Failure prediction for complex load cases in sheet metal forming

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THE SWEDISH **Manufacturing R&D Clusters**

PREDICT – Failure prediction for complex load cases in sheet metal forming

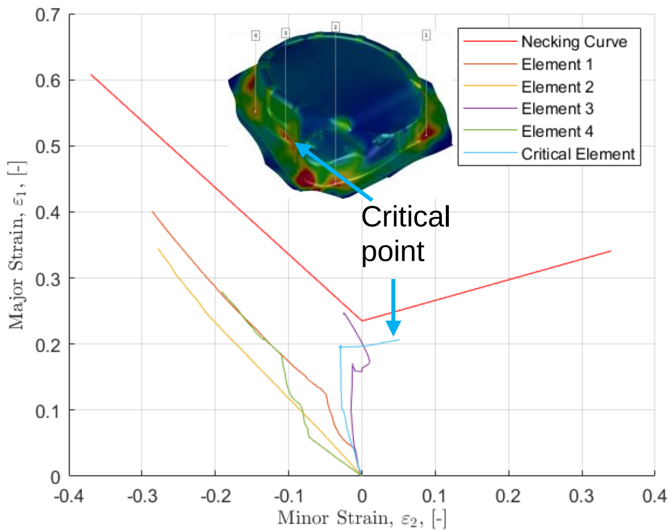
- Scope and objective:
  - Increased accuracy in FE model failure predictions by developing advanced material models and calibration techniques, i.e., FE simulation of phenomena like non-linear strain path and presence of edge cracks during sheet metal forming
  - Development of failure experiments and material characterization techniques as validation
  - Development of FE simulation-driven metamodels to predict formability based on supplier data to make process adjustment for better failure prevention as an important step towards industry 4.0 for the participating partners
- Partners:
- Financing: VINNOVA Hållbar produktion (FFI), diarienr. 2020-02986
- Project duration: from 2021-01-01 to 2023-12-31

