Project Number: LM056

Non-Rare Earth High-Performance Wrought Magnesium Alloys

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Project Overview

Project Timeline

- Start: 10/1/2010
- Finish: 9/30/2014

Budget

- FY11 Funding - $475K
- FY12 Funding - $550K
- FY13/14 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/Vehma
- 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

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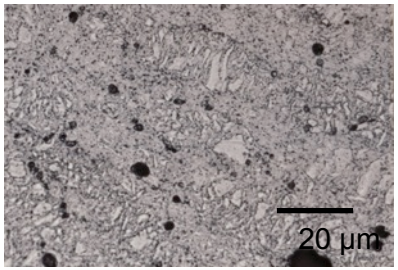
Relevance and Background

- 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

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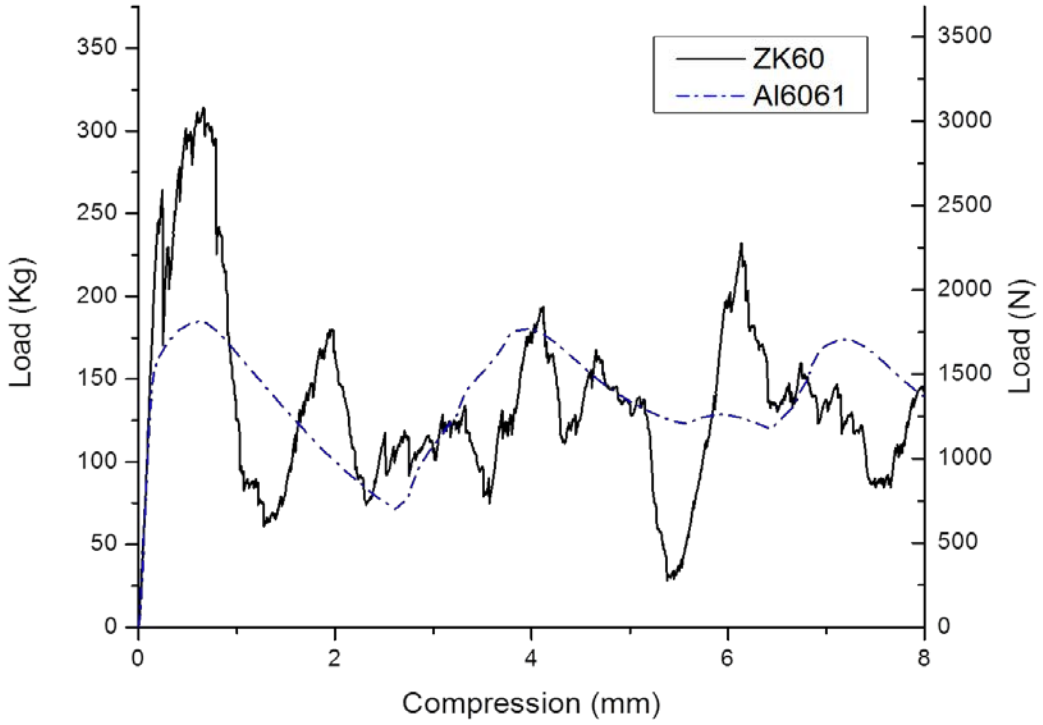
Energy Absorption Testing – Previous Tasks



During FY13 - Similar energy absorption for Al 6061 and Mg ZK60 results in approximately 20% mass reduction

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Milestones – FY 2014

- 3/31/2014 Demonstrate high shear extrusion of the ZK60A alloy at a minimum of 20 inches per minute while retained energy absorption equivalent to the current levels achieved at 5 inches per minute. Met in March

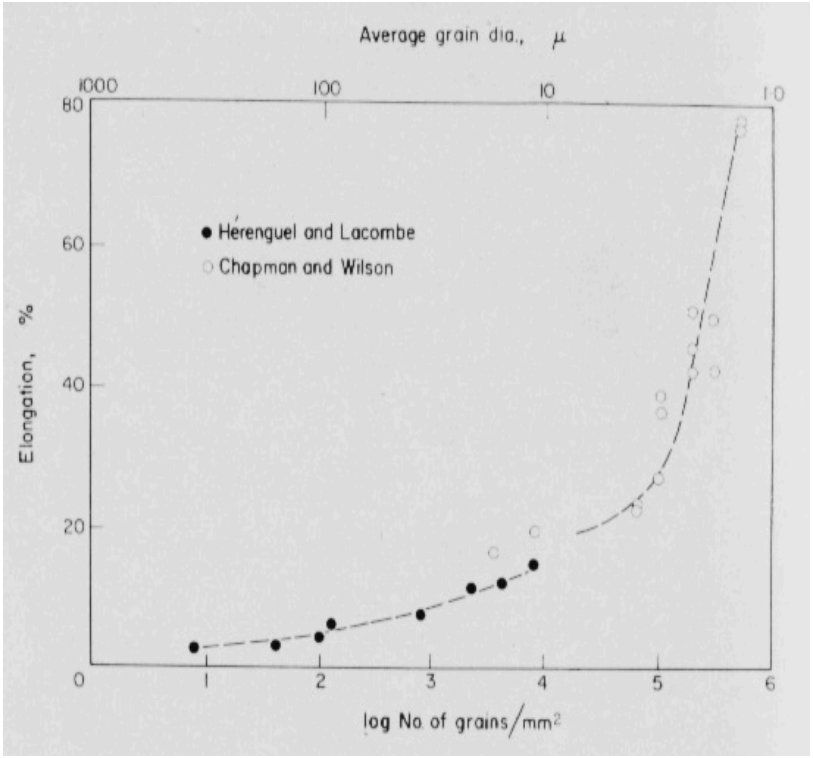
- 9/30/2014 Complete overview report of high shear magnesium extrusion. This report will summarize modeling activities and experimental effort.

