2014 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
June 19th 2014

Project ID: LM079

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Project Overview

Timeline

- Start – 3Q FY12
- Finish – 3Q FY15
- 66% complete

Budget

- Total project funding:
  - PNNL: $1200k/~1150k
  - 50% Industry in-kind

Barriers

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

Targets

- The DOE-VT target 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

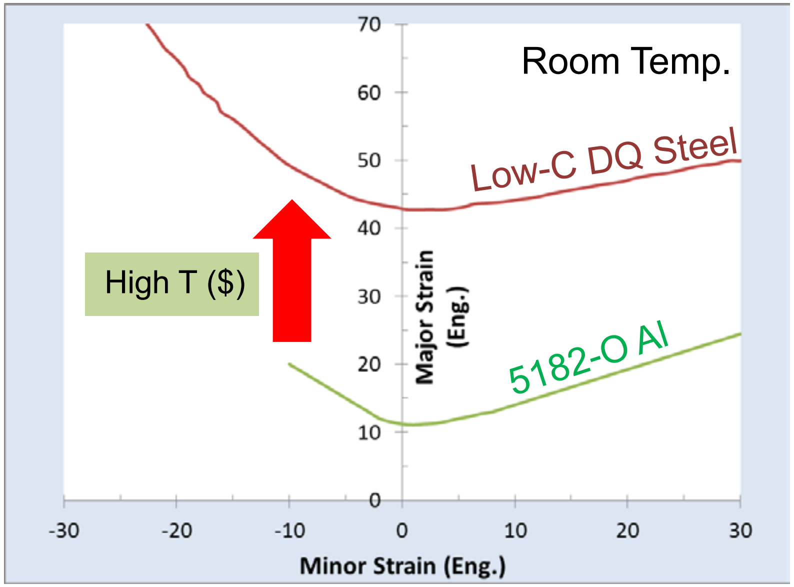
Partners

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

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)

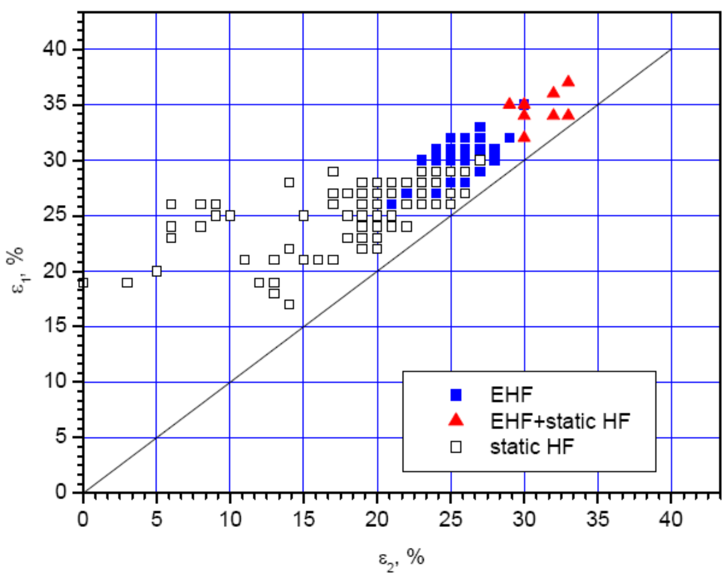


Objectives

- Enable broader deployment of heat-treatable, high-strength, 6xxx and 7xxx aluminum alloys in automotive structural applications through extended formability
- Quantify the process window where enhanced formability in 6xxx and 7xxx Al alloys in feasible

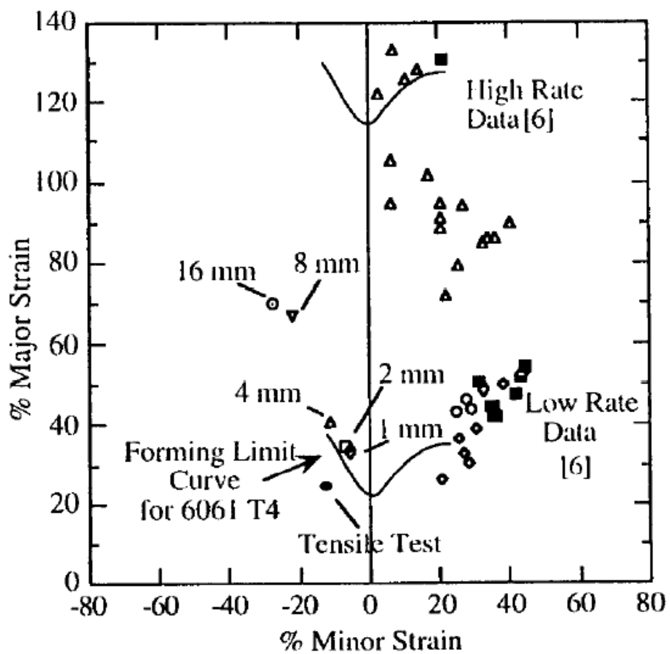
Technical Barriers

- 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 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

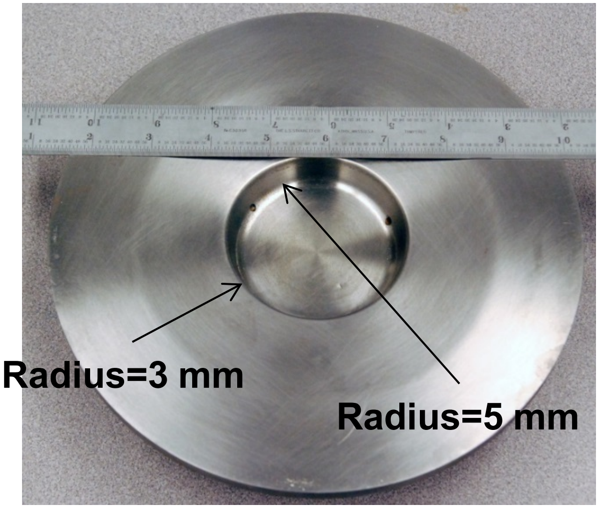
Project Milestones & Deliverables

Milestone/ Deliverable	Description	Due	Status
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	✓
Milestone #5	Develop constitutive relations to describe the room-temperature stress-strain response of the selected 7xxx Al alloy.	06/2014	**No Issues**
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	**No Issues**

Background

Project Plan - Subject Materials

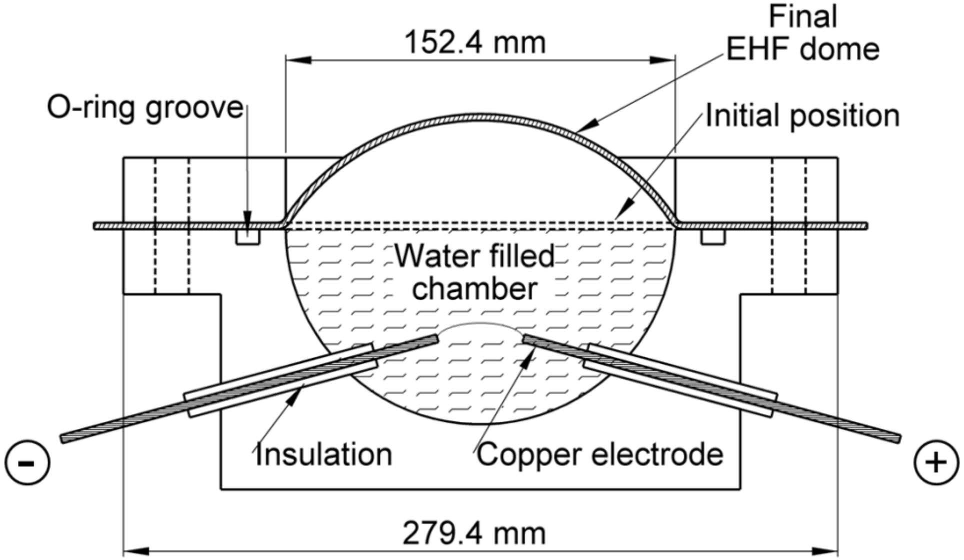
- AA6022-T4E32, 1.2 mm
- **AA7075-T6, 1 mm**
- **AA5182-O, 1 mm (Hat-die)**



