From Blank to Fractured Component: Numerical and Experimental Results of a Laboratory Scale Component

Stefan Marth\textsuperscript{1}, Stefan Golling\textsuperscript{2}, Rickard Östlund\textsuperscript{2} and Mats Oldenburg\textsuperscript{1}

\textsuperscript{1} Luleå University of Technology, 97187 Luleå, Sweden
\textsuperscript{2} Gestamp R&D, Box 828, 97 125 Luleå, Sweden
E-mail: stefan.marth@ltu.se

Abstract. Hot stamping of boron alloyed steel has become a standard in the automotive industry for safety relevant chassis components. Hot stamping of ultra-high strength steel allows the design of complex geometries with superior mechanical properties. In the present work, a laboratory scale test component is followed up from blank to fractured component. The production process starts with a pre-cut blank, which then is austenitized, transferred to the press hardening tool, formed and quenched and ends with post-cooling to room temperature. These components are tested under tensile deformation until fracture, where force, elongation and the strain field on the components surface are measured. The strain field measurements are performed by using digital image correlation (DIC). The laboratory scale test component is evaluated using finite element modelling. The production process is modelled starting with a pre-cut austenitized blank, subsequent transfer and forming operation, and ends with post-cooling. Furthermore, the deformation and fracture under tension/bending is studied using the OPTUS damage model. The as-produced component is measured using a three dimensional scanning system. Shape deviation and thickness change are compared to in the forming simulation predicted geometry after post-cooling. A finite element investigation on the deformation and fracture under tensional/bending loading is conducted applying shape and thickness deviations in the model. The majority of industrial components undergo paint curing before they are included in an assembly. Paint baking is a heat treatment at relatively low temperatures and causes relaxation in a martensitic microstructure. The effect of paint baking on the mechanical response of the laboratory scale test component is investigated. In the present work the reliability of modelling tools from blank to fractured component is shown. The possibility is shown to predict the failure of the component, with the specific phase composition after the hot stamping process obtained from simulations. Furthermore, the influence of the paint baking process on the mechanical properties is presented.

1. Introduction
Hot stamping of boron alloyed steel has become a standard in the automotive industry for safety relevant chassis components. Hot stamping is a process to produce high strength components from low alloyed boron steel, where fully austenitized blanks are formed and sequentially quenched. This process allows the design of complex geometries with superior mechanical properties. Special process design allows the modification of the microstructure in designated areas. The process of hot stamping is further described by [1] and a review on hot stamping
of boron steel sheets with tailored properties is given by [2]. A summary over the latest developments in hot stamping technologies can be found in [3].

The majority of industrial components undergo paint curing before they are included in an assembly. Paint curing is conducted at elevated temperatures between $160^\circ$ C and $190^\circ$ C for a certain holding time, in industry a holding time between 15 and 60 minutes is commonly used [4]. Due to the relatively low temperatures, the paint baking heat treatment causes relaxation in a martensitic microstructure and therewith causes changes in mechanical properties. The effect of paint baking on the mechanical response of the laboratory scale test component is investigated.

Component designs can be analysed by using the Finite Element Method before building the first prototype and therewith leading to shorter development times and lower development costs. However, this needs reliable models for material deformation during forming and deformation under loading. Modelling the prediction of the phase composition in a hot stamping process is presented by [5]. Modelling the deformation and fracture of press hardened material is of great interest in the automotive industry and variants are recently presented by [6, 7].

In the present work the low alloyed boron steel 22MnB5 with an aluminum-silicon coating is used. This is a common steel in the automotive industry for hot stamping applications due to its favourable properties, allowing fully hardened microstructures at industrial reasonable cooling rates. For the present study, blanks are pre-cut, austenitized in a roller hearth furnace, forming and quenching is performed in a special dedicated tool in a single step. The resulting microstructure is a fully hardened, martensitic, microstructure. The industrial process of paint baking is reproduced by similar time-temperature conditions in a convection furnace but without applied paint.

