

2012 DOE Vehicle Technologies Program Review

Pulse-Pressure Forming (PPF) of Lightweight Materials

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Pacific Northwest National Laboratory

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Project ID: LM033

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Project Overview

Project Timeline:

- ▶ Start – 3Q FY08
- ▶ Finish – 1Q FY12
- ▶ 100% complete

Budget:

- ▶ Total project funding:
 - PNNL: \$1450k
- ▶ FY08 Funding Received:
 - \$200k
- ▶ FY09 Funding Received:
 - \$450k
- ▶ FY10 Funding Received:
 - \$500k
- ▶ FY11 Funding Received:
 - \$300k

Targets

- ▶ The VTP target for weight reduction of the vehicle and its subsystems is 50%.
 - Pulse-Pressure Forming (PPF) of aluminum and Advanced High Strength Steels (AHSS) has the potential to achieve 25 to 45% weight savings vs. conventional steels

Barriers

- ▶ Barriers to using PPF of aluminum and AHSS in the lightweighting of vehicles:
 - Lack of understanding of the formability and strain rates that develop during PPF processing
 - Lack of validated constitutive relations for lightweight materials during PPF processing
 - Lack of validation of finite element simulation of PPF processing

Partners

- ▶ OEM and Industry participants:
 - Sergey Golovashchenko (Ford)
 - John Bradley (General Motors)
 - Ajit Desai (Chrysler)
 - US Steel

Relevance to Technology Gaps

Project Objectives:

- ▶ Enable broader deployment of automotive lightweighting materials in body-in-white and closure panels through extended formability of aluminum alloys, magnesium alloys, and HSS/AHSS.
- ▶ Enable a broad set of PPF technologies to effectively extend the benefits of high rate sheet metal forming beyond the limitations of electrically conductive metals (aluminum) that are required for electromagnetic forming (EMF) processes.
- ▶ Aluminum and AHSS have limited formability at room temperature and conventional strain rates. High strain rate forming (PPF) can enhance room temperature formability
 - Extended ductility of most metals
 - Generate greater ductility from lower cost steels
 - Increase formability of Al and Mg alloys
 - Utilize single-sided tooling at lower cost
 - Provide residual stress (springback) management
- ▶ PPF of Lightweight Materials will address technology gaps
 - Demonstrate and quantify extended ductility in Al, AHSS and Mg using PPF process and high speed camera system
 - Validate high-strain-rate constitutive relations for PPF of lightweight materials
 - Characterize material microstructure and texture evolution at high-strain-rates

Approach/Strategy

Task 1 Formability and Fracture Characterization

- Design, fabricate, and demonstrate the operation of the PPF system. This includes procuring high-speed cameras for real-time image capture to quantify deformation history using existing PNNL DIC system
- Perform sheet forming experiments using single-pulse and multi-pulse PPF of Al-5182, DP600, and Mg-AZ31 sheet materials
- Characterize high-rate formability and extended ductility

Task 2 Microstructure and Mechanical Property Evolution

- Develop materials constitutive relations for high-rate forming
- Characterize microstructural and texture evolution
- Characterize post-forming mechanical properties

Task 3 Numerical Simulation of PPF Process

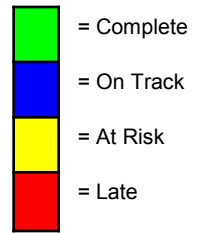
- PPF sheet forming finite element modeling
- Sheet-die interaction during PPF



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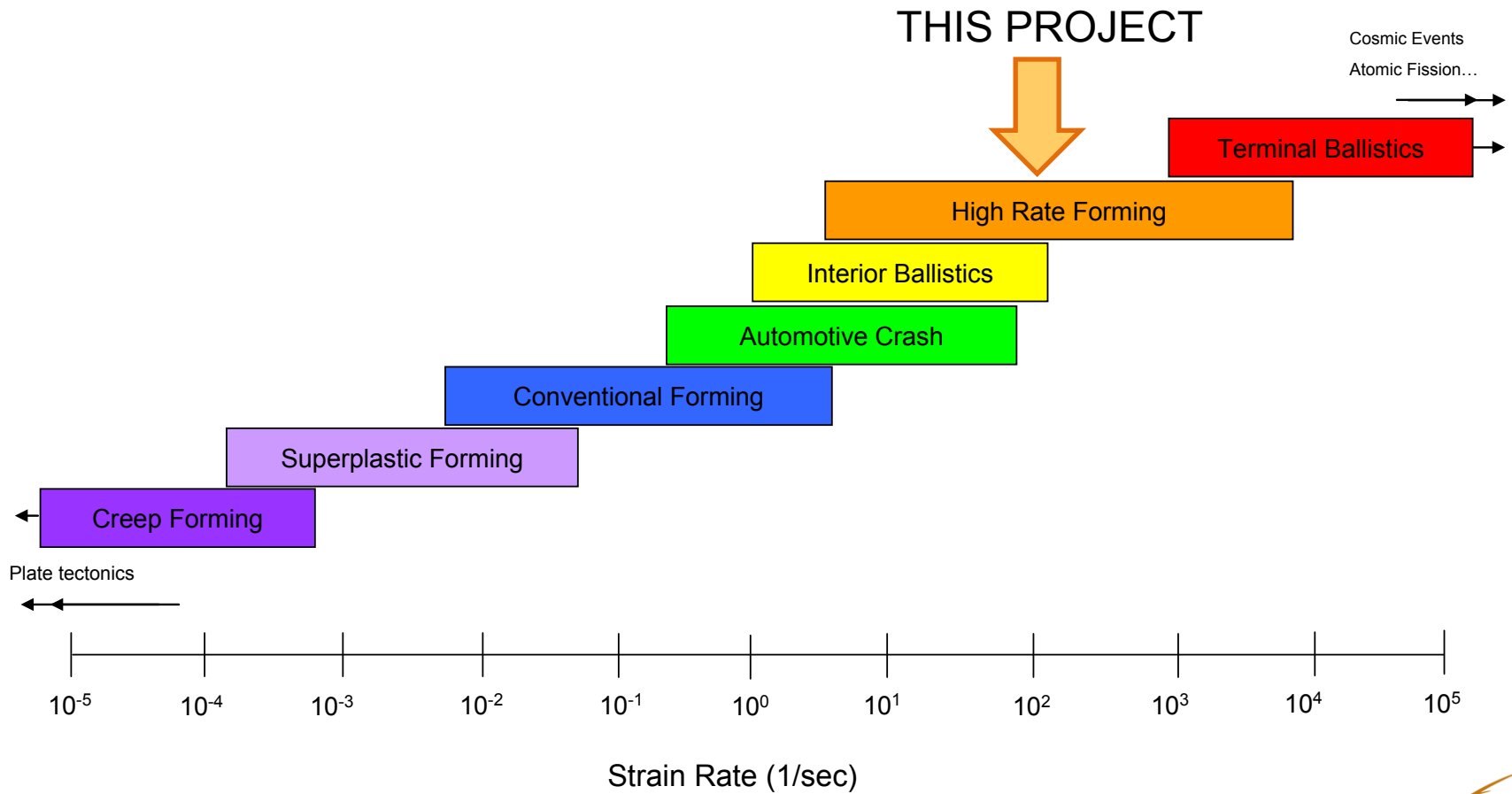
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Project Milestones



Milestones	Due	Status	Issues?
Demonstrate successful operation of the PPF apparatus	11/08		
Complete experimental characterization of PPF process	9/11		
Complete constitutive relations for Al, Mg, and AHSS	3/10		
Complete evaluation of post-forming properties of materials subject to PPF	6/11		
Complete evaluations of numerical simulations	3/11		

