2015 DOE Vehicle Technologies Office Annual Merit Review

Enhanced Room-Temperature Formability in High-Strength Aluminum Alloys through Pulse-Pressure Forming (PPF)

Co-P.I.: Richard Davies, (509) 375-6474, rich.davies@pnnl.gov
Co-P.I.: Aashish Rohatgi,(509) 372-6047, aashish.rohatgi@pnnl.gov

Pacific Northwest National Laboratory

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Project ID: LM079

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Project Overview

Timeline

- Start – 3Q FY12
- Finish – 3Q FY15
- 100% Complete

Budget

- Total project funding:
  - PNNL: $1200k
  - 50% Industry in-kind

Barriers

- Manufacturability *(B)*: Heat-treatable, high-strength aluminum alloys do not possess sufficient formability at room temperature
- Predictive Modeling Tools *(D)*: Lack of quantitative knowledge of strain-rates and strain-path during PPF has hindered development of validated models

Targets

- The DOE-VT target (2011-2015 plan) for weight reduction of the vehicle and its subsystems is 50%
  - Demonstrate formability enhancements of minimum 70% in high-strength 6xxx and 7xxx Al alloys

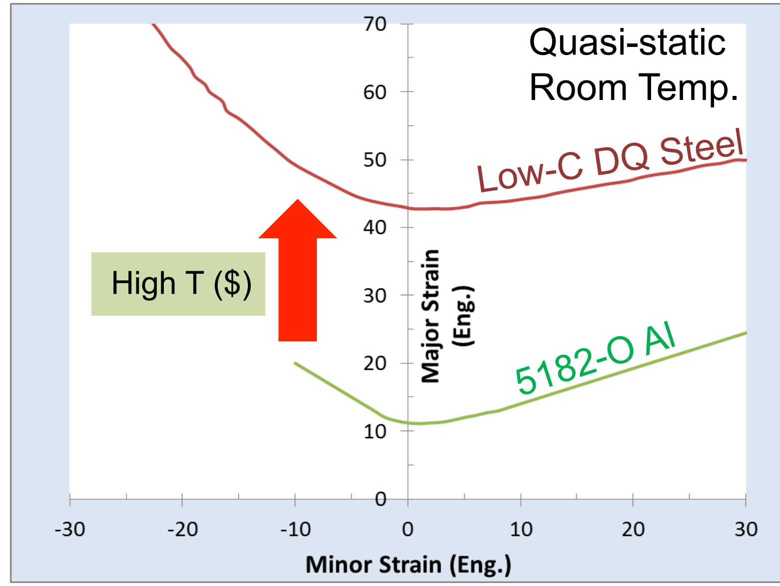
Partners

- OEM and Industry participants:
  - Anil Sachdev, Jon Carter, Jim Quinn, Raj Mishra, Josh Campbell (General Motors)
  - Edmund Chu (Alcoa)
  - American Trim
  - Magna SCFI
  - Clemson University

Relevance/Objectives

Pulse-pressure forming can enhance the formability of Al alloys at room-temperature, i.e. without elevated temperature processing, and thus, lead to lightweighting by enabling the use of Al alloys instead of mild steel

Forming Limit Diagram (FLD)



Overall Objectives

- Enable broader deployment of heat-treatable, high-strength, 6xxx and 7xxx aluminum alloys in automotive structural applications through extended formability

Objective Year III

- (Stretch Goal) Form a part in 7075 (~T6) using PPF

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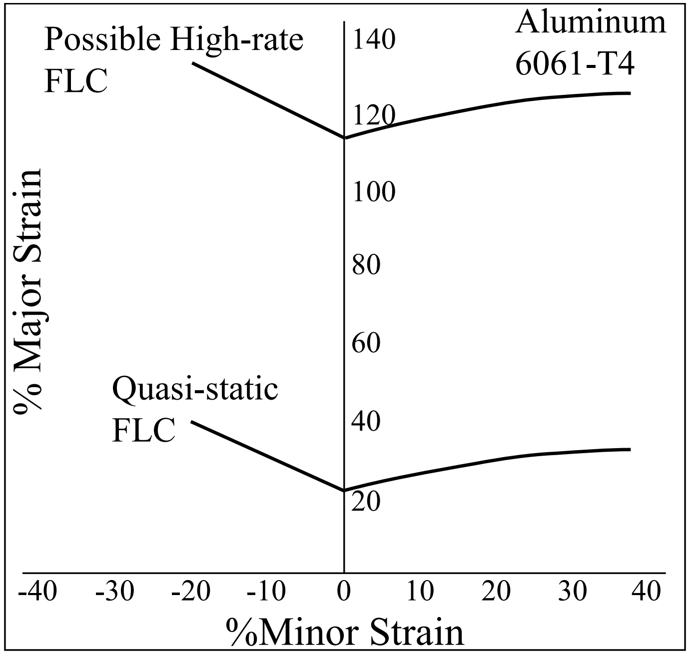
Technical Barriers

- 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



Adapted from Balanethiram & Daehn, Scripta Mat., 1994

Project Technical Approach

Phase I (Year I)

- Alloy and PPF technique selection
- Formability and process-window determination (expt. & modeling)
- Go-No Go Gate

Phase II (Year 2)

- Design of prototypical part formed by PPF
- PPF process development

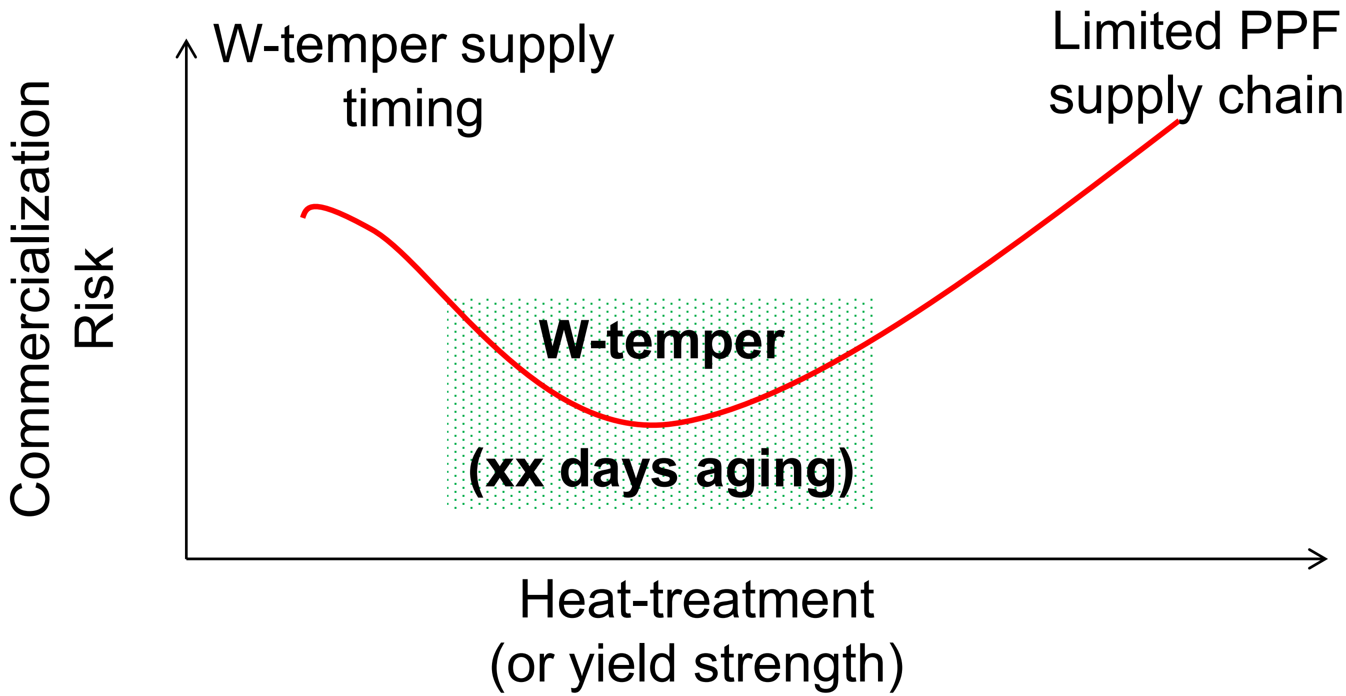
Phase III (Year 3)

