IDENTIFICATION OF PLASTICITY MODEL PARAMETERS OF THE HEAT-AFFECTED ZONE IN RESISTANCE SPOT WELDED MARTENSITIC BORON STEEL

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ABSTRACT: A material model is developed that predicts the plastic behavior of fully hardened 22MnB5 base material and the heat-affected zone (HAZ) material found around its corresponding resistance spot welds (RSWs). Main focus will be on an accurate representation of strain fields up to high strains, which is required for subsequent calibration of the fracture behavior of both base material and HAZ. The plastic behavior of the base material is calibrated using standard tensile tests and notched tensile tests and an inverse FEM optimization algorithm. The plastic behavior of the HAZ material is characterized using a specially designed tensile specimen with a HAZ in the gage section. The exact location of the HAZ relative to the center of the RSW is determined using microhardness measurements, which are also used for mapping of the material properties into an FE-model of the specimen. With the parameters of the base material known, and by assuming a linear relation between the hardness and the plasticity model parameters of base material and HAZ, the unknown HAZ parameters are determined using inverse FEM optimization. A coupon specimen with HAZ is used to validate the model at hand.

KEYWORDS: Martensitic boron steel, Heat affected zone, Plasticity model, Hardening

1 INTRODUCTION

In the last years, the hot stamping process has gained popularity as a manufacturing method for crash-relevant structural components in vehicles. Whereas these 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. In particular the so-called heat-affected zones that are found around resistance spot welds in fully hardened boron steels are potential areas for fracture initiation, which have to be considered in the simulation of the crashworthiness of a vehicle.

The martensitic microstructure of hot stamped components, that is obtained when cooling rates exceed the critical threshold of 27 °C/s, is metastable and tends to decompose into softer microstructures when it is reheated to temperatures just below Ac1 (approximately 720 °C for the 22MnB5 used in this work [1, 2]). This softened zone is generally known as the sub-critical HAZ, in which martensite tempering is the controlling mechanism [3]. Unfortunately, this tempering of martensite cannot be prevented during the resistance spot welding

process, because of the continuously decreasing temperature distribution between weld pool and unaffected base material. The main decomposition products of martensite found in the sub-critical HAZ are cementite and ferrite, which cause the typical decrease in material hardness [4, 5]. The severeness of HAZ softening is known to be mainly dependent on welding parameters and martensite content: an increase in heat input during welding (e.g. by increasing welding times and currents) leads to increased softening in the HAZ [6]; the total extent of softening is proportional to the martensite content of the material [7].

In literature, several different approaches for the identification of HAZ material parameters can be found. Some authors have used an instrumented indentation test [8, 9], converting measured force-indentation depth curves to local stress-strain curves. Another direct method for nugget and HAZ parameter identification is to use miniature specimens taken from actual RSWs [10, 11], which then requires specialized testing equipment. A popular indirect characterization method is to use a Gleeble thermomechanical simulator, which is able to simulate the HAZ temperature history on larger specimens [12].

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In this work, a new approach is proposed that uses a larger tensile specimen with an actual RSW in the gage section. High resolution strain field measurements combined with force-displacement data are used as input for an inverse FEM optimization algorithm, which is able to determine the strain hardening behavior of the HAZ material up to large plastic strains. A coupon test with HAZ is used to validate the calibrated model at hand.

2 MATERIAL PREPARATION

The material used for this study is 22MnB5. Known by the commercial name Usibor® 1500 P, ArcelorMittal has provided the 22MnB5 steel grade with an aluminum-silicon coating that protects the metal against oxidation and decarburization during the press hardening process [13]. In the as-delivered state 22MnB5 has a ferritic/pearlitic microstructure, an ultimate tensile strength of 600 MPa, and a uniform elongation of 0.22. After quenching in cooled stamping tools, a fully martensitic microstructure can be obtained resulting in an ultimate tensile strength and uniform elongation of 1500 MPa and 0.06 respectively. The chemical composition of this material is given in Table 1.

Table 1: Chemical composition of the 22MnB5 used in this work (wt. %) [14].

