Characterization and modeling of fracture behavior of spot welded joints in hot-stamped ultra-high strength steels

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1 Abstract

The development of ultra-high strength, hot-stamped manganese-boron steels (22MnB5) for the application in automotive production has established new potentials for lightweight construction, which combine thin sheet thicknesses and reduced weight with high strength and optimized passive safety performance. In this paper characterization and simulation methods for the failure behavior of spot welded components made of 22MnB5 are shown. Spot weld models are presented, which describe crack initiation in the softened heat affected zone (HAZ) around the spot weld, crack propagation into the components and thereby the influences of the softened HAZ on the component behavior. Therefore the deformation and fracture behavior of the different material zones of the spot welded joints have been characterized and modeled. The failure behavior of spot welded joints in hot-stamped 22MnB5 has been investigated and modeled under different loading types. To validate the simulation models, simulations have been carried out and compared to the results of a special component test with simple boundary conditions, which realizes crack initiation in the softened zone.

2 Introduction

With several thousands of spot welds in a body-in-white, spot welding still represents the most widely used thermal joining process in steel-based automotive production. With the development of hot-stamped ultra-high strength steels, new light-weight potentials have been created, that combine thin steel sheets and thereby reduced weight, with a simultaneous optimization of passive safety requirements. To implement these potentials joining technologies have been adapted to ensure a combination of optimized material and joint strength [1][2][3]. At present hot-stamped manganese-boron steels (22MnB5) are widely used [4][5], especially for load-bearing structural components in parts of the passenger cabin, where deformation and intrusion should be kept at a minimum [6].
To reproduce the global deformation and failure behavior of spot welded joints in crash simulations, several simplified models such as bar, spring or solid elements are available in industrial FE-codes, which describe the behavior of the joints with different constitutive laws and failure models. The parameters of these models can be determined by simulation of simple tests of the joints' behavior. A procedure for the adjustment of these parameters for a single underintegrated solid element and its application at the component level are shown in [7] and [8]. Regardless of the actual failure mode, by pull-out or shear fracture of the spot weld, joint failure is reproduced by elimination of the spot weld element. The connection is dissolved thereby, leaving the previously connected sheets undamaged.

In contrast to non-martensitic steels, hot-stamped manganese-boron steels show softening within the HAZ. Compared to the base material, the strength of this zone is significantly reduced. Due to the mechanical mismatch, this softened HAZ can represent the critical area within hot-stamped sheets or components, limiting its deformation capacity. For a reliable design and evaluation of crash-relevant structures made of hot-stamped steels, not only the joints and their failure behavior, but especially the softened HAZ at spot welds and its influence on deformation and failure behavior needs to be characterized and considered in crash simulations.

3 Spot welds in ultra-high strength steels

The cross-section and the measured hardness profile of a spot weld in the hot-stamped ultra-high strength steel (22MnB5) are shown in Fig. 1. The nugget diameter of the weld is 6.9 mm. The average hardness of the hot-stamped martensitic base metal (BM) is 475 HV0.1. Inside the fusion zone (FZ) and the upper-critical heat affected zone (HAZ) a martensitic microstructure was found with an average hardness of 511 HV0.1. The sub-critical HAZ, where the peak temperature during welding stays below the A_{c1} temperature, shows a significant decrease in hardness, due to tempering of the martensitic microstructure [9]. The minimum hardness inside this softened region is 293 HV0.1.

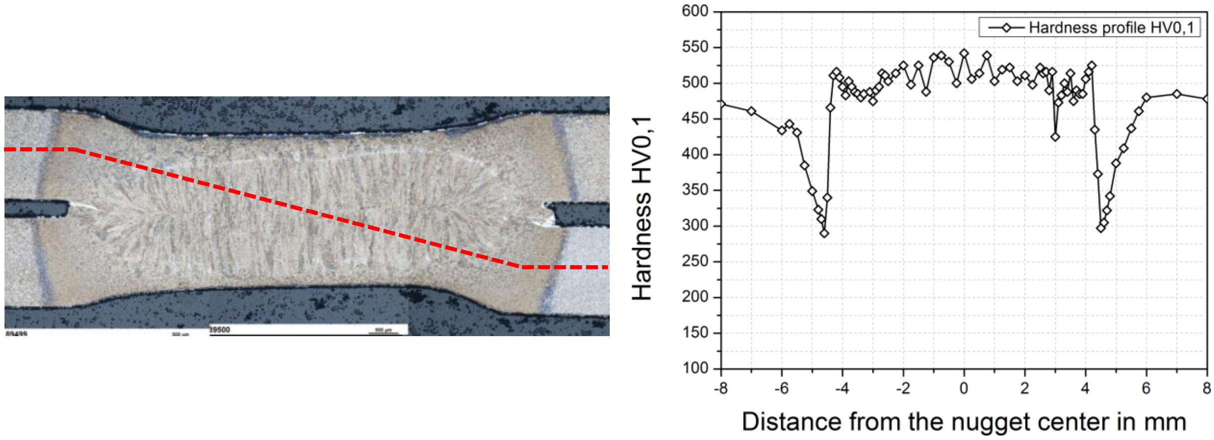

Fig. 1: Cross-section of a resistance spot weld in 22MnB5+AS (left), Hardness profile of the joint along the red line (right)

To determine the influence of HAZ softening on the mechanical behavior of the hot-stamped manganese-boron steel, tensile specimens with spot welds were tested and compared to experimental results of specimens without spot welds [10].
Therefore 2.0 mm thick spot welded sheets were separated by electrical discharge machining and polished to a thickness of 1.5 mm to eliminate the electrode indentations. From these sheets, the tensile specimens shown in Fig. 2 (left) were machined. Fig. 2 (right) shows the comparison of the measured stress-strain curves of the tensile tests. In comparison to the base metal, the tensile strength of the specimen with spot welds decreases by 260 MPa. The uniform elongation of the base metal, which is about 0.05, was not reached by specimens with spot welds. These specimens failed at strains between 0.0175 and 0.02.

