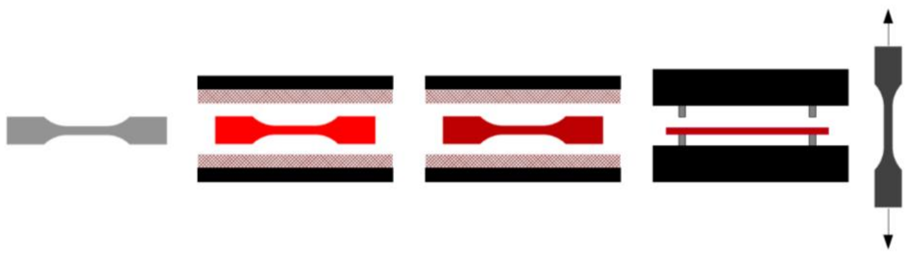
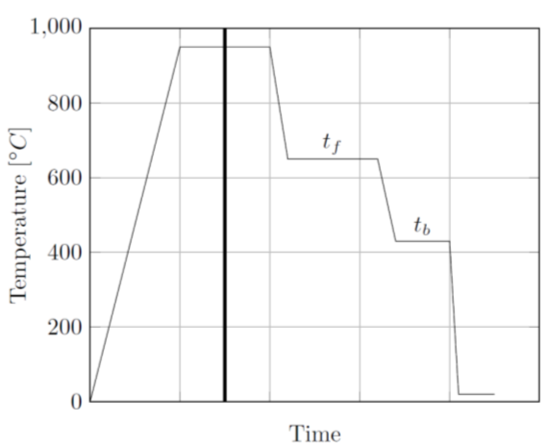
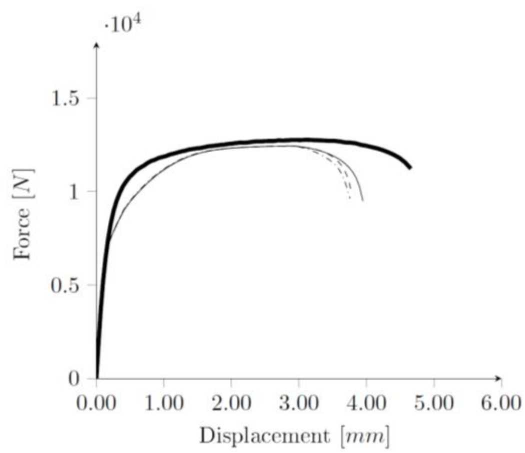
OPTUS 2
Modeling of failure criteria based on microstructure evolution in boron alloyed steel components







Project within: Electronics, software and communication

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Content

1. Executive summary

In recent years, the demand for press-hardened ultra-high strength steels (UHSS) for safety structures in cars increased and the trend is expected to continue. Vehicle components with tailored material properties can be manufactured by controlling the cooling rate of the blank by heating certain regions of the tool. A prerequisite for the introduction of high performance materials is the availability of efficient and accurate models for deformation and failure in crash simulations.

In this work, tensile test specimens with different phase composition are produced. The material studied is the low alloy boron steel 22MnB5. Using the measured mechanical properties of individual pure phases and the volume fraction of formed phases different homogenization methods are compared. Homogenization methods are used to describe the elastic and plastic deformation of the material. A damage model is used for strain localization and a maximum shear stress criterion to predict fracture. The material model for the homogenization of mixed microstructures including damage has been implemented in the commercial finite element code LS-Dyna. Validation by comparison with experimental results shows good agreement for most phase compositions. The main difficulty has been the reliable microstructure characterization.

2. Background

2.1. Hot sheet metal forming

During the last decade, hot sheet metal forming technology, also called hot stamping or press hardening, has become omnipresent in automotive body-in-white design. The driving force for the development of this technology is the demand for further improvement of fuel efficiency and passenger safety.
The demand for hot sheet metal forming technology is steadily increasing and we are now experiencing an outstanding growth in variety of applications, mainly in the automotive sector. For the design of automotive vehicle structures, hot stamping has become the leading technology for solutions with the aim to reduce weight in combination with maintained or increased passenger safety.
Hot stamping is a production process for the hot forming of sheet metals. It combines both the shaping and the heat treatment of sheet metal components into one single process step. The process involves inserting sheets, which have been austenitized, into a cooled forming tool, in which they are quenched. The thermal integrated processing produces a martensitic structure that gives the press-hardened parts an extremely high tensile strength.
Fig. 1 illustrates the production process of a press hardened component. From a coil blanks are cut, either in pre-cut shape or unprocessed. The blanks are austenitized in a

furnace prior to quenching. Depending on the blank geometry at the beginning of the process finishing steps are added after forming.

