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Room-Temperature Stamping of High-Strength Aluminum Alloys

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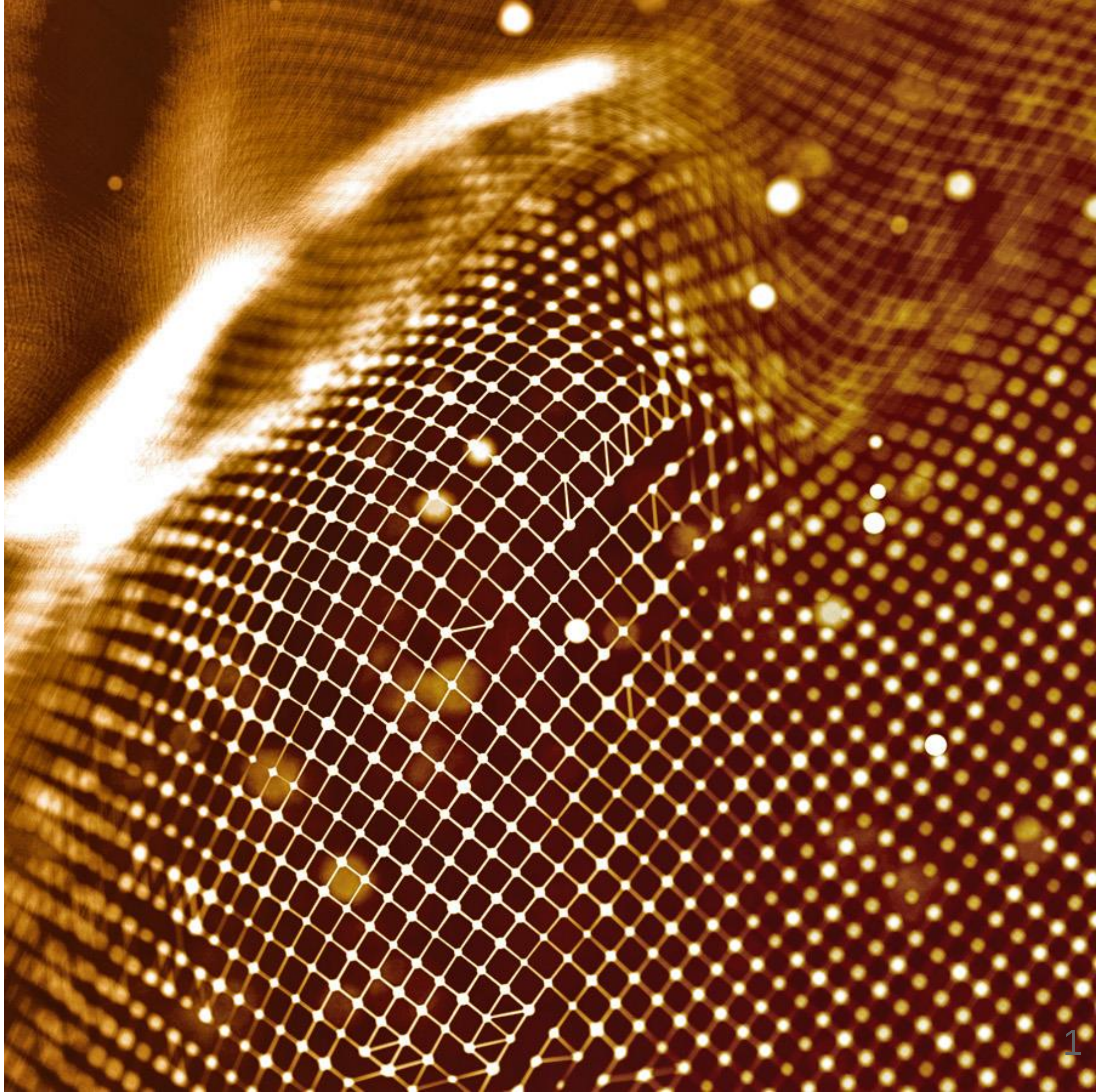
Project ID # mat126