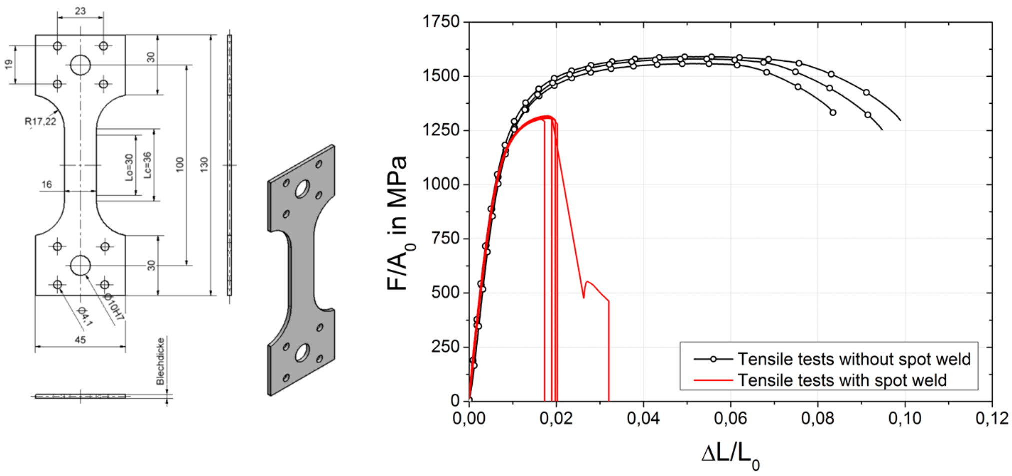

Fig. 2: Geometry of the tensile specimen with and without spot weld (left). Stress strain curves of the tensile tests with and without spot weld (right)

Fig. 3 shows the optically measured deformation behavior (axial strains) of the tensile specimens with spot welds at different loading stages during the tensile test. The softened HAZ can be first observed in the strain distributions as an annular area around the weld nugget with slightly elevated axial strains at about 1100 MPa. With increasing specimen elongation the strains localize inside the softened HAZ. This leads to crack initiation inside the softened HAZ at global strains of 0.0175 – 0.02 and complete failure of the tensile specimens.

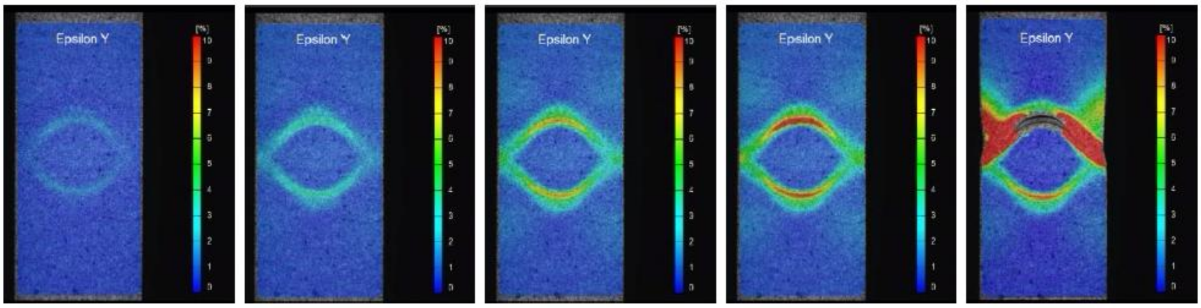

Fig. 3: Aramis measurement of axial strains in a tensile specimen with spot weld at 1100 MPa, 1250 MPa, 1300 MPa, 1320 MPa (immediately before crack initiation) and after crack initiation (left to right)

4 Detailed modeling of the influence of HAZ softening in hot-stamped 22MnB5

To accurately model the mechanical behavior of spot welds and the effects of HAZ softening with detailed finite element models, the deformation and failure behavior of the different material zones of the weld, i.e. base metal, softened HAZ and weld metal, need to be determined. Therefore tensile and shear specimens, as shown in Fig. 4, were cut from the base metal and the welded nugget itself. Material with the properties of the softened HAZ was produced by heat treating base metal sheets in a Gleeble 3150. The time-temperature curves used for heat treatment, were determined in simulations of the spot welding process by the Materialprüfanstalt der Universität Stuttgart MPA [10].

