



Advances in Integrally Formed Metallic Structures

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A Decade of Integrally Stiffened Cylinder (ISC) Technology



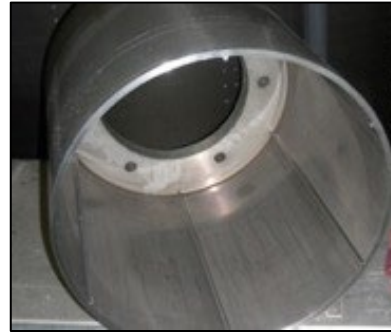
2011-2013:

8-inch Diameter Proof of Concept (Al-Li 2195)



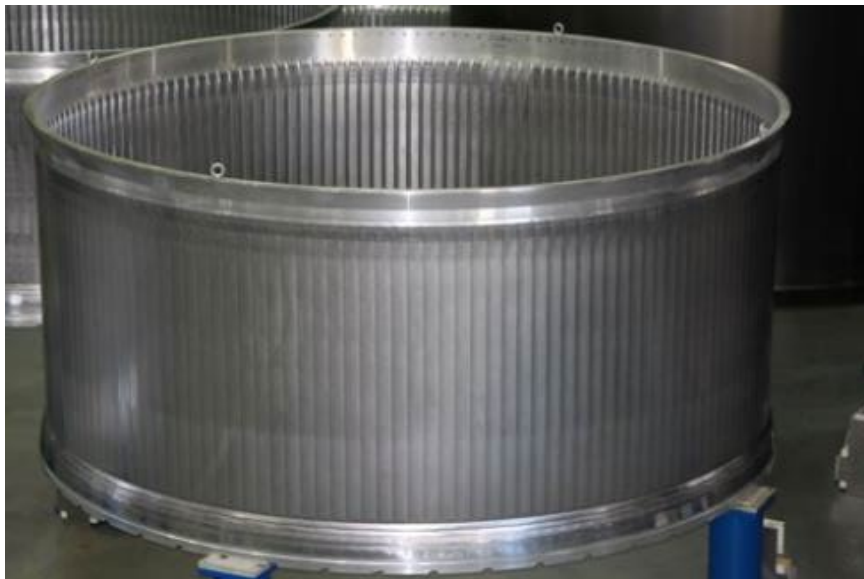
2014-2015:

17-inch Diameter Sounding Rocket Flight Article (Al 6061)



2017-2019:

10-foot Diameter Cryotank Barrel Demonstrator (Al 6061)



2020-2023:

10-foot Diameter Metallic Fuselage Demonstrator (Al 6061)



Advancements championed by NASA Langley prompted establishment of in-house R&D facility

Integrally Stiffened Cylinder Forming Technology

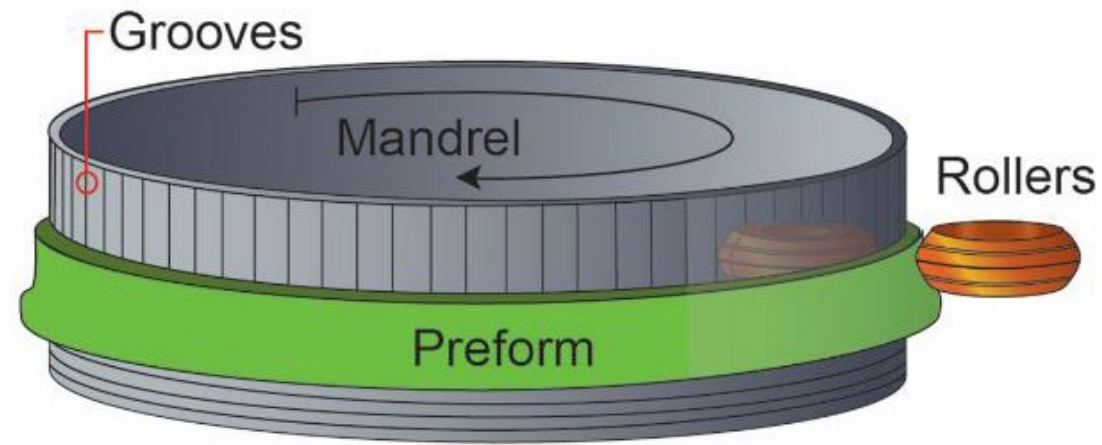


- Exploitation of flow forming process to manufacture single-piece, thin-walled cylinders with integral stiffeners.
 - **Elimination of all longitudinal welds is a key benefit.**

Two 10-ft. diameter ISC grooved mandrels

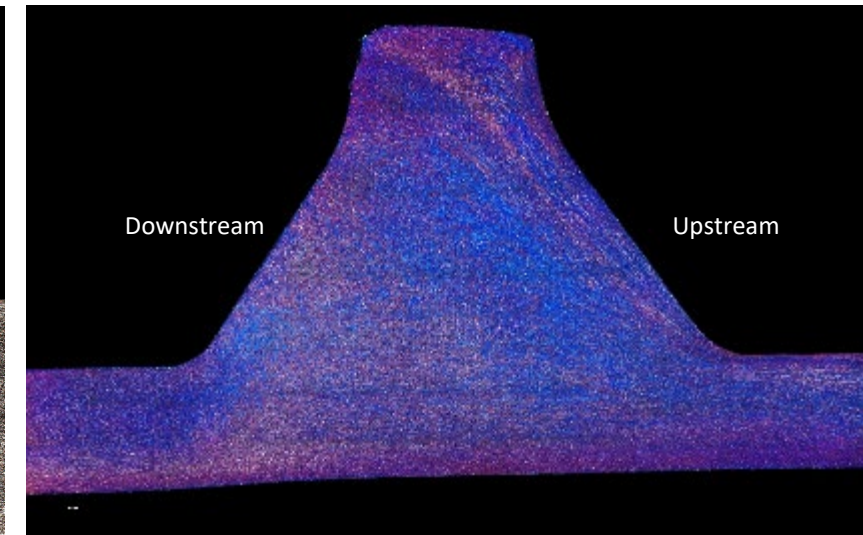
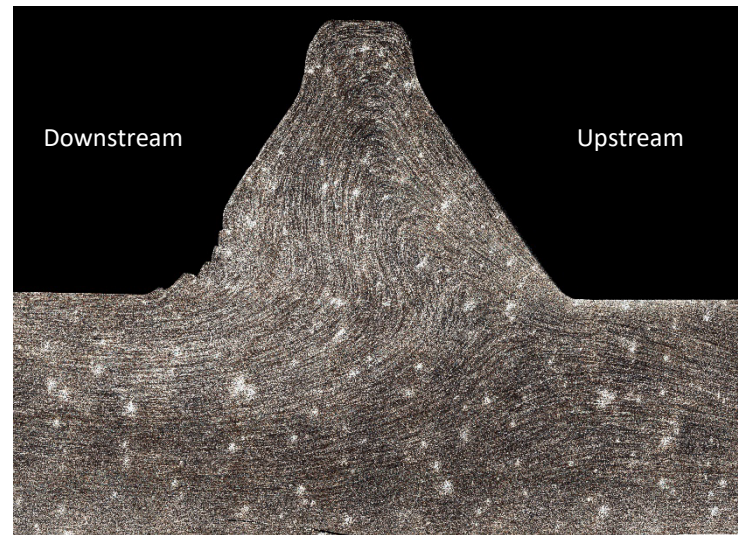
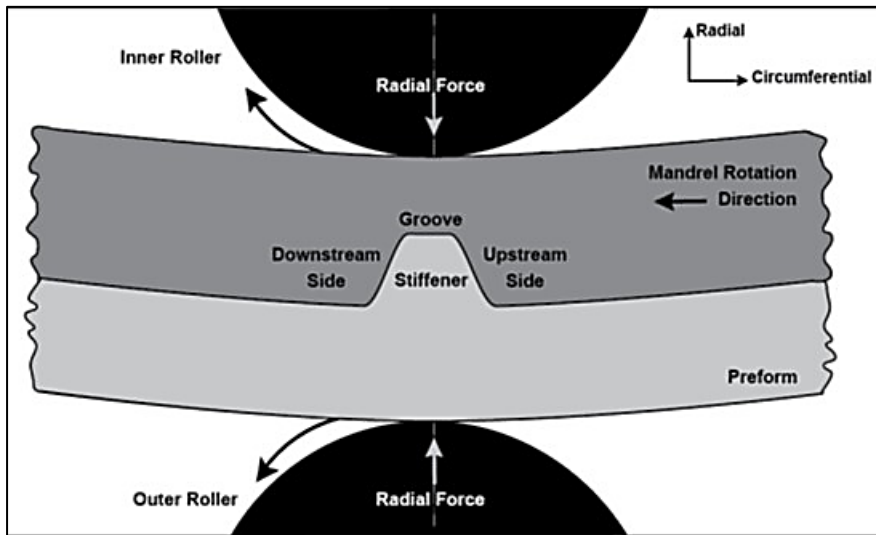


- External rollers reduce wall thickness and increase length of the article, while simultaneously forcing material into grooves to form stiffeners.
- Processing at ambient temperature; however, some adiabatic heating involved.
- Stiffener geometry and spacing dictated by profile of grooved mandrel.



