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Plasticity and fracture modeling of the heat-affected zone in resistance spot welded tailor hardened boron steel

T.K. Eller[a,b,*], L. Greve[a], M. Andres[a], M. Medricky[a], H.J.M. Geijselaers[b], V.T. Meinders[b], A.H. van den Boogaard[b]

[a] Volkswagen AG, Group Research, P.O. Box 1777, 38436 Wolfsburg, Germany
[b] University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

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ABSTRACT

Five hardness grades of 22MnB5 are considered, covering the full strength-range from 600 MPa in the ferritic/pearlitic range to 1500 MPa in the fully hardened, martensitic state. These five grades form the basis for a hardness-based material model for the heat-affected zone found around resistance spot welds in tailor hardened boron steel. Microhardness measurements of resistance spot welds in all five grades are used to determine the location and shape of the heat-affected zone and for mapping of the hardness distributions into FE-models of the specimens used for model calibration. For calibration of the strain hardening of the heat-affected zone, a specially designed asymmetric uni-axial tensile specimen is used that features a well-defined strain field up to fracture initiation. Both the measured force–displacement curves and the strain fields are used as input for an inverse FEM optimization algorithm that identifies suitable strain hardening model parameters by minimizing the differences between experimental and simulated results. A strain-based fracture model is calibrated using a hybrid experimental/numerical approach, featuring two additional specimens in which fracture initiates in the HAZ under different stress states. Strain hardening and fracture strains are assumed to be linearly related to the as-welded material hardness. The calibration and modeling approach are validated by comparing measured and predicted force–displacement curves and strain fields of welded coupon tensile tests.

1. Introduction

The automotive industry is continuously working on the weight reduction of their vehicles, while maintaining or even improving the crashworthiness in accordance with increasing safety demands. For the production of crash-critical structural parts, the hot stamping process is gaining more and more popularity. In the conventional hot stamping process, boron steel blanks are fully austenitized in a furnace, after which they are simultaneously formed and quenched in cooled stamping tools. Due to the high cooling rates during the forming process, the austenitic microstructure transforms into martensite, causing the tensile strength of the material to increase from an initial 600 MPa to 1500 MPa in the final state. A general overview on current hot stamping technologies can be found in Karbasian and Tekkaya (2010), more in-depth views on the underlying microstructural transformations and on modeling approaches for simulation of the hot stamping process can be found in Naderi (2007) and Åkerström (2006), respectively.

Whereas the increased strength obtained during the hot stamping process allows the use of thinner gauge sheet metal, the reduced ductility and the accompanying likelihood of fracture create new challenges in the car body development process. During resistance spot welding, which is the most important joining technique in steel-based automotive production, the thermally unstable martensitic phase decomposes into softer microstructures. The resulting heat-affected zones (HAZs) that are found around the welds are potential areas for fracture initiation.

For local improvement of the energy absorption capacity, car manufacturers have successfully applied new production methods that allow the introduction of regions of reduced strength and higher ductility, e.g. by local reduction of the in-die cooling rate through the use of tool materials with varying thermal conductivities or by using increased die temperatures (George et al., 2012). The resulting softer material grades and potential transition zones contain mixtures of martensitic, bainitic and ferritic/pearlitic microstructures (e.g. Bardelcik et al., 2014; Eller et al., 2014). Recent reports have shown that even in boron steels with a bainitic

* Corresponding author at: Volkswagen AG, Group Research, P.O. Box 1777, 38436 Wolfsburg, Germany.
E-mail address: tom.karl.eller@volkswagen.de (T.K. Eller).

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Table 1
Chemical composition of the 22MnB5 used in this work (wt.%) (ArcelorMittal, 2011).

C	Mn	P	S	Si	Al	Ti	B
0.2–0.25	1.1–1.4	≤0.025	≤0.008	0.15–0.35	≥0.015	0.02–0.05	0.002–0.005

microstructure and a corresponding intermediate tensile strength of approximately 950 MPa, a softened zone is found around resistance spot welds (RSWs) in which fracture initiates under tensile loading (Golling et al., 2015).

To be able to fully exploit the possibilities of fully and tailor hardened boron steel components, it is of paramount importance to attain accurate predictive models of their crash response. Under complex loading conditions, such as the simultaneous bending and stretching of a B-pillar in a side crash, strains might localize in the softened HAZs, which ultimately can lead to fracture initiation. As cracks might propagate into the neighboring base material, leading to loss of structural integrity, the HAZs have to be considered in the simulation of the crashworthiness of a vehicle.

