Project Number: LM056

Non-Rare Earth High-Performance Wrought Magnesium Alloys

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Project Overview

Project Timeline

- Start: 10/1/2010
- Finish: 9/30/2013

Budget

- FY11 Funding - $475K
- FY12 Funding - $550K
- FY13 Funding - $625K
- Cost share to provided by MENA and Magna at appropriate phases

Barriers

- *Performance* of low cost materials needed to achieve the performance needs
  - Conventional Mg alloys have limited energy absorption
- *Higher cost* of lightweight material
  - Rare earth alloying additions increase cost and are of uncertain supply
    - Must be eliminated or minimized
- *Predictive modeling tools.* Adequate predictive tools that will reduce the low cost
  - Conventional Mg alloy processing limits the microstructure and corresponding properties

Partners

- Magna/Cosma
- Magnesium Elektron North America
- Georgia Technology University (sub contractor)

Presentation Outline

- Project Overview
- Goal and Objectives
- Relevance and Background
- Milestones
- Technical Approach
- Progress
- Summary
- Publications/Presentations

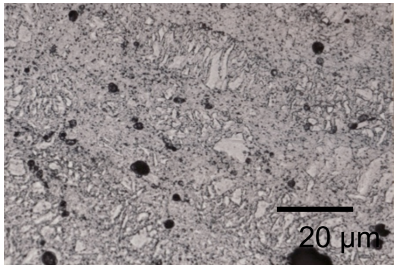
Goals and Objectives

- The Goal of this project is to reduce vehicle greenhouse gas emissions and increase vehicle efficiency by increasing the utilization of magnesium alloys.
  - The goal will be achieved by allowing the use of mass-saving magnesium alloys in structural applications requiring higher performance than that achieved with cast or continuous cast sheet materials.

- The Objectives of the project are:
  - Demonstrate that a magnesium alloy with a compressive and tensile yield strength in excess of 300MPa can absorb energy similarly to AA6061
    - Direct substitution is a 34% mass savings over aluminum
      - In some cases section thickness can raise the savings even greater
  - Using a process path optimization model demonstrate a low cost process to produce the desired microstructure at a minimum cost

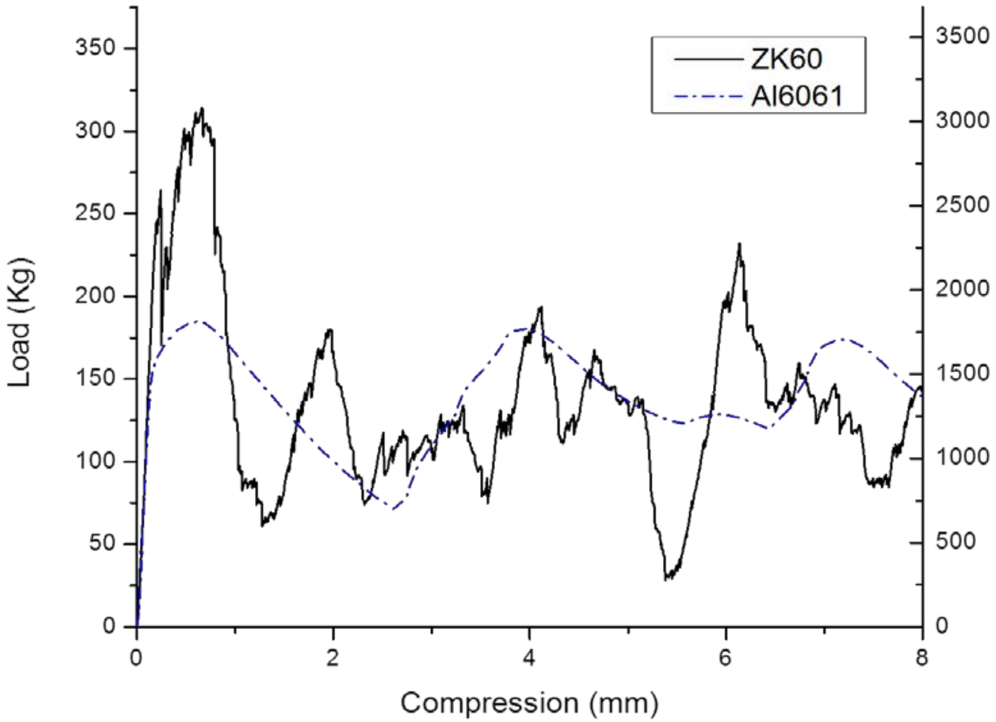
Relevance and Background

- Magnesium holds promise for mass savings at OVT goals
  - Applications are limited by energy absorption of magnesium
  - Energy absorption is a function of strength and ductility
- The project is then focused on determining:
  - If a high performance magnesium alloy can meet the stringent needs of automotive energy absorption
  - If the application of novel process modeling and methods can reduce the cost to automotive needs
- If successful magnesium can be used in many previously impossible applications and achieve OVT goals



Microstructure of high performance RE containing Mg alloy

Energy Absorption Testing – Previous Tasks



During FY 11 to 12 - Similar energy absorption for Al 6061 and Mg ZK60 results in approximately 20% mass reduction

Milestones – FY 2013

- Demonstrate that the high strength non-RE Mg alloy extrusion can achieve the equivalent energy absorption as 6061 using a more cost effective process than rapid solidification and powder metallurgy. September 30, 2013 - On target at time of preparation

Technical Approach

- Three Phases:
  1. Evaluate the energy absorption capability of magnesium alloys processed by novel methods – RE containing
     - Demonstrate energy absorption like AA6061
     - Assess strengthening mechanisms and build model to predict properties and processing relationships
  2. Demonstrate energy absorption of AA6061 with non-RE alloys based on model and characterization
     - Demonstrate with prototypic component – 7 mm OD crush samples
  3. Develop and Demonstrate low cost processing approach - Focus of this Year
     - "Inverse process path modeling" based on ideal microstructures
     - Laboratory demonstrations
     - Prototypic component demonstration – size to be determined in discussions with Magna