Advance → adaptation of flow forming protocols established for smooth-walled cylinders to fabricate integrally stiffened structures

Stiffener Formation During ISC Process



Process Summary

- Material flows asymmetrically into stiffener due to rotary forming
 - flow lines offset toward downstream side
- Material flow rate differential between wall and stiffener suspected of limiting stiffener spacing
 - groove geometry has secondary effects

Al 2219 10-ft Diameter ISC

- Al 2219 considered partially successful
- Adverse effects of friction significant
- Formability restricted by cracking attributed to microstructural condition
- Lesson learned: choose a more formable alloy and use die lubrication

Al 6061 10-ft Diameter ISC

- Al 6061-O considered fully successful
- Longitudinal stiffeners completely formed over 5-foot length
- Achieved stiffener heights up to 1-inch tall
- Shortcoming: not high-strength aircraft alloy or best stiffener geometry

➔ In contrast with smooth-walled cylinders, mechanics of stiffener formation such that plastic flow likely analogous to bulk forming processes (forging/extrusion/rolling)

Advance ➔ Identify alloys that meet aircraft performance specifications, but also exhibit satisfactory bulk formability

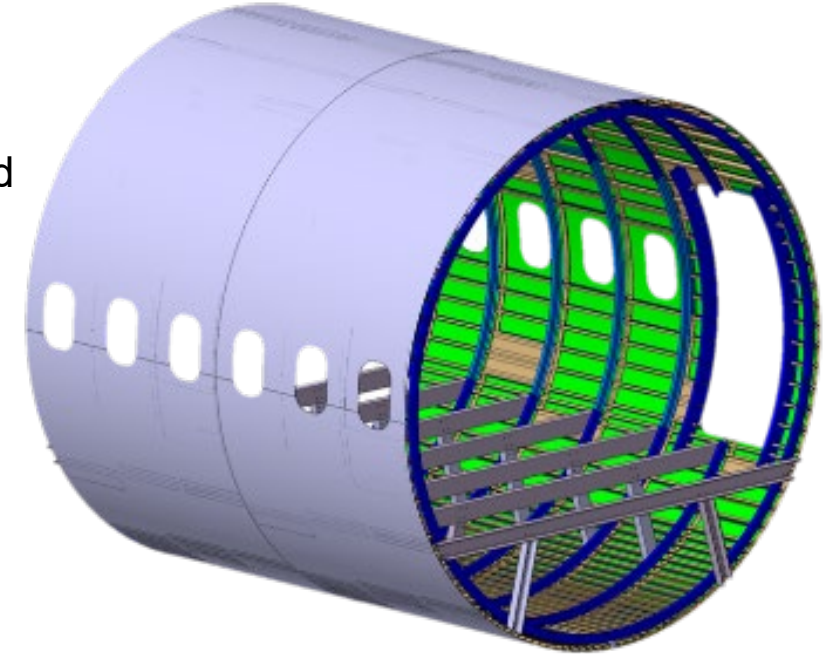
Candidate Alloy Formability Assessment



Candidate Al alloy materials under consideration:

- Benchmark alloy (used for 10-ft. demonstrators);
 - AA 6061: Intermediate strength alloy, good RT ductility; highly formable
- High strength and damage tolerant candidates;
 - AA 2139: Capable of -T8 properties in -T6 temper, i.e. no cold work required
 - AA 2050: Established 3rd gen. Al-Li alloy (reduced density)
 - AA 2043: Emerging 3rd gen. Al-Li alloy (reduced density)
- Product form of starting blank may affect formability;
 - rolled plate (sub-scale preforms)
 - ring-rolled forging (full scale preforms)
 - cast/homogenized billet (TBD)
- Temper of forming blank affects formability and post-forming processing;
 - **O** → fully soft = maximum formability, but requires solution treatment & rapid quench for service properties; high risk of distortion for thin-walled, complex-shaped cylinders
 - **T4** → partially hard (solution treated + naturally aged) = intermediate formability; simplifies heat treatment (direct artificial aging) for service properties

10-ft. diameter manufacturing demonstration article (Al 6061-O)



Advance → Down-select candidate materials with greatest formability potential that also can meet aircraft performance requirements

Objective:

- Advance the SOA of formability metrics (intrinsic material properties) that are employed to define the processing variables necessary for producing defect-free, flow formed cylinders with integral stiffeners

Problem:

- **Spin / flow forming is a complex metal working process (involving over 30 variables)**
 - Trial-and-error determination of process parameters is inefficient and expensive
 - Few computational tools that simulate the spin and/or flow forming process
- **Limited formability data for high-performance, aerospace alloys (i.e. 2xxx series) available**
 - Formability is not an intrinsic material property that can be measured alone
 - Requires assessment of multiple properties that influence metal plasticity
 - Customarily; Formability → sheet forming OR Workability → bulk forming

Solution:

- **Expand the suite of screening metrics to cover both formability and workability**
 - Tensile testing with digital image correlation (DIC) to quantify materials for flow formability
- **Evaluate flow formability of candidate alloy/temper/product form combinations**
 - Convenient DIC tensile testing to provide relevant screening metrics for formability/workability ranking
 - Use WF VUD600 forming trials to allow affordable exploration of forming process limits and stiffener geometries
- **Develop simulation protocols to accelerate materials selection and processing optimization**
 - Commercial software DEFORM® uses intrinsic material property data to model the spin/flow forming process and to simulate the effects of isolated operating parameters

