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Aluminum Formability Extension through Superior Blank Processing

X SUN (PI)
PACIFIC NORTHWEST NATIONAL LABORATORY
RICHLAND, WA, USA

2014 DOE VEHICLE TECHNOLOGY PROGRAM REVIEW
JUNE 16-20, 2014

Project ID#: LM078

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Overview

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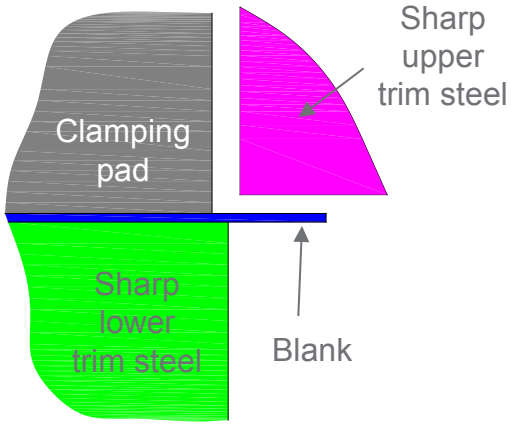
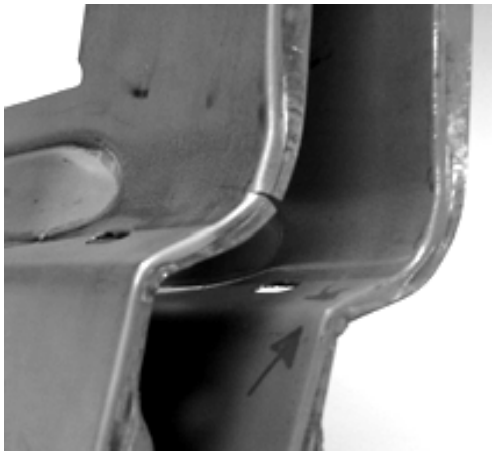
- Timeline
  - Start: Oct. 2011
  - End: Sep. 2014
  - 67% Complete
- Budget
  - DOE - $1,200K
    - FY12 - $400k
    - FY13 - $300k
    - FY14 - $500k
  - Industries (in-kind) - $675K
    - Industry - $225k/YR FY12 – FY14
- Barriers
  - Limited room temperature formability of Al sheets
  - Room temperature formability of the aluminum sheet can be reduced by as much as 50% as a result of inadequate blanking, piercing, and trimming operations
  - High variability in subsequent stretch forming and hemming operations
- Partners
  - Ford Motor Company
  - Oakland University

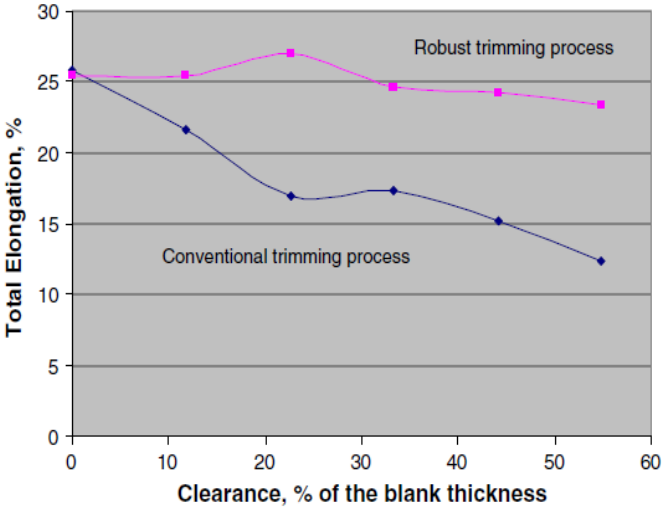
Motivation: Conventional Trimming Process



- Trimmed surface quality is very sensitive to the alignment accuracy of the upper and lower dies.
- Burrs, slivers and splits are typical defects encountered in conventional trimming.
- Tooling alignment is especially difficult in curved areas of the trim line.
- Insufficient die stiffness can be a problem due to the increased trimming forces necessary for AHSS steel.

Examples of splits in production parts





S.F. Golovashenko, International Journal of Mechanical Sciences 48, 2006

Project Objectives

- Objectives: To develop, prototype, and demonstrate superior methods of blanking, piercing, and trimming operations to enhance room temperature sheet aluminum formability by:
  - Building validated predictive capabilities to quantify relationships between trimming condition to trimmed edge quality and to subsequent stretchability:
    - Create computational capability and framework to integrate materials processing information into subsequent coupon- and part-level performance simulations
  - Enhancing coupon- and part-level formability by controlling key edge quality indicators:
    - Edge stretchability
    - Hole expansion

Deliverables and Milestones

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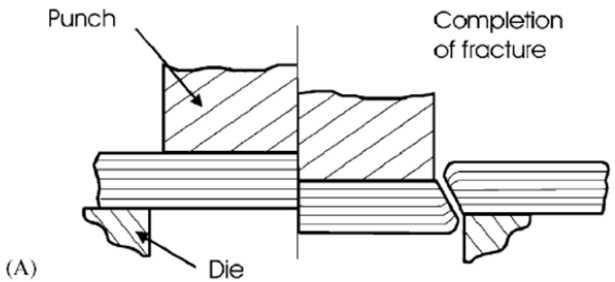
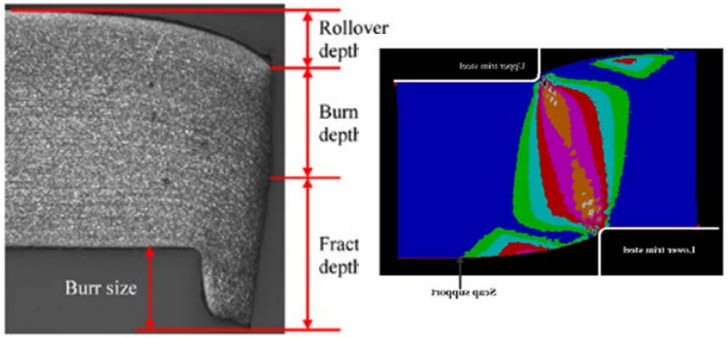
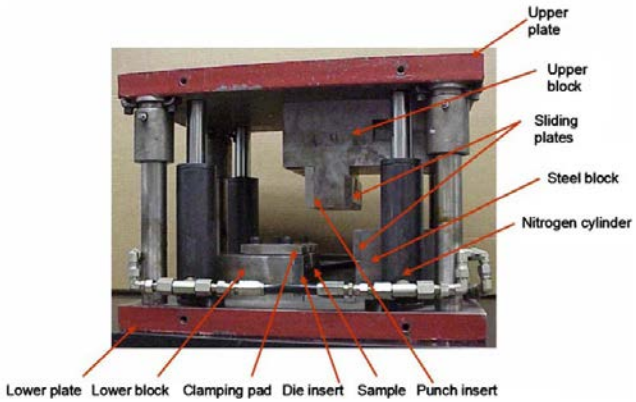
Date	Milestone or Go/No-Go Decision	Description	Status
12/31/2012	Milestone	An experimentally validated trimming process simulation model	Completed
12/31/2012	Go/No-Go Decision	The predicted burr geometry with greater than 90% accuracy compared with experimental measurements	Met
9/30/2013	Milestone	An experimentally validated stretchability simulation model incorporating trimmed edge conditions	Completed
9/30/2013	Go/No-Go Decision	Achieve on average 50% improvement for RT formability	Met
9/30/2014	Milestone	A demonstrated prototype trimming process that enhances the overall formability of aluminum sheet	On-going

