Modeling of multi-phase microstructures in press hardened components: plastic deformation and fracture in different stress states

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Abstract. Hot stamping or press hardening is an industrialized technique with the aim of improving material properties by heat treatment and forming of a component in a single production stage. Within the field of press hardening the method of tailored material properties evolved. Components with tailored material properties possess different mechanical properties in designated areas. This paper presents an approach for modeling the mechanical response of mixed microstructures under different stress states. A homogenization method is used to predict the hardening of the material; the strain decomposition provides the possibility of applying a fracture criterion per phase. To validate the modeling approach for different stress states a set of samples with different notch and hole geometries as well as microstructural composition are produced. The combination of a homogenization method and a fracture criterion show good agreement with experimental results. The homogenization method is suitable to predict the hardening of the material with good accuracy. Fracture for different microstructural compositions is well predicted over a range of stress triaxialities relevant for sheet metal applications. It is concluded that the use of a homogenization method combined with a fracture model can be used to predict the mechanical response of mixed microstructures for a range of different stress states.

1. Introduction

Weight reduction while maintaining crash worthiness is a driving force for automotive manufacturers and their suppliers. During the last decade, the use of hot stamping in the production of ultra high strength steel (UHSS) components has become an important manufacturing process within the automotive industry. Hot stamping is a process where fully austenitized blanks are formed and sequentially quenched, allowing to produce high strength components from a low alloyed boron steel. The cooling rate of the blank can be controlled by special tool steel or tool coatings, modifying the thermal conductivity, or by heated tools. Depending on the cooling rate applied, the microstructure formed from austenite is in its mechanical properties situated between either tough martensite or soft, ductile, ferrite. Intermediate cooling rates promote the formation of bainite or mixed microstructures consisting of two or more phases. Within hot stamping the technique of tailored material properties evolved. Components with tailored material properties are manufactured using tools with heated and cooled sections. Using this approach tough sections can be placed adjacent to ductile regions within a single blank. Between those sections a transition zone forms where
mixed microstructures form. A detailed review on hot stamping and on tailored properties is given by [1, 2].

The modeling of the hot stamping process consists of predicting the phase composition after heat treatment, i.e. after forming and quenching. Constitutive models take the influence of deformation on the phase transformation into account as this has impact on the final properties [3, 4]. In this particular constitutive model a linear rule of mixture is employed to predict the flow properties of the final microstructure. Mean-field homogenization schemes are a more advanced method in modeling dual- or multi-phase materials. Most mean-field approaches rely on the fundamental work of Eshelby [5], here the disturbance in the stress/strain field caused by a single inclusion in a infinite matrix is described in a mathematical way. Based on this work, Mori and Tanaka reformulated the definition to account for interactions between inclusions at non-dilute concentrations. To better render the properties of a dual-phase microstructure a modeling approach termed double-inclusion (DI) is applied in the present work. The DI model uses an interpolation between two differing settings of the Mori-Tanaka method. The DI model as applied in the present work was proposed by Lielens et al. [6] and further explored by Doghri and Ouaar [7], where it was derived from Hori and Nemat-Nasser [8].

In the modeling of fracture in sheet metal applications typically the stress triaxiality is used to describe the stress state of a material. Describing the stress state by only one parameter is possible due to the assumption of plane-stress in thin sheets. The field of ductile fracture and fracture models is a wide and active research field. A concise review on different fracture models and their applicability is given in [9, 10]. In the present work a phenomenological, stress based fracture criterion is used to indicate fracture in the phases, where the overall ductility of the composite is governed by the weakest constituent present in the dual-phase material. The magnitude of stress vector (MSV) criterion was proposed by [11].

Ferritic microstructures allow high elongation before fracture occurs, this is advantageous in component sections where deformation is permitted or desired. Typical examples are the lower section of a B-pillar or zones where welds are placed. In the transition zone mixed microstructures of ferrite and bainite may form.

The aim of this study is to improve the understanding of the influence of phase composition on the ductility of a boron alloyed steel with special emphasizes on mixtures of ferrite and bainite. An isothermal heat treatment process is used to produce tensile specimens with varying amounts of ferrite and bainite. Furthermore, a set of specimens representing different stress states is produced for one mixed microstructure. This allows to study the influence of the stress state and the microstructural composition on fracture. The DI model extended with the MSV fracture criteria are implemented in the commercially available finite element code LS-DYNA.