Figure 1: Schematic representation of the hot stamping process, from decoiling to finished product (image courtesy of voestalpine Steel division).

Within the technology of hot stamping a method called tailored properties evolved. Components with tailored properties have varying material properties in desired zones within the part. Mechanical properties within the blank are altered through forming tools which are sequentially heated and cooled. This type of heat treatment causes regions with high strength and low ductility to be direct placed besides a zone with lower strength and high ductility. The regions are micromechanical linked by a small transition zone consisting of a mixed microstructure or a microstructure with properties in between martensite and ferrite. A B-pillar is a typical example for a hot stamped component with tailored material properties, see Figure 2.

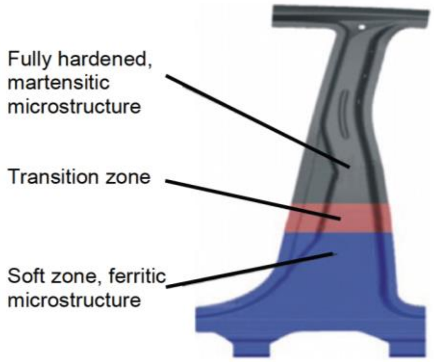


Figure 2: Example for a component with tailored material properties, partially hardened B-pillar reinforcement.

This work centers around the boron alloyed steel 22MnB5 with an aluminum-silicon coating which is commonly used in hot stamping processes. The boron-manganese micro-alloyed steel is available from different steel suppliers. In as delivered condition the steel consists of a fine grained, homogeneously distributed ferritic-pearlitic microstructure. The aluminum-silicon (AlSi) coating fulfills two purposes, during austenitization in a furnace and transfer to the forming tool it protects the blank from oxidation and during service life of the component it prevents from corrosion.

The hot stamping process increases the material strength with up to 250-300% compared to the base material. Reason for this increase is the superior strength of martensite compared to ferritic-pearlitic microstructures. In Fig. 3 different types of steel are compared in elongation and tensile strength. The steel in focus here is in unhardened condition located in the field CMn, carbon steel alloyed with manganese. After processing the steels properties are changed and it locates in the field MART, which stands for martensitic.

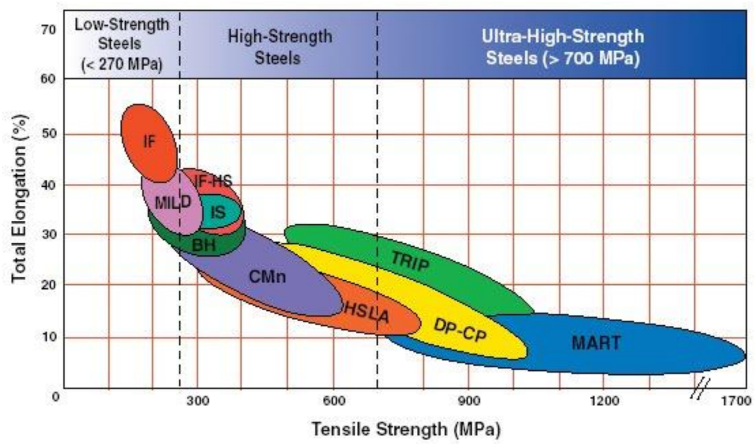


Figure 3: Strength elongation relationship for Ultra High Strength Steel in comparison to conventional High Strength Steel.

3. Objective

The objective of this work is to study and establish the relations between phase composition and the localization and fracture failure behavior in a boron alloyed steel. The studied steel is used for UHSS components in the automotive industry. Knowledge and presence of methods for failure predictions in e.g. crashworthiness analyses are necessary prerequisites for optimal use of UHSS materials in car structures. Heat treatment and welding are important industrial procedures in the manufacturing of boron-alloyed high-strength steel components. Due to the temperature history in these processes the mechanical properties of the material is changed. Accurate modeling is essential for simulation of loaded components in automotive applications.

