(Project 60184/Agreement 22422)

2011 DOE Vehicle Technologies Program Review

Pulse-Pressure Forming (PPF) of Lightweight Materials

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Project ID: LM033

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Project Overview

Project Timeline:

- Start – 3Q FY08
- Finish – 4Q FY11
- 85% complete

Budget:

- Total project funding:
  - PNNL: $1450k
- FY08 Funding Received:
  - $200k
- FY09 Funding Received:
  - $450k
- FY10 Funding Received:
  - $500k
- FY11 Funding Authorized:
  - $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 & James Quinn (General Motors)
  - Ajit Desai & DJ Zhou (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
  - Extend the formability of AHSS at high-rate loading
  - 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

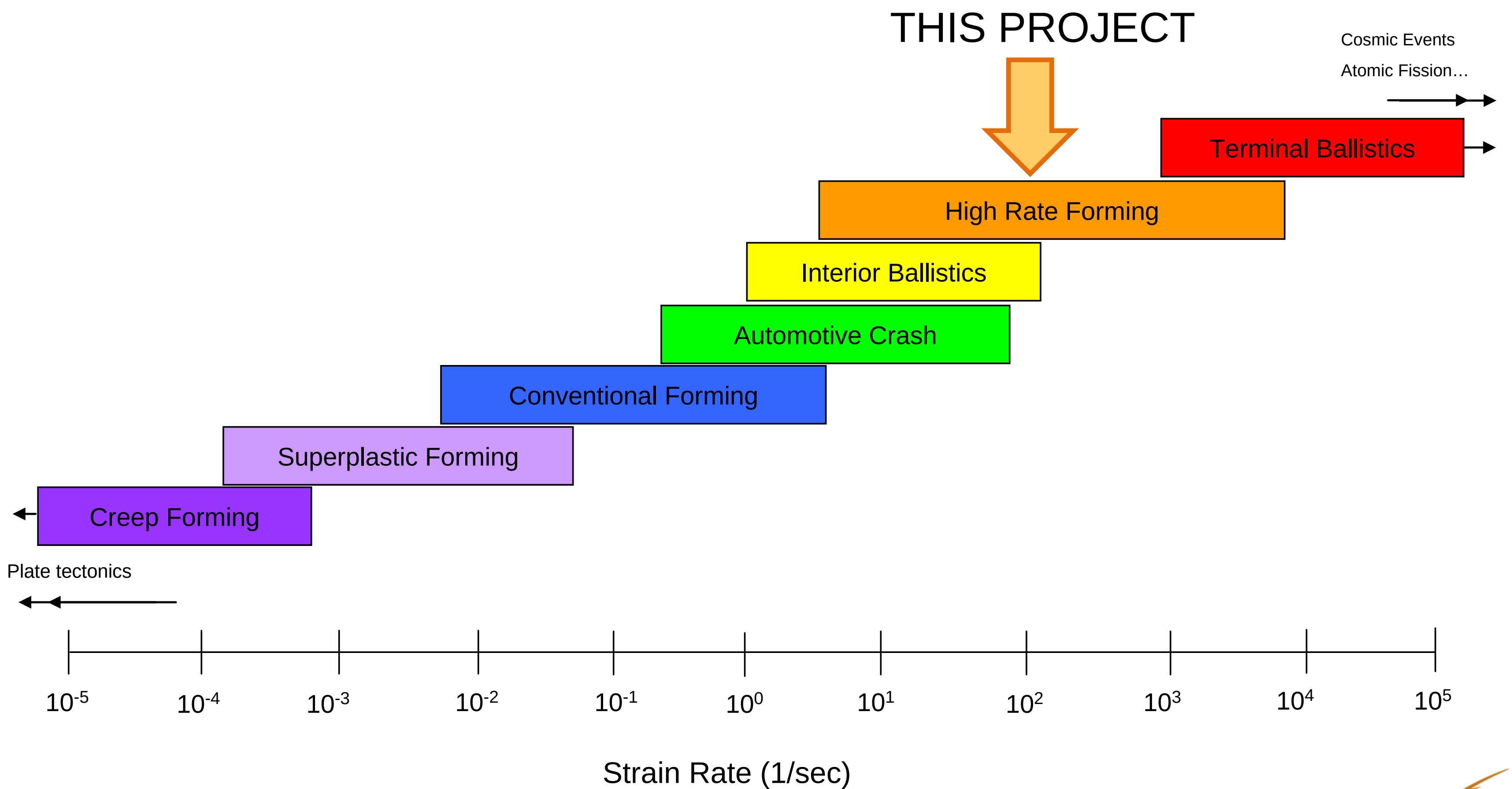
- PPF sheet forming finite element modeling
- Sheet-die interaction during PPF

Project Milestones

= Complete
= On Track
= At Risk
= Late

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		Focus has been shifted to help develop a high-rate forming limit diagram (FLD)
Complete evaluations of numerical simulations	3/11		

