Thermo-mechanical Material Characterization and Forming of AA6016

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Outline

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  - Elastic and inelastic properties, anisotropy and formability
- Material model calibrations
- The stretch bending test
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Introduction

- Global environmental challenges has made lightweight design increasingly in focus for the manufacturing industry
- One example is stamped products made of aluminum alloys. To enable manufacture of complex geometries there is a need to develop hot forming techniques
- Virtual tools are crucial to the success in developing advanced products and manufacturing procedures
- Predicting the final geometry of a component is a complex task, especially if the forming procedure occurs at elevated temperatures


Pictures by AP&T

Scope of study

- Research project - ***Advanced Light Weight Design by Hot Formed Aluminium.*** Funded by Vinnova, LIGHTer.
  - Develop test methods to determine the thermo-mechanical properties of aluminum
  - Screen temperature dependent formability of different aluminum alloys
  - Generate experimental data to calibrate material models and perform FE-analyses of hot forming in aluminum
  - Compare predicted results with experimental observations in a forming case
  - Study tribological aspects related to hot forming in aluminum
  - Industry forming examples

Methods for determining thermo-mechanical properties of AA6016

- Elastic properties as function of temperature
- The RFDA system, non-destructive testing method based on analysis of the vibration and natural frequency of the specimen
- Conductive heating of the specimen to desired test temperature

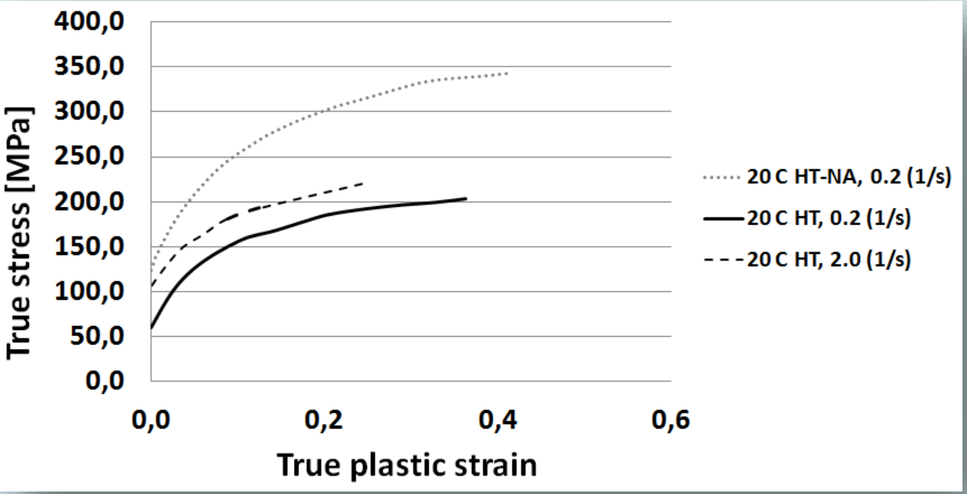
[**E-L. Odenberger, Ll. Pérez Caro, H. Åhlin, M. Oldenburg (2018) Thermo-mechanical Material Characterization and Forming of AA6016, IDDRG 2018, 3-7 June, Waterloo, Canada**]

Methods for determining thermo-mechanical properties of AA6016

Plastic properties, anisotropy and formability, strain rate and temperature dependence

- Inductive heating method
- Temperature resistant and ductile speckle pattern substances for DIC
- Focus on temperature distribution in the evaluation region of the test specimen. Induction coil and specimen geometry interaction
- Yield stress, hardening, Lankford coefficients (R-values), Ag, n

Methods for determining thermo-mechanical properties of AA6016



Time-temperature history prior to testing of AA6016. A soaking time of 90 seconds at 540 °C is applied before cooling to the specific test temperature. The tensile tests start when the temperature has reached the designated temperatures.

Methods for determining thermo-mechanical properties of AA6016

Experimental references used to calibrate material models, 0.2 s^{-1}, E in [GPa] and σ in [MPa].
*Strain rate of 2 s^{-1}.