4. Project realization

The research project was conducted in cooperation between the division of Mechanics of Solid Materials at Luleå University of Technology, the world leader in the technology of hot stamping Gestamp HardTech and Volvo Car Corporation.

4.1. Heat treatment of test specimens

In section 2.1 hot sheet metal forming, an introduction to the industrial process of hot stamping is presented. Hot stamping utilizes the possibility of altering the mechanical properties of steel due to heat treatment. Using time-transformation diagrams it is possible to estimate the amount of formed phases. In general two types of diagrams are useful for planning experiments, the time-temperature-transformation (TTT) and the continuous cooling transformation (CCT) diagram, see Fig. 4. Isothermal heat treatments are not used in industrial applications concerning hot stamping as they are not the most practical. Most industrial processes involve continuous cooling of a specimen to room temperature. For continuous cooling, the time required for a reaction to begin and end is delayed. Thus the isothermal curves are shifted to longer times and lower temperatures. The most important heat treatment used in hot stamping is quenching. The definition of quenching is the rapid cooling of a workpiece to obtain certain material properties, in the case of hot stamping an austenitized blank is rapidly cooled to form martensite. In a CCT diagram, see Fig. 4 to the right, this is visible if the cooling rate is chosen in a way that neither the ferrite nor the bainite field is entered, this quenching rate is termed critical cooling rate. Cooling rates below the critical form other phases than martensite. For rates passing through several fields formation of different phases is possible.

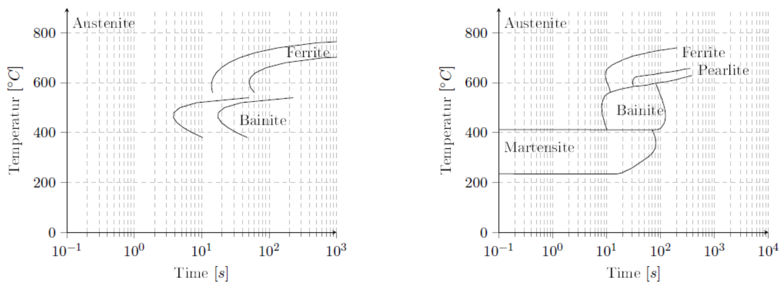


Figure 4: Time temperature transformation (TTT) diagram and continuous cooling transformation (CCT) diagram for the steel used in this study.

A tool with plane surfaces and the possibility of being heated is used for quenching to martensite and isothermal bainite transformations. To achieve simultaneously double sided contact of the specimen with the tool, spring supported holders are used. In Fig. 5 a schematic drawing of tool and specimen is shown. During heat treatment in the tool a pressure of 20MPa is applied on the sample. The temperature in the tool is measured at six points 2 millimeters below the tool surface. In addition the specimen temperature is measured in three points along the gauge length.

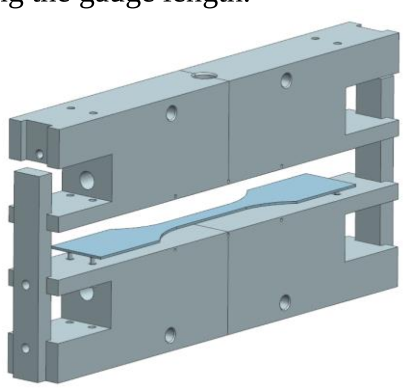


Figure 5: CAD drawing of the tool used to produce heat treated tensile test specimens.

In total fourteen phase compositions were produced. Three phase compositions are reference data for pure phases and eleven heat treatment schemes are used to produce samples consisting of ferrite-martensite, ferrite-bainite, bainite-martensite and ferrite-bainite-martensite.

All samples are austenitized at 900C for four minutes in advance to cooling procedures, a graphical illustration of the process is shown in Fig. 6.