Background



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Introduction

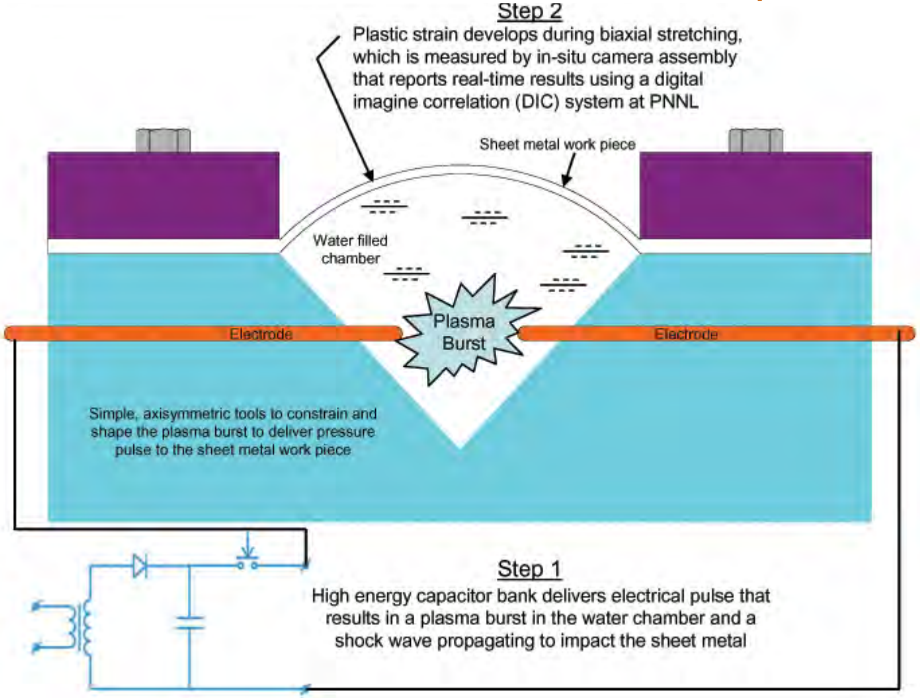
High Rate Forming Technologies

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

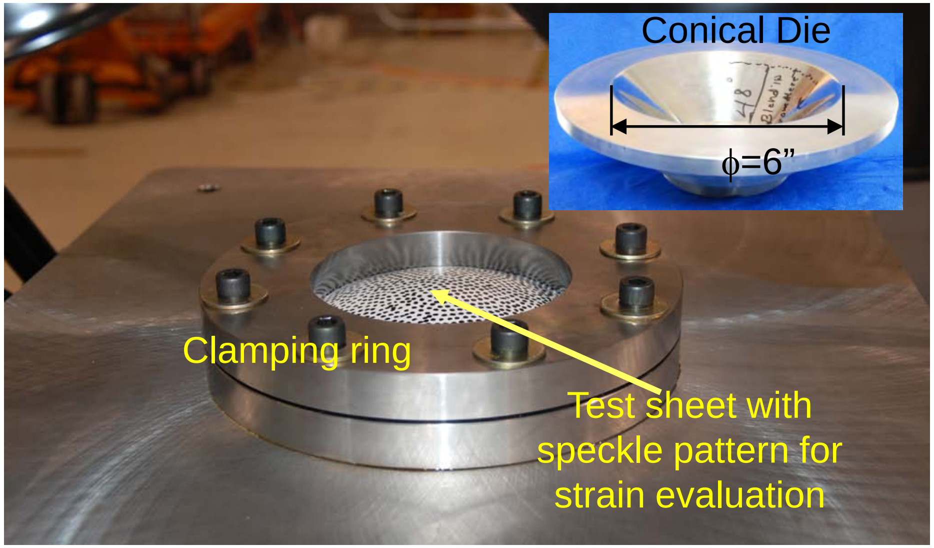
Project Plan - Subject Materials

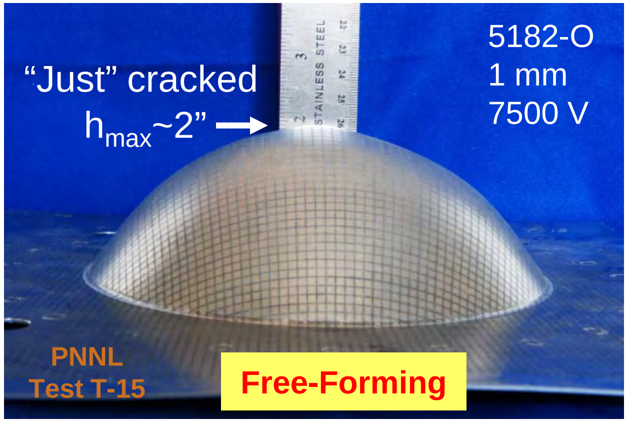
- Aluminum Alloys
  - Initial focus on AA5182-O (1 mm and 2 mm)
- AHSS (and HSS)
  - Initial focus on DP600 (1 mm and 0.6 mm) [*Provided by US Steel*]
- Magnesium Alloys
  - Initial focus on AZ31-O (1 mm)

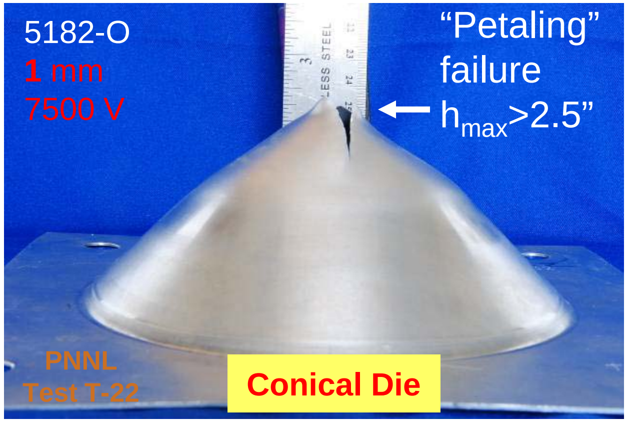
Technical Progress
Task 1.1 - Fabrication, Assembly, and Testing of PPF