Temperature [°C]	E	σ_{00}	σ_{45}	σ_{90}	σ_b	R_{00}	R_{45}	R_{90}	R_b	σ_{00^*}
21	67.50	60.09	54.40	49.40	62.73	0.668	0.397	0.535	1.0	107.5
100	63.91	59.41	49.29	53.68	-	0.656	0.416	0.518	-	96.2
350	51.44	50.55	46.20	52.40	-	0.700	0.546	0.638	-	65.4
420	47.79	37.16	-	-	-	0.670	-	-	-	-
490	44.15	24.77	25.90	25.00	-	0.698	0.601	0.676	-	25.4

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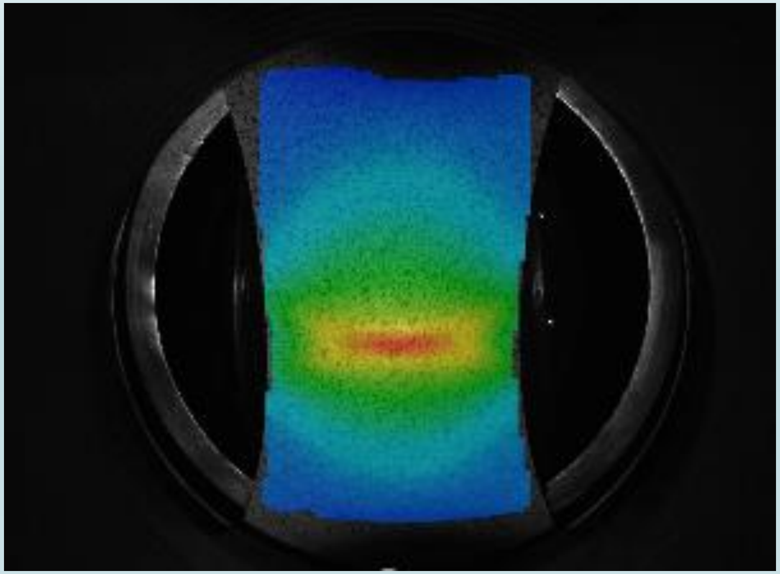
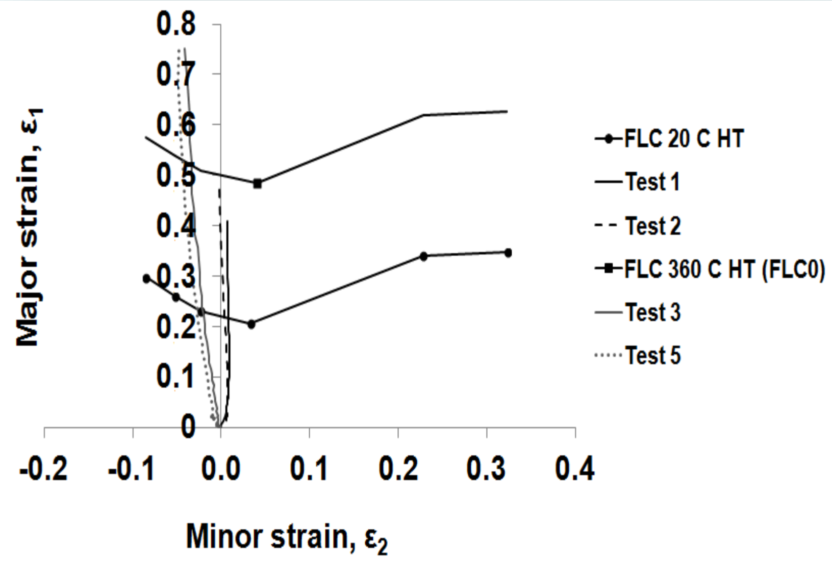
Methods for determining thermo-mechanical properties of AA6016