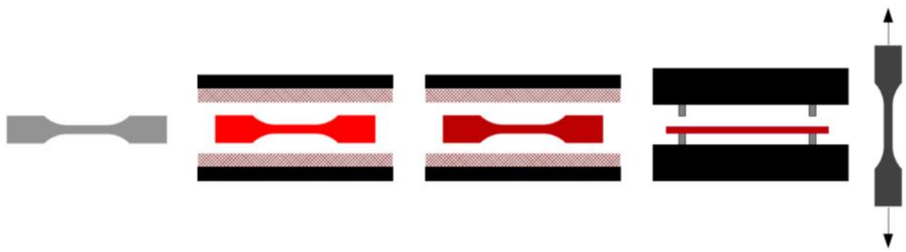


Figure 6: Production process of samples with different volume fraction of phases. A pre-cut tensile test specimen is austenitized at 900C. To form ferrite the sample is held at 650C in a second oven. Bainite is formed in a tool heated to 430C.

A schematic temperature history for the production of specimens is shown in Fig. 7. Ferrite is formed by holding at 650C in a furnace, bainite is formed at 430C. To produce bainitic-martensitic microstructures the samples are after austenitization cooled in the tool, different holding times are used to form varying volume fractions of bainite. The remaining austenite is transformed into martensite by quenching in water.

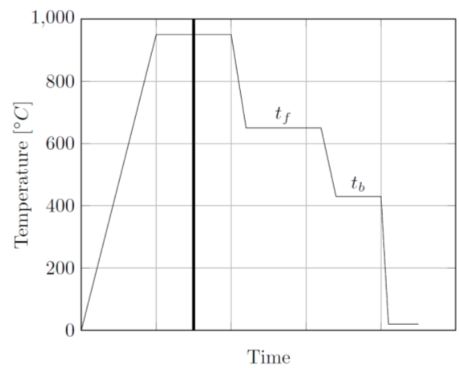


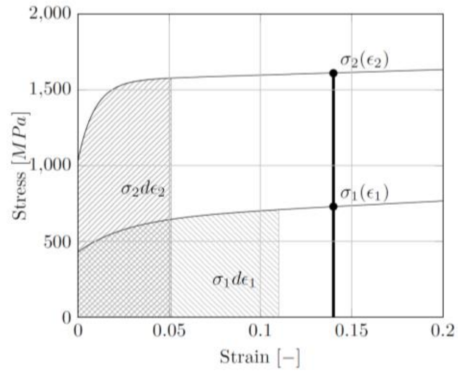
Figure 1: Schematically representation of the heat treatment used to produce different volume fractions of phases in dual- and multi-phase microstructures.

All previously described samples consist of two desired phases and small amounts of austenite not transformed. A sample containing three phases is produced using two holding temperatures, one for the ferrite and one for the bainite transformation.

4.2.Numerical simulation

Homogenization methods are widely used if a material consists of two or more constituents, phases or materials which exhibit different mechanical properties. The aim of the homogenization for alloys is the estimation of the macroscopic response depending on properties of phases or constituents.

Two phenomenological models are the iso-strain and the iso-work assumption. For the iso-strain model it is assumed that all present phases are submitted to the same strain. This is true for materials consisting of phases with similar mechanical properties. For materials where mechanical properties of the phases vary a strain partition is more realistic. The iso-work assumption uses equi-incremental mechanical work to decompose the strain into components applied to the different phases. In Fig. 8 a graphical representation of the two phenomenological methods is presented.



Figur 8: Schematic representation of the iso-strain and iso-work assumption.

Except for the two phenomenological models introduced, two methods are based on the work of Eshelby. The Eshelby solution solves the problem of a single ellipsoidal inclusion in an infinite matrix. An inclusion strain concentration tensor is used to compute the strain in the inclusion and the matrix. The interaction between phases must be taken into account if the volume fraction of inclusion exceeds a few percent. An assumption in this model is the perfect bonding between inclusion and matrix phase. Mori and Tanaka used the Eshelby solution for an ellipsoidal inhomogeneity but it includes certain effects of the inhomogeneity by taking the average strain in the matrix when all inhomogeneities are present. This is in contrast to the Eshelby solution where the average strain in the matrix is taken when none of the inhomogeneities are present. Weng proposed an analytical model for the estimation of the composite response. To estimate the elastic constants the secant moduli are computed, therefore its name secant method. The method in its original version assumes spherical inclusions in a homogeneous matrix. The user needs to decide which phase is the matrix phase, permuting the properties of matrix and inclusion yields fairly different results. Also the user has to take care if the assumption of the matrix phase is physically possible. The second model based on the work of Eshelby is called double-inclusion method. The main difference of compared to the previous model is the computation of the strain concentration tensor. In this method this tensor is computed by an interpolation between two strain concentration tensors. These tensors have the same input data where the first is calculated with one phase as matrix and the other as inclusion, the second is calculated with permuted phases viz. matrix and inclusion are reversed.