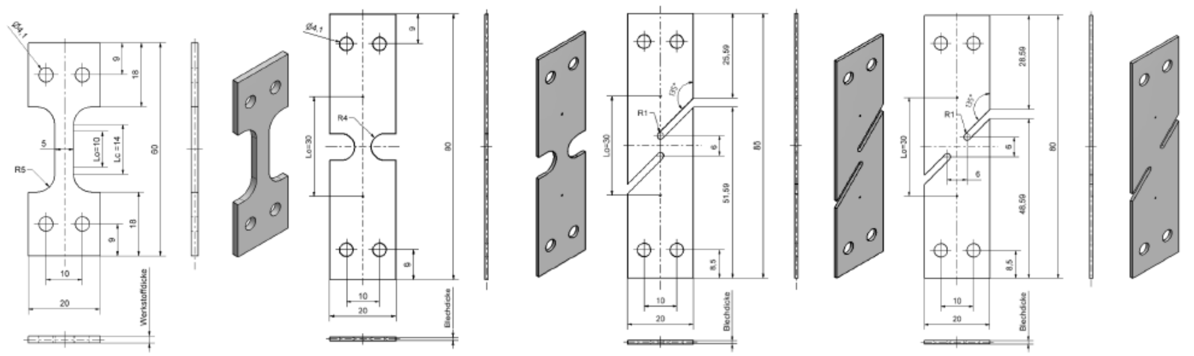

Fig. 4: Specimen geometries for the characterization of material behavior. Tensile, notched tensile (r=4 mm), double notched shear specimen 0° and double notched shear specimen 45° (left to right)

The deformation and failure behavior of the 3 material zones was modeled in LS-DYNA using von-Mises plasticity (*MAT_024) combined with a ductile damage and failure criterion (*MAT_ADD_EROSION) [11]. To describe damage and failure of the investigated materials in tensile and shear loading conditions a failure curve, defined as equivalent plastic strain depending on the stress triaxiality, is applied. The failure curves for all material zones were determined by inverse simulation of the tensile and shear tests. As an example Fig. 5 shows the comparison of calculated and measured normalized force vs. displacement curves from smooth and notched tensile tests and the two shear tests of the base metal. Further experimental and numerical results for the softened HAZ and the weld metal can be found in [10].

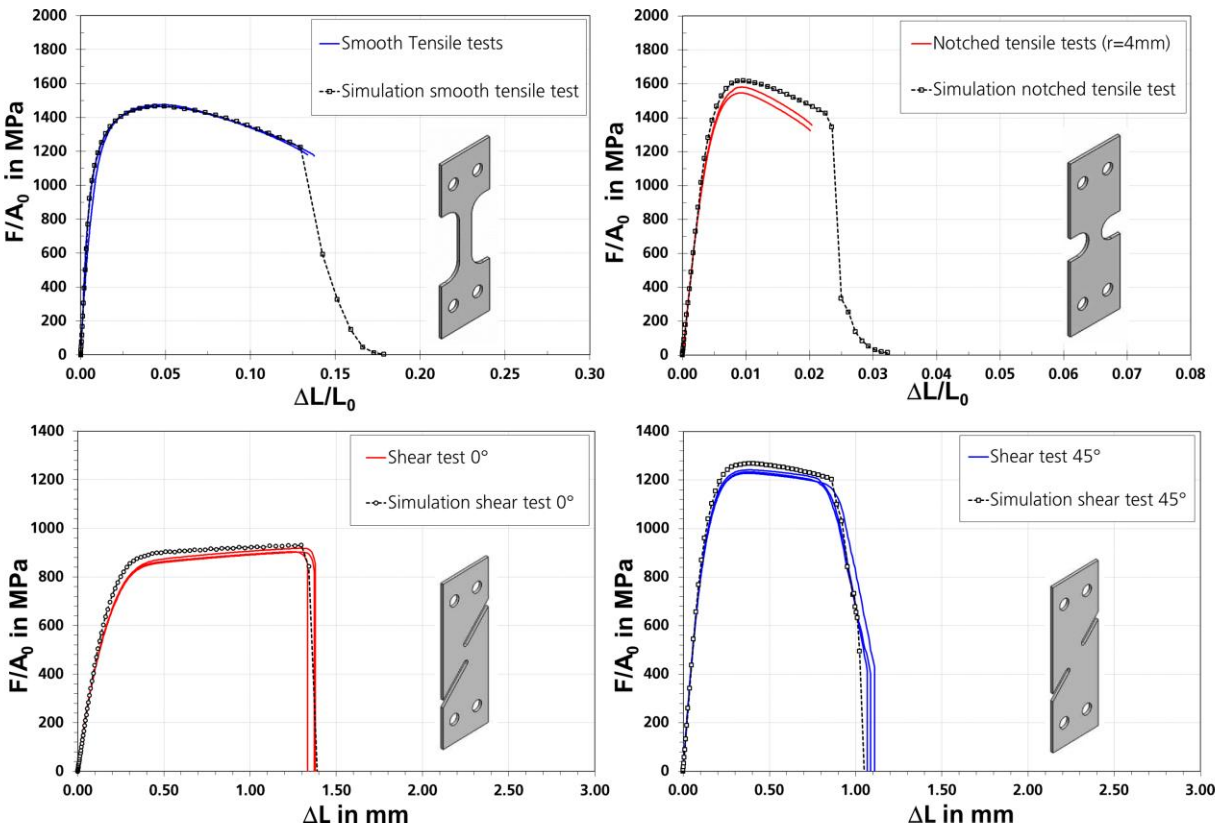

Fig. 5: Comparison of calculated and measured normalized force vs. displacement curves for smooth and notched tensile tests and shear tests for the base metal

To validate the calibrated material models the tensile tests with spot welds and 3-point bending tests on components were simulated. Fig. 6 shows the detailed finite element models with different material zones of the two tests. Due to symmetry only one half of the tensile specimen and one quarter of the 3-point bending test were modeled. The spot welded regions were meshed using eight-noded underintegrated solid elements with edge lengths of 0.1 mm.

