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Characterization of ductile fracture properties of quench-hardenable boron steel: Influence of microstructure and processing conditions

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ABSTRACT

Developments of the hot stamping technology have enabled the production of components with differential microstructure composition and mechanical properties. These can increase the performance of certain crash-relevant automotive structures by combining high intrusion protection and energy absorption. This paper presents a comprehensive experimental investigation on the flow and ductile fracture properties of boron-alloyed steel with a wide range of different microstructure compositions. Three types of dual phase microstructures at three different volume fractions, and one triple phase grade, were generated by thermal treatment. Flow curves extending beyond necking and the equivalent plastic strain to fracture for each grade was determined by tensile testing using full-field measurements. The influence of phase composition and microstructural parameters were further investigated by means of a multi-scale modeling approach based on mean-field homogenization in combination with local fracture criteria. Inter-phase and intra-phase fracture mechanisms were considered by adopting two separate fracture criteria formulated in terms of the local average stress field. The micromechanical model captures with useful accuracy the strong influence of microstructure and processing conditions on the flow and fracture properties, implying promising prospects of mean-field homogenization for the constitutive modeling of hot stamped components.

1. Introduction

Continuous efforts by automotive manufacturers to reduce vehicle weight is of paramount importance to meet emissions legislation and reduce fuel consumption, while still maintaining or increasing passive safety in crash situations. The increase in crashworthiness to weight ratio is partially addressed by the application of new advanced materials and manufacturing processes. One such technology is the simultaneous forming and heat treatment of boron alloyed sheet metal components, termed press-hardening or hot-stamping. During the last decade, much effort has been put in developing the manufacturing process to enable the production of components with spatially varying microstructure and properties, termed tailored properties (TP) components. Using special tool technology, with differential in-die cooling rates by heated tool sections and/or reduced thermal conductivity of the tool material, is one approach to obtain the desired microstructure composition and variation thereof within the final component. Distributed mechanical properties can be advantageous in terms of crash performance for certain parts of the vehicle structure, combining high intrusion protection and energy absorption.

To support the current development, a systematic investigation of the relative influence of various microstructural constituents on the overall flow properties and ductility of quench-hardenable boron alloyed steel is needed. To this end, we have designed processing routes to produce tensile specimens with a comprehensive range of different microstructures. These include dual phase ferritic–martensitic, ferritic–bainitic and bainitic–martensitic compositions, and a triple phase grade consisting of ferrite, bainite and martensite. Additionally, the aim of the current work is to explore the possibilities of a multi-scale modeling approach to ductile fracture prediction. Specifically, if the significant variations in strength and ductility arising from microstructural effects can be captured with useful accuracy, at a computational expense which can be used in crashworthiness predictions of automotive components with tailored properties. Developments concerning the constitutive modeling of boron alloyed steel that takes into account the processing history have been proposed by several investigators. Åkerström modeled the austenite decomposition into daughter phases during continuous cooling and extended it

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with a mechanical module to simulate the complete press hardening process [1,2]. In press hardening the boron alloyed steel 22MnB5 is a common choice in industrial application as in research and hence thoroughly investigated. Modeling the process from austenitization to finished product relies on in depth knowledge of parameters influencing the microstructural composition and the mechanical properties of the finished product. Besides the cooling rate the importance of considering hot plastic deformation in isothermal and non-isothermal forming operations is pointed out [3–5].

Constitutive models for the use in hot stamping applications have typically been formulated with microstructure dependent coefficients, see e.g. [6–9]. An alternative route is to estimate effective material properties based on the properties of the constituent phases and arrangement at the microscale. Homogenization schemes are numerical or analytical methods, devised to estimate macroscopic effective constitutive properties based on the microstructural behavior. Belonging to numerical methods, the computational homogenization is based on discretized microgeometries for which they aim at fully accounting for the interactions between phases.

Mean-field homogenization (MFH) approaches are analytical (semi-analytical in case of non-linear constituents) where the microfields within each phase are approximated by their phase averages. Approximations concerning field fluctuations, geometry and interactions at the microscale render a less computationally demanding scheme. The microgeometry enters the formulation through statistical measures such as volume fractions and phase topology. They provide estimates of the composite material behavior and the average stress and strain fields as well as deformation histories within each present phase. A survey of these types of homogenization methods can be found in [10–12]. Fracture models can be formulated in terms of these microscopic average fields in order to estimate the ductility of the steel with respect to microstructure and process history. Methods to estimate the effective ductility of heterogeneous metals by a combination of MFH and various damage and/or fracture models have been proposed in the literature. Tekoglu and Pardoen [13] integrated a Gurson type damage combined with MFH, where the damage model was applied to the homogenized material in a multi-step approach. They considered an elasto-plastic matrix material reinforced with elastic particles with reference to cast aluminium alloys. A systematic study of the influence on flow behavior of the microstructural parameters of dual phase steels consisting of ferrite and martensite with preliminary results on fracture were presented by [14].