PNNL's Hat Die

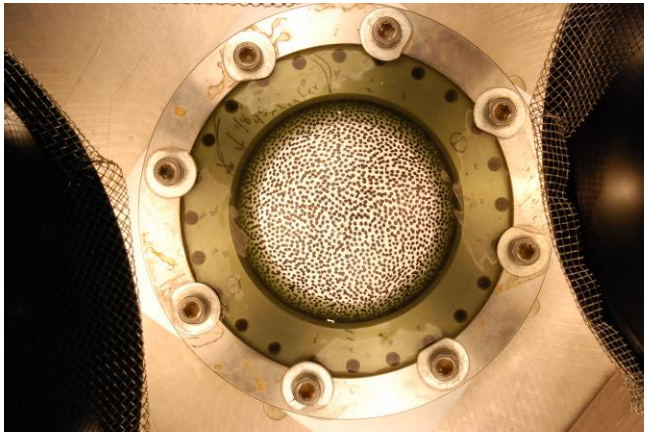
- Compatible with EHF tool
- Similar radii as in structural components identified and provided by GM

PNNL's Electro-hydraulic Forming Tool

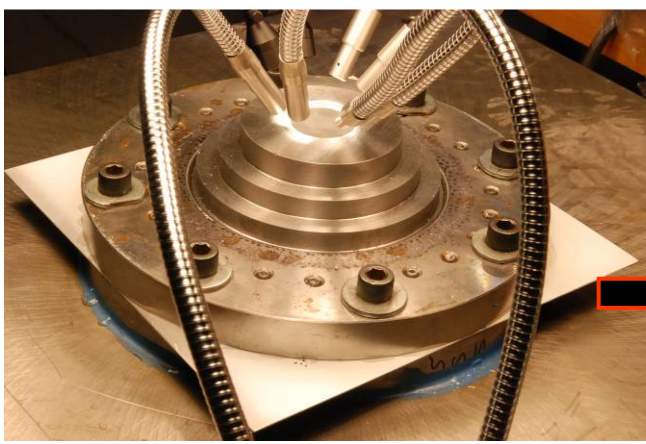


PNNL High-Rate Capabilities

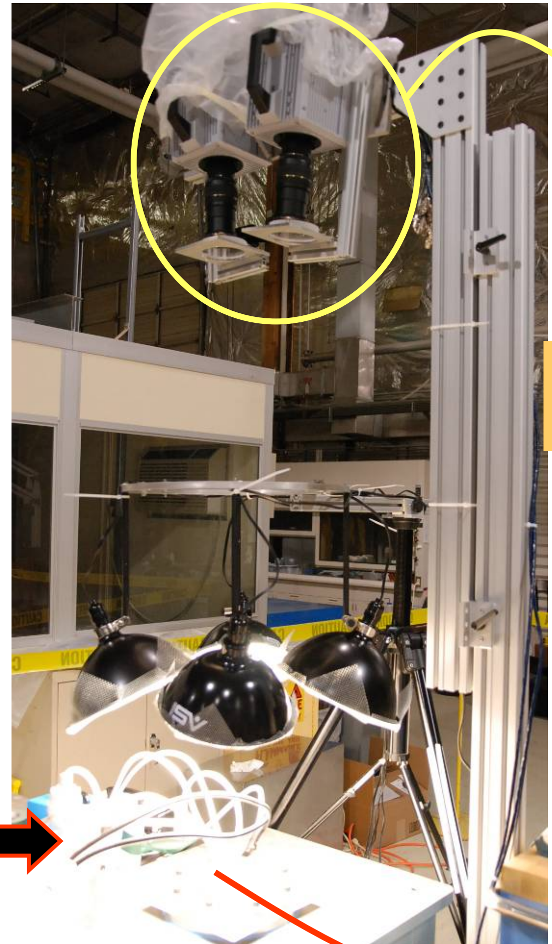
Top View: Free-Forming



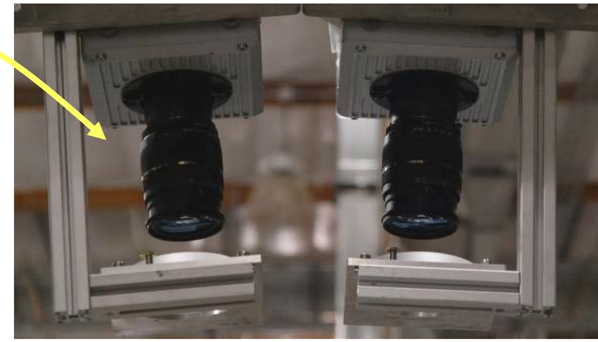
Side View: Cone Die



Imaging Setup

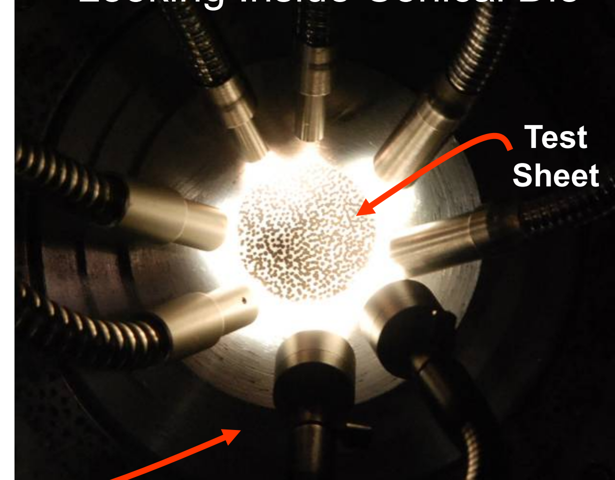


Close-up of Cameras



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

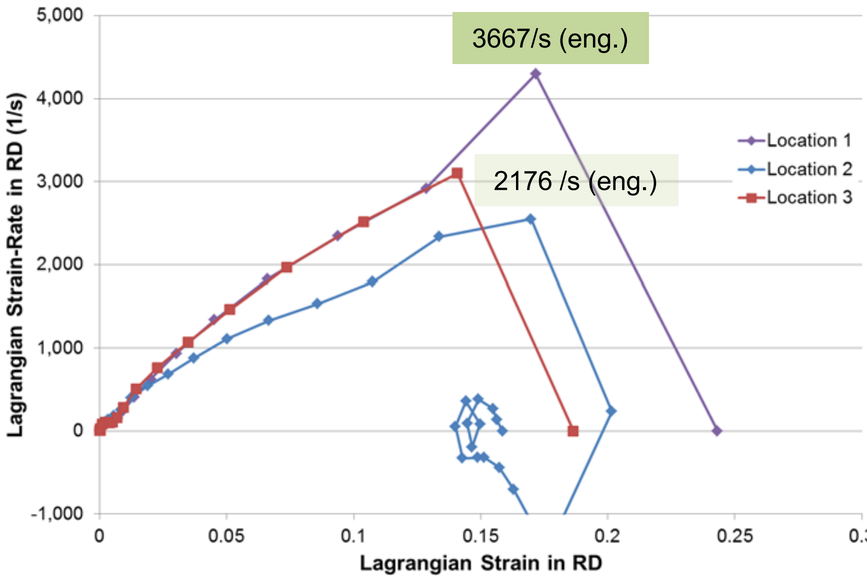
Looking Inside Conical Die

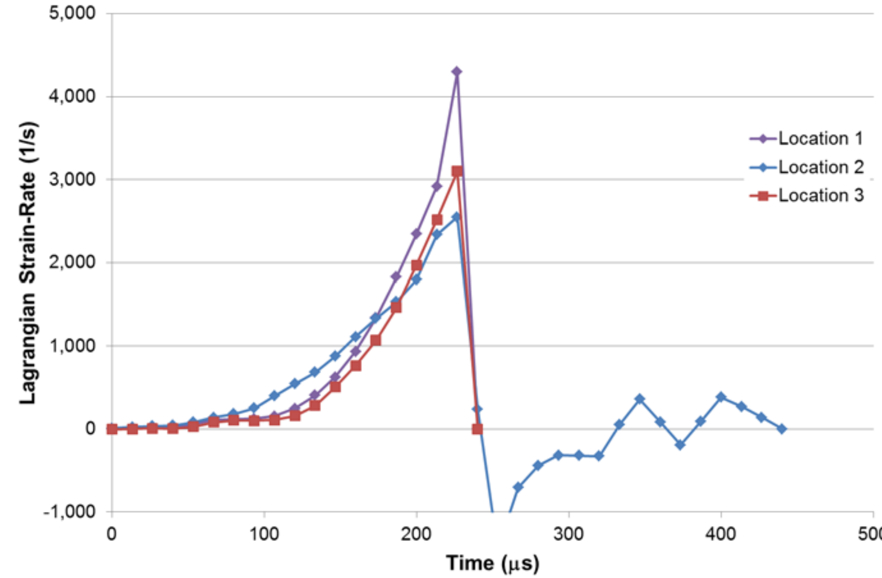


Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