Technical Progress

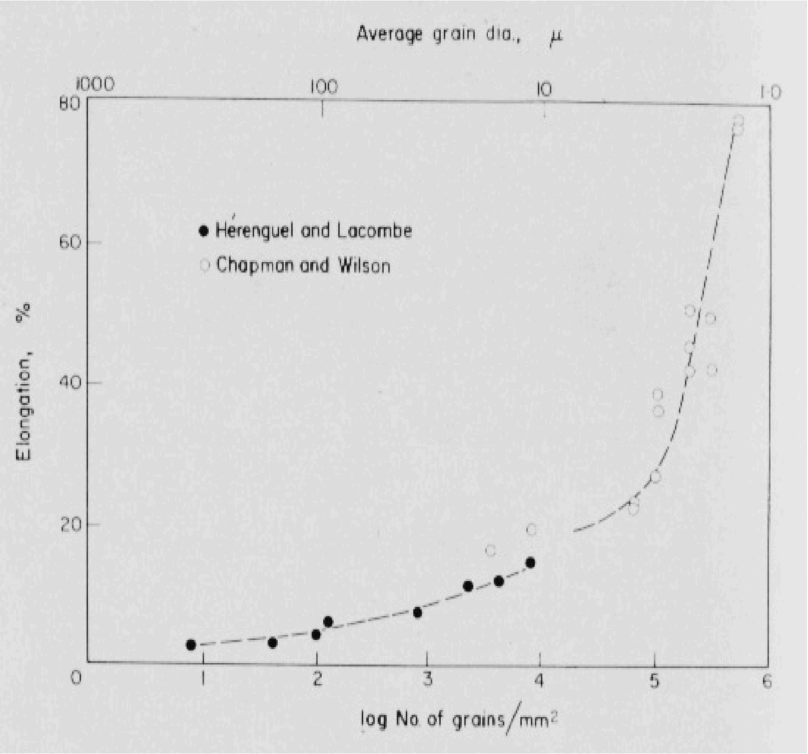
- Three aspects
  - Process Development
    - High Shear Extrusion
  - Mechanical Properties Modeling
    - Dispersion size and fraction
    - "Phi" Model
  - Inverse Process Modeling
    - Intermetallic particle fracture

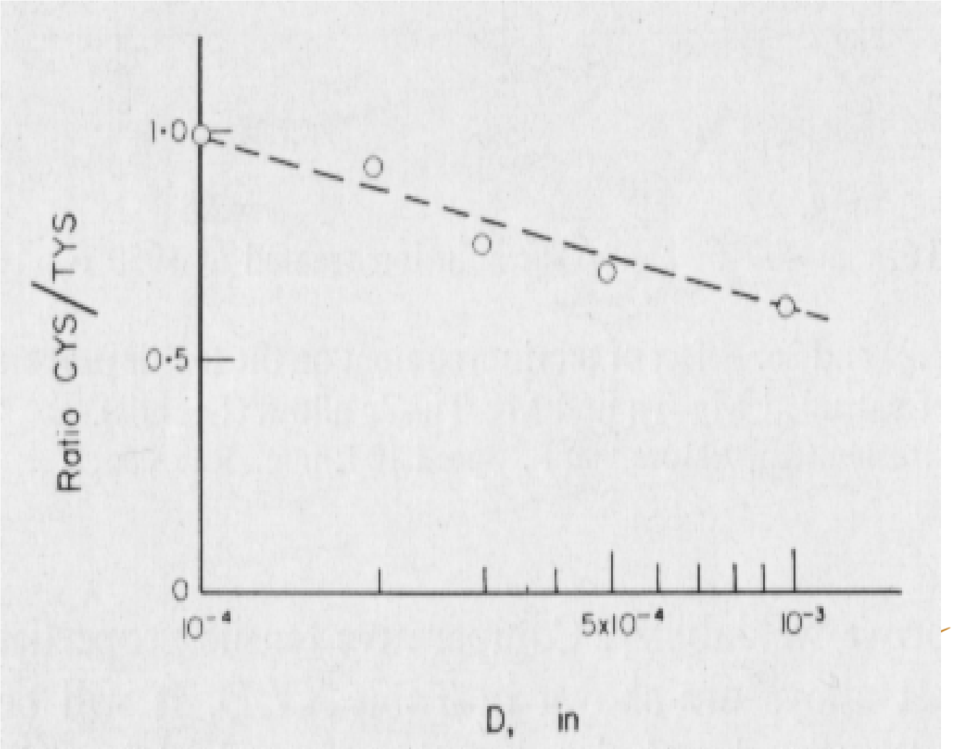
Process Development

- Alloy selection
  - Dispersion volume fraction and chemistry
    - New alloy selected – binary with Si
  - Also carried along ZK60A
    - Faster route to commercialization with conventional alloy
- Process Selection
  - High shear extrusion

Premise behind energy absorption improvement with improved alloy

- Impact of grain size on ductility and cys/tys
  - Can high strength be developed while retaining ductility?
- Goal is 1 to 2 micron grain size