PNNL's PPF Setup For Free-Forming Dome

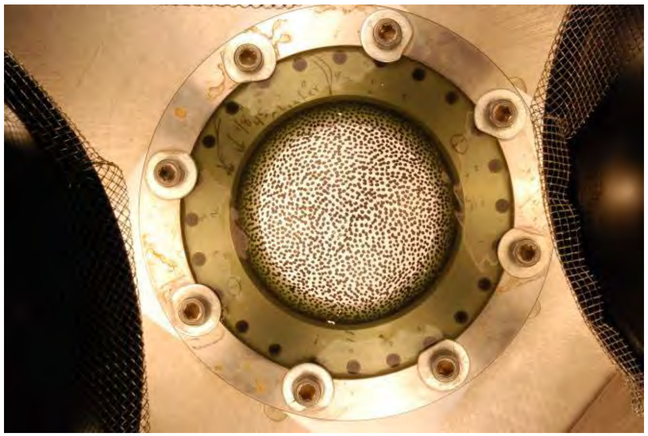




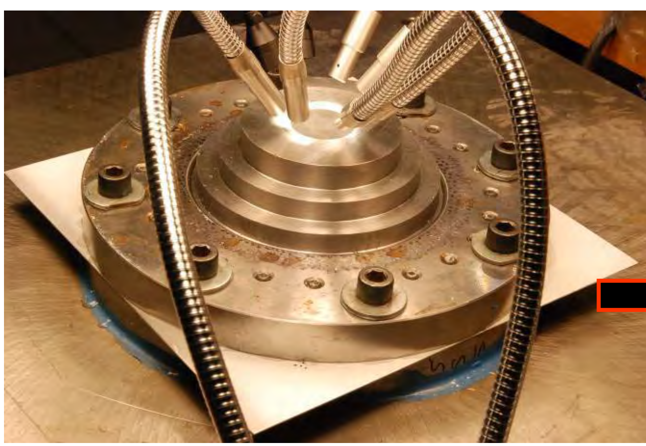


Technical Progress
Task 1.1 - Fabrication, Assembly, and Testing of PPF

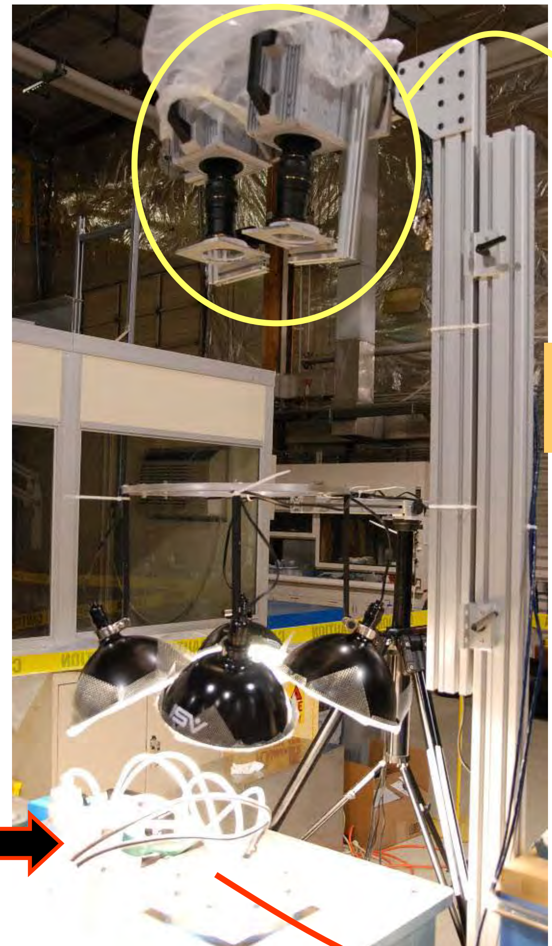
Top View: Free-Forming



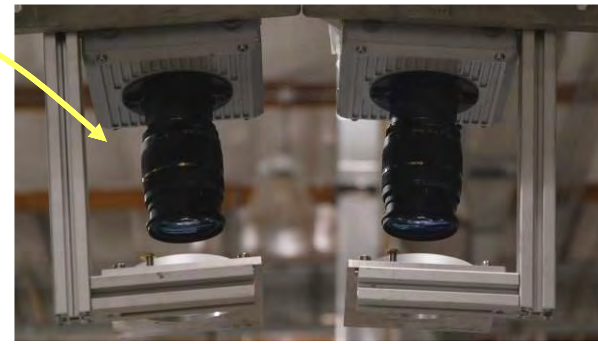
Side View: Cone Die



Imaging Setup

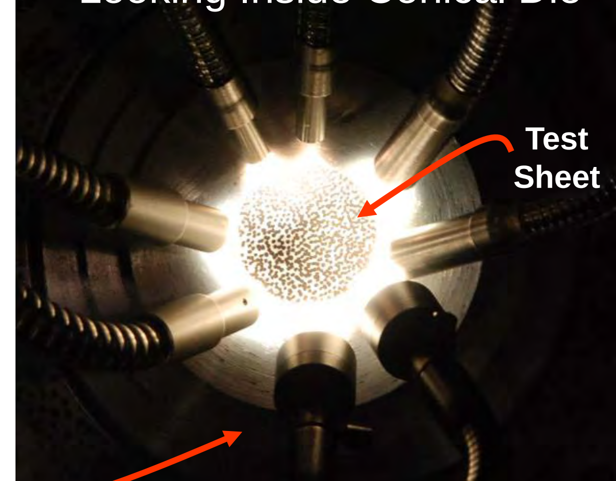


Close-up of Cameras

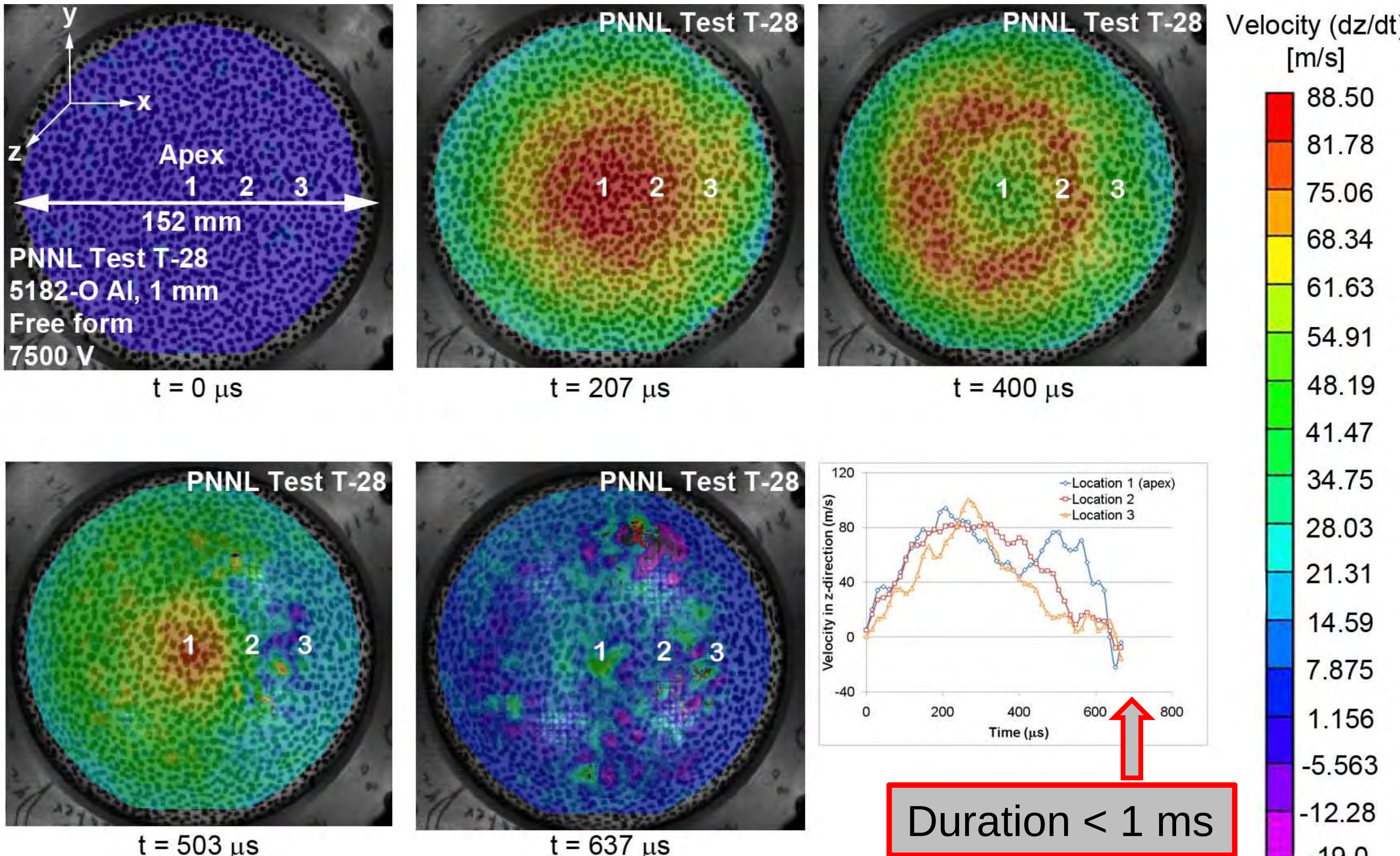