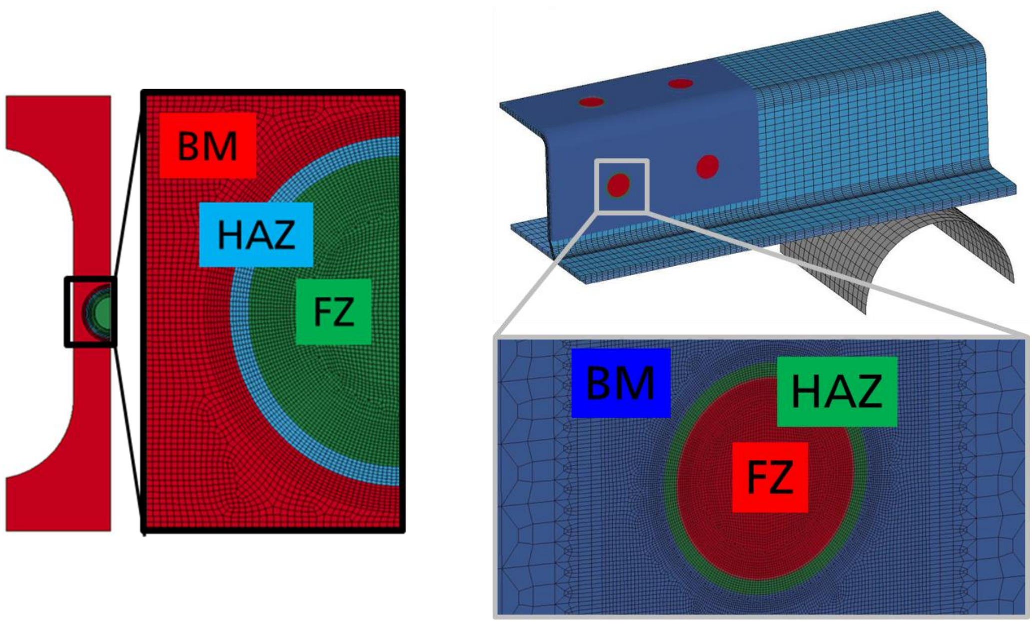

Fig. 6: Detailed finite element models of tensile tests with spot weld (left) and spot welded component tests

Fig. 7 (left) shows the stress vs. strain curves of tensile tests with spot welds from experiments and simulations. The calculated reduction of tensile strength due to the presence of the softened HAZ inside the tensile specimen is in good agreement with the experimental results. The calculated stress and specimen elongation at crack initiation is slightly higher than observed in experiments. Fig. 7 (right) shows the comparison of measured and calculated local axial strains immediately before and after crack initiation in the softened HAZ of the weld.

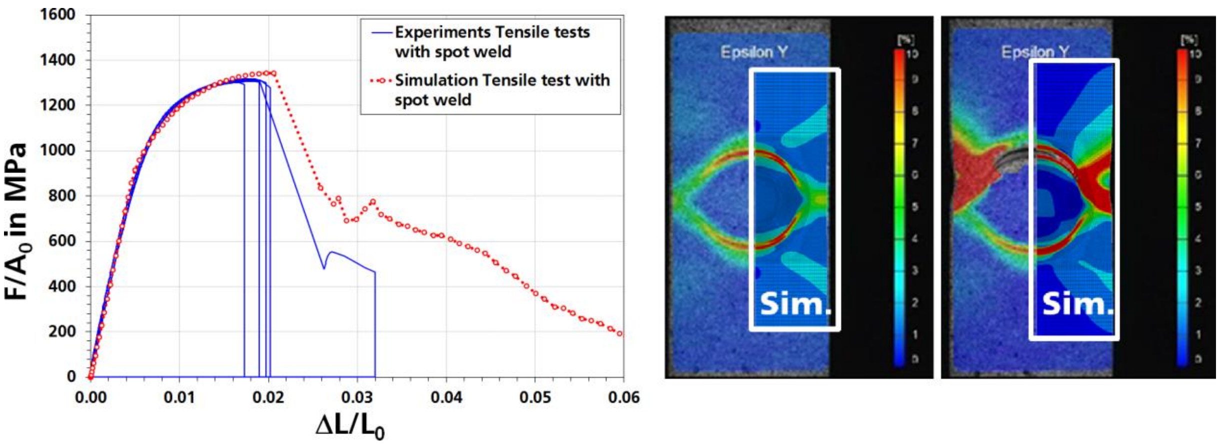

Fig. 7: Measured and calculated stress-strain curves of tensile tests with spot weld (left). Comparison of axial strain distribution in the tensile specimen immediately before and after crack initiation in the softened HAZ of the weld (right)

The calculated and the measured force vs. displacement curves of the 3-point bending tests on components are shown in Fig. 8. The calculated results show very good agreement with the experimental curves. Good agreements can also be observed comparing the local equivalent strain distributions at the critical spot welds in experiments and simulations at different loading stages of the 3-point bending test. As observed in the tensile tests with spot welds, strains concentrate inside the softened HAZ during deformation of the component. At punch displacements of 11.5 mm and a maximum force of 35.9 kN crack initiation occurs in simulations. With increasing deflection the crack grows through the softened HAZ and extends into the base metal. Complete fracture of the component is calculated at a deflection of 18.8 mm. Fig. 8 shows the final deformed states of the test-component from experiments and simulations.

