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 of $140K/yr 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

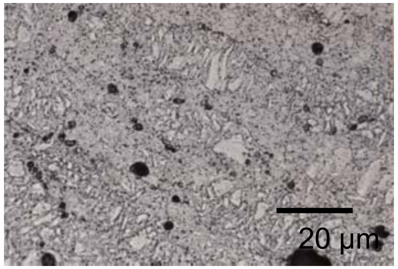
Goals and Objectives

- 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
  - Typically magnesium is not used in bending or energy absorption due to low compressive strength that results in fiber buckling or early yield
    - Tent post is the most publicized example
  - In normal processing the compressive yield strength is 0.65 to 0.75 of the tensile yield.
    - Twinning in compression lowers strength; results in buckling in bending
- Based on prior studies for high performance magnesium alloys
  - Processing was developed to produce high strength, ductile and symmetric (cys/tys) magnesium alloys [cys/tys=1.15]
  - Were shown to outperform 7XXX aluminum in applications requiring high strain rate compression (not necessarily the same as automobile energy absorption)
  - The processing and alloying constituents used are not cost effective for automotive applications
- 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

Milestones – FY2011 and FY2012

- Demonstrate that the high strength Mg RE alloy extrusion can achieve the equivalent energy absorption as 6061 at a mass savings of at least 15%. March 31, 2012 - On target at time of preparation

- Define appropriate test article geometry for energy absorption testing and produce a minimum of 20 meters of extrusion from the Mg non-RE alloy. Completed

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Technical Approach

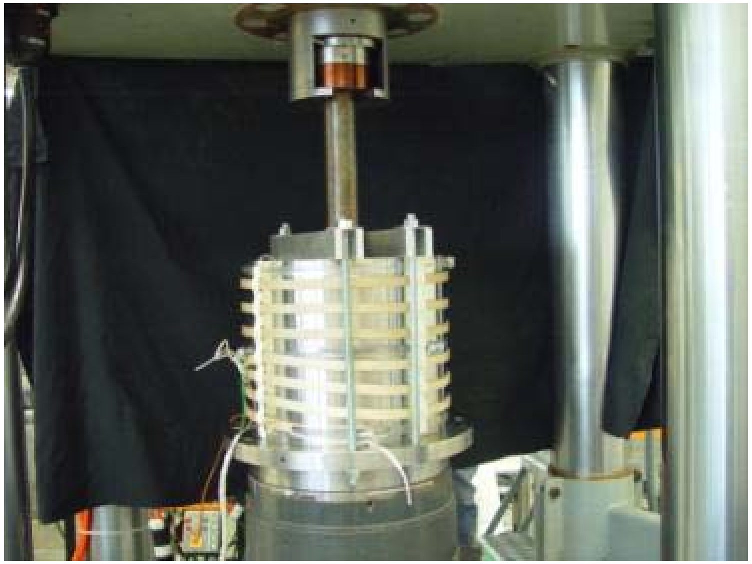
- Three Phases:
  1. Evaluate the energy absorption capability of magnesium alloys processed by novel methods – RE containing
     - Demonstrate energy absorption like AA6061
     - Assess strengthening mechanisms and build model to predict properties and processing relationships
  2. Demonstrate energy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

Alloy Synthesis

- PNNL has been producing magnesium billets with a process that is export controlled:
  - Al, Zn, RE
    - MENA
  - Zn, Zr
    - MENA
  - Zn, RE
    - Custom alloyed at PNNL
  - Zn, Al
    - Custom alloyed at PNNL
  - Others are to be custom alloyed

Examples of billets

PNNL Extrusion



Extrusion die/container with external heating in 4-post 250 ton. Shown with indirect extrusion stem

Extrusion billet (top, 50 mm diameter) shown with extruded rods. Extrusion ratio of approximately 20:1