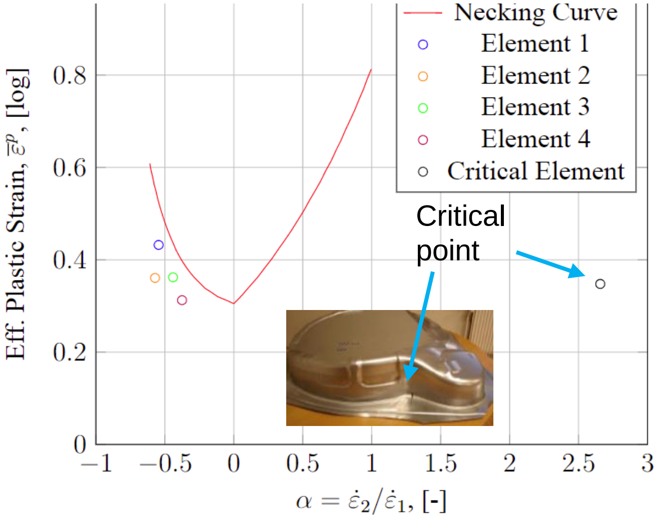
PREDICT

2020-02986

Non-linear strain path

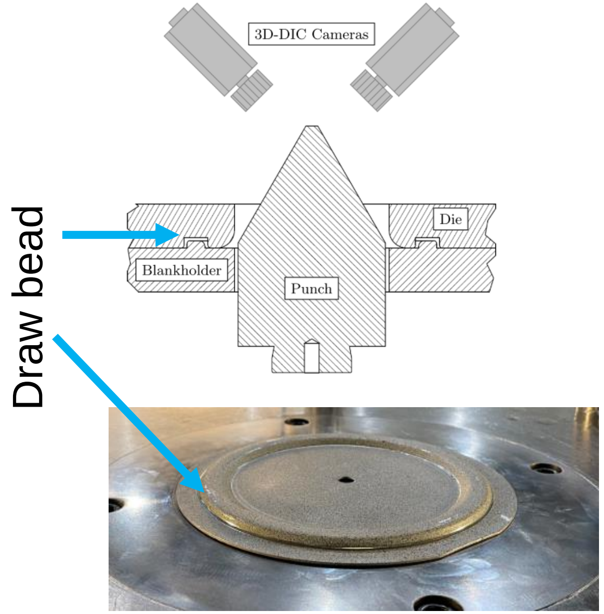
• Transformation of FLC

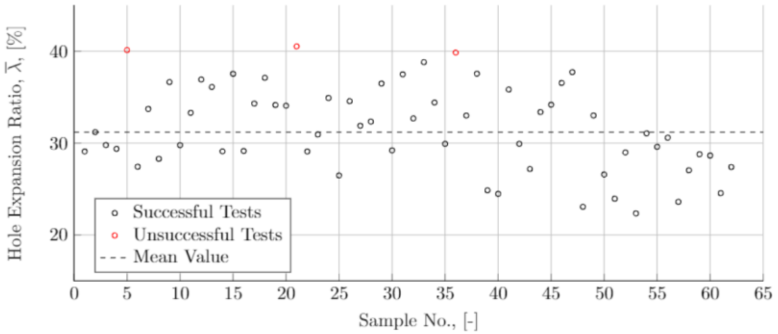




Edge formability

• Hole expansion ratio test • Updated BC • Use DIC

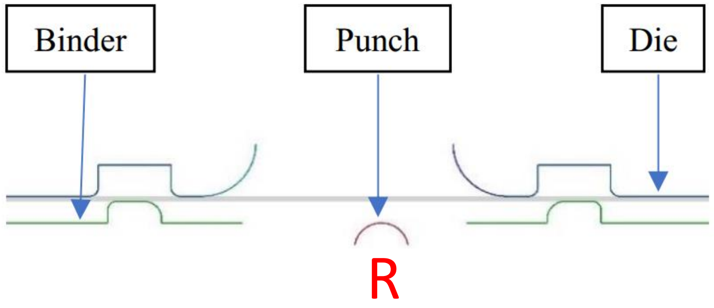


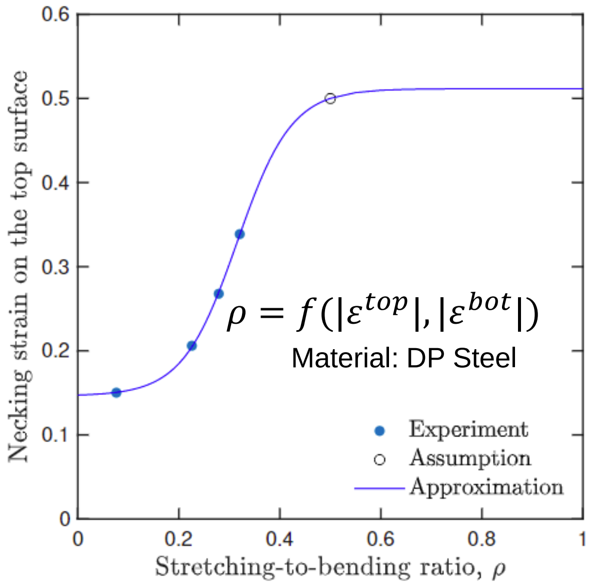


Stretch-bending

•Stretch-bending ratio ρ • Necking strain

Experiment on radius R3, R6, R10





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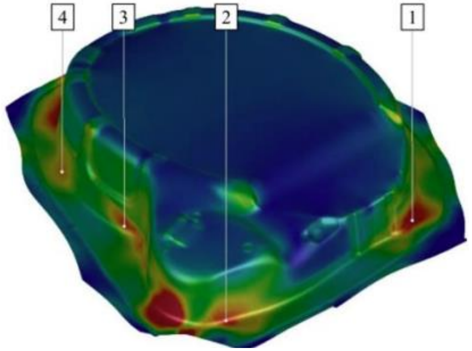
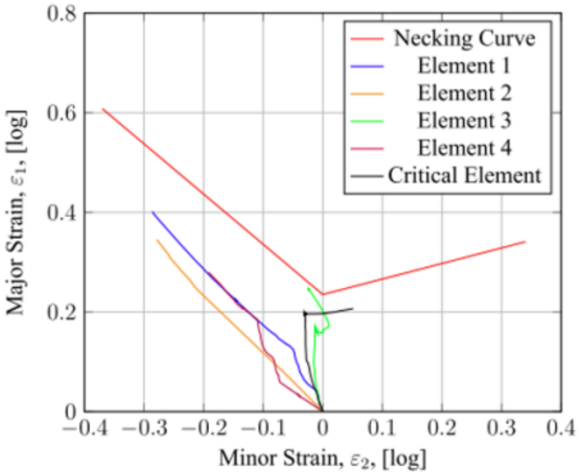
Non-linear strain path

- Challenges:
  - The forming limit diagram (FLD) is the automotive industry standard for predicting failure in sheet metal parts. It consists of a forming limit curve (FLC) which is determined by Nakajima or Marciniak tests. Note: the FLD requires proportional loading, i.e., linear and unbroken strain paths, to be applicable
  - In many forming processes, proportional loading conditions are unlikely to occur, with changing loading directions, such as two-step forming operations, or in parts exposed to combined tension