Key Formability Properties Evaluated

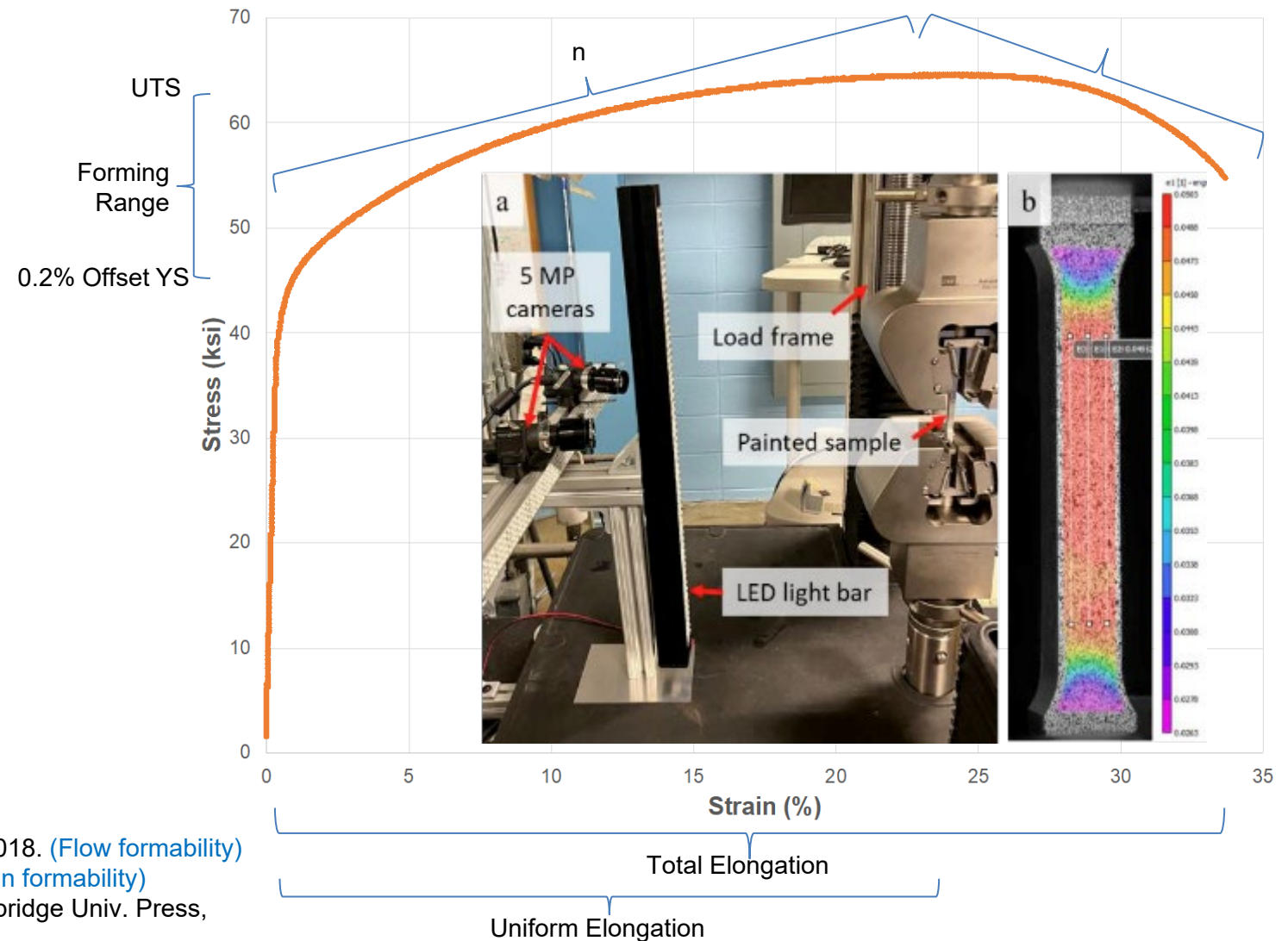


Current State of the Art:

- Area reduction (AR) [ref. 1, 2]
- Strain hardening exponent (n) [ref. 1-3]
- Modulus of resilience (μ_r) [ref. 1]

Often Cited as Influential:

- 0.2% offset yield strength (σ_y)
- Ultimate tensile strength (σ_u)
- Forming range ($\sigma_u - \sigma_y$)
- Total elongation [ref. 2]
- Uniform elongation [ref. 3]
- Anisotropy ratio (r) [ref. 3]
- Modulus of toughness (μ_t)
- Rate of work hardening (Θ)
- Strain rate sensitivity at high strains (m)



Parameter selection guided by prior formability studies:

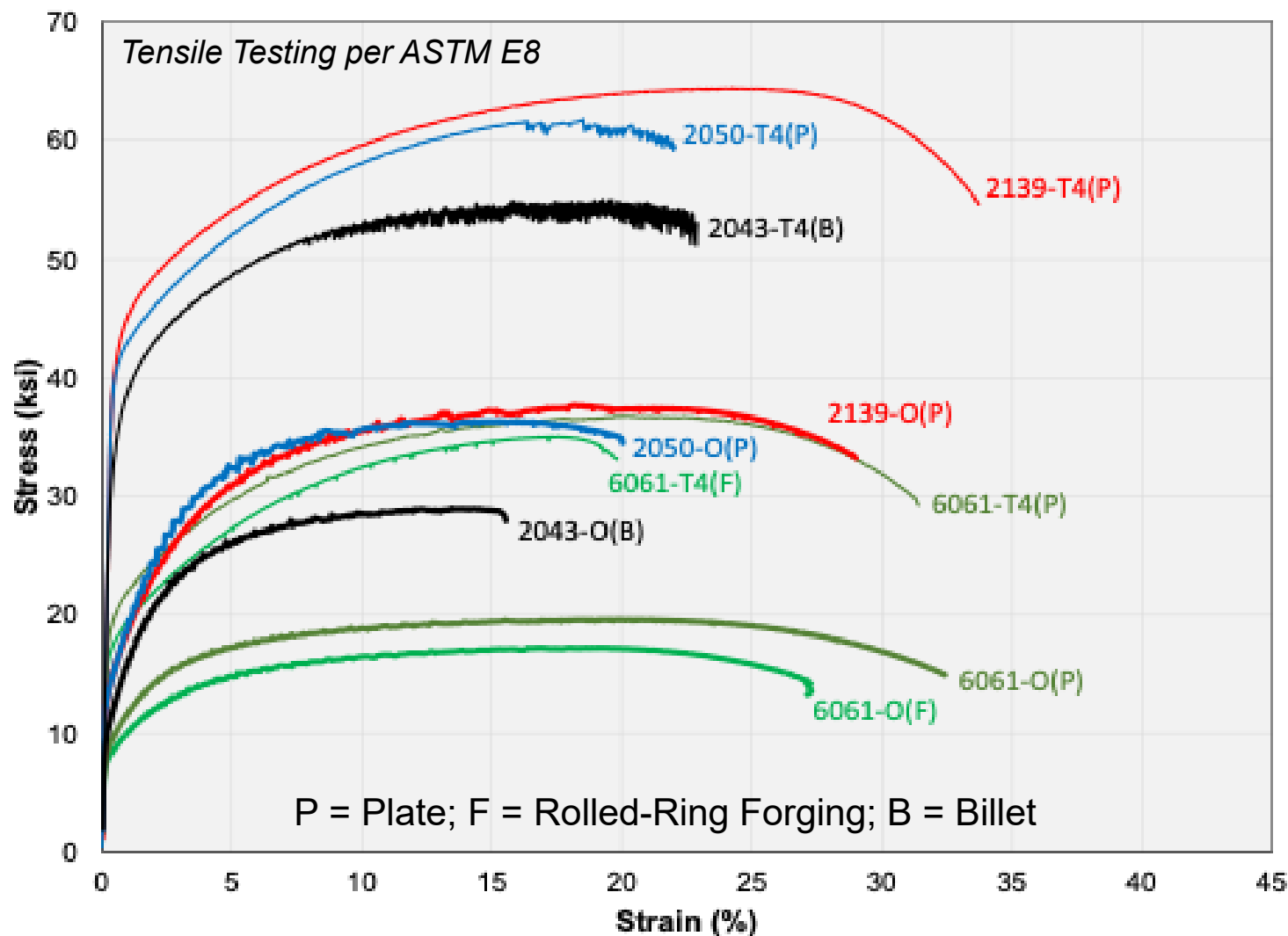
[1] Bylya, et al.; *J Materials Processing Technology*, Vol 252, pp.34-44, 2018. ([Flow formability](#))

[2] Kegg, et al.; *J Engineering for Industry*. Vol 83, pp.119-124, 1961. ([Spin formability](#))

[3] Meyers and Chawla; *Mechanical Behavior of Materials*. 2nd Ed., Cambridge Univ. Press, 2009. ([Sheet metal formability](#))

Advance → Identify the best combination of parameters for formability AND workability screening

Tensile Behavior and Formability Potential



Key Observations:

- Most of the curves indicate serrated material flow; the Portevin-Le Chatelier (PLC) effect
- Plate data (VUD600 preforms)
 - Benchmark 6061-O = pre-necking PLC
 - 6061-T4 = No PLC
 - 2139-O = pre-necking PLC
 - 2139-T4 = No PLC
 - 2050-O = pre-necking PLC
 - 2050-T4 = post-necking PLC
- Both the onset and scale of the PLC effect will affect formability
- PLC dependent on strain and strain rate
- Risk of loss of ductility for stiffener formation