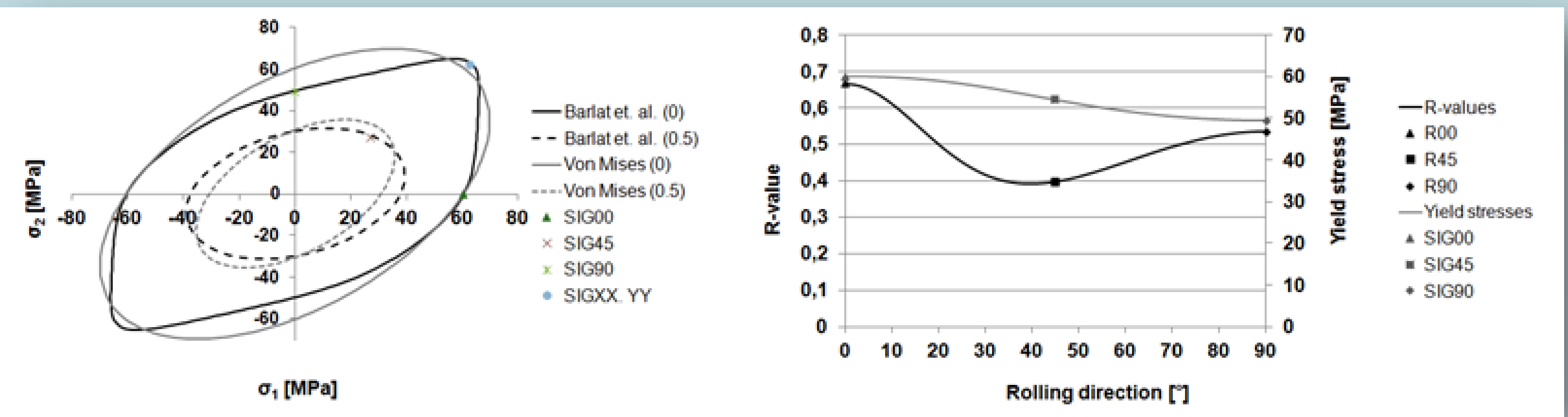




FLC tests

Material model calibrations

- An isotropic yield criterion is compared with an anisotropic model, available in LS-DYNA
  - *MAT_ELASTIC_VISCOPLASTIC_THERMAL
  - *MAT_BARLAT_YLD2000

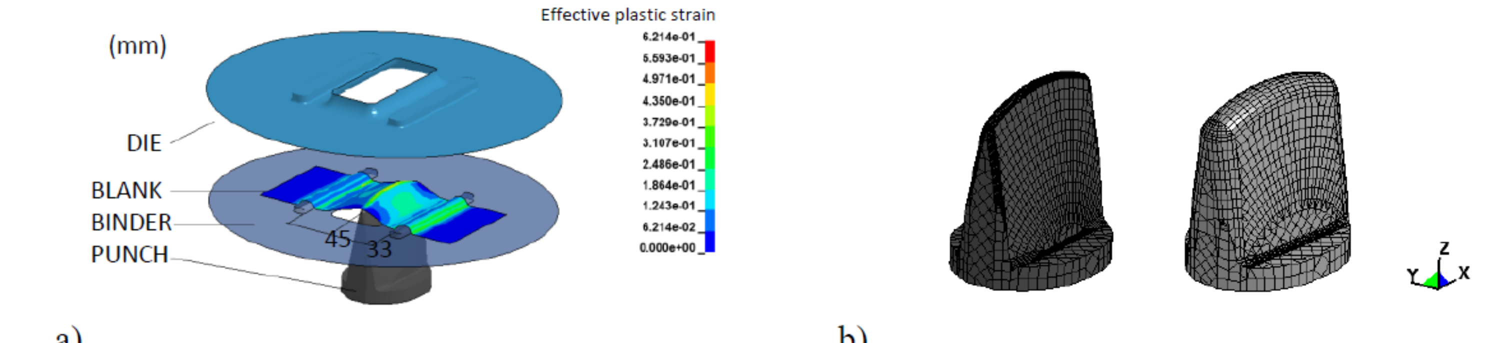


The stretch bending test

- The test are used to compare model predictions with experimental observations. Forming both in RT and at elevated temperatures
  - Double curved punch with different radii, 3 and 10 mm
  - Measure and compare punch force, strain, thinning, spring back, localization and failure
  - HT blanks at 540 C are formed with cold tool parts
  - Temperature measurements using IR with calibrated emissivity