The homogenization scheme is extended with a phenomenological localization and fracture model. The localization and fracture model is an extension of a commonly used radial return mapping algorithm for isotropic von Mises plasticity. Fracture occurs when the localization function reaches its critical value or the maximum shear criterion is fulfilled. The phenomenon of localized deformation is typical for a wide range of solids. A strain localization, or shear band, usually develops during severe plastic deformation of ductile materials. During loading of a body the deformation is homogeneous until a point where it starts to confine to a narrow region. In this region intense straining occurs in the material. Usually, strain localization precedes fracture in tensile loading of ductile materials.

The homogenization and damage model is implemented in the commercially available finite element code LS-Dyna via a user defined subroutine. LS-Dyna solves the fundamental conservation equations in continuum mechanics using an explicit time algorithm. The intention of the material model is the use in sheet metal applications therefore it is implemented for shell elements. Thickness reduction is taken into account using plane stress iterations.

5. Results and deliverables

5.1. Delivery to FFI-goals

One of the programme goals is to create methods and tools for fast and effective automotive development. This project has increased the knowledge in the field of failure modeling which has made it possible to perform more accurate crash simulations. This reduces the cost and especially the time for the development of new hot stamped components for the automotive industry.

5.2. Results of four homogenization models

A general observation of experimental results is the behavior of the initial yield stress throughout all samples. Increasing amount of tougher phase increases the initial yield strength but not in a linear way as the phenomenological models predict. Concerning the prediction of the onset of plastic deformation the micromechanical models show better results. The computation of the composite response has a strong dependency on the difference of mechanical properties of pure phases. Ferrite and martensite show the largest difference of the pure phases, representing the upper and lower bound for all composites. The proper representation of these compositions has therefore the highest sensitivity to changes in the phase volume fraction. Looking at ferrite-bainite and bainite-martensite mixtures the mechanical properties of the phases in these composites the difference is less pronounced. In Fig. 8, two example plots for ferrite-bainite and bainite-martensite composites are shown. The prediction of ferrite-bainite samples showed good agreement with experimental results for the yield curve, the onset of necking is too late for all samples. Comparable to ferrite and bainite, bainite and martensite do not exhibit large contrast in mechanical properties. Though, a phenomena similar to a braze joint alters the mechanical response significant. Bainite-martensite composites with a volume fraction of less than 25% bainite in martensite show a stronger response than the model can predict.

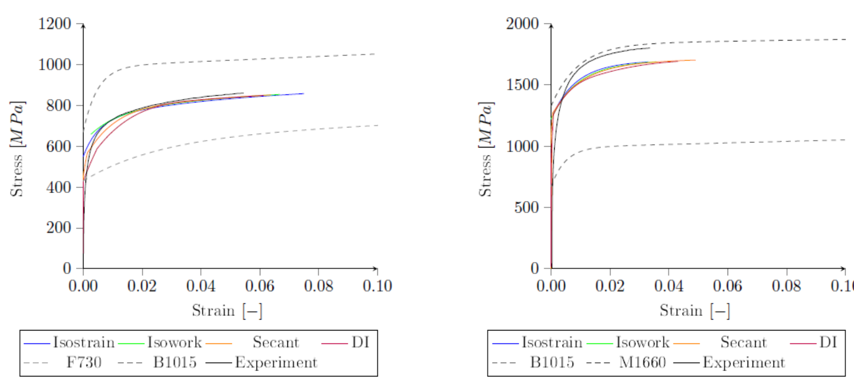


Figure 8: Comparison of yield stress of two samples. In the figure to the left 50% ferrite and 50% bainite, to the right 22% bainite and 78% martensite.

Additional to the two phase composites one mixture containing three phases is produced and compared to the models. In consistency with modeling assumptions taken for two phase samples the results is presented in Fig. 9. All models are in range of the experimental results. The secant method is the only model underestimating measurements. This is expected as this model usually showed the lowest resultant yield curve.