Background



Introduction

High Rate Forming Technologies

- ▶ Electromagnetic Forming (EMF)
- ▶ Electrohydraulic Forming (EHF)
- ▶ Explosive Forming (classical)
- ▶ Laser Shock Forming (LSF)

Project Plan - Subject Materials

- ▶ Aluminum Alloys
 - Initial focus on AA5182-O (1 mm and 2 mm)
- ▶ AHSS (and HSS)
 - Initial focus on DP600 (1 mm and 0.6 mm) [*Provided by US Steel*]
- ▶ Magnesium Alloys
 - Initial focus on AZ31-O (1 mm)



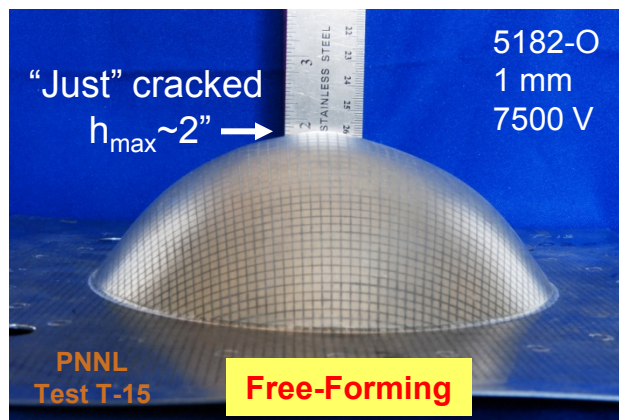
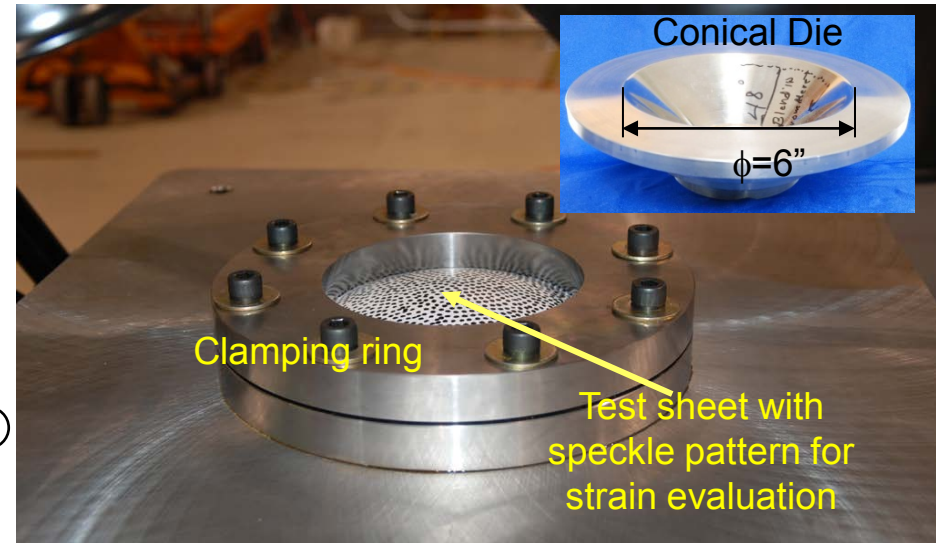
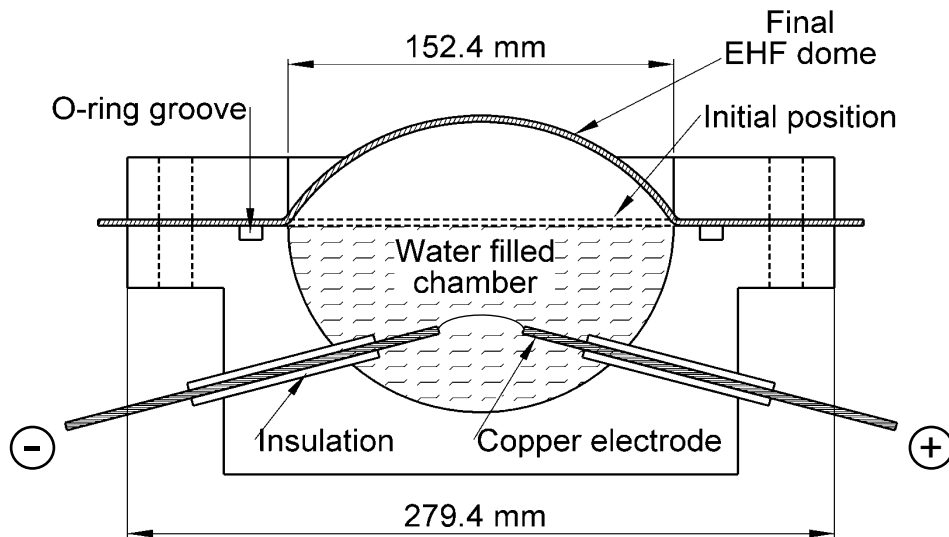
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Technical Progress