Technical Approaches

- Task 1. Literature review and software capability analysis (PNNL and Ford)
- Task 2. Cutting process simulation and experimental validation (PNNL, OU and Ford)
  - Trimming model development
  - Trimming model validation with experiments
  - Obtain damage statistics and process parameter relationship
- Task 3. Forming process simulation and experimental validation (PNNL, OU, Ford)
  - Stretching model development with trimming history
  - Stretching model validation with experiments
  - Obtain quantitative relationship between edge stretchability and edge quality indicators
- Task 4. Develop optimized process parameters based on ability of sheared surface to stretch (PNNL, Ford)
  - Establish process parameter
  - Prototype process development on lab scale
  - Demonstrate technology on commercial relevant component scale







Previous Technical Accomplishments – Trimming Process Simulations

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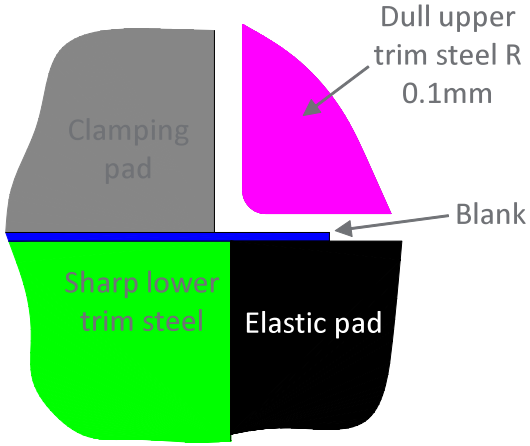
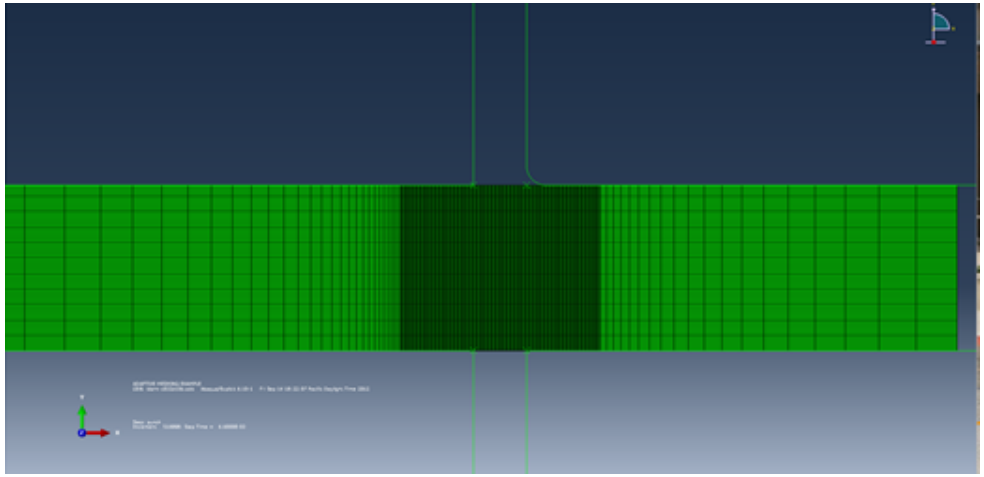
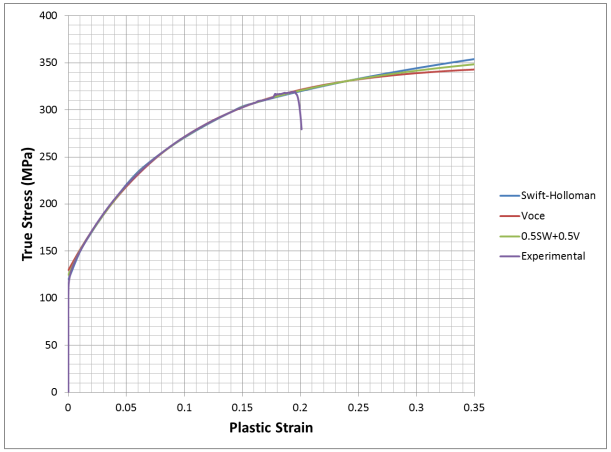
Model development for traditional and advanced trimming processes[1]

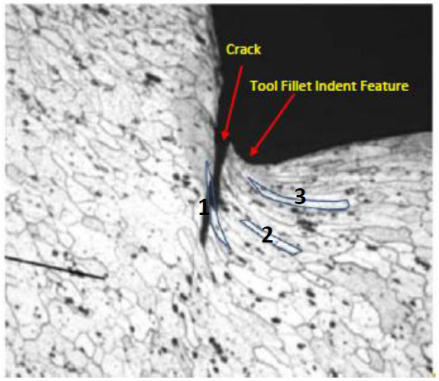


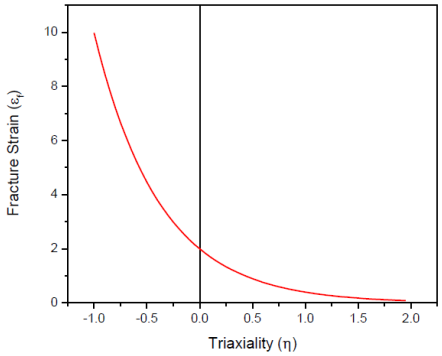




Stress strain curve for AA6111-T4

Rice-Tracey Exponential Damage Model: $\varepsilon_f = Ae^{-B\eta}$





$$\varepsilon = \frac{1}{\sqrt{3}}\ln(r)$$

[1] X. H. Hu, K. S. Choi, X. Sun, S. F. Golovashchenko, *Journal of Manuf Sci & Eng* 136, **2014**.

Technical Accomplishments – OU

Determination of stress-strain curves at large strains

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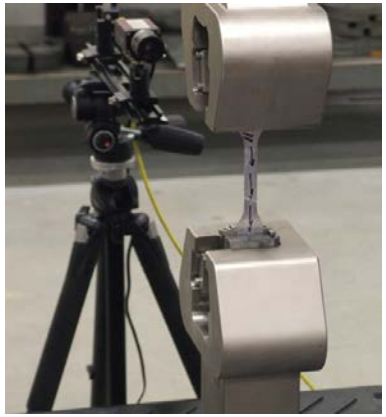
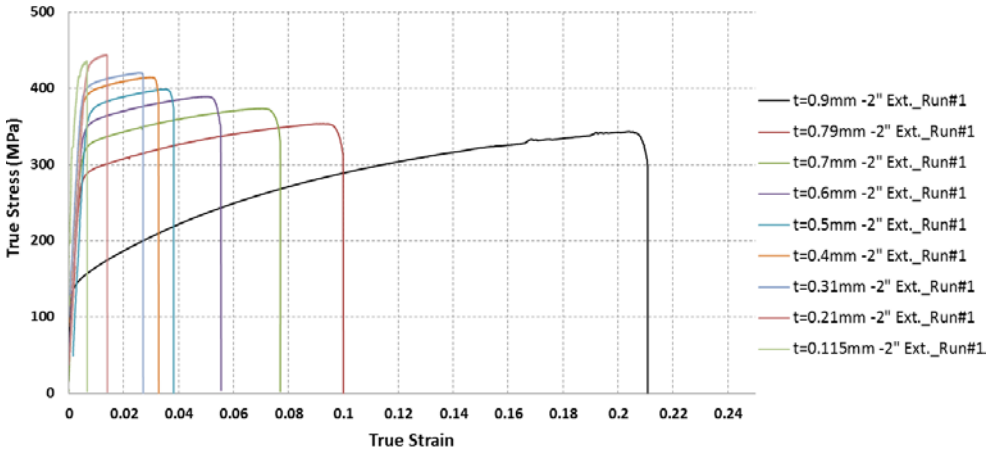
Lab-scale rolling mill

Rolled strips

Tensile samples

Standard tensile tests of samples fabricated from rolled strips with different rolling reductions