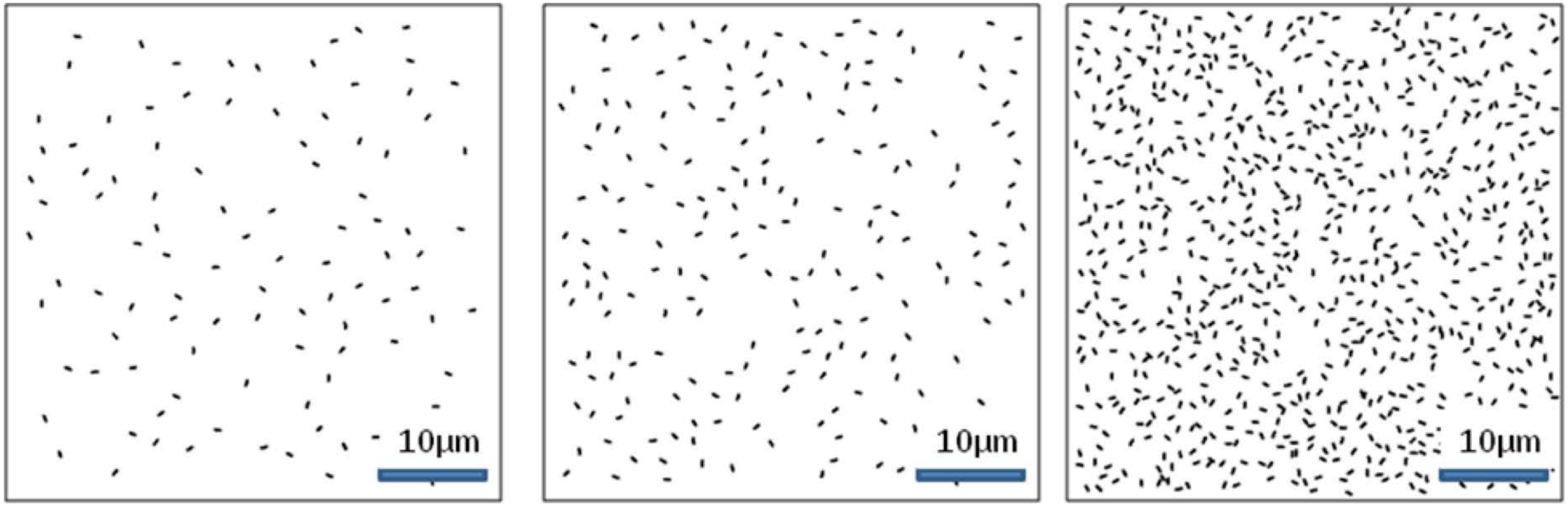




R.S. Busk and T.E. Leontis, Trans AIME, 1950, 188, 297.

Synthetic Microstructure – Interparticle Spacing

- Effect of Volume Fraction



1% 2% 8%

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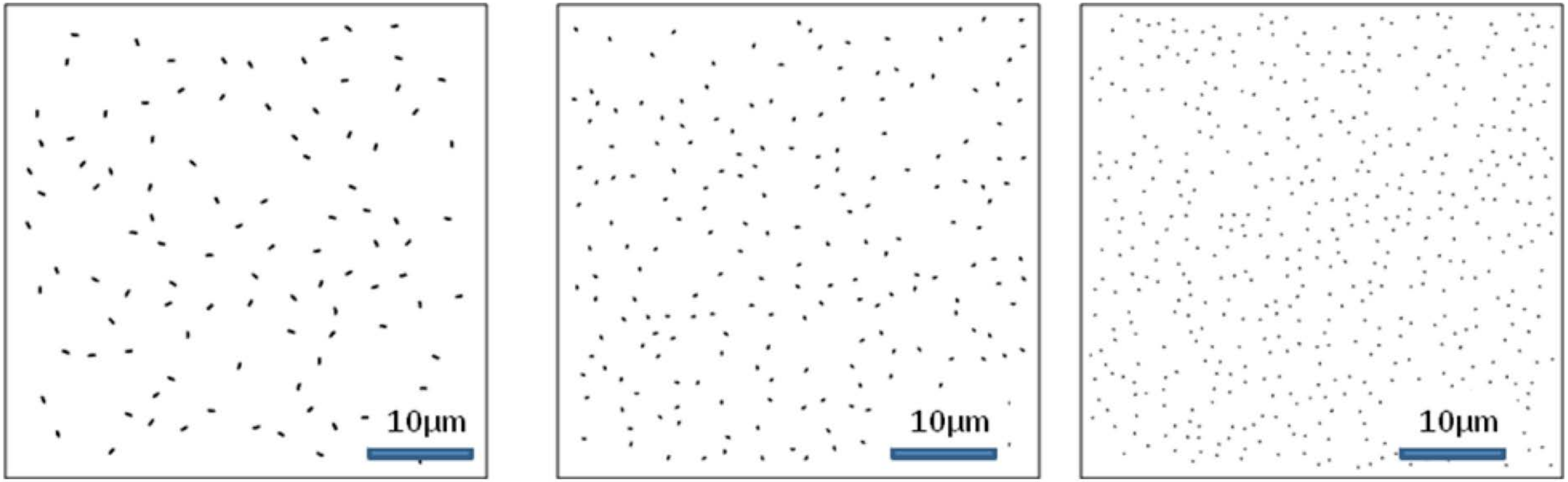
Synthetic Microstructure – Particle Size

- Effect of particle size
  - 1 Volume percent; 3.2, 2.3 and 1.5 micron



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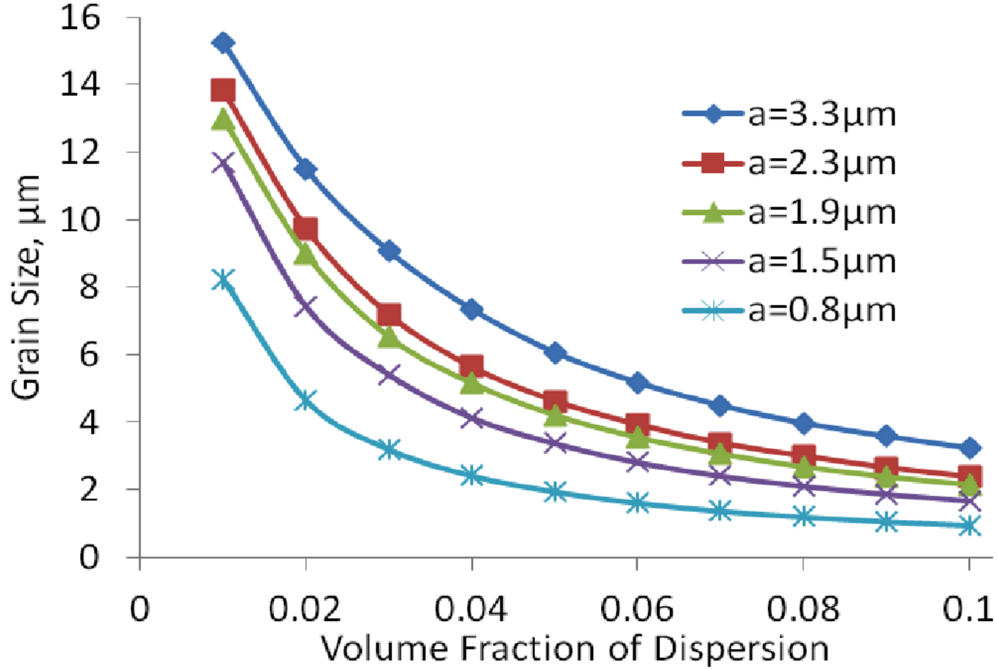
Grain Size and Dispersion

- Assuming effective pinning (70%)
  - Idea of where we need to be in v/f and size
  - Need 6 to 8 volume fraction of 0.8 to 1.5 micron dispersions



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Which Alloying Elements?