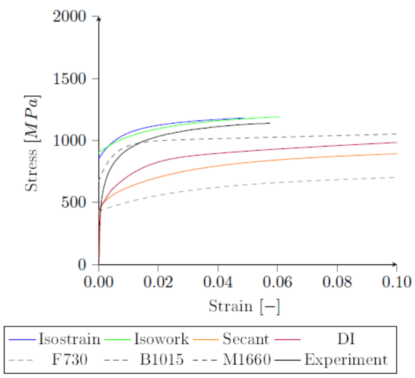
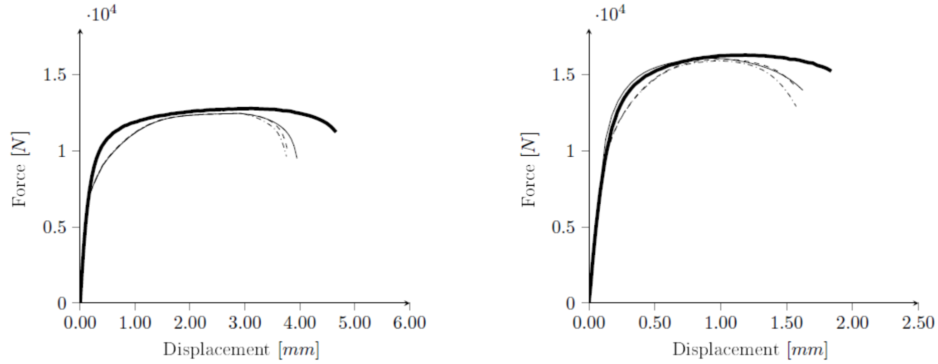


Figure 9: Comparison of yield stress of samples consisting of ferrite, bainite and martensite.

5.3.Evaluation of fracture in mixed microstructures

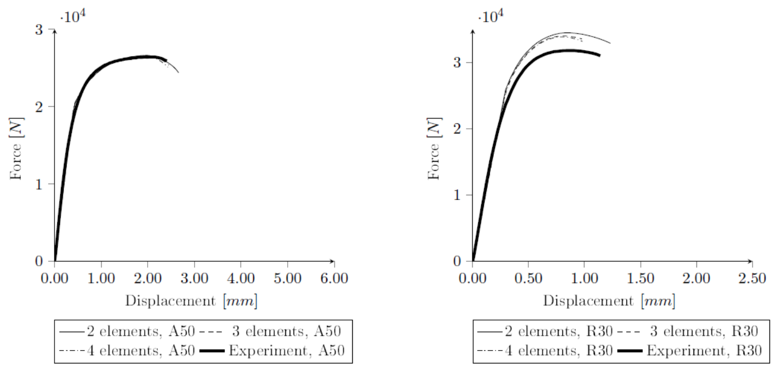
To test the damage function with mesh size compensation and the fracture model for a steel containing ferrite, bainite and martensite four samples with different volume fractions were produced and compared to finite element computations. From digital speckle photography measurements and an evaluation routine using a standard elasto-plastic material model in a radial return algorithm the fracture strain and the stress triaxiality during testing is obtained. Fracture observed in the experiment is always failure of the composite i.e. on macroscopic scale. In the finite element implementation a weakest link criteria is applied. In this case it is assumed that the composite fails if the fracture strain in one of the phases is reached.
Subsequent the result of the finite element analysis for three different mesh sizes is compared to the experimental results. Input data for the material model are the hardening curve, the damage parameters and the phase volume fractions of the present phases.

In the following Fig. 10 to 12, show the result of the finite element simulation for three selected phase compositions which serve as an example.



Figur 10: Comparison of experimental and numerical result of a sample consisting of 50% ferrite and 50% bainite. To the left straight test specimen, to the right notched.

In Fig. 10 the result for a ferrite-bainite composite with equal volume fractions is given. For this sample the prediction of the yield curve up to necking was already shown to be in good agreement in the study of different homogenization schemes. From this study it was already expected that the onset of necking would be overestimated and therefore the localized part of the yield curve would not be well predicted. The general observation is that the qualitative shape of the localization is in good agreement, for both, straight and notched tensile specimen.



Figur 11: Comparison of experimental and numerical result of a sample consisting of 23% bainite and 77% martensite. In the figure to the left the result for a straight test specimen, to the right notched.