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PNNL is operated by Battelle for the U.S. Department of Energy

Overview

Timeline

- Start: 10/2016 (FY17)
- Finish: 09/2020 (FY20)
- % Complete (scope): ~75%

Budget

- Total project funding
  - DOE: $ 1M
  - Industry cost share: 30%
- Funding in FY 2019 = $ 460K
- Funding in FY 2020 = $ 0K
- Future funds anticipated: $ 0

Barriers

- Strength: Develop process for stamping high-strength aluminum (Al) for structural applications without degrading its high strength
- Formability: Develop ways to enable sufficient formability of Al to stamp it at room-temperature

Partners

- Magna-Stronach Centre for Innovation (Tier-1)
- General Motors (original equipment manufacturer (OEM))

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Relevance/Objective

- DOE-VTO
  - Long-term objective → 50% mass reduction of a vehicle
  - 2025 Target → 25% glider mass reduction, relative to comparable 2012 vehicles, at an added cost of no more than $5/lb weight saved
- USDRIVE
  - Aluminum components offer potential overall weight reduction of 40-60% when replacing cast iron/steel
  - Methods to improve the formability of high-strength Al alloys (>600 MPa), to values equivalent to steel, are a high priority research need [USDRIVE Materials Tech Team Roadmap, October 2017]
- Project Objective
  - Develop thermo-mechanical approaches to enable room-temperature stamping of high-strength (7xxx) Al alloys
- Challenges
  - High-strength Al alloys do not have sufficient formability to be stamped at room-temperature
  - Warm/hot stamping is costly and may require post-forming heat-treatments to regain the high-strength

Approach & Milestones

Task Name	FY 2017				FY 2018				FY 2019			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 Component identification	G											
Task 2 Strengthening potential of W-temper 7xxx Al			M									
Task 3 Constitutive relations						G						
Task 4 Stamping simulations												
Task 5 Integrate microstructure and mechanical properties models												
Task 6 Fabricate prototype											M	
Task 7 Characterize prototype												

Phase II (Stamping Simulations)

Phase III In-progress (Microstructural Modeling & Prototype Fabrication)

- ✓ Gate 1 (FY17-Q1): Potential component identification
- ✓ Milestone (FY17-Q3): Forming limit diagram (FLD) determination
- ✓ Gate 2 (FY18-Q2): Stamping simulations predict that the component can be stamped at room-temperature
- Milestone (FY19-Q3): Determine hardness distribution over the as-stamped component
  - [Delayed] Sub-contract signed Q1 FY20; delays in shipping Al blanks and stamping trials

Technical Accomplishments and Progress (FY19)

- An in-production hot-stamped steel side-impact beam was scanned to create a 3-dimensional computer-aided design (CAD) model and provide an initial design for the target Al side-impact beam
- Emulation of in-production design provides a suitable and realistic initial target design for prototype fabrication

Technical Accomplishments and Progress (FY20)

- Microstructure-based model: Estimate strength at different stages of precipitation aging and deformation to optimize strength and formability
  - ✓ Distinguish the effects of GP-I and GP-II zones

- X-ray scattering experiments to determine precipitation aging kinetics
  - ✓ Brookhaven National Laboratory (National Synchrotron Light Source (NSLS-II) 11-BM)
  - ✓ Argonne National Laboratory (Advanced Photon Source (APS) 1-ID-B,C,E)

- Sub-contract for stamping side-impact beams at Magna-SCFI
  - ✓ 7075Al blanks purchased and delivered
  - ✓ Stamping
  - Paint-bake
  - 3-point bend testing