- Galvanically favorable
  - Reduce corrosion
- Intermetallic former
  - Provide pinning dispersions
- Liquidus
  - Realistic melt point for casting

Silicon as an Alloying Addition

- Silicon appears to be a good candidate to validate microstructure and corrosion theory
  - Intermetallic former (Mg_2Si) with neutral galvanic potential

Metal	E_{corr}, V_{SCE}
Mg	−1.65
Mg_2Si	−1.65
Al_6Mn	−1.52
Al_4Mn	−1.45
Al_8Mn_5	−1.25
$Mg_{17}Al_{12}$ (β)	−1.20
Al_8Mn_5(Fe)	−1.20
β-Mn	−1.17
Al_4RE	−1.15
Al_6Mn(Fe)	−1.10
Al_6(MnFe)	−1.00
Al_3Fe(Mn)	−0.95
Al_3Fe	−0.74

RE = rare earth elements.

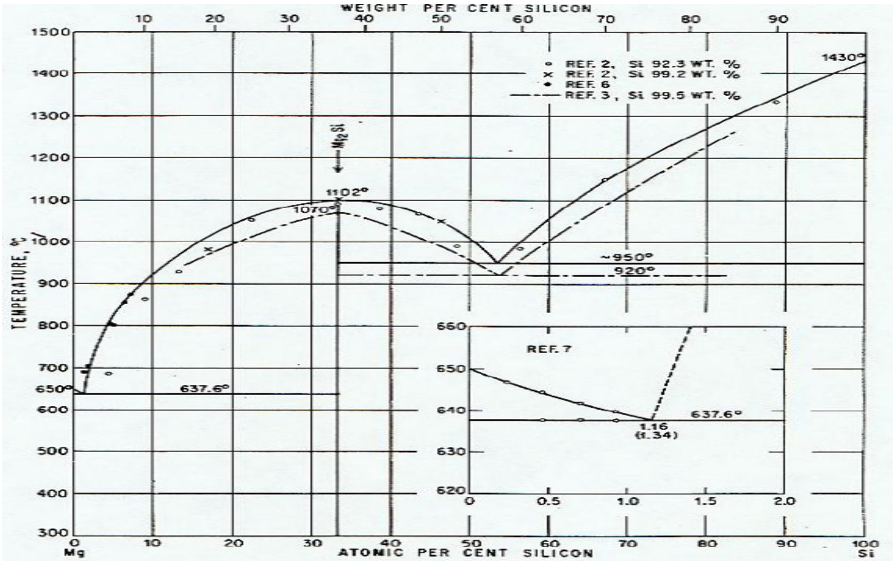
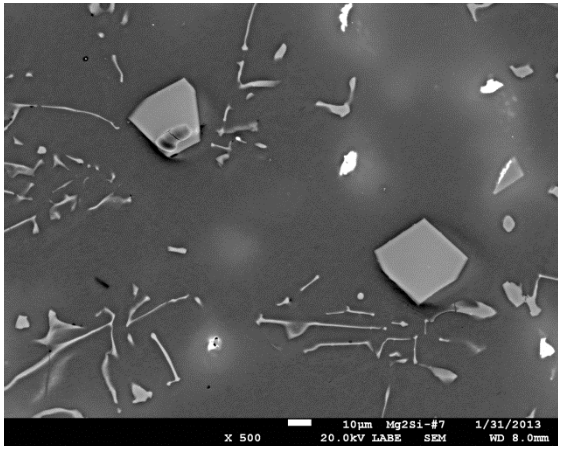


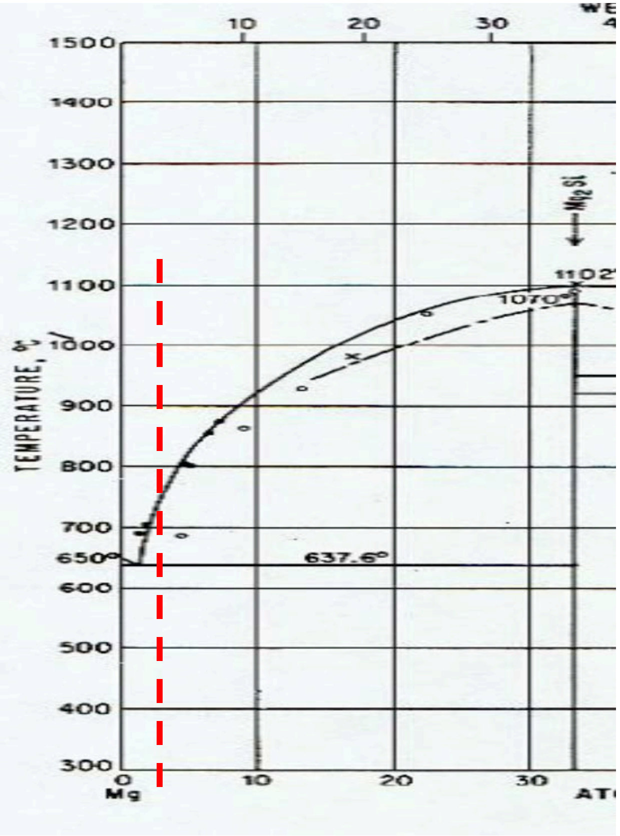
Fig. 507. Mg-Si

Cast Si Binary Alloys

- Mg- 2 and 7 wt % Si
- Book mold cast at 50 mm section thickness 12 cm by 36 cm
  - Cast at CANMET