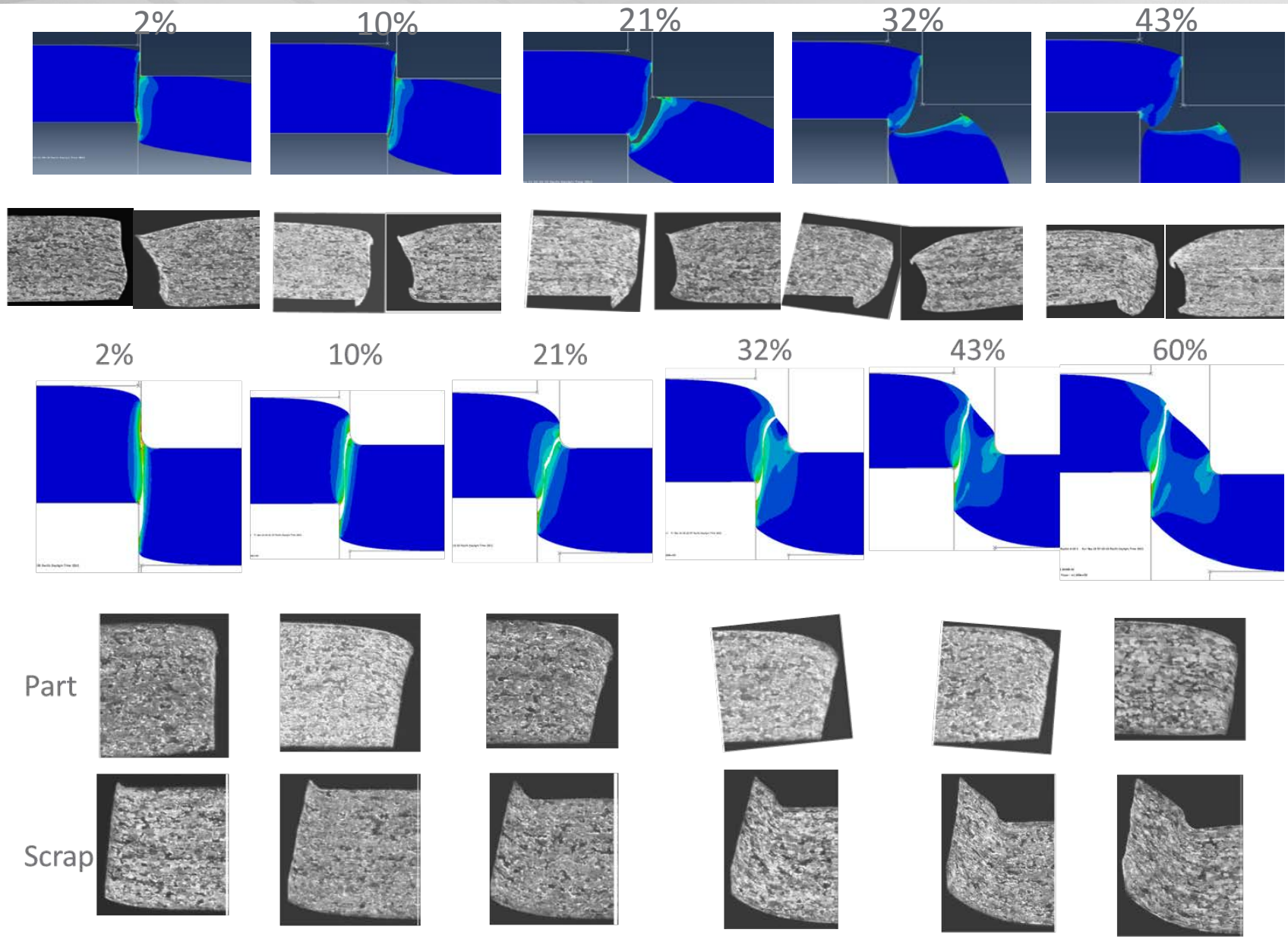




Obtained large strains stress-strain results are very close to that the stress-strain curves extrapolated from results the uniaxial tensile tests which is used in the trimming [1] and stretchability model [2] discussed in later slides.

[1] X. H. Hu, K. S. Choi, X. Sun, S. F. Golovashchenko, *Journal of Manuf Sci & Eng* 136, **2014.**
[2] X. H. Hu, X. Sun, S. F. Golovashchenko, *Computational Materials Science* 85, **2014.**

Previous Results on Trimming Process Simulations – Traditional and Advanced Trimming



Integrated Manufacturing Process Simulations from Blanking to Stretching

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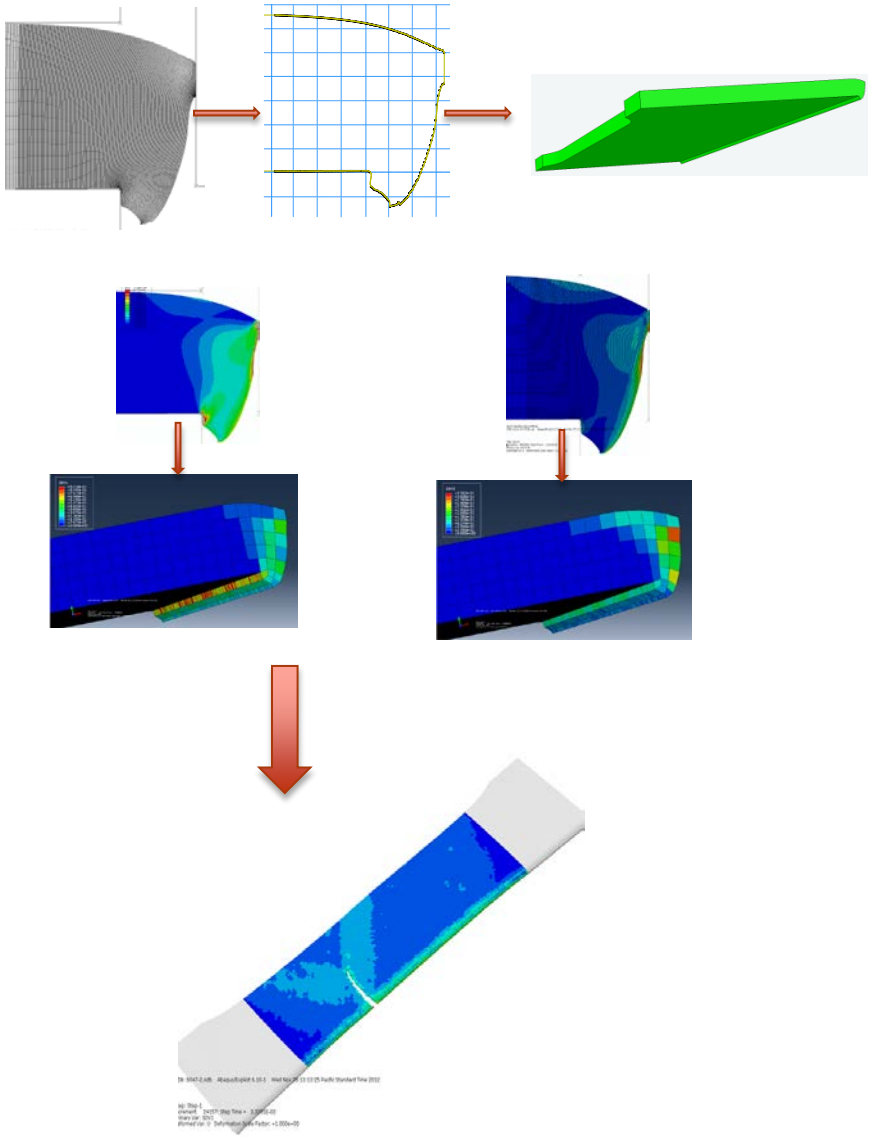
- Burr geometry
- Initial plastic strains
- Cutting induced damage
- Cutting induced residual stresses
- Material model
  - Work hardening law
  - Damage model
  - Taylor factor used to consider grain level heterogeneity

- Failure mode
- Ductility (or stretchability)
- Cases studied:
  - Traditional Trimming/Tensile Stretching
  - Advanced Trimming/Tensile Stretching
  - Hole piercing/Expansion



Predicted Failure Modes and Ductility in Quantitative Agreement with Experimental Observations