Estimated May-June '20

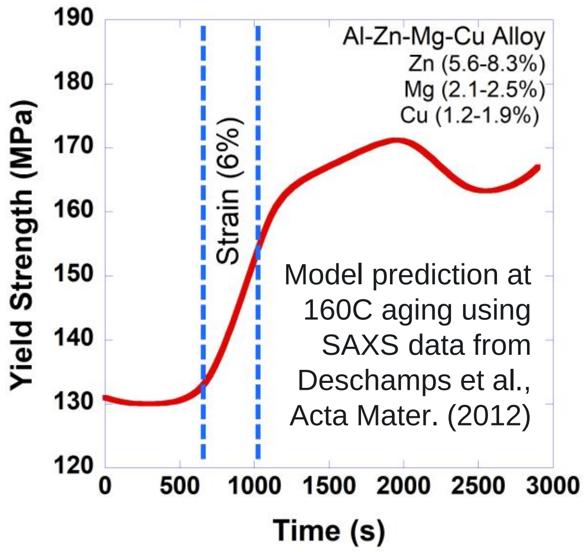
Technical Accomplishments and Progress

Model Development and Preliminary Application to 7xxx Al:

- Shearable and un-shearable precipitates
- Platelet geometry of precipitates (specific for 7xxx alloys)
- Plasticity-precipitation coupling

$$\sigma = \sigma_i + \Delta\sigma_{ss} + \sqrt{\Delta\sigma_d^{\,2} + \Delta\sigma_p^{\,2}}$$
$$\Delta\sigma_{ss} = M\mu b \varepsilon_{ss}^{3/2}\sqrt{C_{ss}}$$
$$\Delta\sigma_d = M\alpha\mu b\sqrt{\rho}$$
$$\Delta\sigma_p = M\Delta\tau$$

σ = Yield strength
σ_i = Intrinsic strength
$\Delta\sigma_{ss}$ = Yield strength increment (solid solution strengthening)
$\Delta\sigma_d$ = Yield strength increment (dislocation strengthening)
$\Delta\sigma_p$ = Yield strength increment (precipitation strengthening)
M = Taylor factor
μ = Shear modulus
α = Constant – dislocation contribution to flow stress
b = Burger's vector
ε_{ss} = Misfit strain due to solute
C_{ss} = Mean solute concentration
$\Delta\tau$ = Shear stress increment
ρ = Dislocation density



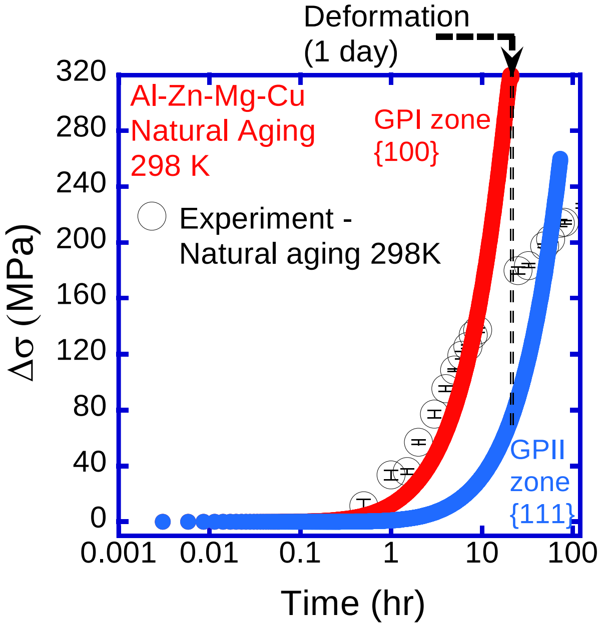
- Model output
  - Rapid increase in strength during straining
  - Peak in strengthening
  - Over-aging
- Predicted W-temper yield strength is in good agreement with that of similar Al alloy (Al-5.5%Zn-2.5%Mg-1.5%Cu, ~100 MPa) *[J. R. Davis, Aluminum and aluminum alloys, ASM International, 1993]*

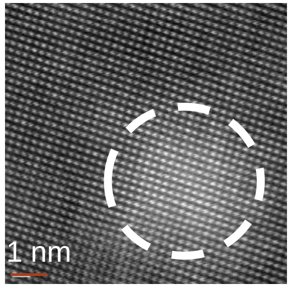
The model captures the key features of precipitation strengthening evolution in 7xxx Al