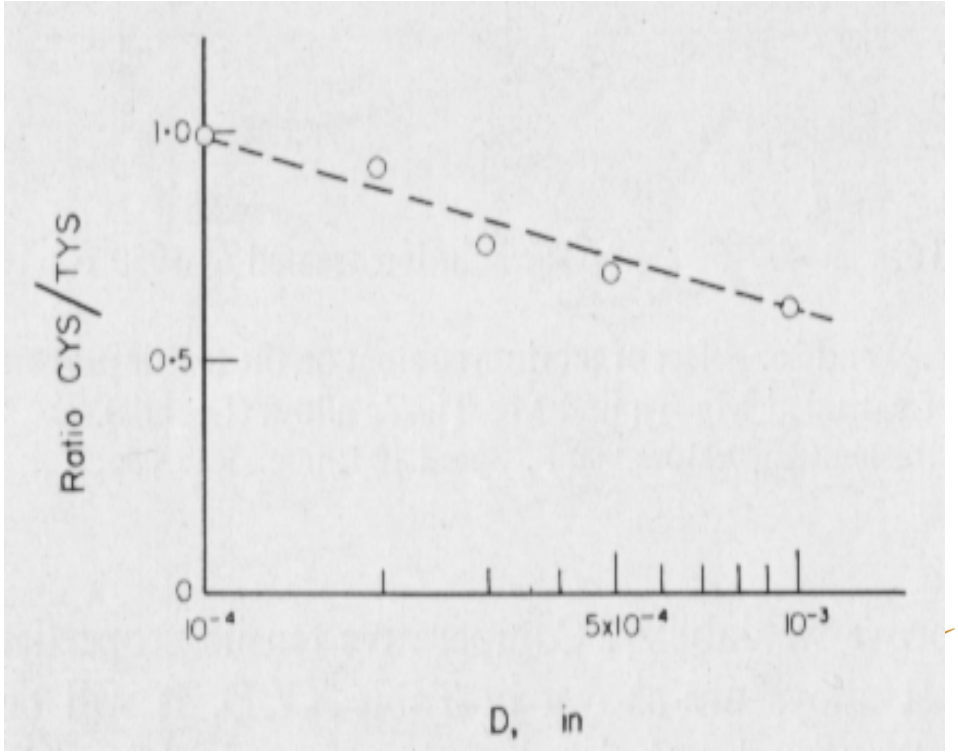
Technical Approach

- 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
     - "Inverse process path modeling" based on ideal microstructures
     - Laboratory demonstrations
     - Prototypic component demonstration – size to be determined in discussions with Magna – Focus ensuing year and end of project

Process Development - Reminder

- To develop fine grain size through alloy and TMP
- Chosen high shear extrusion
  - Goal is 1 to 2 micron grain size



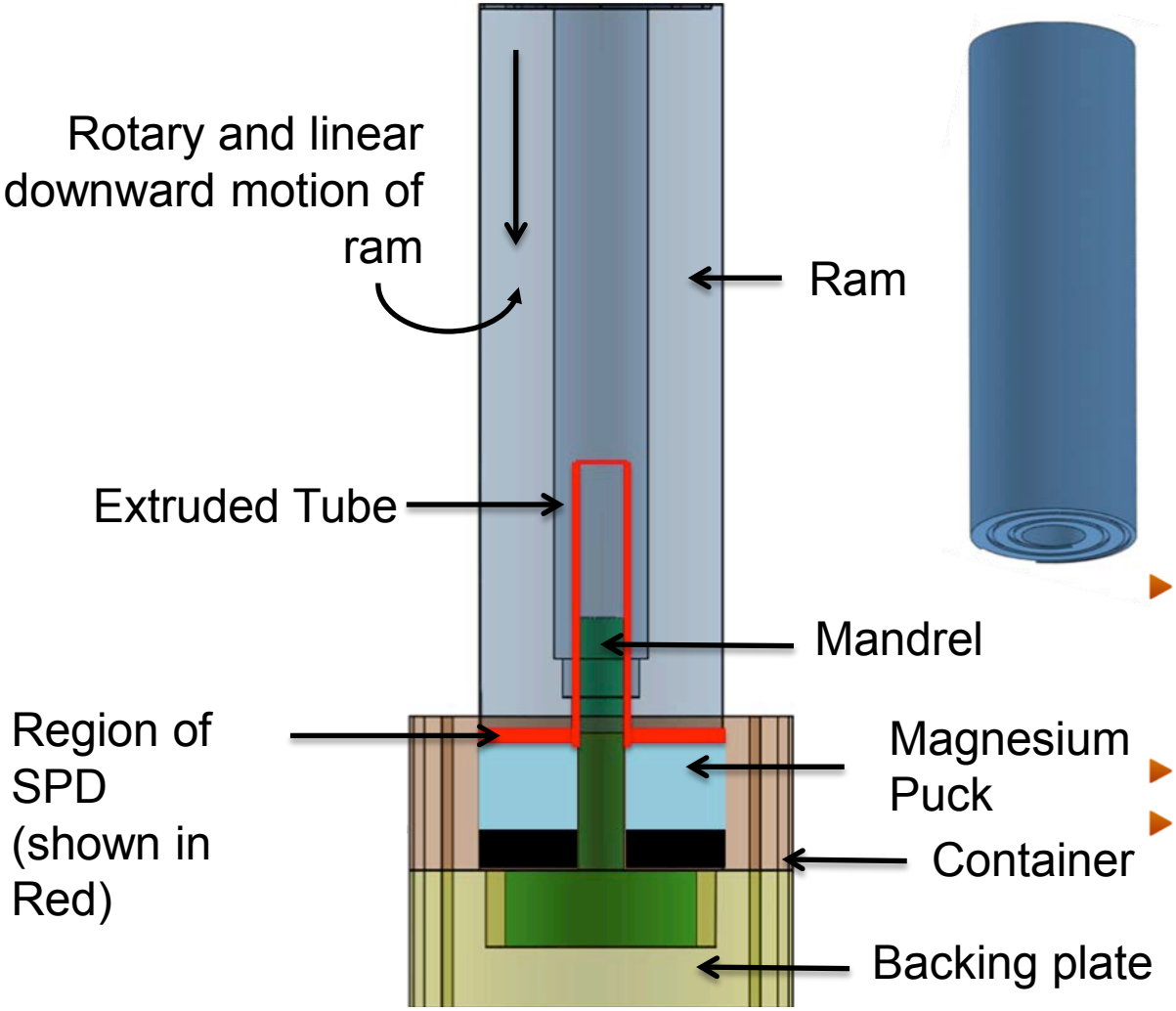


R.S. Busk and T.E. Leontis, Trans AIME, 1950, 188, 297.