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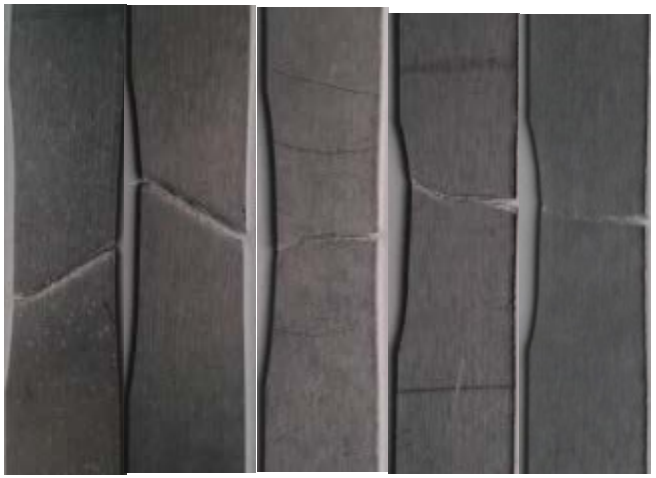
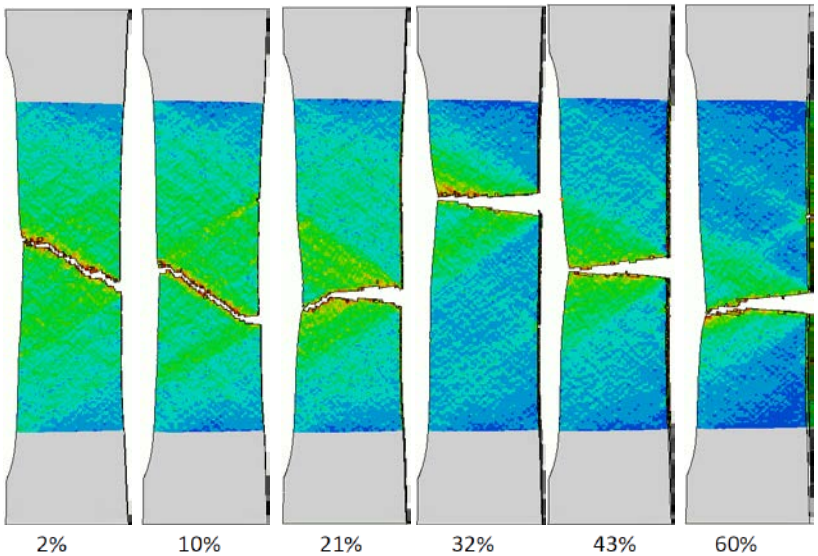
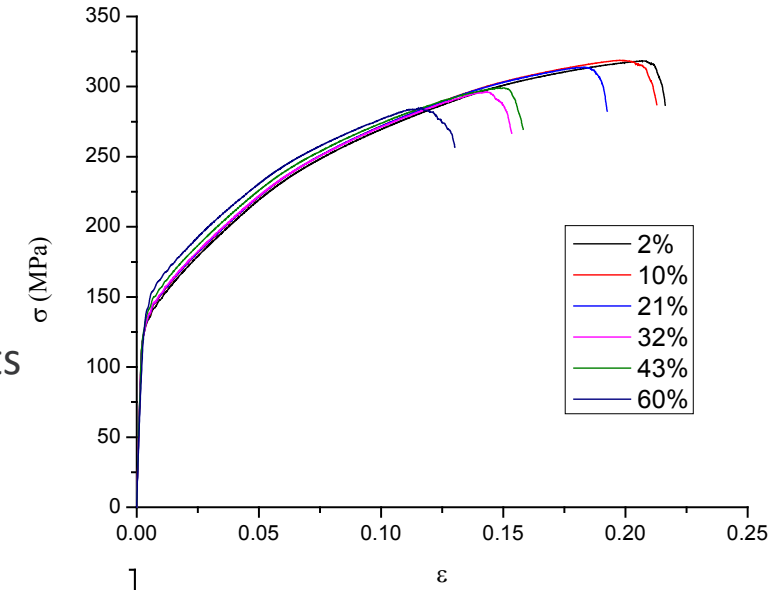
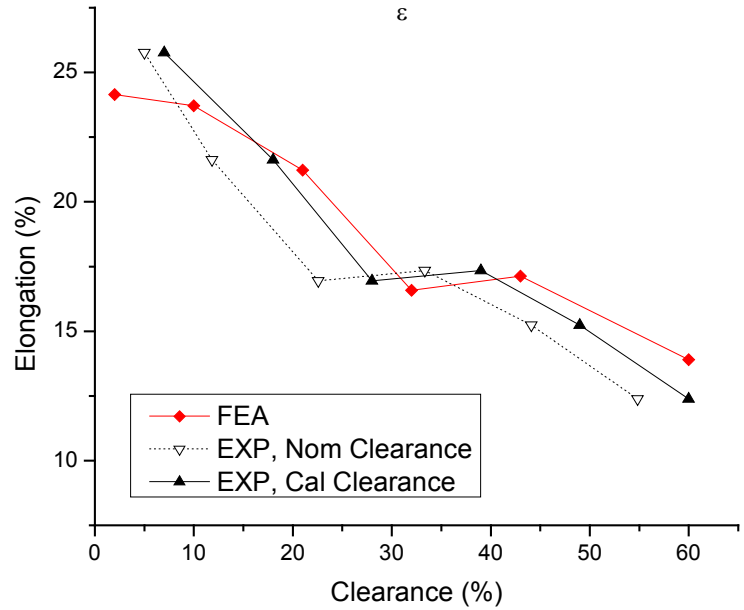
Predicted failure modes similar to those experimentally observed for different cutting clearances