Technical Accomplishments and Progress

Precipitation Strengthening in 7075 Al

- Guinier-Preston (GP-I) zones (Mg-rich): Point-like
- Guinier-Preston (GP-II) zones (Zn-rich): Plate-like
- Strength at t < 24 hr. natural aging: GP-I zones
- Strength at t > 24 hr. natural aging: GP-II zones

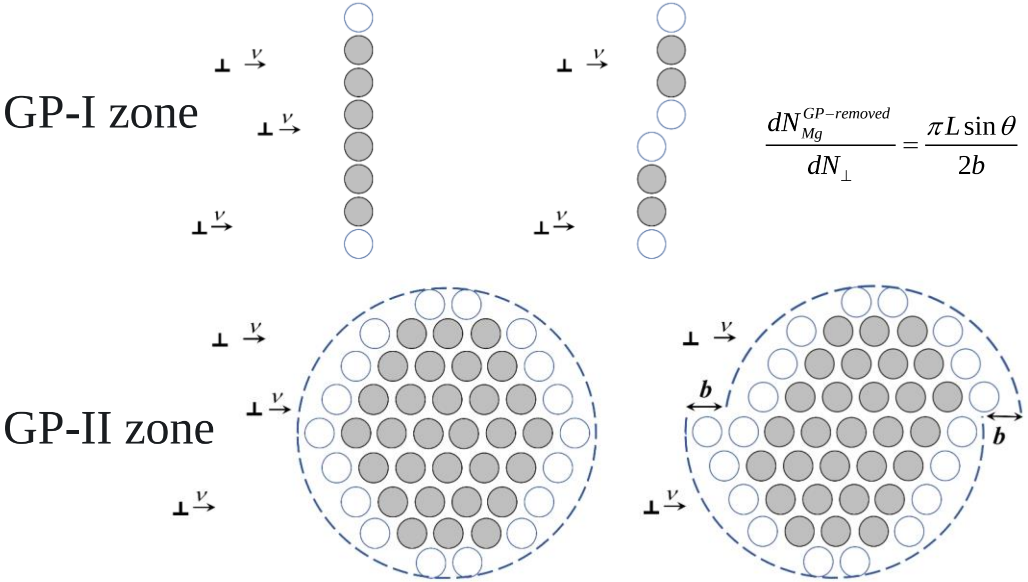




GP-I zone from side-view {100}

Differentiating individual strengthening behavior of GP-I vs. GP-II zones during natural aging by modeling

Dislocation Interactions with GP Zones



$$\frac{dN_{Mg}^{GP-removed}}{dN_{\perp}} = \frac{\pi L \sin\theta}{2b}$$

$$\frac{dN_{Zn}^{GP-removed}}{dN_{\perp}} = \frac{b/2}{b/2} = 1$$

Shear induced dissolution:

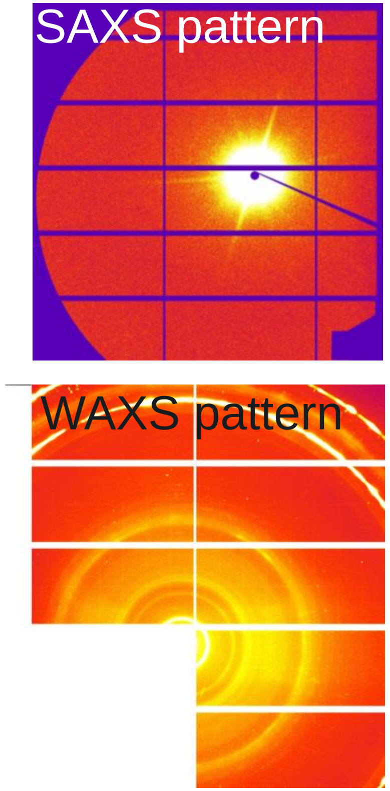
GP-I zone >> GP-II zone

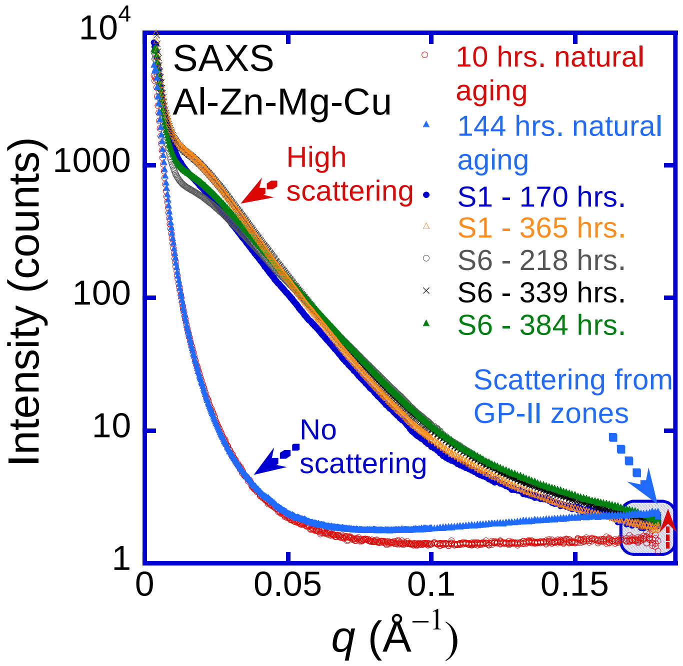
Technical Accomplishments and Progress

Experiments at Brookhaven National Laboratory- National Synchrotron Light Source

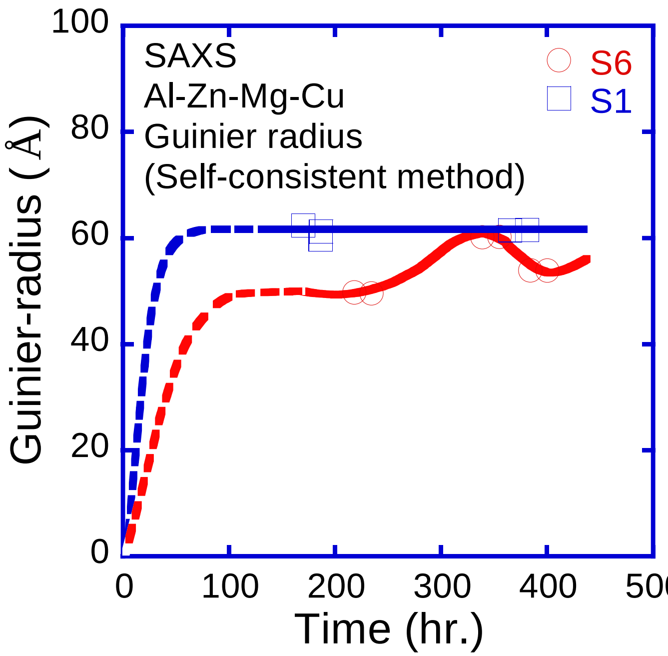
- Small and Wide Angle X-ray Scattering (SAXS/WAXS)
- Different natural aging conditions (S1 and S6)

- SAXS Data → Calculate radius vs. time
- Cyclic oscillations → Dynamic state of precipitates which indicates an increased solute flux into the Al-matrix





Instability in precipitate size during long-term natural aging was observed and its potential influence on mechanical properties of 7075 Al components, made by room-temperature forming, needs to be considered



