Development of a high-temperature double-layer bulge test for failure prediction in gas-based hot forming of a high-strength aluminium alloy

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Abstract. In order to meet the continuously increasing environmental concerns, automotive lightweight concepts of replacing steels with high strength aluminium alloys are one promising solution. Therefore, complex automotive structural components manufactured with new processes like rapid gas-based hot sheet metal forming can become a key factor from a forming technology point of view. A product and process development phase, which is mainly assisted by numerical simulations, mandates knowledge of the material forming limits under the process conditions. The aim of this work is to determine the FLD of a 6xxx precipitation-hardening aluminium alloy within the solution heat treatment temperature range under gas-based hot forming process conditions. For this purpose, a hydraulic double-layered bulge test, as introduced by Banabic, is used as the basis and a high-temperature test setup as well as a characterization methodology are established. FE simulations are utilized to optimize the specimen geometries aiming at specific strain paths. Experiments are conducted with the optimized specimen geometries and the high-temperature FLD is extracted. The FLD is further used in simulations for process parameter identification for failure-free gas-based hot forming of a laboratory scale benchmark component. Experimental validations showed the reliability of the methodology and the determined FLD for failure prediction in the novel forming process.

1. Introduction

Automobile and aerospace industries are experiencing enormous pressure to design the mobility of the future in a resource-efficient and eco-friendly manner. To enhance the automotive lightweight design, hot forming processes like hot stamping have been invented and developed for high strength manganese-boron steels. Nowadays, the high strength lightweight alloys such as aluminium alloys of 6xxx and 7xxx series and titanium alloys that can potentially replace steel from a mechanical point of view are being considered. However, due to their limited formability at room temperature, several new forming processes at elevated temperatures are being invented. Due to their improved ductility at elevated temperatures, relatively complex geometries can be realized, especially by using active media for forming operations instead of/in combination with traditional deep drawing processes. The current study is related to the gas-based hot forming of EN AW-6010-S precipitation hardening aluminium alloy.

The novel forming processes are nowadays studied with the help of Finite Element Analysis (FEA) to enable an effective and efficient process development. In order to efficiently model the limits of material formability and predict the failure within FE simulations, forming limits of the material are
input to the simulation. Commonly, Forming Limit Diagram (FLD), which quantitatively describes the sheet metal formability under different strain states is used. For this purpose, the FLD needs to correspond to the process conditions and it should cover the strain states that occur within the component. The gas-based hot forming process currently under investigation is characterized by high temperature and strain rate and the strain paths are unlike punch-based deep drawing processes. Therefore, a novel high temperature testing concept and a setup that represents the strain states and paths as in gas-based forming processes are necessary.

2. State of the art

2.1. Failure prediction during hot forming
Several conventional punch-based and nonconventional active-media-based hot sheet metal forming processes are being developed since the last few decades [1]. For failure prediction during the process layout, a knowledge of the material forming limits is necessary. This can be done with help of formability parameters obtained from qualitative process-specific tests such as limiting drawing ratio from drawing tests [2] or limiting bulge height from a bulge test [3]. Some studies like [4] involved development and calibration of complex damage models based on these tests and their implementation in process simulations to model the failure. Unlike the process-specific tests, the material formability can be quantitatively described with help of a FLD comprising the forming limits under different strain states. FLDs are therefore widely and most commonly used for failure prediction in sheet metal forming. Apart from traditional strain-based FLDs, stress-based FLDs also exist and these are better at prediction of failure especially in active media based forming processes due to their strain path independency [5]. However, mostly strain-based FLDs are used because the stresses cannot be experimentally measured and require additional plasticity model based correlation procedures from strain measurements [6].

2.2. High temperature FLDs and characterization methods
For FLD determination, punch-based Nakajima and Marciniak tests are widely used. However, the high temperature setup with hot tools gets more complicated compared to traditional setups. In some studies like [7] and [8], an elevated temperature Nakajima test setup was realised to determine the warm and hot formability of aluminium. The FLDs determined by these tests are generally influenced by friction between the specimen and the punch. Moreover, they usually show strain paths similar to those of punch-based deep drawing processes.