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

2.1 BASE MATERIAL

The as-delivered sheets have a thickness of 1.5 mm and are first fully austenitized in a furnace at 950°C for approximately 6 minutes, after which they are transferred to a water-cooled stamping tool. After opening the furnace and taking the sheets out, transfer from furnace to tool takes on average 3.8 seconds, after which another 5.8 seconds pass until full closure of the tool. During the total transfer time of 9.6 seconds, the sheets cool down to approximately 700°C. The press, which is cooled to a constant temperature of 25°C, is solely used to ensure good contact between tool surface and sheet, no plastic deformations are applied. After a holding time of 15 seconds, the sheets are removed and left to cool down to room temperature in air. A measured cooling curve is superimposed on the CCT diagram of 22MnB5 in Figure 1, from which can be seen that the achieved cooling rates clearly exceed the critical cooling rate for martensite formation. Hardness measurements taken on polished cross sections of the as-treated base material showed an average hardness of 497 HV10.

Fig. 1 Measured cooling curve superimposed on the CCT diagram of 22MnB5

2.2 RESISTANCE SPOT WELDING

The resistance spot welds are made on the martensitic base material using a NIMAK C-type servo spot weld gun combined with a HWH control system. A constant electrode force of 3 kN is applied with squeeze and hold times of 2000 ms and 200 ms respectively. The squeeze time is used to ensure that the required electrode force has been reached at the start of the heat cycle. When the contact force between electrode face and outer surface of the sheet is too low, the electrical resistance and thus the heat generation will be excessively high leading to material expulsion, voids in the weld and electrode damage. The hold time is the time that pressure is maintained after the heat cycle and it allows the molten material to solidify before releasing the welded sheets. Two weld pulses with welding currents of 3.0 kA and 5.7 kA are applied with a 20 ms delay in between. An overview of the welding cycle is shown in Figure 2.

Fig. 2 Overview of welding cycle

3 EXPERIMENTAL WORK

3.1 HARDNESS MEASUREMENTS

In order to determine the location and geometry of the HAZ corresponding to a RSW made with the welding parameters and sheet thicknesses described in Section 2, both in-plane and cross-sectional surface hardness measurements are made. For this purpose, small samples are cut from the welded sheets and mounted in epoxy resin. For the cross-sectional measurement, the RSW is carefully cut along a symmetry plane. For the in-plane measurement, a 15 x 15 mm sample with the entire RSW is mounted and grinded until full removal of the electrode print. After several grinding steps up to 4000 grid SiC paper, Vickers hardness measurements are taken with a 0.5 kg load. For the cross-sectional measurement a grid spacing of 0.15 mm is used, resulting in a total of 1800 HV0.5 measuring points. For the in-plane measurement the grid spacing is 0.3 mm, resulting in 2500 measuring points. The resulting hardness maps are shown in Figure 3.

Fig. 3 Hardness maps of a RSW in 22MnB5

Both the in-plane and the cross-sectional measurement confirm the base material hardness of 490 – 500 HV found in Subsection 2.1. The material of the weld nugget, which was heated above the melting point and rapidly cooled, shows the same material hardness, corresponding to a martensitic microstructure. At 3.6 mm from the spot weld center, the lowest hardness value of the HAZ, approximately 275 HV0.5, is found. The in-plane measurement shows that the HAZ has a perfectly circular geometry in the x-y plane; the cross-sectional measure-

ment in the x-z plane reveals an elliptic shape of the hardness distribution.

3.2 EXPERIMENTS FOR BASE MATERIAL CALIBRATION

For calibration of the plasticity model parameters of the martensitic base material, standard uni-axial tensile tests and notched tensile tests with a 5 mm notch radius are performed. For both tests, quasi-static strain rates of 0.002 s^{-1} are applied, displacements are measured using a contact-type extensometer with sensor arms and a measuring accuracy of $\pm 1 \text{ }\mu\text{m}$. A small preforce of 60 N is applied to minimize the effects of specimen curvature and initial grip misalignments on the extensometer output. Force measurement inaccuracy is 0.5% starting from 0.5 kN. The resulting force-displacement curves are shown in Figure 4.

Full field strain measurements are performed for the notched tensile tests using a 3D digital image correlation (DIC) system. The DIC system, equipped with two cameras with each a resolution of 2448 x 2050 pixels, is connected to the material testing machine and able to receive both force and displacement signals, such that every measured strain field can be linked to a point on the corresponding force-displacement curve in Figure 4.

Figure 5 shows the measured surface strains in x-direction (ϵ_{xx}) along the longitudinal axis of symmetry of the specimens at displacements of 0.5 mm and 0.7 mm. At a displacement of 0.5 mm, which is approximately at the force maximum, a bell-shaped strain distribution is found with maximum strains of 0.05. At 0.7 mm displacement, two strain peaks are found on the specimen surface, corresponding to the two tips of an X-shaped through-thickness necking zone, see the illustration in Figure 5. The excellent repeatability of both the force-displacement curves and the strain field measurements is a beneficial result, because this will be the input for the optimization algorithm that determines the base material strain hardening parameters.