PPF Results on AA7075-T6: DIC Data





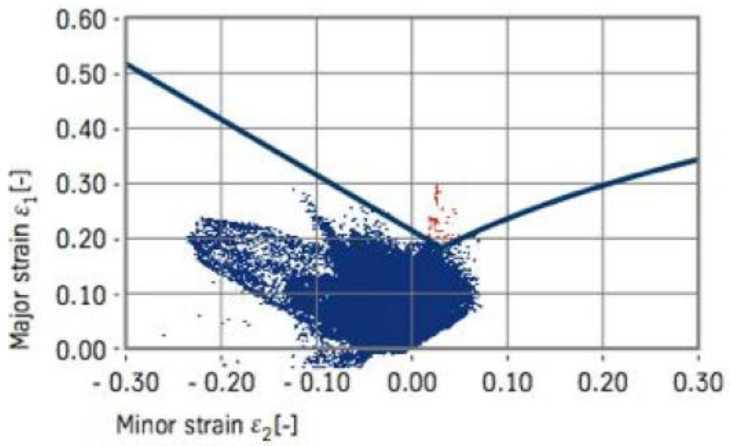
<u>DIC Results</u>

- Peak in-plane strain-rate ~2100-3670 /s (eng.)
- Maximum post-deformation strain ~0.14 (eng.)

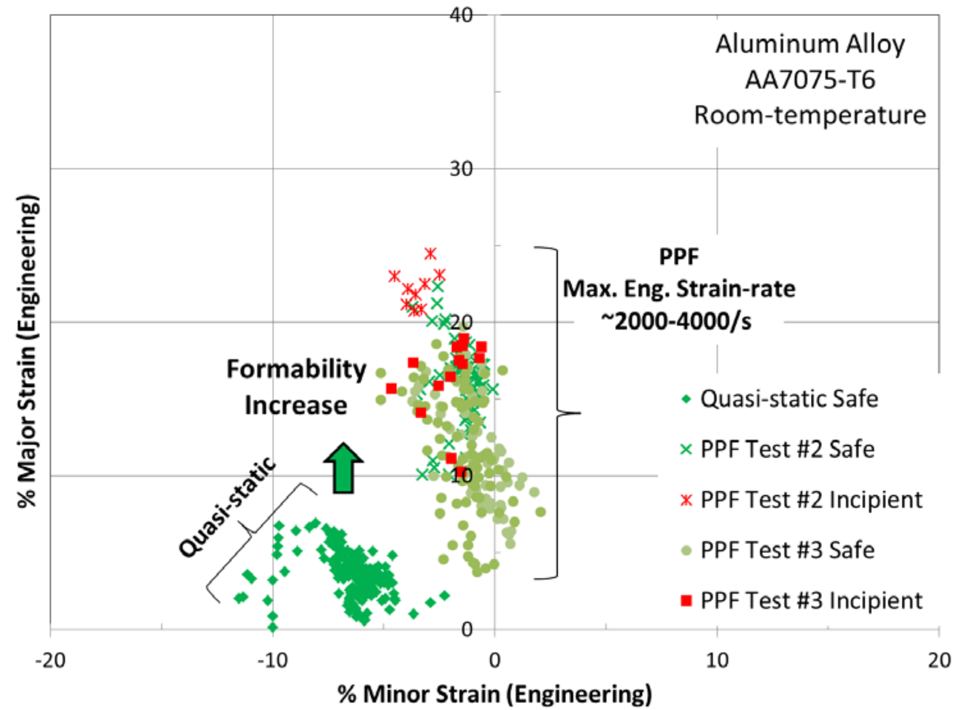
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

AA7075 PPF Strains vs. Steel B-Pillar Strains



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



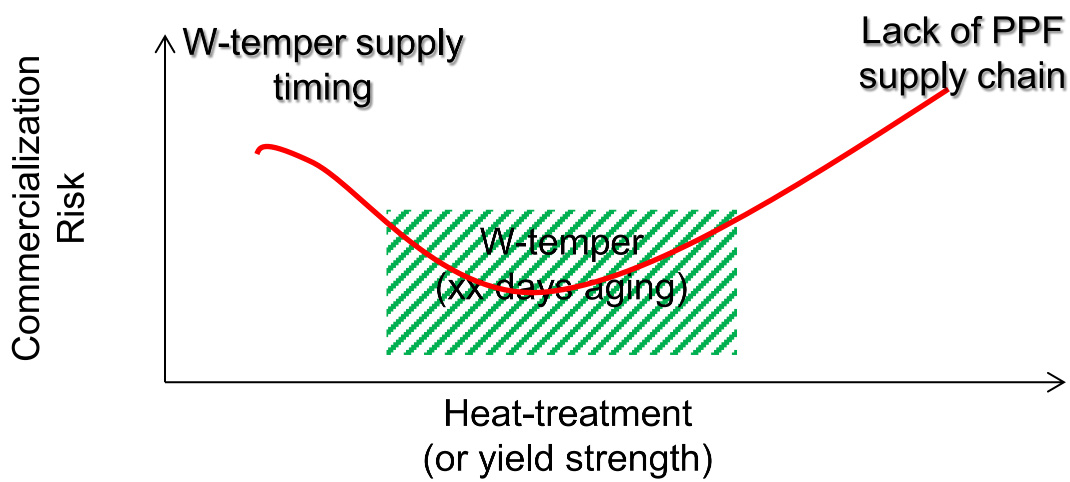
- Strain-grid data shows that PPF safe strains (~0.15-0.2 (eng.)) are achievable
- DIC data shows the required peak strain-rate to be > ~2000 /s

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Potential Approaches and Risks