When it comes to active media based forming processes, these frictional effects are absent and the strain paths are different. Therefore several active media-based tests for determination of FLDs are being developed. Hydraulic bulge test [9] is a classical example, but it gives the formability of the material at lower temperatures under biaxial scenario only. Hot gas bulge test [10] is a modified version of hydraulic bulge test which is capable of determining the biaxial forming limits at high temperatures. Some works, for instance [11], enhanced hot gas bulge test by modifying the ellipticity of the die as in [9] to obtain different strain paths and succeeded in determining the right side of the FLD of Magnesium alloy AZ31B sheets at 400°C. Apart from punch-based tests and bulge tests, another recent study [12] investigated in-plane test concepts for FLD determination of AA7075 alloy in between 200 and 400 °C.

Banabic et al. developed a novel hydraulic double-layer bulge test [13] to determine the entire FLD of AA6016-T4 at room temperature. Others also determined FLDs at high temperatures by using double layered gas based test methods. For example in [14] the specimen has two slits instead of circular holes to reduce the stress concentration. Another example is [15] where FLDs of a titanium alloy were determined at 970°C under constant strain rate by controlling the gas pressure rate. In this study, bi-layered gas bulge tests were performed with circular and elliptical dies and specimen geometries with elliptical holes. Moreover, the study [16] involved tests with similar specimen geometries with holes for FLD determination for electrohydraulic forming.

Several studies investigated the hot sheet formability through advanced test setups. But, applying these techniques to aluminium alloys at their solution heat treatment temperature complicates the DIC
analysis due to the ductility and extreme surface enlargement of the material. This is a major point that makes the extraction of FLD quite challenging that is less emphasised on. Moreover, currently no studies known to the authors exist, that employ the extracted FLD to predict failure during a gas-based forming process. The current study aims to fill these gaps by realising a test setup and a systematic pattern for DIC analysis for hot FLD determination and its validation by laboratory scale benchmark tests.

3. Test setup and materials

3.1. Material
This study aims to determine the FLD of the 1.5 mm thick EN AW-6010-S aluminium alloy sheet at 565°C. During the experiments, the material is heat-treated according to the gas forming process route which involves solutionising at nearly 565°C for 20 minutes and subsequent specimen deformation until failure. Since the material is annealed at solution heat treatment temperature, complete recrystallization took place. Therefore, no significant anisotropic effects were observed and hence neglected in this study.

3.2. Test concept and setup
3.2.1 Test concept. The current test concept is based on the hydraulic double-layer bulge test [13] in which the test specimen with two holes is deformed with help of a carrier sheet and fluid pressure. This technique is adopted to high temperature conditions with hot tools and gaseous active medium. As shown in Figure 1a, the setup involves four major parts: heated die and blank holder, carrier blank and the specimen. The carrier blank gradually bulges and acts as a punch where it transmits the deformation load to the specimen. By varying the hole geometry and distance between the holes of the specimen, different strain paths can be obtained. The specimen geometries suggested by Banabic et al. [13] are shown in the Figure 1b. This comprises of five different specimen geometries resulting in two strain paths on the left side (uniaxial-like, intermediate (+)), one on the vertical axis (plane strain) and two strain paths on the right side (intermediate (+)), biaxial).

3.2.2 Test setup. The test setup designed for realising the above mentioned test concept shown in Figure 1a is realised by modifying the existing biaxial hot gas bulge test [10], which was earlier developed for high temperature material characterization at the Institute. The heated die and blank holder have an outer diameter of 206 mm and the die has an inner opening hole diameter of 100 mm. The outer diameter of the specimen and the carrier blank correspond to the tools, i.e., 206 mm. The geometry and size of the specimens’ holes vary according to the aimed strain path. In order to simplify the experiments, carrier sheets are also made of same alloy as the specimen to be consistent with the solution heat-treatment temperature and time. The carrier sheet thickness is taken to be 4 mm, which is significantly higher than the specimen thickness of 1.5 mm. By this, the carrier sheet should remain intact until the thinner specimen fails.

