High Strain-Rate Characterization of Magnesium Alloys

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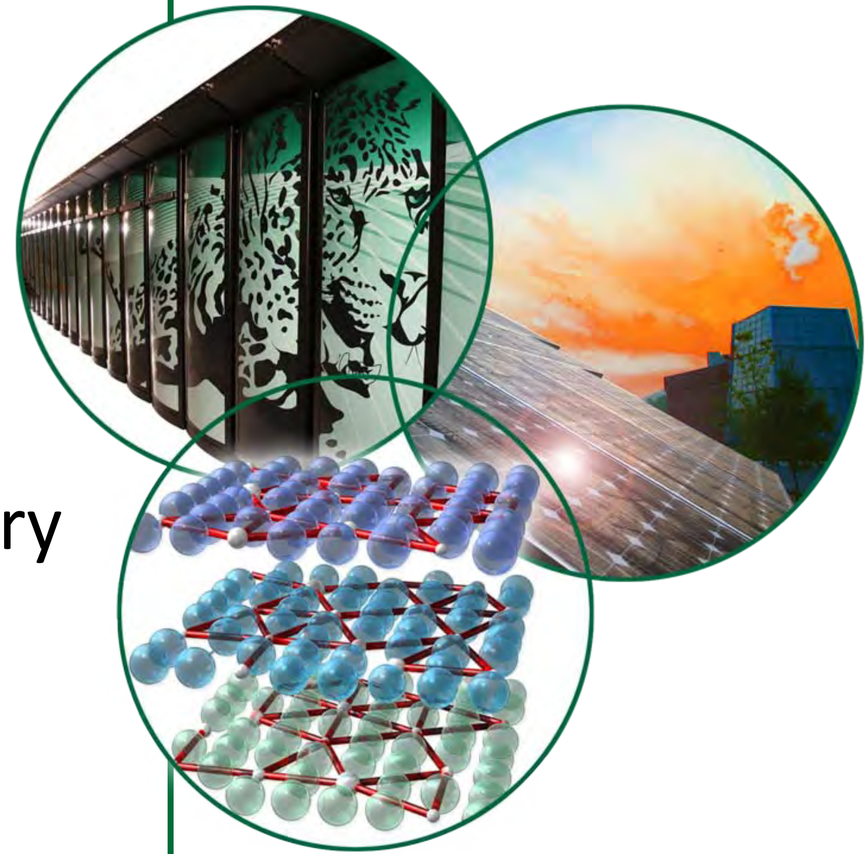
May 9-13, 2011



Project ID # LM032

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Overview

Timeline

- Project start date FY2008 (4 qtr)
- Project end date FY2011
- Percent complete 70%

Budget

- Total project funding
  - $825 K
- Funding received in FY 2010
  - $275 K
- Funding for FY 2011
  - $200 K

Barriers

- Design data and modeling tools
  - *Adequate design data (material property databases), test methods, analytical tools (i.e., models), and durability data are inadequate for widespread applications of lightweight materials.*
- Performance
  - *Materials needed to achieve the specific performance objectives may not exist today as durable, reliable, well-characterized and understood materials.*

Partners

- Mg Front End R&D
- Project lead: ORNL

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Objective

- Provide enabling technologies for use of lightweight materials (Mg alloys) in automobiles by the development of:
  - High strain rate test methods
  - Methods for characterization of material property degradation (damage) evolution under high rates
  - Methods for failure characterization at high rates
  - Databases of material properties
  - Constitutive models for FEM simulations
- **Technology developed in this project is directly applicable to Mg alloys and other lightweight materials.**

Relevance to VT Program

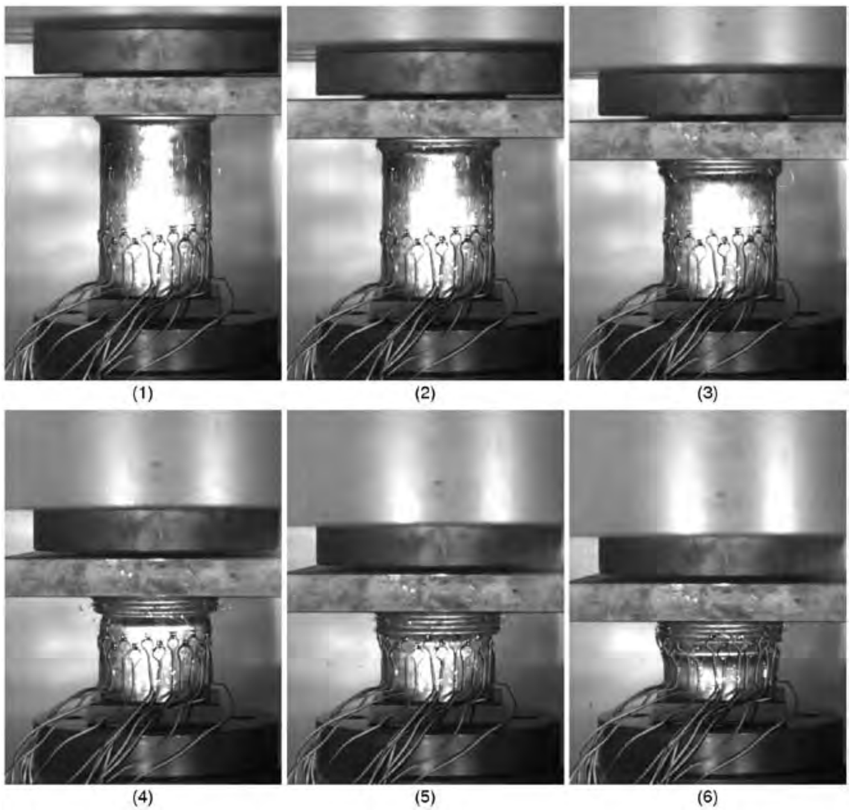
- The current designs with lightweight materials result in overdesigned components in order to compensate for the uncertainties in the deformation and failure mechanisms.
- Reducing uncertainties in component design greatly improves the overall vehicle system reliability and enables weight reduction (**Technical Target: Vehicle Weight**).
- Vehicle designers need (**Barriers C and G**):
  - Mechanical properties under impact, damage and failure characterization, material and failure models, FEM technology
  - Methods for material characterization under impact
  - *Very limited material data and models are currently available for crashworthiness of Mg alloys*
- **This project develops enabling technologies and material data for use of Mg alloys in automotive structural applications.**