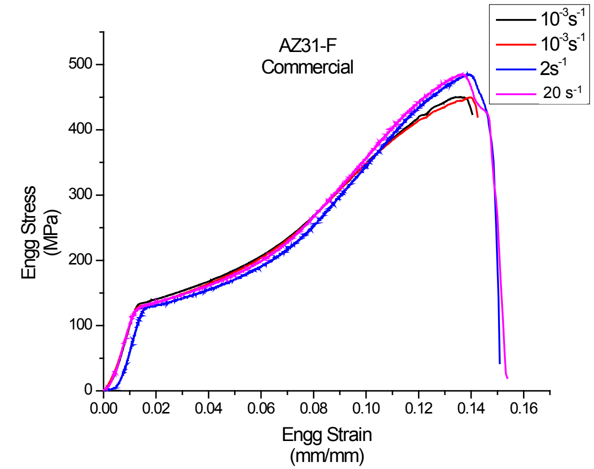
Crush Tube Sample is Test Article for Project

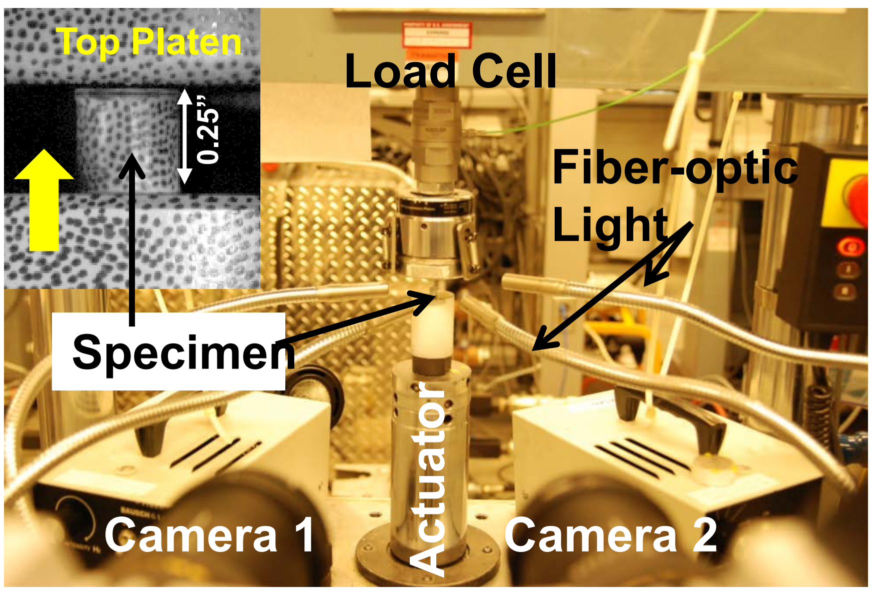
- Tube Sample
  - Length and wall thickness determined by simulation using compression and tension stress strain curves
  - Iterative sample development process from model to experiment
  - Current sample is 7mm OD, 0.5mm wall thickness and 15 mm long
    - At the time of this presentation

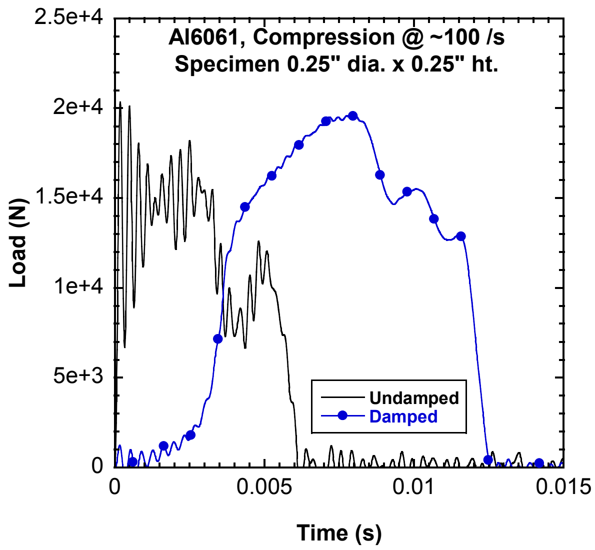
- PNNL Test Facilities for Crush Tube Testing
  - Camera systems and speckle strain imaging up to 90,000 frame/second
  - Servo-hydraulic with piezo-electric load cell up to 2500 mm/sec
  - Standard Servo-hydraulic systems for rates up to 20 mm/sec