Figure 1. (a) Schematic of test setup and (b) specimen geometries and strain paths from [13]
The die and blank holder are heated via circumferential heating collars and appropriately insulated to avoid heat loss to the environment. The heat transfer to the press is compensated with help of integrated cooling water channels at the interfaces between the press and tools. Therefore, the tools can be maintained at a nearly constant test temperature of 565°C throughout the experiments with help of two separate PID temperature controllers and type K thermocouples. During the experiment, the specimen and the carrier blank are placed between the hot tools, where they get conductively heated up to the test temperature and undergo solution heat treatment for 20 minutes before the deformation. The forming medium is high-pressure nitrogen gas that passes through the gas distribution hole at the centre of the blank holder and acts on the carrier sheet, which bulges and simultaneously deforms the specimen. During the experiment, the carrier sheet and the specimen might undergo slight cooling (max. 10 K) because of convection due to pressurized gas. But, due to conduction between the hot dies and specimen sheets the temperature loss is compensated and therefore near isothermal conditions can be assumed. The rate of gas pressure can be controlled linearly with help of an integrated valve-setup and is set to 2 bar/s. The blank holder force is set to be constant at 250 kN, which ensures a complete sealing throughout the experiment.

3.3. DIC and pattern design with preliminary biaxial hot gas bulge tests
The DIC based GOM Aramis 4M setup is used to track the specimen deformation and the local major and minor strains. As a part of this, two cameras continuously record the specimen in the deformation zone through the die opening. Since the 6xxx alloys exhibit high ductility and high surface enlargement under the solution heat treatment temperature conditions, a temperature resistant and stable pattern that adheres well to the surface of the specimen is necessary for DIC analysis. Preliminary studies showed that the typical manually created stochastic pattern where a secondary contrasting colour is finely sprayed on an initial primary black or white coated specimen surface disintegrates during the deformation. The patches of newly generated aluminium surface at high specimen surface enlargement are moreover highly reflective and inhibit the GOM Aramis system from pattern deformation detection until specimen failure. Therefore, the existing methods of stochastic pattern creation are not very useful under current conditions and a stable pattern needs to be developed through further preliminary studies before proceeding with the actual experiments for FLD determination.

A significant part of the current study deals with development of a new multi-layer pattern concept in a step-by-step manner to improve the deformation analysis via DIC technique. As a first step, the initial specimen surface roughness is increased by sand blasting which further improved the adhesion of the paint to the specimen. After this, different stochastic pattern combinations are tested in order to check the stochastic pattern quality and integrity. It was observed that the conventional method of spraying stochastic pattern onto a primary coating did not give satisfactory results. Therefore, alternative methods of stochastic pattern generation were evaluated. Finally, a random Matlab-generated stochastic pattern was chosen and applied via laser marking. Marking this on an initially roughened specimen coated with high temperature resistant white furnace paint enhanced the pattern detectability as shown in Fig. 2e.

(a) Traditional white coating + Black sprinkles  (b) Sand blasting + White sprinkles  (c) Sand blasting + White coating + Laser marking (GS: 130)  (d) Sand blasting + White coating + Laser marking (GS: 160)

Figure 2. (a – d) Selected instances of tested stochastic pattern combinations for the DIC analysis showing the pattern quality and the amount of detectable region of the biaxial specimen at 565 °C
The laser marking results in local surface modification as the initial white coating is removed and the underlying aluminium surface is selectively oxidised. In contrast to manual spraying method, this is advantageous because a stable stochastic pattern can be applied via a reproducible and robust method by modifying the aluminium surface layers. Finally, increasing the grey-scaling value (GS) during laser-marking to 160 recorded a major strain of up to 83% at the dome region as shown in Fig. 2d and this turned out to be the best pattern among all. Adjusting the grey-scaling changes the sensitivity of the laser at which it considers a grey value as to be marked or not.

4. Simulation-aided verification and optimization of the specimen geometries
Following the test conception and setup, it should first be investigated if the specimen geometries proposed in [13] result in the desired strain paths with current material under the high temperature conditions. Therefore, the FE models are setup, the simulations are performed starting with the existing specimen geometries ranging from uniaxial to biaxial strain states and the resulting strain paths are analysed.