Milestones

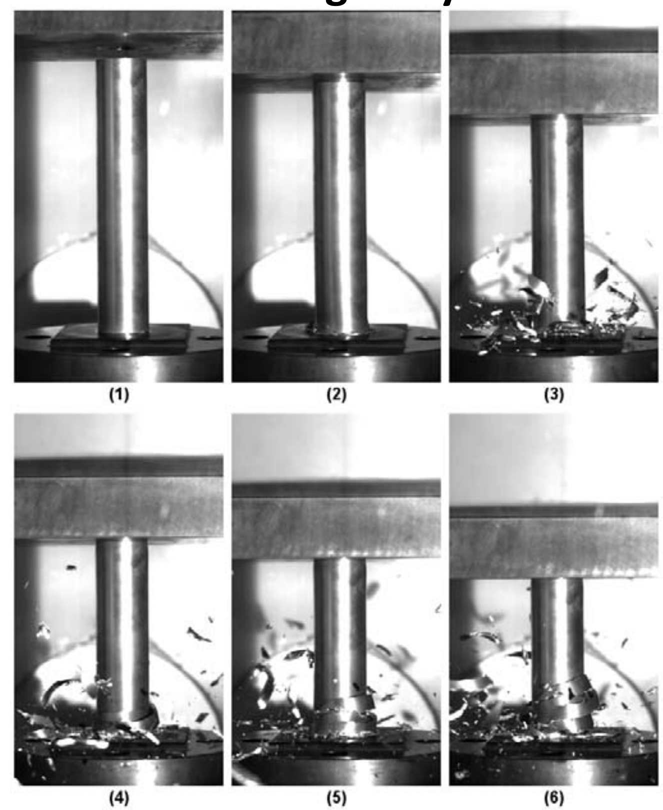
Month/Year	Milestone
February 2010 Completed 7/10	Resolve discrepancies in test measurements and develop force and displacement measurement system for AM60B alloy sheet specimens
April 2010 Completed 11/10	Complete microscopic analysis for quasi-static damage evolution of internal defects for AM60B
June 2010 Completed 8/10	Complete tensile strain rate tests of up to 1000/s for AZ31 Mg alloy
September 2010 *April 2011*	Complete interrupted tensile loading tests from strain rate tests of up to 1000/s for AZ31 (*test matrix extended to include AM60*)
Month/Year	**Milestone**
November 2010 Completed 11/10	Test design for shear testing under high strain rates
December 2010 Completed 2/11	Develop constitutive models based on damage evolution under tensile tests AM60B
March 2011	Shear specimen strain rate tests up to 100 /s
May 2011	Complete microscopic analysis for strain rate damage evolution of internal defects for AM60B
August 2011	Develop constitutive models based on damage evolution under tensile and shear tests AM60B

Crashworthiness Tests

HSLA



Mg Alloy



- Impact energy dissipation in Mg tube occurs by different process than in the conventional automotive materials.
- **Vehicle designers need to understand initiation and evolution of internal state and failure processes in Mg alloys as functions of loading type and loading rates.**

Strain Rates in Automotive Design

- **Low (quasi-static) rate tests** - entire system is in equilibrium at all times
- **Fast rate tests** - single impact pulse travels through the system
- **Intermediate rate tests (between 1/s and 1000/s)** - multiple wave reflections in the system
  - Difficult to establish dynamic equilibrium in the sample and the system
  - These rates are important because maximum **strain rates in automotive crash** are in the interval of 10-1000/s (also important for forming)
- It is essential to:
  - Reduce mass in the system
  - Develop lightweight load cells and sensors
  - Understand and control oscillations in the system
  - Combine multiple measurement techniques for the same data
- Intermediate strain rate tests have not been standardized
  - Active research field
- **This project develops new testing methodologies and material information for the strain rates of interest in vehicle design.**

Approach/Strategy

- Develop new methods and procedures for measurement of material behavior at intermediate strain rates.
  - Develop test methods, loading equipment, control, sensors, specimens, fixtures.
- Test measurements must be based on multiple sensor types.
  - We must have multiple data sources for each measured quantity.
- Verify measurements throughout the range of strain rates of interest.
  - As some sensor types reduce accuracy with increasing speeds, new sensors must gradually take over.
  - Validity of a new sensor type must be established in the transition region.
- Develop new methods for strain-interrupted tests at high rates.
  - Essential for investigation of strain-rate dependency of damage evolution.
  - **It is easier to speed up than to instantly stop, especially at 500 in/sec.**
- Investigate formation and growth of voids in Mg alloys using microscopy for strains and strain rates of interest.
- Distribute data as soon as possible.

Technical Approach

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Materials and Test Instrumentation

Materials Tested:

AZ31 sheet metal
AM60B cast (top hat)
AM60B unprocessed
Materials for test development (AHSS)

Custom Designed Hydraulic System

Max Velocity=700 in/s
(18.5 m/sec) over approx. 4 in (100 mm) Range

Load Capacity : 9000 lbs (40 kN) static, 5500 lbs (25 kN) dynamic

Total Stroke: 15.5 in (400mm)

Working Stroke: approx. 7.0 in (175 mm) with slack adapter in the load train

Control: MTS 407 servo - hydraulic controllers, with external command signal (drive file). In-house developed synchronization and DAQ systems.

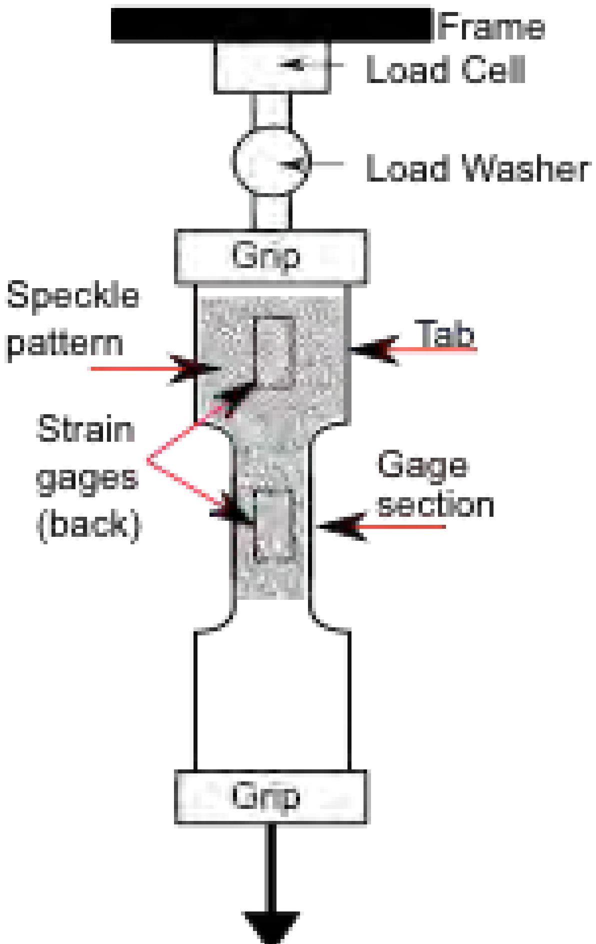
High speed digital imaging system

Max. Frame rate: 1000000 fps
3D imaging capability for full field displacement map

Control and synchronization of multiple data sources are essential for accuracy at high speeds.