Volvo Cars component with failure after forming due to non-linear strain path



FE model with 4 arbitrary control elements in areas with high plastic strains

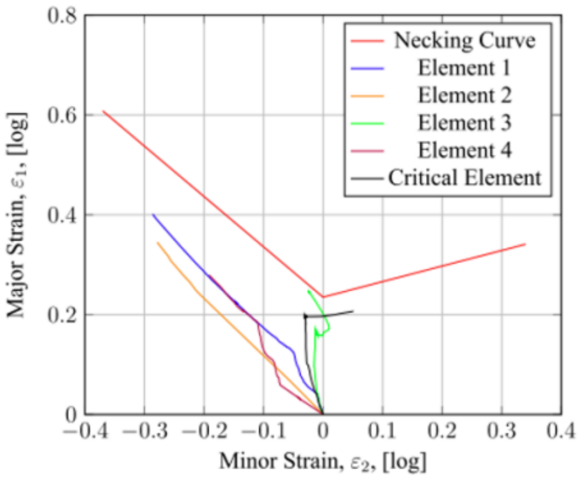


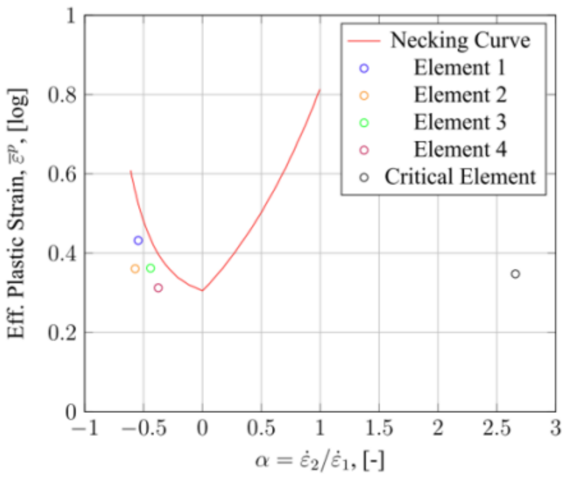
Strain paths of the 4 control and 1 critical elements

Non-linear strain path

- Plans and Results:
  - Transformation of the FLC from the strain to stress space:
    - The FLC was transformed to material flow direction α at the end of forming and the effective plastic strain plane
    - *α* is the ratio of minor and major principal strain rates at the last increment of deformations. Note: for an associated flow rule, *α* is related to the principal stress ratio and this is in called stress based FLC. For this transformation, BBC05 and Hill48 yield criteria were used. It was determined that the criterion for the transformation could not be decoupled from the material model used for the simulation
    - Clearly, FLC does not predict failure here as the final strain is under the red FLC. Failure is not predicted in the transformed evaluation plane either, since the most critical black dot in the plot is located away from the transformed FLC. It was concluded that this approach should be further investigated

The critical element was located where fracture occurred in the component, showing a clearly non-linear strain path with a 90° turn



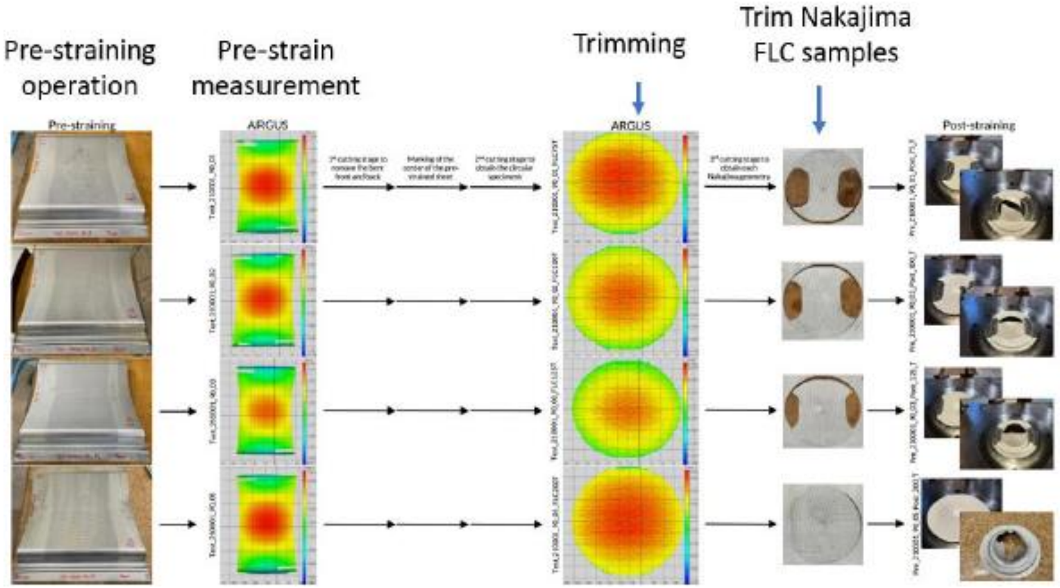


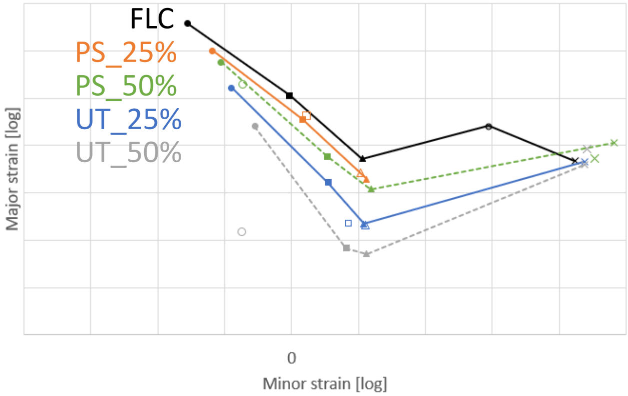
Strain at the end of the forming operation of the same elements in the transformed evaluation plane

