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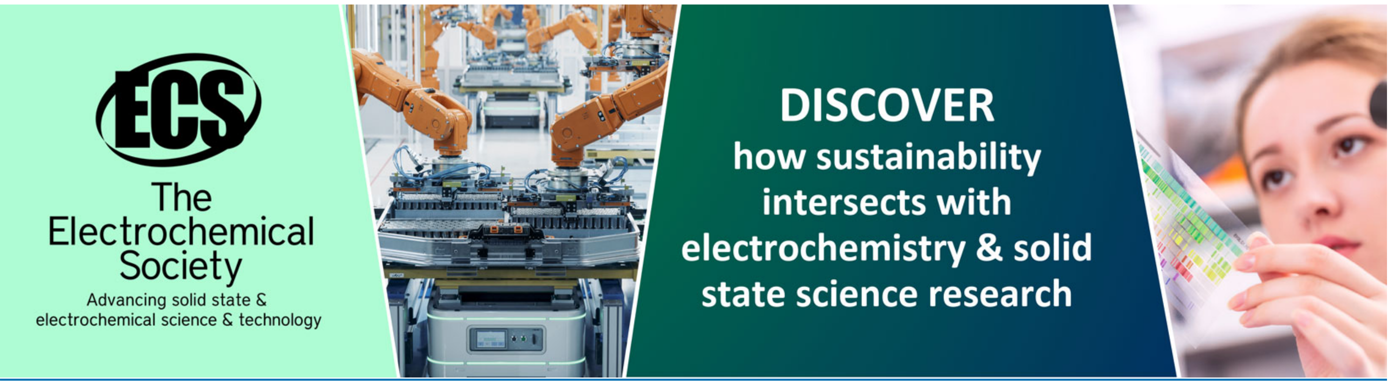

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Thermo-mechanical Material Characterization and Stretch-bend Forming of AA6016

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Abstract. Lightweight design has become increasingly in focus for the manufacturing industry. Global environmental challenges, goals and legislations imply that lighter and sustainable products are imperative to remain competitive. One example is stamped products made of aluminum alloys which are of interest to the automotive industry, where lightweight designs are essential. In order to increase formability and to produce more complex geometries in stamped aluminum components there is a need to develop hot forming techniques. The Finite Element Method (FEM) has enabled important advances in the study and design of competitive manufacturing procedures for metal parts. Predicting the final geometry of a component is a complex task, especially if the forming procedure occurs at elevated temperatures. This work presents selected results from thermo-mechanical material testing procedures, FE-analyses and forming validation tests in AA6016 material. The material tests are used to determine the thermo-mechanical anisotropic properties, strain rate sensitivity and formability (Forming Limit Curves, FLC) at temperatures up to 490˚C. Stretch-bending tests are performed to compare predicted results with experimental observations such as punch force, strain levels, thinning, forming temperatures, springback and failure. It was found that the heat-treatment and forming at elevated temperatures substantially increased formability and that measured responses could in general be predicted if care was taken to model the initial blank temperatures, heat transfer and thermo-mechanical material properties. The room temperature case confirms the importance of considering anisotropy.

1. Introduction

The aluminum 6016 alloy is widely used for outer body automotive parts stamped at room temperature. This alloy in T4 condition presents an optimal corrosion resistance, good mechanical properties and formability. The alloying process of AA6016 and its chemical composition can be optimized for demanding parts in terms of formability at room temperature. However, in order to further increase the strain at fracture of the alloy and thus increase its formability, the blank can be heated above solutionizing temperature. As observed by Kumar [1], when the blanks are heated at 560 °C for minimum 4 min, the ultimate tensile strength (UTS) values after paint-bake reach a plateau, indicating that full solutionizing is reached. The material in this work is heat-treated at 540 °C for 90 seconds before cooling to desired test temperature assuming that a full solutionizing is not reached but close.

This study intended to develop methods for determining the thermo-mechanical material properties up to 490 °C of AA6016 and compare FE-predicted and measured responses in stretch-bending tests. All tests are evaluated using Digital Image Correlation (DIC) and the temperature distribution is continuously measured and evaluated. FE-analyses of the stretch-bending tests using the isotropic von Mises yield criterion were compared with an anisotropic yield criterion [2]. It was found of importance to consider anisotropy but foremost to accurately model the initial temperature distribution and heat transfer during forming and cooling. The purpose has been to determine mechanical properties, investigate model applicability, identify challenges and study the amount of increased formability and obtained springback using heat-treated blanks for future studies in forming industrial lightweight parts.