- Prototype part fabrication
- Metal forming simulation capability development

Project Milestones & Deliverables

Year	Milestone/ Deliverable	Description	Due	Status
Years I & II	Milestone #1	Demonstrate formability improvement of minimum 70% in AA6022-T4 and AA7075-T6 through PPF	12/2012	✓
	Milestone #2 Gate	GATE (Technical): Demonstrate via a forming limit diagram that aluminum alloy AA7075 in the T6 or W temper conditions have sufficient formability to produce a typical automotive B-pillar component at strain rates below 10^4 /s	05/2013	Go/No-Go
	Milestone #3	Determine the baseline room-temperature quasi-static formability of a 7xxx Al alloy under plane-strain and equi-biaxial conditions in three different W-tempers.	12/2013	✓
	Milestone #4	Determine the room-temperature formability of the selected 7xxx Al alloy under plane-strain (pulse-pressure forming) in three different W-tempers, the target PPF formability in W-temper to exceed the quasi-static T6-temper formability by at least 70%.	03/2014	✓
Year III	**Milestone #5**	**Develop constitutive relations to describe the room-temperature stress-strain response of the selected 7xxx Al alloy.**	**06/2014**	✓
	Milestone #6	**Determine the time and temperature required for heat-treating post-formed 7xxx Al alloy, deformed at 1 quasi-static and 1 pulse-pressure forming strain-rate, to achieve strength within 80% of its T6 condition.**	**09/2014**	✓
	Milestone #7	**Select a component with automotive supplier that may be formed in 5xxx, 6xxx or 7xxx Al using PPF.**	**12/2014**	✓
	Milestone #8	**Stretch: Fabricate a prototypical component in 5xxx, 6xxx or 7xxx Al via pulse pressure forming**	**3/2015**	**Simulation**
		Regular: Predict the high-rate FLD of AA7075 at rates necessary to achieve B-pillar forming strains		✓

Technical Approach (FY15)



- Forming in T6 (High-rate) → Limited supply chain
- Forming in W-temper (Quasi-static) →
  - Scheduling “correct” temper for stamping
  - Post-forming heat-treatment to regain T6 strength

Experiments

Subject Materials

- AA7075-T6, 1 mm

Heat Treatment (7075-W temper)

- Solutionize (480C-30 min.) + Water-quench + Natural aging
  - 1 day and 6 days

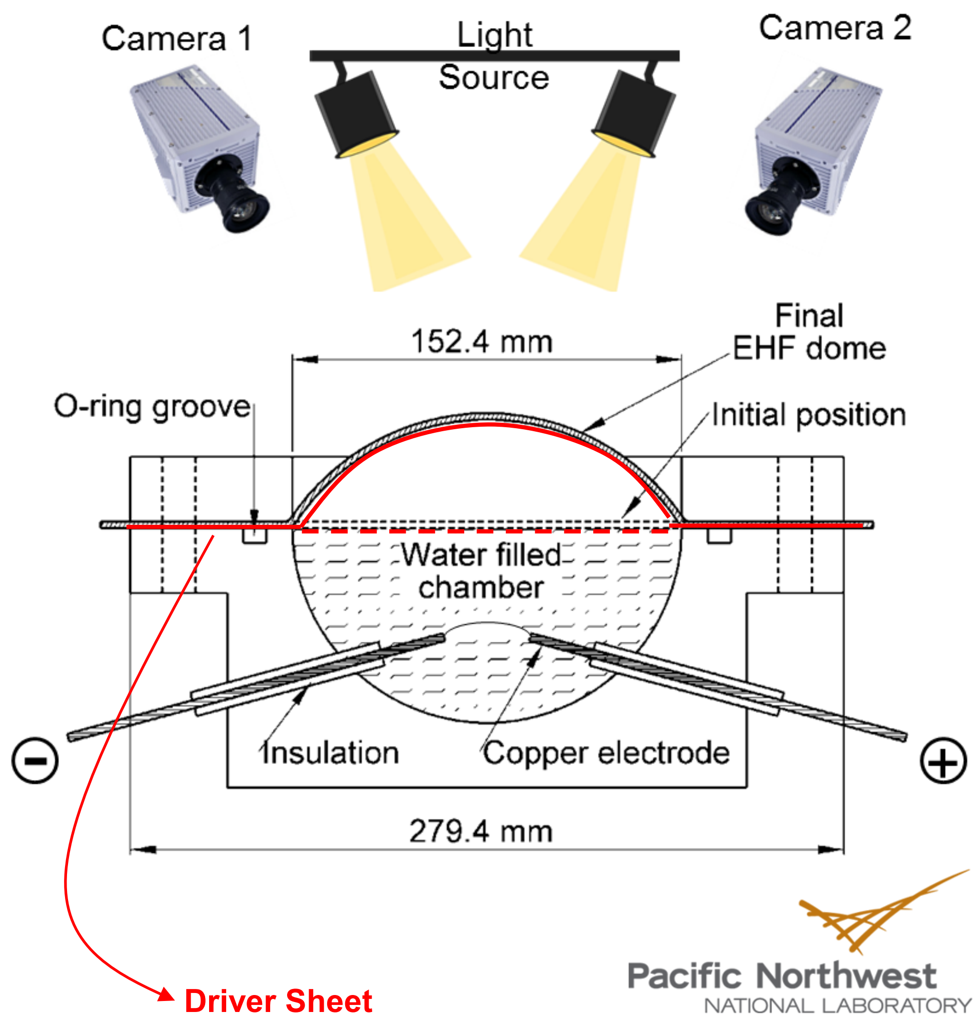
Formability

- High-rate FLD → PPF
  - Novel combination of high-speed imaging and DIC
- Quasi-static FLD → LDH

