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The softened heat-affected zone in resistance spot welded tailor hardened boron steel: a material model for crash simulation

T.K. Eller[1,2], L. Greve[1], M. Andres[1], M. Medricky[1], H.J.M. Geijselaers[2], V.T. Meinders[2], A.H. van den Boogaard[2]

[1] *Group Research, Volkswagen AG, P.O. Box 1777, 38436 Wolfsburg, Germany*
[2] *Department of Nonlinear Solid Mechanics, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*

Abstract

A hardness-based model for tailor hardened boron steel is presented that takes into account the softened heat-affected zone of resistance spot welds. The computational model is designed for crashworthiness simulation of fully and partially hardened components obtained by tailored tooling. Five different hardness grades of 22MnB5 are used for model calibration. The proposed model is validated with a specially designed tapered tensile test specimen with hardness transition zone and resistance spot weld in the gauge section.

Keywords: Hot forming, Tailor hardened components, Resistance spot welding, Heat-affected zone, Crashworthiness

Introduction

In the last years, the hot stamping process has gained popularity as a manufacturing method for crash-relevant structural components in vehicles. Whereas hot stamped components benefit from their exceptionally high strength, allowing weight reductions while maintaining, or even improving crashworthiness properties, the reduction in ductility and the accompanying likelihood of fracture is a major issue in modern car design. For local improvement of the energy absorption capacity, regions of reduced strength and higher ductility can be introduced in components. One way to accomplish this is by locally reducing the in-die cooling rate through the use of increased die temperatures. The resulting tailor hardened components contain mixtures of martensitic, bainitic and ferritic/pearlitic microstructures, with tensile strengths ranging from 600 MPa up to 1500 MPa in the fully hardened state.

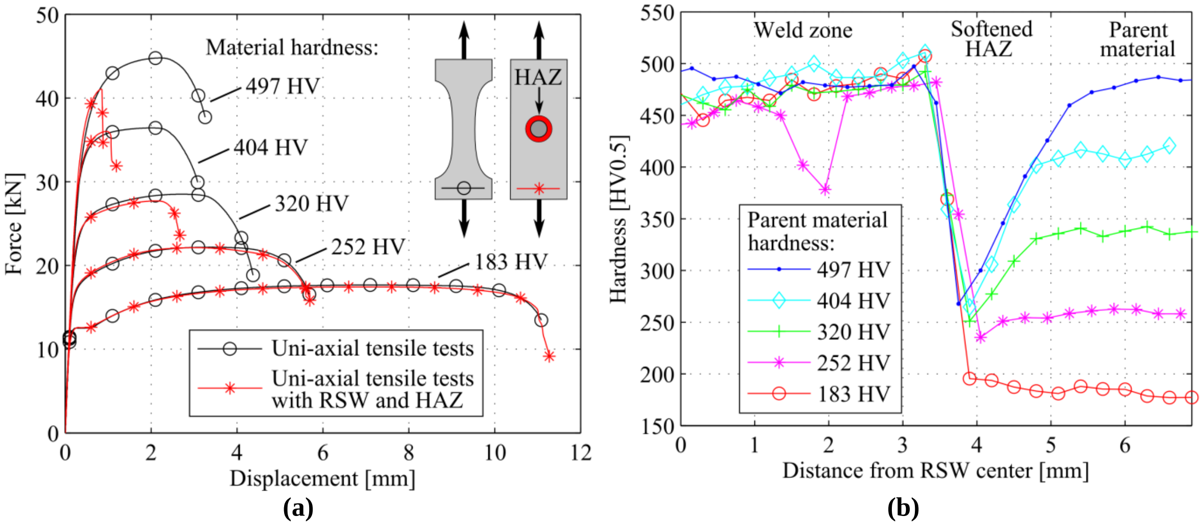
An important aspect that has to be considered when using hot formed steels for crash-relevant structural components is the change in microstructure in the proximity of thermal joints. During resistance spot welding, which is the most important joining technique in steel-based automotive production, thermodynamically unstable phases of the hot formed material decompose into softer microstructures. In particular the so-called softened heat-affected zones (HAZs) that are found around resistance spot welds (RSWs) are potential areas for fracture initiation, which have to be considered in the simulation of the crashworthiness of a vehicle [1,2].