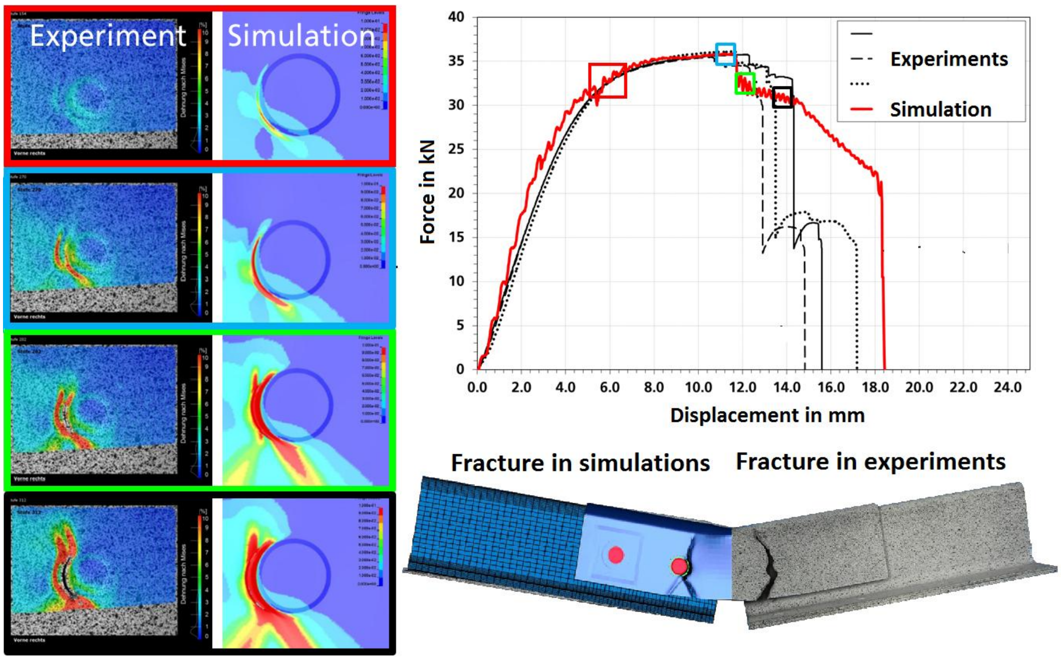

Fig. 8: Comparison of local equivalent strain distributions, force vs. displacement curves and final deformed states of the 3-point bending tests on components from experiments and simulations

5 Simplified modeling of spot welds and the softened HAZ in hot-stamped 22MnB5

For crash simulations simplified models of spot welds, which describe the deformation and fracture behavior of the spot welded joints, are needed. In case of ultra-high strength steels, the phenomenon of crack initiation inside the softened zone and the crack growth into the hot-stamped base metal has to be taken into account for an accurate description of the mechanical behavior of spot welded hot stamped steel sheets or components. Therefore the material and failure models for the hot stamped base metal and the softened HAZ have been adjusted for shell elements with an element size of 0.5 mm. To minimize the mesh size dependency of the calculated failure initiation for increasing element size, the failure curves were scaled depending on the element size. The scale factors were determined by inverse simulations of tensile tests. Fig. 9 shows the failure curves for element sizes 0.5 mm, 1.25 mm, 2.5 mm and the corresponding results of the tensile tests on hot stamped base material.

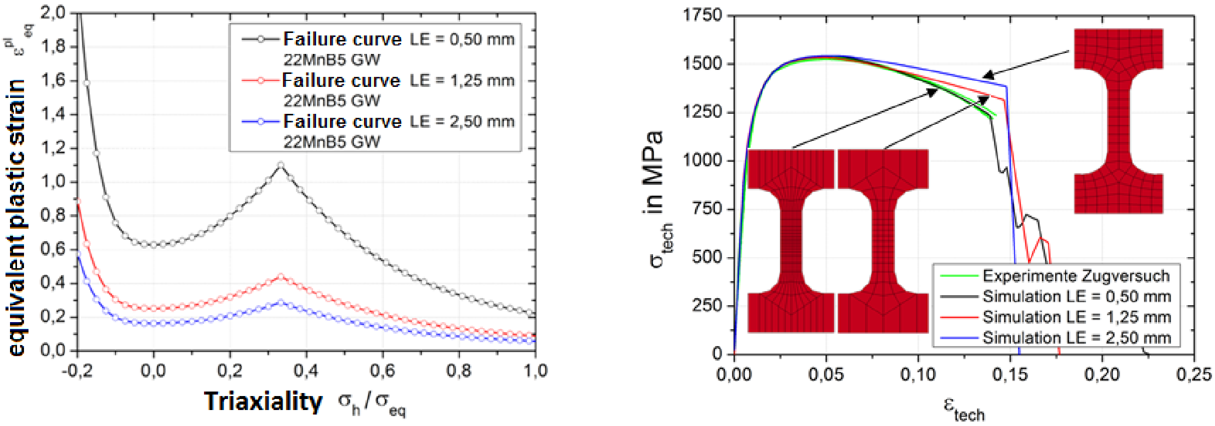

Fig. 9: Failure curves for element sizes 0.5 mm, 1.25 mm and 2.5 mm (left). Comparison of measured and calculated stress vs. strain curves for tensile tests with increasing mesh size using mesh size dependent failure curves (right)

As a first step, the applicability of the mesh size dependent failure curves for the hot stamped base material and the softened HAZ was investigated in simulations of the tensile tests with spot welds. The tensile specimens have been modeled with shell elements with an element size of 0.75 mm, 1.5 mm and 3.0 mm (Fig. 10). The softened HAZ was modeled using one single row of shell elements surrounding the spot weld.