Advance → Candidates show good formability potential, but serrated flow (PLC effect) warrants investigation

Properties of Candidate Al Alloys; Plate in -O and -T4 Tempers



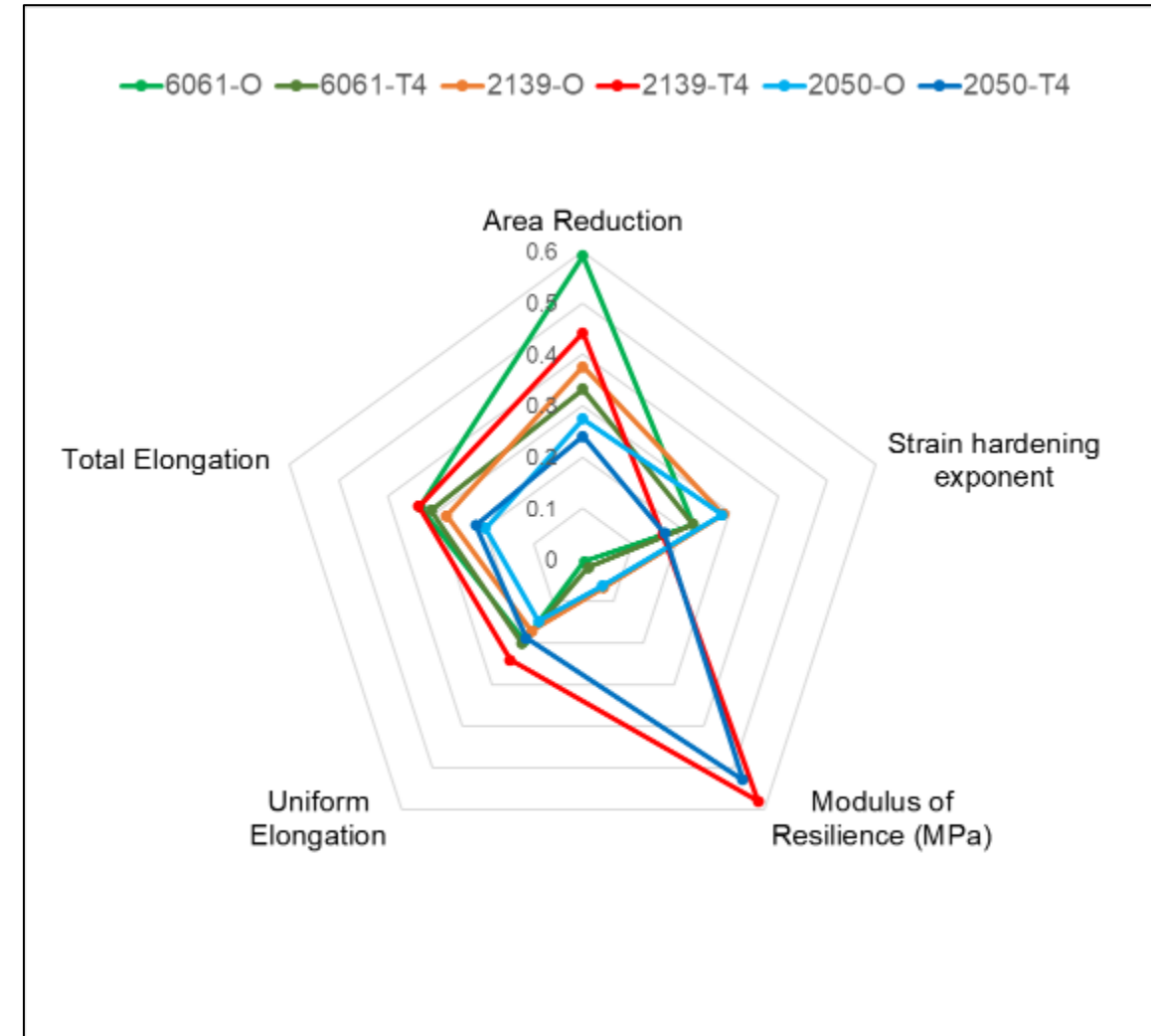
Alloy	6061		2139		2050	
Temper	O	T4	O	T4	O	T4
Uniform Elongation (%)	19.5	20.1	17.1	24.1	14.7	18.8
Total Elongation (%)	33.3	31.1	27.9	33.6	20.0	21.9
Area Reduction (%)	59.2	33.2	37.6	44.2	27.4	24.1
Strain hardening exponent (n)	0.225	0.224	0.287	0.163	0.284	0.167
Modulus of Resilience (MPa)	0.004	0.018	0.067	0.580	0.063	0.529

Implications:

- AR not encouraging;
Al 2139-O and Al 2050-O vs. Al 6061-O
- AR promising;
Al 2139-T4 vs. Al 6061-O

Concerns:

- Onset and scale of serrated plastic flow not covered
- PLC effect may ultimately skew the formability metric hierarchy

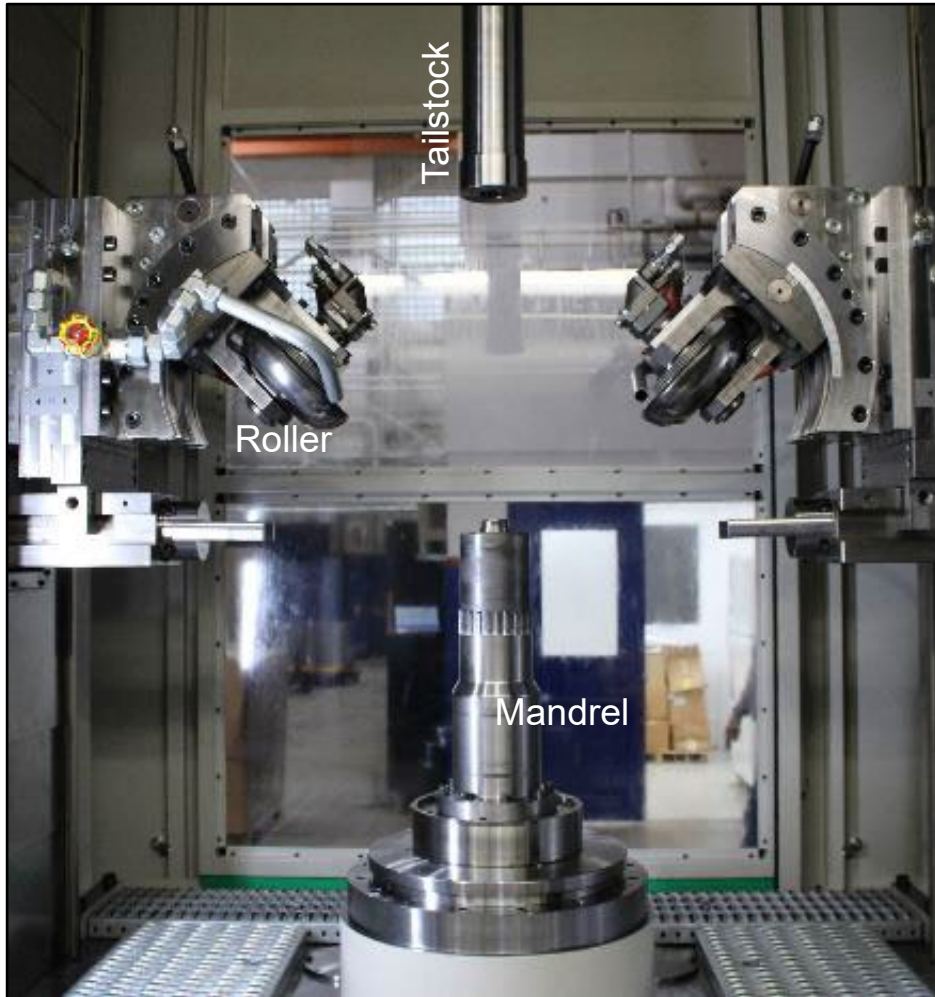


Advance → VUD600 forming trials aimed at correlating formability metrics with process variables