Technical Approach

Uniaxial Tension Tests for Intermediate Strain Rate Regime Use Multiple Sensors

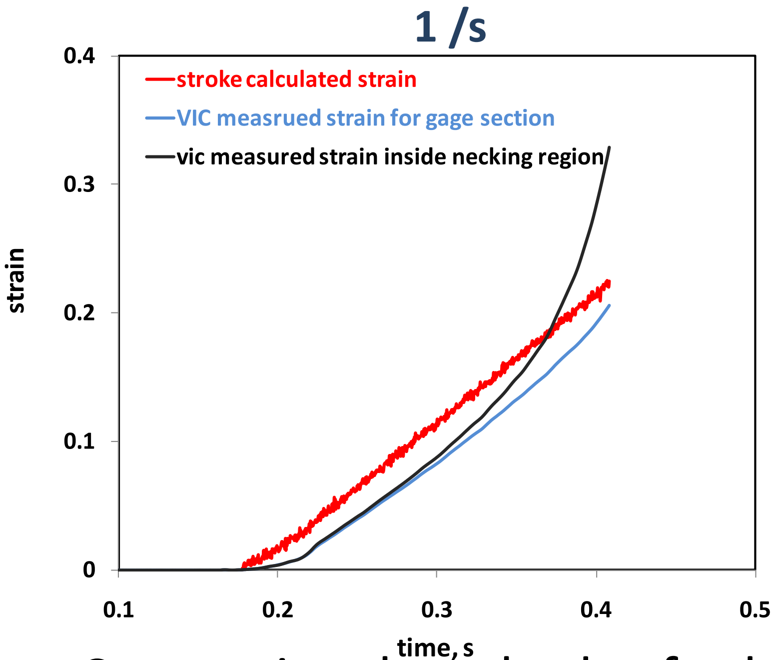


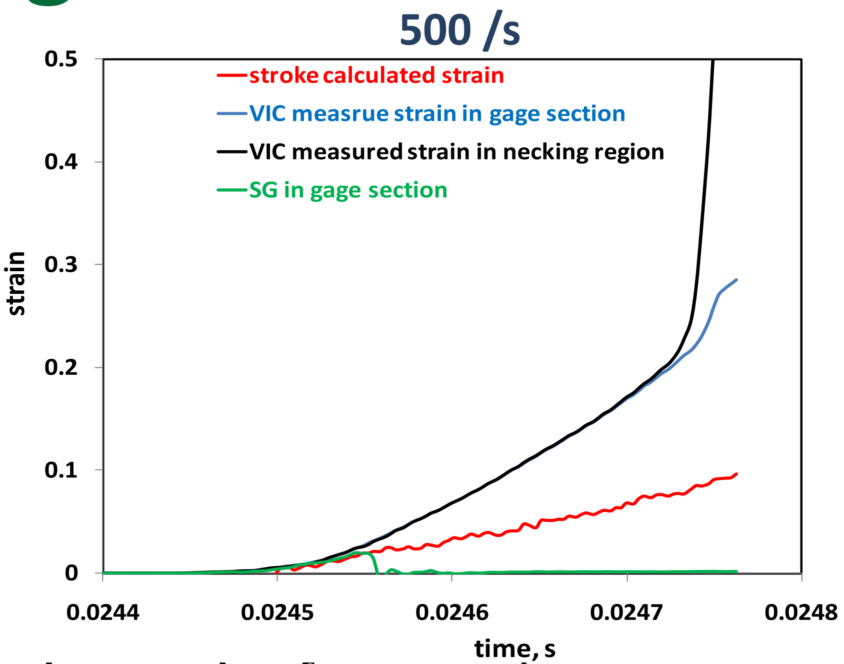
Specimen and sensor schematics

Test Instrumentation and Setup

- Elimination of ringing in the system is the most challenging task.
- Standard load cells loose accuracy at high rates due to inertia of the devices.
- Strain gages on the specimen are used for strain and stress (tab region) measurements.
- Optical strain measurements from high speed camera are used for strain and stress measurements across the specimen.
- Measurement from different sensors is compared for different strain rates in order to establish correlations and estimate errors.

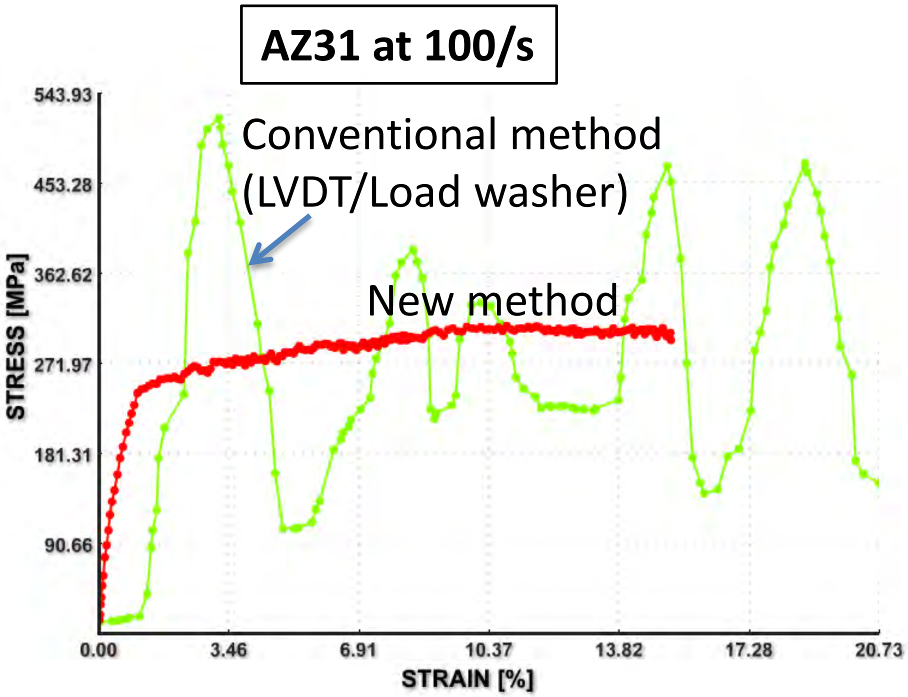
New Test Setup Provides for Accurate Measurements of High Strains and Rates

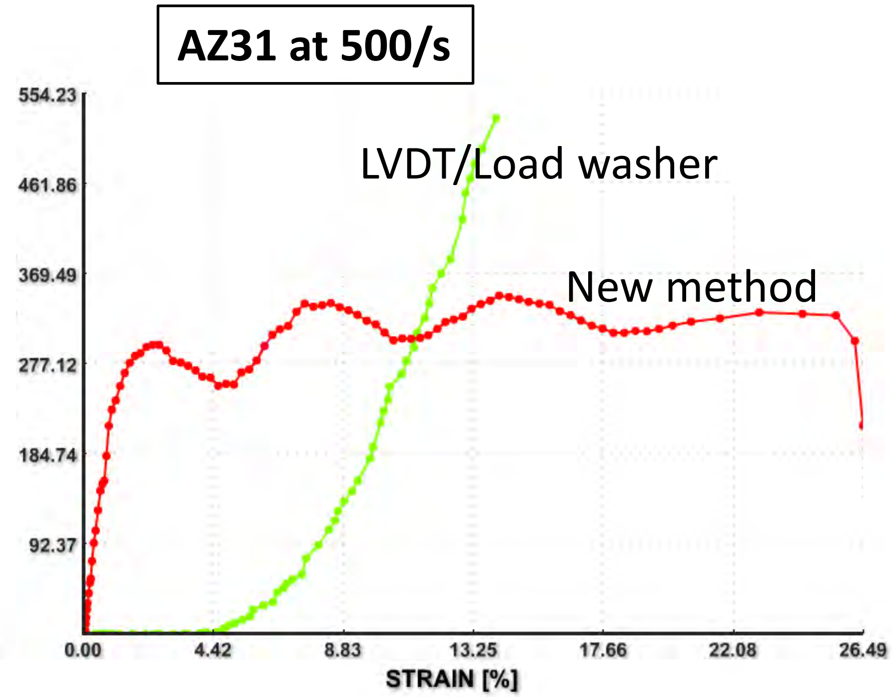




- Conventional methods of calculating strains from stroke are not accurate.
  - At low strain rate (1 /s), strain calculated from stroke tends to overestimate the average strain of the gage section.
  - At high strain rate (500 /s), strain calculated from stroke tends to underestimate the average gage section strain.
- **Digital Image Correlation (VIC) enables measurement of strains well beyond the range of fast-response bondable foil gages.**

