MULTIPHYSICS FINITE ELEMENT SIMULATION OF RESISTANCE SPOT WELDING TO EVALUATE LIQUID METAL EMBRITTLEMENT IN ADVANCED HIGH STRENGTH STEELS

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ABSTRACT

Advanced high strength steels (AHSS) open new possibilities in lightweight design in the automotive industry. However the risk of liquid metal embrittlement (LME) of modern zinc coated advanced high strength & high ductility steels (AHSS HD) during resistance spot welding (RSW) is a limiting factor for the use of such steels in the cars body in white. The goal of this work is to evaluate and exclude this risk for the high ductility dual phase steel DP1200HD. In the RSW process two electrodes are pressed to similar or dissimilar metal sheets, which are heated and joined by means of Joule heating. An experimental RSW study of similar two-sheet stack ups of DP1200HD showed zinc induced LME for certain welding conditions. Commonly trial and error testing is applied to determine proper welding conditions in order to increase the spot weld quality and to decrease LME. To avoid this extensive testing and to better understand the effect of the local physical conditions on the formation of LME a finite element model of the RSW process has been developed. This multi-physical model couples electrical, thermal, mechanical and metallurgical effects and provides local quantities for current density, temperature, strains, stresses and phase compositions. In addition a damage parameter for LME has been developed based on experimental findings and the local mechanical quantities from the simulations. The simulation results have been validated against experimental RSW tests.

Keywords: resistant spot welding, finite element simulation, advance high strength steels, liquid metal embrittlement

INTRODUCTION

Safe and lightweight construction in automotive has become a driving factor of material development. Advanced high strength steels with high ductility (AHSS) open up new possibilities for lightweight design and, hence, fuel and emission reduction. In cars body in white these steels as well as their joints have to show a high crashworthiness. In this study a dual phase steel with high ductility (DP1200HD) was investigated. Modern dual phase steels are unalloyed steels with high ultimate tensile strength and a martensitic and ferritic microstructure.

A preferred joining method of thin steel sheets in automotive is resistance spot welding (RSW) [1]. RSW represents a quick and reliable joining technique that is also highly automatable. As seen in figure 1 two electrodes clamp the metal sheets together. In the next step a defined electrode force F is applied and after that the welding current I passes through the electrodes and metal sheets. In the centre between the sheets the temperature rises due to Joule heating. The heating takes mainly place between the sheets, because there electrical resistance is at this interface about ten times larger than between sheet and electrode. A molten pool of metal also called nugget develops and connects the sheets. After the current is switched off the force is kept constant for a defined time while the nugget solidifies.

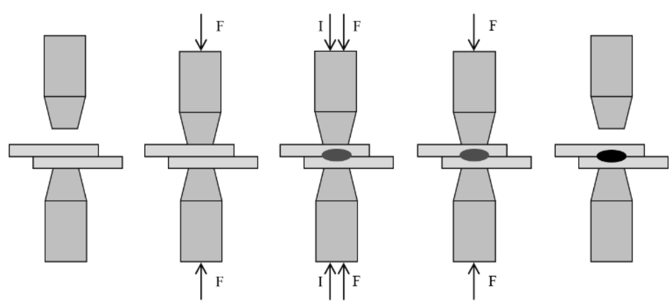

Fig. 1 Scheme of the different steps in resistance spot welding process including the force and current application

Resistance spot welding with bare steel sheets is a quick and reliable process. However, in the particular case considered here zinc is used as cathodic surface protection of the steel sheets. Zinc coating is applied via an electrogalvanizing process and a thin layer of about 10 µm is deposited.

Electrogalvanized DP1200HD has high potential as a new high strength material for car bodies in white. However, when introducing new materials the whole processing has to be taken into account and adapted to the new material.