Task 1.1 - Fabrication, Assembly, and Testing of PPF Apparatus

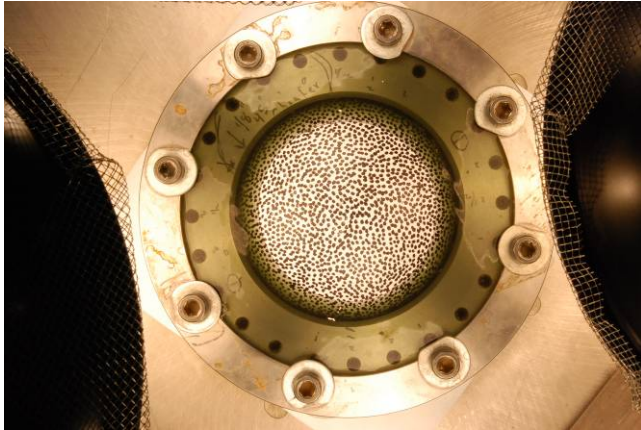
PNNL's PPF Setup For Free-Forming Dome



Technical Progress

Task 1.1 - Fabrication, Assembly, and Testing of PPF

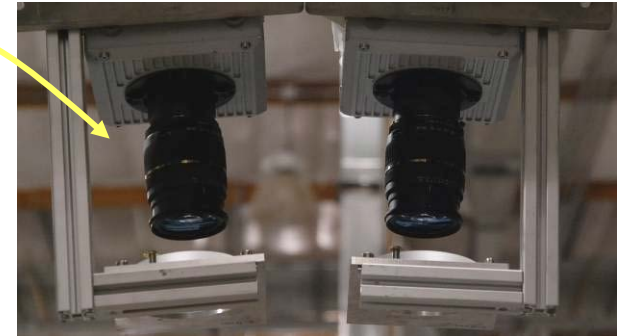
Top View: Free-Forming



Imaging Setup

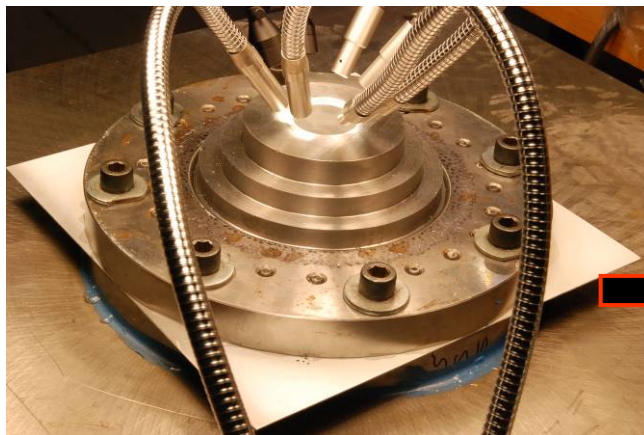


Close-up of Cameras

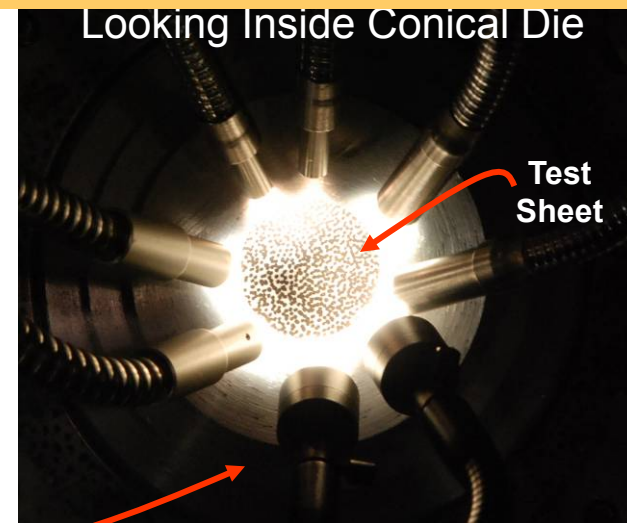


- Imaging at ~75000 frames/second (~13 microseconds per frame)

Side View: Cone Die



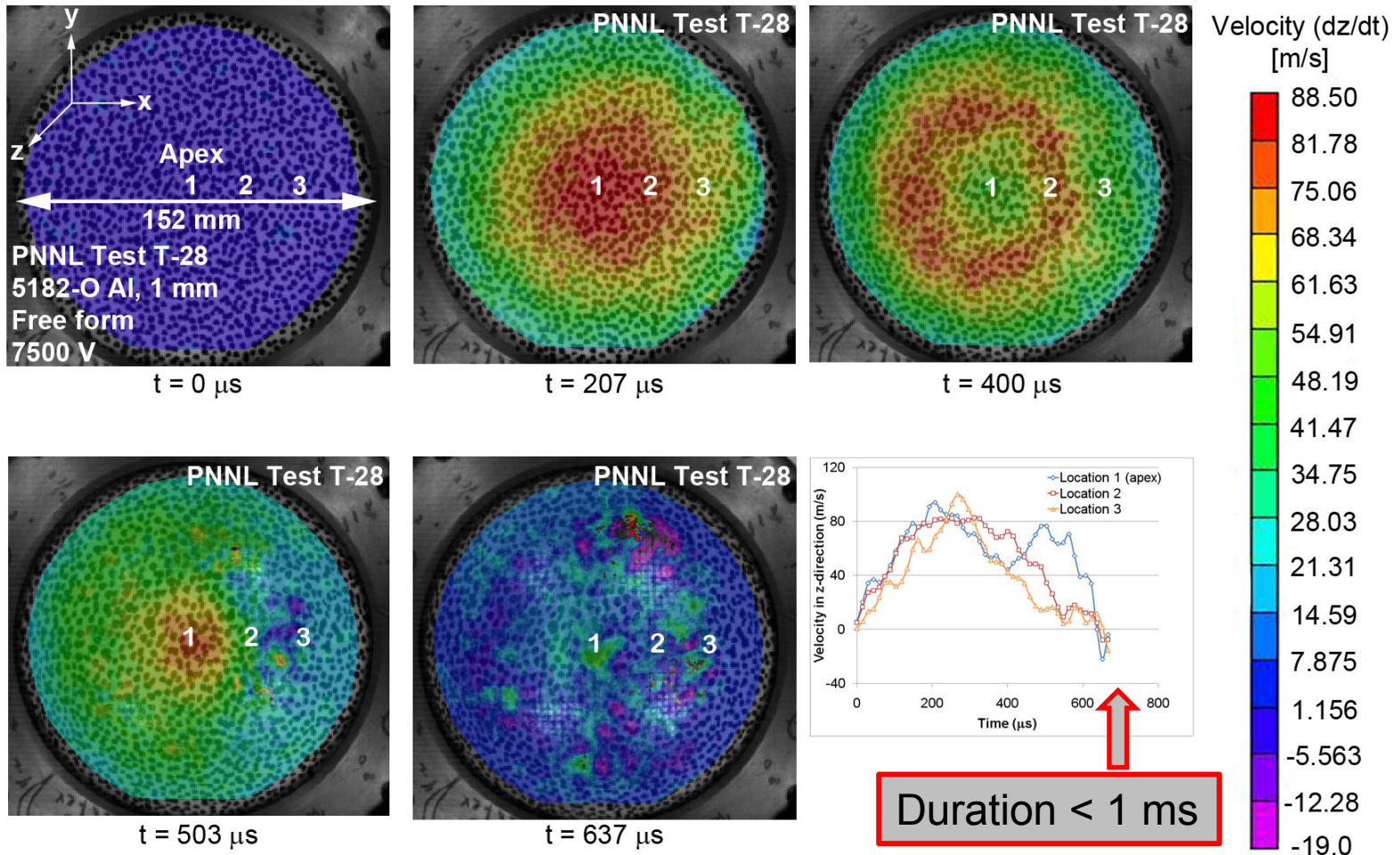
Looking Inside Conical Die



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Technical Progress (*PPF Deformation Evolution*)

Task 1.2 - Single-pulse PPF



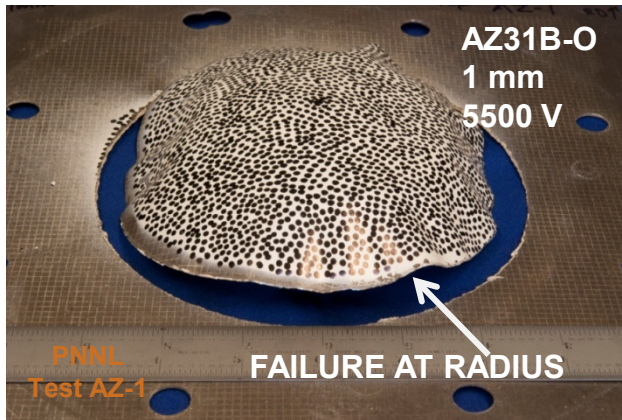
High-speed Cameras
+
Digital Image Correlation

Deformation history obtained
at any location on the sheet

Technical Progress (*Free-Forming of Mg, Al, DP600*)