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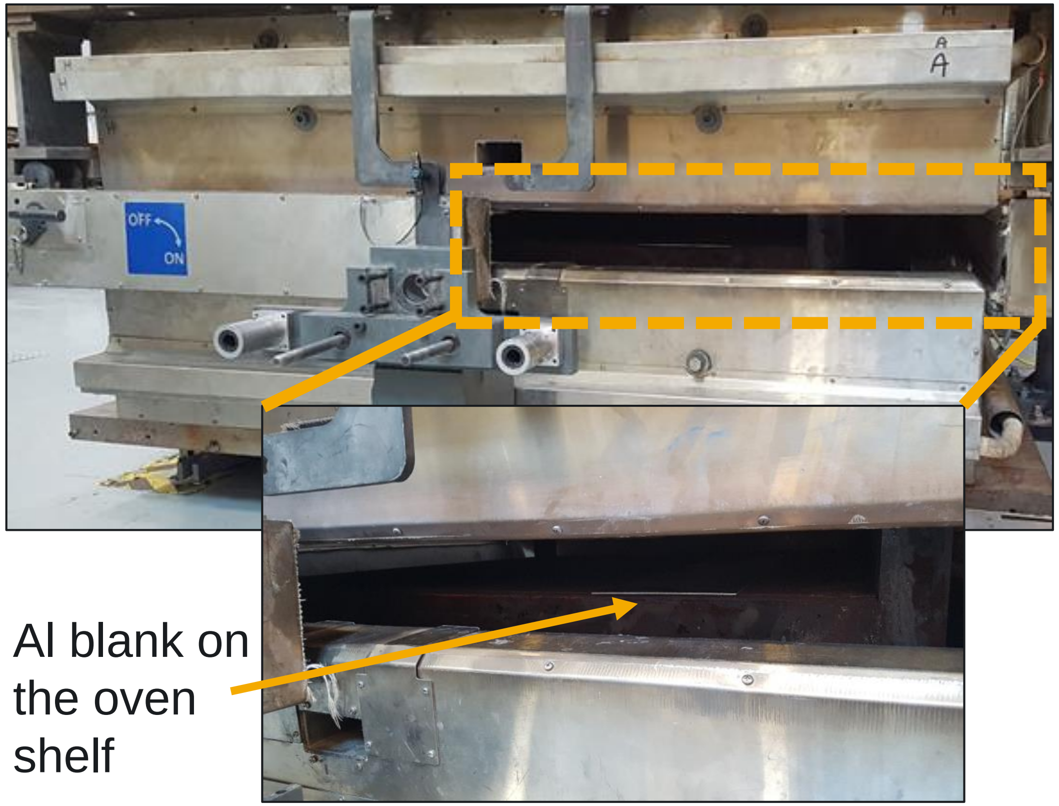
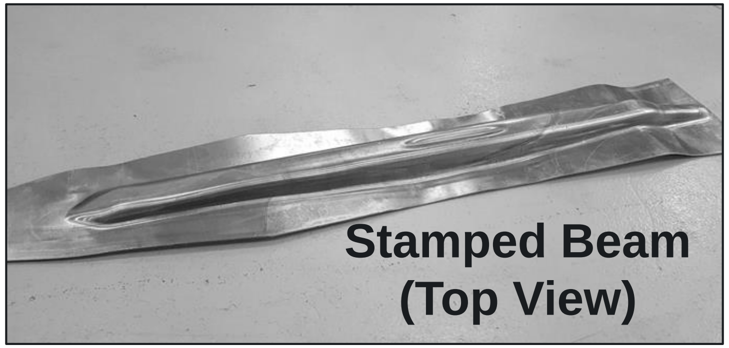
Accomplishments and Progress

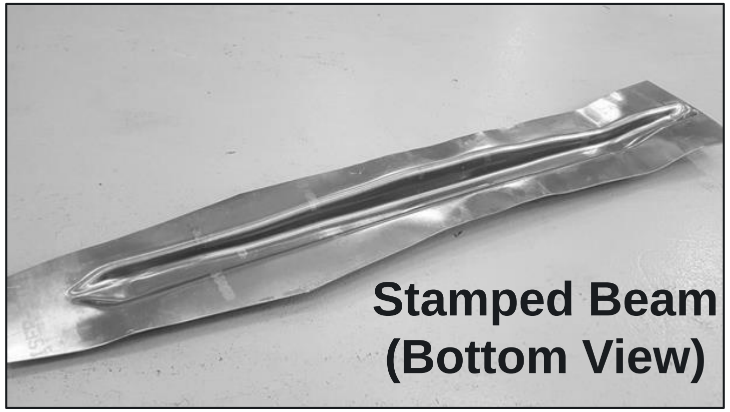


Al blank on the oven shelf

HotBox Oven for Heating Al Blanks

Untrimmed Stamped Al Beams





Stamping of beams is underway → To be delivered to PNNL for mechanical characterization