New Strain Rate Testing Method





- Conventional approaches give inaccurate measurements that need to be filtered and cannot provide data for small strains and for high strain rates.
- **We accomplished significant improvement in measurements of stresses, strains and strain rates in the intermediate strain rate regime.**

Technical Accomplishments

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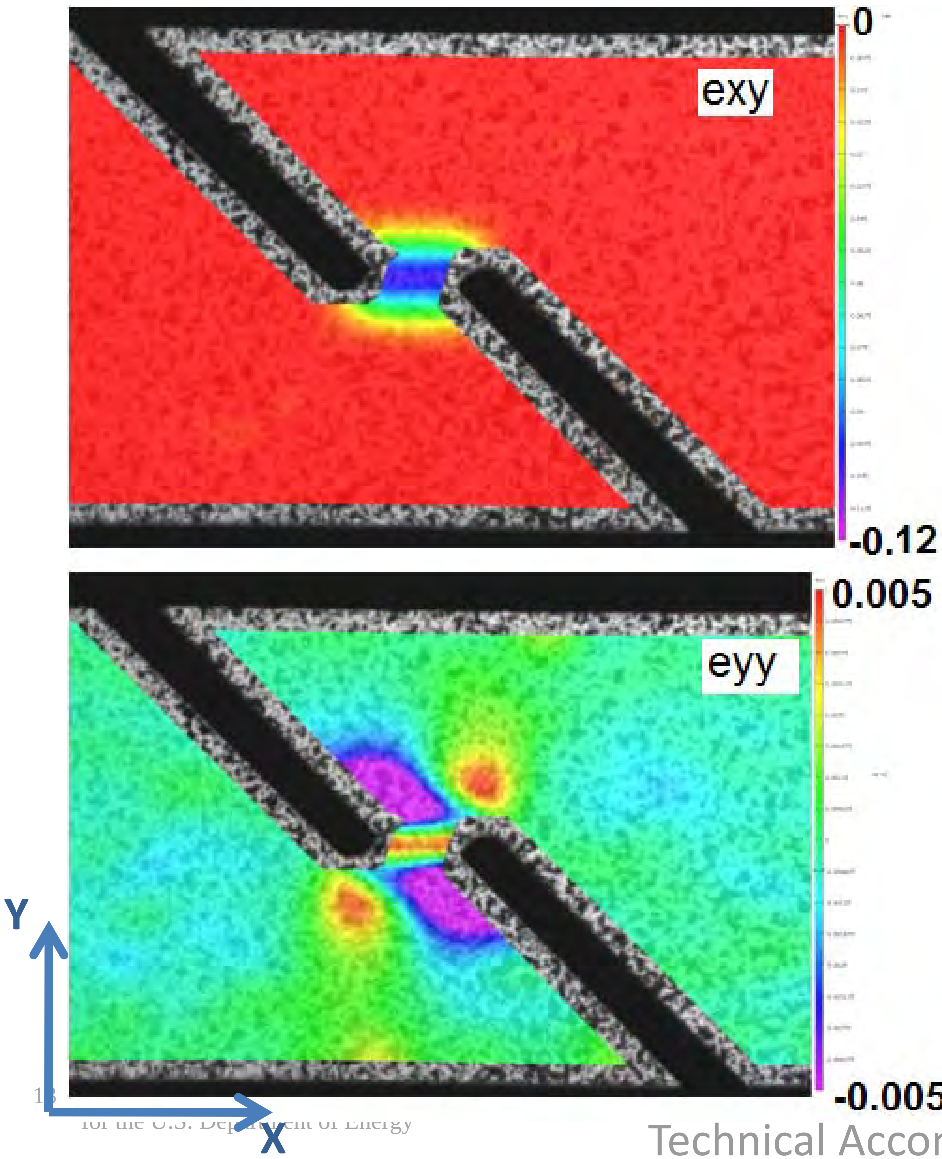
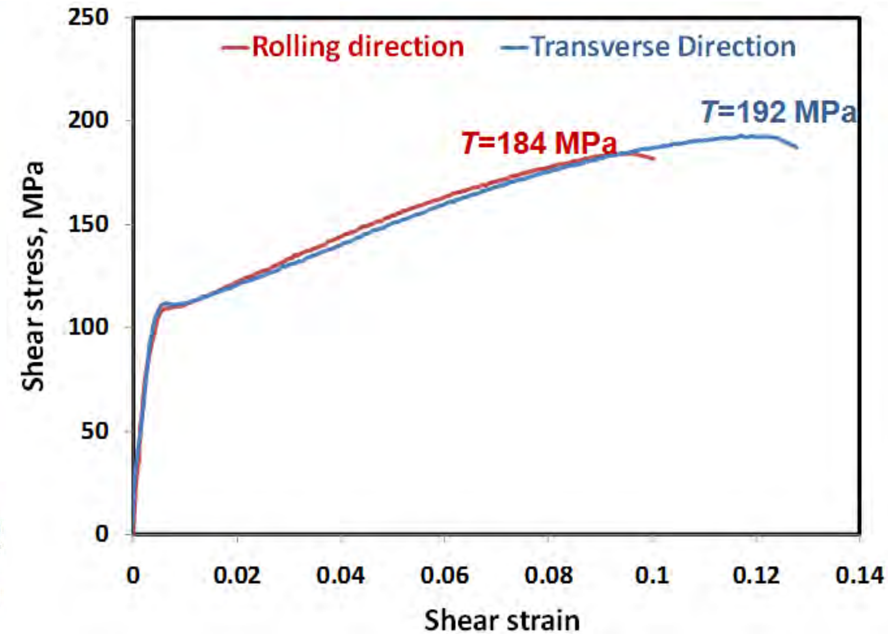
Initial Shear Tests for AM60 Have Been Successful