- Imaging at ~75000 frames/second (~13 microseconds per frame)

Looking Inside Conical Die



Technical Progress *(PPF Deformation Evolution)*
Task 1.2 - Single-pulse PPF

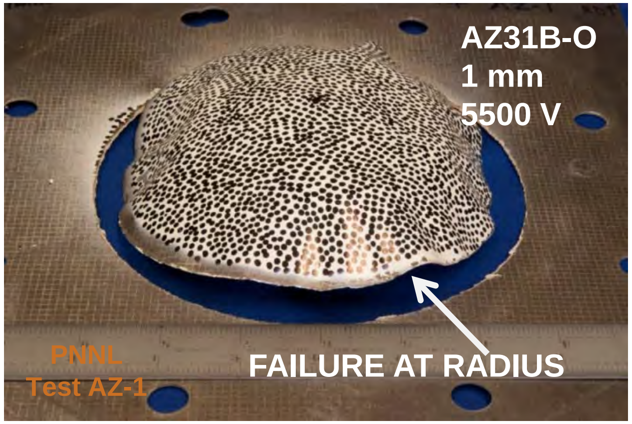


High-speed Cameras
+
Digital Image Correlation

→ Deformation history obtained at any location on the sheet

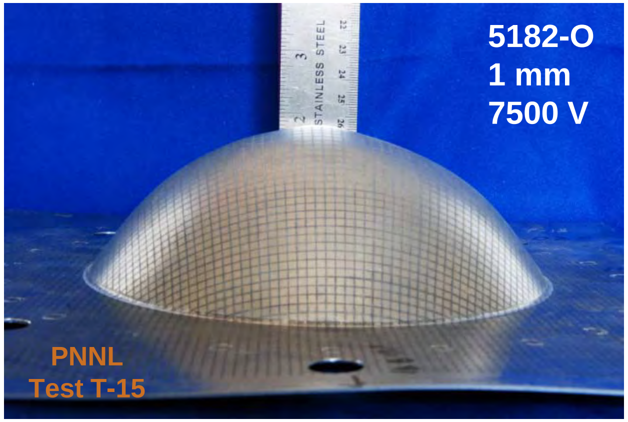
Technical Progress *(Free-Forming of Mg, Al, DP600)*
Task 1.2 – Single-pulse PPF