Non-linear strain path

- Plans and Results:
  - The effect of non-linear strain paths on the formability of a mild steel:
    - A mild steel was experimentally tested in newly designed pre-straining tool. The material sheets could be pre-strained in uniaxial tension and plane strain at about 25% and 50% of forming limit
    - All pre-strained specimens were trimmed to four different Nakajima geometries, ranging from uniaxial to plane strain to and biaxial, and tested to evaluate post FLC. These two straining operations generated bi-linear strain paths in the specimens

Pre-straining tests at RISE Olofström





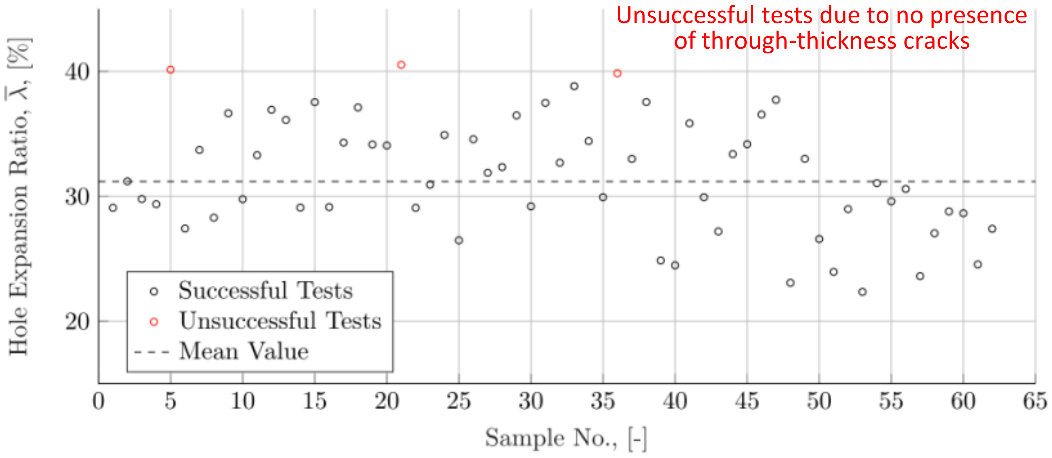
Effect of pre-straining in the FLC

Edge formability

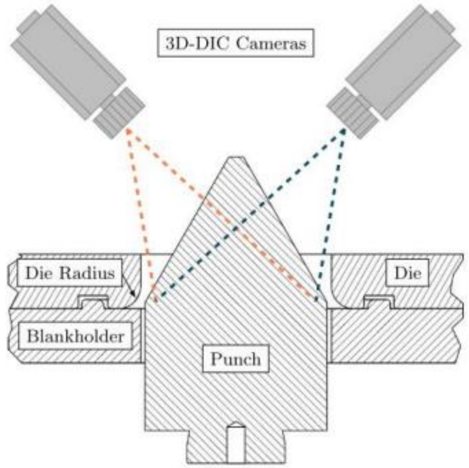
- Challenges:
  - The formability of sheet material is reduced due to unfavorable process conditions during trimming of the part in the stamping process. This effect is more pronounced for DP steels and Aluminum alloys
  - Edge formability is investigated using the ISO 16630 standardized hole expansion test (HET), which quantifies the hole expansion ratio (HER) for a given sheet metal. However, the HER values for specific sheet metal can exhibit considerable variation, posing challenges to its reliability
- Plans:
  - Perform HET on DP steel samples with special focus on the boundary conditions in the ISO standard which do not require the use of draw beads to lock the test specimen more firmly. The scatter in HER can be caused by a less-controlled blank holding method
  - The standard boundary conditions were modified, and the Nakajima test setup was used for HET that clams the specimen with draw beads

Edge formability

- Results:
  - The DIC system ARAMIS was used for full-field strain measurements
  - The proposed method minorly improves the HER scatter situation yet shows the potential of using a standard Nakajima test setup for HET
  - The findings indicated that the restraining force of boundary conditions acting on the sample during the test is not the primary cause of the observed scatter in HER results