OU experiments

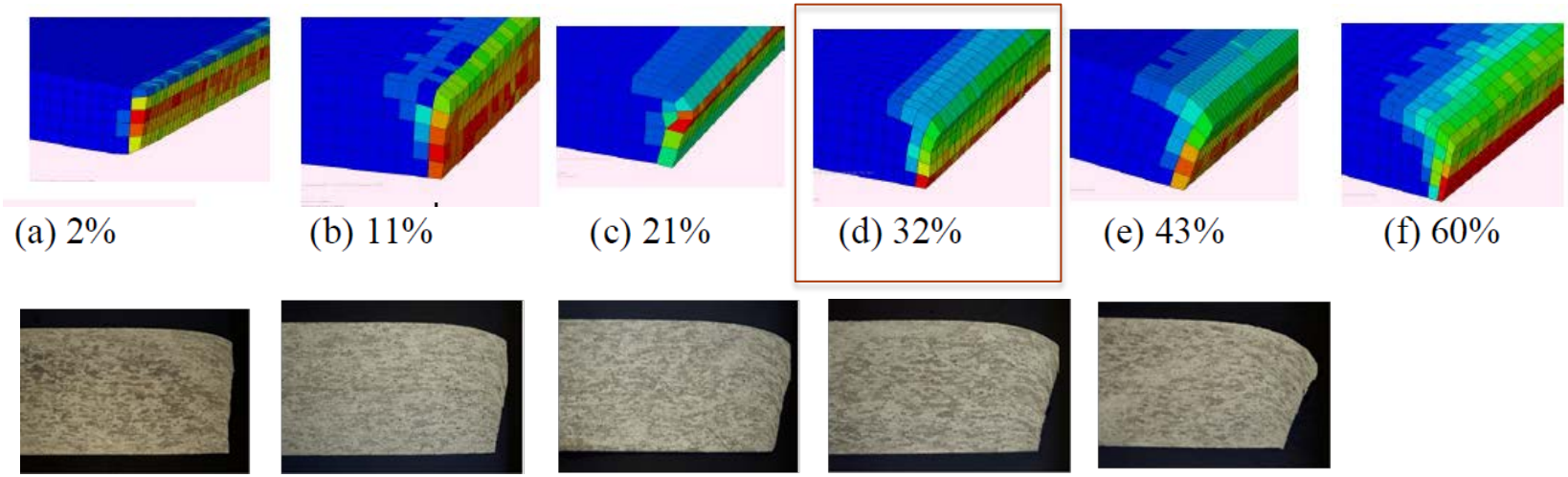


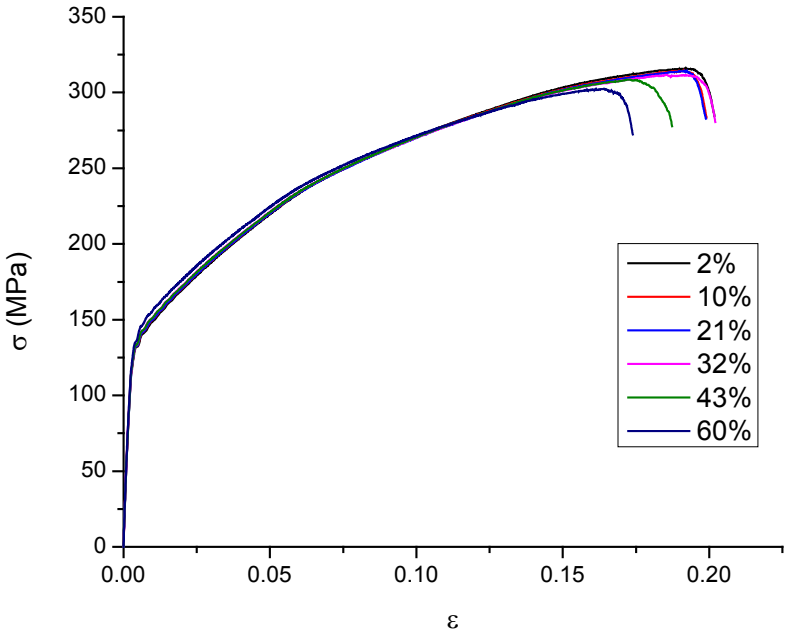


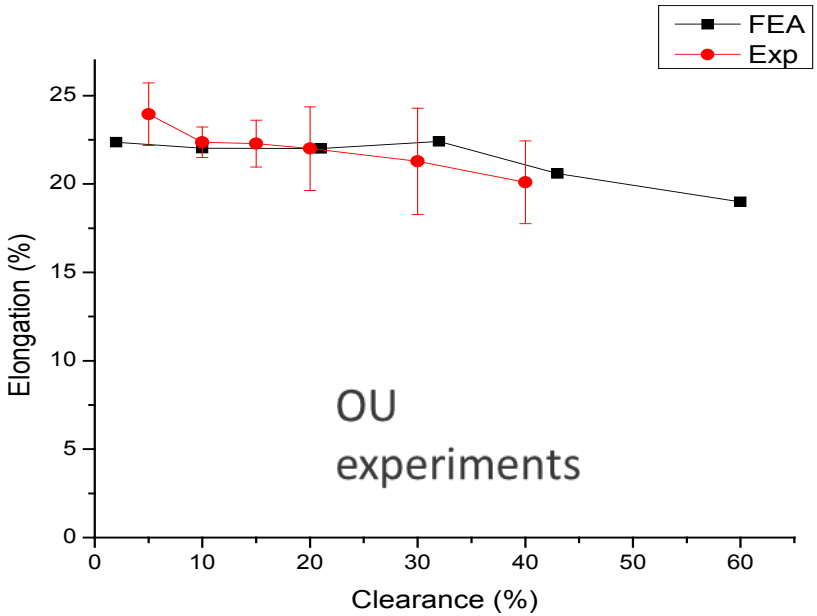


X. H. Hu, X. Sun, S. F. Golovashchenko, *Computational Materials Science* 85, **2014.**

Advanced Trimming with Scrap Support







Key Factors Influencing Trimmed Edge Stretchability

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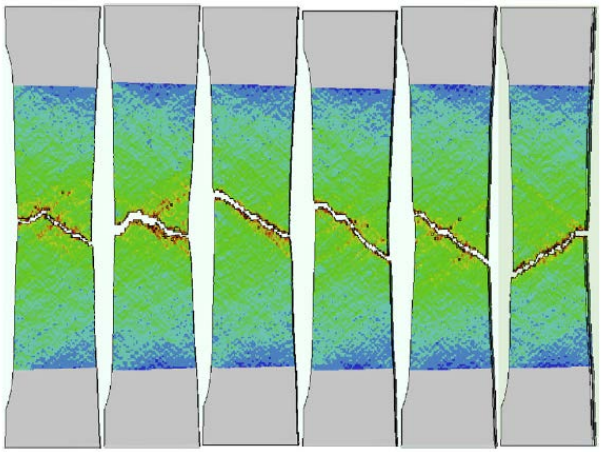
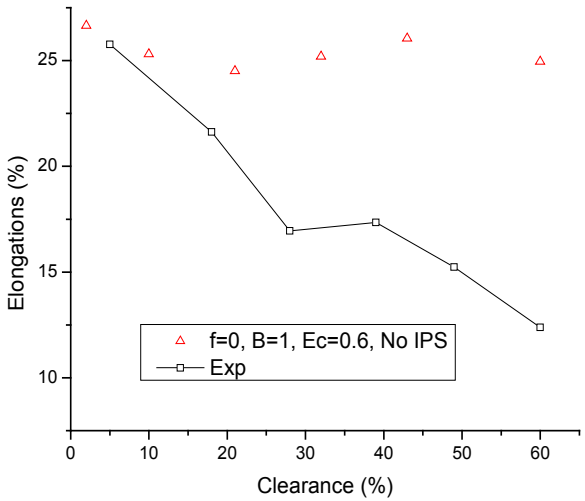
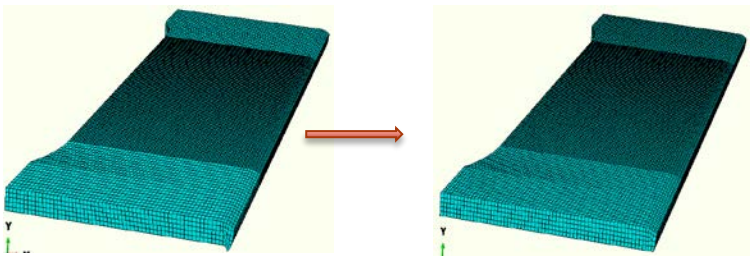
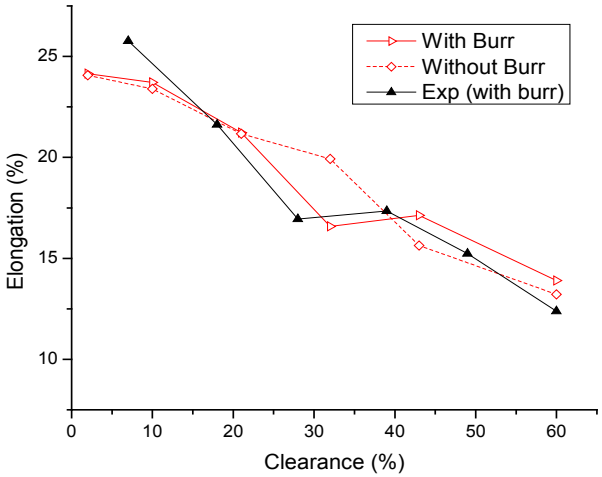
Initial Plastic Strain Removal





Burr Removal





Conventional trimming process

X. H. Hu, X. Sun, S. F. Golovashchenko, *Computational Materials Science* 85, **2014.**

Ford Developed New Method in Measuring Safe/Fail Strains Similar to FLD in Quantifying Sheared Edge Stretchability