Elevated Strain Rate Compression Testing

- Medium-rate compression testing capability
  - Determine strain-rate sensitivity ($10^{-3} \rightarrow 10^{2}$ /s)
  - Screening tool for microstructural effect
  - Strain measurement via speckle imaging
- Modeling tube compression
  - Used from empirical fit stress strain in compression
  - Incorporate strain-rate sensitivity







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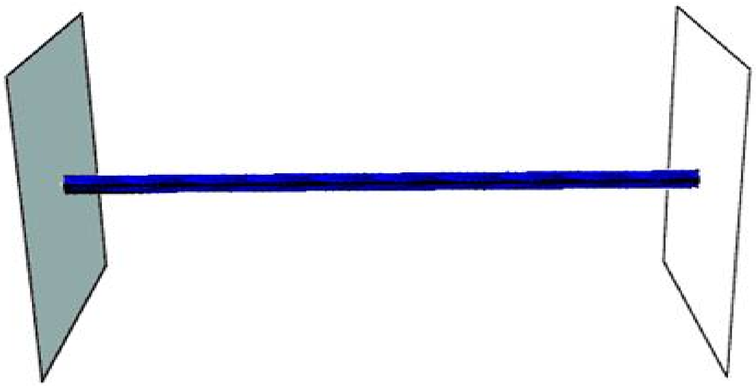
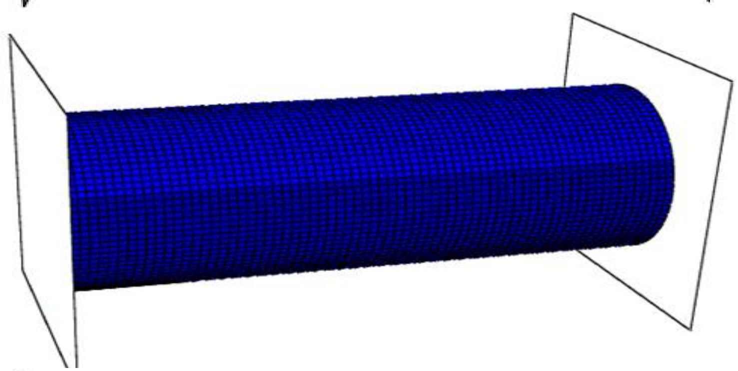
Energy Absorption Sample Development

Sample Size Determination from simulation/experimental iteration

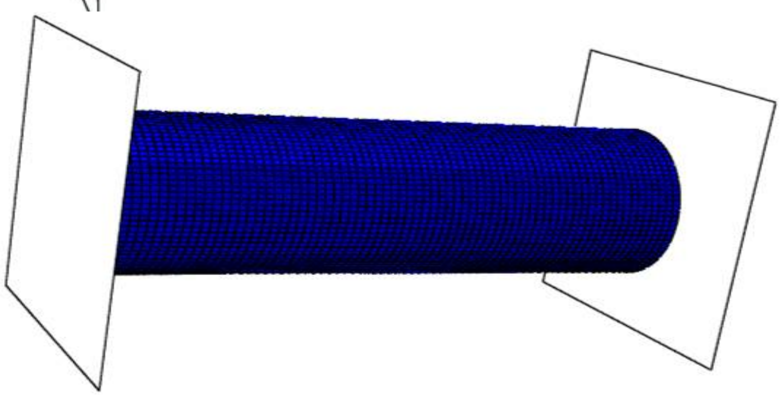
Click on images to run videos



Too Slim!