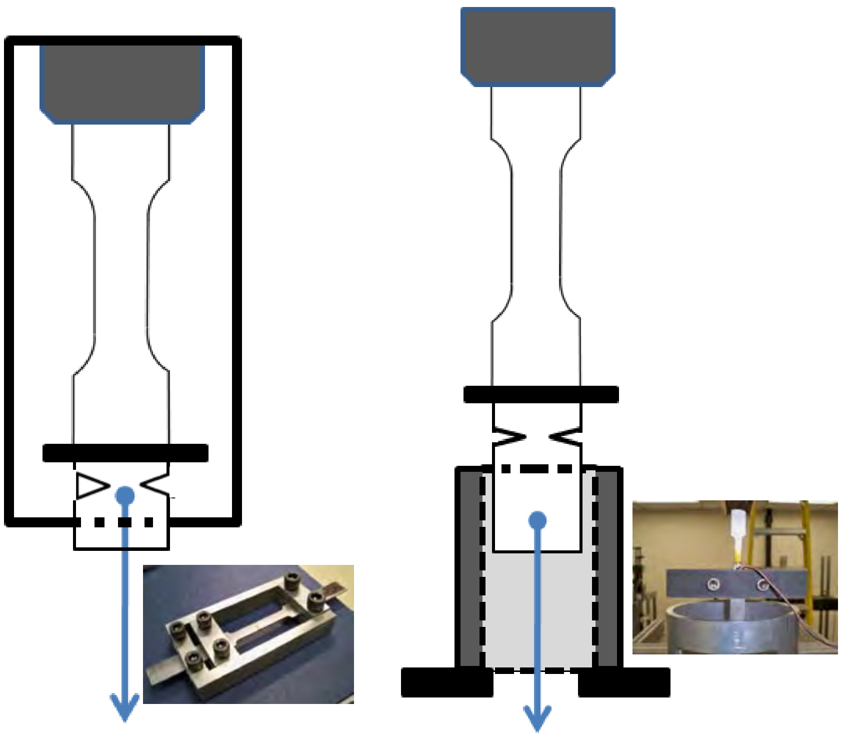




- The tests show reasonable strain distributions in the test specimens.
- Test data correlates well with the tension tests.

We have Designed New Test Fixtures and Specimens for Prescribed Strain Application at High Strain Rates

Attempts at New Fixture Designs

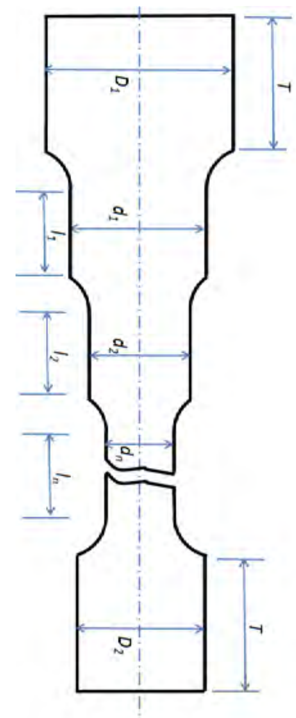


Type I

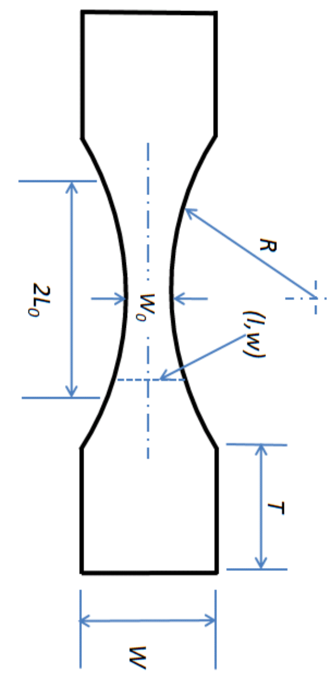
Type II

- Difficult to control
- Problems increase with speed
- Requires a large number of tests
- **Scrapped, went with new approach**

New Specimen Designs



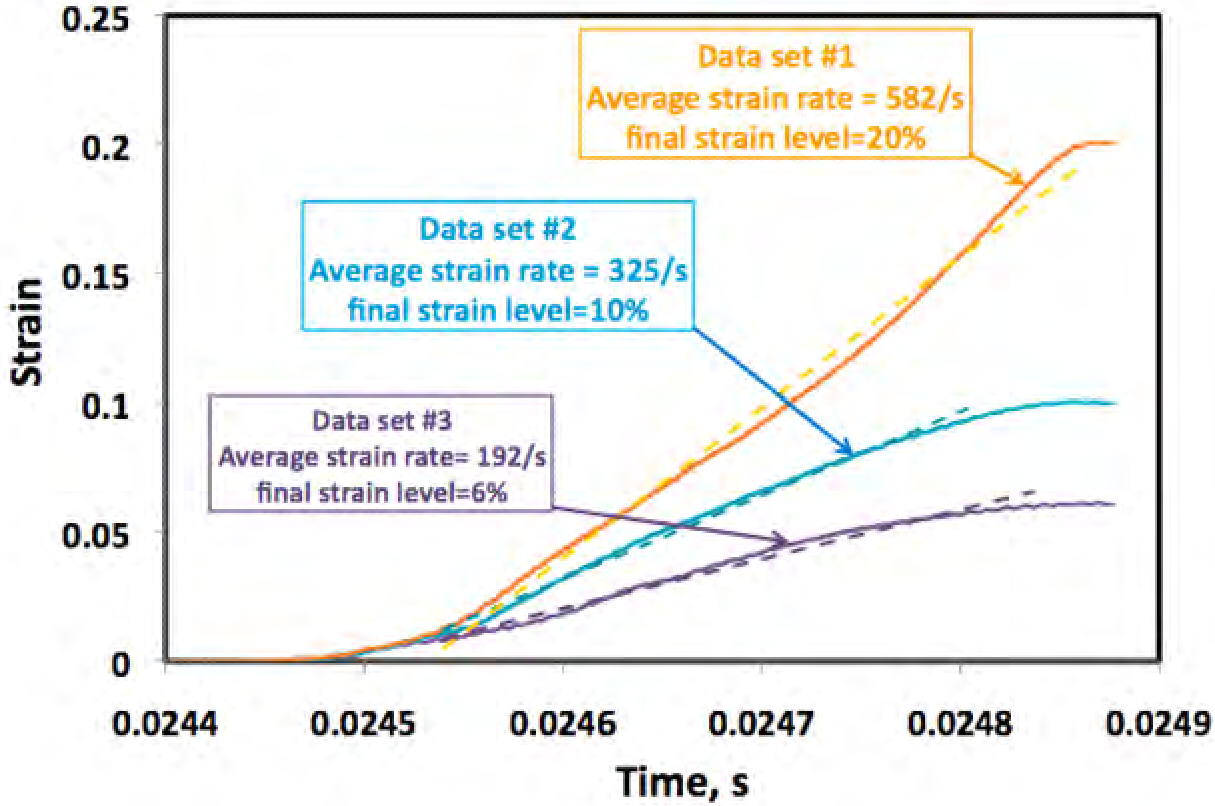
Multi-gage



Tapered shape

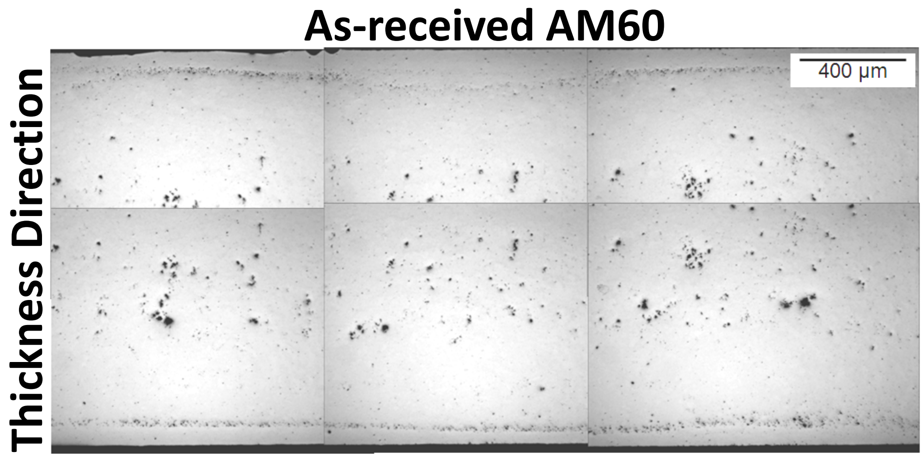
- Reduces the number of tests and specimens
- Shape design is determined by modeling
- No added mass, simpler, cheaper method
- Invention application in process