Mechanical Testing

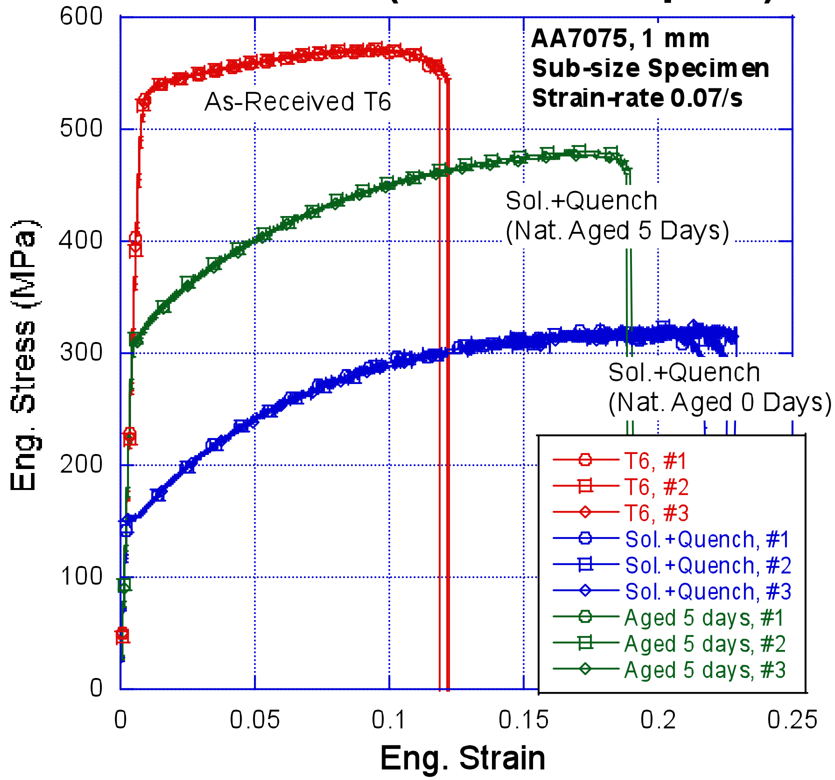
- Quasi-static and high-rate tension
- Hardness = f(natural aging, strain)

PNNL's Electro-hydraulic Forming System



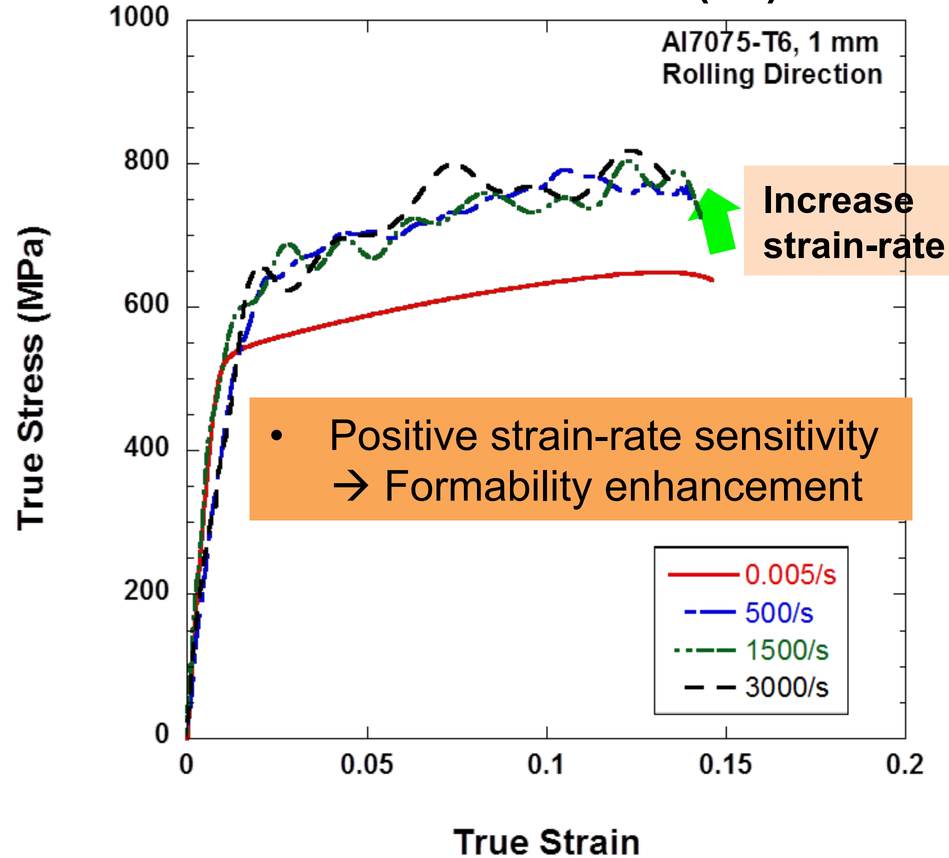
Results: Effect of Temper and Strain-rate

Quasi-static (T6 & W tempers)



- Large design space to optimize formability
- W temper → heat-treatment to regain T6 strength

Strain-rate Effect (T6)



- Positive strain-rate sensitivity → Formability enhancement

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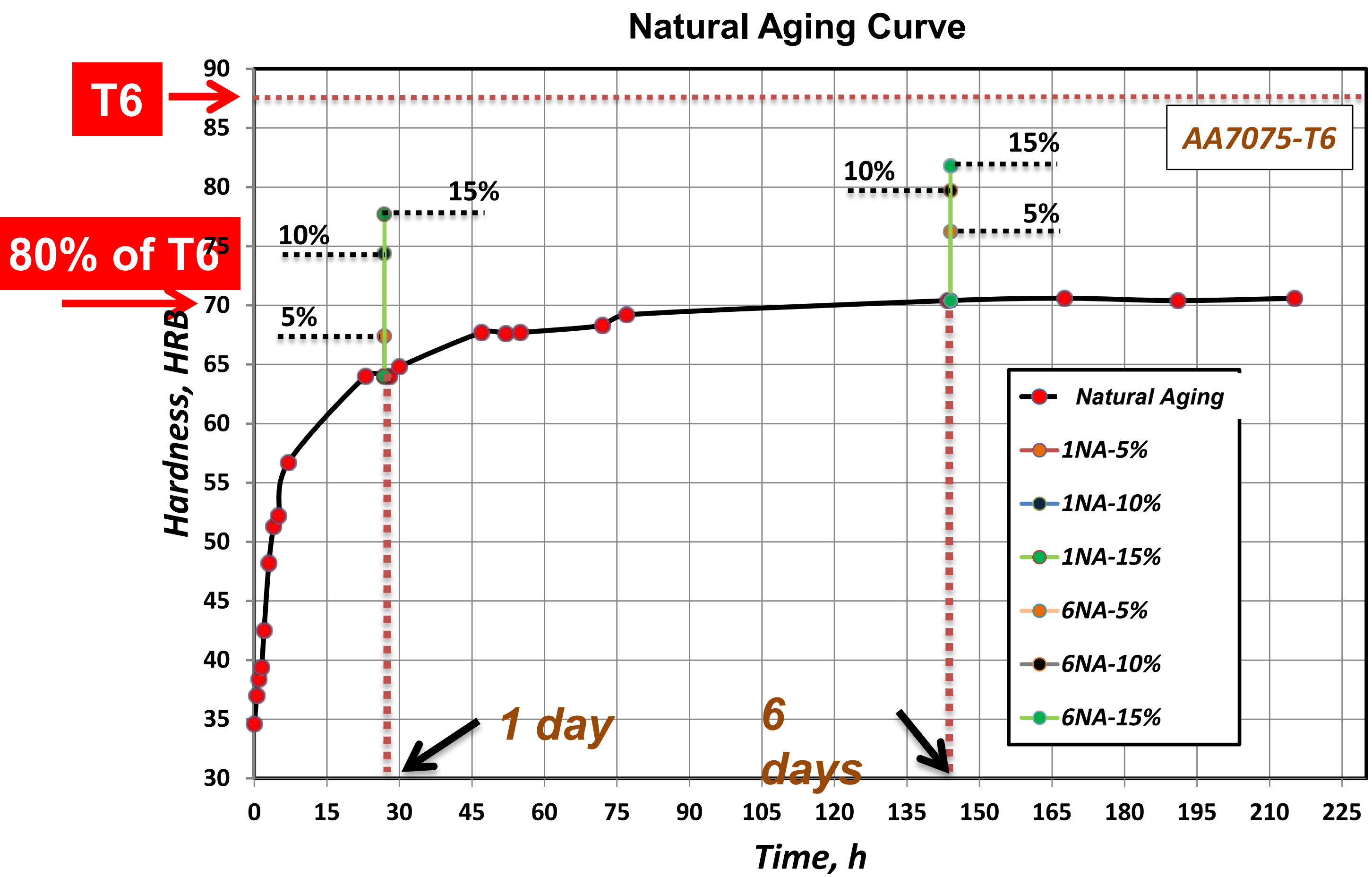
Results: Hardness vs. Natural Aging & Strain