4.1. Model setup and definition of boundary conditions
With help of symmetry boundary conditions a quarter FE model according to the experimental concept is setup as shown in the Fig. 3a. The geometries of the tools, carrier sheet and the specimen with notches are designed in Solidworks 2018, meshed in Hypermesh and the FE model is setup in LS-PrePost V4.3 and simulated in LS-Dyna V9.0. The simulations are carried out using an explicit FE solver with an automatic time step increment.

4.1.1 Modelling and discretization of parts. The die and blank holder are modelled as rigid bodies with Type-2 Belytschko-Tsay shell elements of 1 mm element size. The elastic deformation of tools is neglected and only the surfaces of the tools are modelled with shell elements in order to minimise the computational effort. The die is fixed and the blank holder is free to only translate in the vertical direction under action of blank holder force. The carrier sheet and specimen are modelled as elastoplastic deformable bodies with Type-2 shell elements of section thicknesses 4 mm and 1.5 mm respectively. The average mesh size for discretization of these deformable bodies is finalised to be 1 mm based on a mesh convergence analysis. For thickness discretization, nine integration points are taken in shell normal direction. The material properties for deformable bodies are taken from author’s previous work [17] and the plasticity modelled using the piecewise_linear_plasticity card in LS-Dyna. The simulations are isothermal at a temperature of 565°C.

4.1.2 Interactions and loads. The three different interactions between the tools and deformable bodies are modelled by forming_surface_to_surface contact algorithm. For the time being, friction is modelled according to the Coulomb model with the friction coefficients of 0.17 and 0.1 corresponding to the Boron Nitride and Graphite sprays taken from literature [18]. Two different loads corresponding to the experiment should be represented in the model, the gas pressure and the blank holder force. The pressure load is modelled as a surface load acting on the elements of the carrier sheet with help of the card load_segment_set. The linearly increasing pressure load is taken as in the experiments. As the carrier sheet starts bulging, the pressure load is transmitted to the specimen that also deforms along with the carrier sheet. A constant blank holder force of 250 kN is applied on the blank holder in the vertical direction as a rigid body force in order to hold the carrier sheet from drawing into the die during process.

4.2. Simulated strain paths and modification of geometries
The simulated strain paths are shown in the following Fig. 3b and it can be seen that all the geometries exhibit the strain paths as intended. The plane strain geometry is further investigated in terms of the size of the notches and the distance between the notches. Based on this simulation study, the specimen dimensions are finalised.
5. Experimentation and determination of FLD

5.1. Specimen preparation
The experiments are performed with the finalized specimen geometries. To track the evolution of the strain paths and to identify the instance of failure, the previously finalised stochastic pattern combination is applied on the specimens as shown in Fig. 4.

5.2. Experimentation and strain measurement via DIC technique
During the experimentation, as the gas is gradually released the carrier blank gradually bulges simultaneously deforming the specimen along with itself. As the specimen deforms, the strain increases at the polar region. The evolution of the strains is continuously monitored by the GOM-Aramis. The major strain distributions before the specimen failure are also shown in the following Fig. 4.
5.3. Analysis of strain paths and extraction of FLD

The standards (ISO 12004) of Nakajima tests are used to analyse the formability and to analyse the strain paths and extract the limiting major and minor strains at the instance of failure. Comparison of progression of the simulated and experimental strain paths in Fig. 5 shows that they are almost similar with very slight deviations. These deviations can be reasoned in differences between experiment and simulation, for example, temperature drop because of cooling due to gas, evolving friction coefficient, variation in chamber pressure evolution, etc. The limiting strains at the dome at the instance of crack propagation are extracted and these are connected to construct the FLC. It can be seen that the plane strain forming limit is below all the remaining specimens and as the plane strain is the critical point and breaks at minimum. This FLC is further evaluated with help of a cross-die benchmark test as described in the following chapter.

6. Validation with a cross-die benchmark test

6.1. Benchmark test setup and experimentation

An existing cross-die benchmark specimen shown in Fig. 6a, formed via pure gas-based forming process is used to validate the determined FLC. Similar to the setup in [17], this benchmark test consists of hot die and blank holder at 565°C as shown in the Fig. 6b. The 1.5 mm thick EN AW-6010-S initial blank whose shape is already optimized for the current gas-based hot forming process is placed in between the die and blank holder, solutionised and formed with help of continuously increasing gas pressure by simultaneous regulation of the blank holder force.