Good sample geometry size



Too thick – compression test

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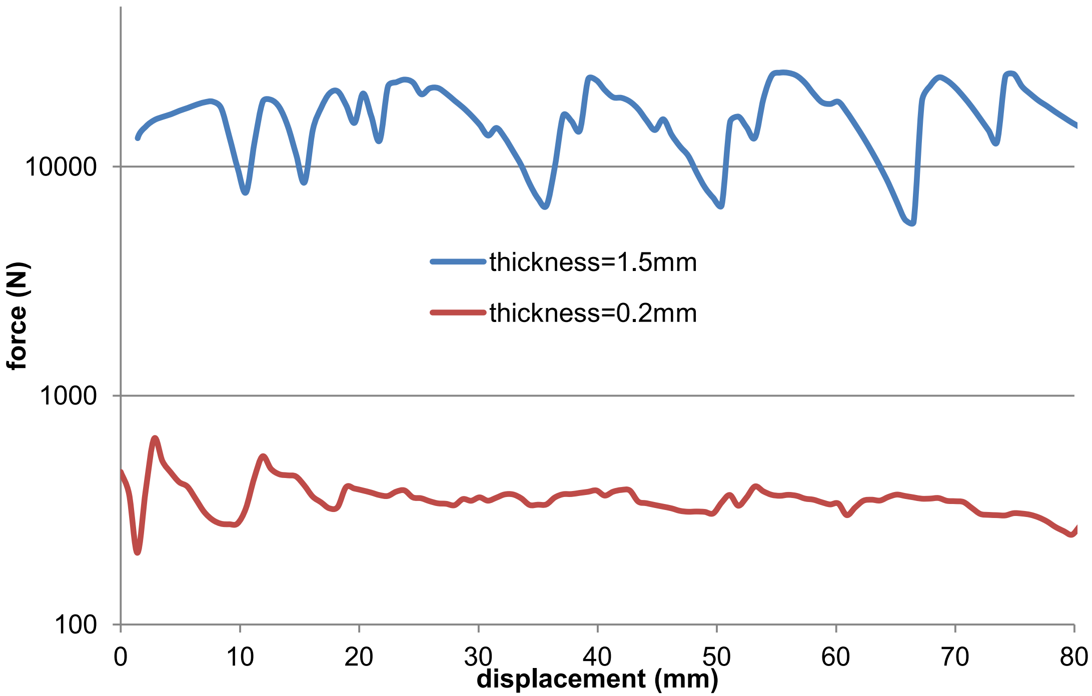
Energy Absorption is related to the sample geometry size



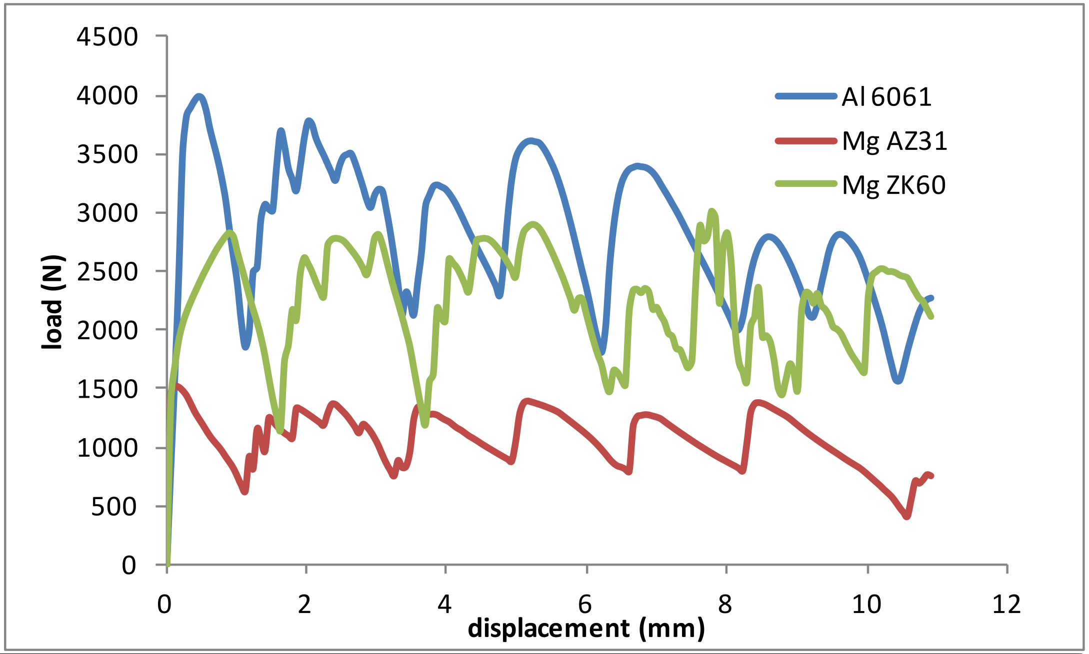
Absorption Energy (J/m^3)