The possibility of locally adjusting the strength and ductility within a single structural component results in a substantial expansion of the design space. Several additional factors have to be considered when using tailor hardened boron steels, such as the position and shape of hardness transition zones and the location of RSWs with corresponding softened HAZs. To be able to fully exploit the possibilities of tailor hardened boron steels, it is thus important to attain accurate predictive models of their crash response. Therefore, in this work, a hardness-based model for tailor hardened boron steel 22MnB5 is presented that takes into account the softened HAZ. The model is an extension to the hardness-based model presented in [3].

1. Model description

In previous work of the authors, a hardness-based constitutive model for tailor hardened 22MnB5 was presented [3]. Three hardness grades that cover the full strength-range of 22MnB5 were used as basis for the model. For the three considered hardness grades, plasticity and fracture models were calibrated using data from five different experiments: uni-axial, notched and central hole tensile tests, a shear test and a bulge test. By applying piecewise linear interpolation between the separate strain hardening and fracture models based and the material hardness, a hardness-driven material model was introduced that is able to approximate the behavior of arbitrary grades.

The model presented in [3] is extended to take into account the softened heat-affected zone that is found around resistance spot welds [1]. To enhance the resolution of the model, a total of five 22MnB5 hardness grades are considered with Vickers hardnesses between 183 and 497 HV. Figure 1a presents measured force-displacement curves of standard uni-axial tensile tests and tensile tests with resistance spot weld performed with these 5 hardness grades. The hardest two material grades clearly show the most severe reduction of displacement to fracture in the welded case. The grade of intermediate hardness (320 HV) still loses approximately 40% of its ductility after welding. In the softest two grades, no negative influence of the softened HAZ was found: fracture occurs in the base material relatively far away from the weld. This can be explained when looking at the hardness measurements presented in Figure 1b. Clearly, the severity of the hardness drop in the HAZ depends on the hardness of the parent material: where the hardest parent material (497 HV) has a hardness reduction of more than 200 HV, the second softest grade (252 HV) shows a reduction of approximately 20 HV. The softest grade (183 HV) does not feature a zone of reduced hardness at all.



(a) **(b)**

Figure 1: Measured force-displacement curves of welded tensile tests compared to results of corresponding unwelded tensile tests (a) and hardness measurements of resistance spot welds (b).

To obtain calibration data for the HAZ-extension of the hardness-based material model for 22MnB5, three different tests with welded specimens have been used: an asymmetric uni-axial tensile test, a central hole test and a bending test. The asymmetric uni-axial tensile test with softened HAZ was used for calibration of the HAZ strain hardening behavior. An inverse FEM optimization strategy was used to obtain the HAZ strain hardening model parameters. Measured force-displacement curves and strain fields were used as input [1,4]. For calibration of the HAZ fracture model under different stress states, all three welded specimens were used. The central hole specimen features a HAZ at the edge of the hole, where fracture occurs under uni-axial tension. In the bending test, a narrow specimen is used such that most of the deformation, and eventually fracture initiation, take place in the HAZ [1].

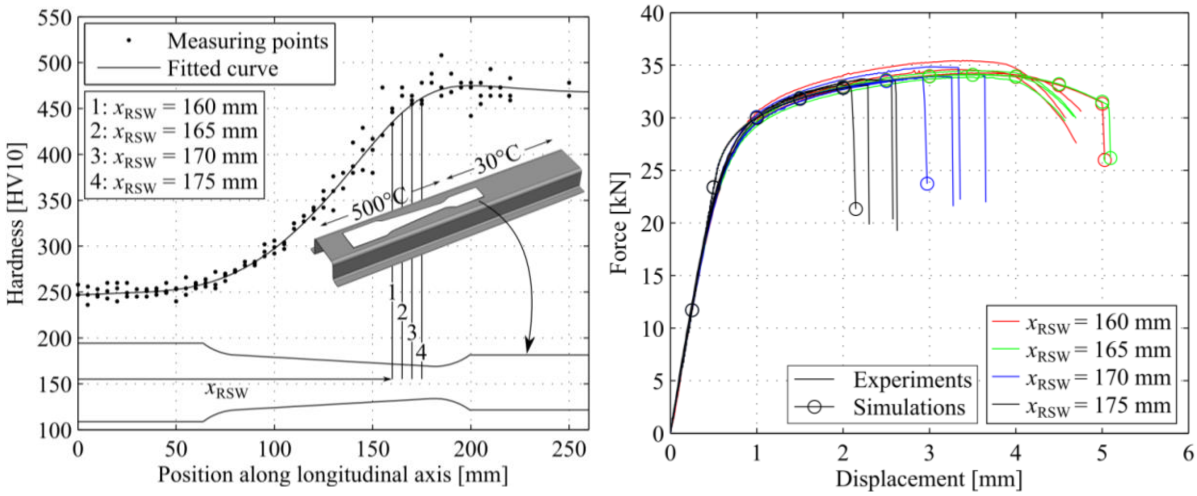
In the simulation models, the parent material hardness and the hardness of the softened heat-affected zones is mapped. The material properties of the individual elements are initialized from the corresponding hardness values. The calibrated model consists of a hardness dependent strain hardening model for parent material and softened HAZ and a stress-state and hardness dependent fracture criterion. The strain rate dependency is also defined as function of the material hardness. In the remainder of this work, a validation example is presented.