2. Material

The sheet material studied in this work is the aluminum alloy AA6016 with a sheet thickness of 1.51 mm delivered by Novelis. The material is heat-treated (HT) at 540 °C for 90 seconds before cooling to desired test temperatures. Also naturally aging (NA) in room temperature for six days, after HT, was allowed prior to deformation in some tests. The chemical composition is presented in Table 1.

Table 1. Chemical composition of the specific batch of AA6016 [%].

Si	Mg	Fe	Mn	Cu	Cr	Ti	Zn	Other	Other
1.0-1.5	0.25-	≤0.50	≤0.20	≤0.20	≤0.10	≤0.15	≤0.20	≤0.05	≤0.15

3. Experimental procedure

This section briefly describes the experimental procedures used in this study. It comprises material tests to characterize the thermo-mechanical material properties and determine experimental reference data for calibration of material models such as initial yield stress, hardening and anisotropy parameters. Also, this section comprises forming tests performed at room temperature and at elevated temperatures with previously heat-treated blanks to compare predicted results with experimental responses.

3.1 Material characterization

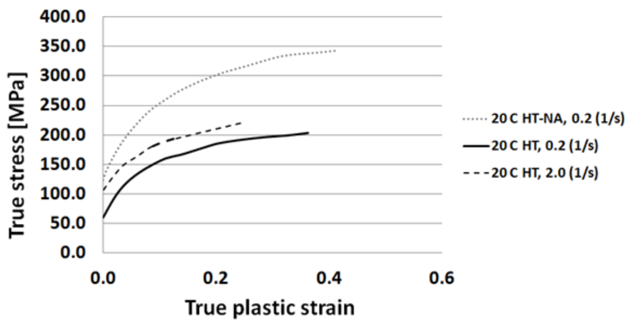
Non-destructive tests to determine the elastic properties, Young´s modulus (E), at elevated temperatures were performed using the RFDA system and impulse excitation technique, based on the analysis of the vibration of a test sample after being excited, cf. Table 2. A detailed explanation of the test method can be found in [3].

Table 2. Experimental references used to calibrate material models, strain rate of 0.2 s^{-1}, E in [GPa] and σ in [MPa]. R-values are determined in the true plastic strain range 0.0-0.07. *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

Uniaxial tensile tests were performed at temperatures up to 490 °C applying the heat-treatment prior to cooling to the desired test temperatures using specimens extracted in three different in-plane directions referenced to the rolling direction: along (00), transverse (90) and diagonal (45). The heat-treatment consists of heating the specimens up to 540 °C and applying a subsequent holding time of 90 s before forced air cooling to desired test temperatures. Tests were performed at a strain rate of 0.2 s^{-1} and 2.0 s^{-1}.

Inductive heating was applied using a coil designed to generate an evenly distributed temperature field in the evaluated region of the specimen (±5 °C), chosen such that it includes the necking area. Specimen deformation was observed and calculated using DIC with the ARAMIS™ optical strain measuring system. An appropriate stochastic pattern was applied on the specimen surfaces, capable of resisting high temperatures and large deformations. The temperature was continuously measured and logged at the centre surface of the specimens using an IR-sensor for which the emissivity was calibrated against each temperature using a thermo-couple (type K). Results from tests in room temperature and along rolling direction (00) are presented in Figure 1 with anisotropy parameters in Table 2. Initial yield stress denoted (σ) and Lankford coefficients (R). The HT-NA test shows that the properties change towards as-received.



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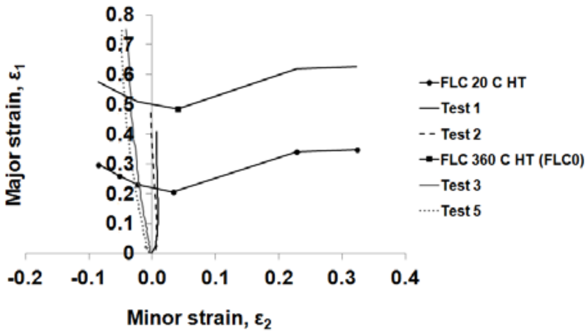


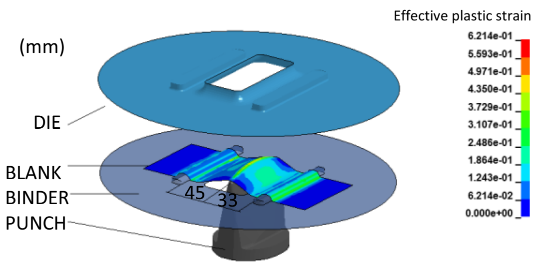
b)

Figure 1. a) Uniaxial tensile true stress vs. true plastic strain curves at 20 °C with different strain rates in the (00)-direction and b) FLCs with strain paths of the stretch-bending tests 1, 2, 3 and 5.