For samples consisting of bainite and martensite see Fig. 11 to compare experimental to numerical results. In this case the homogenization schemes did not reach the level of the experimental result, literature suggests using the yield curve of martensite. This approach leads to good agreement compared to experimental results until the onset of necking for the straight specimen. For the notched specimen the numerical result and the experiment are not in good agreement. A possible explanation is the production process. The bainite transformation is a compared to the ferrite transformation fast. Due to handling small differences in time can occur and change the phase composition. The difference between experiment and calculated result is within the error margin of the phase characterization. From the study on homogenization methods it is known that the onset of necking is better predicted for this microstructure. The localization and fracture are close to experimental observations.

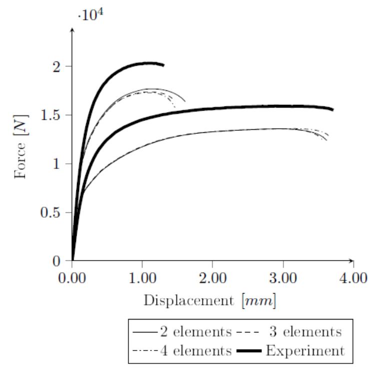


Figure 12: Comparison of FE and experimental result for a sample consisting of three phases. Upper curves represent the notched geometry, lower curves the straight specimen.

The sample consisting of three phases is for both test specimen geometries depicted in Fig. 12. Numerical results clearly underestimate the experimental observation but in terms of elongation before fracture good agreement is obtained. The material model uses for all composites the same pure phase input data and spherical inclusion shape, the only parameter to be changed is the volume fraction of present phases. Microstructure characterization of the samples showed a significant error margin and therefore the only parameter possible to adjust underlies an uncertainty.

6. Dissemination and publications

6.1. Knowledge and results dissemination

The results of this research project have been disseminated orally through presentation at an international conference and will be circulated in written through journal articles and licentiate thesis. Furthermore, the Division of Mechanics of Solid Materials at Luleå University of Technology has had a long and successful cooperation with Gestamp Hardtech AB concerning modeling and simulation of hot stamping. This research has led to the possibility of further developing, improving and evaluating material models and analysis methods for numerical simulations of the simultaneous forming and quenching process.
A complete thermo-mechanical material model for simulation of hot stamping and similar processes is implemented in the commercial FE code LS-Dyna and is used by Gestamp Hardtech AB in the product development process to adjust component and tool geometry. The model developed in this work is implemented in LS-Dyna and can be used in future component development.

6.2. Publications

S. Golling, R. Östlund and M. Oldenburg, Implementation of Homogenization Scheme for Hardening, Localization and Fracture of Steel with Tailored Material Properties, Proc. 4th International Conference on Hot Sheet Metal Forming of High Performance Steel, July 9-12 2013, Luleå, Sweden

7. Conclusions and future research

Applying the implemented material model on other microstructure compositions, taking some modeling assumptions into account, it is possible to get reasonable results for most composites. The main difficulty found is the reliable estimation of present phase volume fractions. Microstructures consisting of two distinct phases are easier to characterize and the error margin is comparable small. The three phase sample showed a larger error margin and therefore the model result is influenced as the phase volume fraction is the only parameter possible to change without altering modeling assumptions.

7.1. Future research based on results from Optus 2

In an ongoing study detailed models of spot-welds are investigated and compared to experimental results using DSP measurements. The aim is to validate the implemented model on spot welds and their proximity. This study is motivated by the use of spot welding as major method in joining components of a body-in-white. The experimental procedure includes blanks with two different base microstructures, one ferritic and the other fully hardened martensitic. These types of microstructures are commonly found in press hardened components with tailored material properties.

To further evaluate the material model it will be tested on component level. In a first stage a test specimen with a more component like geometry will be developed. The requirement of the specimen is the in-house production and testing in a standard tensile test machine. It is demanded that changes in the pre-cut of the specimen change the stress triaxiality in a designated area of the geometry. Experimental results will be compared to the material model implemented in LS-Dyna.

A set of samples consisting of ferrite and bainite with varying amounts of respective phase are produced. For all compositions five different specimen geometries, representing distinct stress triaxialities are available. This study aims to improve the understanding and modeling of fracture in this type of mixed microstructures. Due to the variety of specimen geometries it is intended to improve the calibration of fracture models.

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