Technical Progress

- Three aspects
  - Process Development
    - High Shear Extrusion incorporating mandrels and die features – emphasis of this FY
    - Extensive trials and parameters – patent has been filed
    - The next step is a variant on the process
      - Small scale trials been performed and are very promising
        - IP will be involved
  - Mechanical Properties Modeling
    - Dispersion size and fraction
    - “Phi” Model
    - Properties Prediction
  - Inverse Process Modeling
    - Intermetallic particle fracture

Shear Assisted Indirect Extrusion Process



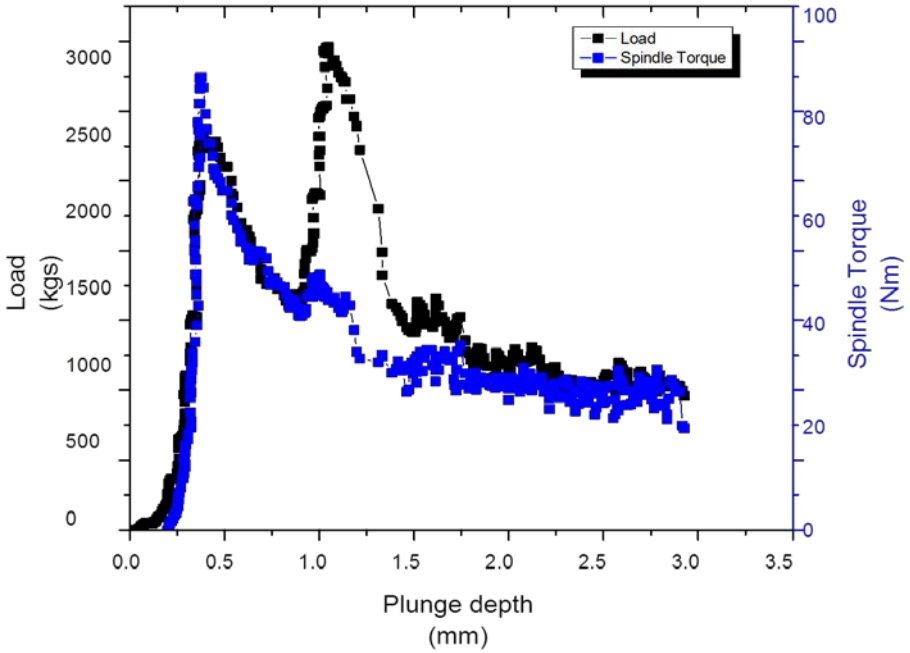
Flute/ Scroll profile on the Ram

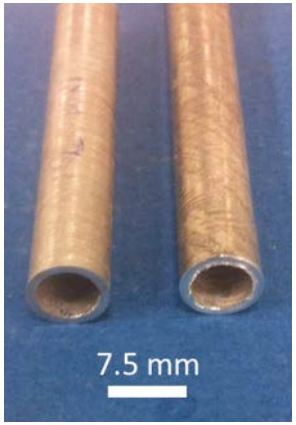
- **Process is similar to indirect extrusion but uses a rotating ram that assists in material flow and fracture of intermetallic particles**
- **No external heating**
- **The die was installed existing PNNL equipment**

Patent Application No.: 61/804,560

Process Data

- Large number of alloys have been processed
  - ZK60A shows good promise and is commercially available
- Extrusion forces are very low when compared to conventional extrusion
  - Possibly two-orders of magnitude