2. Model validation

To validate the proposed hardness-based model for tailor hardened 22MnB5, a specially designed tapered tensile specimen is used. The gauge section of this specimen, see Figure 2a, features both a hardness transition zone and a resistance spot weld. To obtain the specimens, as-delivered sheets of 22MnB5 have first been fully austenitized in a furnace at 950°C, after which they were formed to top hat sections in a tailored tool (see Figure 2a for an illustration of the top hat section and corresponding tool temperatures). The tailored tool consisted of two tool halves separated by an air gap of 0.1 mm. One tool half was heated to 500°C, the other tool half was actively cooled to a temperature of 30°C. The resulting hardness distribution along the longitudinal axis of the specimens was measured in steps of 5 mm, see Figure 2a. By varying the position of the spot weld through parameter x_{RSW}, fracture either takes place in the unwelded base material on the left-hand side of the gauge section or in the HAZ on the right-hand side.

The strain fields and the displacements were measured using a high resolution 2D-DIC system. The full length between the specimen shoulders, including the radii, was used as initial gauge length (L_0 = 135.8 mm) in order to have recognizable points for the virtual extensometer in the DIC-measurement. Four variants of the welded tapered tensile test have been considered: x_{RSW} = 160, 165, 170 and 175 mm, with corresponding pre-welded material hardnesses at the spot weld position of 435, 445, 454 and 461 HV (see Figure 2a). The simulations have been performed with a mesh size of l = 0.5 mm. Figure 2b shows the measured and predicted force-displacement curves, corresponding strain fields are presented in Figure 3a. Three test repetitions have been performed for each value of x_{RSW}, with excellent repeatability of both the force-displacement curves and the fracture location.