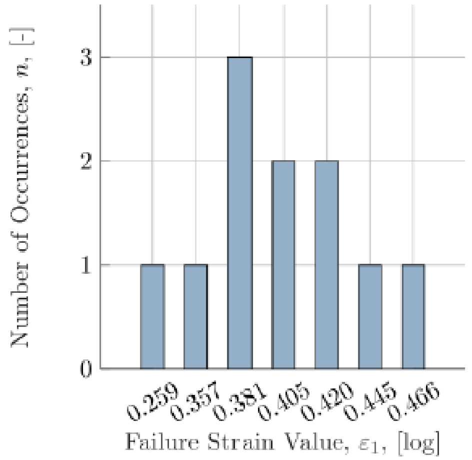
HET of the 62 tests conducted



New experimental setup with draw beads and DIC system

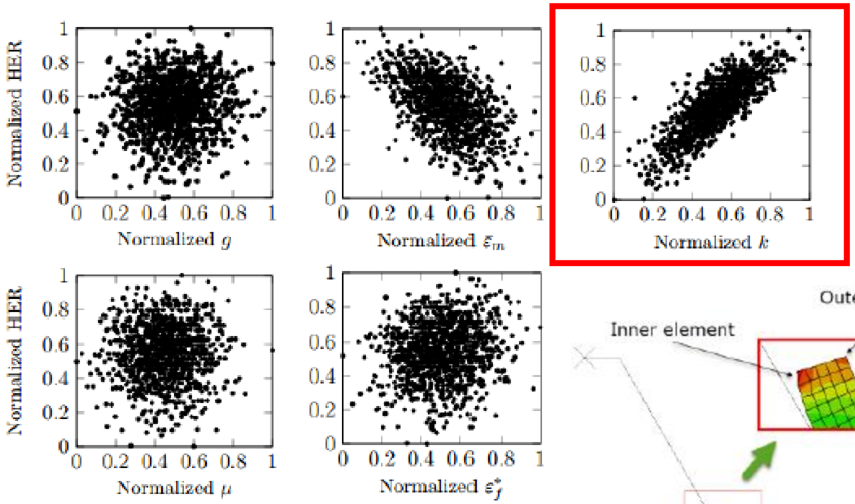
Edge formability

- Results:
  - A similar degree of scatter (or uncertainty) was also observed in the HET edge fracture obtained through inverse finite element modelling
  - To address this unwanted scatter, an uncertainty quantification study was conducted using an FE model where 5 key factors contributing to HER variability were identified

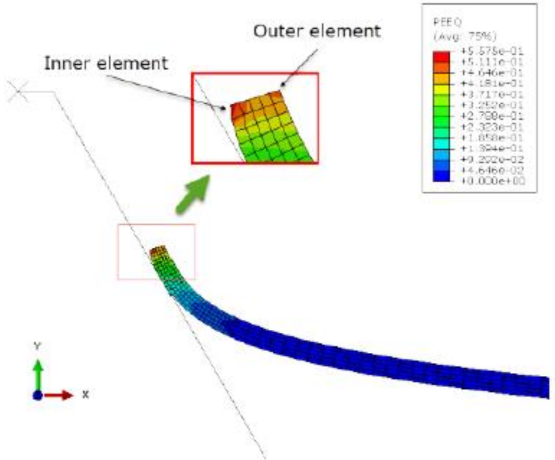


Failure strain for the surface layer in the FE model

Variable x_i	Physical mean
g (mm)	Hole-edge quality
$\bar{\varepsilon}_m$	Maximum pre-strain
k	Pre-strain scaling factor
μ	Friction coefficient
ε_f^*	Fracture strain

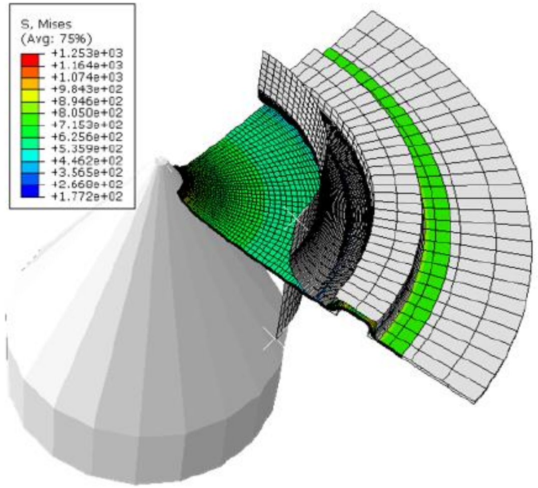


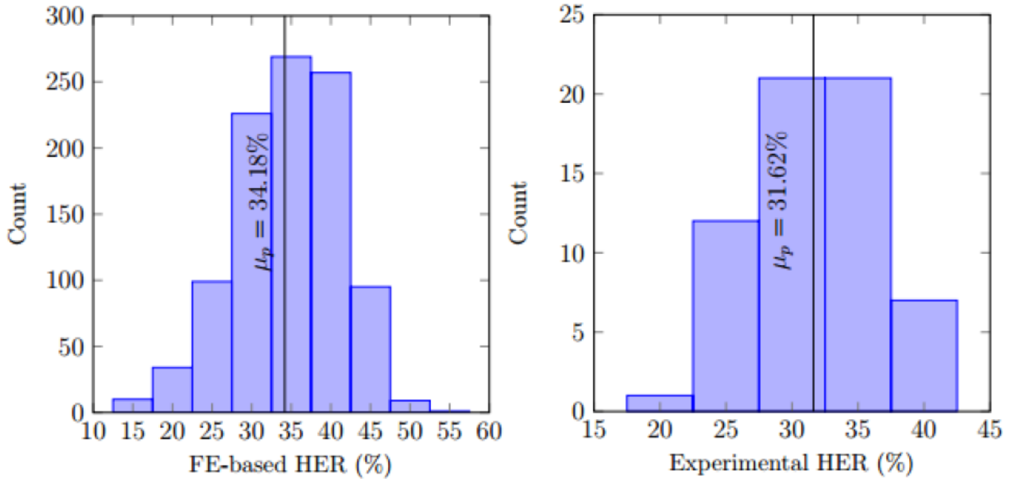
Correlations between the normalized HER and input variables in the FE simulations of HET