Example Extrusions

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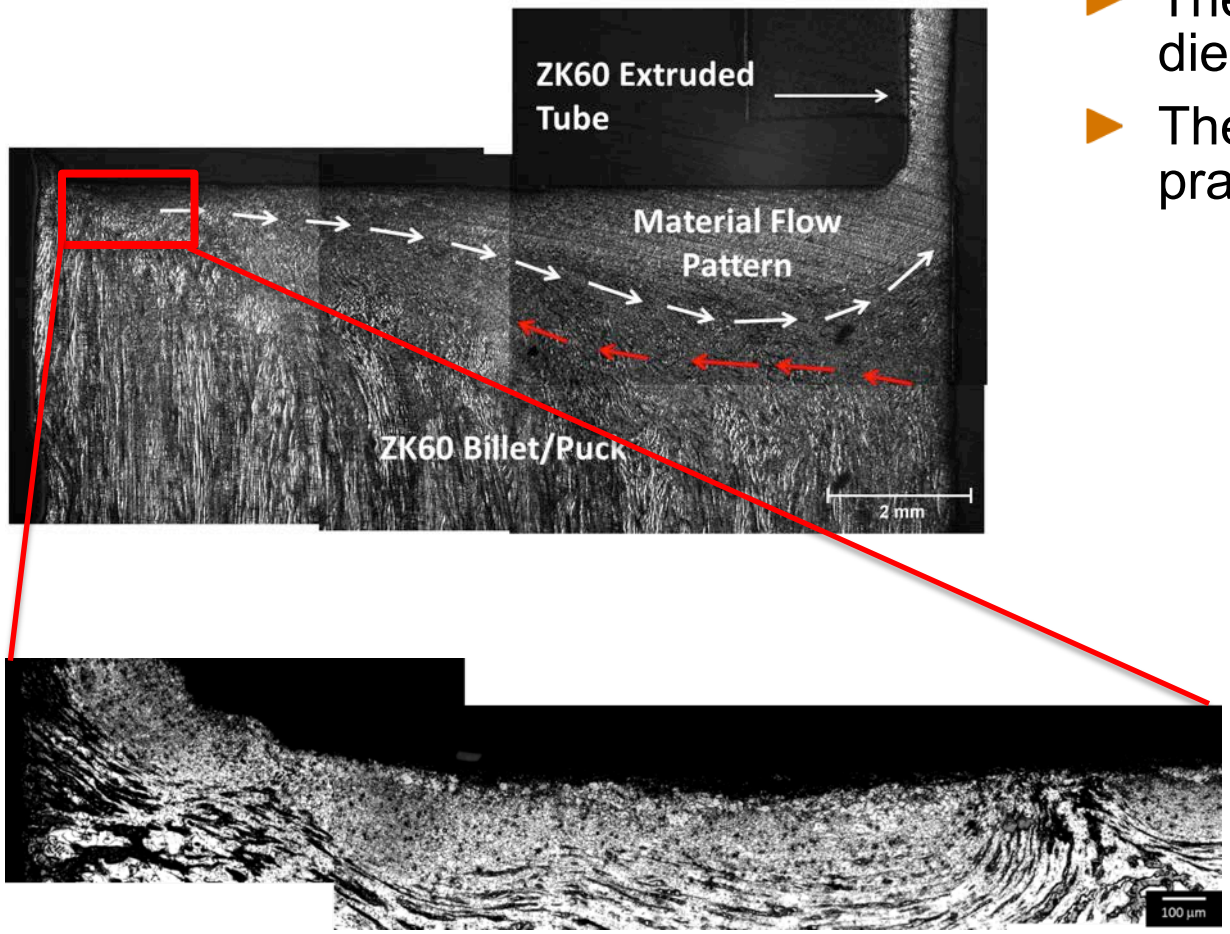
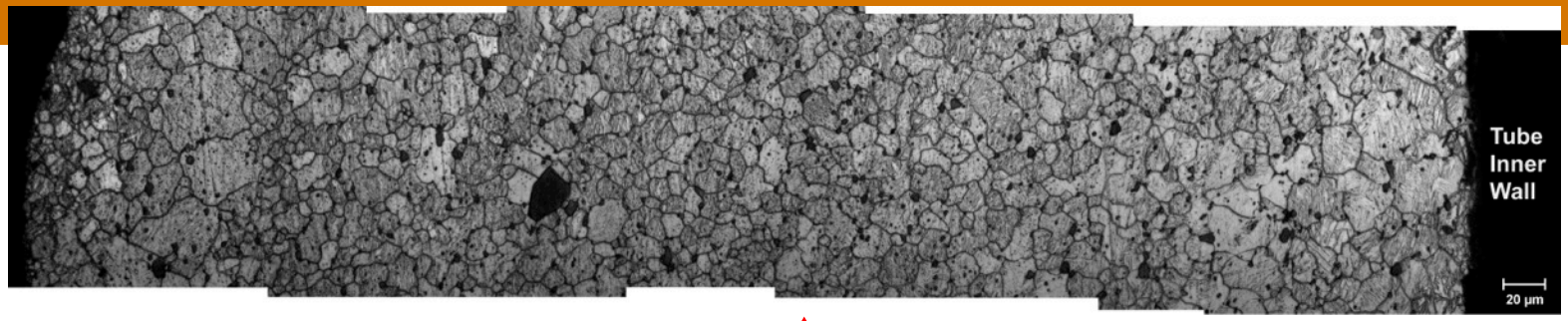
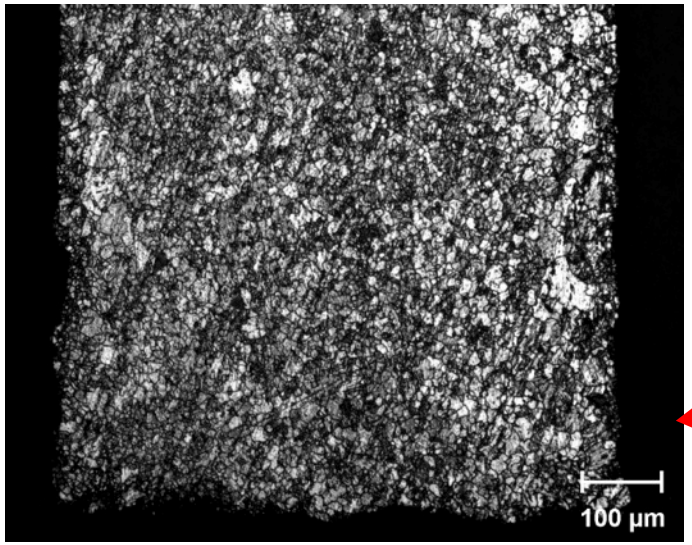
Microstructural Characterization of the SAIE-ZK60

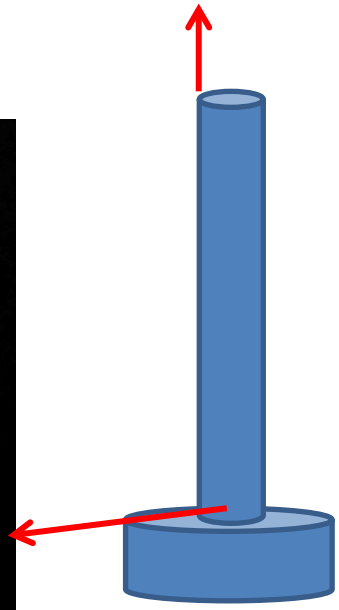


- The material flows “out” the die gap
- The rest of the area remains practically undisturbed