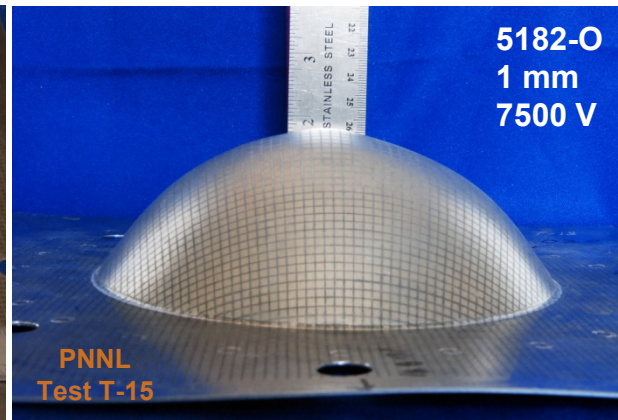
Task 1.2 – Single-pulse PPF

MAGNESIUM



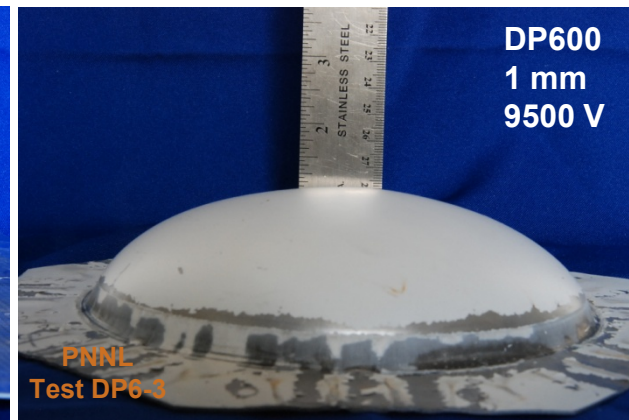
Almost No Formability

ALUMINUM



Formable

DP600



Formable

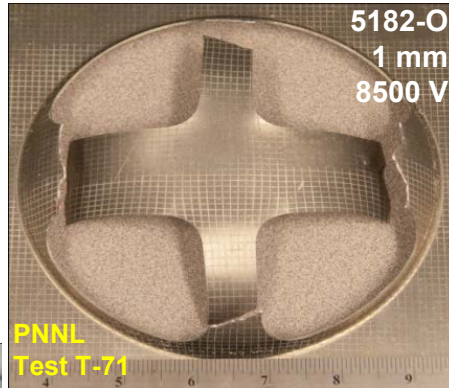
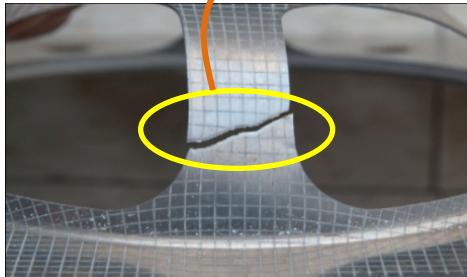
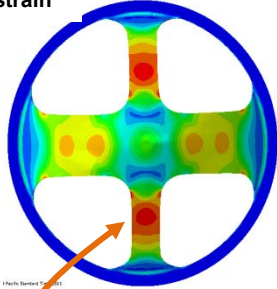
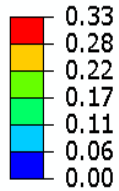
Room temperature forming of AZ31B
needs experimental re-designs to
prevent failure at tool-radius

Technical Progress (*Determination of FLD_o*)

Task 1.3 – Characterize High-Rate Formability

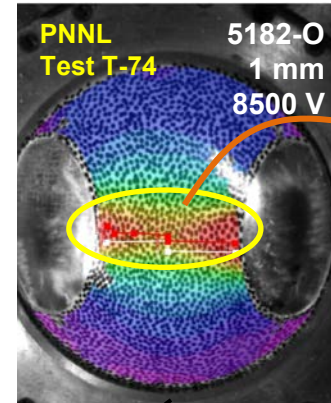
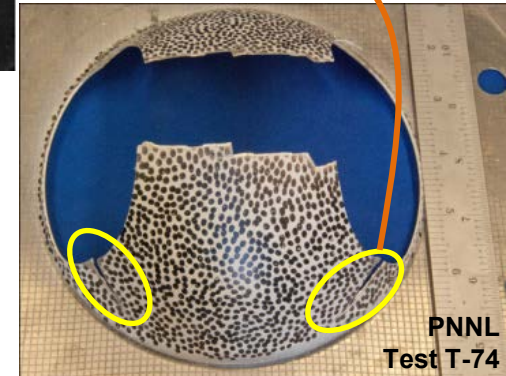
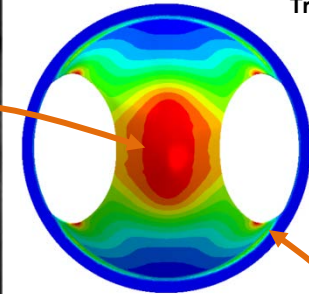
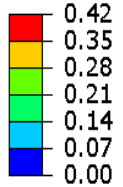
Model 1

True eq. plastic strain

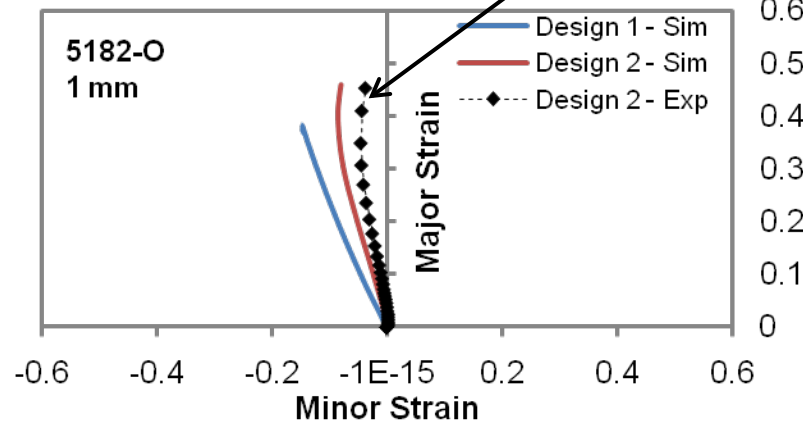


Model 2

True eq. plastic strain



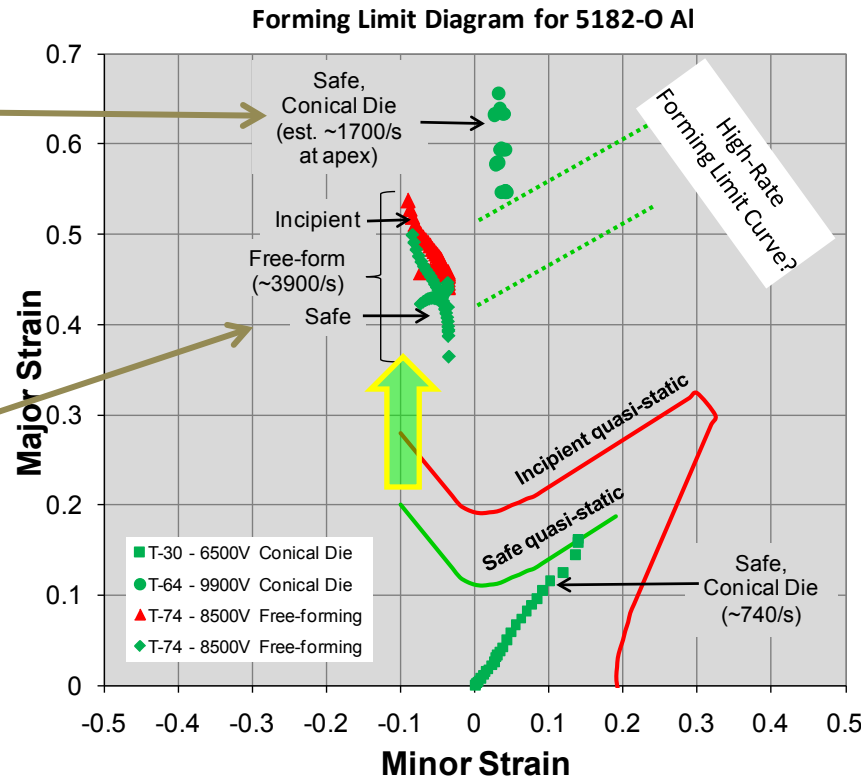
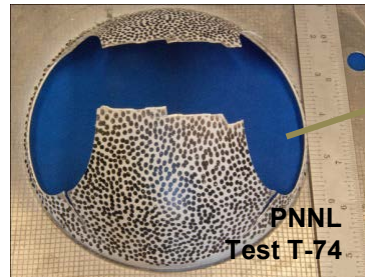
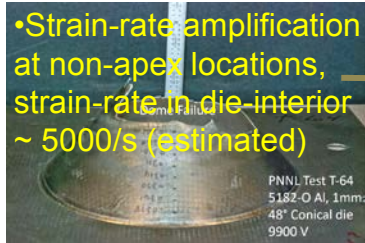
Strain-Path during PPF