The New Test Generates Multiple Strain Rates in a Single Specimen



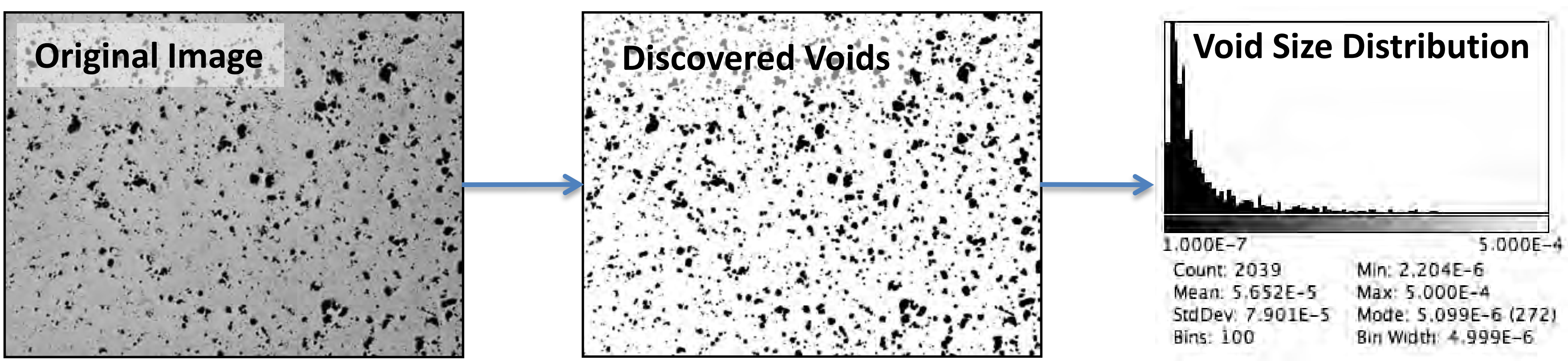
- **The new method generates smoothly increasing strain path to the final strain under reasonably constant strain rate.**
- Further test development is planned for in order to improve the control of strain and strain rate distribution.

Damage Analysis in Mg Alloys

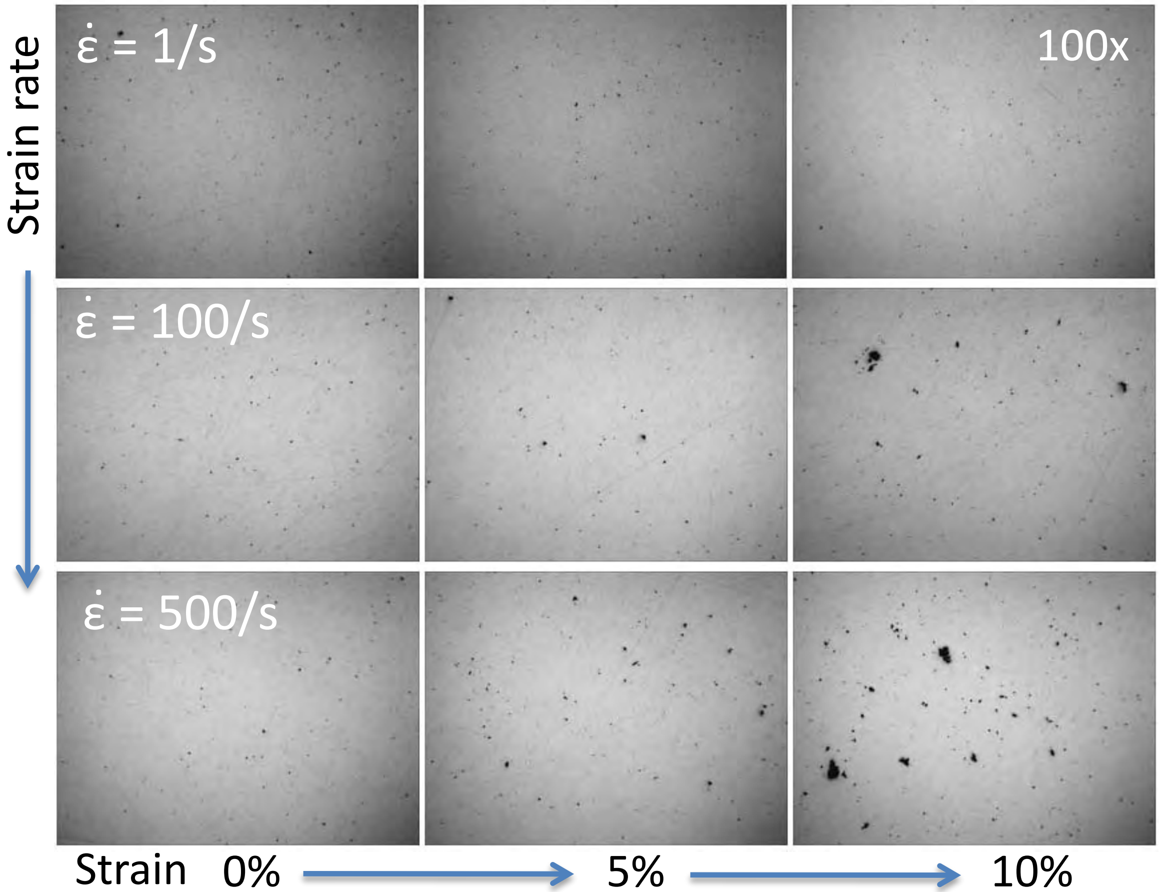


- **Non-uniform distribution** of the pores/mirostructure needs to be considered when locating the area of interest.

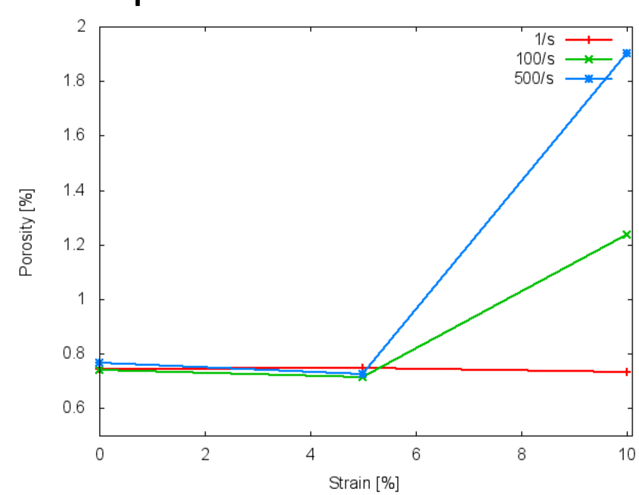
- The void statistics are generated by image processing.
  - Data can be used for calibration of micromechanics-based material and failure models for FEM simulations.