Microstructural Characterization of the Extrusion-ZK60

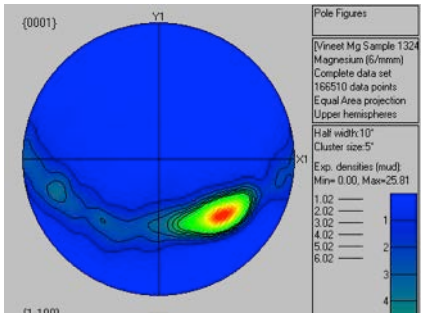


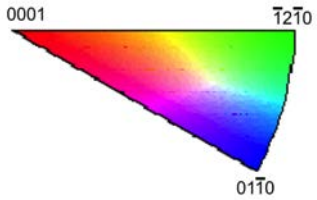


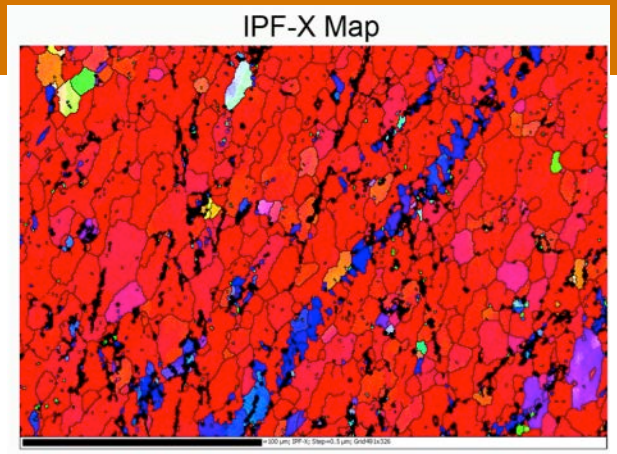


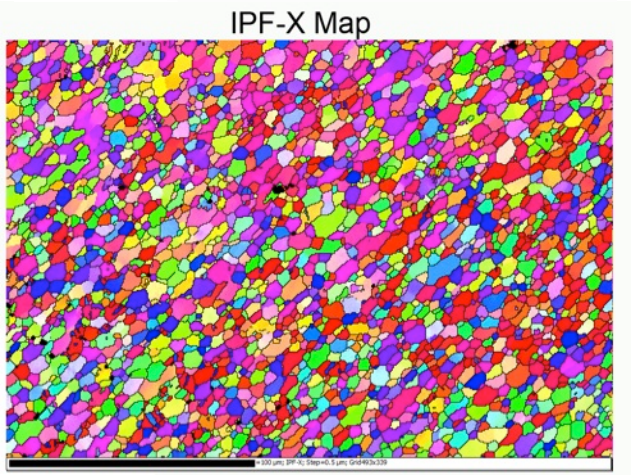
Fine grain size in extrusion achieved

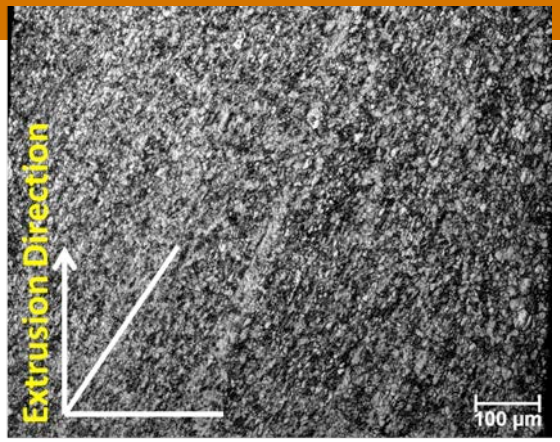
Promise from the Processing Side ZK60

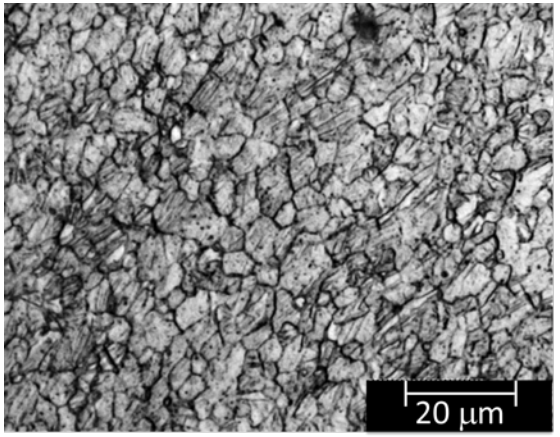






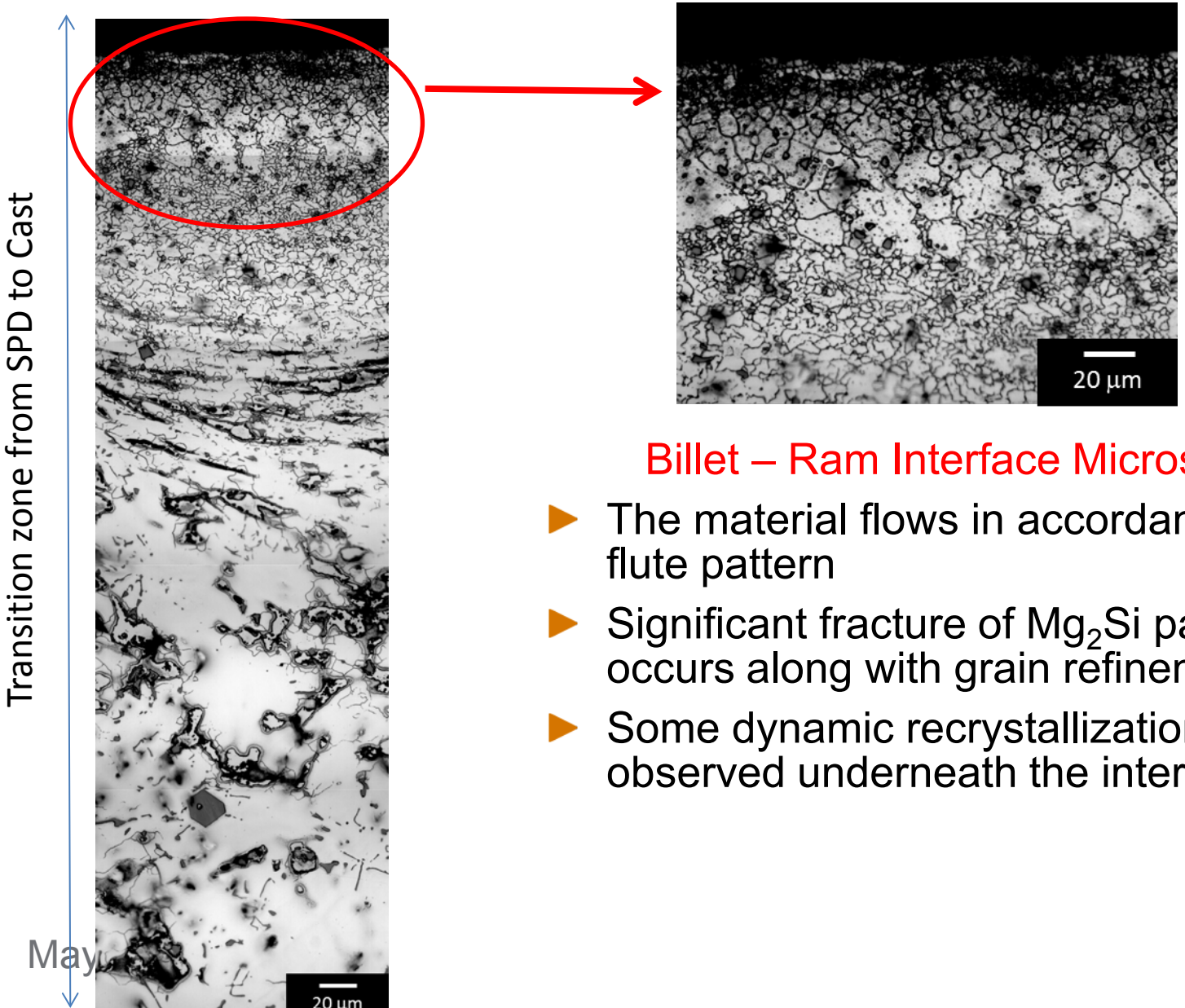






GS less than 5 microns and oriented 45deg to the extrusion axis

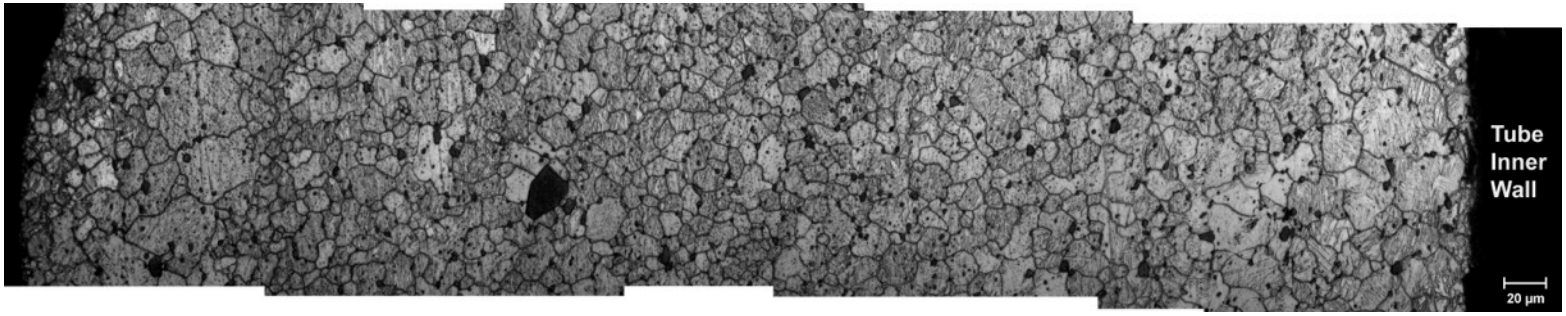
Microstructural Characterization of the Extrusion- Mg- 2wt% Si



Billet – Ram Interface Microstructure

- The material flows in accordance to the flute pattern