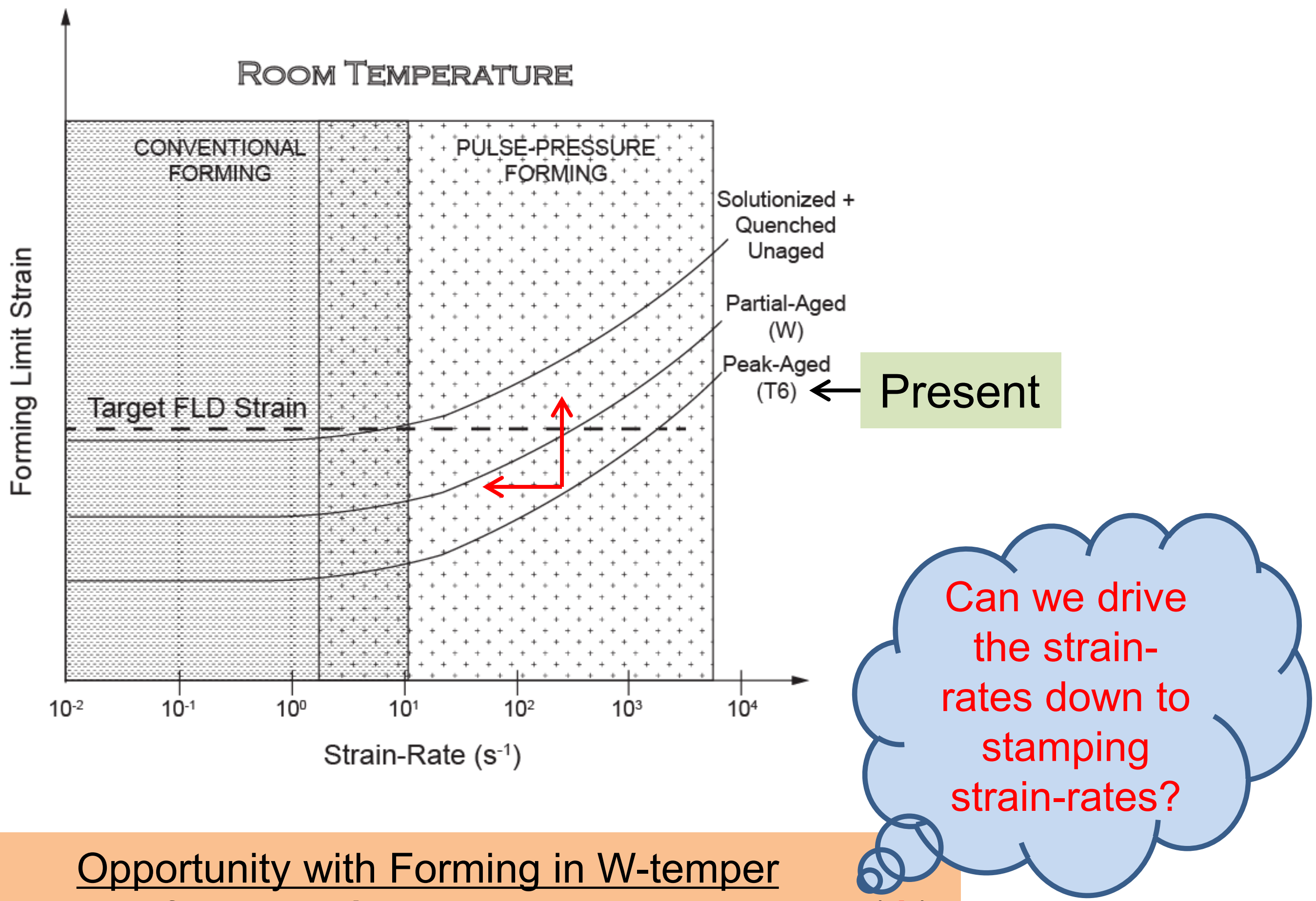
- Forming in W-temper: e.g. solutionized + quenched, xx days aging, etc.
  - Target post-forming heat-treatment: Paint-bake for strength → T6
- Single high-strain-rate pulse or multiple “lower” strain-rate pulses
- Minimize risk by broadening the temper-strain rate window



Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

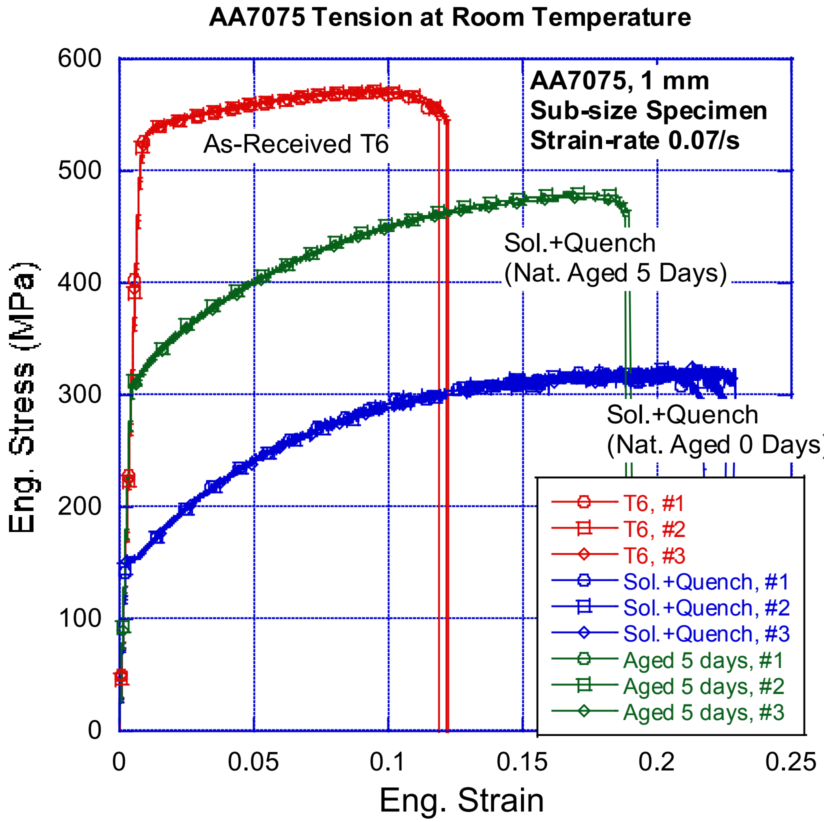
Potential Approaches and Risks



<u>Opportunity with Forming in W-temper</u>

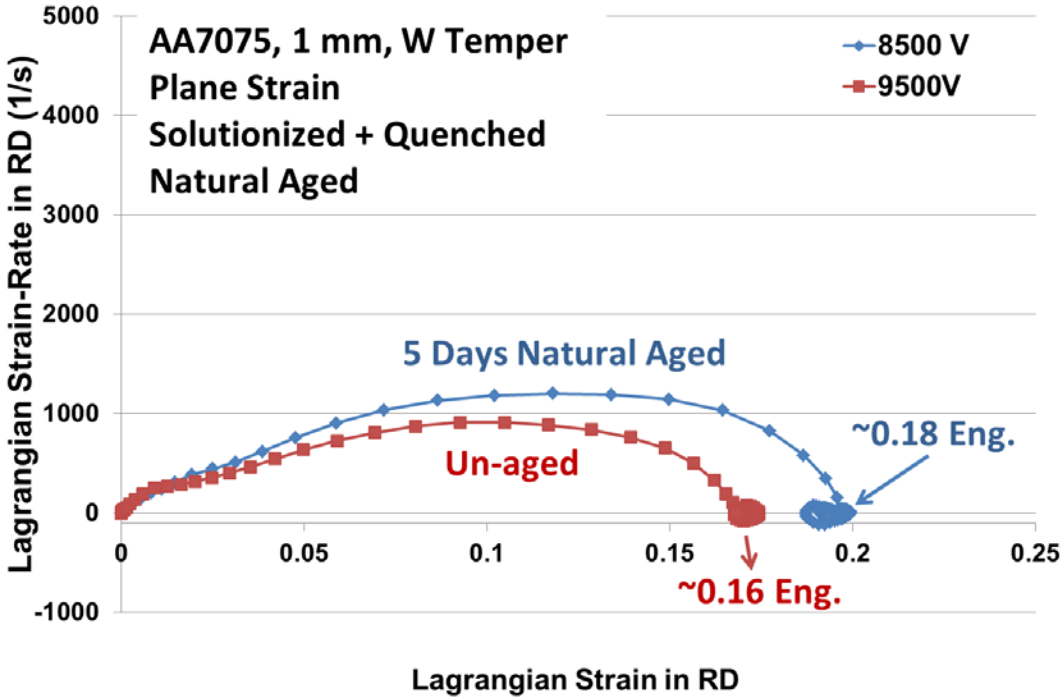
- For a given formability → Lower the required strain-rate (←)
- For a given strain-rate → Increase the formability (↑)