Novel specimen geometries developed to determine plane-strain formability during PPF

Technical Progress

FLD at High-Strain-Rates during PPF



All data in engineering units

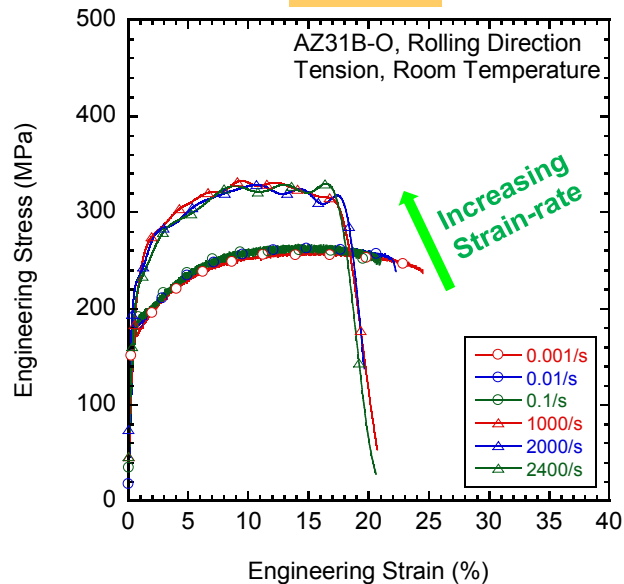
PPF high-rate forming
vs.
quasi-static forming
(Reynold's data)

- Enhanced formability is observed in Al during PPF:
 - FREE-FORMING (◆) and CONICAL-DIE(●)
 - Strain-rates ~4000/s and up
- **DEFORMATION HISTORY QUANTIFIED**

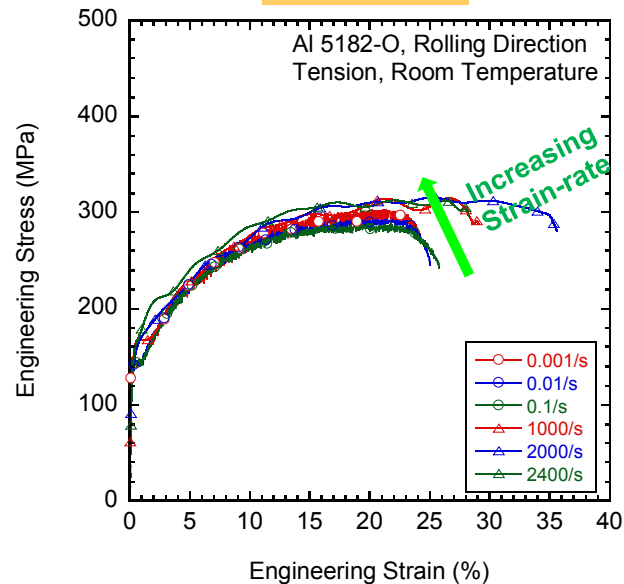
Technical Progress (Mechanical Characterization)

Task 2.1 – Constitutive Relations

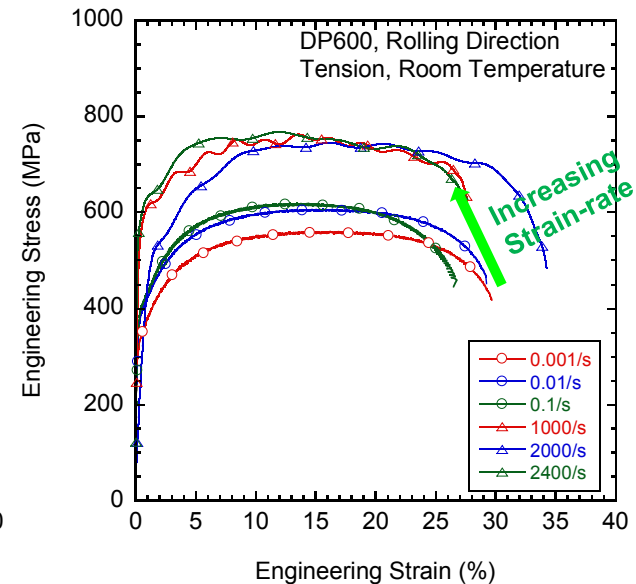
AZ31B



5182-O Al



DP600



- Tensile behavior quantified at quasi-static and high-strain-rates
- Constitutive equations are used to model sheet behavior during pulse-pressure forming



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Technical Progress

Constitutive Model w/ Variable Strain Rate Sensitivity

Constitutive Model

Adapt Hollomon Equation to capture variable strain rate sensitivity (m)

$$\sigma = K \bar{\epsilon}^n \dot{\epsilon}^m$$

$$K = 538$$

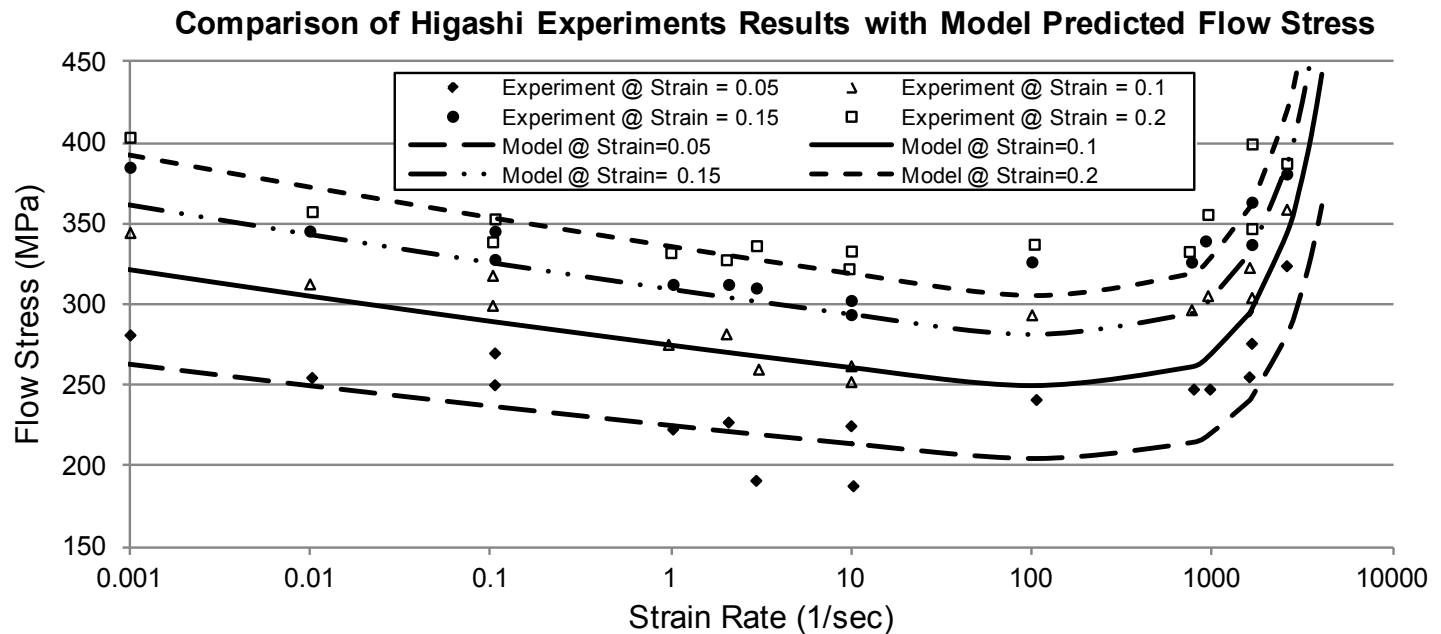
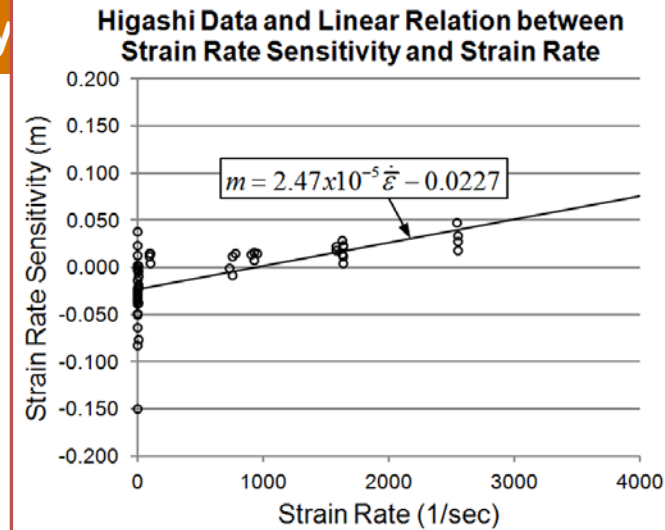
$$n = 0.292$$