Cast Microstructure Chinese Script as well as cube shaped Mg_2Si Intermetallic

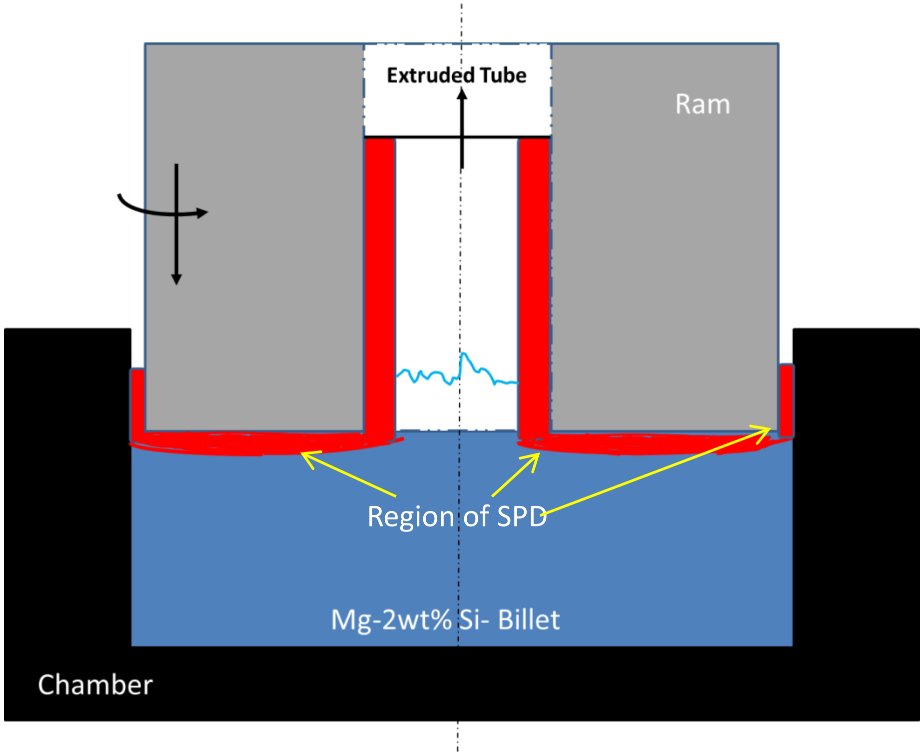




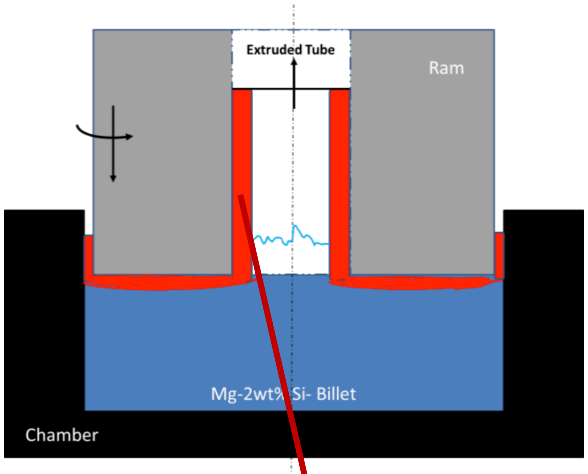
High Shear Processing

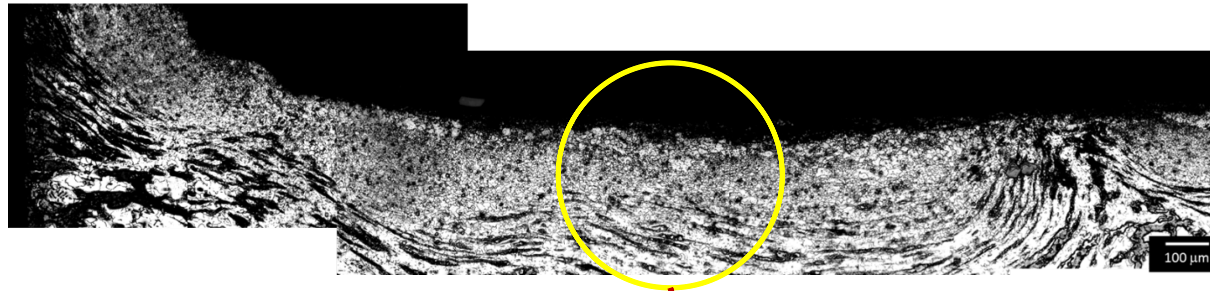
- How do we have fine particles and homogenously distribute them?
  - High solidification rate
  - High strain
  - Additives – MMC
- To date processes have been limited
  - Cost Effective Casting thickness
  - Strain limitations from rolling/extrusion
  - MMC's with micron-ish particle materials are difficult to make
- We selected High Shear Extrusion