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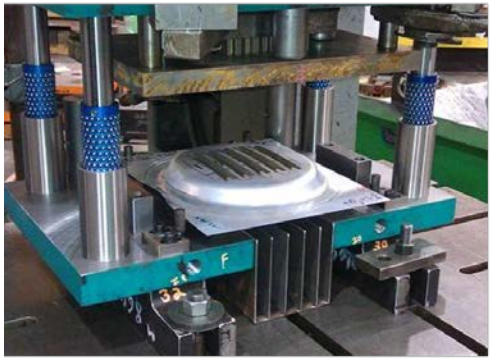

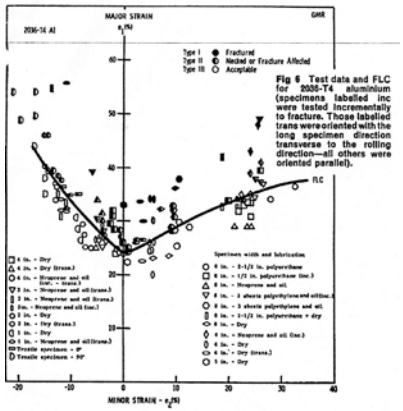

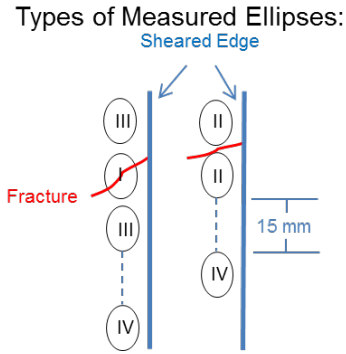

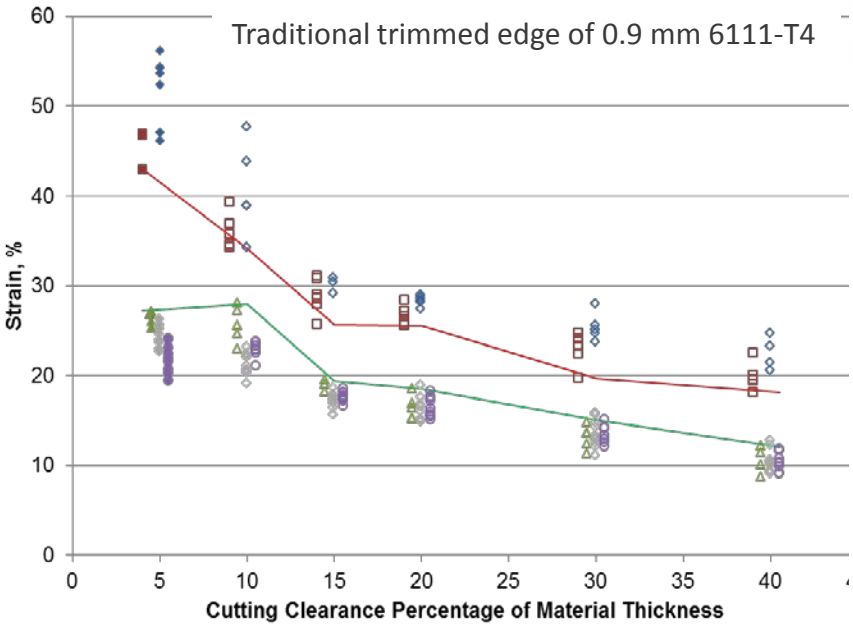

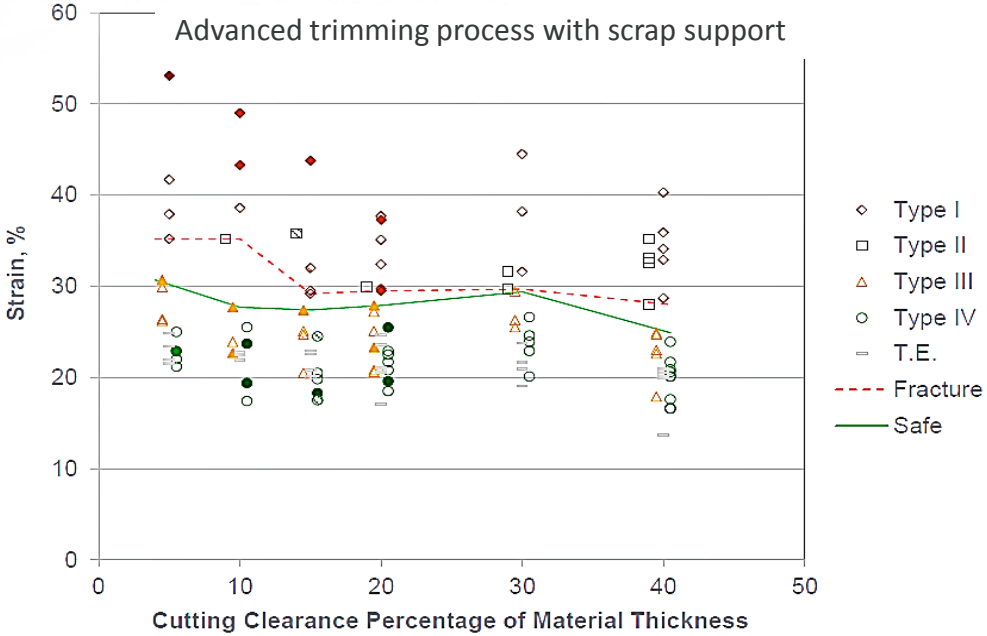

Q. B. Le, J. A. deVries, S. F. Golovashchenko, J. J. F. Bonnen, *Journal of Materials Processing Technology* 214, 2014.

Ford – Experimentally Examined Effects of Various Trimming Factors on Trimmed Edge Ductility

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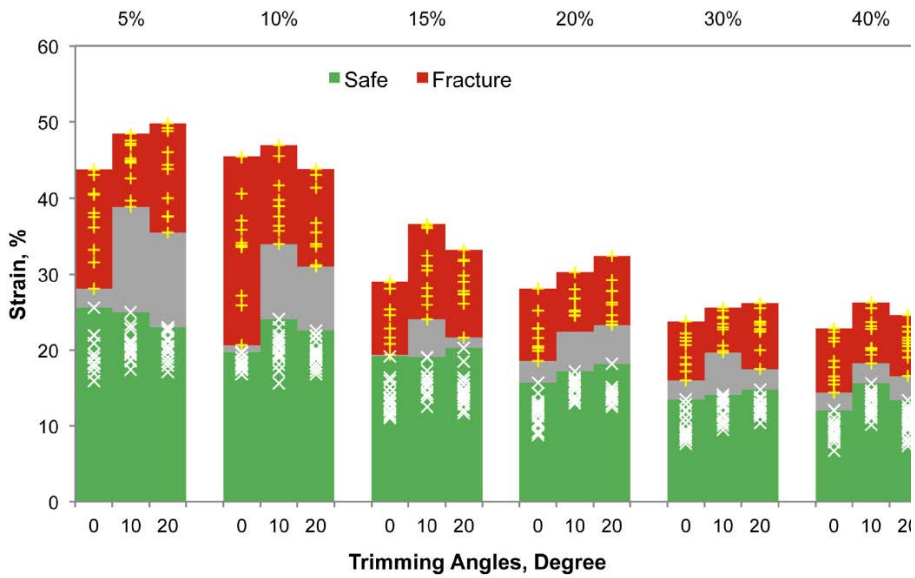
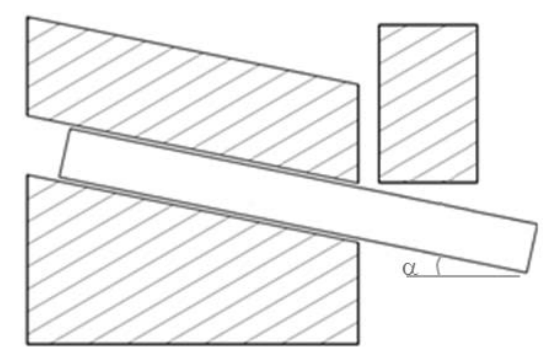
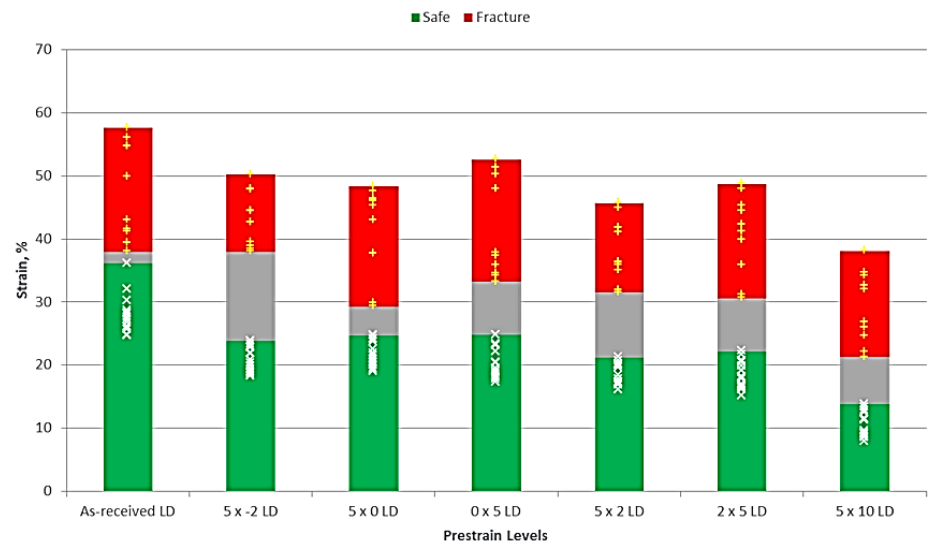
Effect of trimming angle