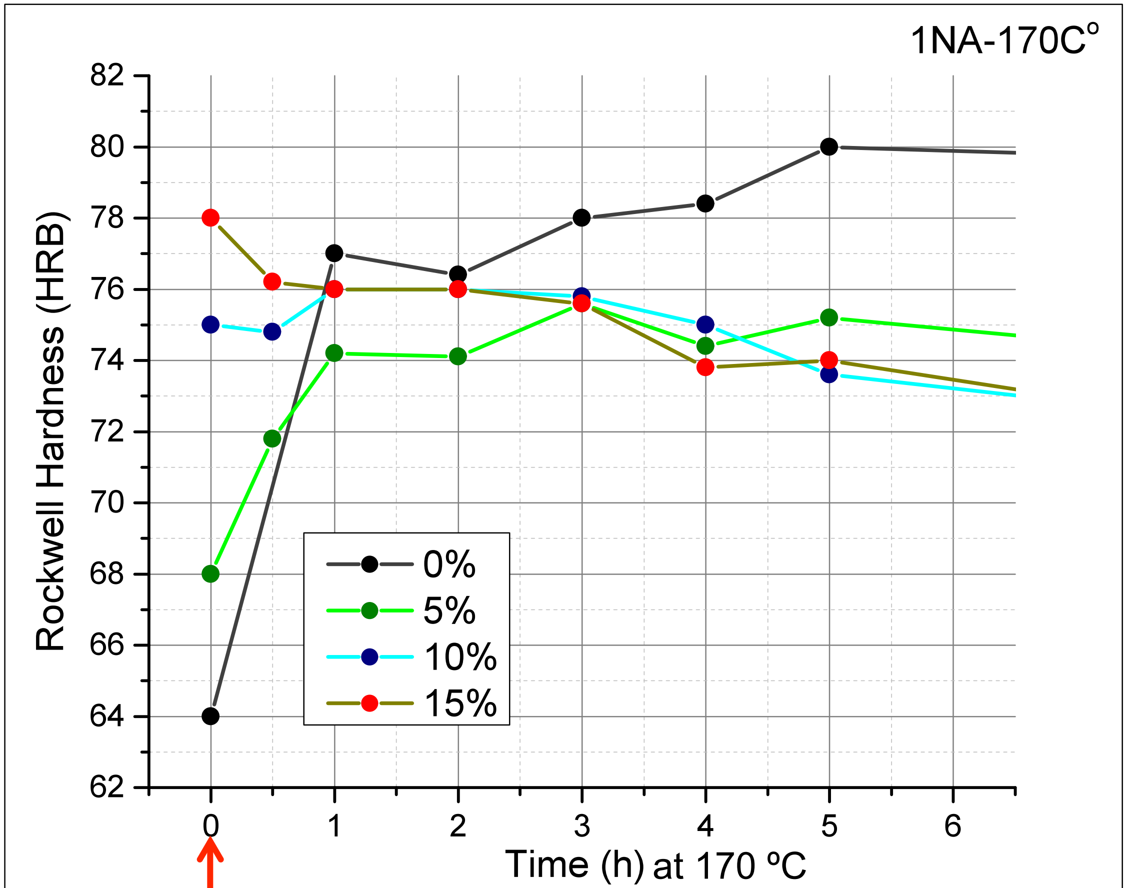


Precipitation Sequence

Solid-solution
↓
GP Zones
↓
Metastable η'
↓
Stable η

•Natural aging + forming → hardness within 80% of T6 hardness; i.e. additional heat-treatment could be avoided
•Effect of paint-bake?

Results: Hardness vs. Natural Aging & Strain



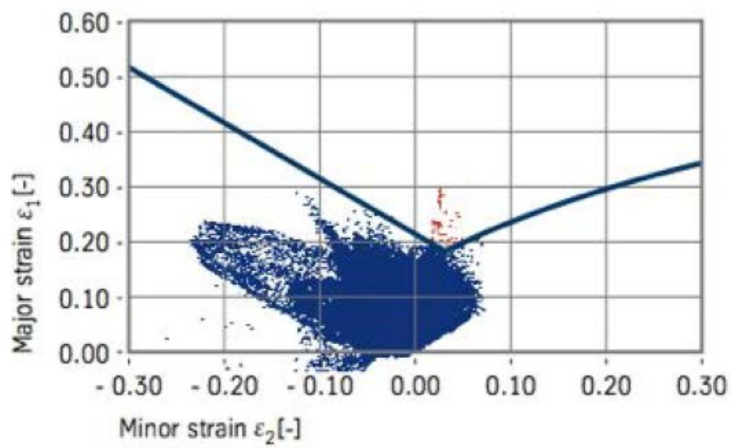
1 day natural aged

Precipitation Sequence

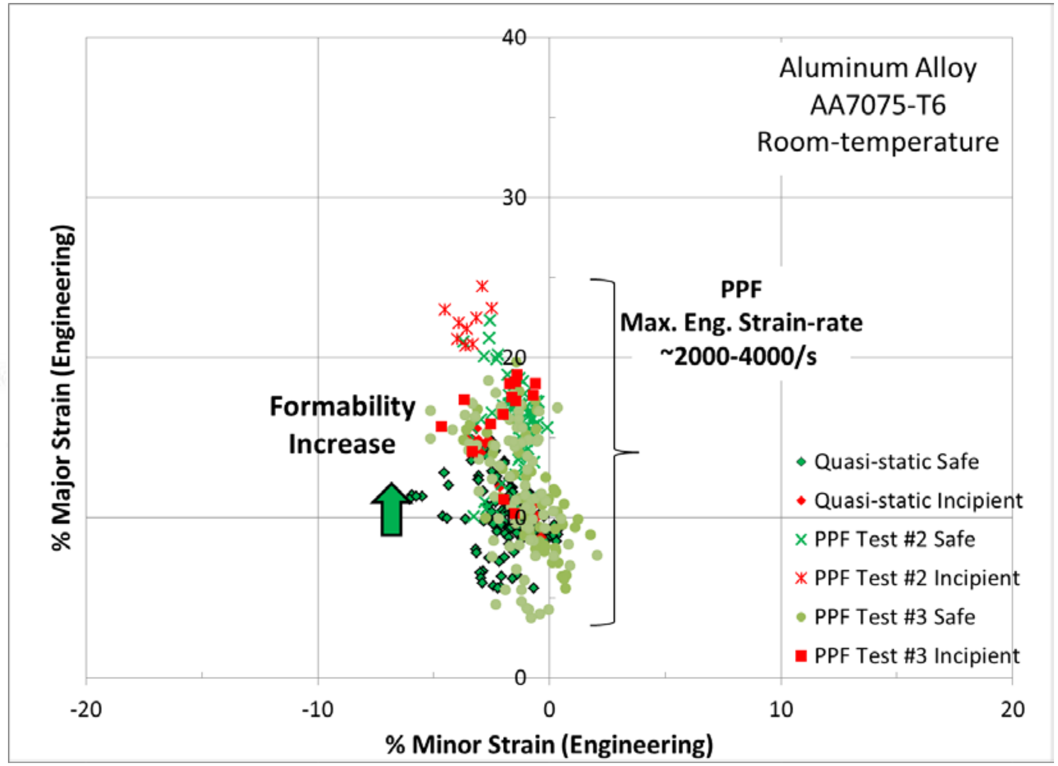
Solid-solution
↓
GP Zones
↓
Metastable η'
↓
Stable η