Silicon rubber bulge tests at room temperature were performed to generate data with a balanced biaxial stress state. The biaxial reference point ($\varepsilon^{p}_{thickness}$= 0.203, σ = 193.57 MPa) from the bulge tests was used to determine the initial biaxial yield stress. Also, Nakazima tests were performed according to ISO DIS 12004 -2 in order to study formability at different strain states and temperatures cf. Figure 1b. The FLC 360 °C has been scaled based on the experimental point (FLC0) at 360 °C from the 20 °C curve. The tests were performed with a punch speed of 25 mm/s corresponding to the lower strain rate obtained in the uniaxial tensile tests.

3.2 Forming tests

A stretch-bending test developed by Volvo Cars (Sigvant M. et al.) using, in this case two of several different punch geometries were applied to form blanks of AA6016 with different start temperatures cf. Figure 2. The blanks with a dimension of 90x200 mm were heated in an oven to 540 °C (180 s) followed by a holding time of 90 s prior to air cooling to the desired start temperatures of forming.



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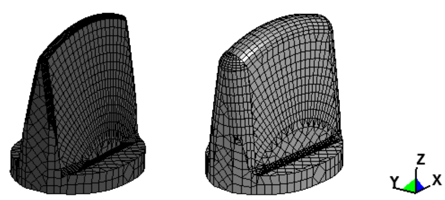


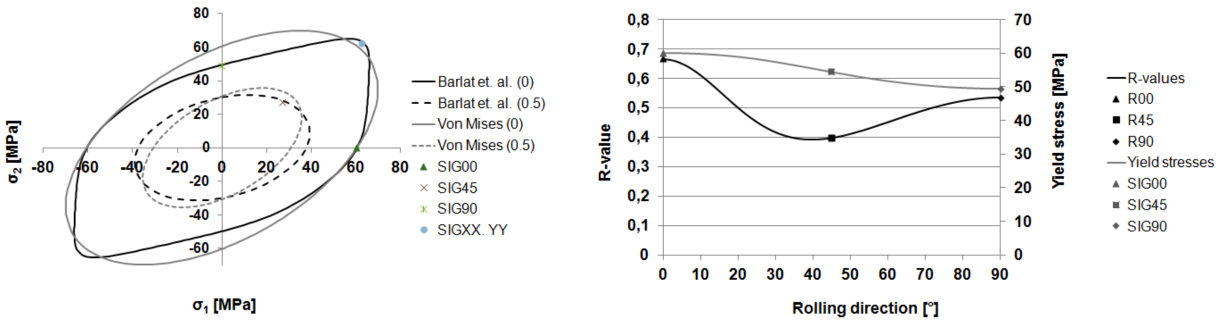
b)

Figure 2. 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 blank temperatures just before start of forming were higher in one of the short edges compared to the other ranging from e.g. 408.2 °C to 397.2 °C over the punch centre and down to 306.5 °C at the other end due to handling of the blanks from the oven to the forming tool. Double-curved punch geometries with radius 3 or 10 mm were used. All tool parts were room tempered prior to forming. Tests were performed until failure or deformed to a specific draw depth (z-displacement) in order to study springback. During forming the punch forces and blank temperatures, corresponding to the position of the punch centre using an IR pyrometer, were measured. All tests were evaluated using DIC to determine draw depth, thinning and strain at failure. IR camera pictures with calibrated emissivity were used as a complement. Shape deviation was evaluated using 3D-scanning and best fit CAD-evaluations.