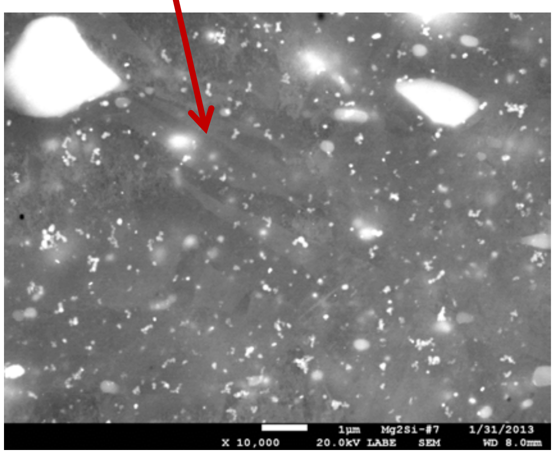
Indirect Tube Extrusion with High Shear

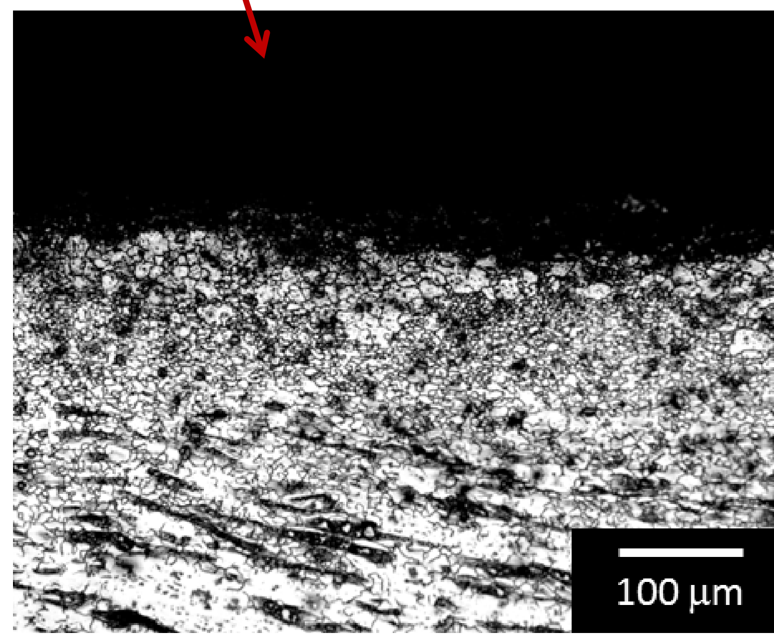


Microstructure of Mg2Si Extrusion





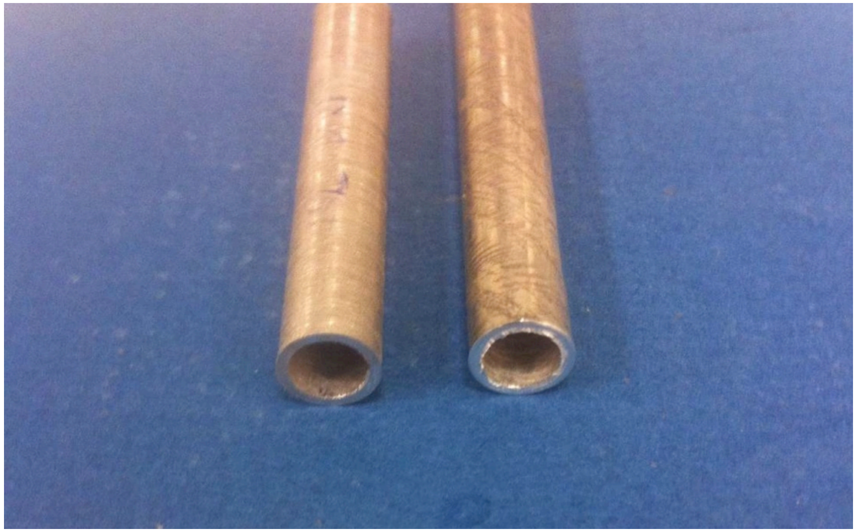




Highly deformed zone with grain sizes and intermetallic sizes less than one micron. *Microstructure Goal Achieved*

Tubes Produced

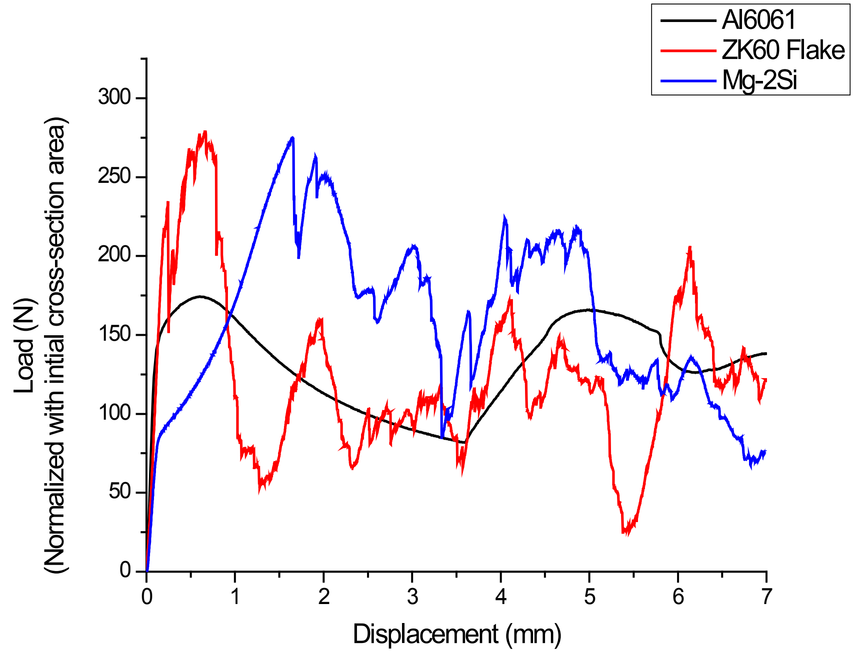
- Tubes were extruded to match the 7 mm OD by 0.5 mm wall used in compression testing (energy absorption)
- Alloys Produced
  - 2 and 7 wt % Si; ZK60A and AZ31



Tubes produced from Mg_2Si at 1 ft/min (left) and 12 ft/min (right)

Energy Absorption from High Shear Extruded Tubes

- Mg with 2 wt% Si met or exceeded prior test energy absorption
  - High shear extrusion can produce desire microstructure that develops high performance properties
    - ZK60A by high shear was similar to Mg2Si (not shown for clarity)



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Modeling – Two Areas

- "Phi" Model – Leveraged by PNNL FSCD
  - Uses a weighting factor that sums the effect of grain size, precipitation, twinning and texture.
    - The total is a multiplier to the Visco Plastic Self Consistent (VSCP) model
  - Describes the relative importance of major microstructural features.
- Inverse Modeling – Led by Georgia Inst. of Technology
  - Need a relationship between strain in shear process and intermetallic break up to produce fine dispersions
    - Uses matrix strength and Griffith fracture criteria to fracture particles in Mg matrix.
- Simple Questions lead to complex models!