Ductile fracture is a field with intensive research focus for different materials and loading conditions. The microstructure of a material has a strong influence on fracture properties, typical influence factors are voids, inclusions and micro cracks. The nucleation of voids, their growth and coalescence, is usually seen as the predecessor of ductile fracture. Recently, Bai and Wierzbicki [15] published a comparative study on 12 ductile fracture models and divided them into three groups, physics based, empirical and phenomenological models. Two general types of approaches to capture ductile fracture are described in the literature [16]. The first approach utilizes damage accumulation within the continuum, these models couple constitutive and fracture model. The second approach assumes fracture as a sudden event in an undamaged continuum where failure is postulated if the stress and strain state reaches a critical limit. In the literature the former type is referred to as coupled and the latter as uncoupled fracture modeling. In the field of physics based, coupled, constitutive and ductile fracture models the stress-state dependence caused by growth and coalescence of micro-defects using numerical simulations of unit cells and experimental observations over a wide range of triaxialities is studied and good correlation is found [17,18]. Li et al. [19] present a detailed review of coupled and uncoupled damage criteria which are implemented in a commercially available FE code and compared to experimental results of tensile and compression tests with different specimen geometries. Malcher et al. [20] extended the GTN model with a shear mechanism and compared it to CDM based Lemaitre damage model and the Bai–Wierzbicki [21] model (termed B–W model), it is concluded that for high stress triaxiality the B–W model is in closer agreement with experimental results compared to GTN and Lemaitre's model, while for low triaxialities all constitutive models have limitations. For completeness it should be mentioned that the B–W, like the Johnson–Cook [22] model and CrashFEM [23], is an empirical based model. Among the phenomenological models are the oldest fracture models proposed, the maximum shear stress (MSS) and the Mohr–Coulomb criteria, for both aforementioned models literature reports modified versions. Cockcroft and Latham [24] proposed a ductile fracture criteria which integrates the maximum principal tensile stress over incremental plastic strain i.e. the energy density is calculated. Among the phenomenological fracture criteria the magnitude of stress vector (MSV) criteria was proposed more recently [25]. The MSV criterion showed good results in comparison to a number of phenomenological and empirical fracture criteria. Phenomenological models captivate due to their simplicity in calibration, usually only few specimen geometries are needed to obtain a small number of parameters.

Concerning quench-hardenable boron steel, recent experimental investigations have focused on materials characterization and on the manufacturing of components with distributed mechanical properties, among other aspects. In traditional hot stamping or press hardening the material properties are obtained by quenching of the blank. In order to obtain spatially varying mechanical properties within a single component special tool design and/or tool materials are necessary. The thermal conditions necessary to obtain TP components are a major field of interest. The tool design utilizes in-die heating and cooling as well as two different tool steels with varied thermal conductivity. A u-shaped beamed is formed showing martensite formation in the cooled section and a ferritic microstructure in the heated tool section [26]. Experimental evaluation of parameters influencing the press hardening process is performed on lab-scale TP component using in-die heating and cooling technology. The influence of tool temperatures and temperature gradients on phase formation is a crucial factor in the production of TP components [27]. Bardelcik et al. [6] based their constitutive model on experimental data obtained from specimens quenched at five different cooling rates, by forced air convection, producing microstructures that ranged from bainitic to martensitic, with intermediate mixed microstructures. In order to produce larger amounts of ferrite, a dual furnace and tool-quenching system can be used [28]. However, a study on the flow behavior and ductile fracture properties of boron steel with direct reference to the mechanical properties of the constituents and arrangement at the microscale is, to the authors knowledge, missing. Such an investigation is relevant in establishing predictive tools for determining performance envelopes of press hardened components with distributed microstructure composition.

In this work we employ a dual furnace and cartridge-heated plane quenching tool processing system to produce tensile specimens with an extensive range of microstructure compositions. Fracture data and flow curves extending to large plastic strains are obtained from tensile tests using full-field deformation measurements. We propose a multiscale approach to ductile fracture modeling within the framework of mean field homogenization. Two non-interacting fracture criteria are formulated in terms of the local average stress field, referring to inter-phase and intra-