Fig. 4 Force-displacement curves of the uni-axial and notched tensile tests

Fig. 5 Total strains ε_{xx} of the notched tensile tests measured along the longitudinal axis of symmetry at displacements of 0.5 and 0.7 mm

3.3 EXPERIMENTS FOR HAZ CALIBRATION

For calibration of the HAZ plasticity model, a specially designed tensile specimen is used with the HAZ of an actual RSW specimen in the gage section. For this purpose, 1.5 mm thick sacrificial plates are spot welded onto 220 x 30 x 1.5 mm coupons using the welding parameters described in Subsection 2.2. The two welded sheets are then carefully separated by wire EDM, which was found to be a very suitable method for this application, because the thin wire can get in-between the two welded sheets and cut through the hard nugget without damaging the surrounding HAZ. The specimen contour is also cut using wire EDM to ensure a high surface quality and to avoid heat from affecting the material. An overview of the final specimen geometry is shown in Figure 6. In order to avoid scatter in the strain field measurements, the specimen is designed such that only one half of the HAZ is located in the narrow gage section, the other half lies in the specimen-shoulder, which has an increased cross-section. With this specimen geometry, necking and fracture always occur at the same location.

Fig. 6 Geometry of the tensile specimen with HAZ

Experimental setup and test settings are the same as for the base material samples described in the previous subsection. Both the resulting force-displacement curves and the measured strain fields, see Figures 7 and 8, show very little scatter. Note that the x-coordinate in Figure 8 corresponds to the x-coordinate of the hardness map in Figure 3. Two strain peaks are found on the specimen surface in

the area of the HAZ, again caused by through-thickness necking (see also Figure 5).

Fig. 7 Force-displacement curves of the tensile tests with HAZ

Fig. 8 Total strains ε_{xx} of the tensile tests with HAZ measured along the longitudinal axis of symmetry at a displacement of 0.4 mm

4 MATERIAL MODEL CALIBRATION

4.1 BASE MATERIAL PLASTICITY MODEL

In order to determine the strain hardening behavior of the martensitic base material, the force-displacement curves of the uni-axial tensile tests in Figure 4 are converted to true stresses (σ) and true plastic strains (ε_p). An average (σ - ε_p)-curve is extracted from the data and plotted in Figure 9. Because the conversion from forces and displacements to true stresses and true plastic strains is only valid up to the strain at which necking begins, experimental data only reaches up to a strain of approximately 0.035. The strain field measurements of the notched tensile tests in Figure 5, however, show local strains of almost 0.15, which means that extrapolation of the (σ - ε_p)-curve is required. For this purpose, both the classical Swift power law and a Voce type saturation law (Equa-

tions 1 and 2, respectively) are fitted to the experimental data, see Figure 9.

$$\sigma_{swift}(\bar{\varepsilon}_p) = k(\bar{\varepsilon}_p + \varepsilon_0)^n \quad (1)$$

$$\sigma_{voce}(\bar{\varepsilon}_p) = Y_0 + R_{sat}(1 - e^{-n_v \bar{\varepsilon}_p}) \quad (2)$$

From Figure 9 it can be seen that both laws provide acceptable fits for small strains, but behave very differently in the extrapolated area. Assuming that the true strain hardening curve lies somewhere in between these lower (Voce) and upper (Swift) bounds, both laws are combined using a strain-dependent exponential mixing law:

$$\sigma_y(\bar{\varepsilon}_p) = (1 - \lambda)\sigma_{swift} + \lambda\sigma_{voce} \quad (3)$$

in which mixing parameter λ is a function of $\bar{\varepsilon}_p$:

$$\lambda(\bar{\varepsilon}_p) = \lambda_{final} + (\lambda_{initial} - \lambda_{final})e^{-\alpha \bar{\varepsilon}_p} \quad (4)$$

where $\lambda_{initial}$ is the starting value of λ , representing the Voce-influence for small strains, λ_{final} is the final value of λ , representing the Voce-influence for large strains, and α is a shape parameter.