Void Profile Examples for AM60

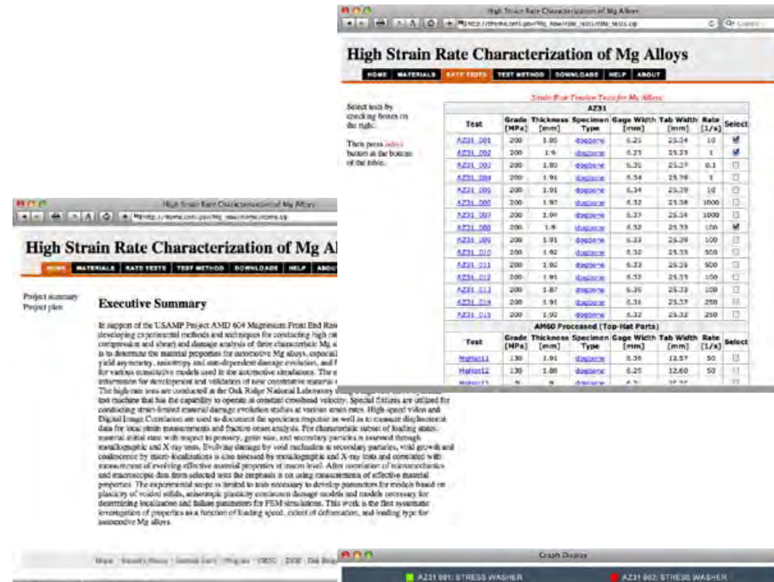


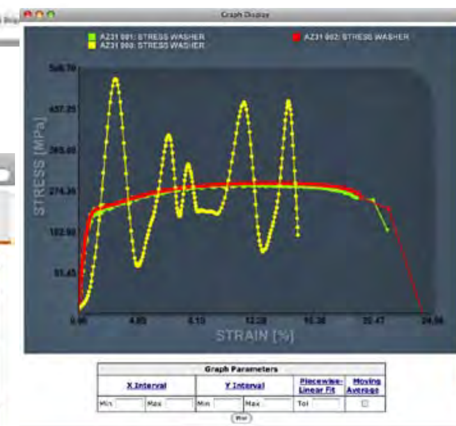
- Results are generated by the new test method
- The tests show that void nucleation and growth (damage) intensifies with strain rates for AM60.
  - More test are needed for different initial porosities

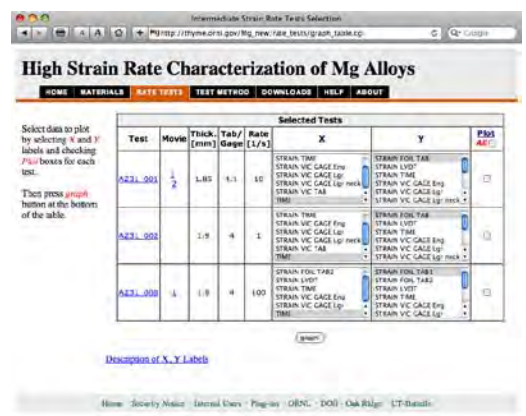


Collaboration and Coordination with Other Institutions

- Collaboration with Mg Front End R&D Project
  - Materials supplied by OEMs
- Technology Transfer
  - Test data distributed via www
    - http://thyme.ornl.gov/Mg_new
  - Users can select/view/process data and download it for FEM material models
  - Direct communication to OEMs
- Education
  - Two postdoctoral students
  - 8 student interns so far
  - 9 summer students for 2011







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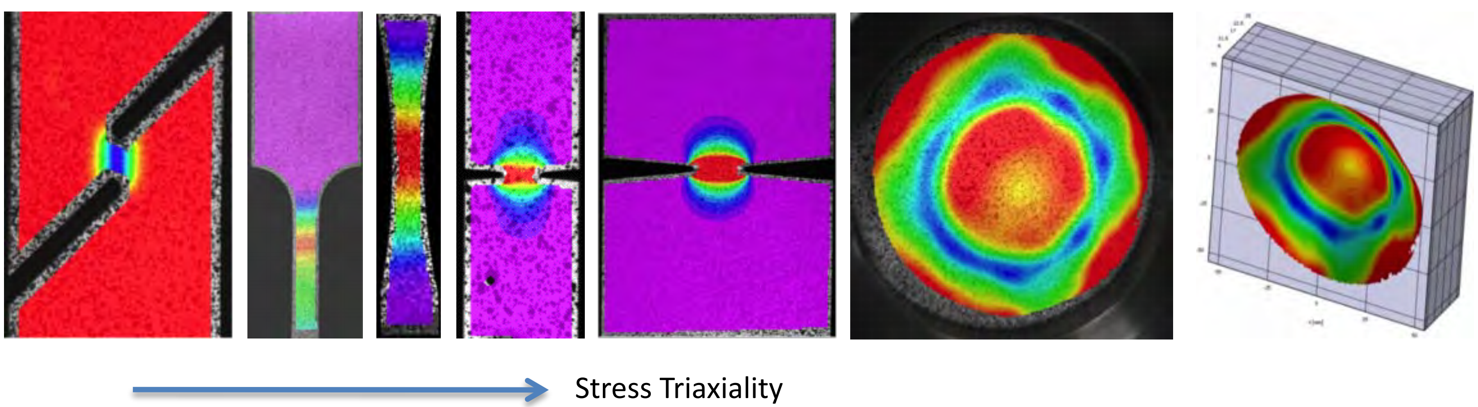
Proposed Future Work

- In-depth characterization of ***damage evolution*** in Mg alloys of interest to automotive designers at various strain rate conditions, loadings and initial microstructures.
  - Design new methods for tailored *strain* application under intermediate strain rates.
- Advance technology for intermediate strain rate testing in ***tension, shear*** and ***multi-axial loading*** configurations.
  - Essential for development and calibration of advanced material models for lightweight materials. The damage models require wide region of stress states and loading paths.
  - Support development of forming technologies and new material processes such as asymmetric rolling for Mg alloys



- Development of methods for characterization of ***fracture/failure*** properties of Mg sheet materials.