The stretch bending test

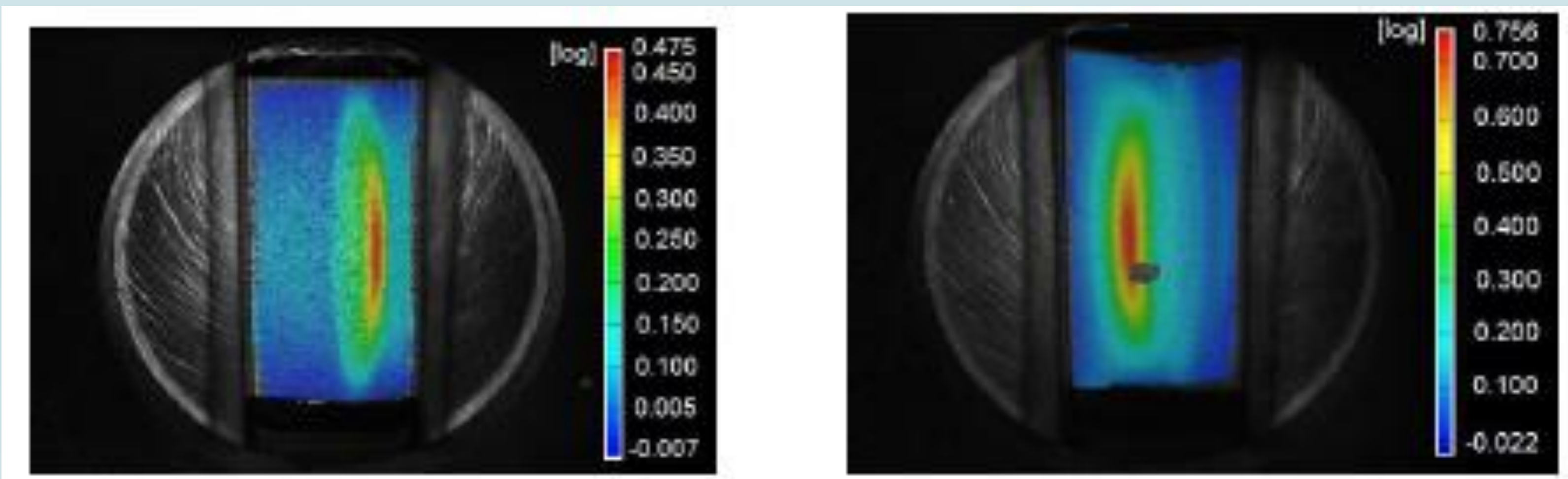
- The FE-setup, room-temperature case
  - Double curved punch with different radii, 3 and 10 mm
  - Punch are mounted with an off-set from centre by 6 mm
  - Punch velocity is 25 mm/s



a) FE-setup for the stretch-bending test in room temperature and b) punch geometries with a radius of 3 or 10 mm, respectively.