MAGNESIUM



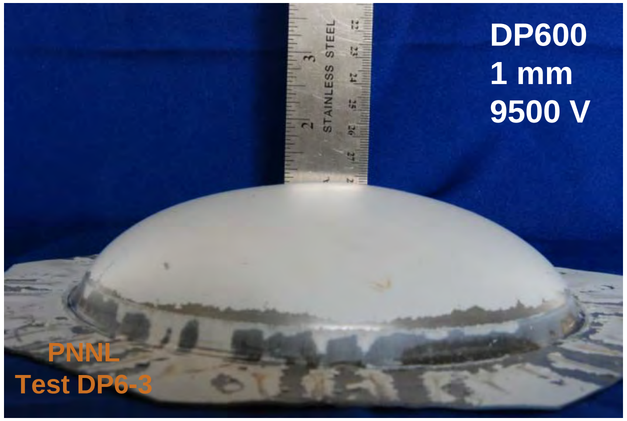
Almost No Formability

ALUMINUM



Formable

DP600

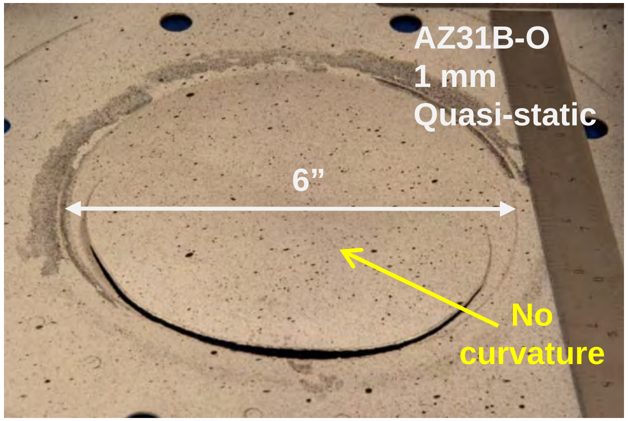


Formable

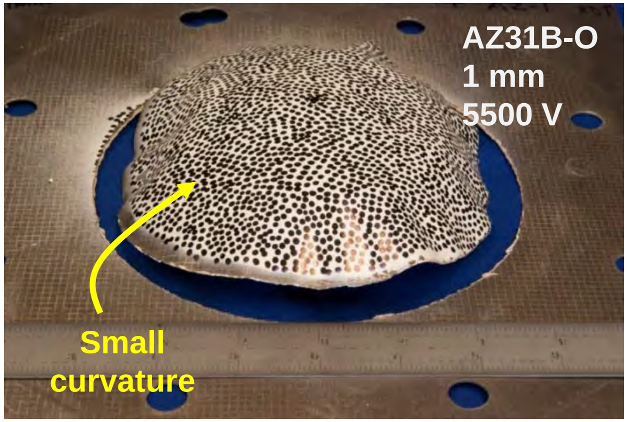
Room temperature forming of AZ31B needs experimental re-designs to prevent failure at tool-radius

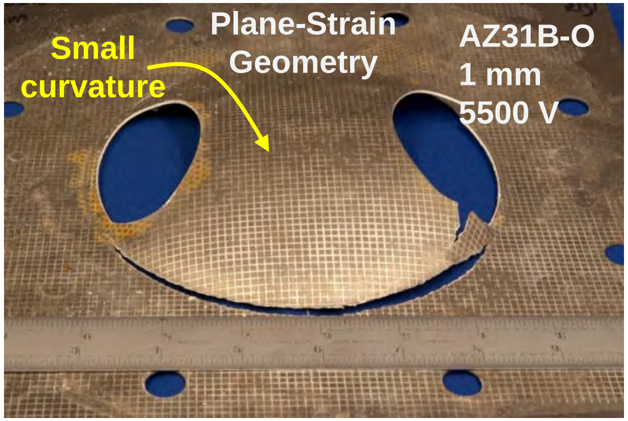
Technical Progress *(Mg: Quasi-static vs. PPF)*
Task 1.2 – Single-pulse PPF

Quasi-Static Pressure Forming



(High-Rate)
Pulse-Pressure Forming





- High-strain-rate <u>may</u> improve Mg formability, somewhat, over quasi-static formability
- Requires PPF tooling re-design to verify

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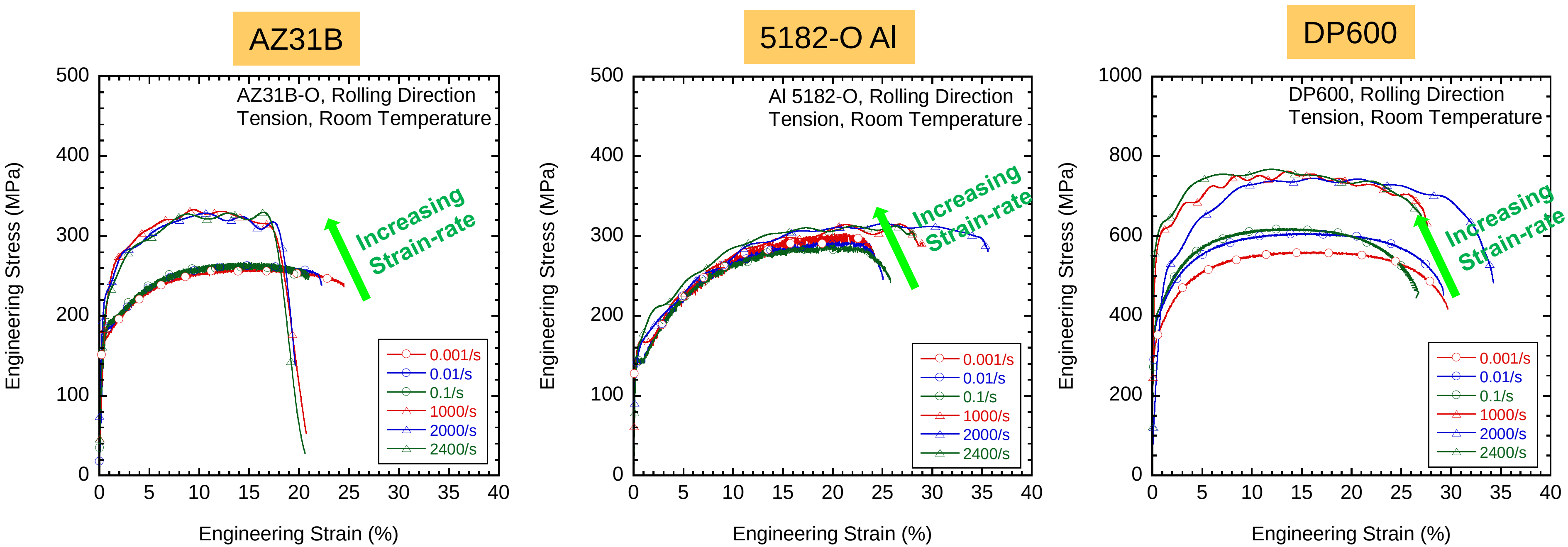
Technical Progress *(Mechanical Characterization)*
Task 2.1 – Constitutive Relations

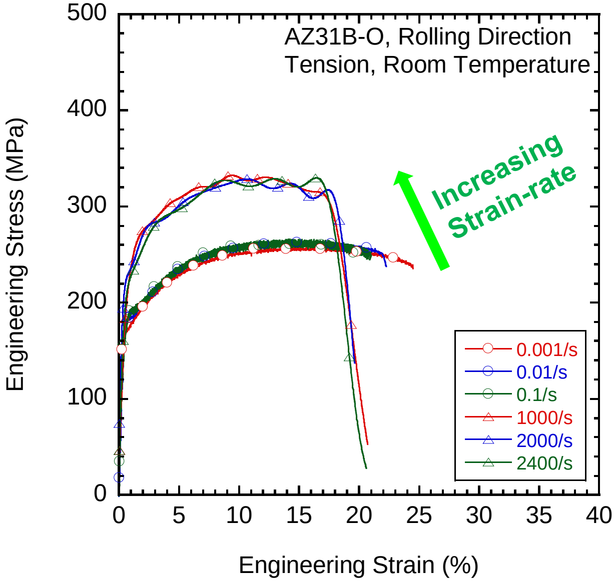


- Tensile behavior quantified at quasi-static and high-strain-rates
- Constitutive equations are used to model sheet behavior during pulse-pressure forming