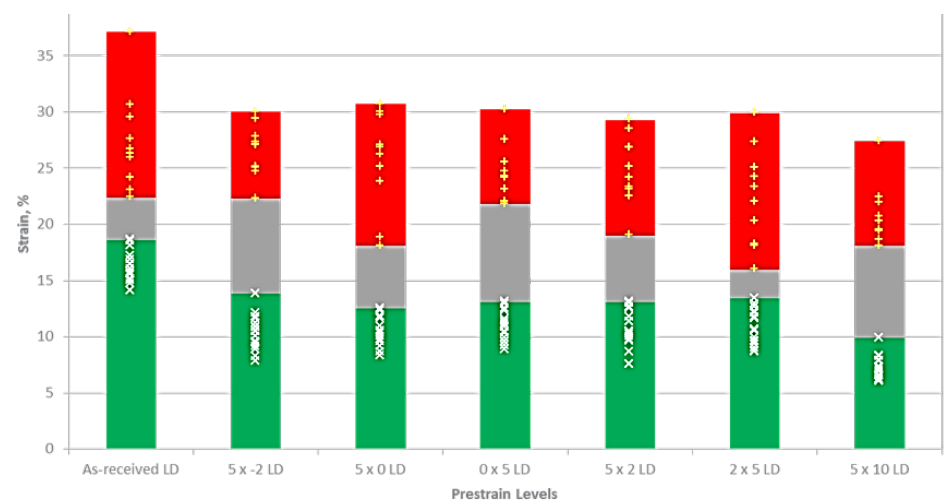


b) Downhill Angle, D: 10° and 20°

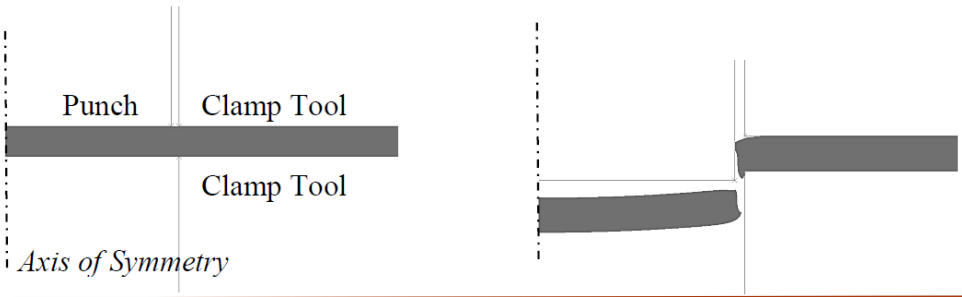
Effect of Prestrain at 0° Trimming Angle, 10% Clearance



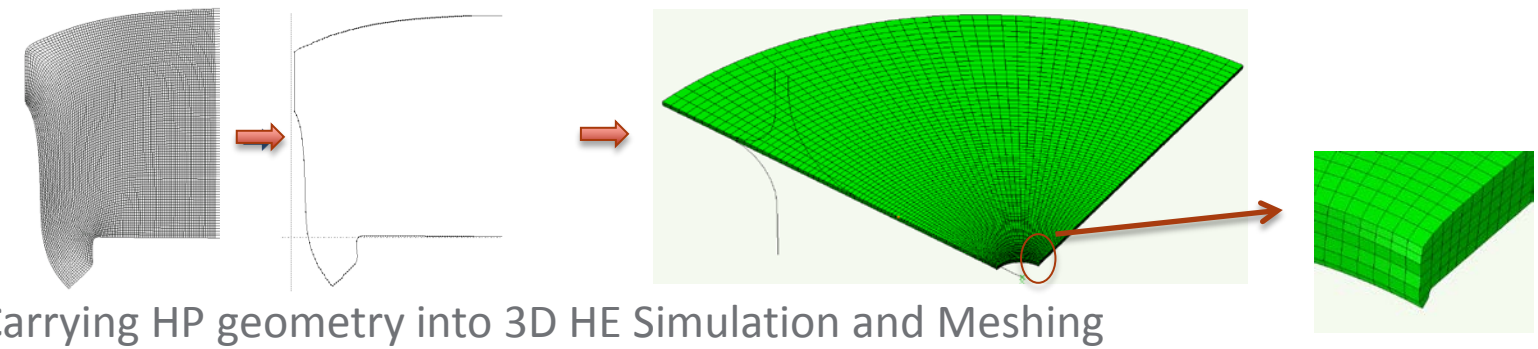
Effect of Prestrain at 0° Trimming Angle, 40% Clearance



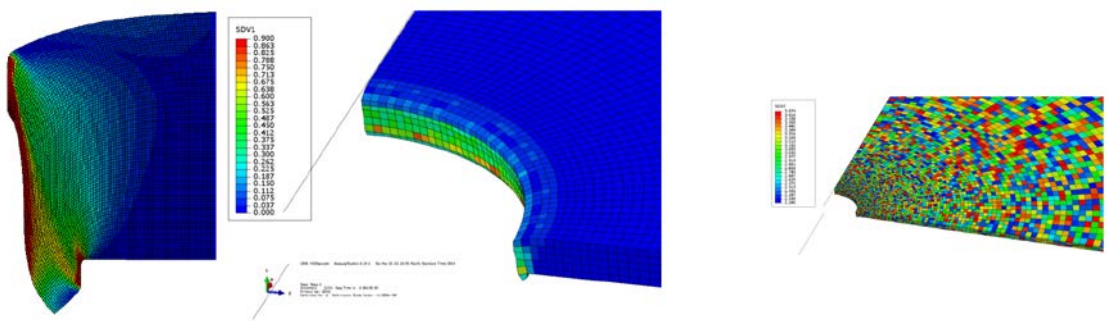
From Hole Punching (HP) to Hole Expansion (HE) Simulations



