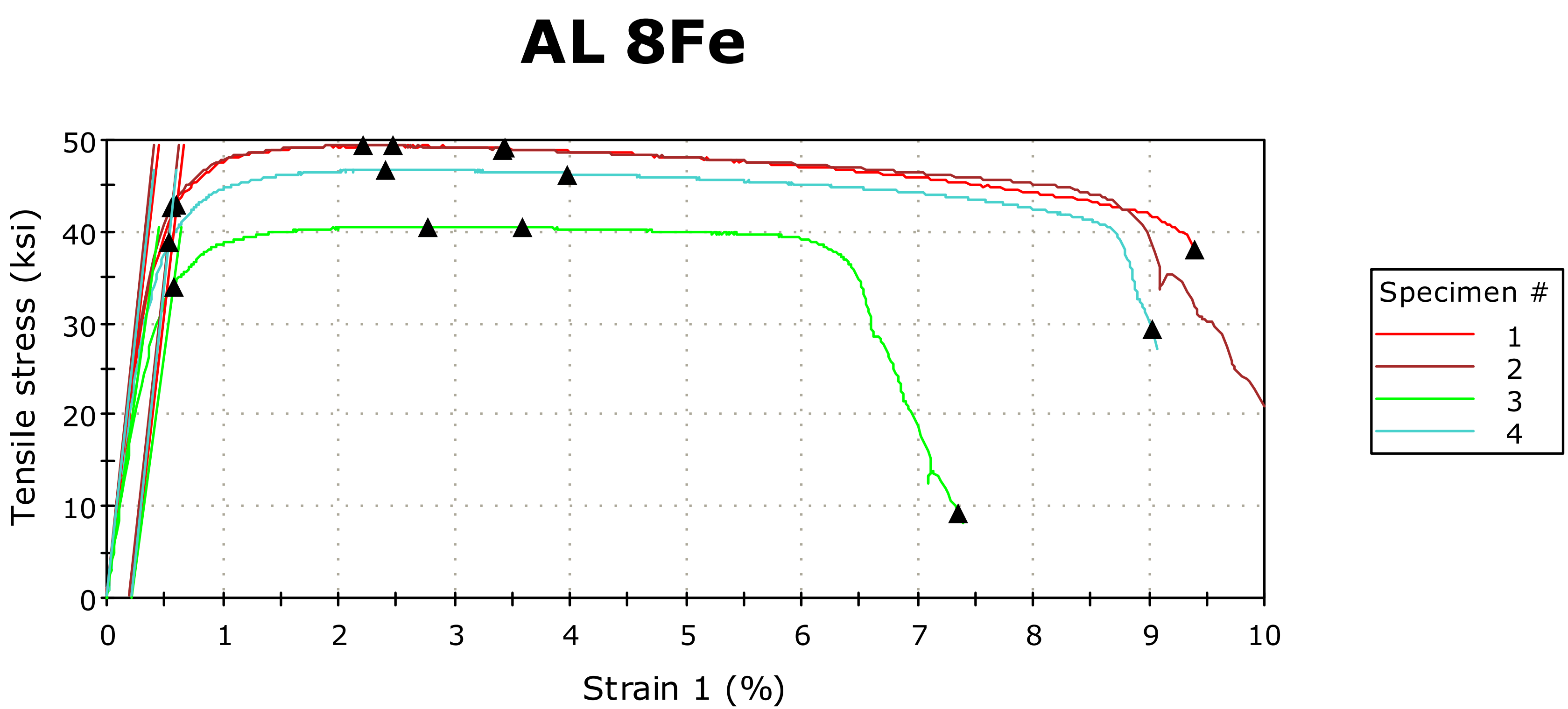

Note: Tensile specimens were taken from different sections of the extruded rod

Tensile Test Results for Flake Extrusion Al8Fe-1 @ 300°C

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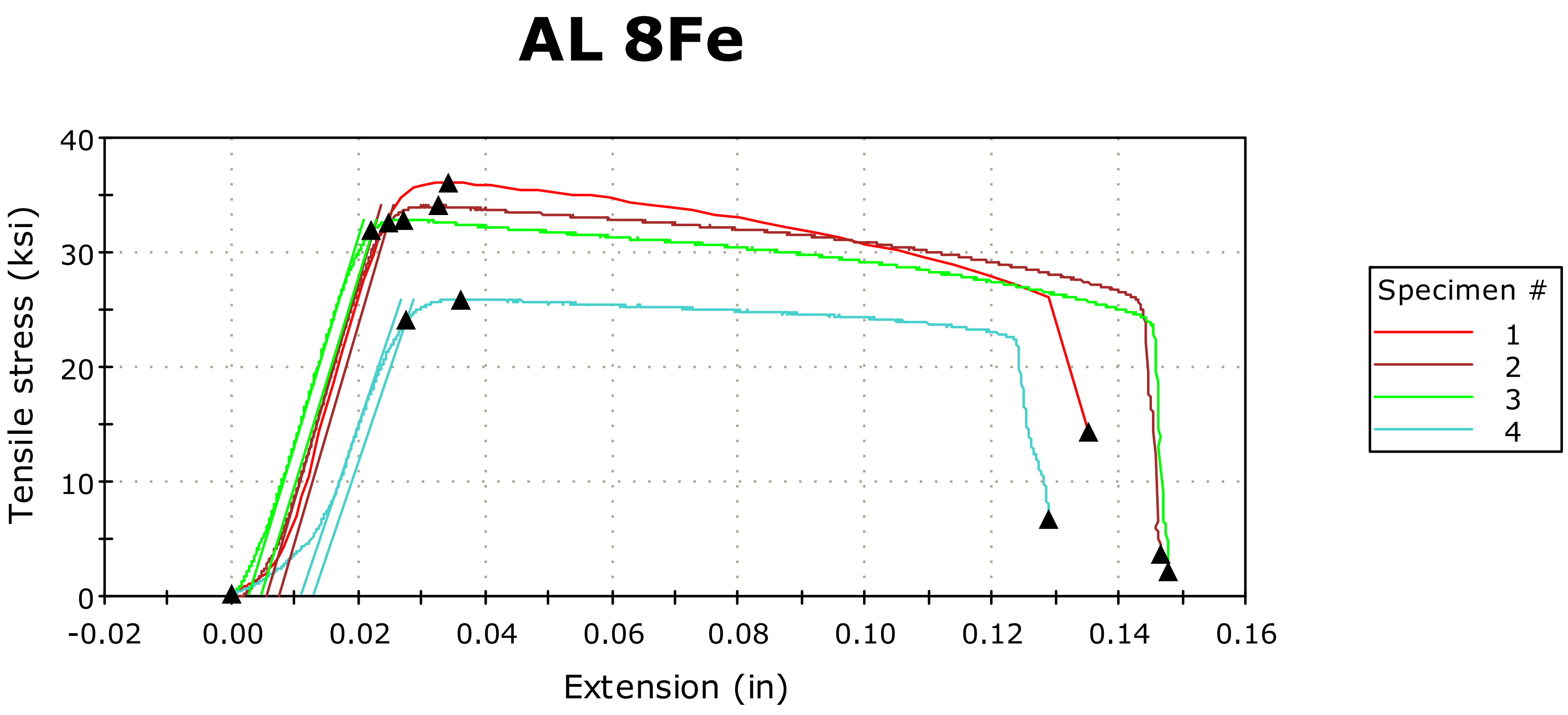

Tensile Test Results for Flake Extrusion Al8Fe-1

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Specimen Group ID	Test Temperature (C)	Tensile YS Strength MPa (ksi)	Tensile Strength (UTS) MPa (ksi)	Failure Strain (extension) %
Al8Fe-RT (avg. 3 specimens)	Room Temp. 23 C	294.3 (42.6)	340.9 (49.4)	9.92
Al8Fe-300 (avg. 3 specimens)	300 C	226.3 (32.8)	237.0 (34.3)	12.27
Allied Signal Published (FVS0812)	Room Temp. 23 C	390 (56.6)	437 (63.4)	10
Allied Signal Published (FVS0812)	315 C	244 (35.4)	261 (37.8)	9

Note: AS FVS0812 is nominal 8.5 Fe. Al8Fe-1 nominal 8.0Fe

Technical Accomplishments and Progress- Al-8%Fe Flake Extrusion

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- Tensile tests completed for RT and 300 C, with results showing lower than expected RT strength, but very good 300 C strength
- Alloy composition of the Al-8%Fe below 8 w/o Fe (Allied target 8.5%Fe)
- Completed metallography on the Al-8%Fe extruded materials from two locations (nose and middle of extrusion)
- Metallography shows evidence of “secondary” phase (aluminum with Fe, Si and V intermetallics) and some consolidation voids
- Al-12%Fe appears to melt and melt spin similar to the Al-8%Fe
- Completed design and fabrication of vacuum hot pressing tools to pre-consolidate flake billets prior to extrusion
- Completed design for closed die forging tooling to simulate extrusion + forging to component preform shape
- Large scale commercialization route would be RS flake melt spin + Can-less billet + upset extrusion consolidate + Extrude to rod or shape

HS/HT Aluminum Task Plan – Future Work