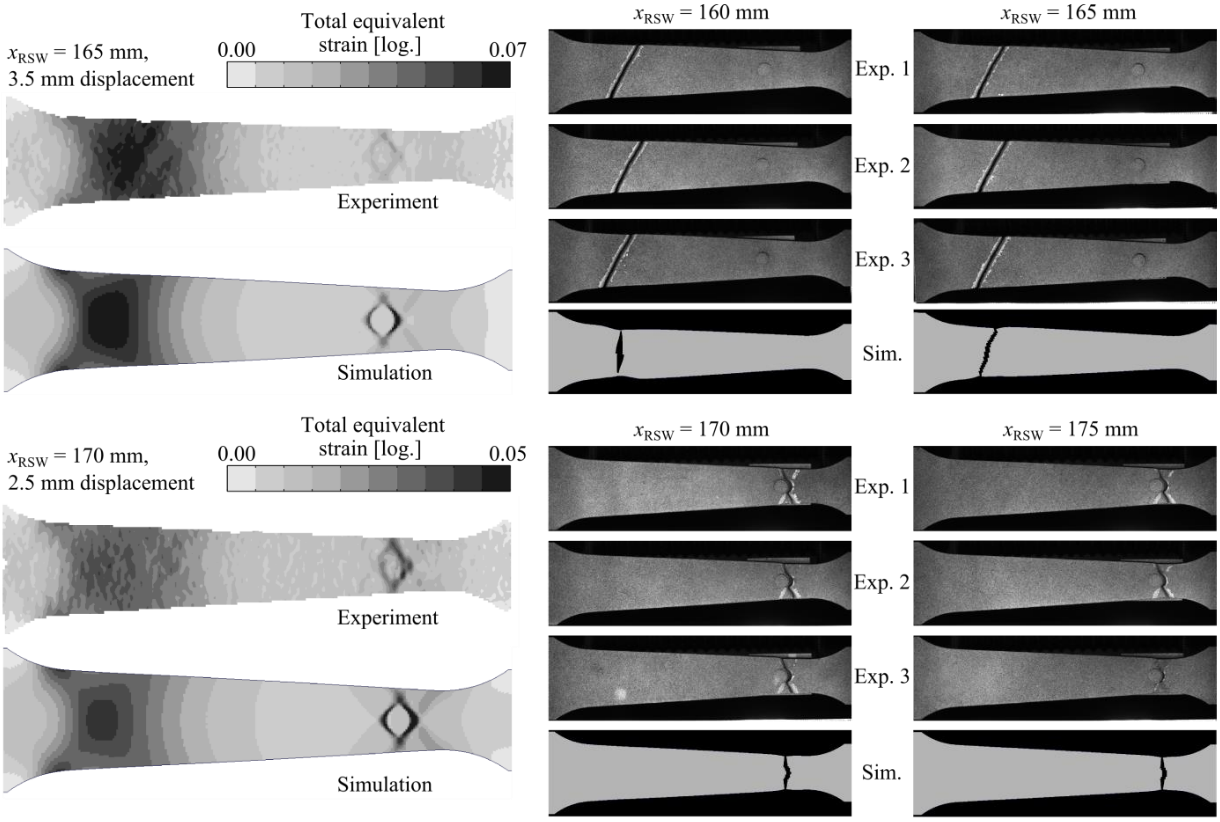
In the variants with x_{RSW} = 160 and 165 mm, fracture takes place in the unwelded material on the soft, left-hand side of the gauge section, see Figure 3b. This results in a gradual decrease of the force after F_{max} due to necking, until fracture initiates at approximately 4.7 mm displacement. The simulations predict fracture at approximately 5.1 mm displacement and show a similar gradual decrease of the force towards fracture. The location and magnitude of the strain localization on the left-hand side of the gauge section are predicted with good accuracy, see Figure 3a (x_{RSW} = 165 mm). This results in a correct prediction of the fracture location, as shown in Figure 3b. In the predicted strain fields, a mesh size of l = 0.5 mm was used. Due to the relatively large measuring field, the smallest obtainable facet size in the measurements was 2 mm. As a result, it was not possible to accurately capture the high strain gradients in the HAZ in the measurements.



(a) (b)

Figure 2: Measured hardness distribution along the longitudinal axis of the tapered tensile test specimen (a) and measured and predicted force-displacement curves of the welded tapered tensile tests (b).

When shifting the weld towards the narrow and harder side of the gauge section, the HAZ becomes more critical. This is related to the hardness drop in the HAZ, which is more severe in base materials with a higher hardness (see Figure 1b). A 5 mm shift of the RSW (x_{RSW} = 170 mm) causes the fracture location to shift from the soft side of the specimen to the HAZ on the right-hand side, resulting in a considerable reduction of the displacement to fracture. With a further increase of x_{RSW}, the displacement to fracture reduces even more. In Figure 2b it can be seen that the model captures this trend with good accuracy. The corresponding strain fields and fracture locations, see Figures 3a and 3b, are predicted with good accuracy as well.



(a) **(b)**

Figure 3: Comparison of measured and simulated strain fields of the welded tapered tensile tests (a) and pictures of fractures specimens compared to simulation results (b).

3. Conclusions

A hardness-based model for tailor hardened 22MnB5 has been presented that takes into account the softened heat-affected zone of resistance spot welds. Five different hardness grades of 22MnB5 have been used as basis for model calibration, ranging from soft ferritic/pearlitic material to fully hardened martensite. A specially designed welded tapered tensile test specimen, which features both a hardness transition zone and a spot weld in the gauge section, confirmed that hardness-based modeling of both base material and softened heat-affected zone provides excellent results.

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