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Evaluation of localization and failure of boron alloyed steels with different microstructure compositions

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ABSTRACT

Within the press hardening technology, where hot sheet blanks are simultaneously formed fixed and quenched, new methods with differential thermal treatment come to light. With controlled tool temperature variation, components with tailored properties can be produced. Automotive components combining high energy absorption and intrusion protection in a crash situation are feasible. In the present work the mechanical properties of three different material qualities, beginning with the same base sheet metal subjected to different thermal histories, are investigated. A strategy for modelling post-necking response and crack initiation using shell elements larger then the typical bandwidth of the localized neck is used. The model relies on a sequence of full field measurements throughout a tensile test; i.e. digital speckle photography (DSP). The full field experimental method allows for evaluation of mechanical and failure properties at different analysis lengths, providing parameters for a model which accounts for shell element size. Additionally the model contains a strain based failure criteria as a function of stress triaxiality. Good correlations between a simulated tensile test and experimental results were found. A detailed metallographic study of the three grades was performed and is presented.

1. Introduction

The increasing demand to reduce vehicle weight in the automotive industry has led to an increase in use of ultra high strength press hardened safety structures. The press hardening process uses boron steel blanks which are first austenitized at a temperature of ~900 °C and then formed and quenched between cold tools. The coming generation of these components can have tailored mechanical properties, providing additional means for designing the structural response in a crash situation. Soft zones in certain areas of the component can give an advantageous crash deformation mode, whilst retaining homogeneous thickness. Varying properties can be obtained by controlling the cooling rate during the forming process. By controlled tool temperature variation, zones of bainitic–ferritic microstructure with continuous transition to ultra high strength martensite gives the desired mechanical properties. The final microstructure composition of a press hardened part can be predicted by finite element simulations using the constitutive model suggested by Åkerström et al. (2005). This is based on modelling of the decomposition of austenite into daughter phases during simultaneous forming and quenching (Åkerström and Oldenburg, 2006). Material parameters for boron alloyed steel where estimated in Åkerström et al. (2007).

An important precondition for the application of tailored components in vehicle structures is the characterization of deformation and fracture properties of the different material grades present in the component. This study comprises of evaluation of mechanical properties including post-necking and failure behaviour three material grades. The material grades are produced by press hardening of a boron alloyed steel with different thermal histories according to those typically used for soft zones. They are labelled HT400, HT550 and HT800 according to their yield strength.

During initial tensile plastic deformation of a sheet metal, plastic strain is generally distributed uniformly within the volume. If further loaded, the plastic strain often localizes first forming a diffuse neck and finally a localized neck preceding rupture. Once a neck has formed, subsequent straining is confined within the neck. This causes an instability when the increase in stress due to decrease in load-carrying area is greater then the increase in load-carrying ability of the metal due to strain hardening. The rate of decrease in cross-sectional area may also be accelerated due to material deterioration caused by ductile plastic damage. Localized necking is the dominant mechanism leading to fracture of safety components in a crash.

In this work the localization process is observed experimentally using full field digital speckle photography (DSP) measurements in

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accordance with the method used by Eman (2007). The DSP method produces a two-dimensional displacement field determined at a very small measuring length compared to ordinary tensile testing with extensiometer. In this work a smallest measurement length of 0.5 mm is sufficient for capturing localization and obtaining material data, however, higher resolutions are possible which was discussed in Eman (2007). Calculation of the strain field is described in Eman (2007), where the theoretical background can be found in textbooks such as Bonet and Wood (2008). Hencky's logarithmic strain tensor is used. With this method the evolving strain field during a tensile experiment can be measured over time, and the strain levels within the localized band surface up to rupture can be determined. Using digital image correlation for materials characterization is described further by Kajberg and Lindkvist (2004), who used an inverse procedure to obtain material parameters.

Finite element analyses using various yield criteria and constitutive relations have been widely applied to analyse plastic deformation of ductile materials and predict strain localization behaviour. Strategies to alleviate mesh-dependence includes rate dependant material description (Needleman, 1988), and non-local constitutive relations (Borst and Mühlhaus, 1992) in which a material characteristic length scale is introduced.

The aim of the current work is to be able to cost-effectively predict the mechanical response of the three investigated material qualities under large-scale industrial simulation circumstances using the finite element method. Traditionally, this precludes an element size small enough to spatially resolve localized necking, since the size of the localized zone is comparable to sheet thickness.