4. Numerical procedure

The FE-model consists in total of 32423 elements. The blank was modeled using quadratic fully integrated thermal shell elements with an element length of 1mm and seven integration points through the thickness. The contact in the thermo-mechanical simulations were modeled using the *CONTACT_ONE_WAY_SURFACE_TO_SURFACE_THERMAL in LS-DYNA. HTC was set to 3500 W/m^{2}K. All tool parts were modeled as rigid with the coulomb friction law assuming a friction coefficient of 0.25 [4] at a constant temperature of 20 °C. The material models used in this work are the anisotropic material in LS-DYNA (*MAT133) based on the yield criterion developed by Barlat et al. [2] and the isotropic von Mises model (*MAT106). The anisotropic yield criterion is calibrated against data from the uniaxial tensile and silicon rubber bulge tests according to table 2. The m-parameter was assumed equal to 8. The isotropic von Mises criterion was calibrated using only the uniaxial tensile tests along the rolling direction (00) at different temperatures and strain rates thus assuming the Lankford coefficients to be equal to one. The calibrated yield surfaces with corresponding R-values and initial yield stress depending on rolling direction at 20 °C are shown in Figure 3.

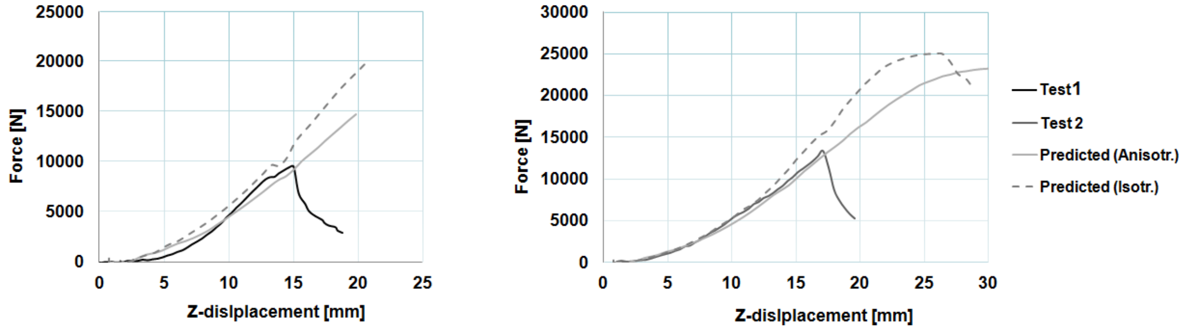


a) b)

Figure 3. a) Calibrated yield surfaces for AA6016 at 20˚C for different amount of shear stress (0.0, 0.5) and b) Measured and predicted R-values and initial yield stress depending on rolling direction at 20 °C.

5. Results

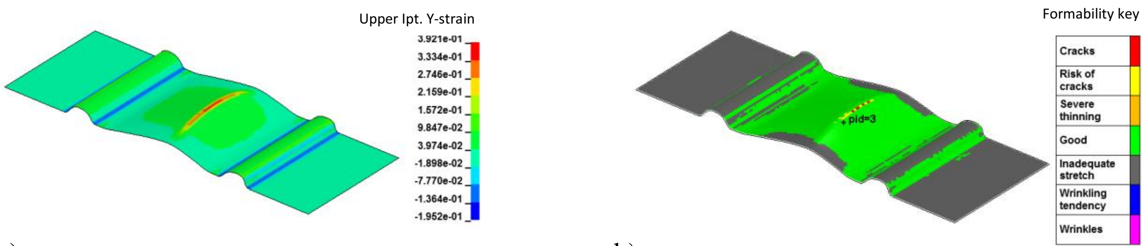
Selected results from the stretch-bend forming tests are presented in this section. The room temperature tests illustrate the importance of considering the anisotropy. Predicted and measured forming forces indicate a larger deviance as isotropic von Mises is assumed, cf. Figure 4. Also, the formability based on the FLC is underestimated using the isotropic model (predicted failure at a draw depth of 11.79 mm) whereas the anisotropic model correlates well with measured values (predicted failure at 14.23 mm and measured at 14.25 mm), cf. Figure 5. Further on, the predicted shape deviance correlates better with measurements using the anisotropic model cf. figure 6.



a) b)