- Significant fracture of Mg_2Si particles occurs along with grain refinement
- Some dynamic recrystallization was also observed underneath the interface.

Microstructural Characterization of the Extrusion- Mg- 2wt% Si



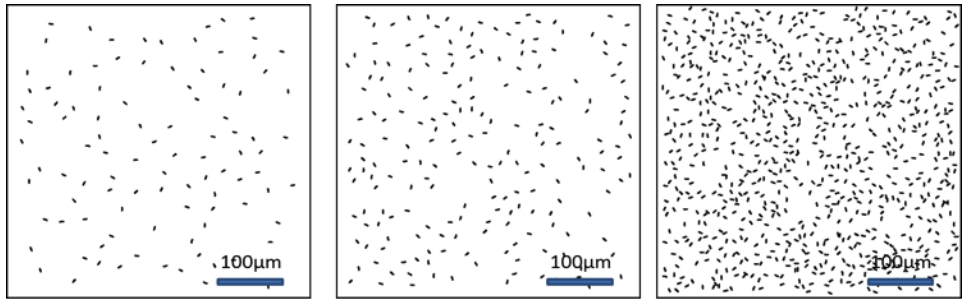
Tube cross-section montage, sectioned along the extrusion axis (500X)

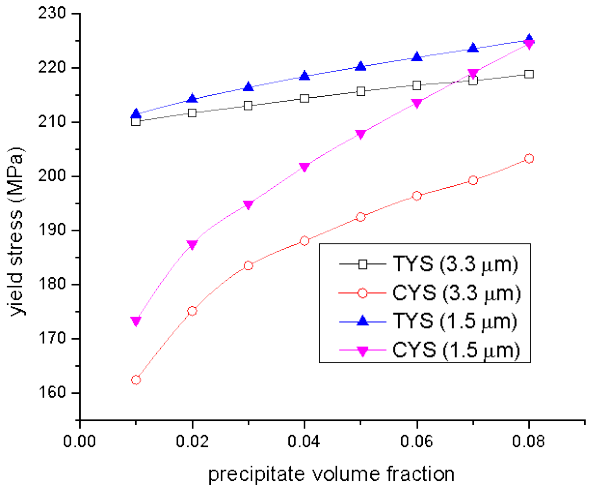
Tube Microstructure

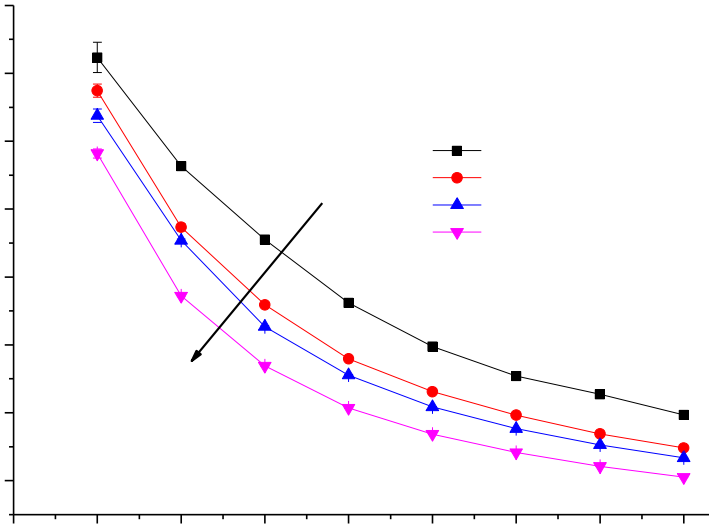
- The grain size at the edges were 20-30 μm in size whereas the ones at the interior were less than 5 μm
- The script Mg_2Si intermetallics seem to have fractured and uniformly distributed across the microstructure