The aim of this study is to prove the reliability of modelling tools from blank to fractured component by comparing a laboratory scale test component, followed up from blank to fractured component, with simulations of the forming and fracture. Furthermore, the influence of the paint baking process on the mechanical properties is presented.

2. Method

2.1. Experimental work

A laboratory scale test component is followed up from austenitized blank to fractured component. The schematic design of the laboratory scale test component is shown in Figure 1. The component is intended to be loaded in longitudinal direction and consequently the centre cross-section is in bending. Consequently, the surfaces in the double bended area in the centre are under compressive and tensile loading. The flanges of the component are intended to maintain a high stress triaxiality, i.e. close to the biaxial stress state, in the critical cross-section during loading.

![Figure 1. Schematic design of the laboratory scale test component.](image-url)
The production process starts with a 1.5mm thick pre-cut blank low alloyed boron steel 22MnB5, which is austenitized for five minutes at a temperature of 950°C, transferred to the cooled press hardening tool, where it is formed and quenched simultaneously. After the press-hardening the component leaves the press for post-cooling to room temperature. The cooling parameter in the press are chosen to produce a fully hardened martensitic microstructure. To enable the investigation on shape deviation and thickness change, the as-produced component is measured using a three dimensional scanning system. Shape deviation and thickness change are compared to the predicted geometry after post-cooling.

The majority of industrial components undergo paint curing before they are included in an assembly. To study the effect of paint curing conditions on the mechanical response of the laboratory scale test component, certain components were heat treated for 20 minutes at 175°C and investigated similar to the fully hardened components. For characterization of the microstructure in the produced component Vickers microhardness measurements are performed using a load of 500g and a standard Vickers pyramid. A fully hardened martensitic microstructure is assumed to have a Vickers hardness of approx. 500 HV, [8].

The components are tested under tensile loading until fracture, where force, elongation and the strain field on the components surface are measured. The tensile testing is performed with a cross-head speed of 0.1mm/s. The strain field measurements are performed by using digital image correlation (DIC), where the lower side of the component has a painted random speckle patter. The frame rate for the images was correlated to the strain rate of the testing process to obtain a series of approximately 100 images per test. The commercial system, GOM ARAMIS, was used to determine the local deformation of the specimens’ lower surface during testing. The history of the stress triaxiality for the initial fracture point is computed from these local strain field measurements as presented in [9].

2.2. Modelling

The laboratory scale test component is evaluated using finite element modelling in LS-DYNA. The whole component is modelled with approximately 25 000 fully integrated shell elements, LS-DYNA type 16 elements, with five integration points through thickness. The initial shell thickness is 1.5mm, mapping is used between simulation stages and therefore shell thickness is not homogeneous after forming. Elasto-plastic material properties and damage parameters are taken from literature, see [6, 10, 11].

2.3. Process simulation

The production process is modelled starting with a pre-cut austenitized blank which represents the state of the component leaving the furnace. The transfer time between furnace and tool is the first of three thermo-mechanical simulation steps. Blank transfer is modelled using convection and radiation boundary conditions; the actual physical movement of the blank is not included in the simulation. The second step of the process simulation is the simultaneous forming and quenching. The FE model of the tooling consists of shell elements with prescribed initial temperatures, reproducing the real tooling situation. This step in the process simulation is performed using the explicit solver of LS-DYNA. The third step of the process simulation is the post-cooling; the formed component is similar to the first stage air cooled using boundary conditions. A springback analysis is conducted during post-cooling. Both, the first and third stage are performed using the implicit solver in LS-DYNA. Increasing the hold time in the tool during the second step would make the third simulation stage unnecessary as room temperature would be reached. This approach is not chosen due to the desire of reproducing an as close as possible industrial process. In industry formed components are taken out of the tool after passing the martensite finish temperature and no further phase transformations are possible.
2.4. Tensile test simulation

Furthermore, the deformation and fracture under tension/bending is studied using the OPTUS damage model. The OPTUS model is described in detail in [10] and hence only a brief description is included in the present paper. The basis of the constitutive model is a modification of the von Mises yield equation

\[ f = \sqrt{3J_2} - \sigma_y (1 - L) \]  