Polycrystalline Viscoplasticity Model: ϕ-model

ϕ-model

$$\mathbf{D} = \mathbf{A}\cdot < \mathbf{A} >^{-1} \cdot\overline{\mathbf{D}} \qquad \mathbf{S} = \mathbf{B}\cdot < \mathbf{B} >^{-1} \cdot\overline{\mathbf{S}}$$

$$\mathbf{A} = \left[\mathbf{L} - \beta n\left(\frac{\phi-1}{\phi}\right)\mathbf{M}\right]^{-1}\left[\tilde{\mathbf{L}} - \beta n\left(\frac{\phi-1}{\phi}\right)\mathbf{M}\right]$$

$$\mathbf{B} = \left[\mathbf{I} - \beta n\left(\frac{\phi-1}{\phi}\right)\mathbf{M}\cdot\mathbf{M}\right]^{-1}\left[\mathbf{I} - \beta n\left(\frac{\phi-1}{\phi}\right)\mathbf{M}\cdot\tilde{\mathbf{M}}\right]$$

VPSC

$$\mathbf{D} - \overline{\mathbf{D}} = \hat{\mathbf{M}}\cdot(\mathbf{S} - \overline{\mathbf{S}})$$

$$\hat{\mathbf{M}} = n^{eff}(\mathbf{I} - \mathbf{E})^{-1}\cdot\mathbf{E}\cdot\overline{\mathbf{M}}$$

M'Guil, S., Ahzi, S., Barlat, F., Gracio. J.J., 2011. Int. J. Plast, 27, 102-120.

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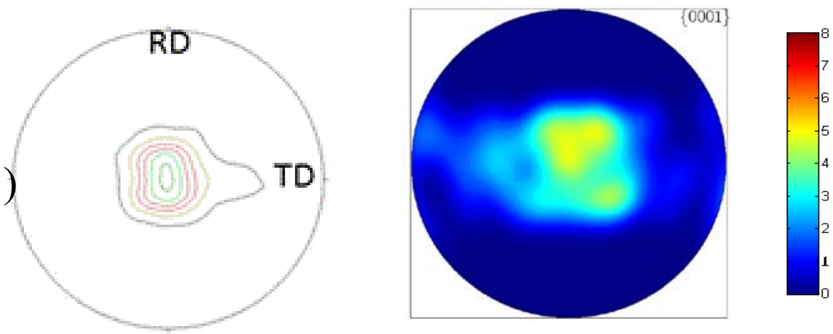

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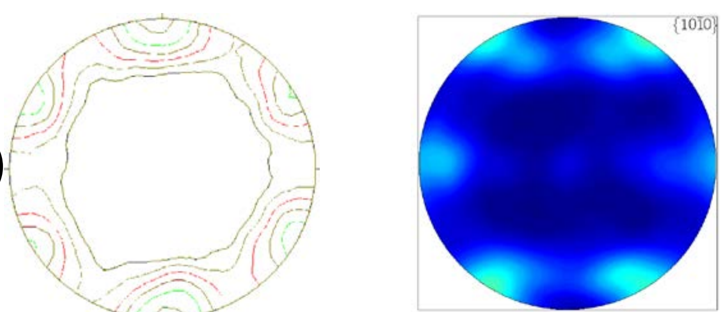
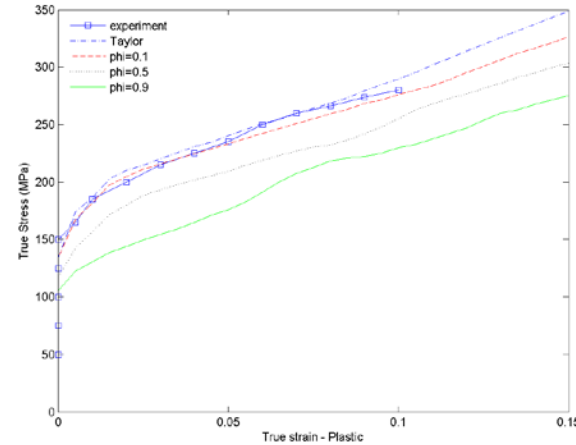
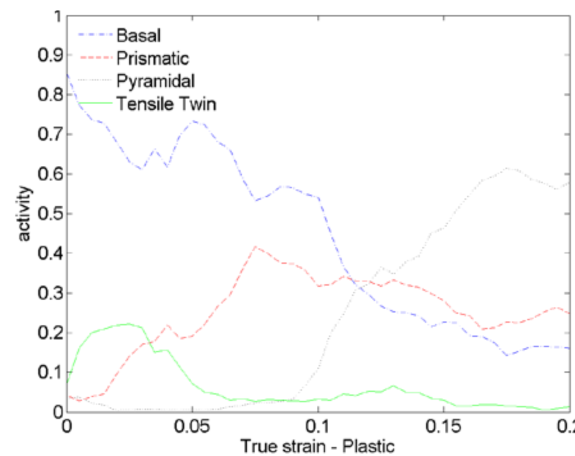


experimental Simulated

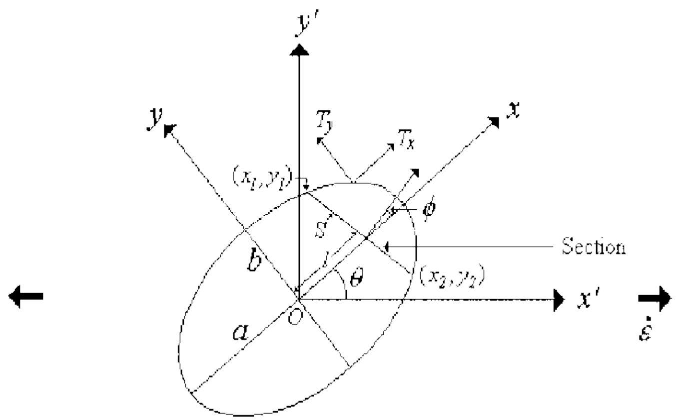


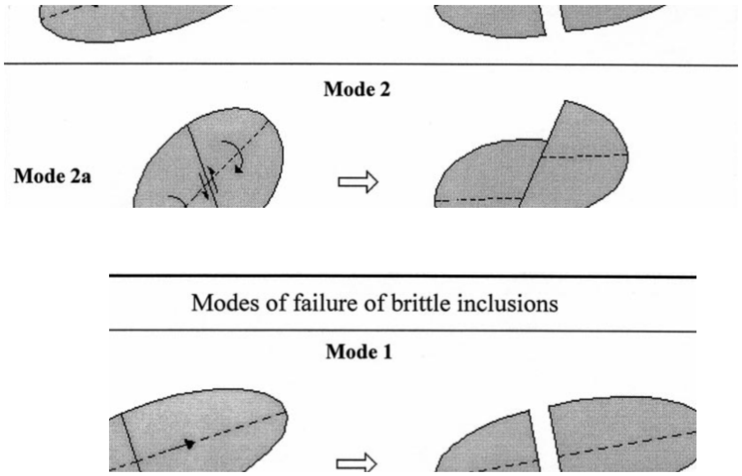


Inverse Process Modeling – Particle Fracture

- Fracture of Intermetallics by traction tensors and Griffith's Theory
  - Traction Tensors: Jeffery, G.B., *Proceedings of the Royal Society of London. Series A, 1922.* ***102****(715) 161-179.*