Proposed Task Plan

- Melt and run additional Al-Fe flake in Al8.5%Fe and Al-10% to 12%Fe, UConn alloy and AFM alloy (Complete 1Q, CY2012)
- Completed visit to Transmet to discuss approaches for larger-scale flake melt spinning runs (Completed 1Q, CY2012)
- Can, consolidate and extrude 2-3 billets of each alloy and characterize properties and microstructure (To be completed 3Q, CY2012)
- Identify additional extrusion resources for larger-scale flake consolidation and extrusion (To be completed 3Q, CY2012)
- Cummins to determine additional characterization and testing needs (Completed 1Q, CY2012)
- Conduct baseline evaluation of extrusion + forging process (To be completed 3Q, CY2012)
- Cummins to evaluate test data and validate performance targets (To be completed 4Q, CY2012)

Summary and Conclusions

- CRADA Project with Cummins, Inc., initiated May, 2011
- Initial phase of project has focused on selection of candidate aluminum alloys with potential to meet 300 MPa strength at 300 C
- Rapidly solidified Al-Fe alloys have been successfully melt spun and flake materials characterized – properties of RS approaching properties of previous MA
- Laboratory-scale extrusion tooling capable of consolidation and hot extrusion of Al-Fe alloys has been designed, fabricated and used to extrude project materials
- Initial Al-8Fe flake has been consolidated by extrusion and tensile specimens tested at room temperature, 250 C and 300 C
- The project is currently focused on optimization of consolidation and extrusion processing methods to eliminate porosity and improve high temperature properties
- The next phase of the project will focus on selection of component(s) for application demonstration and identification of the commercialization path forward

Collaboration

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