For validation of the current FLC, two different scenarios with different values of blank holder force are chosen so that in the first scenario a successful component is manufactured and in the second scenario a failure in the component is recorded. The blank holder force in the first scenario is varying from 10 kN to 70 kN during the forming process whereas in the second scenario it is initially 14 kN which increases to 70 kN during forming. The rate of increase of gas pressure is 5 MPa/s in both of these experiments.

Figure 5. Simulated and experimental strain paths and the FLC of EN AW 6010-S 1.5 mm at 565°C

Figure 6. (a) Cross-die specimen, (b) experimental setup for forming the cross-die benchmark specimen and (c) corresponding simulation model
From the resulted cross-die components in Figure 7 it can be observed that a failure-free component with complete form-filling resulted in first scenario when the initial blank holder force is lower, whereas in the second scenario the specimen cracked and could not deform further due to gas leakage. The second scenario also shows an insufficient material draw-in in the flange region.

Figure 7. (a) Experimental, (b) simulation results and (c) corresponding strain states of first scenario (upper) with 10 kN and second scenario (lower) with 14 kN initial blank holder force

6.2. FE modelling, simulation and validation
The FE model of cross-die benchmark forming process consisting of rigid tools and deformable blank is setup according to the simulation methods in [17] with Type-2 shell elements. All the boundary conditions in the simulation are modelled as close to the experiment as possible. Simulations with aforementioned values of blank holder force are carried out. By taking the experimental FLC previously shown in Fig. 5, formability investigations are carried out using the ‘Formability-Key’ option in LS-Dyna during post processing and the resulting strain-states (Fig. 7c) are analysed. The line indicating ‘risk of cracks’ region is taken to be 10% below the FLC.

It can be observed that the simulation corresponding to first scenario shows only thinning, but no cracks or no risk of cracks. In simulation of the second scenario, cracks are observed in the concave wall region of the cross-die as highlighted in Fig. 7b. This is because of high initial blank holder force, which restricts sufficient material flow from flange region that ultimately resulted in risk of cracks and subsequent cracks. The first instance of occurrence of crack is depicted here. Once the cracks are observed, the further deformation of the specimen is not realistic as the gas escapes through the cracks. Even though a slight temperature drop is observed in the benchmark test due to convection and the FLC is determined at nearly isothermal conditions, the results of crack prediction are quite reliable. So, it can be said that the FLC is validated with the cross-die simulation model successfully.

7. Summary, conclusions and future work
A test concept for extracting the high temperature FLD for failure prediction during gas-based hot forming processes is devised, developed and taken into operation. Experiments are carried out and the high temperature FLD of ductile aluminium alloy is determined. The FLC is further used in simulations of a laboratory scale cross-die benchmark component for failure prediction and the simulation results are experimentally validated. Based on the work done, the following key findings can be reported:

- The existing hydraulic double layer bulge test [13] has been successfully adapted for testing ductile aluminium alloys under high temperature conditions by substituting the liquid medium with gaseous medium and integrating appropriate heating and cooling elements.
A promising method for generation of heat resistant and mechanically stable DIC patterns for highly ductile materials has been developed. This method involves surface roughening by sand blasting, primary coating with temperature resistant white paint and application of stochastic pattern via optimised laser marking.

The specimen geometries from [13] resulted in nearly linear strain paths for the investigated EN AW 6010-S alloy even under high temperature conditions. Accordingly, a high temperature FLD at 565°C is successfully determined.

The FLC applicability is partially validated for rapid gas-based hot forming process with help of a laboratory-scale cross-die component. Failure occurrence during the forming process is reliably predicted within corresponding FE simulations.

In future, the simulation models could be further improved so that the experimental and simulated strain paths correspond even more to each other by further investigations on the thermo-mechanical and frictional boundary conditions. Following this, the specimen geometries could be further optimized to obtain the ideal strain paths and additionally the strain path corresponding to deep drawing. Moreover, FLD determination under process relevant non-linear strain paths could be investigated. Also, strain rate control could be implemented within the experiments to determine FLDs at different and constant strain rates.

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