$$A = 2.47 \times 10^{-5}$$

$$m = A \dot{\epsilon} + m_{\text{quasistatic}}$$

$$m_{\text{quasistatic}} = -0.0227$$

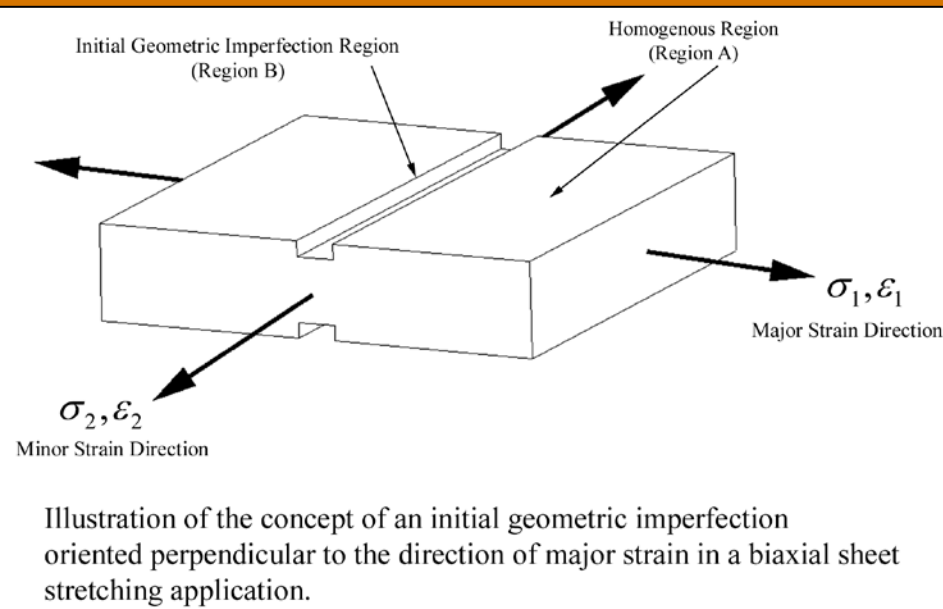
$$\sigma = 538 \bar{\epsilon}^{-0.292} \dot{\epsilon}^{(2.47 \times 10^{-5} \dot{\epsilon} - 0.0227)}$$



Higashi, K., et al., *The Microstructural Evolution During Deformation under Several Strain Rates in Commercial 5182 Aluminum Alloy*. Journal De Physique IV, Colloque C3, October 1991. p. C3-347.

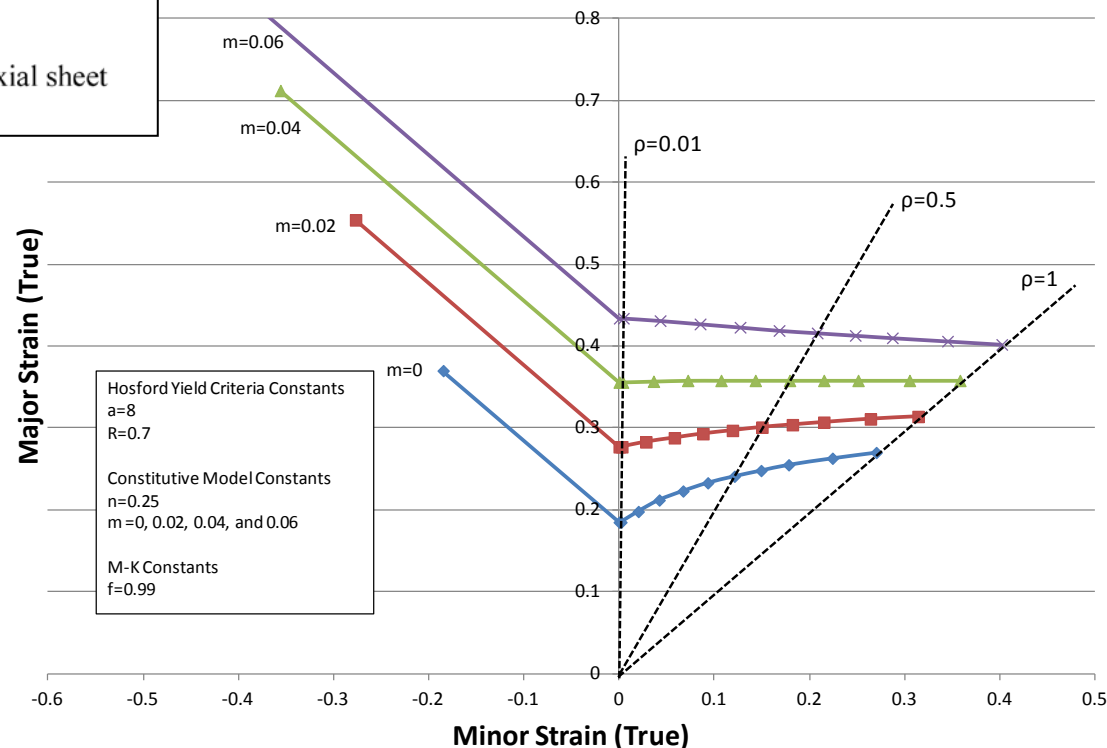
Technical Progress

M-K Method Predictions of Forming Limits



- ▶ Use a classical M-K method imperfection model using
 - ▶ Anisotropic yield locus
 - ▶ High rate constitutive model