Approaches concerning the modelling of post-localization material behaviour under these circumstances with large spatial discretization (compared to the studied phenomena) has been presented in literature. See Kessler et al. (2009) where a post-instability strain is calculated based on element dimensions, to minimize mesh dependency on failure prediction. The objective of this work is similar in the sense that the intent is not to model the phenomenon of localized necking, but rather its effects on load response and subsequent rupture. This leads to a methodology adopted here which suggests that constitutive and failure parameters should be adapted to element size, by introducing an 'analysis' length scale into the yield equation. Analysis length is not viewed as a material parameter, but rather as a coupling between local plastic strain and the plastic strain calculated with at certain mesh size. From the experimental DSP evaluation at a small analysis length, parameters for a model which minimizes mesh dependency on both post-localization response and failure prediction can be determined.

2. Materials

The base steel material investigated is USIBOR 1500 P produced by ArcelorMittal. This steel contains boron which suppresses the nucleation of proeutectoid ferrite on austenitic grain boundaries, thereby increasing the hardenability. Prior to heat treatment, USIBOR 1500 P exhibits homogeneous distribution of pearlite and an equiaxed grain ferritic matrix. By a controlled tool temperature process in a plane hardening tool, the hot blanks are subjected to different thermal cycles. The sheet is first heated to austenitization temperature and then cooled at a controlled rate and finally post-cooled, see Fig. 1. Three different multi-phase microstructures were developed and characterized by a combination of light-optical metallography and electron backscattered diffraction. These grades are intended to be used in vehicle components with tailored properties. The microstructural phase fraction content of the materials is shown in Table 1. The addition of boron is a necessary requirement for a successful heat treatment to obtain these grades. Three different plasticity and fracture test specimen geometries are cut from the sheets, one with notch radius 30 mm, second with notch radius 10 mm and a third straight sample.

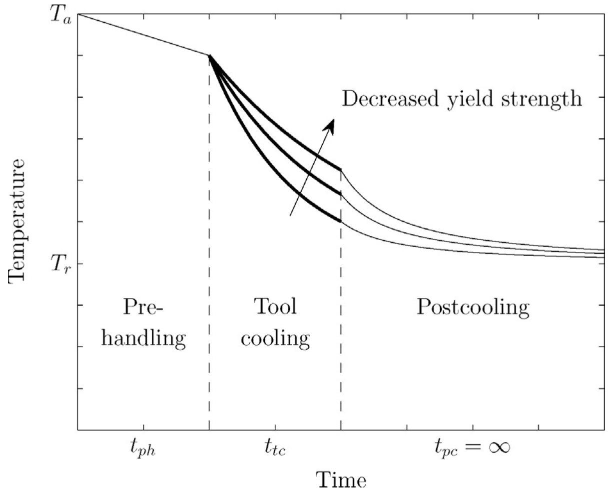

Fig. 1. Schematic illustration of temperature history with the definitions of process sequences. Temperatures illustrated are T_a which is the austenitization temperature and T_r denotes ambient temperature. t_{ph} is the time for pre-handling between furnace and tool, t_{tc} is the tool cooling time and t_{pc} is the post-cooling time.

3. Modelling

Mesh dependency issues in conventionally conducted finite element analysis of localization phenomena incorporates several aspects. Loss of ellipticity of the governing equations causes numerical solutions to be inherently mesh dependent as the width of the localized band is set by the mesh spacing (Needleman, 1988). The ability of the finite element mesh to resolve localized necking clearly influences numerical results. Both of these effects have a significant impact on computed stiffness and deformation characteristics. As earlier mentioned the aim of the current work is to include predictive capability of post-localization load response using elements larger then the localized zone. A modification of von Mises yield equation is suggested,

$$f = \overline{\sigma} - \sigma_y(1 - L), \quad \overline{\sigma} = \sqrt{3J_2}, \tag{1}$$

where σ_y is the current yield strength and J_2 is the second deviatoric stress invariant. L is termed the localization function introduced

Table 1
Phase fraction content.

Grade	Phase content (%)					
	Austenite	Ferrite		Bainite		Martensite
		Polygonal	Irregular	Upper	Lower	
HT800	0.75 ± 0.3	–	–	–	97.0 ± 2.0	1.00 ± 0.5
HT550	1.50 ± 0.5	–	25.0 ± 15.0	75.0 ± 25	≤5.0	2.25 ± 0.5
HT400	1.75 ± 0.5	≤0.50	95.0 ± 5.0	≤3.0	–	3.50 ± 1.0