Tensile Stress-Strain Curves



- Very large design space (σ_{yield}, σ_{UTS}, n, elongation)
- If forming is done in non-T6, post-forming heat-treatment (e.g. paint+bake) is needed for T6-equivalent strength

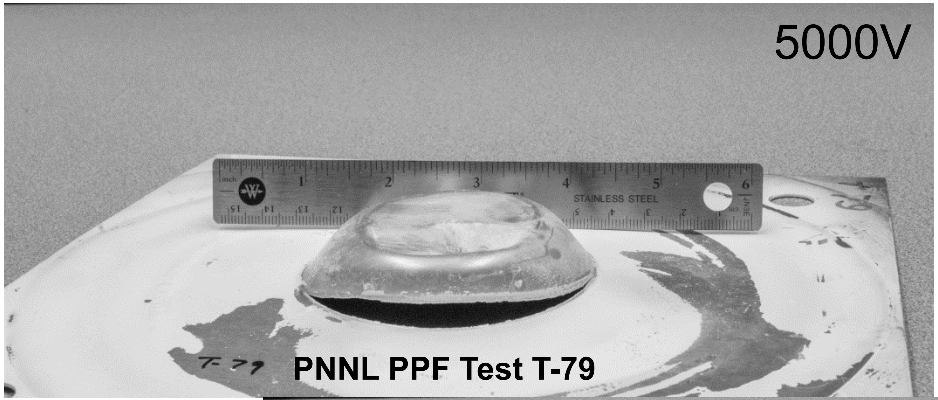
PPF Results on AA7075-W: DIC Data

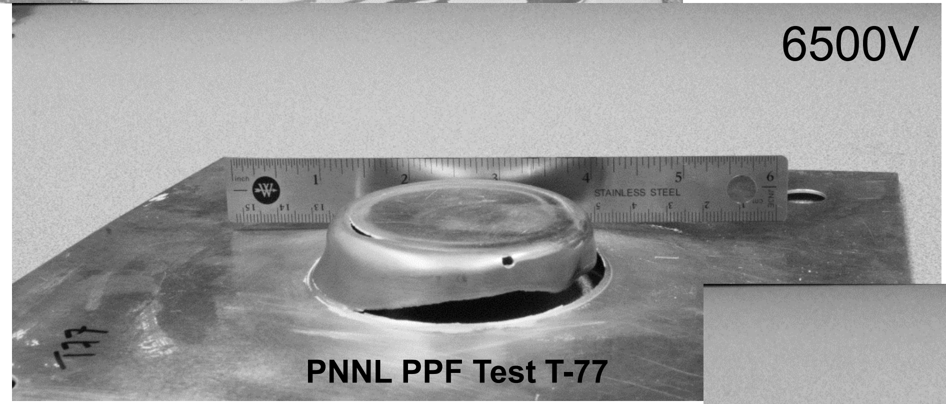


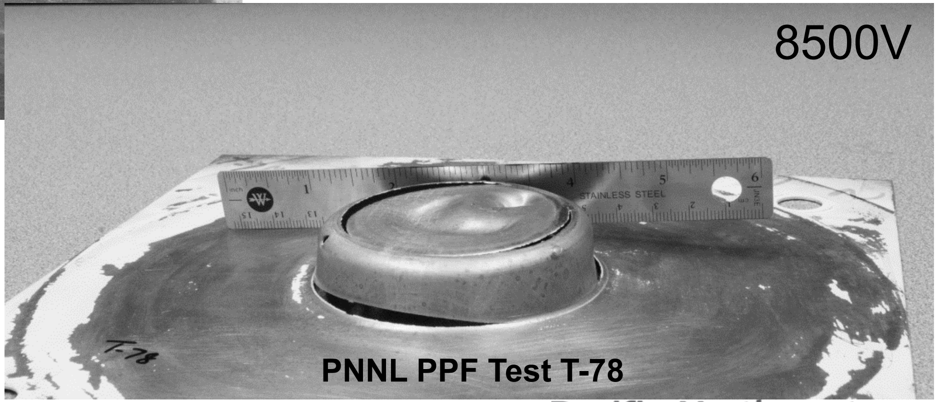
SPECIMENS NOT FAILED

- Experiments needed to “fail” the specimens and plot the “safe” and “unsafe” strain data on the FLD

Examples of PPF Formed Hats



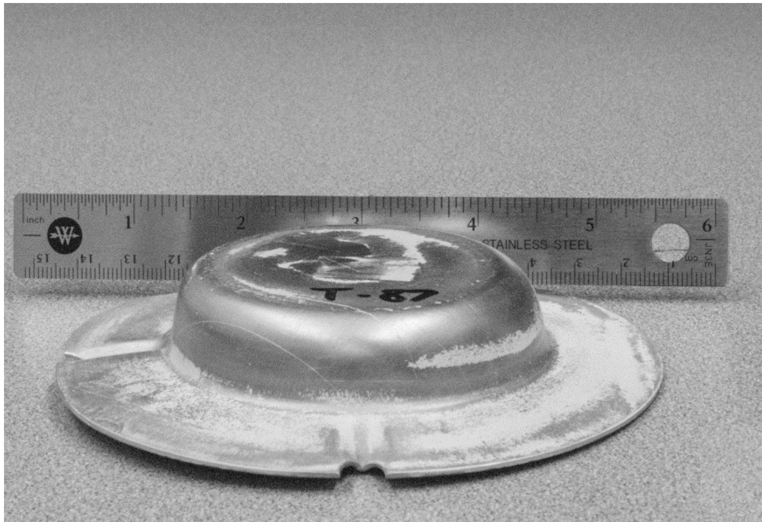


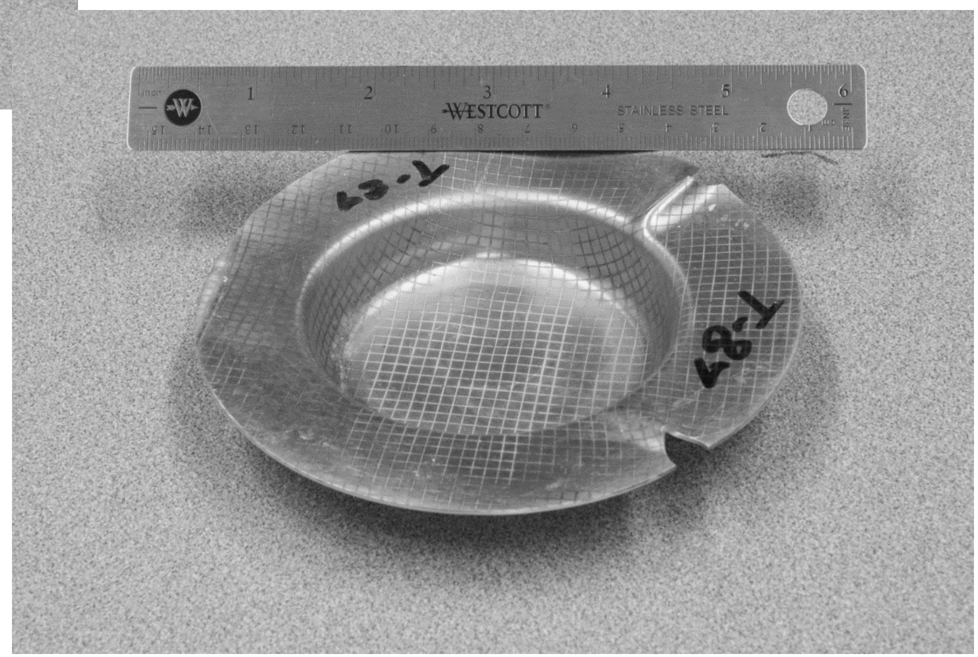


<u>Single-hit PPF</u>

- 6” blank
- Bolted
- Almost all stretching
- Failures at both radii

Example of Formed Hats (successful)