Theoretical Forming Limit Diagrams - Influence of m-value

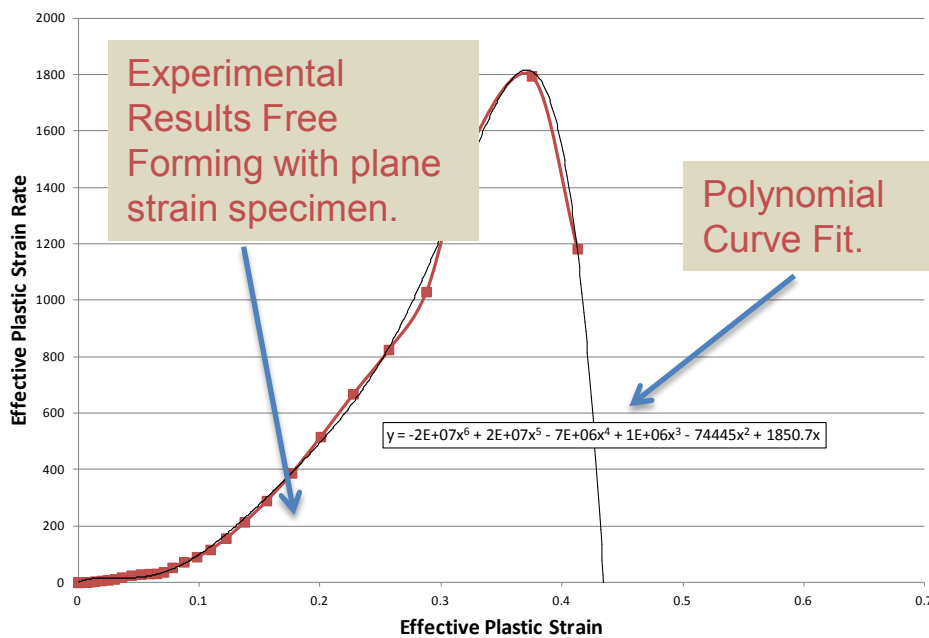


- ▶ M-K method capture the influence of the strain rate sensitivity of the materials

Technical Progress – Model Validation

Comparing Formability Model to Experiments

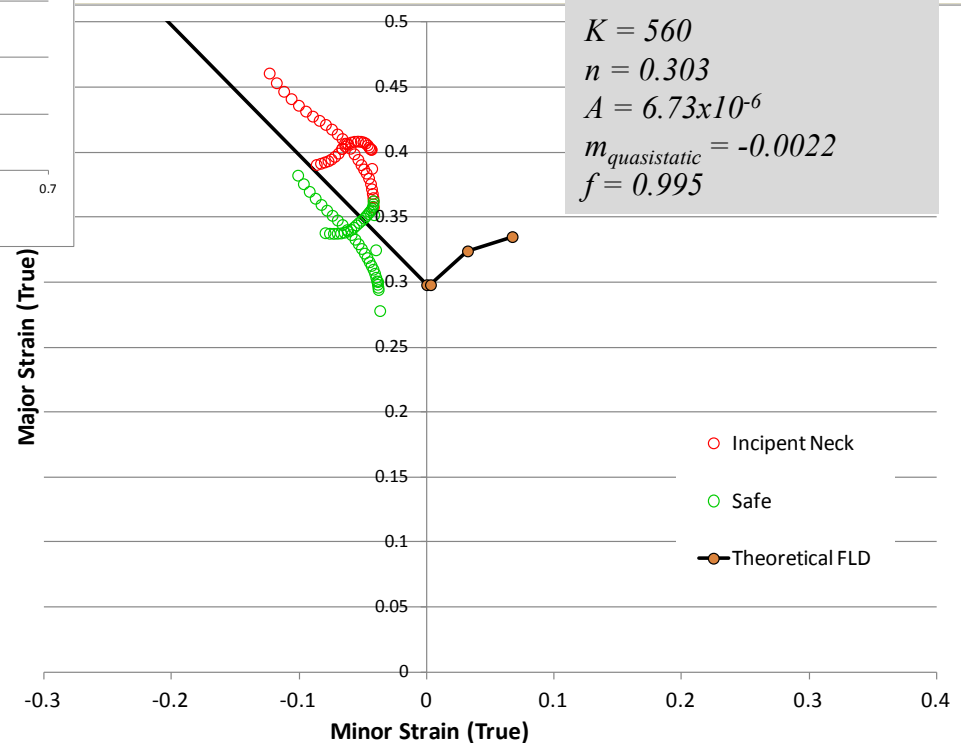
Effective Plastic Strain and Strain Rate for T74 Apex



- Approximate the experimental data using a polynomial curve fit to describe the relation between effective plastic strain rate and effective plastic strain

- Formability model accuracy is validated through experiments

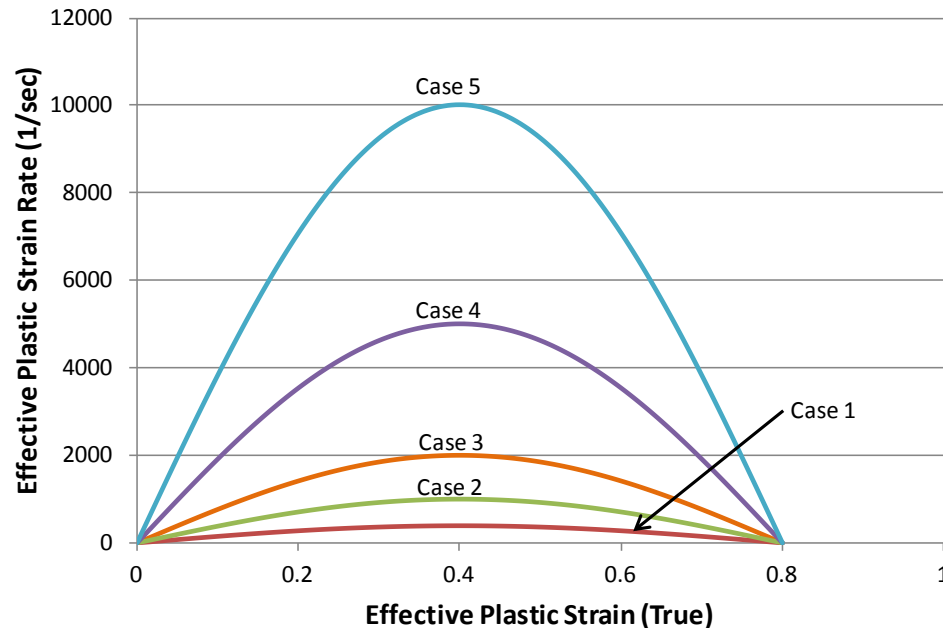
- M-K method approach
- Modified Hollomon relation
- Polynomial fit above



Technical Progress

Parametric Investigation of Formability

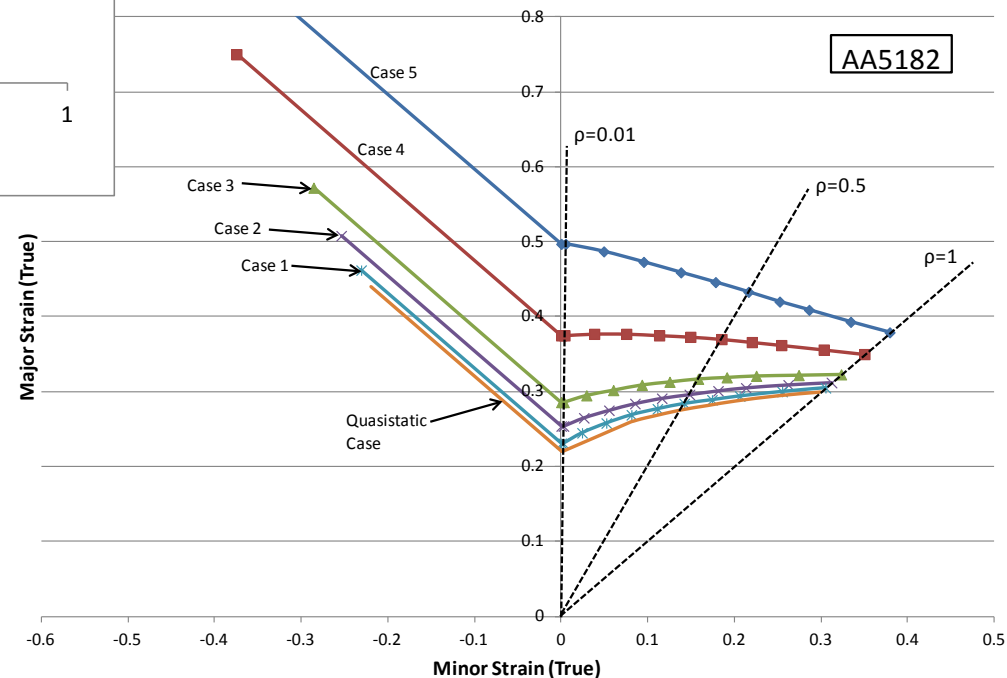
Ideal Sinusoidal Waveforms



- ▶ Parametric analysis shows the importance of the peak strain rate on the formability of the AA5182 materials.