Edge formability

- Results:
  - *k* determines how fast the pre-strain from hole punching operation in HET decreases from the shear cutting edge to away from the edge
  - One way of determining pre-strain distribution around the hole is to perform hardness tests in a grid within a few millimeters from the hole edge





Histogram of the HER examined from the developed database

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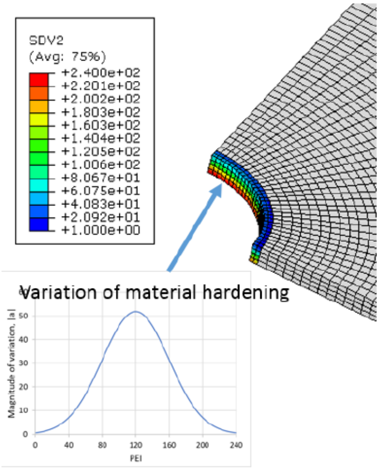
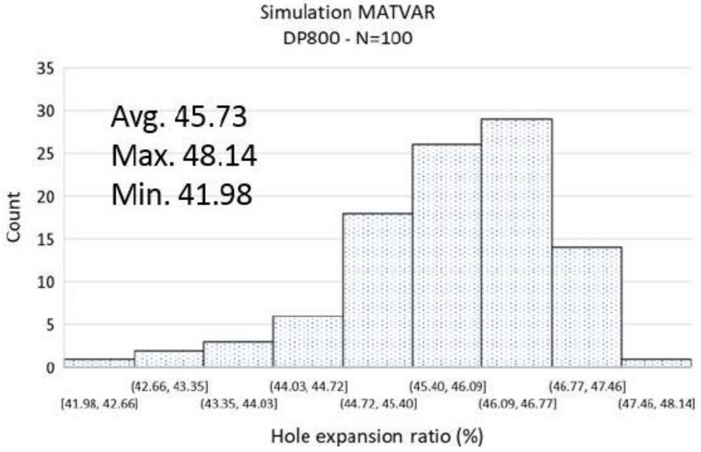
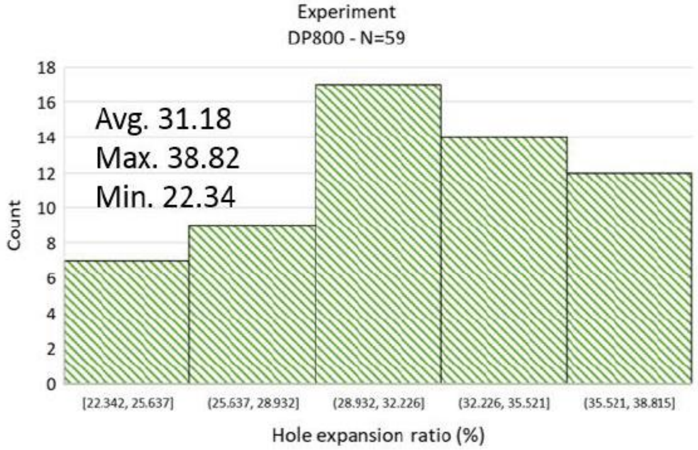
Edge formability

- Remaining challenges:
  - A separate pre-studies of stochastic material property distribution were made where the hardening curve was normally scaled and assigned to elements near the hole edge of HET 3D simulation model
  - The spread of simulated and experimental HER is shown. Although the modeling needs more maturity, nevertheless, this showed promising result of using such stochastic modeling for uncertainty quantification





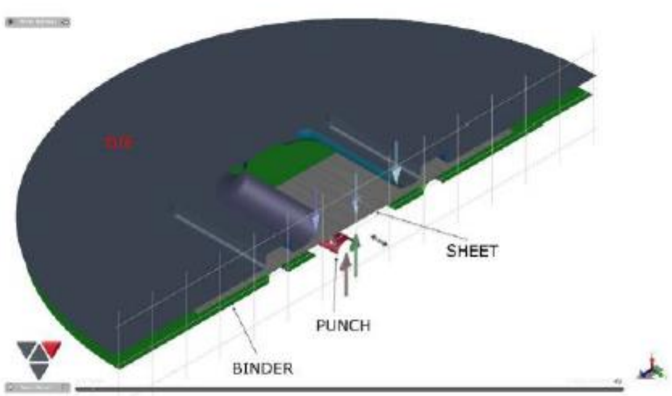


FE-simulated scatter of HER by material property variation near hole edge vs Experimental HER