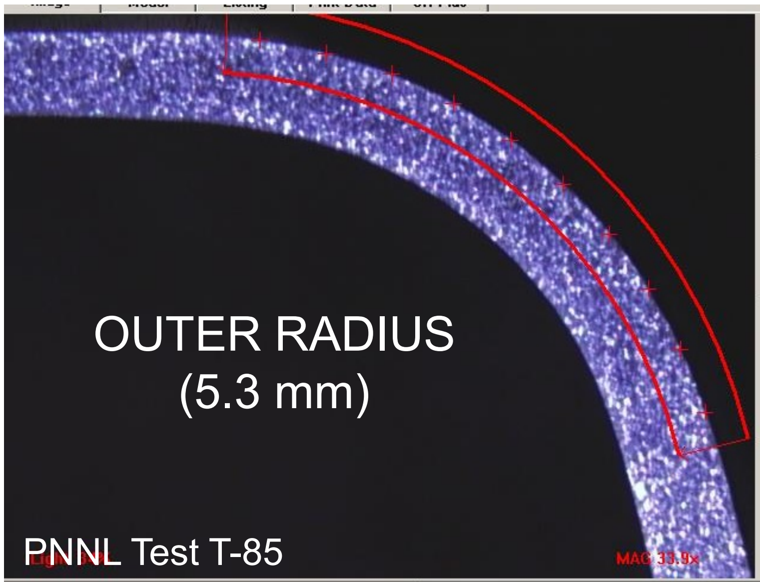


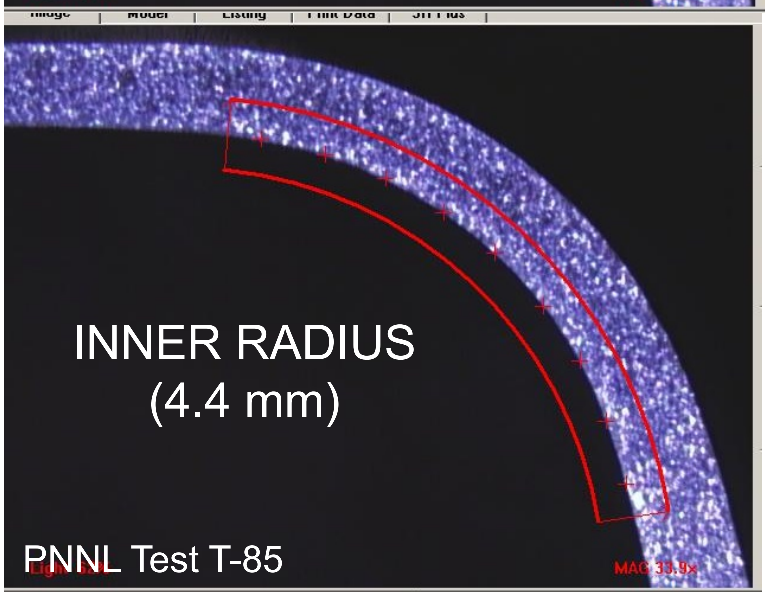
- Allowed draw-in of the blank
- Prevented excessive buckling in the flange by notching the blank

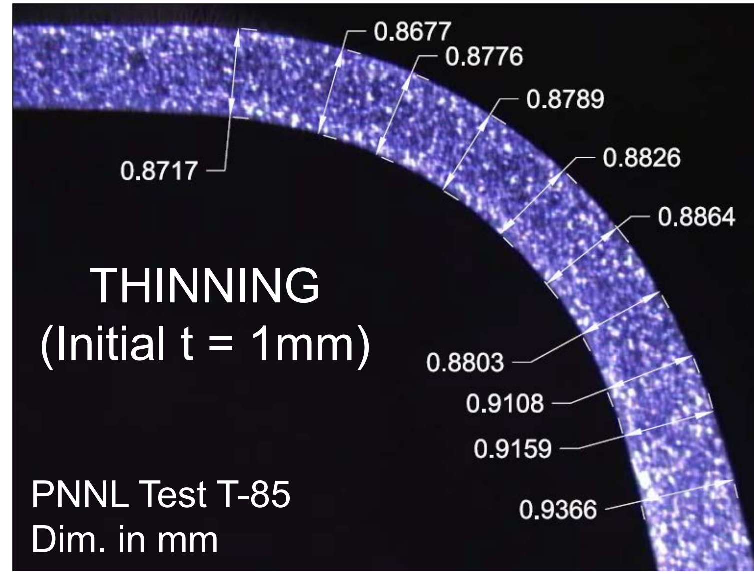
Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Example of Formed Hats (successful)





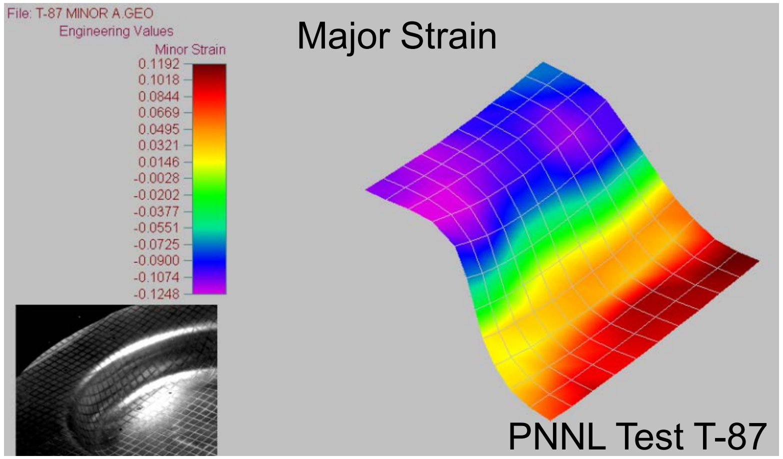


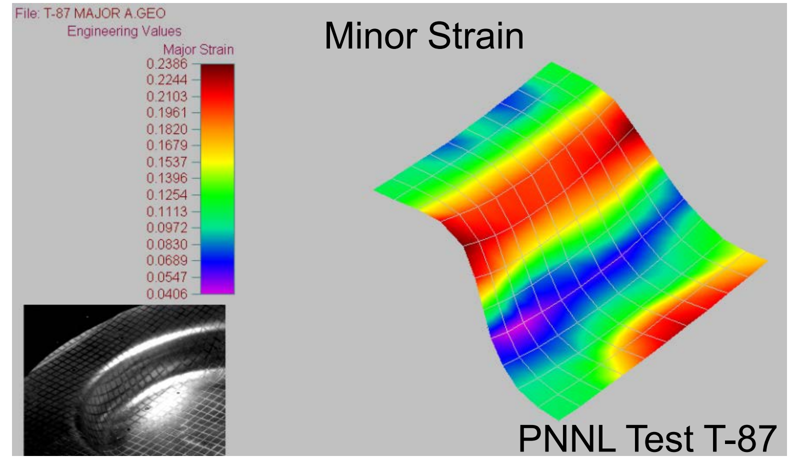
- Demonstrated PPF of non-dome geometry
- Die geometry needs to be optimized to take advantage of sheet-die interactions (that increase formability)