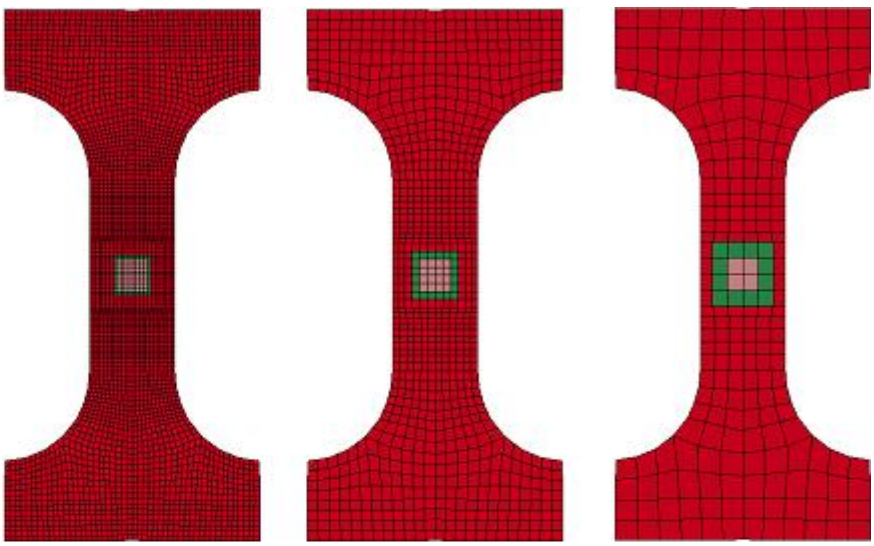

Fig. 10: Tensile specimens with spot weld modeled with shell elements with an element size of 0.75 mm, 1.5 mm and 3.0 mm (from left to right). The softened HAZ is shown in green.

Fig. 11 shows the comparison of calculated and measured stress vs. strain curves from experiments and simulations with mesh size dependent failure curves of tensile tests with spot welds. Simulations with an element size of 0.75 mm and 1.5 mm show good agreements with experimental results concerning load bearing capacity and fracture initiation inside the softened HAZ. Due to the increased fraction of the softened HAZ in the cross-sectional area the simulations with an element size of 3.0 mm showed a significantly lower tensile strength. In this case the true width of the softened HAZ is considerably overestimated. The specimens' elongation at failure initiation is thereby overestimated by a factor 2.
If HAZ softening around spot welds should be modeled in crash simulations with element sizes exceeding the true width of the HAZ significantly, one possibility would be to adjust the material properties, i.e. yield and failure curve of the softened HAZ, by an inverse parameter identification. For the element size 3.0 mm this was done in simulations of tensile tests with spot welds. The measured yield curve was therefore increased and the scaling factor for the failure curve for element sizes larger than 1.5 mm was decreased. The result of this inverse parameter identification is shown in Fig. 11 on the right. It should be noted, that this kind of parameter identification is purely phenomenological and should be revised in further simulations and experiments on components, such as 3-point bending tests shown in Fig. 8.

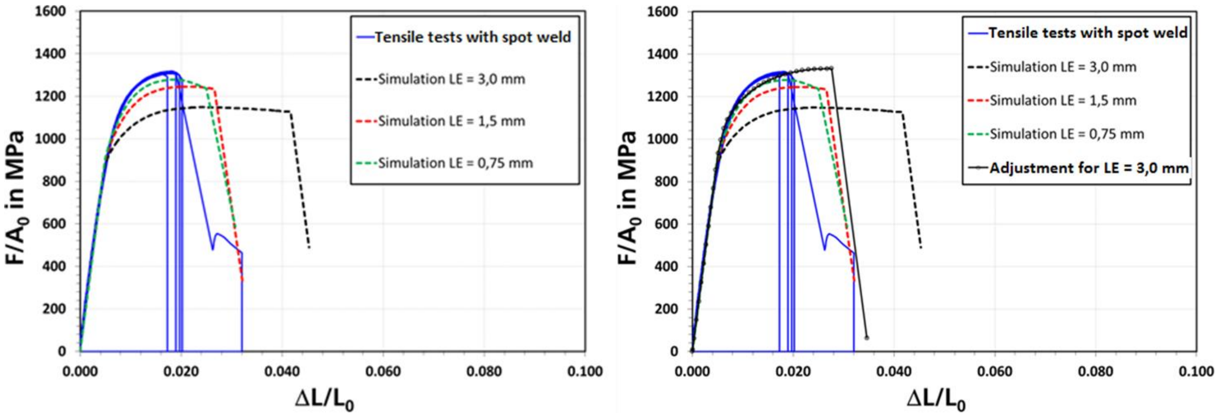

Fig. 11: Comparison of measured and calculated stress vs. strain curves of tensile tests with spot welds using different mesh sizes

To describe the deformation and failure behavior of the spot welds in shear, axial and combined loading conditions with simplified models *MAT_100_DA [11] in LS-DYNA was used. The parameters of the simplified model were determined in simulations of KS2-specimens tested at the Laboratorium für Werkstoff- und Fügetechnik der Universität Paderborn (LWF) in [2]. Fig. 12 shows the finite element models of KS2-specimens with loading angles 0°, 30°, 60° and 90° (left) and one half of the modeled KS2-specimen (right). For the spot welds one single eight-noded hexaedron element was used, which was tied to the shell elements of the steel sheets (*CONTACT_TIED_SURFACE_TO _SURFACE). The softened HAZ is modeled using one single row of shell elements around the spot weld element. The sheets are modeled with shell elements with 2.5 mm edge length and the adjusted material models for the base metal and the softened HAZ.