Flow Forming Facility at NASA Langley Research Center



WF-Maschinenbau VUD-600 machine



Forming Blank
8-Inch Diameter

Spin forming

Forward Flow
Forming

Stiffener
Forming

Backward Flow
Forming

Advance → Devising systematic method that reduces trial-and-error and accelerates R&D

Correlating Formability Metrics with Forming Trial Results



Alloy	6061		2139	
Temper	O	T4	O	T4
Uniform Elongation (%)	19.5	20.1	17.1	24.1
Total Elongation (%)	33.3	31.1	27.9	33.6
Area Reduction (%)	59.2	33.2	37.6	44.2
Strain hardening exponent (n)	0.225	0.224	0.287	0.163
Modulus of Resilience (MPa)	0.004	0.018	0.067	0.580

- Same forming protocol used for Al 6061-O executed using Al 6061-T4 and Al 2139-O
- Similar failure mode for Al 2139-O and Al 6061-T4
- **AR is customarily correlated with spinnability, i.e. maximum permissible bite per pass**

Al 6061-O

✓ Successful forming



Al 6061-T4

✗ Unsuccessful forming



Al 2139-O

✗ Unsuccessful forming



Advance → Seek ways to modify forming protocol to compensate for AR deficit

Progress in Rationalizing Forming Dynamics



Al 6061-O



Goal

Adjust forming protocol (roller motion dynamics) to compensate for difference in ductility (AR deficit)

Processing Modifications

- Lift off between passes, release the bite in the part at each pass
- Added an additional forming pass. (smaller bites)

Al 2139-O plate

Success implementing forward flow forming ☺
Cracking observed before stiffener formation ☹

Planned Next Steps

- Use DEFORM® to simulate damage
- Evaluate plastic flow instability effects
- Initiate forming parameter study (feed rate)

Al 2139-O



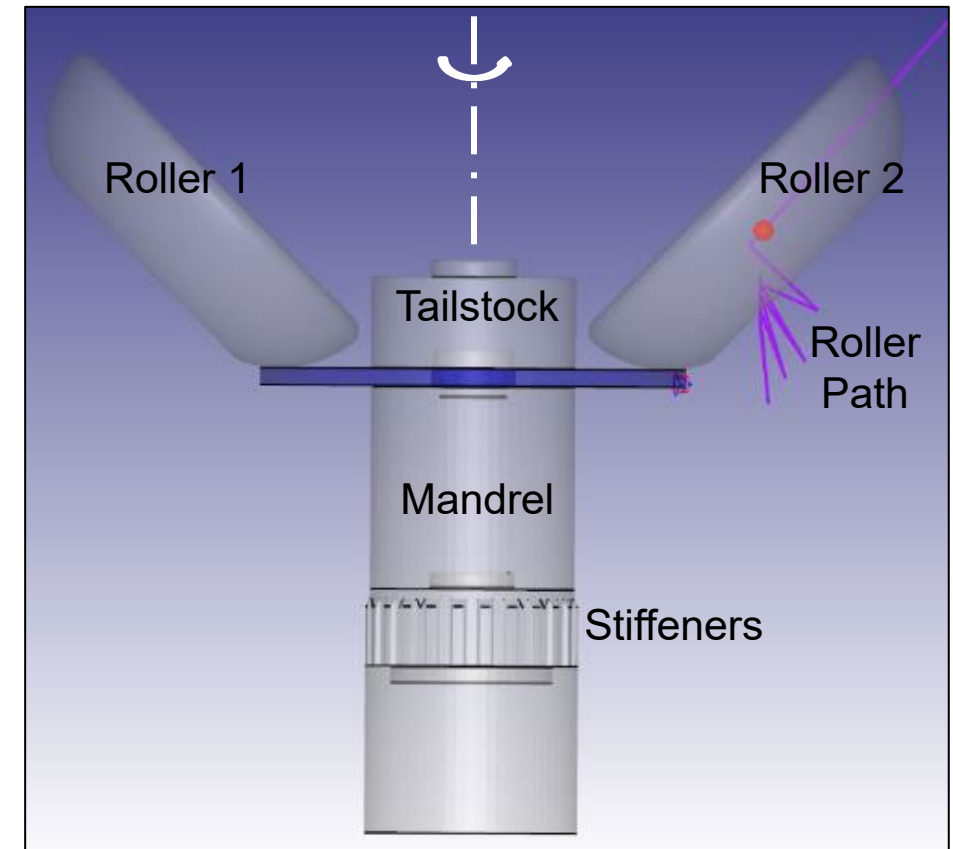
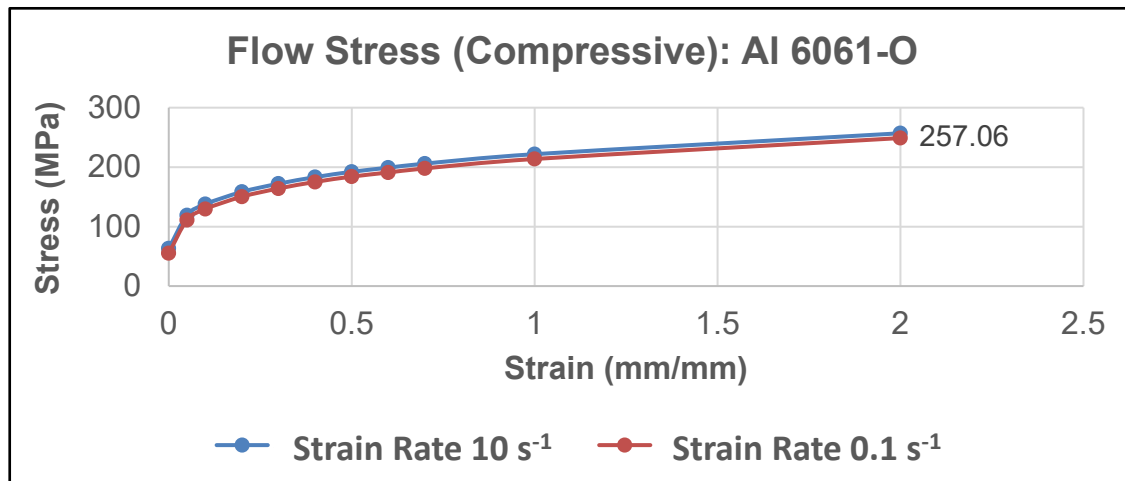
Advance → Interrogate plastic flow phenomena/mechanisms

Modeling of Flow Forming Process with DEFORM®



- DEFORM® – Commercial forging/plastic deformation simulation suite
- Large strain deformation, finite element model: solves continuity, momentum, energy using nodal velocities
- Input mechanical property data from formability testing to simulate material deformation
- Utilize modeling tools to guide process parameter selection

Inputs	Material flow stress curves (below), tool paths, and starting geometry
Outputs	Stress and strain mapping, deformed geometry, damage accumulation
Solver	3D Implicit Lagrangian



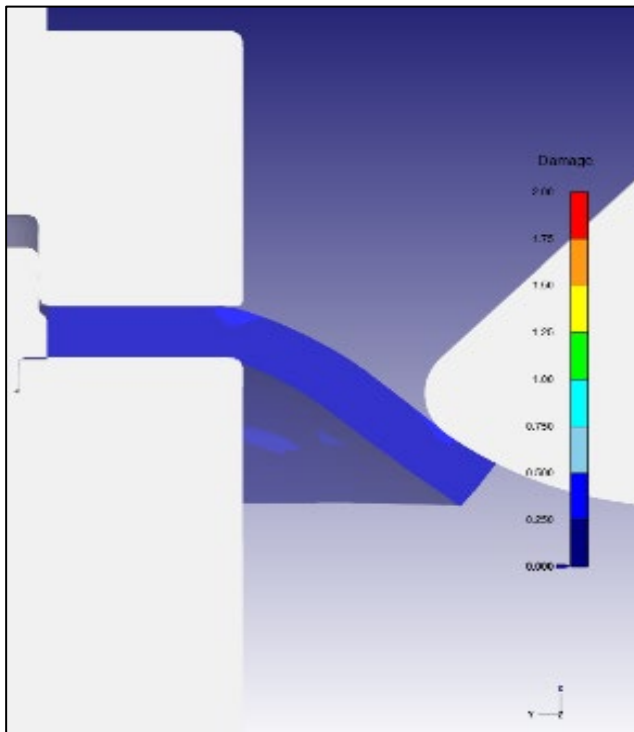
Advance → Model predictions from inputs that depend on alloy, temper, and product form