•Paint-bake increases hardness if prior plastic strain < ~15%
•Paint-bake slightly reduces hardness if prior plastic strain >15%

Results: Room-temp. FLD 7075-T6



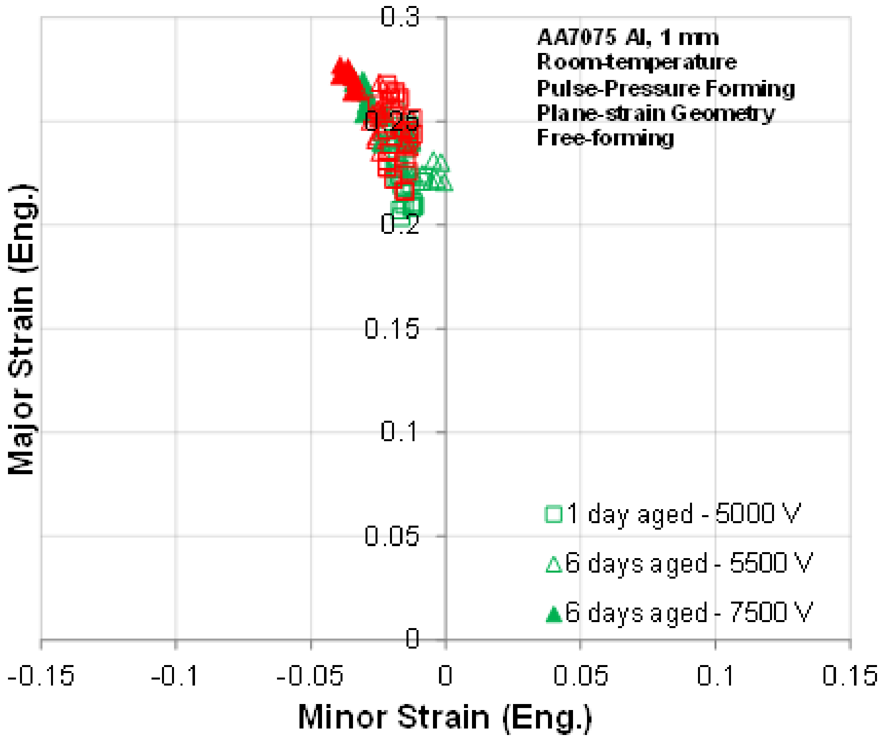
Predicted strains in a B-Pillar TPN-W 900 Steel
http://incar.thyssenkrupp.com/4_01_041_BS02_Umformen.html?lang=en



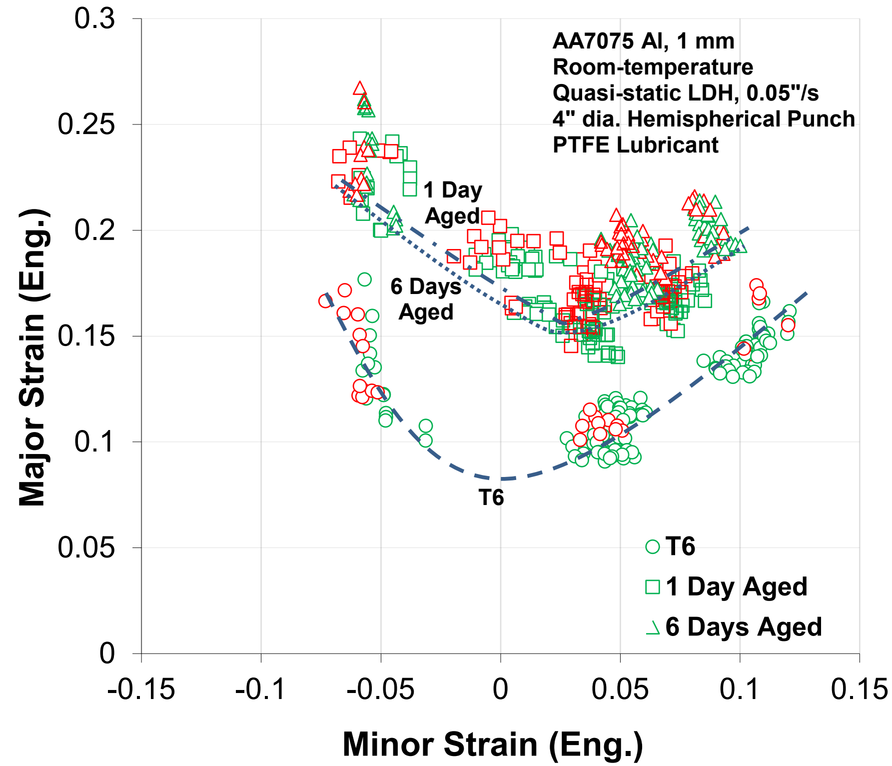
- T6 temper: High-rate forming enhances formability

Results: Room-temp. FLD 7075-W temper

High Strain-rate (PPF)



Quasi-static (LDH)



Highest Formability

PPF (W) → PPF (T6) → Quasi-static (W) → Quasi-static (T6)

Lowest Formability

Response to Previous Year Reviewers' Comments

- Approach (Favorable)
  - Comment: “.. novel experimental techniques and material characterization are valuable results from this work….. project has produced enough results to transfer the technology to the next step….. could it be used to make structural components b-pillars and rockers..?”
  - Response: We have engaged Am Trim (for PPF) and Magna SCFI (stamping side-impact beam in W temper)
- Technical Accomplishments? (Progress in understanding 5xxx, 6xxx and 7xxx alloys acknowledged)
  - Comment: “…well planned and executed…. only a bit of work reported on 7075…”
  - Response: Explored formability for AA7075 in various tempers and strain-rates to address long-standing challenge with Al alloys (poor room-temperature formability)

Response to Previous Year Reviewers' Comments

- Proposed future research (Path to commercialization not clear)
  - Comment: "…costs associated with scale up of the electro forming process are likely to be quite high….limited discussion of the path to commercialization is troubling.."
  - Response: We engaged AmTrim to study the feasibility for forming a prototype GM part using PPF. Overall, limited supply chain is a barrier for commercial use of this technology.
- Support overall DOE objectives? (Supportive)
  - Comment: ".. Reducing the process temperatures will be a good strategy to reduce the cost…if high strength Al can be formed at room temperature it will be more readily used in vehicles, thus saving weight."
  - Response: Reviewers' comments reaffirm our efforts to drive down the processing temperature for Al sheet forming.