To identify the parameters of the exponential mixing law in the frame of large plastic deformations, an inverse FEM optimization scheme is used that takes into account both the measured force-displacement curves and strain fields of the notched tensile tests and the force-displacement curves of the uni-axial tensile tests (Figures 4 and 5). For this purpose, Equations 1-4 are implemented in the modular material model (MMM) framework [15] for the explicit FEM code VPS (Virtual Performance Solution) and used in combination with an isotropic Yld2000-2D yield function [16]. To ensure an accurate representation of the strain field, 0.1 mm underintegrated 8-node solid elements with one integration point are used.

Similar to the approach used in [17], the overall cost function Y to be minimized is defined by a weighted least-squares deviation between simulated and measured forces and strains:

$$Y(\mathbf{X}) = \beta Y_F(\mathbf{X}) + (1 - \beta) Y_\varepsilon(\mathbf{X}) \quad (5)$$

in which $Y(\mathbf{X})$, $Y_F(\mathbf{X})$ and $Y_\varepsilon(\mathbf{X})$ are the overall, the force and the strain field cost functions, respectively. Y_F contains the force-displacement curves of both the uni-axial and notched tensile tests:

$$Y_F(\mathbf{X}) = Y_{F,uni}(\mathbf{X}) + Y_{F,notched}(\mathbf{X}) \quad (6)$$

in which, e.g., $Y_{F,uni}$ is defined as:

$$Y_{F,uni}(\mathbf{X}) = \frac{1}{n} \sum_{i=1}^n \left(\frac{F_{sim}(d_i, \mathbf{X}) - F_{exp}(d_i)}{\frac{1}{n} \sum_{j=1}^n F_{exp}(d_j)} \right)^2 \quad (7)$$

where n is the number of sample points on the force-displacement curve and $F(d_i)$ is the force at sample point i . The strain field cost function Y_ε consists of the strain fields at displacements of 0.5 and 0.7 mm (see Figure 5) and has a similar definition as the one for the forces in Equations 6 and 7.

Fig. 9 Swift and Voce hardening laws fitted to experimental (σ - ε_p)-curve and optimized fit with exponential mixing law

Figures 10 and 11 show average curves of the experimental force-displacement results and the measured strain fields of the notched tensile tests. On both curves, 40 sample points (n) are defined at which the deviation between experimental and simulated value is calculated. A trust-region-reflective algorithm is used to minimize the cost function with $[\lambda_{initial}, \lambda_{final}, \alpha] = [0.5, 0.5, 1]$ as initial values. After a total of 10 iterations the algorithm stops because the step size is smaller than a predefined threshold.

Looking at Figure 10, it can be seen that up to the force-maximum the exponential mixing law does not have much influence on the simulated force-displacement curve, which is confirmed when looking at the simulated strain field at $d = 0.5$ mm, see Figure 11. This can be explained when looking at Figure 9: up to a strain of 0.04, the Swift and Voce laws are very similar, meaning that mixing them will not change much in the final result. At higher strains, e.g. after initiation of through-thickness necking ($d = 0.7$ mm in Figure 11), the lower and upper bounds diverge, leading to an increasing influence of the mixing law.

When comparing the simulation results with initial parameters to the simulation results with optimized parameters ('Step 10'), it is seen that both the prediction of force-displacement curves and strain fields is greatly improved. The final strain hardening curve, which is plotted as dashed line in Figure 9, seems to provide a better fit to the experimental data as well.

Fig. 10 Average experimental force-displacement curve of the notched tensile test with several simulated optimization steps

Fig. 11 Average curves of the measured total strains ϵ_{xx} along the longitudinal axis of symmetry of the notched tensile tests with several simulated optimization steps

4.2 HARDNESS BASED INTERPOLATION APPROACH

The specimen that will be used for calibration of the HAZ strain hardening parameters, see Figure 6, features a narrow transition zone from martensitic base material to the softer, tempered martensite of the HAZ. In the hardness maps of Figure 3, the lowest hardness value found in the HAZ is 275 HV, which is a reduction of 222 HV compared to the 497 HV base material. In the transition zone, the martensitic base material is tempered to a lesser extent, resulting in intermediate hardness values between 275 and 497 HV. Similar to the approach used in [18], the strain hardening behavior in the transition zone is assumed to be linearly related to the material hardness:

$$\sigma_y(\bar{\epsilon}_p) = (1 - X_{HAZ})\sigma_{y,BM} + X_{HAZ}\sigma_{y,HAZ} \quad (8)$$

in which $\sigma_{y,BM}$ and $\sigma_{y,HAZ}$ are the strain hardening equations for the base material and the softest part of the HAZ, respectively, and X_{HAZ} is the coeffi-

cient of the HAZ material within the convex combination of the two hardening models. X_{HAZ} is linearly related to the material hardness through:

$$X_{HAZ}(HV) = \frac{HV - HV_{BM}}{HV_{HAZ} - HV_{BM}} \quad (9)$$

where HV is the input hardness, HV_{BM} is the base material hardness and HV_{HAZ} is the lowest hardness value of the HAZ.