Under specific conditions, electrogalvanized steels tend to show liquid metal embrittlement (LME) in the spot weld during RSW. LME describes the drastic loss of tensile ductility of an otherwise ductile metal. DP1200HD shows as a high strength steels a higher susceptibility to LME than low or medium strengths steels, which has to be investigated properly in order to adapt the welding process and, hence, to guarantee a satisfying welding result. The main reasons for LME are on the one hand that zinc remarkably decreases the bulk and grain boundary cohesion [2] in many metals, including steel [3], and on the other hand that the liquid zinc state and its very high wettability leads to high zinc mobility. Since the phase state of zinc and the zinc diffusivity in steels are depending on temperature, the temperature is an important factor in LME [4-5]. For LME cracking a minimum threshold stress has to be present. These cracks nucleate at surfaces wetted with liquid zinc [6] and cause brittle cracking [7-8]. Liquid metal, stress and high temperatures therefore count as main influences to LME in a susceptible material. In RSW a local temperature of 700°C has been found as critical threshold for LME cracking [9] although in general LME might also occur at lower temperatures.

The main welding parameters with an impact on LME cracking are electrode force, welding time and welding current because these process parameters have the highest influence on the local temperature and stress state. To find process parameters that avoid LME cracking two different approaches are possible. In the first approach the welding parameters are identified by means of extensive RSW testing. In this case a large number of tests has to be conducted and the local conditions remain unknown and, hence, a deeper understanding of the governing mechanisms and local driving forces is not possible. The second approach is based on a validated finite element based RSW simulation, which has the advantage that less testing is needed, the local effects can be investigated and radically new process concepts can be easily evaluated. In the literature a number of different finite element modelling approaches with different model complexities are reported [10-12]. Many of these models have in common that the effects stemming from phase transformation are neglected and a proper LME cracking criterion has never been described. In the current paper a multi-physical finite element model considering phase transformation effects was developed in order to calculate current densities, temperature fields, stresses, phase transformation and furthermore to estimate the local LME risk by a first very simple damage indicator. The aim of this paper is to describe the novel and due to the consideration of phase transformation more complete modelling approach for the first time. The approach is demonstrated using pre-existing data and shows reasonable results.

EXPERIMENTAL

Extensive spot weld tests were realised to investigate nugget formation, nugget size, penetration depth, heat affected zone (HAZ) and LME cracking. The process parameters welding current, welding time, electrode force and holding time were systematically varied. To investigate the influence of the zinc coating comparable experiments for coated and uncoated steel sheets were carried out. For these tests, a Nimak pedestal welder with a Matuschek controller and C-shaped calliper was used. Two 1.6 mm thick metal sheets were stacked and placed unconstrained between the electrodes on a table. Dome shaped and water cooled copper-chromium alloy electrodes of the type F1-16-20-6 were used. The welding process was started manually and the sample was removed after cooling down to room temperature.

Figure 2 shows the characteristic zones of a typical spot weld. In the centre of the spot weld a nugget, also called fusion zone (FZ), formed where the material was melted and re-solidified. This zone mechanically connects the two steel sheets. The nugget is surrounded by the upper-critical HAZ, where the material was austenitized. The next zone is the sub-critical HAZ, where only an annealing of the initial microstructure without phase transformation took place. This zone is followed by the unaffected base material (BM). Due to the material characteristics of the investigated DP1200HD the HAZ and FZ consists mainly of martensite and the BM consists of martensite and ferrite.

The LME cracks can be grouped in three types that all occur in the upper-critical HAZ: Type one forms from the surface of the sheets at the boundary of the indentation, type two forms at the surface directly underneath the electrode near its axis and the third type forms at the boundary of the nugget between the two sheets, see Figure 2. Cracks of type one are most common and can easily exceed a length of 100 µm. The type two cracks are typically small and uncritical. The type three cracks are rare, but might also reach higher crack lengths. In the micrograph in Figure 2 cracks of all types can be found. The largest type one cracks reach 170 µm, the type two cracks 30 µm and the type three cracks 220µm.