Stretch-bending

- Challenges:
  - At combined stretch and bending load cases, sheet metal formability in aluminum alloy and DP steel were observed to increase at various levels in plane-strain conditions in previous studies* using a special tool setup

Detail of stretch-bending test setup



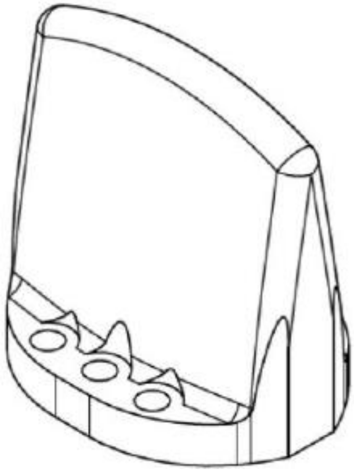
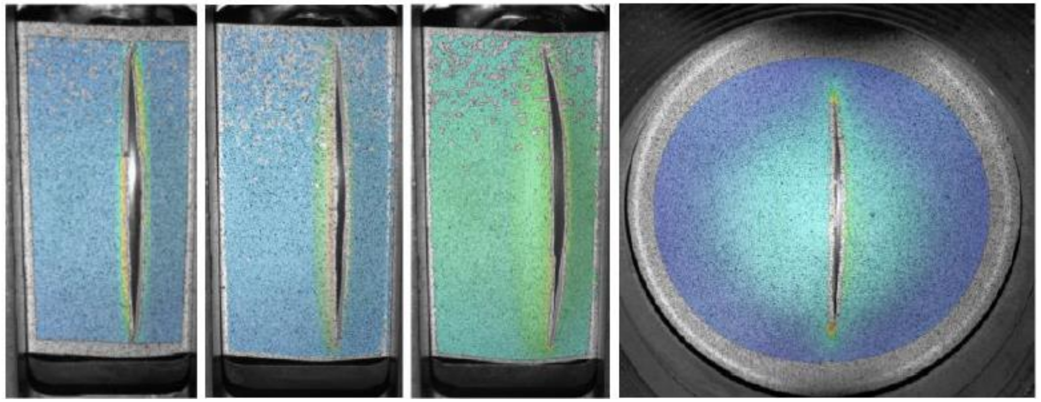


Illustration of the R6 punch

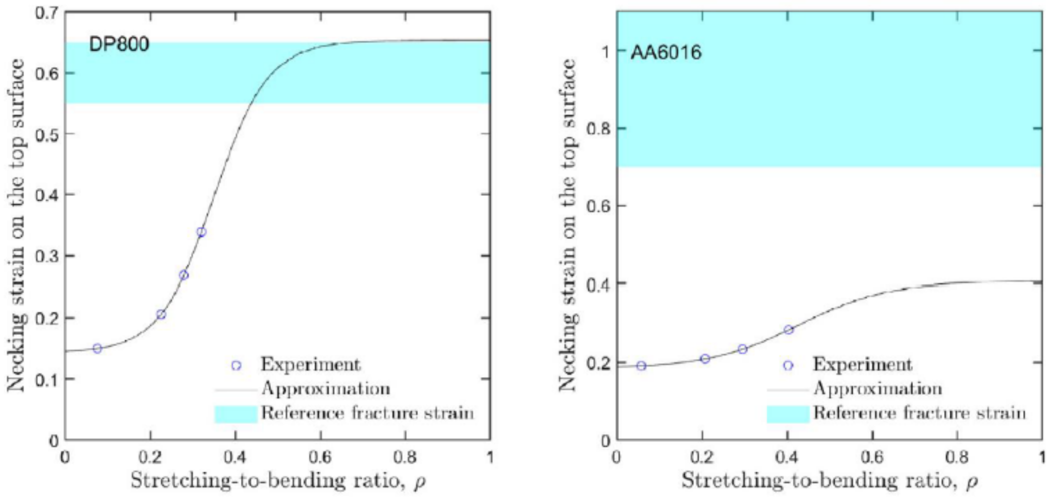
- Plans:
  - Develop a modeling approach to predict strain localization during sheet metal forming processes undergoing stretch-bending
  - Propose the use of the “stretch-to-bending ratio” to characterize the loading conditions experienced by an element in an FE model during stamping, using necking strain as function

Stretch-bending

- Results:
  - To explore forming limits under different proportion of combined stretch–bend loads, four stretch–bending test types with different punching tool radii of R3, R6, R10, and R50 were performed on two automotive sheet metals: DP800 and AA6016. Full strain field at failure from DIC is used to find the failure strain at each stretching-to-bending ratio
  - Based on these tests and a Boltzmann function, the necking limit curve of the tested materials is identified