Collaboration

- GM
  - Prototypical component identification
  - Test material selection
  - Project path guidance
- Alcoa
- American Trim
  - Prototype fabrication via PPF process
- Magna SCFI
  - Forming simulation of side-impact crash beam

Remaining Challenges and Barriers
(with respect to PPF technology)

<u>Challenge</u>

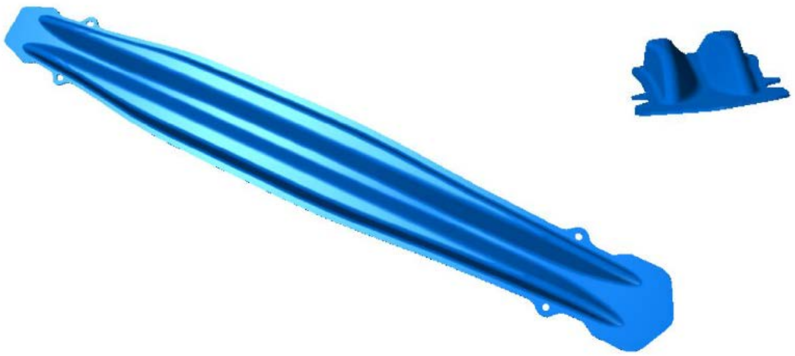
- Development of hybrid process (PPF + conventional stamping) → Formability prediction under complex, non-proportional strain-paths
- Poor room-temperature formability of AHSS: High-rate formability should be explored

<u>Barrier</u>

- Limited supply chain for PPF technology

Proposed Future Work

- Current project is nearly complete
- Forming in W temper 7075 is being explored with Tier-1 supplier (Magna)



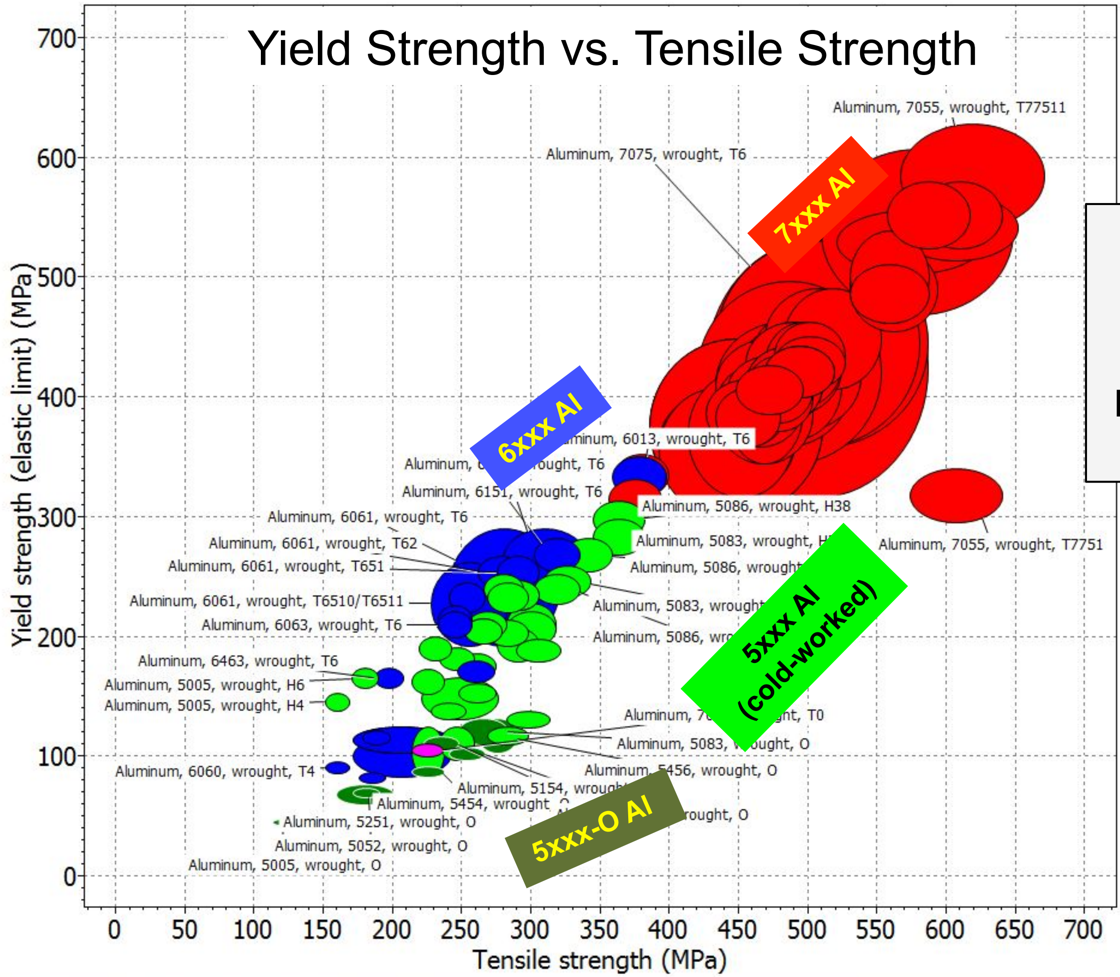
Side-impact crash beam

Summary

- **Room-temperature Forming of AA7075**
  - If T6 is the preferred temper for forming, then high-strain-rate forming is necessary
  - If quasi-static forming (e.g. stamping) is the preferred path, then W temper is required
- **Post-forming Heat-treatment**
  - Combination of W temper and room-temperature plastic deformation during forming may be sufficient to regain 80% T6 hardness
- **Commercialization of PPF Technique**
  - Limited supply chain is a key barrier for PPF commercialization