DEFORM® Modeling: Al 6061 and Al 2139 Forming Behavior

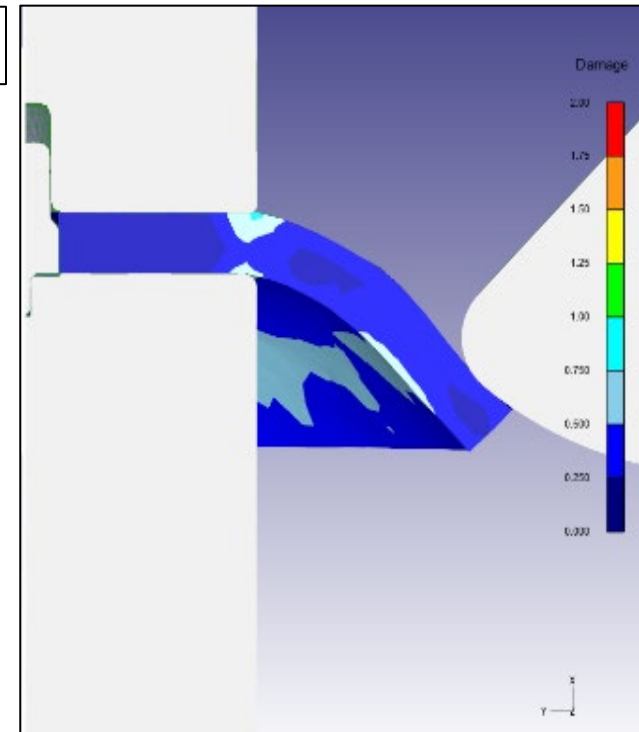


- Identical simulations (same time step, meshing routine, toolpaths) run with different flow curves yield different material responses
- 2139 shows significant pile up behavior in front of the roller and damage accumulation at clamp region
- Running simulation beyond experimental material failure shows non-physical geometries

Al 6061



Al 2139



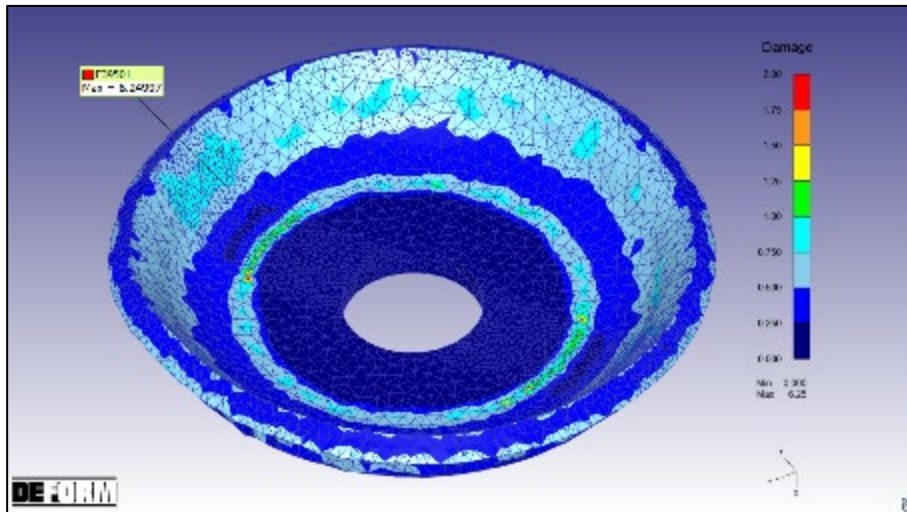
Advance → Model Predictions: Al 6061 = damage-free and Al 2139 = damage accumulation

DEFORM® Simulation of Flow Forming Process

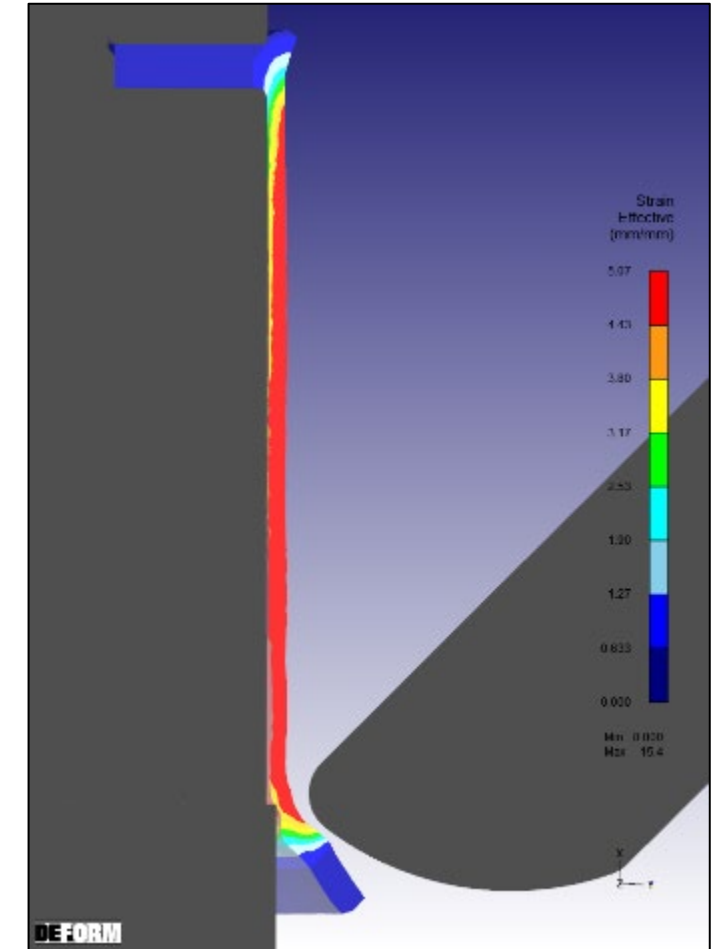


- Predicted damage location in Al 2139 correlates with failure during forming
- Model predicts through-thickness strain gradient: maximum at outer surface (roller); minimum at inner surface (mandrel)
- Process modeling allows for toolpath refinement, stiffener geometry investigations, and candidate alloy down-select

Damage location predicted by model



Premature fracture during forming

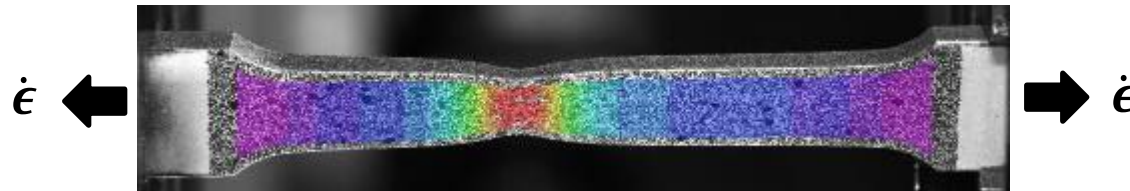


Predicted strain distribution during flow forming of Al 6061-O plate

Expanding the Suite of Formability Metrics



Tensile test data has more to offer beyond SOA metrics !