(1)

where \( J_2 \) is the second deviatoric stress invariant, \( \sigma_y \) is the current yield stress and \( L \) is termed localization function introduced to reduce the load bearing capacity of the material. The localization function is defined as

\[ L = \frac{A_0}{l} \left[ \exp(B_0 (\bar{\varepsilon}_p - \bar{\varepsilon}_0)) - 1 \right] \]  

(2)

where \( A_0, B_0 \) and \( \bar{\varepsilon}_0 \) are parameters calibrated from experiments, \( \bar{\varepsilon}_p \) is the equivalent plastic strain and \( l \) is the analysis length calculated from the square root of the element area and normalized to the shell thickness. Using the localization function the load bearing capacity of the material is reduced. It is possible to use fracture criteria to indicate material failure and to remove failed elements from the mesh. In the present work no fracture criteria is incorporated. Therefore, the material is degraded until the load bearing capacity is reduced to zero.

The simulation of the tensile test uses as boundary conditions the area equal to the experimental gripping system. The fixture in the tensile test machine is a grip with an area of 60x40mm, on one side of the FE model nodes in a corresponding area are fully constrained, on the opposite side displacement in tensile direction is permitted. A constant velocity is prescribed to this end of the model.

The virtual tensile test is performed using the model geometry and thickness obtained by the forming process simulation as input for the FE model.

3. Results and discussion

3.1. Process simulation

The final shape is predicted using a three stage simulation, transfer cooling, forming and post cooling. The process simulation is conducted in LS-DYNA with a thermo-mechanical constitutive model. Result of the process simulation is the phase content of microstructures after the completed process and the predicted shape of the test component. For characterization of the microstructure in the produced component, Vickers hardness measurements are performed at several locations. It is found that the hardness of the specimen which did not undergo post heat treatment, i.e. paint bake hardening, is 527 HV. This can be compared to the specimens heat treated in conditions comparable to paint bake hardening, here a hardness value of 505 HV is found. The FEM simulation showed a fully hardened martensitic microstructure in the test specimen. This is in accordance with the Vickers hardness measurement results.

Figure 2 shows a comparison of the thickness deviation from the nominal thickness of 1.5mm, where Figure 2a shows thickness deviation between 3D thickness measurement and nominal CAD model and Figure 2b the predicted shell thickness from forming simulations. It can be seen that the simulated thinning prediction is concentrated in the top of the flanges, which is also measured on the experimental components after forming. The measured thickening in the components centre is also predicted in the simulations. In general good agreement is found between three dimensional scanning and forming analysis. Thickness deviation of about \( \pm 0.15 \text{mm} \) is measured and predicted although the areas are slightly smaller in the measured surface. It is to be expected that a certain error margin exist in the measured surface as an optical system is applied. Manual measurement of some points support the result from scanning but are likewise prone to error due to manual handling of the micrometer calliper.
3.2. Tensile Testing

The test specimens, both with and without post heat treatment, are tested in longitudinal direction applying a tensile load. The lower surface of the specimen i.e. the surface no visible in Figure 2, is during the test continuously under tensile loading. The central cross-section is under bending load and hence one surface experiences tensile loading while the opposite surface is under compression. The surface under tension is painted with a stochastic pattern using black and white paint. During testing images of this surface are taken and analysed with digital image correlation (DIC), calibrated for three dimensional measurements. The elongation of the test specimen is measured from the DIC data using a virtual extensometer with an initial length of 40 mm. The elongation in the simulations is taken from two nodes with an initial distance of 40 mm to get comparable results.

The tensile force is measured and compared to the simulation result, presented in Figure 3, where the tensile force at fracture is marked with 'X'. It can be seen, that the post heat treated specimen achieve an approximately 10% higher tensile forces than the fully hardened specimen without post heat treatment. This is assumed to be mainly caused by the relaxation in the martensitic microstructure. The simulated force-elongation relation is presented by the blue line, where the results from the forming simulation are taken as input for the simulation.