- ▶ Five parametric cases studied where the maximum strain rate was modeled between quasistatic and 10,000/sec

Theoretical Forming Limit Diagrams: Cases 1 Through 5



Project Plan

Technology Transition including Industry Partners

- ▶ Industrial partners: GM, Ford, and Chrysler:
 - Review project progress
 - Guidance on material and process priorities
 - Results available for internal process development
 - Review commercialization opportunities
- ▶ PNNL has partnered with OEM and materials suppliers who have active development programs in this topic area. The research plans and results are actively shared with those collaborative partners



Future Work (FY12-FY14)

► Follow-on work

- Enhanced Room-Temperature Formability in High-Strength Aluminum Alloys through Pulse-Pressure Forming
 - Evaluating the formability and demonstration of forming for 6000 series and 7000 series heat treatable Al alloys



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Summary

► Unique Experimental Capability Yields Unique Results

- Time-resolved measurements of full-field deformation during PPF
- High-rate forming behavior quantified for Al
- Safe plane-strains as high as ~50% at ~3900/s peak strain-rate observed in free-forming of aluminum
- Safe plane-strains of ~65% at ~2000/s peak strain-rate (apex) measured when aluminum is formed in a conical die

► Mechanical Properties

- Characterized the mechanical properties of AA5182, AZ31, and DP600 sheet materials from quasistatic to $2.5 \times 10^3/\text{sec}$
- Developed a modified power law model that accurately described the properties

► Formability Modeling

- Applied the M-K method model along with the newly developed constitutive model to accurately predict experimentally observed formability results
- Conducted a parametric analysis show the effect of strain rate on formability

► Publications

- 7 journal and conference articles published, submitted, and in preparation



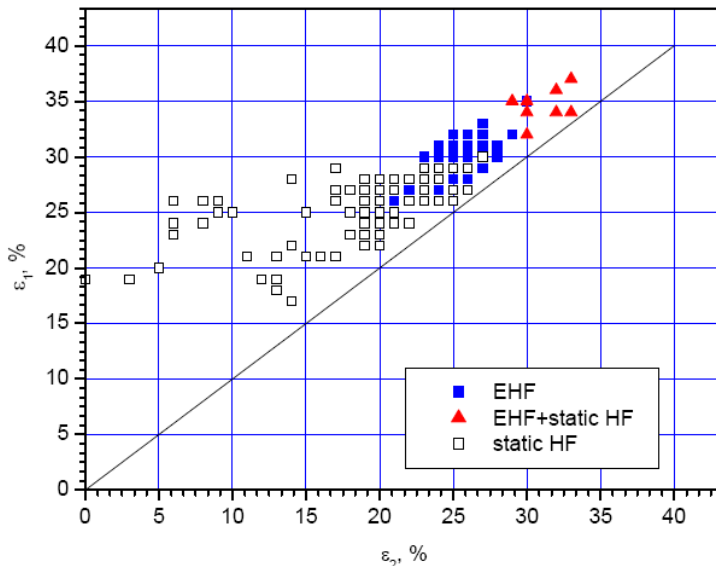
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Technical Back-up Slides

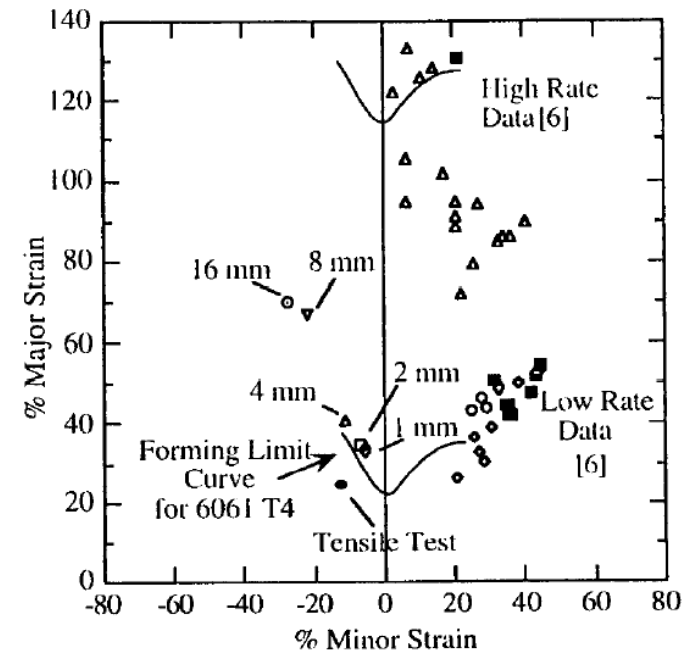
Introduction - Technical Barriers

- ▶ lack of understanding of the formability and strain rates that develop during PPF processing
- ▶ lack of validated constitutive relations for lightweight materials during PPF processing
- ▶ lack of validation of finite element simulation of PPF processing



Experimental results on formability of AA6111-T4 sheet with HF, EHF and HF+EHF

Golovashchenko, S; and Mamutov, V.; 2005. Electrohydraulic Forming of Automotive Panels; Symposium on Global Innovations in Materials Processing & Manufacturing, TMS.



Tamhane, A; Altynnova, M; Daehn, G.; 1996. Effect of Sample Size on the Ductility in Electromagnetic Ring Expansion; Scripta Materialia, Vol. 34, No.8, pp1345-1350.

Project Plan

Detailed Gap Analysis

	Technical challenges	Today	Tomorrow	how to get there
Task 1	Formability and Fracture of Metals during PPF			
1A	lack of method to characterize strain rate during PPF	No detailed understanding of strain rates during PPF processes	Apparatus to measure strain rates during PPF	1.1
1B	lack of understanding of the strain rates and strain rate variability developed during PPF	Estimates of strain rate based on total deformation in final parts/specimens and estimated process time process	A detailed understanding of the variable strain rate developed during single pulse PPF	1.2
1C	Lack of understanding of the influence of incremental PPF on sheet metal formability.	Some experience suggest incremental PPF may be more favorable than single pulse PPF from an overall material formability and properties standpoint.	A detailed understanding of how incremental forming influences sheet metal formability and properties	1.3-1.4
Task 2	Microstructure and mechanical property evolution during PPF			
2A	Lack of validated constitutive relations for automotive materials during PPF processing	Understanding of the detailed strain rate and strain rate variability during PPF processes is unknown	PPF laboratory experiments that detail strain rates, and a set of validated constituent relations for relevant automotive materials	2.1
2B	Lack of understanding of the microstructure and post-forming properties of materials subject to PPF	Most R&D limited to formability investigations, with limited research on the microstructure evolution and post-forming properties	Complete investigation of the microstructure and crystallographic texture evolution during PPF, and a detailed characterization of the post-forming properties of automotive lightweight materials.	2.2-2.3
Task 3	Numerical simulation of PPF process			
3A	Limited constitutive relations and detailed experimentation to validate FEA of PPF	PPF is a process that has a duration of microseconds, and little or no detailed strain data is available for validation	Detailed characterization of the strain rate coupled with numerical simulation comparisons to validate FEA predictions of PPF	3.1-3.2