Technical Back-Up Slides

Opportunity with High-Strength Al Alloys



Strength/weight

7xxx Al

500 MPa/2.8 g/cc ~178

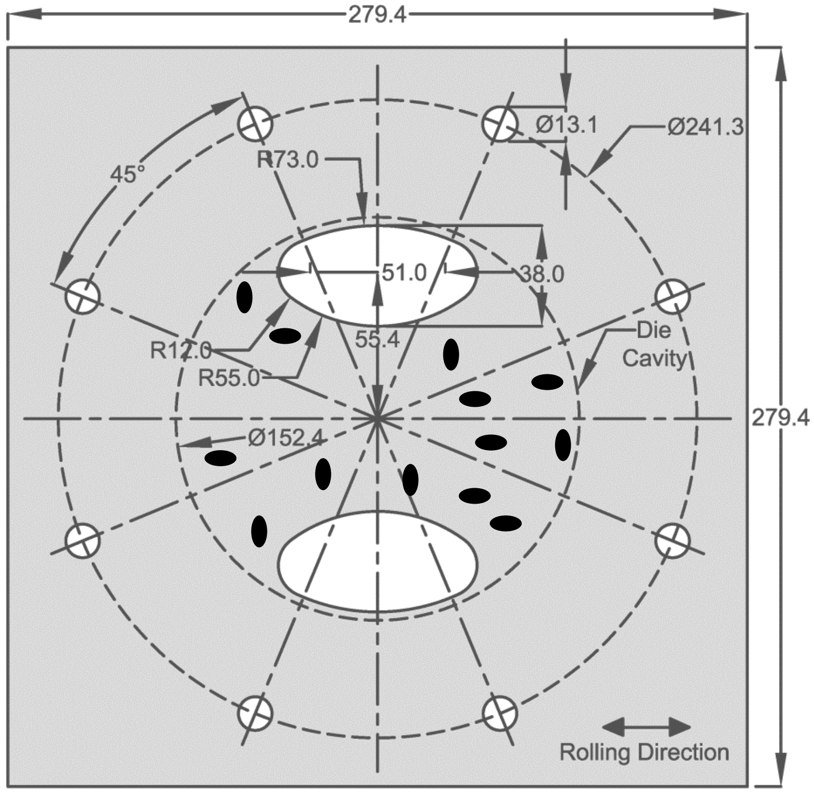
Press Hardening Steel

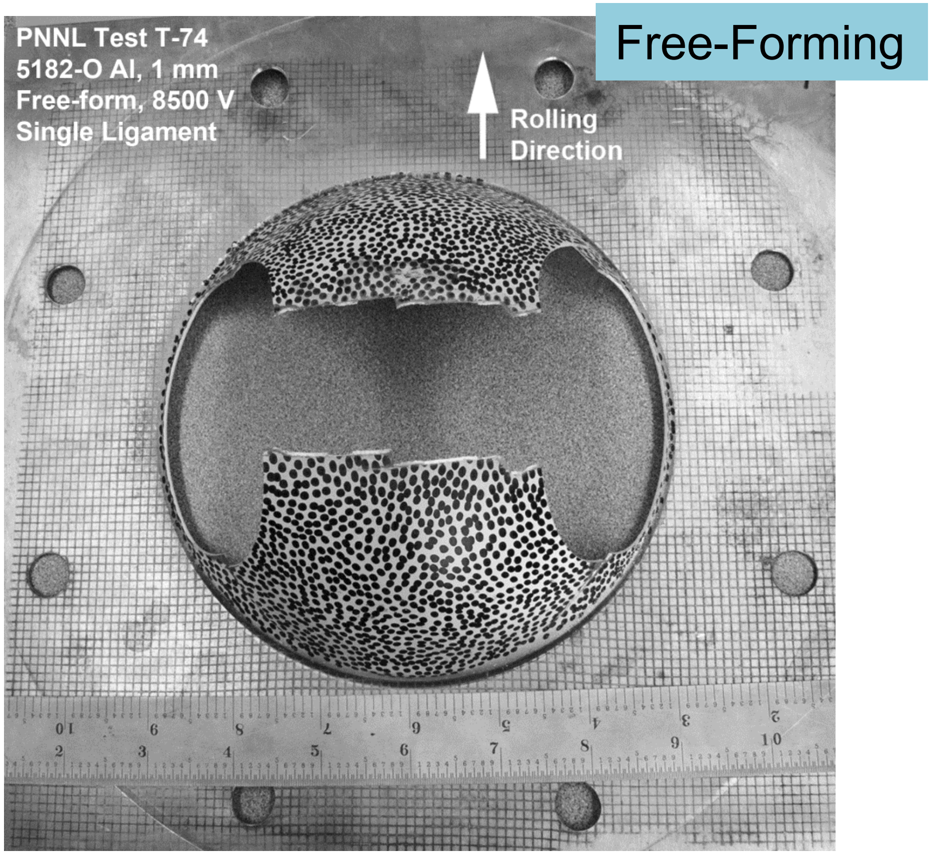
950 MPa/7.8 g/cc ~122

Challenge

- **Higher strength α 1/Formability**
- **Age-hardening Al alloys → Form in lower strength state + heat-treatment (maybe) to regain the strength**

PPF Test Specimen (~Plane-strain Geometry)





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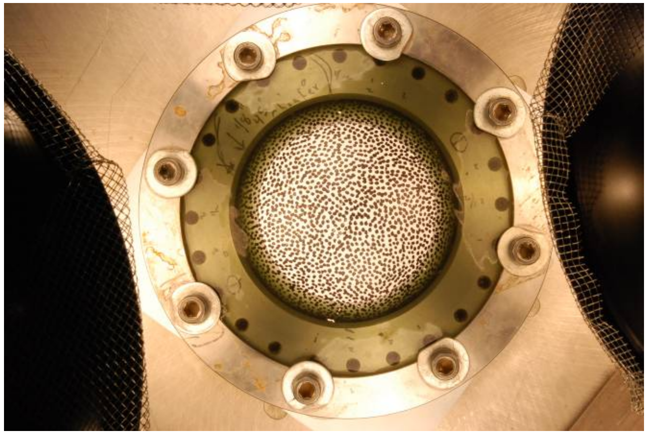
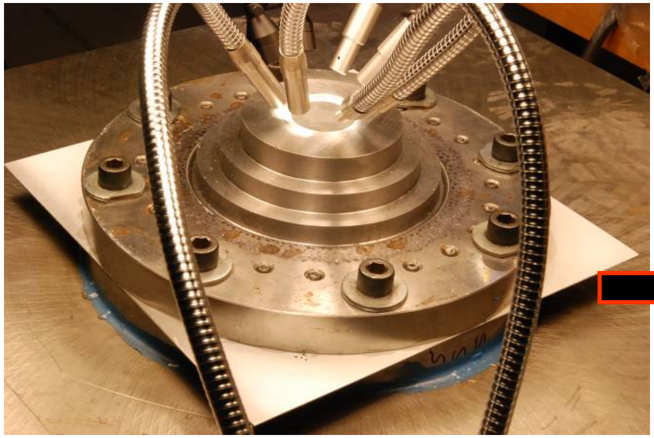
PNNL High-Rate Capabilities

Top View: Free-Forming

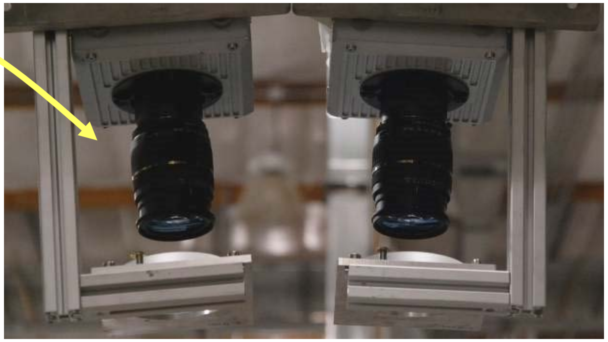


Side View: Cone Die



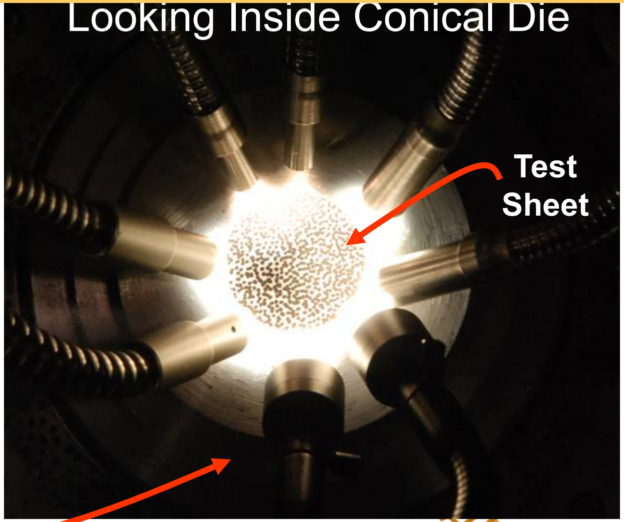
Imaging Setup

Close-up of Cameras



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

Looking Inside Conical Die



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Technical Progress
Constitutive Model w/ variable Strain Rate Sensitivity

<u>Constitutive Model</u>

Adapt Hollomon Equation to capture variable strain rate sensitivity.