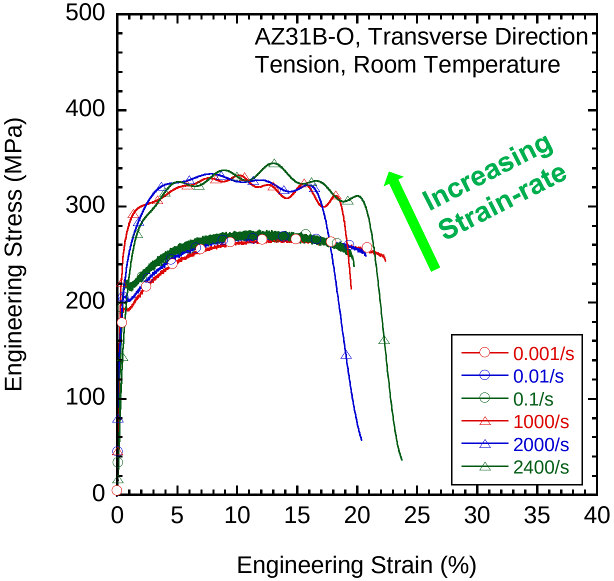
Test data from Prof. K.S. Vecchio, UC San Diego

Technical Progress *(Mg: Strain-rate Effects)*
Task 2.1 – Constitutive Relations

AZ31B
Rolling Direction



AZ31B
Transverse Direction



- Positive strain-rate sensitivity → High-rate forming has potential for forming magnesium
- Limiting factors: Low ductility, texture

Test data from Prof. K.S. Vecchio, UC San Diego

Technical Progress
Forming Limit Diagram (FLD) for High-Rate Forming

PPF Dome-forming

- Different locations have different strain-paths.

- Dome formability limited by the location that crosses the 'safe' forming-limit first

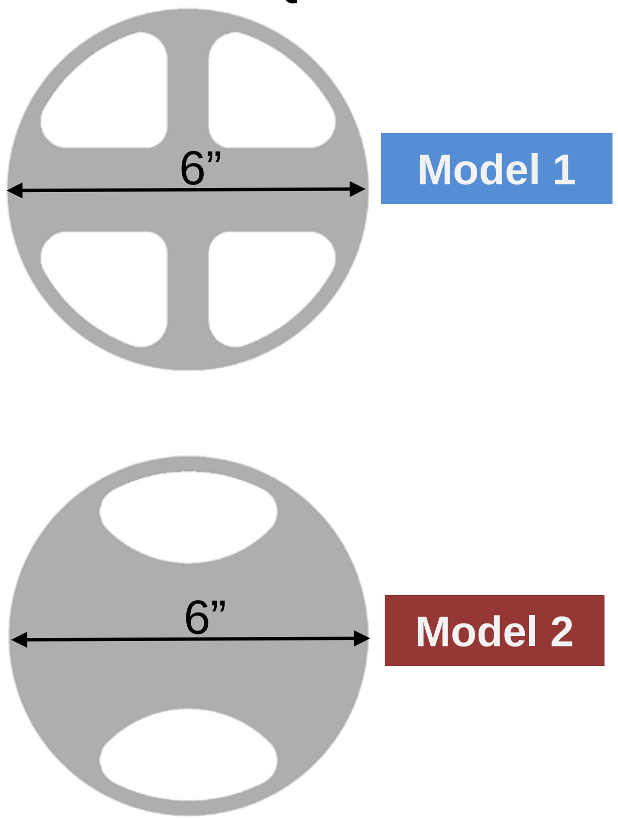
- Free-forming has not shown extended ductility in literature

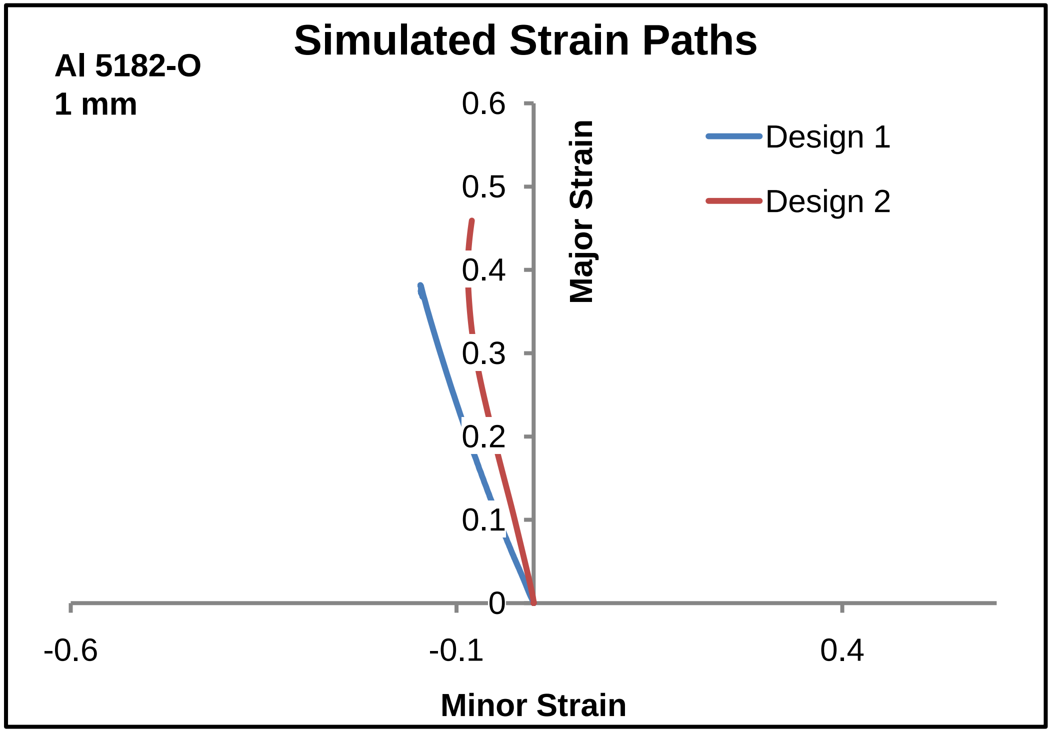
PNNL's Approach

- New specimen design to impose plane-strain deformation
- This will provide lower limit of formability