$$\sigma = K \epsilon^n$$

$$\sigma = C \dot{\epsilon}^m$$

n → strain hardening

m → strain rate sensitivity

Describes the ϵ dependence

Describes the $\dot{\epsilon}$ dependence

Governs when necking starts

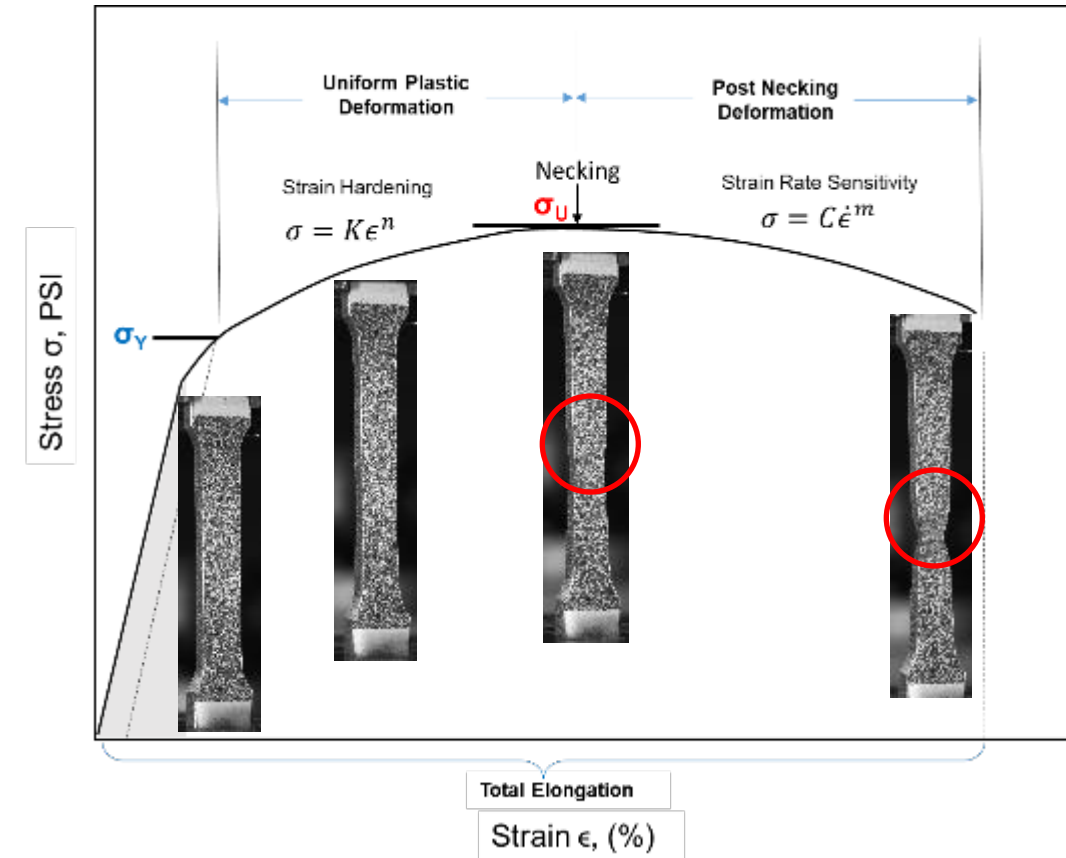
Governs necking characteristics

↑ **n** delays onset of necking

↑ **m** delays localized necking

Pre-necking deformation

Post-necking Deformation



Advance → Flow stress parameters that include strain rate sensitivity exploited to screen for formability/workability

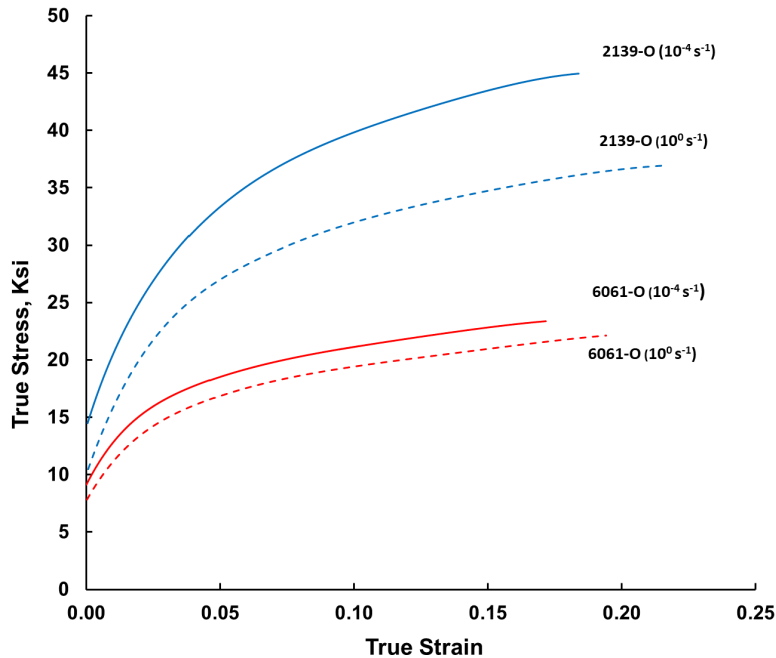
Addressing an Expanded Suite of Formability Metrics



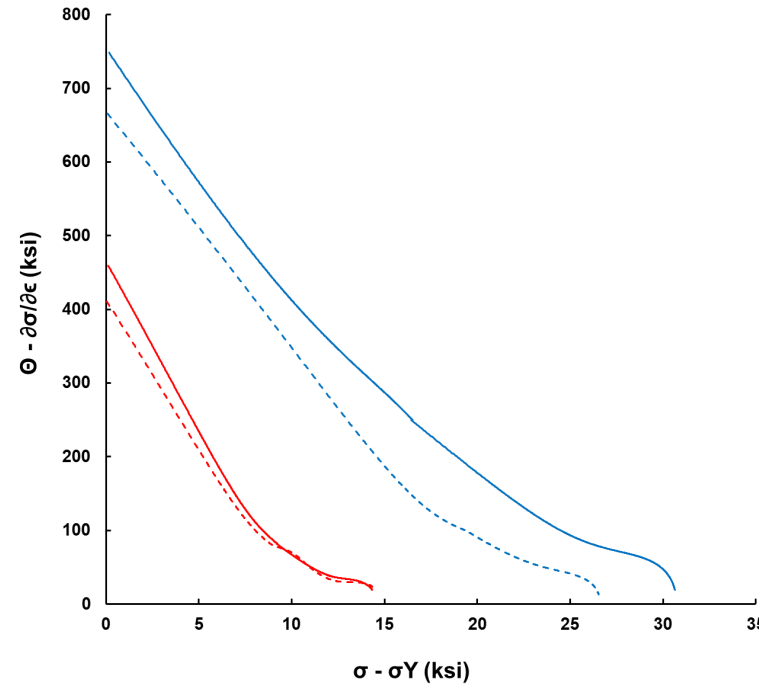
Flow forming is a dynamic process with strain rates $\leq 10^1 \text{ s}^{-1}$

➔ Tensile testing at higher strain rates germane

Stress-strain curves for uniform deformation zone



Kocks-Mecking (K-M) plots



Strain rate effect on formability metrics

Alloy/Temper	Al 6061-O		Al 2139-O	
Strain Rate (s^{-1})	$\times 10^{-4}$	$\times 10^0$	$\times 10^{-4}$	$\times 10^0$
Uniform Elongation (%)	20	22	17	21
Total Elongation (%)	33	36	28	31
Area Reduction (%)	59	67	38	52
Strain Hardening Coeff.	0.225	0.254	0.287	0.310

Implications:

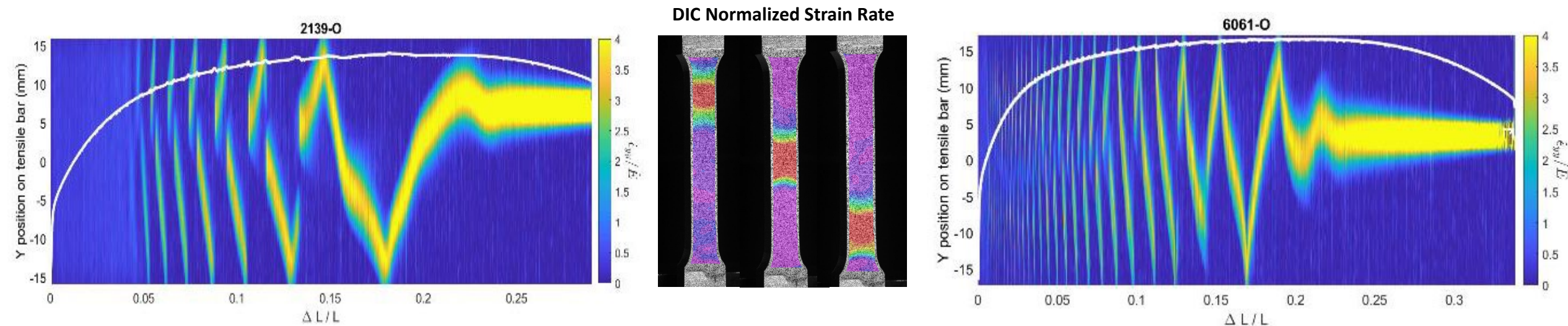
- Higher strain rate $\leq 10^0 \rightarrow$ negative strain rate sensitivity (m)
- Work hardening coefficient $\uparrow$ with $\uparrow$ strain rate
- AR and elongation $\uparrow$ with $\uparrow$ strain rate
- Slope of K-M curve (Θ) tied to recovery of dislocations in the material

Advance ➔ Correlating intrinsic material properties with forming parameters is a moving target

Evaluating Plastic Flow Instability Effects



- Plastic flow serrations (PLC effect) exhibited by most of the alloys and heat treatment conditions; indicative of dynamic strain aging and negative strain rate sensitivity.
 - Spatio-temporal plots reduced from DIC data highlight flow localization within PLC bands.
 - Frequency and velocity of PLC bands in Al 2139-O is lower than in Al 6061-O.



- Current work focused on elevated strain rate testing and strain rate jump testing to investigate rapid changes in strain rate (akin to a forming increment by a passing roller) on formability metrics such as n , AR , etc.

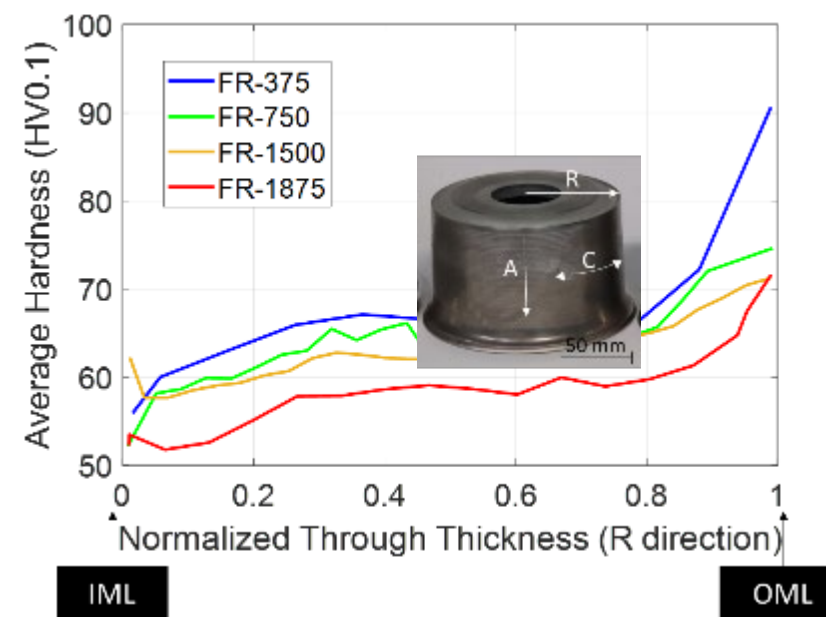
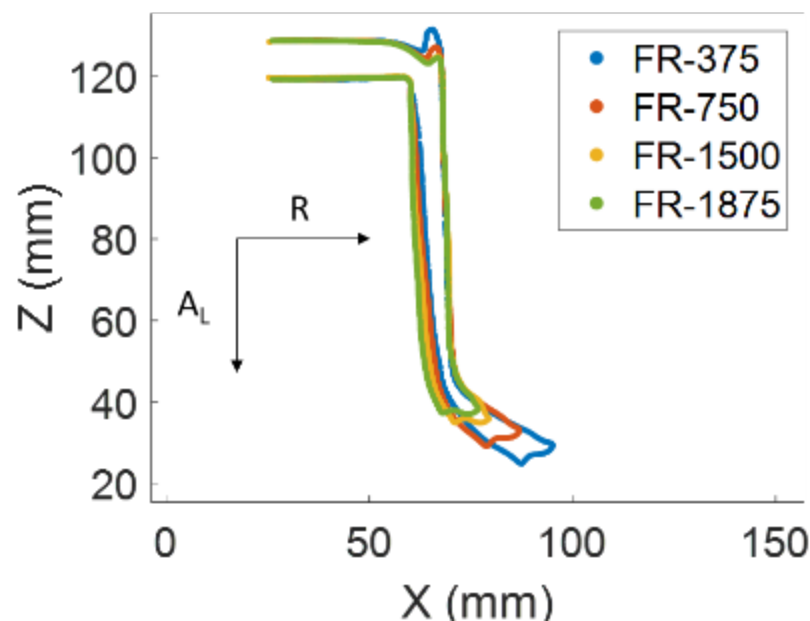
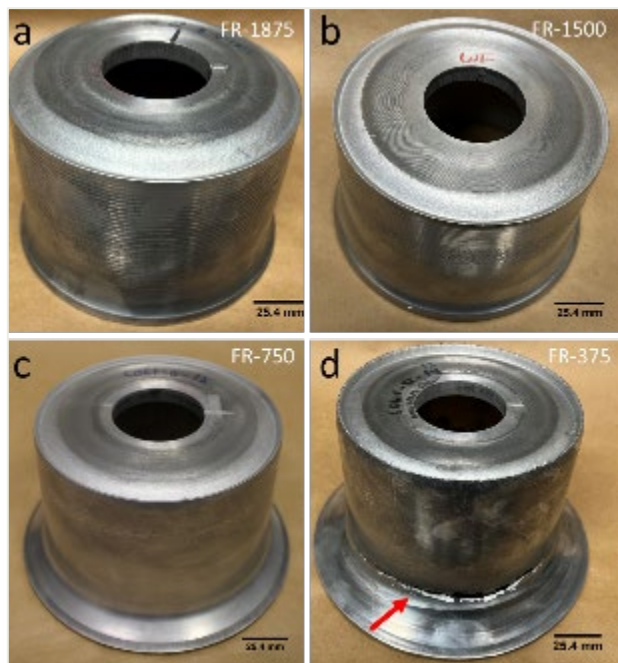
Advance → increase in AR with elevated strain rate suggests that in-situ strain rate variations may not adversely affect formability

Influence of Feed Rate on Properties and Microstructure



Performed 4 spin forming trials at varying feed rates in the range of 375-1875 mm/min:

- As feed rate **increased**;
 - peak roller forces **increased**
 - total roller force over time **decreased**
 - hardness at outer mold line (OML) **decreased**
 - wall thickness and part elongation **decreased**
 - grain structure and micro-texture **unaffected**
 - through-thickness variability in microstructure noted



Advance → Feed rate can control mechanical properties and geometry, but is ineffective for microstructure

- Flow forming of complex-shaped cylinders presents unique challenges;
 - Forming of integral stiffeners includes plastic flow more reminiscent of forging
 - Evaluating the formability of high-strength Al alloys (RT deformation characteristics)
- Incumbent formability metrics are insufficient for bulk workability assessment
- Integrated stiffener formation (groove filling) suggests expanded suite of metrics
- Additional formability metrics need to be evaluated;
 - Rate of work hardening
 - Plastic anisotropy ratio
- Intrinsic material property data must be extended to higher strain rates and elevated temperatures;
 - Account for strain rate sensitivity
 - Mitigate PLC effects (dynamic strain aging)
- DEFORM® modeling can predict damage accumulation with appropriate inputs
- Feed rate and tool path are convenient forming parameters to interrogate

Future Work: Formability screening tests beyond tensile data will be required to fully define the flow forming envelope (processing map)

Thank You

Questions?