The general agreement between simulation and experiment is good. The difference between experimental results was already discussed and explained by relaxation of the fully hardened microstructure. Although the paint baking temperature is comparable low a slight effect of annealing can be seen. The influence of this low temperature annealing improves the ductility of the material leading to a delayed fracture and its turn to a slightly higher load bearing capacity. This effect is known for fully hardened microstructures where high cooling rates are applied.

The as-produced specimen is measured using a 3D scanning system and compared to the shape of the process simulation. In an overlay of predicted specimen geometry and measured surface good agreement is found. Due to the relative simple specimen geometry it is possible to conduct 3D scanning of both surfaces in one single run, allowing to measure the thickness of the specimen. Again, comparing measurement and simulation good agreement is found. The difference between simulation and experimental tensile test curves is attributed to small geometric deviations.

To conclude the FE simulation of the tensile testing of the specimen, the general agreement
Figure 3. Load-displacement response, where the black lines are the fully hardened components, the red are the fully hardened components with the bake hardening treatment and the blue line represents the simulated force-elongation relation based on the resulting thickness and surface from the forming simulation. The experimental maximum force at fracture is marked for each curve with ‘X’.

between simulation and experiment is good, and taking experimental scattering in account the simulation shows sufficient results for the present case.

The strain fields on the components lower surface during the tensile testing are obtained by 3D DIC measurements. The effective von Mises strain field at the last image before fracture initiation is compared with the effective von Mises strain obtained by FEM simulations and are presented in Figure 4. In Figure 4a the effective von Mises strain field obtained by 3D DIC measurement for one sample is presented. The virtual extensometer is indicated, as well as the fracture initiation point marked in the centre with a effective strain value of 28.8%. The predicted effective von Mises strain field, shown in Figure 4b, shows the strain field obtained from FEM simulation based on the resulting thickness and surface from the forming simulation on the components lower surface.

In Figure 5 the stress triaxiality history in the fracture initiation point on the lower side of the component is presented, comparing experimentally DIC measurements and FE simulation. The blue line shows the simulated history triaxiality versus effective von Mises strain taken from lower integration point of the element where the fracture is initiated during the tensile deformation until failure is predicted. The stress triaxiality history for the initial fracture point on the component during tensile testing is computed from the local strain field measurements. Here the black lines are again the fully hardened components without post heat treating and the
red lines with post heat treating. It is seen that the post heat treated samples have a higher strain at fracture than samples without the post heat treatment. However, the stress state history for all component samples are comparable and follow the same trend from initially biaxial, $\eta = 0.66$, tending towards plane strain. This behaviour is also captured by the simulation.

Figure 4. Predicted and measured strain field on the components lower surface obtained by DIC measurement and FEM simulation.

Figure 5. Stress triaxiality in the fracture initiation point on the lower side of the component, comparing experimentally DIC measurements and simulation.
4. Conclusion
A laboratory scale component is followed up from blank to fractured component. The component is produced using the hot stamping technology, forming and quenching the component to achieve a fully hardened martensitic microstructure. This forming and quenching process is simulated using the finite element method. The components surface and thickness are compared from the simulation and from 3D measurements of the samples. A good agreement between the simulated and the measured thickness distribution can be stated. To study the influence of paint curing on the component certain samples are post heat treated under conditions close to the paint curing process. The component samples are tested under tensile deformation until fracture occurs. This tensile testing of the components is simulated by using the forming simulation result as the input model. The agreement between the experimental and simulated load displacement relations are in general good and a slight variation in fracture loads is observed. The post heat treated specimen achieve higher tensile forces than the fully hardened specimen without post heat treatment. This is assumed to be mainly caused by the relaxation in the martensitic microstructure. The effect of paint baking is small compared to formation of softer microstructures but it is noteworthy that fracture can occur at an earlier stage in a quenched, unpainted component. This effect might be relevant for thin sheets where high cooling rates are achieved in cooled tools and the finished product is close to ambient temperature after removing from the tool and no post tempering occurs, neither through air cooling or paint bake hardening. Finally it can be concluded that the laboratory scale component study shows possibilities to simulate a whole product cycle from blank to fractured component in a reliable way.

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