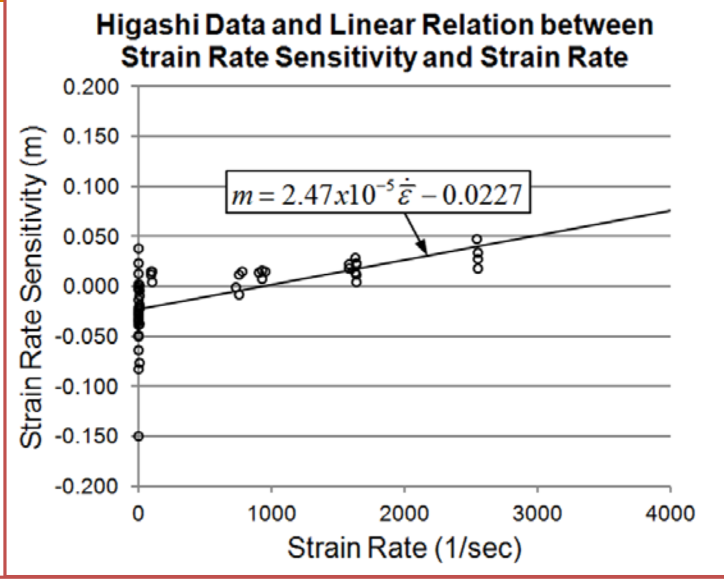
$$\sigma = K\bar{\varepsilon}^n\dot{\bar{\varepsilon}}^m \qquad K = 538$$

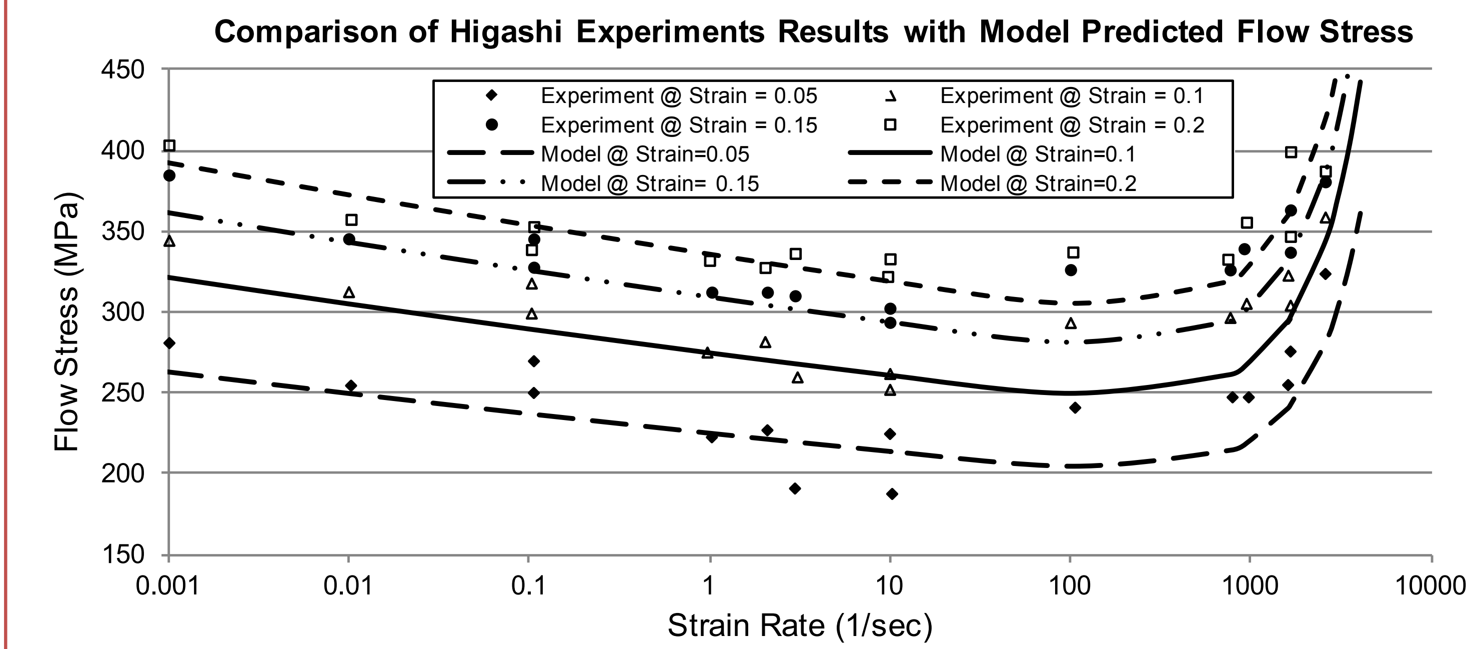
$$n = 0.292$$

$$m = A\dot{\bar{\varepsilon}} + m_{quasistatic} \qquad A = 2.47x10^{-5}$$

$$m_{quasistatic} = -0.0227$$

$$\sigma = 538\bar{\varepsilon}^{0.292}\dot{\bar{\varepsilon}}^{(2.47x10^{-5}\dot{\bar{\varepsilon}} - 0.0227)}$$





M-K Method Predictions of Forming Limits

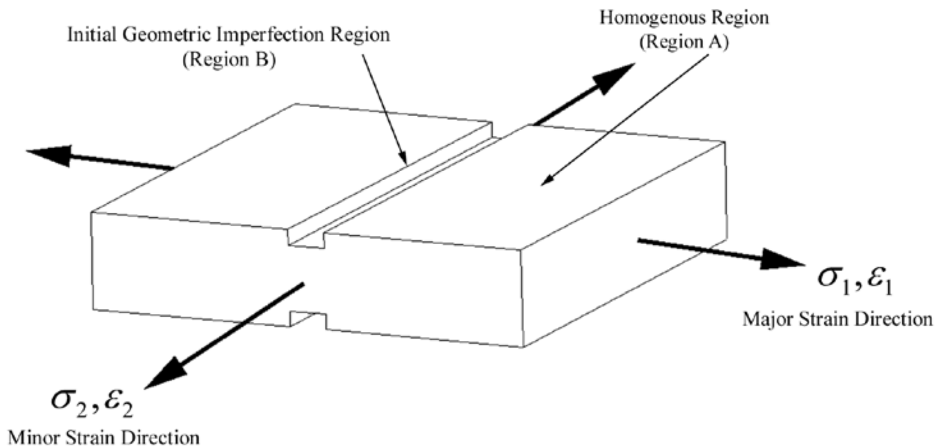


Illustration of the concept of an initial geometric imperfection oriented perpendicular to the direction of major strain in a biaxial sheet stretching application.

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

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