Technical Progress *(Determination of FLD_0)*
Task 3.1 – Numerical Simulation of Sheet Forming

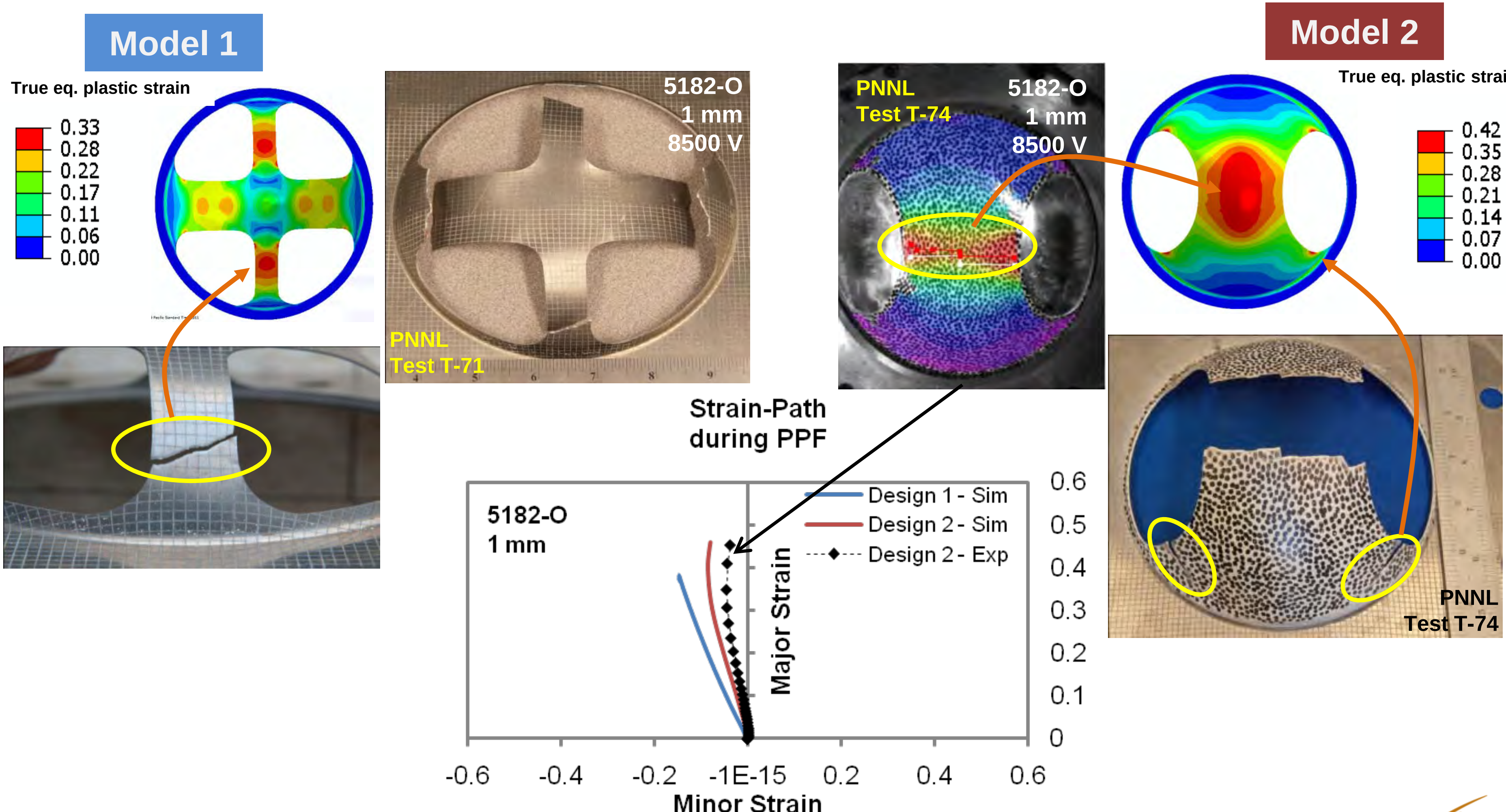
Question: What is the minimum formability at high-rates





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

Technical Progress *(Determination of FLD_o)*
Task 3.1 – Numerical Simulation of Sheet Forming