The stretch bending test

- Room temperature vs. thermo-mechanical case. Start temperature of 403˚C
- DIC animations of major true strain using the punch radius of 3 mm



The stretch bending test

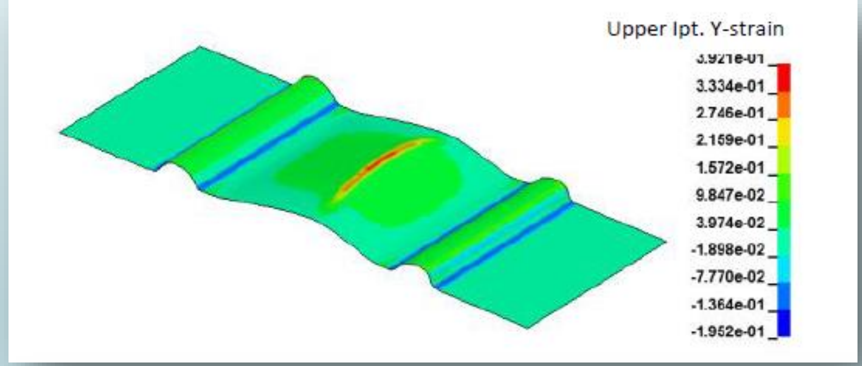
Room temperature case, punch radius 3 mm

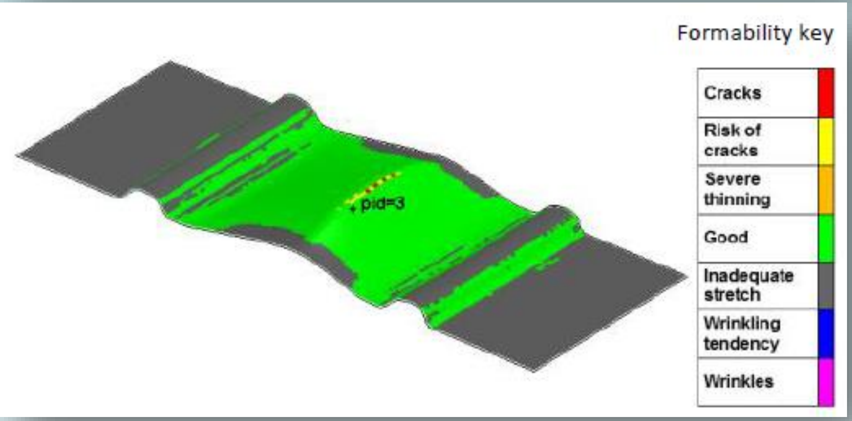
Measured draw-depth at failure: 14.25 mm

Predicted assuming isotropy: 11.79 mm

Predicted using anisotropy: 14.23 mm

Prediction of localization and failure is conservative using an isotropic assumption