Defining the Microstructure using ICME

Effect of Precipitate Volume fraction on the CYS/TYS ratio





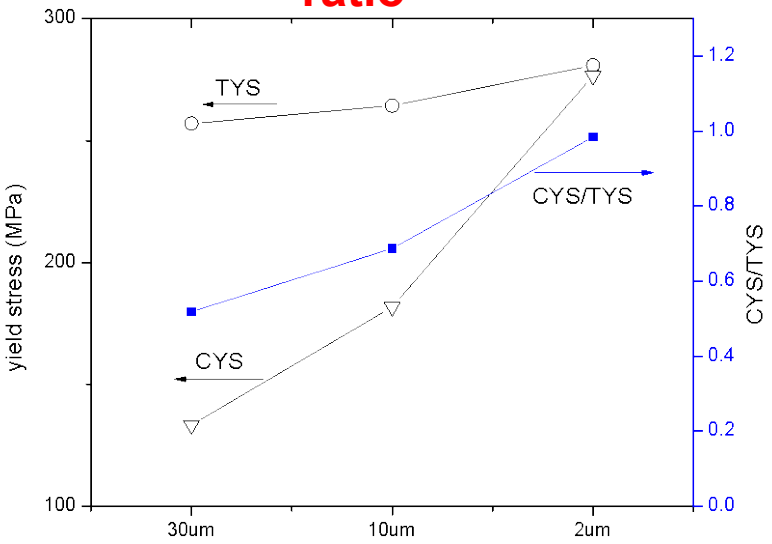


- Strengthening the material can also be achieved by dispersion strengthening or aging
- In order to understand the effect of intermetallic size on the grain size and the mechanical properties was simulated quantitatively by coupling a stochastic **second phase grain refinement model** and a modified polycrystalline crystal viscoplasticity φ-model.
- **It was determined that the mechanical properties are optimum volume fraction of intermetallics is more than 6% and should be fine.**

Dongsheng Li, et.al., :Strengthening and Improving Yield Asymmetry of Magnesium Alloys by Second Phase Particle Refinement under the Guidance of Integrated Computational Materials Engineering"

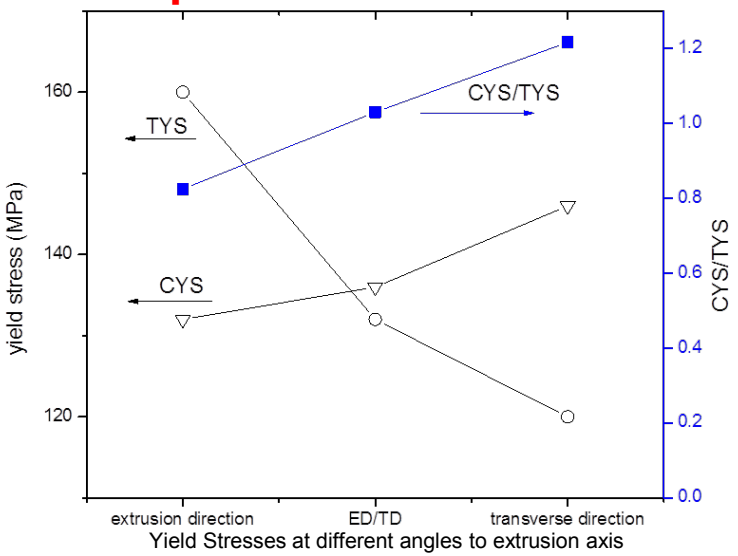
Determination of Grain size and Texture using ICME

Effect of grain size on CYS/TYS ratio



- The influence of grain size on deformation was predicted by modified ϕ-model and polycrystalline viscoplasticity model.
- **It was determined that the CYS/TYS ratio increases as the grain size decreases**

Determine the Texture to improve CYS/ TYS ratio



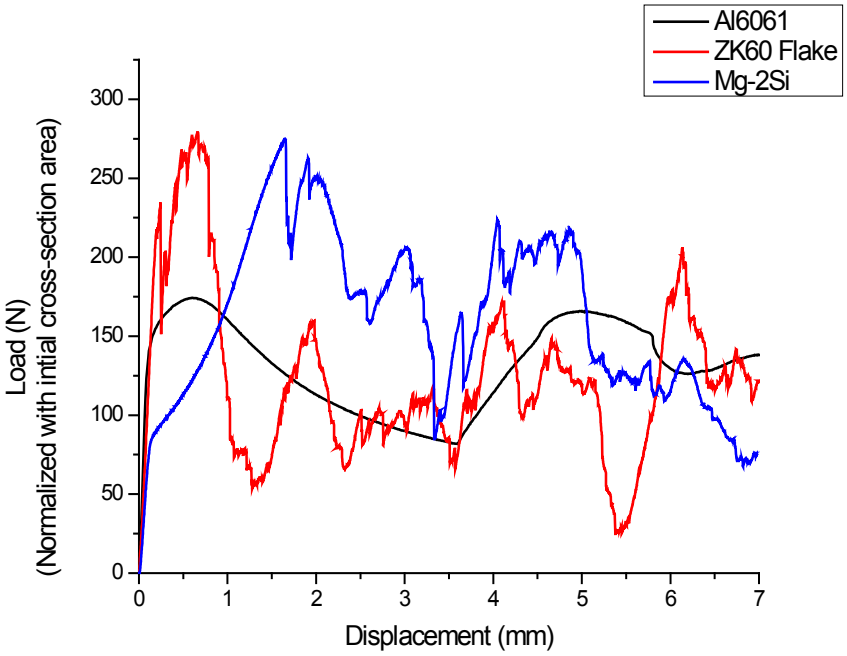
- The influence of texture on the mechanical properties was determined using the smooth particle hydroynamics and modified ϕ-model and polycrystalline viscoplasticity model.
- **It was determined that basal planes should be oriented at least 45^{o} to the extrusion axis**

*The models were compared with experimental values both in literature and lab tests for ZK60 and AZ31

Dongsheng Li, et.al," Yield Asymmetry Design of Magnesium Alloys by Integrated Computational Materials Engineering", ***Computational Materials Science*** , 79, 448-455, 2013

Energy Absorption from High Shear Extruded Tubes

- High shear extrusion can produce desire microstructure that develops high performance properties