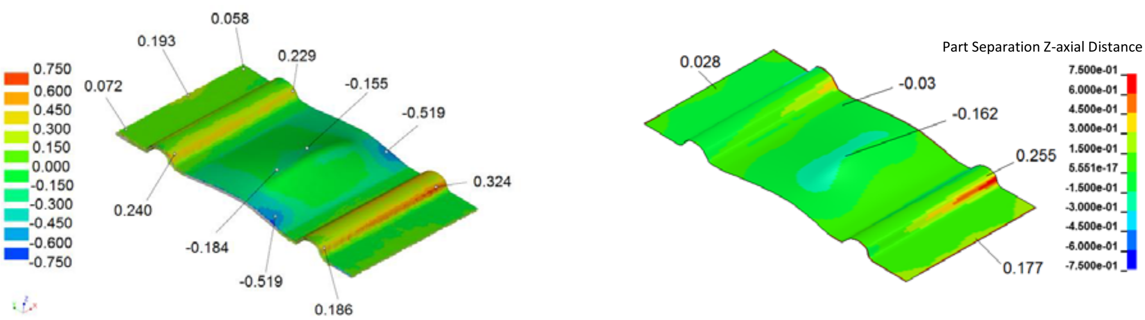
Figure 4. Measured and predicted (FEA) punch forces for forming at room temperature (RT) with different punch radii. a) 3 mm, Test 1. b) 10 mm, Test 2.

The elevated temperature Nakazima tests (FLD) and the thermo-mechanical stretch-bending tests confirmed the increase in formability with increasing temperature. The FLC major strain value, close to the plane strain condition, increased from 0.219 in room temperature to 0.485 at a temperature of 360 °C. The strain values just before visible cracks detected using DIC were substantially higher for the both punch radius cf. Figure 12. Yet, the draw depth was higher only for the test with a punch radius of 3 mm. The predicted and measured forming forces for the stretch-bending tests with different punch radius and starting blank temperatures are presented in Figure 7. The corresponding predicted and measured temperature histories are presented in Figure 8. During forming the position of where the maximum strain values occurred changed from the right hand side of the punch radius to the left hand side of the punch where the crack finally appeared, cf. Figures 11 and 12.



a) b)

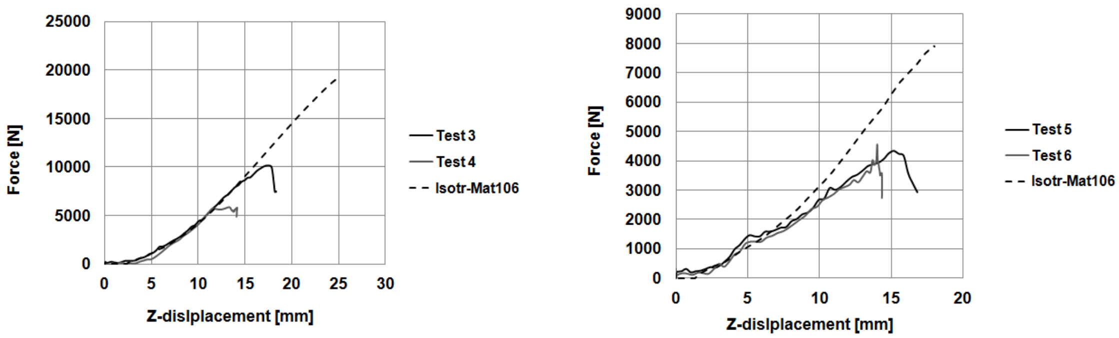
Figure 5. a) Predicted (FEA) upper integration point y-strain at failure, draw depth 14.23 mm and b) formability plot using the FLD. Test at 20 °C, punch radius 3 mm using the anisotropic yield criterion.



a) b)

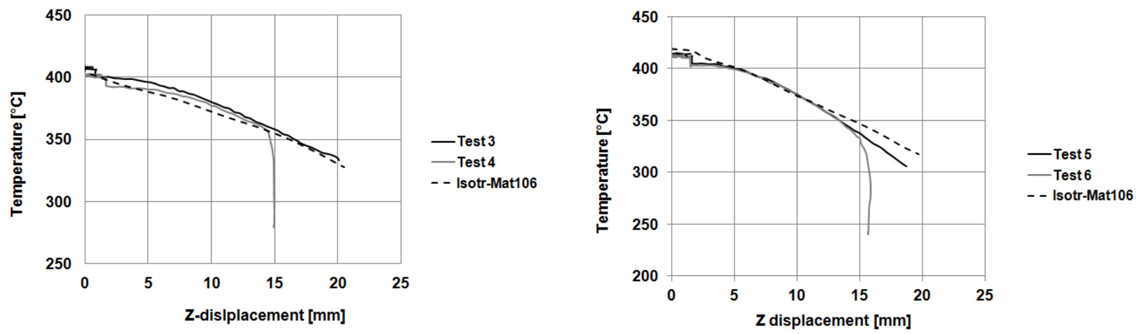
Figure 6. a) Measured shape deviation using a punch radius of 3 mm, forming at 20 °C, draw depth 11.3 mm and b) predicted shape deviation using the anisotropic yield criterion.