2. Experimental approach
The low alloyed boron steel 22MnB5 is one of the most common steels used in automotive hot-stamping applications. Due to its relevance in industrial applications it is selected for the present study. In as-delivered condition it has a ferritic-pearlitic homogeneous microstructure, an aluminium-silicon coating protects the blank from oxidation during heat treatment and corrosion during service life. In total five different specimen geometries are cut perpendicular to rolling direction of the sheet using abrasive water jet cutting. The specimen geometries are depicted in figure 1a. Objective of the specimen geometries is to generate different stress states at fracture during tensile loading. A heat treatment process aiming for the reliable and repeatable generation of phase volume fractions is used. A ferritic-bainitic microstructure is chosen because of its significance in transition zones. In tailored properties components soft zone, ferritic microstructure, is produced by low cooling rates. Martensitic, tough zone material, is formed by quenching e.g. high cooling rates. In transition zones located between soft and tough zone the cooling rate is intermediate and mixed microstructures may form. The experimental heat
treatment process consists of austenitization at 950°C for five minutes, holding at 650°C to form ferrite and cooling in a plane tool which is heated to 430°C to transform remaining austenite into bainite. In total six different microstructural compositions are used in the present investigation. Samples F730 and B1015 are assumed as single phases i.e. they consist of predominantly one distinct phase. Samples labeled FB1-4 are mixed microstructures of ferrite and bainite with different phase content. In table 1 measured phase volume fractions are summarized. Tensile tests are conducted using a servo-hydraulic machine with a constant cross-head displacement rate of 0.1 mm/s. Digital image correlation (DIC) is used to determine the deformation gradient on the specimen surface. The necessary random surface pattern is generated by sand blasting of the specimen. The measured displacement fields and force recordings are the basis for the determination of the flow curve beyond the onset of necking and the equivalent plastic strain values at the location and instance of fracture initiation. Details on this evaluation process can be found in \[12, 13\]. Applying this evaluation approach the MSV fracture criterion can be calibrated using data already available in the method. In figure 2 fitting of model parameters to experimental data is depicted, details on modeling parameters can be found in \[14\].

3. Modelling
The modelling strategy follows the implementation presented in \[14, 15\], hence only a brief summary is given. The single phases properties are the input data to the homogenization and
Figure 2: Flow and fracture limit curves for each constituent phase. In (a), the power-law fit and the corresponding points obtained from experiments and image correlation. The fracture criterion is illustrated in (b), where squares, triangles etc. indicate fracture initiation as obtained from experiments, and the solid lines are the fracture limit curves according to the MSV criterion. The legend entries in (b) refer to the test specimen number as depicted in figure 1, and applies to (a) and (b).

fracture model. It is assumed that each constituent obeys $J_2$ elasto-plasticity with isotropic hardening according to the Ludwik equation.

$$\sigma_y^{(r)} = \sigma_{y0}^{(r)} + K^{(r)}\varepsilon^{(r)}m^{(r)} \quad (1)$$

Where $\sigma_y^{(r)}$ is the current yield stress, $\varepsilon^{(r)}$ the effective plastic strain. The parameters $\sigma_{y0}^{(r)}$, $K^{(r)}$ and $m^{(r)}$ are the initial yield strength, hardening parameter and hardening exponent, respectively. The superscript $(r)$ is a placeholder for the phase.

3.1. Homogenization scheme

A mean-field homogenization is applied to estimate the materials macroscopic stress and strain relations. On the microscale, the stress and strain fields within the constituents are expressed by their phase averages. The average fields on the macroscopic scale correspond to

$$\langle \sigma \rangle = \sum_r v_r \langle \sigma \rangle_{(r)} \quad , \quad \langle \varepsilon \rangle = \sum_r v_r \langle \varepsilon \rangle_{(r)} \quad (2)$$

where $v_r$ is the volume fraction of phase $r$. The overall stress and strain fields are related to the per-phase average fields by the stress and strain concentration tensors $A_r$ and $B_r$ through

$$\langle \sigma \rangle_{(r)} = A_r : \langle \sigma \rangle \quad , \quad \langle \varepsilon \rangle_{(r)} = B_r : \langle \varepsilon \rangle \quad (3)$$