2D HP Simulation

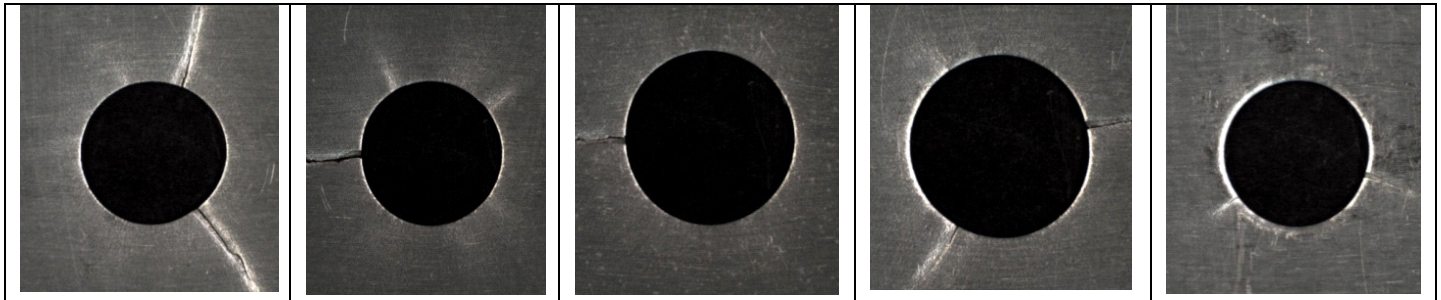


Carrying HP geometry into 3D HE Simulation and Meshing

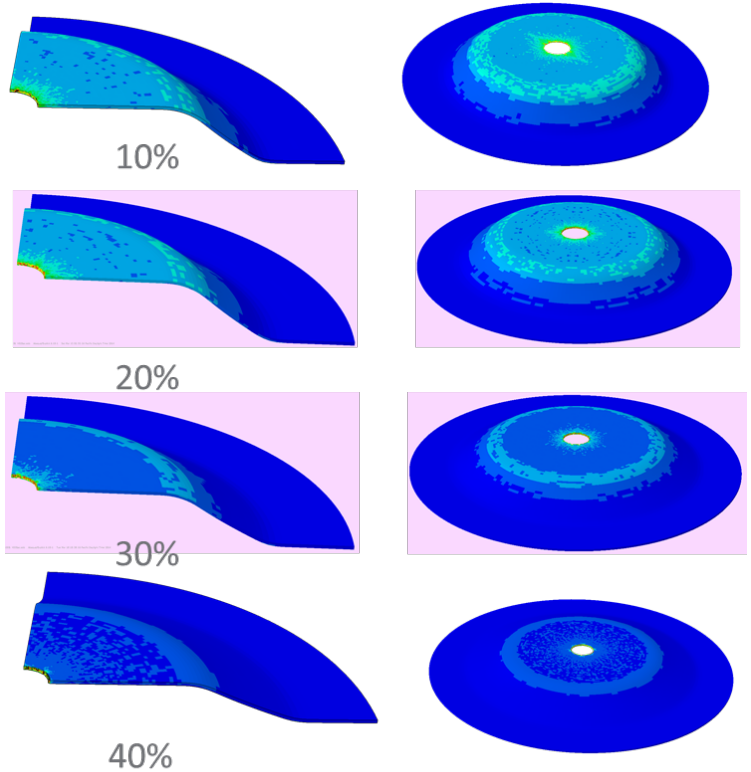


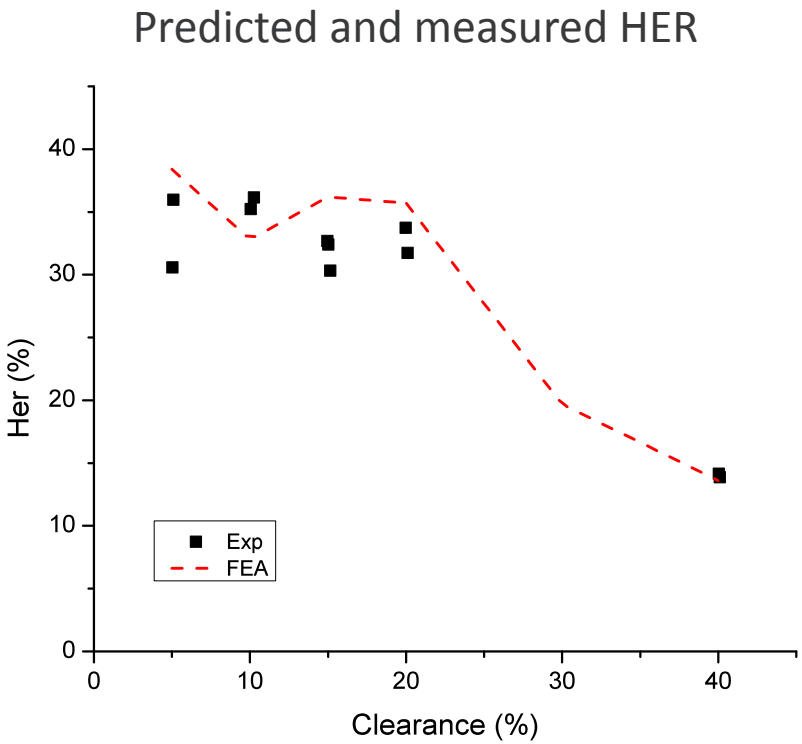
Mapping Field Variables and Considering Heterogeneity and axis-symmetry

Prediction and Experiments Performed at Ford/OU



5% clearance	10% clearance	15% clearance	20% clearance	40% clearance





Collaborations

- Experimentally obtain hardening parameters at large strains (OU)
- Experimentally obtain quantitative relationship between edge stretchability and edge quality indicators (Ford+OU).
- Develop predictive modeling capability linking trimming conditions to edge stretchability (PNNL)
- Develop optimized process parameters based on ability of sheared surface to stretch (PNNL+Ford).
- Lab scale prototype and component scale demonstration (Ford + PNNL)

Responses to Previous Year Reviewers' Comments

- Technical Accomplishments:
  - This reviewer stated that the modeling efforts seem well integrated, but the reviewer has concerns that the resolution of the models may not be able to match the scale and complexity of the fracture surfaces.

  Response: We have considered the complexity of the fracture surface upon trimming and the material microstructural level heterogeneity through the introduction of Taylor factor.

  - This reviewer stated it was difficult to assess the universality of the results and insights due to the lack of detail in the scientific process of putting the damage details into the model.

  Response: The detailed processes involved in the integrated simulation and experimental process are now published in various peer-reviewed journal publications.

- Collaboration and coordination with other institutions
  - This reviewer said that it seems okay, but silo-ed.
  - This reviewer indicated that PNNL seems to be driving the efforts, but it did not feel like Oakland University and Ford were full partners.

  Response: The project is structured such that we want to use validated models to guide the process development for improved edge stretchability. In the first couple of years, we have focused heavily on model development and model validation with experimental support from Ford and OU. In FY14, as shown in this presentation, Ford and OU have done tremendous amount of experimental work on both model validation and process parameter studies.

  - This reviewer indicated that collaboration is good, but it is regrettable that Ford is putting a lid on the results. The reviewer observed that, after all, a good part of the funding is done through public funding.
  - This reviewer said it seems okay. The reviewer added that the speaker kept alluding to other aspects of the progress but then did not discuss them, which was a bit tiresome.

  Response: Most of the results Ford was holding back in FY13 are now published, and some are presented this year. Ford wants the results to be either patented or published before it is released to the public domain.

Presentation Summary

- Relevance
  - Aluminum trimmed edge stretch formability is highly dependent on the processes that prepare the edges. This project develops innovative edge trimming methods/conditions to improve room temperature edge stretechability by 50%.
- Approach
  - An integrated experimental-modeling approach is used where validated models are used to guide and shorten process development cycle.
- Technical Accomplishments
  - Validated stretchability model is developed with trimmed edge condition incorporated -PNNL
  - New characterization method is developed to quantify hardening parameters at large strain levels - OU
  - New method is developed to measure safe/fail strains similar to FLD in quantifying sheared edge stretchability – Ford
  - Different methods in improving edge stretchability by 50% identified
- Collaborations
  - OEM (Ford) and academia (OU)
- Future work
  - Complete hole expansion work
  - Prototype level demonstration