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Summary

- We have developed and demonstrated test methods for characterization of materials under strain rates typical of vehicle crash.
  - Tension and shear configurations were developed.
  - Tests provide much needed data for Mg alloy applications.
  - Tests are used for material model development and calibration.
- A new method for interrupted strain rate tests have been developed that enables characterization of material internal state under intermediate strain rates.
- The developed expertise can be used to address complex problems of characterization of fracture and failure in sheet materials.
- Technology transfer occurs via www

http://thyme.ornl.gov/Mg_new

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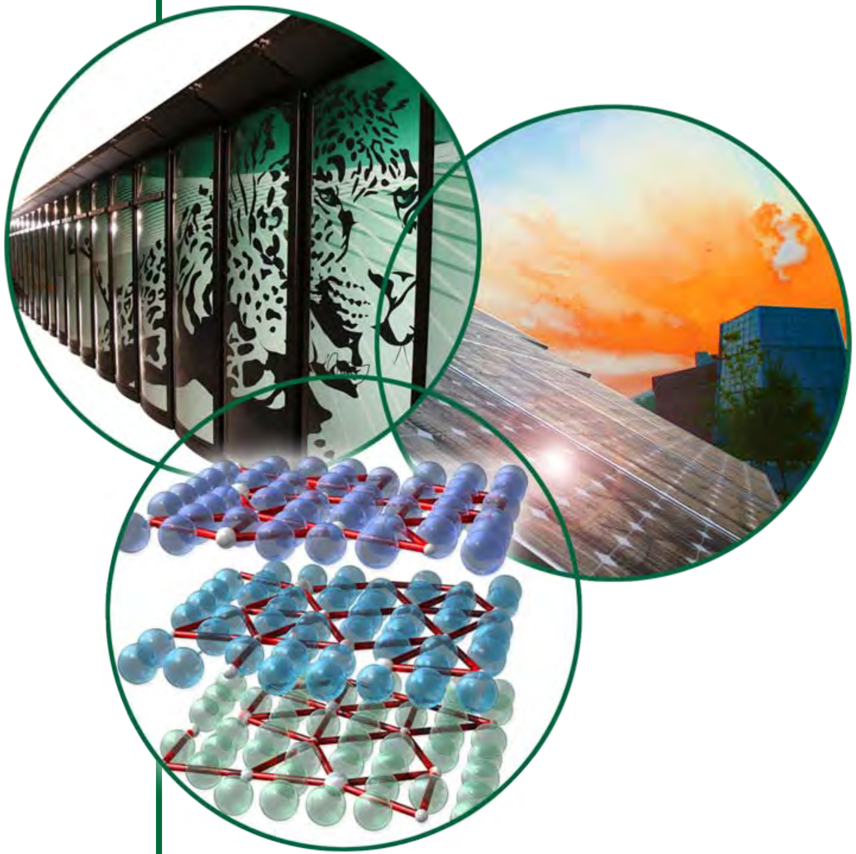
Technical Back-Up Slides



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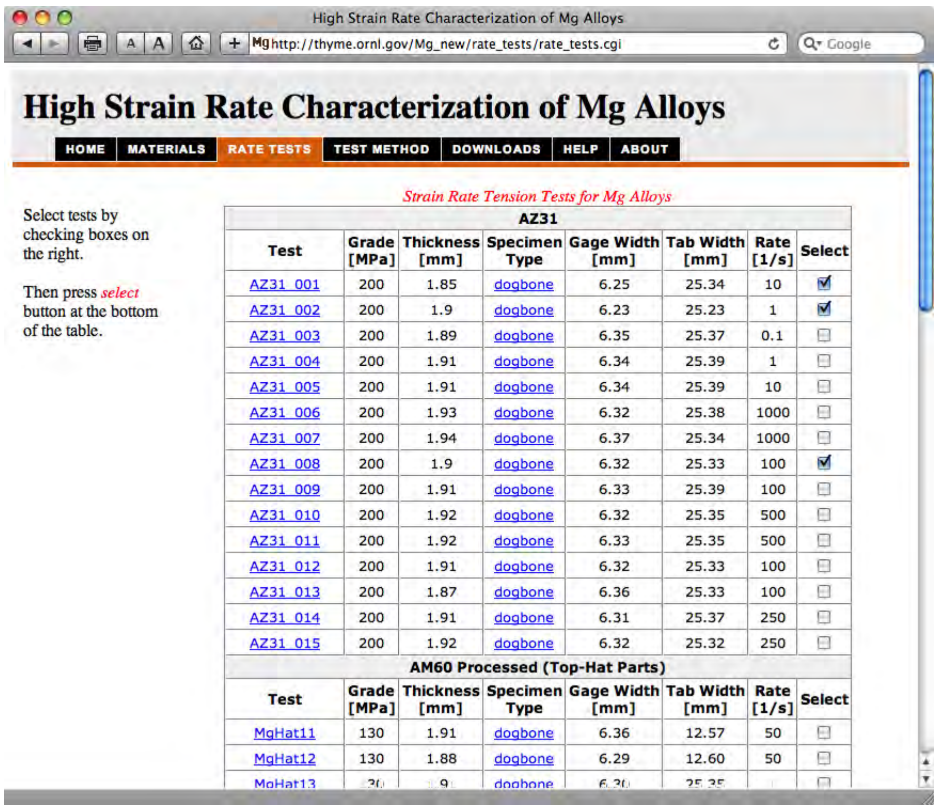
Project Information on the WWW
http://thyme.ornl.gov/Mg_new



High Strain Rate Characterization of Mg Alloys

http://thyme.ornl.gov/Mg_new/rate_tests/rate_tests.cgi

High Strain Rate Characterization of Mg Alloys

HOME | MATERIALS | RATE TESTS | TEST METHOD | DOWNLOADS | HELP | ABOUT

Select tests by checking boxes on the right.

Then press *select* button at the bottom of the table.

Strain Rate Tension Tests for Mg Alloys

Test	Grade [MPa]	Thickness [mm]	Specimen Type	Gage Width [mm]	Tab Width [mm]	Rate [1/s]	Select
AZ31							
AZ31_001	200	1.85	dogbone	6.25	25.34	10	☑
AZ31_002	200	1.9	dogbone	6.23	25.23	1	☑
AZ31_003	200	1.89	dogbone	6.35	25.37	0.1	☐
AZ31_004	200	1.91	dogbone	6.34	25.39	1	☐
AZ31_005	200	1.91	dogbone	6.34	25.39	10	☐
AZ31_006	200	1.93	dogbone	6.32	25.38	1000	☐
AZ31_007	200	1.94	dogbone	6.37	25.34	1000	☐
AZ31_008	200	1.9	dogbone	6.32	25.33	100	☑
AZ31_009	200	1.91	dogbone	6.33	25.39	100	☐
AZ31_010	200	1.92	dogbone	6.32	25.35	500	☐
AZ31_011	200	1.92	dogbone	6.33	25.35	500	☐
AZ31_012	200	1.91	dogbone	6.32	25.33	100	☐
AZ31_013	200	1.87	dogbone	6.36	25.33	100	☐
AZ31_014	200	1.91	dogbone	6.31	25.37	250	☐
AZ31_015	200	1.92	dogbone	6.32	25.32	250	☐
AM60 Processed (Top-Hat Parts)							
Test	Grade [MPa]	Thickness [mm]	Specimen Type	Gage Width [mm]	Tab Width [mm]	Rate [1/s]	Select
MgHat11	130	1.91	dogbone	6.36	12.57	50	☐
MgHat12	130	1.88	dogbone	6.29	12.60	50	☐
MgHat13	[illegible]	[illegible]	dogbone	[illegible]	[illegible]	[illegible]	☐

- Test Method – describes test setup and procedures
- Help – usage of test data

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