Mean-field homogenization models usually differ in their expressions of the concentration tensors. However, the majority relies on the solution of the elastic field of a single inclusion embedded in an infinite matrix [5]. In order to account for interactions between inclusions modifications to the original expression where suggested by [16]. The difference to the original formulation is the replacement of the macroscopic field in equation (3) by the average matrix field, denoted with subscript m. If a multi-phase microstructure is idealized, a combination of non-dilute concentrations of inclusion phases, dispersed within a matrix phase, and the formation of interwoven networks need to be taken into account. To represent this necessity an interpolation
between two concentration tensors is performed. This approach is termed double-inclusion (DI) model and was proposed by [6]. For incremental elasto-plasticity, the average strain increment of inclusion phase \( r \) is related to the average strain increment in the matrix \( m \) by

\[
\langle \dot{\varepsilon} \rangle_{(r)} = B_{(r)} : \langle \dot{\varepsilon} \rangle_{(m)}, \quad \text{where} \quad B_{(r)} = \left[ (1 - \xi)B_{(r)} + \xi B_{(r)^u} \right]^{-1}
\]

and

\[
B_{(r)}' = \left[ I + \mathcal{E}_{(m)} : \left( D_{(m)}^{-1} : D_{(m)} - I \right) \right]^{-1}, \quad B_{(r)}^u = I + \mathcal{E}_{(r)} : \left( D_{(r)}^{-1} : D_{(m)} - I \right)
\]

Where the superscript \( l \) and \( u \) are the upper and lower bound, determined by permuting the matrix and inclusion tangent moduli. The function \( \xi_{(r)} \) is a smooth interpolation function depending on the volume fraction of phase \( r \).

3.2. Fracture modeling

Fracture in the mixed microstructure is modelled by a stress based criteria. The strain to fracture of the single-phase microstructures ferrite and bainite is determined using digital image correlation (DIC). The displacement field obtained by DIC is used in a stepwise modeling method which allows the determination of stresses and strains on the specimen surface, the method is in detail described in [13]. The obtained stresses are used to calibrate the magnitude of stress vector (MSV) criterion [11], details about the calibration can be found in [14]. The MSV criteria is formulated per-phase \( r \) and reads

\[
\langle MSV \rangle_{(r)} = \left( 3\langle \sigma^{mean} \rangle_{(r)}^2 + \frac{2}{3} \langle \sigma \rangle_{(r)}^2 \right)^{^{1/2}} = c_1(r)\langle \sigma^{mean} \rangle_{(r)}^2 + c_2(r)\langle \sigma \rangle_{(r)}^2 + c_3(r)
\]

3.3. Enhanced shell element

A broad range of ductile materials show the formation of a shear band in a narrow zone during severe deformation. The localization of strain is a typical precursor to the failure of a material because large deformations within the shear band lead to damage and fracture. The formation of a localized zone is the response of a structure loaded up to material instability. The size of the localization zone decreases upon further loading. In the finite-element method, the constant decrease of the width of the localized band causes mesh-dependent solutions because the mesh size defines the maximum width of the localized zone. To overcome this issue an enhanced shell element [17] based on the Belytschko-Lin-Tsay shell element [18] is used. The enhanced shell element is activated if strain localization occurs. An instability criterion derived from a bifurcation analysis is used for the indication of localization. This criterion is embedded into the plane-stress plasticity model. The necessary condition for bifurcation in the plane of a thin sheet is given by [19] and [20]. A in detail description of the implementation and discussion on the enhanced shell element is given in [21].

4. Results

Four different ferritic-bainitic microstructural compositions are presented. For samples FB-1 to FB-3 only specimen geometry #1 is considered, for sample FB-4 all specimen geometries are produced and analyzed. The microstructural composition is presented in table 1 and specimen geometries in figure 1. The focus of this study is primarily on the predictive capabilities of the DI homogenization approach combined with the MSV fracture criteria.

In figure 3a the influence of different phase compositions on the overall ductility is depicted. The constitutive model is integrated using a constant stress triaxiality of \( \eta = 0.57 \) which corresponds to the average value obtained by evaluation of the experimental measurements of specimen geometry #1. Comparison of measured and calculated overall ductility on material
point level are illustrated in the space of macroscopic equivalent plastic strain at fracture $\bar{\varepsilon}_f$ and the relative volume content of constituent phases. In the homogenization scheme ferrite is seen as the matrix phase even at high volume fractions of bainite, bainite is therefore seen as the inclusion phase. In the homogenization scheme spherical inclusion geometry is assumed. For spherical inclusions volume fractions above the maximum packing concentration of $(v_i)_{\text{max}} \approx 0.75$ is physically not meaningful and due to this calculation for volume fractions exceeding this value are not included. Permuting ferrite to inclusion and bainite to matrix is feasible but did not prove to yield a change in results. This is explained by the strain/stress concentration into the ferrite phase indicating failure even for low amounts of ferrite in a bainitic matrix. Fracture is indicated in ferrite irrespective set as matrix or inclusion phase for all volume fractions presented. A general observation is that the modeling approach underpredicts experimental results for all phase compositions presented. For sample FB-4 five different specimen geometries, see figure 1, are produced and analyzed using DIC. The equivalent plastic strain at fracture $\bar{\varepsilon}_f$ and the stress triaxiality $\eta$ are determined from experimental measurements and compared to numerical results in figure 3b. For the modeling of fracture a weakest link criteria is assumed i.e. if one of the constituents reaches its critical value the composite fails. Generally, the composite does not exceed the fracture strain of a single phase microstructure. For all specimen geometries and phase compositions fracture is indicated in the ferrite phase. For stress triaxialities up to $\eta = 0.5$ measured results agree well with the calibration of single phase ferrite, these results support the assumption of the weakest link criteria. On microstructural level the deformation localizes into the ferrite, hence causing fracture in the soft phase. For samples with higher stress triaxialities, fracture is also indicated in ferrite but occurs earlier compared to the single phase. The DI model is used to calculate the macroscopic strain at fracture. This strain value corresponds to the plastic strain in the mixed microstructure at the point where the weakest link fails.