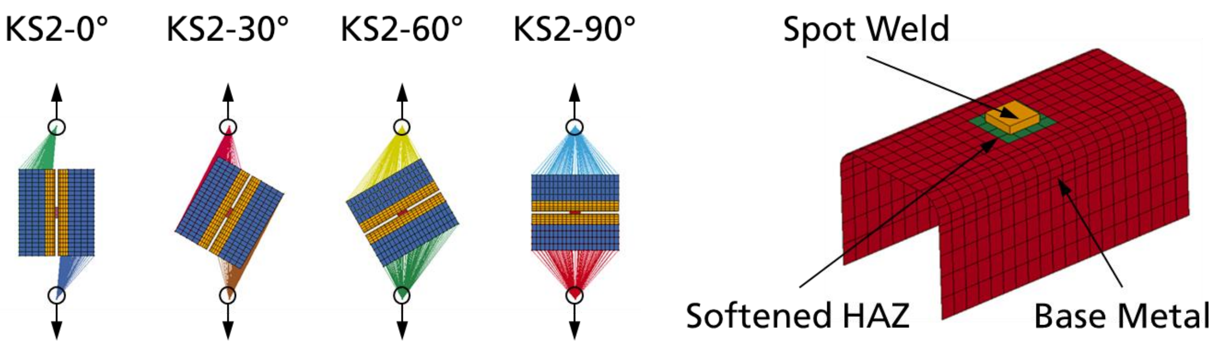

Fig. 12: Finite element models of KS2-specimens with loading angles 0°, 30°, 60° and 90° (left) and one half of the modeled KS2-specimen showing the spot weld and the different material zones (right)

The deformation behavior of the simplified spot weld element is adjusted in simulations of the KS2-0° tests. Afterwards all KS2-tests are simulated to evaluate the normal-, bending and shear stresses in the solid element during deformation. Based on the results the parameters of the stress based failure criterion, i.e. failure stresses for normal, shear and bending loading, are determined. The measured and the calculated force vs. displacement curves of the KS2-specimen in 0°, 30°, 60°, 90° and coach-peel loading are shown in Fig. 13 (left). The calculated and the measured load bearing capacity of the joints, divided into their axial and shear components, in different loading angles is shown on the right in Fig. 13.

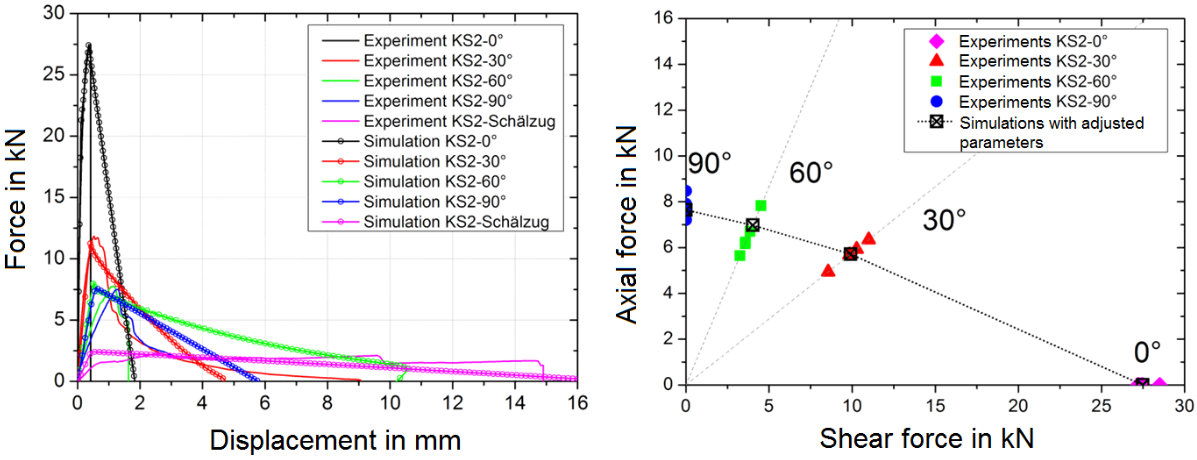

Fig. 13: Measured and calculated force vs. displacement curves of the KS2-specimen (left). Measured and calculated load bearing capacity split into axial and shear force components (right)

To validate the material and failure models for the base metal, the softened HAZ and the simplified models of the spot welds, the 3-point bending tests on test-components have been simulated and compared to experimental results. Fig. 14 shows the finite element models of this test-component modeled with element sizes of 0.75 mm, 1.5 mm and 3.0 mm. Due to symmetry of the tests only one half of the 3-point bending test has been modeled.

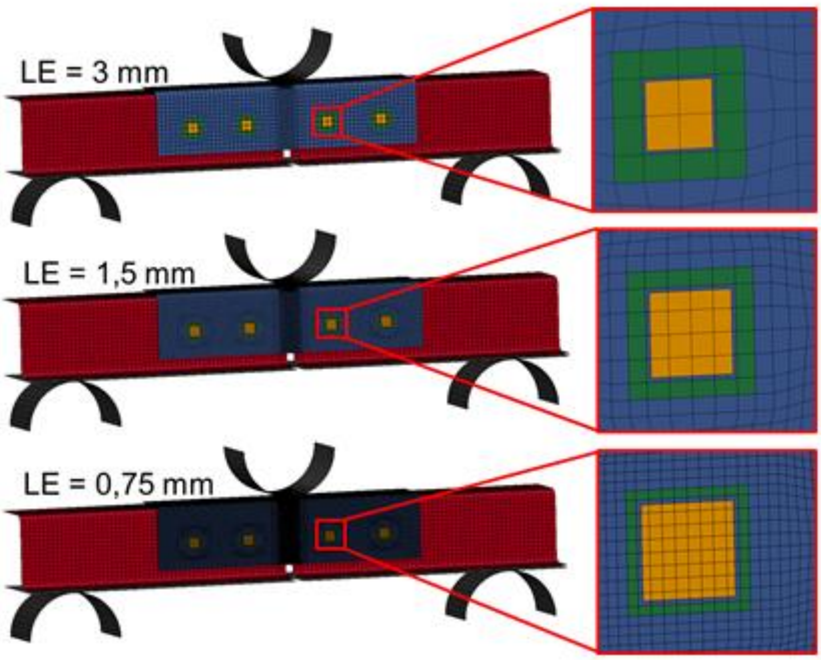

Fig. 13: Finite element models of the 3-point bending test on components with different mesh sizes