The hardness scans shown in Figure 3 are used for rotational symmetric mapping of the hardness distribution into an FE-model of the specimen, see Figure 12. At the start of the simulation, the material properties of the individual elements are initialized from the corresponding hardness values. To ensure an accurate representation of both the hardness distribution and the resulting strain field, the element size is reduced to 0.1 mm in the range of the HAZ.

Fig. 12 FE-model of the tensile specimen with HAZ with mapped hardness distribution

4.3 HAZ PLASTICITY MODEL

With the strain hardening parameters of the base material known and by assuming a linear relation between hardness and strain hardening behavior, the same inverse FEM optimization scheme as for the base material is now used for the HAZ. In this case, it is not possible to determine initial Swift and Voce fits for the exponential mixing law (Equation 3) as it was done in Subsection 4.1. For that reason, and in order to keep the number of free model parameters within bounds, the 3-parameter Swift law will be used, which is known to provide good results for softer material grades [18]:

$$\sigma_{y,HAZ} = k_{HAZ}(\bar{\epsilon}_p + \epsilon_{0,HAZ})^{n_{HAZ}} \quad (10)$$

in which k_{HAZ} , $\epsilon_{0,HAZ}$ and n_{HAZ} are to be determined. Considering the HAZ hardness of 275 HV, an educated guess for the initial parameters of $[k_{HAZ}, \epsilon_{0,HAZ}, n_{HAZ}] = [1, 0.002, 0.07]$ is used. Equation 10 is substituted into Equation 8 and used

in combination with the same isotropic yield function as for the base material to simulate the tensile test with HAZ.

Figure 13 shows an average curve of the experimental force-displacement results together with the sample points used for the optimization and two simulation results: with initial and final (optimized) parameters. When comparing the two simulated curves, it can be seen that the strain hardening parameters of the HAZ have a significant influence on the global force-displacement behavior, which is a good result as this increases the accuracy of the optimization routine. The simulation with optimized parameters provides a good approximation of the experimental results.

The corresponding strain plots are shown in Figure 14. Again, the results with initial and final parameters are shown, confirming the significant influence of the HAZ parameters on the simulated behavior. Whereas the simulation with initial parameters overestimates the strains, the optimized material model provides a good fit to the experimental results.

Fig. 13 Average experimental force-displacement curve of the tensile test with HAZ with two simulated optimization steps

Fig. 14 Measured total strains ϵ_{xx} along the longitudinal axis of symmetry of the tensile tests with HAZ with two simulated optimization steps

5 VALIDATION

In order to validate the model at hand, coupon specimens with HAZ are tested and compared to simulations. For the specimen preparation, the same approach is used as for the tensile specimens with HAZ: 1.5 mm thick sacrificial plates are spot welded onto larger 220 x 30 x 1.5 mm coupons and then carefully separated by wire EDM. The 200 x 20 mm specimen contour is then also cut using wire EDM; an overview of the final specimen geometry is shown in Figure 15.

Fig. 15 Geometry of the coupon specimen with HAZ

In Figure 16, the measured and simulated strain fields just before fracture initiation are compared. In the area of the HAZ a mesh size of 0.1 mm is used, resulting in a very detailed representation of the hardness distribution and the resulting strain field. It can be seen that the model is able to predict the experimental strain field with good accuracy, both considering the magnitude of the strains and the shape of the strain field.

Fig. 16 Measured (right) and simulated (left) strain field of the coupon test with HAZ

6 CONCLUSIONS

An inverse FEM optimization routine has been used to determine the plasticity model parameters of fully hardened 22MnB5 base material and its corresponding HAZ. Main focus has been on an accurate representation of strain fields up to high plastic strains, which is required for subsequent

calibration of the fracture behavior of both base material and HAZ.

For calibration of the base material model, experimental results of notched and uni-axial tensile tests have been used; for the HAZ material model a specially designed tensile specimen with HAZ in the gage section was tested. By assuming a linear relation between measured hardness and strain hardening behavior, the same optimization routine could be used for both base material and HAZ. The calibrated, hardness dependent material model was validated using a coupon specimen with HAZ, resulting in excellent agreement of simulated and experimental data.

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