Plane-strain formability during PPF demonstrated

Numerical model validated

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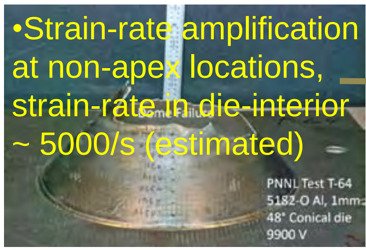
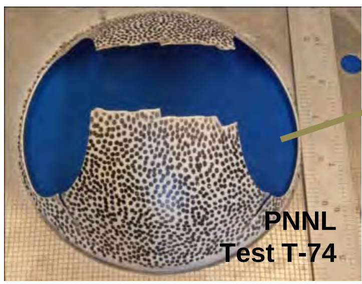
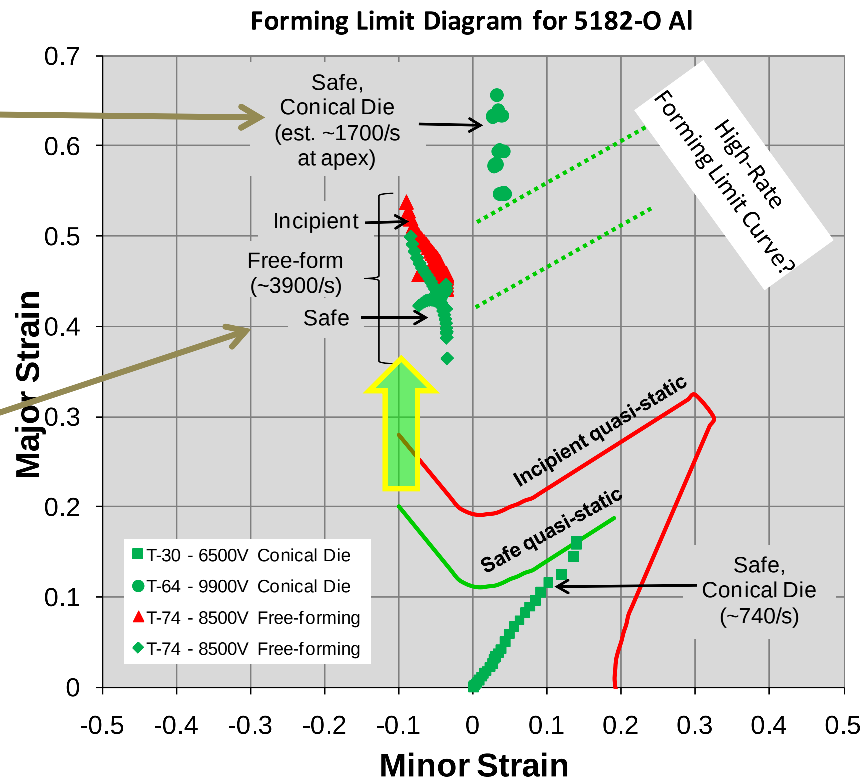
Technical Progress
FLD at High-Strain-Rates during PPF







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 (◆) <u>and</u> CONICAL-DIE(●)
  - Strain-rates ~4000/s and up
- **DEFORMATION HISTORY QUANTIFIED**

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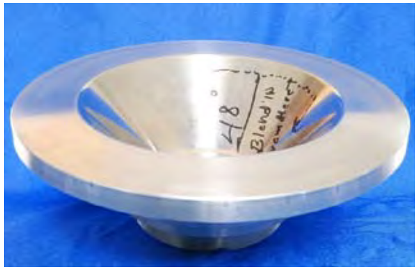
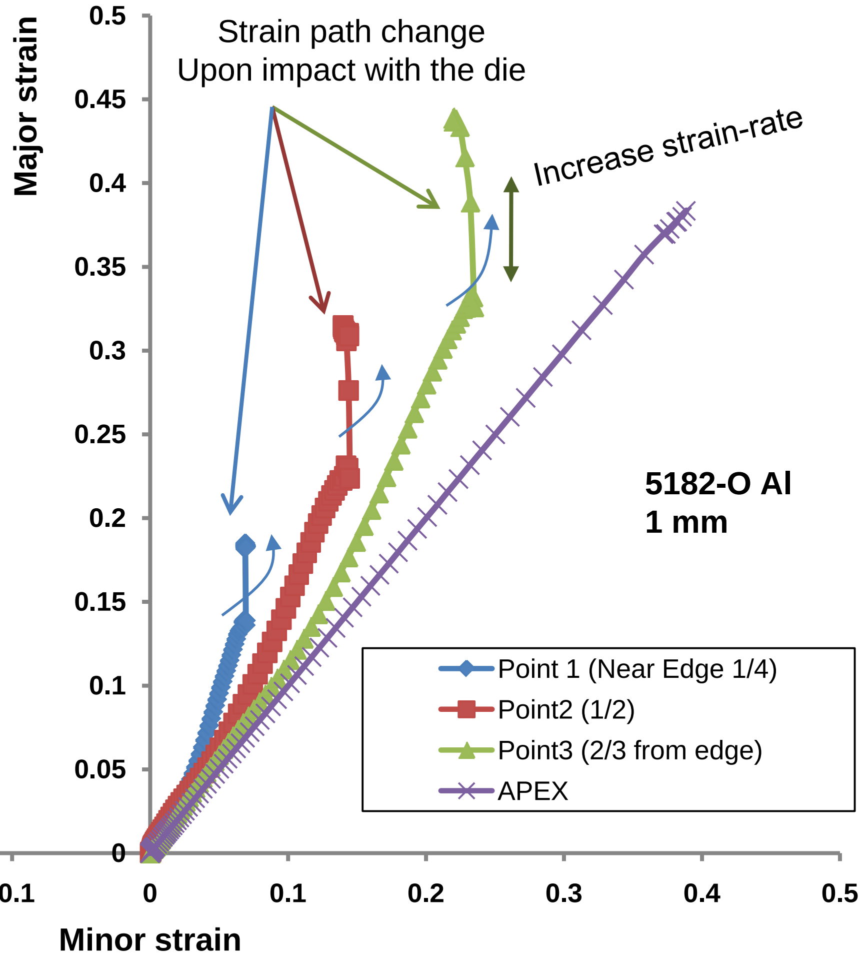
Technical Progress *(Strain-path Changes)*
Task 3.2 – Numerical Simulation of Sheet-Die Interaction

PNNL's Conical Die



- Impact of sheet with the die may lead to:
  - Strain path changes → Strain-rate increase
  - Compressive stresses → Void suppression
- Net result: Increased formability
- Opacity of die makes it extremely challenging to experimentally determine deformation history and verify model predictions



Future Work
(Remainder of FY11)

- Pulse-Pressure Forming of Magnesium
  - Specimen re-design
- Quasi-static Dome Forming
  - Plane-strain formability: Quasi-static vs. High-rate
  - Conventional pre-forming + pulse-pressure forming (re-strike)

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
- 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

Summary

- **Unique Capabilities Developed**
  - 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
- **Experimentally-validated Numerical Simulations**
  - Novel PPF specimen geometries designed and validated to determine FLD_0
  - Analyzed sheet-die interactions and pulse-pressure profiles
- **Mechanical Characterization**
  - Quasi-static and high-strain-rate tensile testing of AZ31B-O, 5182-O Al and DP600 performed → Constitutive equation development
- **Publications**
  - 1 journal manuscript submitted and several others are in preparation
- **Presentations**
  - International conferences: IDDRG-2010 and Plasticity-2011