The stretch bending test

Room temperature case

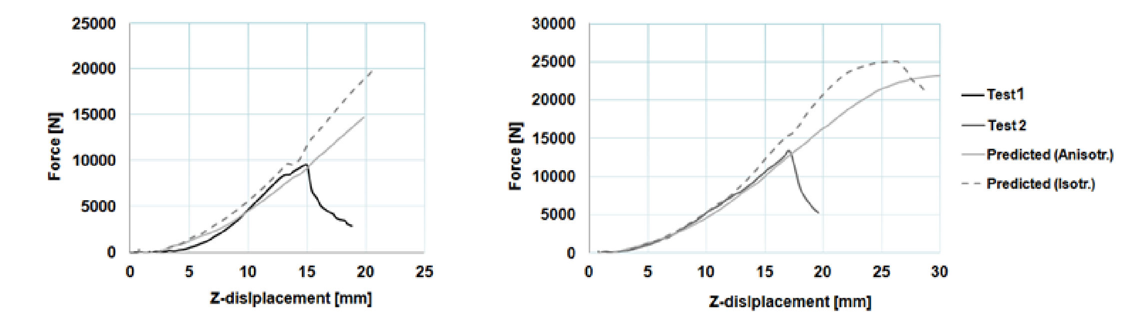
punch force and spring back

punch radius 3 mm

Predicted punch force

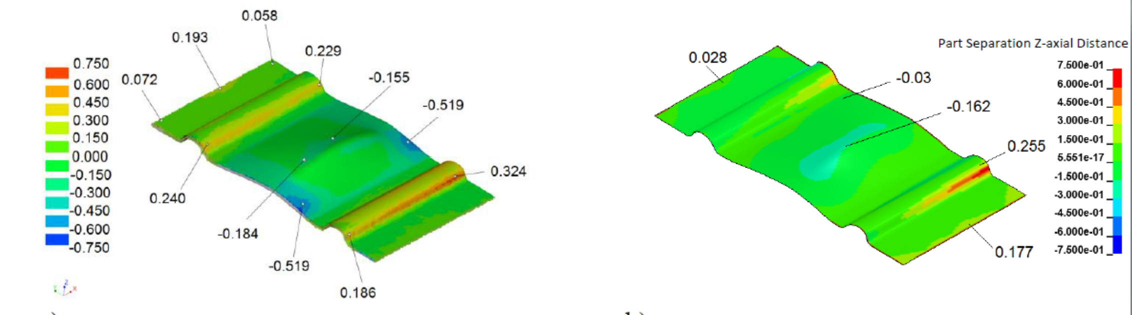
is overestimated using

an isotropic assumption



a) b)

Measured and predicted (FEA) punch forces for forming at room temperature (RT) with different punch radii. a) 3 mm, Test 1. b) 10 mm, Test 2.

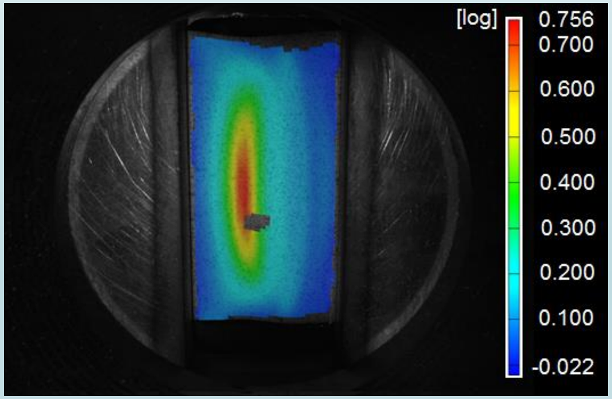


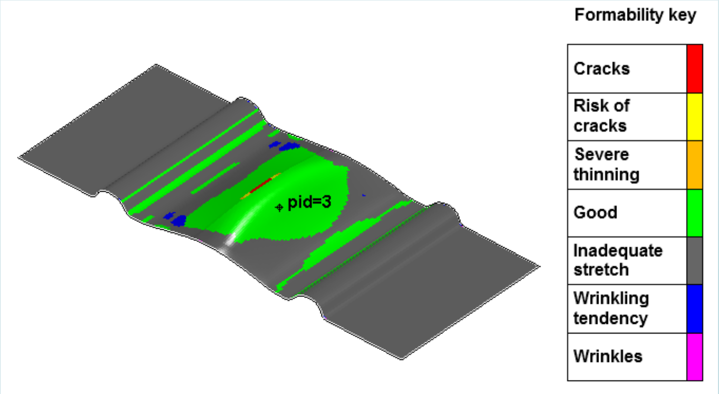
a) b)

a) Measured shape deviation using a punch radius of 3 mm, forming at 20 °C, draw depth 11.3 mm and b) predicted shape deviation using the anisotropic yield criterion.

The stretch bending test

Thermo-mechanical case, punch radius 10 mm. HT at 540˚C, forming starts at 405˚C





Measured draw-depth at failure: 16.77 mm

Predicted assuming isotropy *MAT_106: 13.02 mm

Prediction of localization and failure is conservative using an isotropic assumption

The stretch bending test

Thermo-mechanical case, punch radius 10 mm. HT at 540˚C, forming starts at approximately 400˚C

- Study of temperature distribution just prior to start of thermo-mechanical forming using IR-camera with calibrated emissivity
- The initial blank temperature were found of importance to predict the stretch-bending procedure accurately

The stretch bending test

Thermo-mechanical case, punch radius 10 mm. HT at 540˚C, forming starts at approximately 400˚C