$7.15*10^7$ (thickness=1.5mm)

$1.13*10^7$ (thickness=0.2mm)

Specific absorbed energy increases with the decrease of thickness at the beginning, then drops down the sample is too thin. There is an optimal size of thickness with high SAE. In our experimental setup, we chose sample thickness as 0.5mm

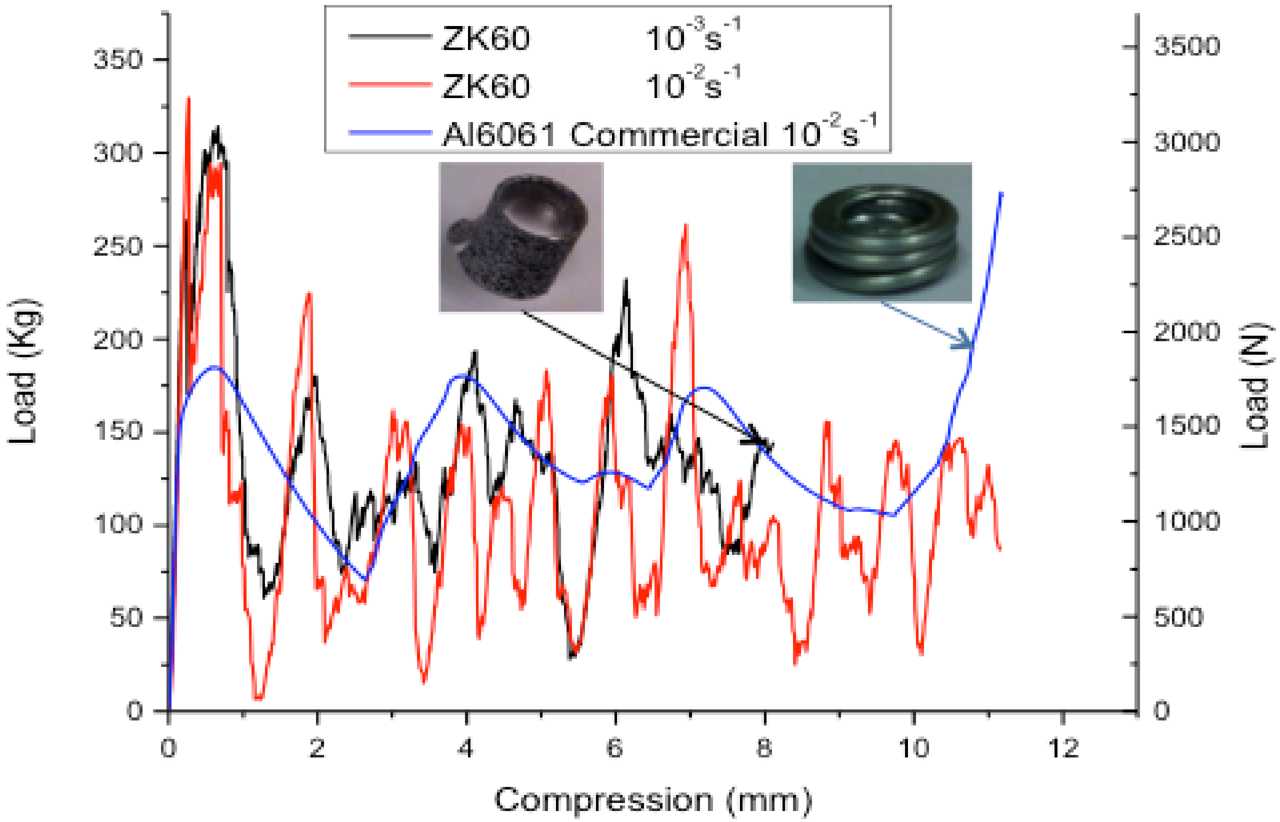
Comparison of Simulated Energy Absorption of Magnesium and Aluminum



	Al 6061 Al 6160	Mg AZ31	Mg ZK60
density kg/cm^3	2.7	1.74	1.74
absorbed energy (kJ)	14.94	6.94	11.71
normalized SAE	1	0.73	1.22

We compared two magnesium alloys, AZ31 and ZK60, and one aluminum alloy, Al6061. Specific absorbed energy (SAE) from AZ31 is 27.8% lower than Al6061; while SAE of **ZK60 is 21.6% higher than Al6061**.