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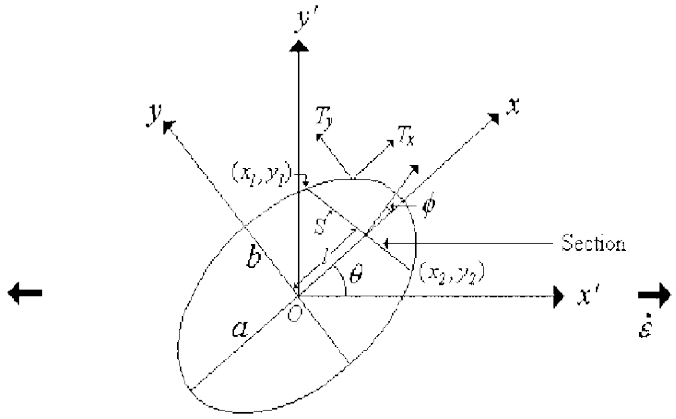
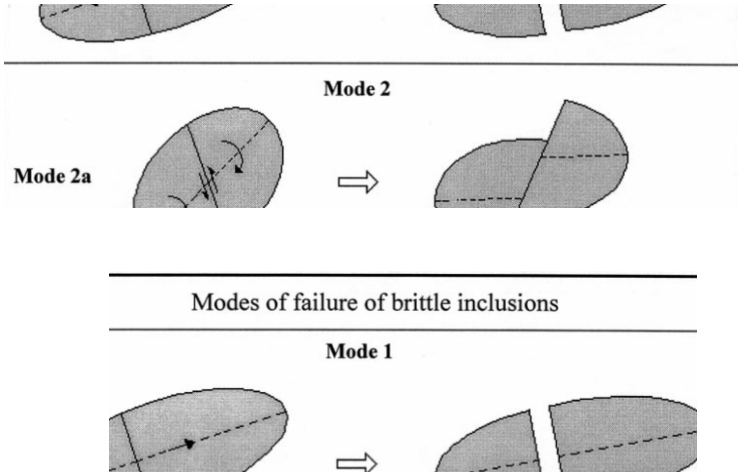
Inverse Process Modeling – Particle Fracture

- 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.*

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



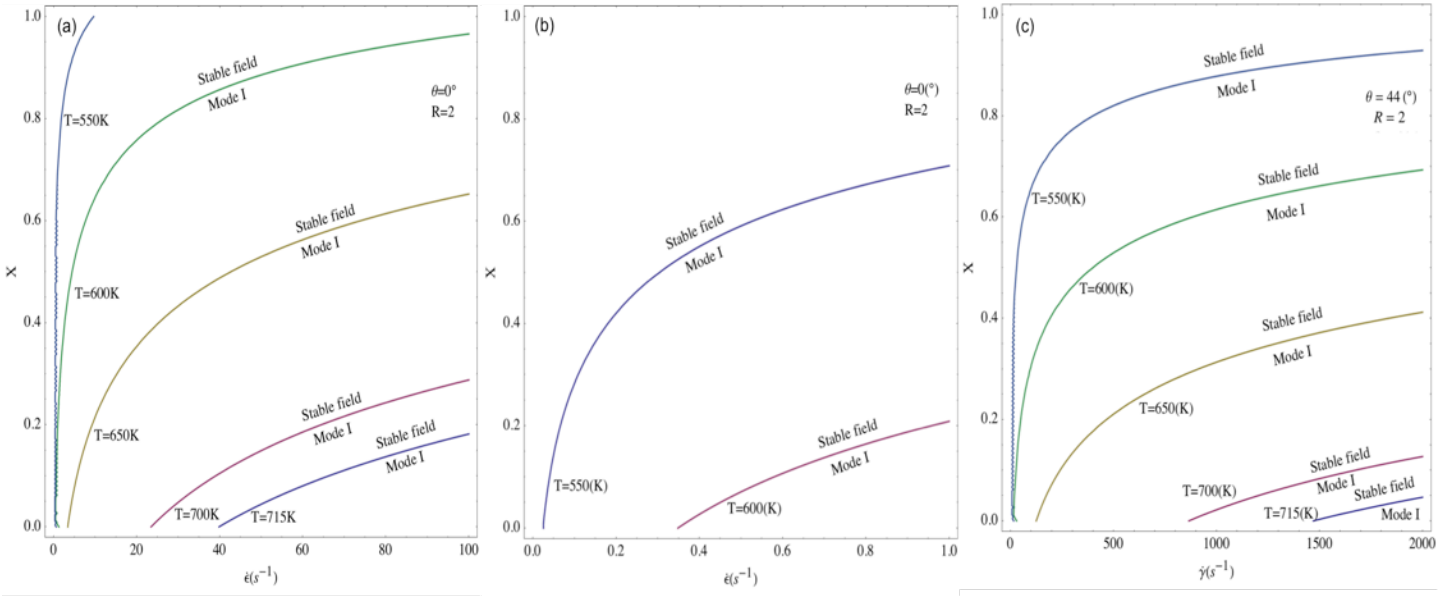


Fracture of intermetallics important to high strain processing – Model to predict behavior developed

Mode 2 desired

Modeling of Particle Fracture

- Georgia Institute of Technology modeling



Effect of temperature on failure behavior in (a) &(b) plane strain compression and (c) pure shear

Tabei A, D Li, CA Lavender, and H Garmestani. 2013. *Effects of Morphology and Geometry of Inclusions on Two Point Correlation Statistics in Two Phase Composites*. PNNL-SA-95353, Pacific Northwest National Laboratory, Richland, WA.

Collaborations

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

Future Work

- Most original technical targets on small scale have been met or appear attainable – next step is reporting on future development needs
  - Full understanding texture will require scale up
- Scale up will require different modeling length scale to understand true cost
  - Move from microstructural to engineering scales

Summary

- A series of magnesium alloys were extruded using high shear to produce high performance tubes with fine grain size
  - Grain sizes appear to be less than 5 μm
  - Novel extrusion system developed and demonstrated
- Tubes extruded with high shear at high speed exhibit energy absorption like that of aluminum
  - 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
  - Used to inform future extrusion development and characterization
- A model to predict the “high shear-extrusion” state of stress needed to facture particles has been developed papers submitted for publication