Responses to Previous Years Reviewers' Comments

- No reviewer comments

Collaboration and Coordination

- Magna-SCFI (Tier-1)
  - Component selection and modeling
  - Stamping simulations
  - Prototype fabrication
- Brookhaven National Lab (National Synchrotron Light Source (NSLS-II) beamline
  - X-ray beamline experiments and data analysis
- Argonne National Lab (Advanced Photon Source (APS) beamline)
  - X-ray beamline experiments and data analysis
- General Motors (OEM)
  - Internal studies on lightweighting
  - Component and Al alloy selection
  - Component design
  - Die design

Remaining Challenges and Barriers

- Determine the thermomechanical processing that allows simultaneous formability (at room-temperature) and high strength in the formed component
  - Final mechanical properties of the stamped beams remain to determined
- High-strength Al can continue to undergo natural aging after forming
  - Post-formed mechanical properties need to be evaluated for long-term thermal stability
- Integrate microstructure and mechanical property models
  - Distinguish different strengthening mechanisms
- Cost-effectiveness of the proposed approach is unknown

Proposed Future Work

- Complete prototype stamping (Magna)
  - Trimming of stamped beams
  - Paint-bake treatment
- Characterize the stamped component (PNNL and Magna)
  - 3-point bend test
  - Hardness measurements
- Integrate microstructure and mechanical property models (PNNL)
  - Analysis and modeling using in-situ aging data (APS beamline experiments)
  - In-situ TEM experiments for improved understanding of precipitation/dissolution

Any proposed future work is subject to change based on funding levels

Summary

- Goal is to develop a process to stamp high-strength Al at room-temperature without a separate precipitation-hardening heat-treatment
- Modeling suggests strengthening during initial stages of natural aging is controlled by GP-I zones, and subsequently by GP-II zones
- Analysis of beamline data suggests cyclic variation in precipitate size during long-term natural aging which indicates a complex state of precipitate evolution
- Stamping of prototype side-impact beam made of 7075 Al on-going in conjunction with a Tier-1 supplier

Acknowledgments

- Brookhaven National Lab (National Synchrotron Light Source (NSLS-II) beamline
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Technical Backup Slides

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Approach

- Phase I (3 months)
  - Task 1: Identify 3-5 potential stamped sheet components
  - Gate 1: Demonstrate potential for sufficient return on (DOE) investment and the potential for commercialization to replace high-strength steel with high-strength Al

- Phase II (15 months)
  - Task 2: Determine strengthening potential of W temper formed 7xxx Al alloys
  - Task 3: Determine constitutive relations for selected Al alloys
  - Task 4: Perform stamping simulation for the selected prototype structural component
  - Gate 2: Stamping simulations that predict with confidence that the selected component can be stamped in at least one 7xxx Al alloy-temper combination at room-temperature

- Phase III (18 months)
  - Task 5: Integrate microstructure and mechanical property models for the selected Al alloys
  - Task 6: Fabricate prototype component
  - Task 7: Characterization of prototype component

Example of Prior Literature Reviewed

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3. Skszek, T., Zaluzec, M., Conklin, J., and Wagner, D., "MMLV: Project Overview," SAE Technical Paper 2015-01-0407, 2015, doi:10.4271/2015-01-0407.

4. Plourde, L., Azzouz, M., Wallace, J., and Chellman, M., "MMLV: Door Design and Component Testing," SAE Technical Paper 2015-01-0409, 2015, doi:10.4271/2015-01-0409.

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7. Reaburn, R., "Ultra-light Door Design," presentation given at the DOE Vehicle Technologies Office and Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., 2017. https://energy.gov/sites/prod/files/2017/06/f35/lm120_skszek_2017_o.pdf

8. Kumar, S.D., Amjith, T.R., Anjaneyulu, C., Forming Limit Diagram Generation of Aluminum Alloy AA2014 Using Nakazima Test Simulation Tool, In Procedia Technology, Volume 24, 2016, Pages 386-393.

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