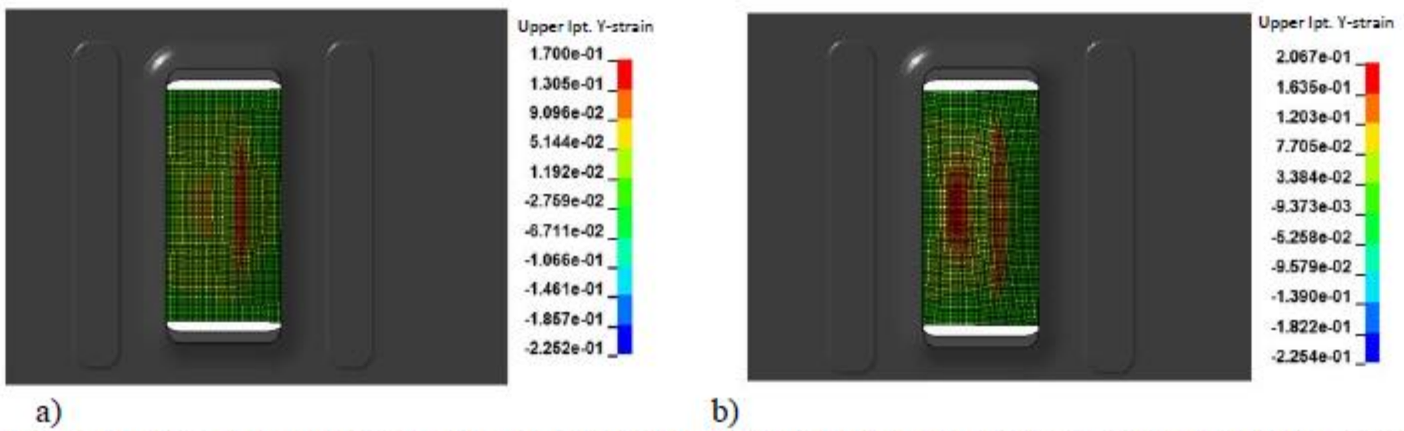


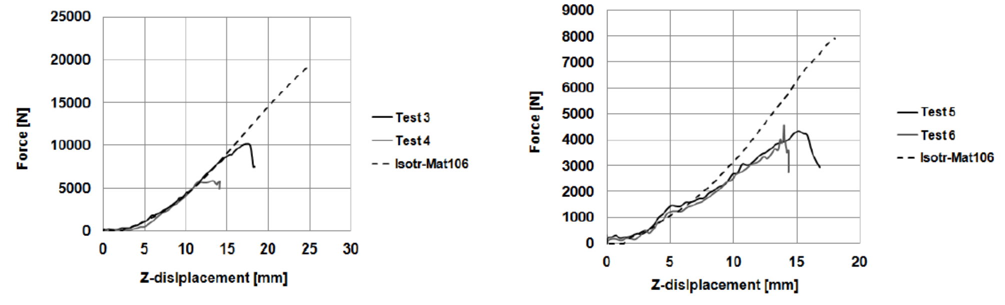
Figure 11. The characteristic double pole strain localization for thermo-mechanical forming with a punch radius of 10 mm, Test 5. Predicted upper integration point y-strain at z-displacements 8.20 and 11.81 mm.

The initial blank temperature were found of importance to predict the stretch-bending procedure accurately