The constitutive model is implemented in the commercial available finite element software LS-DYNA using a user-defined subroutine. To compensate for mesh size sensitivity an enhanced user-defined element is used. Four of the possible five specimen geometries are used in finite element simulations with mesh size of two millimeters. The shear specimen has a finer mesh of 0.3mm in the critical cross-section, a refinement is necessary as the mechanical response would be overly stiff otherwise. Due to the mesh refinement the enhanced shell element is not possible to use and a standard Belytschko-Tsay element is used instead. The effectiveness of the enhanced

Figure 3: In (a), ferrite matrix with bainitic inclusions. Results obtained by a constant triaxiality corresponding to specimen geometry #1. In (b) strain at fracture at different stress triaxialities for sample FB-4.
Figure 4: Force-displacement curves for the notched tensile specimen #1, with a dual-phase microstructure consisting of various volume fractions of ferrite and bainite.

shell element in compensating for different mesh sizes is shown in figure 4. For the phase composition FB-1 to FB-3 specimen geometry #1 is computed with mesh size of 1.5\text{mm} and 3\text{mm}. Comparison of numerical results for this two mesh sizes show good agreement. Fracture of the specimens is indicated at a higher elongation compared to experimental results. This is contradicting the result shown in figure 3a where fracture in the constitutive model is indicated before reaching experimental values. Explanation for this discrepancy is how the constitutive model is evaluated. On material point level, figure 3a, a constant stress triaxiality is used while in the finite element model the stress triaxiality during loading changes. Reason for the change in triaxiality is the deformation of the geometry during loading.

![Force-displacement curves](image)

Figure 5: Comparison of experimental results and prediction made using the implementation of the DI-model in combination with the MSV-fracture criteria in the finite element program LS-DYNA.

During mechanical testing, force and elongation are measured a comparison to numerical results is shown in figure 5. The presented experimental results are the average of seven tested samples for each specimen geometry, the standard deviation is indicated by bars. A general observation of experimental tensile test results is the low scatter of results. This indicates that the heat treatment process has a good repeatability. Results of the finite element analysis overpredict the experimental results at lower deformation levels, with increasing elongation good agreement is obtained. The deviation at initial loading can be explained by the used formulation describing the hardening of the phases. The Ludwik equation shows reduced accuracy at low
effective plastic strain values, using a different description could improve results. From the results presented in figure 3b the indication of fracture on material point level and its accuracy could already be seen. The result as provided by the finite element implementation corresponds to this expected result. For the shear specimen the mesh size is comparable small and captures the shear band relative good and hence the prediction of fracture is in good agreement without using the enhances shell element.

5. Conclusion
A finite element modeling approach using a mean-field homogenization scheme, a stress based fracture criteria and an enhanced shell element is applied. The input data for the model are measured properties of the single phase microstructures ferrite and bainite. The homogenization scheme predicted the hardening of four mixed microstructures with reasonable accuracy. Deviations from experimental results could eventually be minimized by a different formulation of the hardening law. The compensation for mesh size sensitivity shows applicable results for the range of presented mesh sizes. The embedded band element causes only a minimal increase in computational time and is hence interesting for larger models as found in industrial applications. Advantageous for calibration of fracture data is that no mesh regularization functions needs to be calibrated for different mesh sizes. The prediction of fracture of mixed microstructures shows good agreement compared to experimental observations. For one mixed microstructure different stress states are evaluated and good agreement was found.

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