This experimentally observed characteristic strain localization behavior was also predicted when care was taken to include the uneven temperature distribution of the blank at the start of the forming cf. Figures 9, 11 and 12. As for the room temperature case failure was predicted earlier than experimentally measured most likely due to the isotropic assumption cf. Figures 9 and 12b) with a predicted draw depth of 13.0 and measured 16.8 mm.



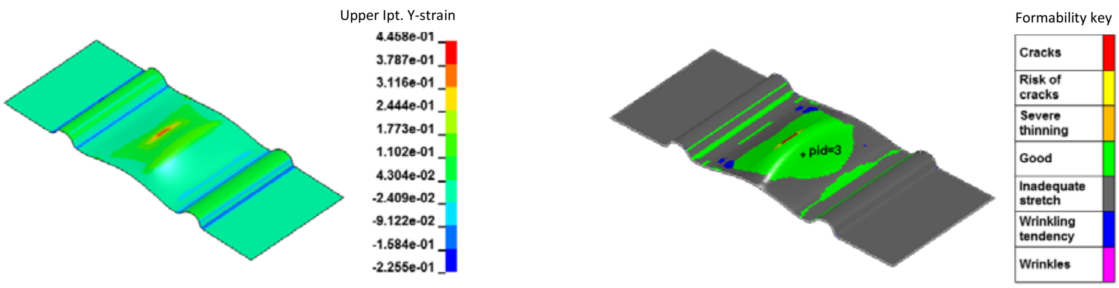
a) b)

Figure 7. 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.



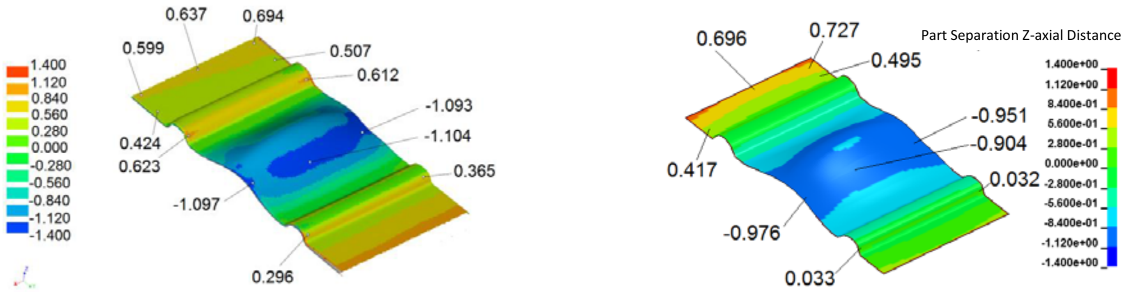
a) b)

Figure 8. 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.



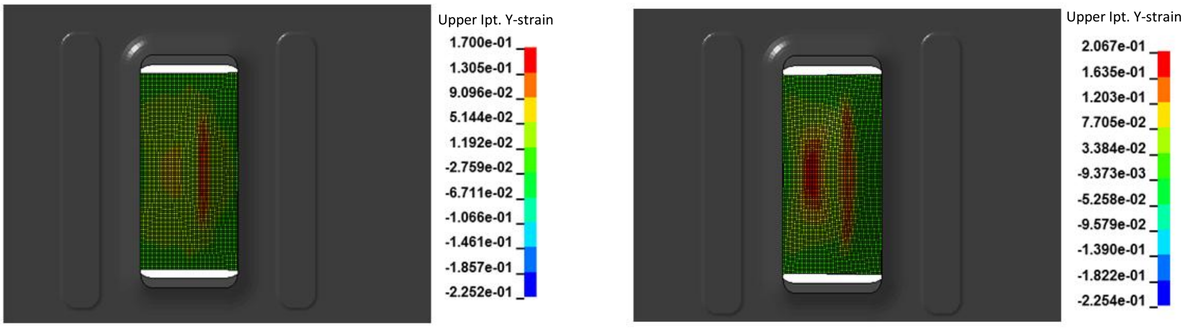
a) b)

Figure 9. Strain localization in the thermo-mechanical forming with a punch radius of 10 mm, Test 5. a) Predicted (FEA) upper integration point y-strain at failure, draw depth of 13.02 mm and b) formability plot using the FLC at 360 °C and the isotropic material *MAT106.