Pacific Northwest
NATIONAL LABORATORY

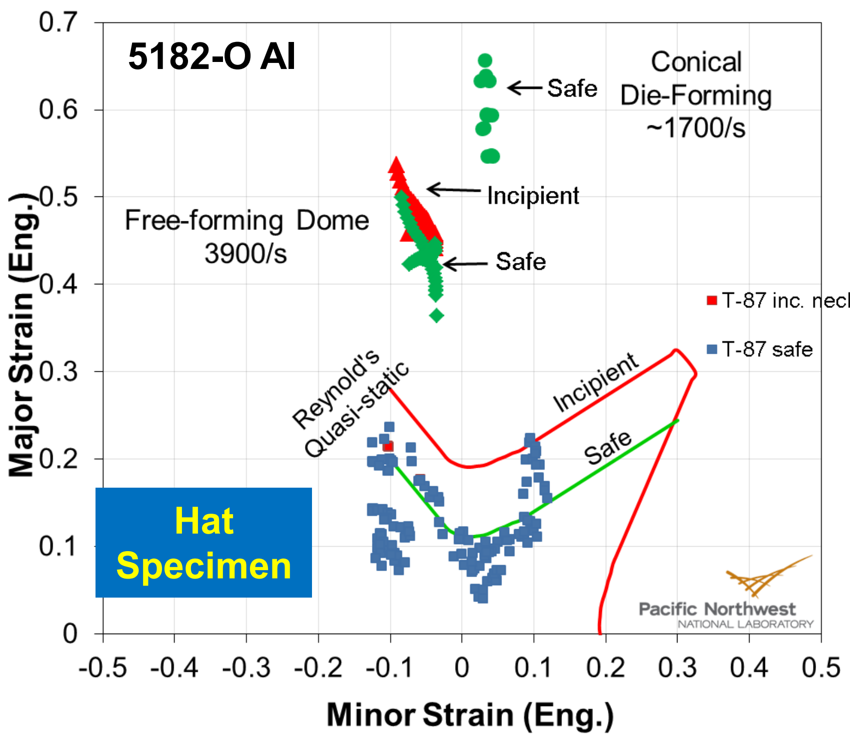
Proudly Operated by Battelle *Since 1965*

Example of Formed Hats (successful)





- Die design needs to be optimized to take advantage of sheet-die impact → Formability enhancement



Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

Response to Previous Year Reviewers' Comments

- Approach? (Well described and interesting but some concern about commercialization)
  - Comment: "..the limiting factor in pulse pressure forming is the cost of the process and this is a much better project direction than to develop the formability studies."
  - Response: We have engaged a commercial automotive supplier with commercial experience with PPF; discussions are on-going to perform cost analysis for specific components that cannot be formed by conventional stamping but are feasible using PPF.
- Technical Accomplishments? (Progress acknowledged but suggest focus on process development)
  - Comment: "…The reviewer advised the project team consider re-focusing future research on process development."
  - Response: Prior guidance from automotive OEMs indicated "process development" was in "competitive space" and suggested PNNL focus on pre-competitive space – such as materials' behavior. We have also engaged a commercial automotive supplier with experience in PPF to help with the process development.

Response to Previous Year Reviewers' Comments

- Support overall DOE objectives? (Equally supportive and critical)
  - Comment: "..this project is definitely a relevant piece of work as it will enable parts to be made out of light but strong alloys of Al.
  - Comment: "…this project remotely enables the use of Al."
  - Response: Despite the existence of hot/warm forming technology for many years, the use of Al sheet, let alone high-strength Al alloys, in complicated 3-d shapes is still commercially limited in high-volume. This project is trying to overcome the hurdles to hot/warm forming and the use of high-strength Al alloys.

Collaboration

- GM
  - Prototypical component identification
  - Test material selection
  - Project path guidance
- Alcoa
- American Trim
  - Commercialization of PPF process
  - Cost analysis

Remaining Challenges and Barriers

- Demonstrate commercialization potential for pulse-pressure forming (PPF) techniques for automotive parts
- There is limited experimental data in the literature on AA7075 in W tempers (e.g. correct constitutive equations, post-formed properties)

Proposed Future Work

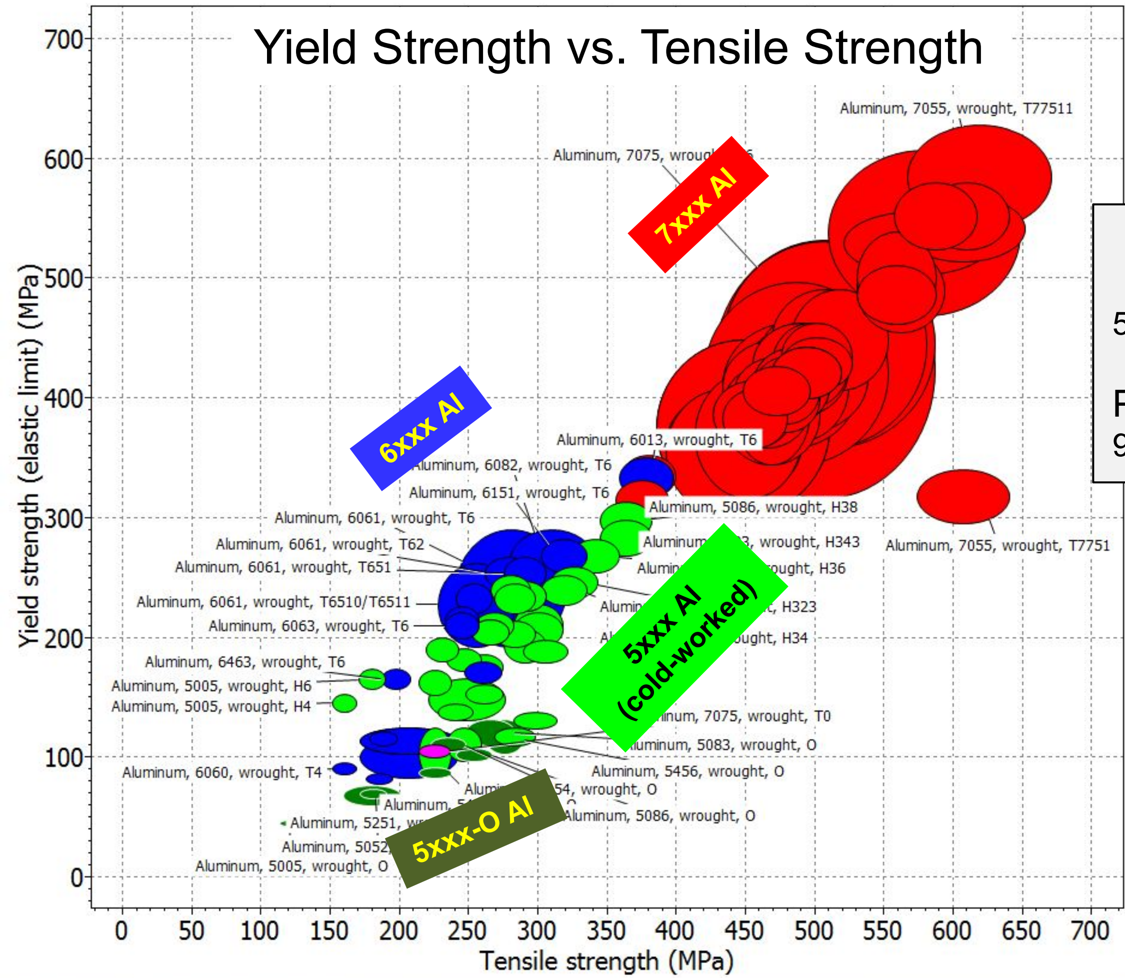
- Work with commercial supplier of components (PPF-made) to determine cost-effectiveness of PPF processes for fabricating automotive components
- Determine constitutive behavior of W temper AA7075 to enable modeling of its forming behavior
- Determine heat-treatment(s) necessary to achieve T6-equivalent strength in post-formed W temper AA7075