Energy Absorption Testing



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

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Deformation behavior prediction using dislocation based crystal plasticity model

Experimental based constitutive model was used
to predict behavior for tube crush;

Microstructural data from high performance magnesium alloys are being used to populate constitutive models to be used in performance predictions

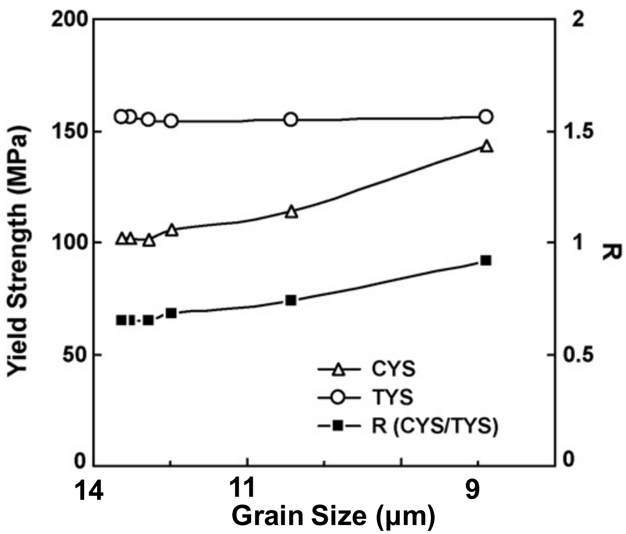
- The twinning model assumes homogeneous grain deformation, localizes deformation in a volume fraction of the grain:

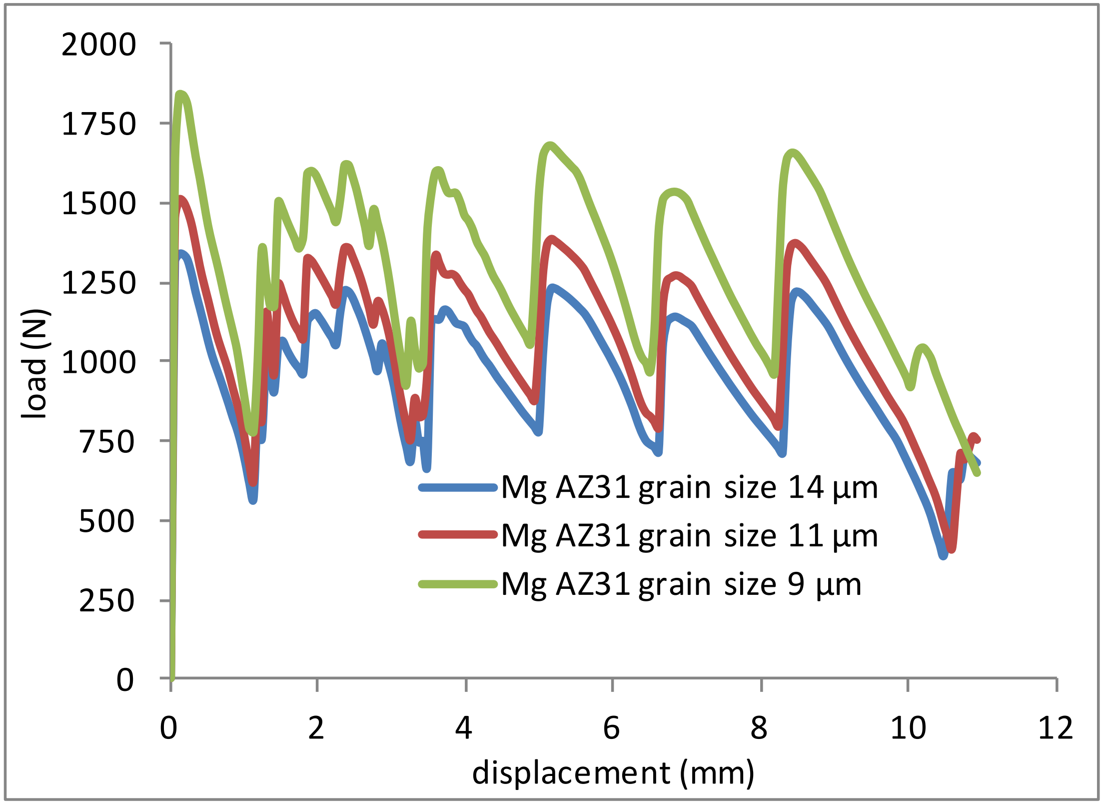
$$\Delta g^{n,t_i} = \frac{\Delta \gamma^{n,t_i}}{S}$$