The stretch bending test

Thermo-mechanical case, punch force and spring back, punch radius 10 mm

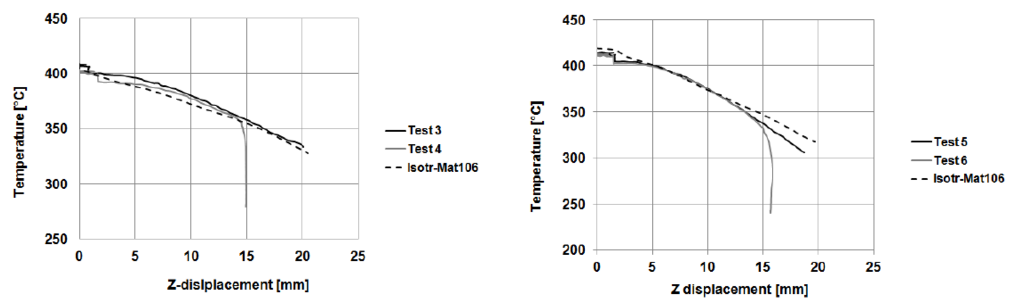
Predicted punch force is slightly overestimated using the isotropic assumption



a) b)

Measured and predicted (FEA) punch forces for thermo-mechanical forming with different punch radius. Punch radius of a) 3 mm for test 3 and 4, b) 10 mm for test 5 and 6.

Measured and predicted temperature history at the punch radius center position of the blank

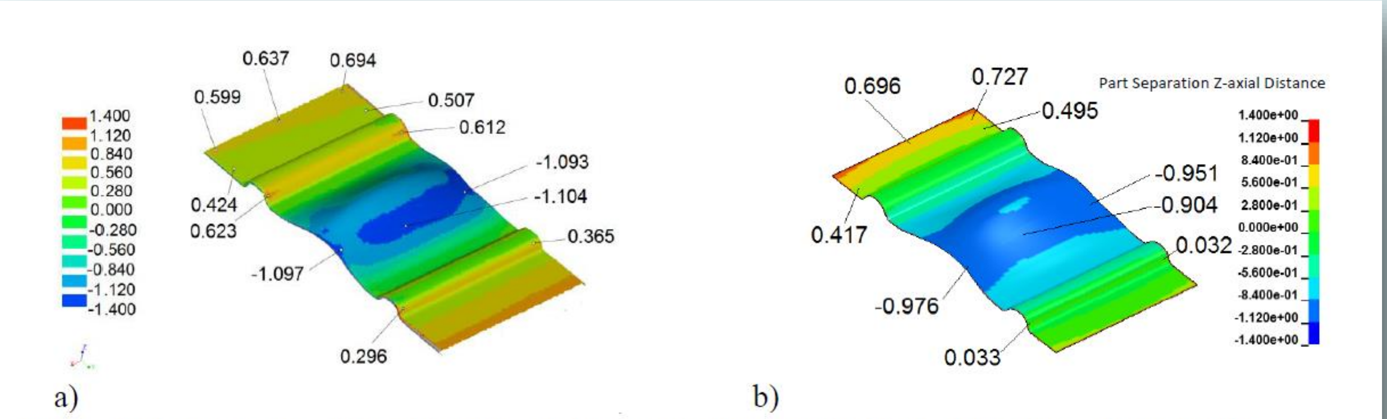


a) b)

Measured and predicted (FEA) temperature-histories during thermo-mechanical forming with different punch radii a) 3 mm for test 3 and 4 and b) 10 mm for test 5 and 6.

The stretch bending test

Thermo-mechanical case, punch radius 10 mm. HT at 540˚C, forming starts at approximately 400˚C



Shape deviation using a punch radius of 10 mm in thermo-mechanical forming, draw depth 15.52 mm (Test 6). a) Measured and b) predicted shape deviation using the isotropic material *MAT106.

Measured and predicted shape distortion using a CAD-best fit evaluation determined in a least square sense

Conclusions and future work

- The thermo-mechanical anisotropic behavior and strain rate sensitivity of the alloy was determined
- The stretch-bending tests illustrate the importance of considering anisotropy.
  - Punch force was over-predicted using an isotropic assumption
  - Formability was under-estimated using the isotropic assumption
  - Using an anisotropic model, the punch force, spring back, localization and failure (using FLC) could be predicted accurately
- Possible extensions to the study
  - Include shear tests in the material model calibration
  - Applying an anisotropic yield criterion to the thermo-mechanical stretch-bending case

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