In the open literature, several different approaches for characterizing the heat-affected zone material behavior can be found. Some authors have used an instrumented indentation test, where local mechanical properties of fusion zone and surrounding HAZ are obtained from measured force–displacement curves. Material parameters can be identified from the measurements by various methods, e.g. by using representative stresses and strains that depend on indenter shape, using the method of artificial neural networks or by inverse FEM-modeling (Sun et al., 2014; Ullner et al., 2012; Zarzour et al., 1996). Although it is possible to obtain the basic mechanical properties of the HAZ, including the elastic modulus, yield stress and the hardening behavior up to relatively high strains, this method does not allow for calibration of the fracture characteristics of the material. Another method for characterizing RSW-nuggets (i.e. fusion zones) and heat-affected zones is to use miniature specimens extracted from actual welds (Tao et al., 2008; Tong et al., 2005). As the specimen width in the gauge section is generally in the sub-millimeter range, this method requires special testing equipment and careful specimen preparation to avoid scatter in the experimental results. Furthermore, when there are steep gradients in material properties, even a very small specimen may not exhibit homogeneous properties. Another approach is to apply the heat-affected zone temperature curve on larger specimens using a thermo-mechanical simulator (e.g. Burget and Sommer, 2012; Dancette et al., 2011). Obtaining the required heating and cooling rates was proven difficult and achievable results strongly depend on the sheet thickness used.

In this study, a novel, more pragmatic approach is proposed in which larger specimens with actual RSWs in the gauge section are used. For calibration of the HAZ strain hardening behavior, an asymmetric uni-axial tensile test is used. Measured force–displacement curves and strain fields are used in an inverse FE optimization scheme that optimizes the hardening model parameters in the frame of large plastic deformations. For characterization of the fracture behavior, two additional specimens are used: a central hole tensile test and a bending test, both featuring a HAZ in which fracture initiates. For validation of the calibrated HAZ models, coupon tensile tests with RSW are used. Five different grades of 22MnB5 are considered, covering the full range of possible hardness values from a soft ferritic/pearlitic microstructure to fully hardened martensite.

2. Material description and base material preparation

The boron steel sheet metal used in this work is 22MnB5 with a sheet thickness of 1.5 mm and a two-sided 150 g/m^2 aluminum–silicon coating. The as-received microstructure consists of ferrite/pearlite with an ultimate strength of 600 MPa. In the fully hardened state, the tensile strength increases to approximately 1500 MPa. The chemical composition is given in Table 1.

The 22MnB5-sheets in the as-delivered condition were first fully austenitized in a furnace at 950 °C. In order to create material samples with different hardnesses, the sheets were subjected to carefully controlled cooling processes in cooled and heated stamping tools. After 6 min in the furnace, the sheets were transferred to the tools, which took on average 3.8 s. Another 5.8 s passed until full closure of the tools. At the moment of tool closure, the sheets had cooled down to approximately 700 °C. The press, which applied a holding pressure of 12.5 MPa, was used to ensure good contact between tool surface and sheet, no plastic deformation was applied. The used tool temperatures and holding times are summarized in Table 2, together with the resulting microstructures and material hardness values. For a detailed description of the processing steps, cooling curves and the microstructural analysis, the reader is referred to Eller et al. (2016).

3. Resistance spot weld characterization of 22MnB5

The calibration approach for the HAZ material models presented in this work is based on larger specimens with actual RSWs in the gauge section. For identification of the material model parameters, detailed welding simulations will be performed in which local material properties are mapped into FE-simulations based on the local material hardness. In this section, a set of fixed welding parameters is defined that will be used for all RSWs in this work. The temperature history of the weld area, obtained from a welding process simulation, is correlated to hardness measurements in order to identify the different zones of the weld. Preliminary mechanical investigations with welded coupon tensile tests are performed to identify in which of the five considered hardness grades a RSW with corresponding HAZ leads to deterioration of the mechanical properties. At the end of this section, the required nomenclature that will be used throughout the remainder of this work is presented.

3.1. Welding parameters and heat cycle

All resistance spot welds considered in this work were made using the welding cycle presented in Fig. 1. A constant electrode

Table 2
Tool temperatures, holding times and the resulting microstructures and hardness values of the five 22MnB5 material grades. The critical heat-affected zone (CHAZ) hardness is the lowest hardness found in the HAZ.

	Thermal history	Base material microstructure	Base material hardness [HV0.1]	CHAZ hardness [HV0.5]
Hardness grade 1	As-delivered	Granular pearlite, ferrite	183	–
Hardness grade 2	Heated tool (500 °C, 20 s)	Upper bainite, pearlite traces	252	230
Hardness grade 3	Heated tool (425 °C, 30 s)	Lower bainite	320	248
Hardness grade 4	Heated tool (350 °C, 30 s)	Lower bainite	404	266
Hardness grade 5	Cooled tool (25 °C, 15 s)	Martensite	497	276