$$\sigma_n = f(\sigma(\beta, m, \dot{\varepsilon}), \sigma_h, R, t(x,y), \theta, \phi)$$

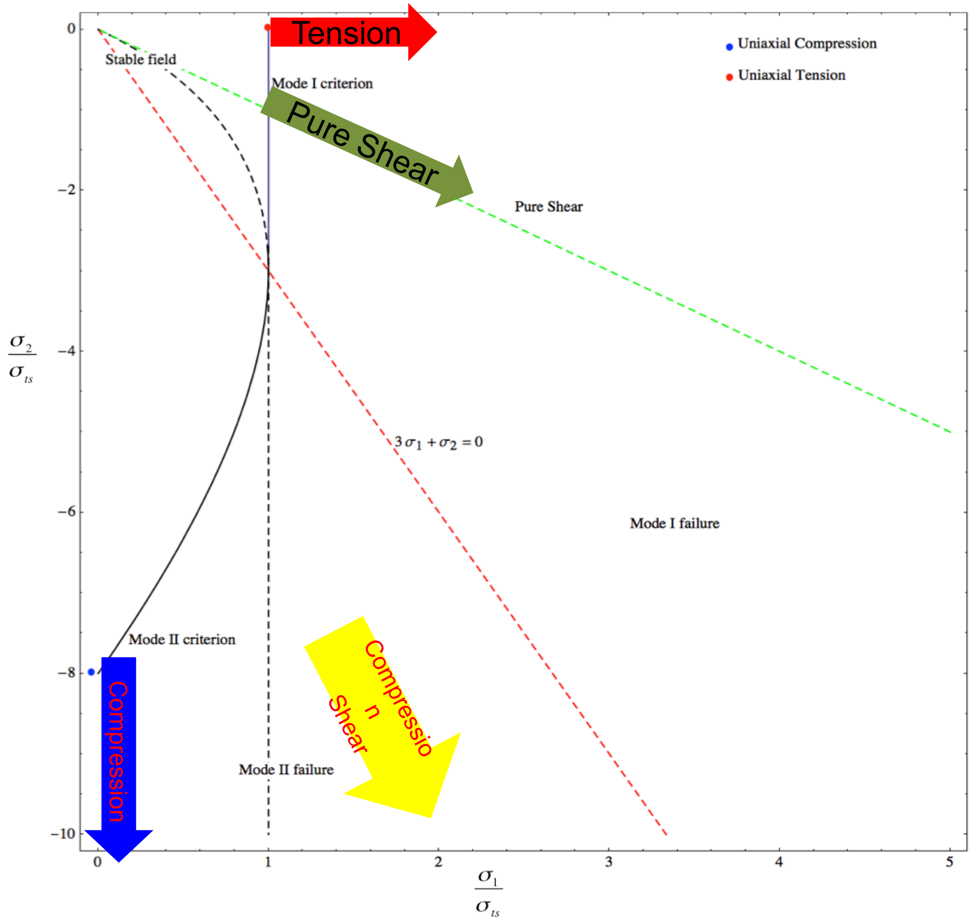




Fracture of intermetallics important to high strain processing – Model to predict behavior developed

Mode 2 desired

Inverse Process Modeling – Usefulness of Particle Fracture Model



- Even pure shear causes failure in mode I
- For failure in Mode II a compressive component of stress is needed. e.g. : Let's assume a state of stress for hydrostatic compression-shear:

$$\sigma_{ij} = \begin{bmatrix} -\sigma & \tau \\ \tau & -\sigma \end{bmatrix} \rightarrow$$

Pricipal Stresses:

$$\sigma_1 = \tau - \sigma$$

$$\sigma_2 = -\tau - \sigma$$

Model predicts stress-state needed for particle refinement

Collaborations

- Magnesium Electron North America has provided master alloys and alloys for processing
  - CANMET has also provided castings
- Magna/Cosma Engineering has provided property goals and extrusion design
- Georgia Tech has started characterization efforts to provide precipitate structure and composition
  - Leveraging DOE/BES in mechanical strength models

- Technology transfer will start in more detail this FY due to the nature of the project phases.

Future Work

- Increase the size scale of high shear extrusion to produce relevant automotive geometries
  - Mg2Si and ZK60A will be pursued.
- Develop extrusion model with capability to predict the evolution of microstructure and mechanical properties with different processing parameters.
  - More scope than originally expected – high shear modeling needs more development.
  - GT’s partical fracture model will be implemented into the smooth particle hydrodynamics model to model extrusion.
- Apply microstructure based FEM to predict mechanical responding with reconstructed statistical stable representative volume element
  - Influence of twinning will be integrated…impact from high performance Mg.
  - Accomplished by providing properties and microstructural data to the VPSC enhanced by the Phi model.

Summary

- A series of magnesium alloys were extruded using high shear to produce high performance tubes with fine grain size dispersions
  - Grain sizes appear to be less than 5 μm
  - Dispersions less than 2 microns

- Tubes extruded with high shear exhibit energy absorption like that of aluminum
  - Mg_2Si and ZK60A exhibited energy absorption like 6061

- Microstructural modeling has been initiated to help understand the behavior and predict energy absorption
  - Grain size, precipitation, twinning and texture as it impacts stress strain has been implemented in the VPSC material model

- A model to predict the “high shear-extrusion” state of stress needed to facture particles has been developed