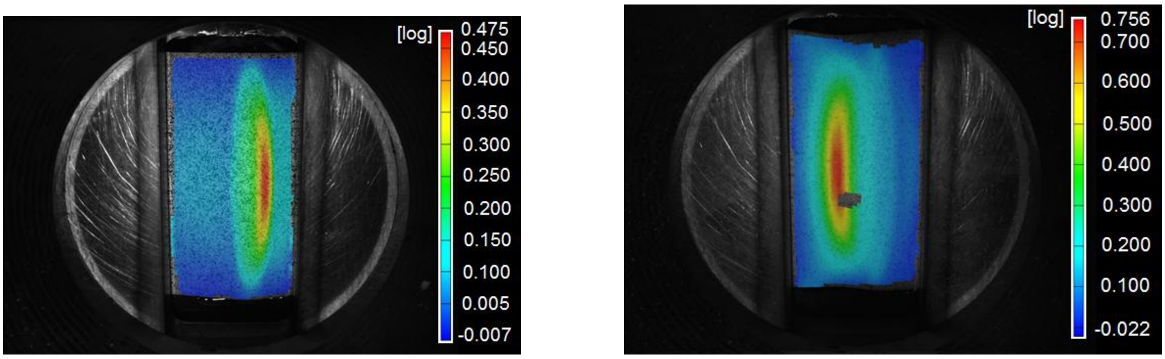
a) b)

Figure 10. 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.



a) b)

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.



a) b)

Figure 12. Major strain just prior to fracture for forming with a punch radius of 10 mm a) at 20 °C, draw depth of 17.10 mm (Test 2) b) forming start temperature 405.4 °C, final temperature at 323.4 °C, draw depth of 16.77 mm (Test 5).

6. Discussion and conclusions

The work in this paper intended to develop a test method to characterize the anisotropic thermo-mechanical properties of the aluminum alloy AA6016 up to temperatures close to the melting temperature. The uniaxial tensile test method involves DIC using a speckle pattern applied to the specimen surface capable of sustaining high temperatures and large deformations. Also, the induction system is in combination with the specimen geometry designed to yield an even distributed temperature in the evaluation region. Two different material models applied in cold and thermo-mechanical forming of AA6016 were evaluated using the stretch-bending tests. The comparison of predicted and experimental observations was used to evaluate model applicability and limitations. The Nakazima tests and the stretch-bending tests were used to evaluate the increase in formability with increasing temperature.

From the results it can be concluded that it is of importance to consider the anisotropy of AA6016. The ability to accurately describe the initial blank temperatures as well as predict the heat transfer and thereby the actual temperatures during forming are crucial to be able to successfully predict thermo-mechanical forming in aluminum. The anisotropic material model predicted punch force, strain localization and springback with promising agreement compared to performed tests at room temperature whereas the isotropic von Mises model overpredicts the punch forces and springback yet underestimates formability. Despite the model simplicity for the thermo-mechanical cases, it was possible to predict the evolution of the characteristic double pole strain localization. The deformation was initially concentrated to the right hand side of the punch, during the progress of the forming straining evolved on the left hand side of the punch radius where finally fracture occurred. However, formability was underestimated and the predicted punch forces were not spot-on measured values. A lubrication system including boron nitride in combination with coated tools preserved tool surfaces and minimized friction.

Although the distribution of the predicted shape deviance was captured for the thermo-mechanical case cf. Figure 10, it would be desirable to improve the prediction accuracy especially in terms of predicting strain localization and failure. An interesting continuation would be to apply an anisotropic material model suitable for thermo-mechanical FE-analyses such as presented in the work by e.g. Bagheriasl, Ghavam and Ghaffari et al. [5-7]. Based on the results from the stretch-bending tests at room temperature an anisotropic material model may increase prediction accuracy. Also, the calibration of the yield surface may be improved by adding complementary reference tests such as in shear loading [8, 9]. In order to further refine the models, time dependent material properties such as stress relaxation or creep may be necessary to consider. Also, a model for damage and failure would be of interest.

Acknowledgements

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