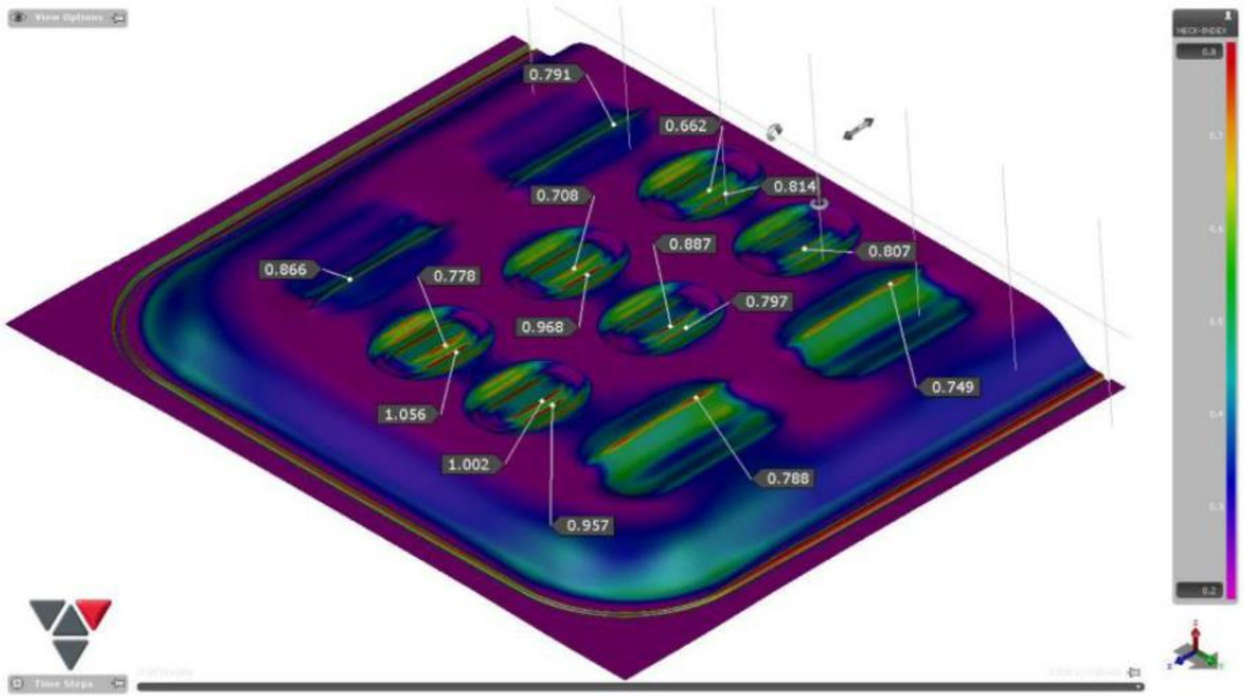
R3 R6 R10 R50 (Nakajima test)



Forming limit of the tested materials
under combined stretch-bending loads

Stretch-bending

- Results:
  - The calibrated necking limit curve of the AA6016 sheet is then employed in AutoForm R10 software to successfully predict the necking and failure of a stamped panel



A necking index was defined that updates the failure strain based on stretching-to-bending ratio and indicates how close the element under evaluation is to necking. The necking index is calculated using the maximum principal strains of the upper and lower layers of the element of interest. Here, an index equaling to or more than 1 means the necking limit has been reached

Detailed view of the simulated panel with the necking index distribution

Public report and list of publications

Link: https://www.productdevelopment.se/predict-2021/

PREDICT | 2020-2024

Post by: Tobias Larsson 28th October 2020 4 Comments

Concluding remarks and results

Public report here

PREDICT has generated results and tools that are used to increase reliability of failure prediction of sheet metal forming simulation in finite element models (FE-model). The work in this project was focused to

- **C6**: Barlo, A., Sigvant, M., Islam, M. S., Pérez, L., Olofsson, E., Al-Fadhli, M., ... & Odenberger, E. L. (2023, June). Proposal of a New Tool for Pre-Straining Operations of Sheet Metals and an Initial Investigation of CR4 Mild Steel Formability. In IOP Conference Series: Materials Science and Engineering (Vol. 1284, No. 1, p. 012079). IOP Publishing.
- **J1**: Pham, Q. T., Islam, M. S., Sigvant, M., Caro, L. P., Lee, M. G., & Kim, Y. S. (2023). Improvement of modified maximum force criterion for forming limit diagram prediction of sheet metal. International Journal of Solids and Structures, 273, 112264.
- **J2**: Pham, Q. T., Islam, M. S., Barlo, A., Sigvant, M., Caro, L. P., & Trana, K. (2023). Modeling the strain localization of shell elements subjected to combined stretch–bend loads: Application on automotive sheet metal stamping simulations. Thin-walled structures, 188, 110804.
- **J3**: *Uncertainty quantification for conical hole expansion test of DP800 sheet metal (Submitted for Journal publication)*
- **L1**: Barlo, A. (2023). Failure Prediction of Complex Load Cases in Sheet Metal Forming: Emphasis on Non-Linear Strain Paths, Stretch-Bending and Edge Effects (Licenciate dissertation, Blekinge Tekniska Högskola).
- **T1**: Eriksson, A. (2021). Non-Linear strain paths in Sheet Metal Forming.
- **T2**: Aisvaran, C. (2021). Study of non-linear strain path in sheet metal forming.