Fig.14 shows the comparison of calculated and measured force vs. deflection curves of the 3-point bending tests. The global force vs. deflection curves of the tests are reproduced by all simulations. For the simulations with element sizes of 0.75 mm and 1.5 mm failure initiation inside the softened HAZ is calculated at a deflection of 11.0 mm and 10.6 mm respectively. With an element size of 3.0 mm and the material behavior for the softened HAZ adjusted by inverse simulations of the tensile tests with spot welds, failure initiation appears at 10.6 mm deflection. Using the true material behavior of the soft zone for the mesh size 3.0 mm, failure initiation occurs at a deflection of 12.2 mm. In contrast to the tensile tests with spot welds, the calculated force vs. deflection curve with this element size showed good agreements with the experimental results. Subsequent to crack initiation the crack grows through the softened HAZ and into the base metal with increasing deflection (Fig. 15 left). Final fracture occurs at a deflection of 14.6 mm.

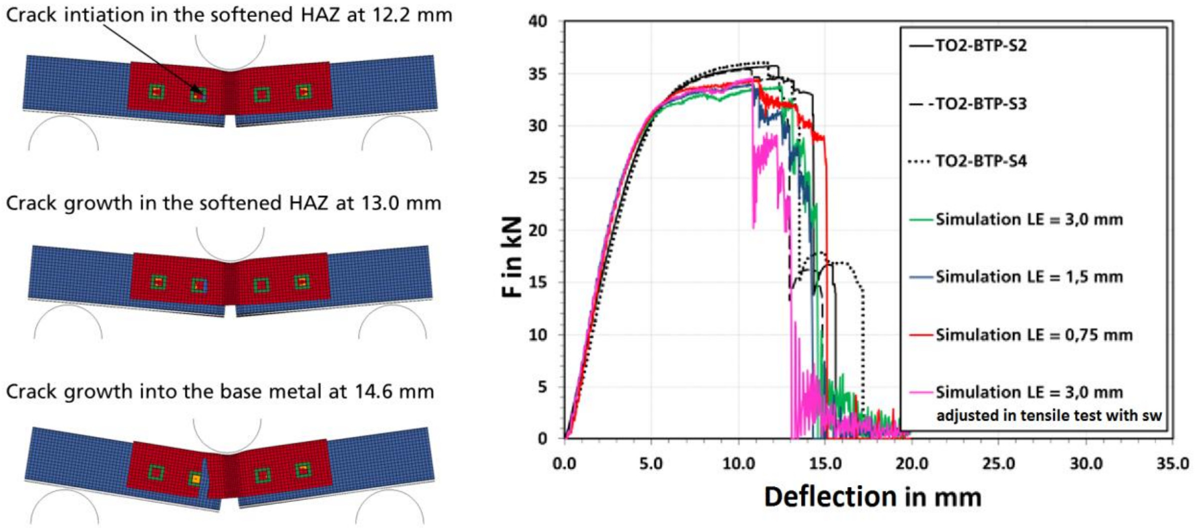

Fig. 15: Calculated failure in 3-point bending test with mesh size 3.0 mm (left) Measured and calculated force vs. deflection curves (right)

6 Conclusion and Summary

Spot welding of hot-stamped ultra-high strength manganese-boron steel leads to tempering and softening of the martensitic microstructure inside the sub-critical heat-affected zone of the weld. Compared to the base metal a drop in hardness and strength of the material inside this softened zone of about 40% could be observed. The influence of the softened HAZ on the mechanical behavior of the hot-stamped manganese-boron steel has been investigated in tensile tests with spot welds and 3-point bending tests on test-components. As a result of the mechanical mismatch between the base metal, the softened and the upper-critical HAZ, deformation concentrates in the softened HAZ and leads to failure initiation in both tests.
The influence of HAZ softening in the hot-stamped steel has been modeled using detailed and simplified finite element models. To accurately model the stress and strain distributions within the softened HAZ, detailed finite element models and material models, representing the mechanical behavior of the different material zones of the weld, were used. These models showed very good agreements with the experimental observations in tensile tests with spot welds and 3-point bending tests on components. Furthermore such models can be used to investigate the influence of factors such as residual stresses [10], sheet thickness or other geometric quantities.
Simulations with simplified spot weld models for crash simulations showed good agreements with the conducted experiments for element sizes 1.5 mm and smaller. For larger elements, the width of the softened HAZ is significantly overestimated. Using the yield curve and mesh size dependent failure curves adjusted in tensile tests of the softened HAZ, the simulations did not show satisfying results in tensile tests with spot welds. In this case a purely phenomenological adjustment of the material behavior of the softened HAZ by simulations of the tensile tests with spot weld was applied and validated in simulations of 3-point bending test on components.

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