- The parameters used in crystal plasticity models , such as viscoplasticity self consistent model, hybrid model, or phi-model, are calculated from continuum dislocation dynamics proposed. The crystal plasticity model will be used to predict the texture evolution and mechanical response in polycrystalline materials.

Plastic velocity gradient:	$L^p = \sum_{\alpha=1}^{N} \dot{\gamma}^\alpha n^\alpha \otimes m^\alpha$	(1)
Plastic shearing:	$\dot{\gamma}^\alpha = \rho_M^\alpha b v_g^\alpha$	(2)
Total Dislocation density:	$\rho^\alpha = \rho_M^\alpha + \rho_I^\alpha$	(3)
Dislocation glide velocity:	$v_g^\alpha = v_0 \left\| \frac{\tau^\alpha}{\tau_{CR}^\alpha} \right\|^{1/m} \mathrm{sgn}(\tau^\alpha)$	(4)
Resolved shear stress:	$\tau^\alpha = \sigma : n^\alpha \otimes m^\alpha$	(5)
Slip resistance:	$\tau_{CR}^\alpha = \tau_0 + \tau_d^\alpha + \tau_\rho^\alpha$	(6)
Irradiation hardening:	$\tau_d^\alpha = \beta d \mu (\rho_d d)^n$	(7)
Dislocation Interaction hardening:	$\tau_\rho^\alpha = \alpha b \mu \sqrt{\sum_m \Omega^{\alpha m} \rho^m}$	(8)

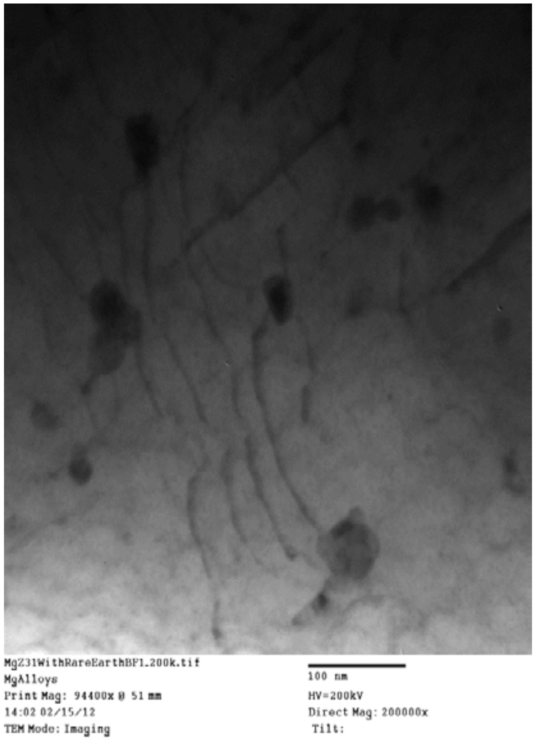
Simulated Influence of Grain Size on Absorbed Energy