Summary

- Demonstrated Formability Enhancements at Room-temperature
  - AA7075-T6: ~100%, peak strain-rate ~2000-4000 /s (Current work)
  - AA6022-T4: >70% (Previous work)
  - AA5182-O: ~2x-6x (Previous work)
- Demonstrated PPF Inside Hat-die
  - 5 mm corner radius in AA5182-O
    - Control of draw-in and stretching
- PPF in W Temper
  - Strains as high as ~18% with 5-day aging window, with potential for further straining
  - Take advantage of potentially large design space offered by W temper to control formability
- Planning to Demonstrate Commercialization of PPF
  - Discussions held between PNNL-GM-American Trim

Technical Back-Up Slides

Opportunity with High-Strength Al Alloys



<u>Strength/weight</u>

7xxx Al

500 MPa/2.8 g/cc ~178

Press Hardening Steel

950 MPa/7.8 g/cc ~122

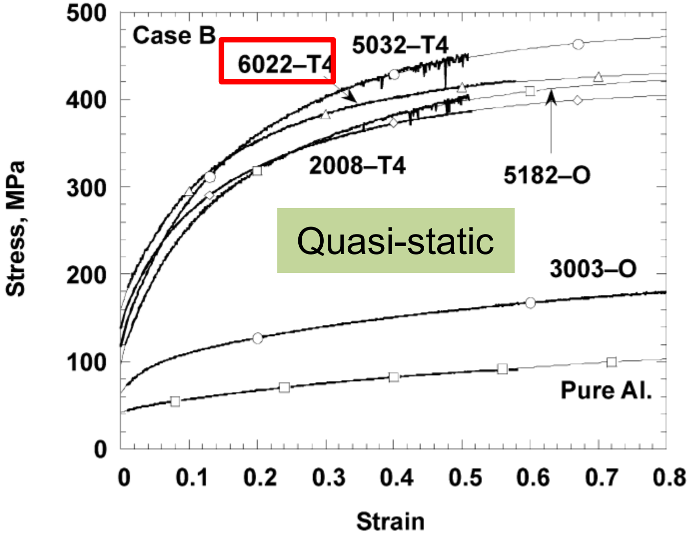
- **Can HIGH-STRENGTH 6xxx and 7xxx Al alloys formability be increased via PPF?**
- **Challenge: Strength α 1/Ductility**

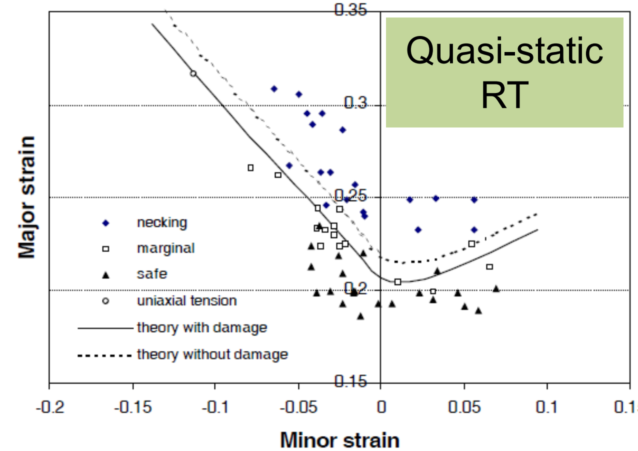
Pacific Northwest NATIONAL LABORATORY

Operated by Battelle *Since 1965*

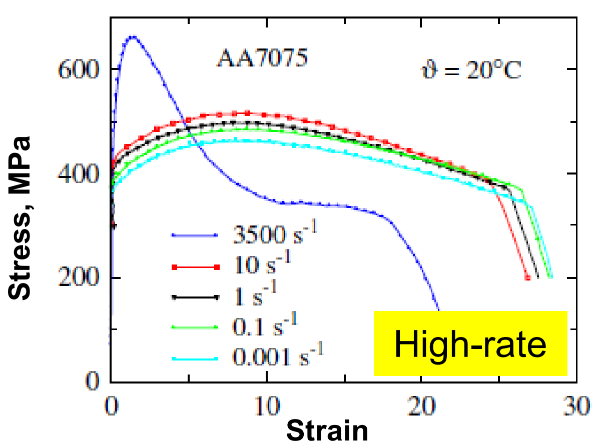
Literature: High-rate Data for 6xxx/7xxx

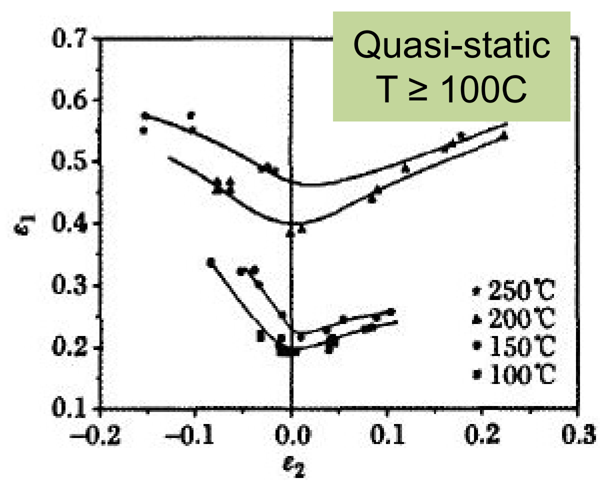
AA6022-T4





AA7075-T6





- **Limited/no high-rate data is available in literature**

M-K Method Predictions of Forming Limits

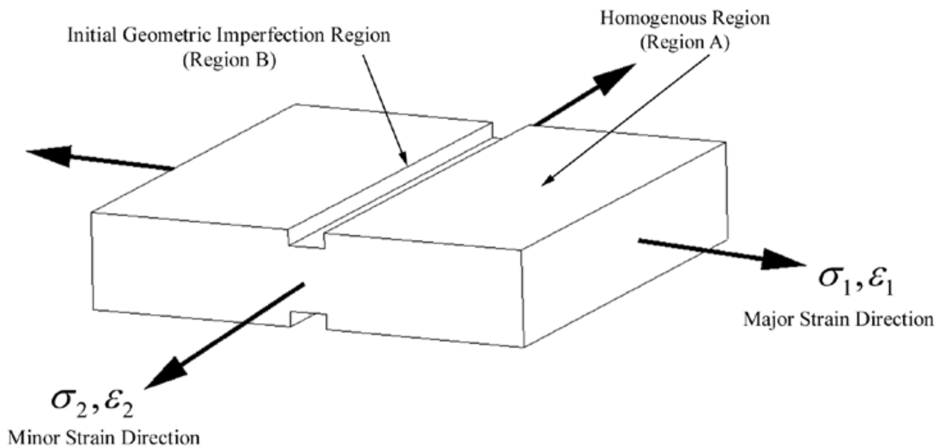


Illustration of the concept of an initial geometric imperfection oriented perpendicular to the direction of major strain in a biaxial sheet stretching application.

- 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