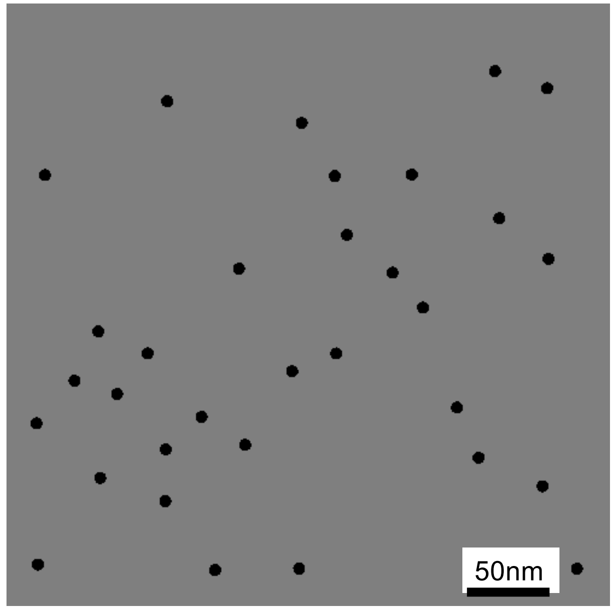


With the decrease of grain size, the compression yield stress increases and the SAE increases. For AZ31, the magnitude of increase with decreasing grain size is not large enough to exceed Al6061. For ZK60, grain size refinement is a good approach for improved SAE

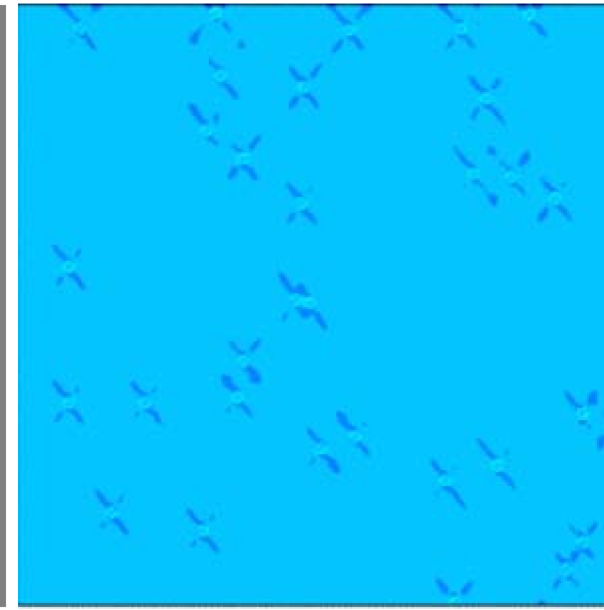
Influence of precipitates on properties



TEM micrographs shows precipitates in ZK60 with size between 10-40nm.



Simulated microstructure with precipitates with size 15nm



Simulated mechanical deformation behavior

From the statistical information of the microstructure, a large high resolution image was reconstructed. The influence of precipitates on mechanical response (stress strain curve) was investigated, then fed into crash model.

Collaborations

- Magnesium Electron North America has provided master alloys and alloys for processing
- Magna/Cosma Engineering has provided property goals and extrusion design
- Georgia Tech has started characterization efforts to provide precipitate structure and composition

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

Future Work

- Develop extrusion model with capability to predict the evolution of microstructure and mechanical properties with different processing parameters.
- Investigate the influence of tension/compression asymmetry on crush in magnesium by introducing material subroutine (VUMAT).
- Implement and apply dislocation dynamics based crystal plasticity model in ZK60
- 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
- Produce prototype extrusion for large scale evaluation

Summary

- A series of magnesium alloys were synthesized and extruded to produce high performance magnesium alloys with fine grain size dispersions
  - Grain sizes appear to be less than 5 μm
  - Dispersions near 15 nm interact with dislocations
- A test article was developed to compare energy absorption of aluminum to magnesium
  - 7mm OD 0.5 mm wall tube 15 mm in length
  - A high rate compression test was developed to understand strain rate sensitivity given that predominate deformation mechanism is changing in compression
    - Strain rate sensitivity has not been observed to date
- A non rare earth containing magnesium alloy processed for fine grain size and dispersion can absorb energy similar to 6061 aluminum
  - This is a 20% mass savings over 6061
  - Mode of failure is different
- Microstructural modeling has been initiated to help understand the behavior and predict energy absorption
  - Grain size as it impacts stress strain has been implemented
  - Strengthening with hard second phase has been added
  - This work will now leverage fracture and ductility project