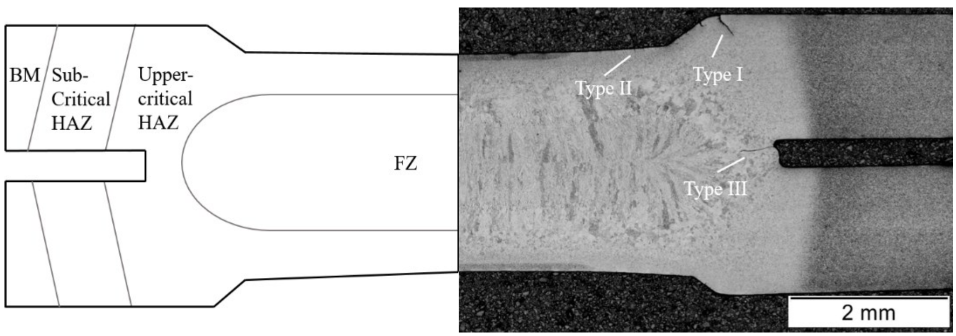

Fig. 2 left: schematic representation of different regions in a spot weld; right: corresponding microstructure of sample D

For this work four exemplary chosen weld conditions as listed in Table 1 are compared to the results of the simulation.

Table 1 List of applied welding conditions of the spot welds exemplarily investigated in the present paper.

Sample	Electrode force [kN]	Welding current [kA]	Welding time [ms]	Holding time [ms]
A	4.5	5.2	380	300
B	4.5	6.9	380	300
C	4.5	5.2	760	300
D	4.5	6.9	760	300

MODELLING

The present model was developed using the commercial finite element software package Abaqus Version 2017 [12]. Modeling the RSW process is a complex multi-physics problem [13]. Figure 3 shows the different phenomena and their interactions taking place in RSW. The built-in models in Abaqus cover the electrical, thermal and mechanical part of the problem, but the phase transformation related evolution laws were implemented using a set of user defined subroutines.

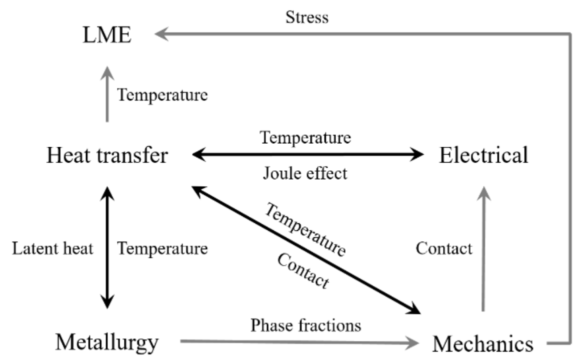

Fig. 3 Interaction of electrical, thermal, mechanical, metallurgical modules and LME damage parameter [14]

The electrical current between the electrodes lead to Joule heating of the steel sheets in between. The electrical contact resistivities at the interfaces between the two zinc coated steel sheets and between the electrodes and the zinc coated steel as well as the temperature dependence of the resistivities are of great importance for the local heat generation. In the current state of the project most material data such as the electrical conductivity [14] are taken from literature on DP1000 material [15]. For the heat transfer problem in the steel sheet measured temperature dependent thermo-physical properties were used. With increasing temperature the material undergoes in the upper-critical HAZ and the FZ a phase transformation from the initial microstructure to austenite. Furthermore, in the FZ the material melts. During cooling, the affected material first re-solidifies and later on transforms to a martensitic microstructure. In case of the diffusive phase transformations and the melting the Johnson-Mehl-Avrami-Kolmogorov approach [16] was applied. The martensitic phase transformation follows a Koistinen-Marburger relation [17]. For all phase transformations the latent heat is considered by means of a body heat source and the transformation induced plasticity (TRIP) is modelled using Leblond's model [18]. The latent heat for the solid-solid phase transformations were experimentally measured. Missing material data such as temperature dependent Young's modulus, temperature dependent flow curves, thermal expansion coefficients and the parameters of the TRIP model, which has yet to be measured for the investigated DP1200, are taken from literature on a DP1000 steel [19]. Additionally, a first and very simple indicator for assessing the local LME risk has been developed. It ranges from 0 (i.e. no risk) to 1 (i.e. certain LME damage). This simple LME indicator gets non-zero if the local temperature at the investigated material point is above the for the investigated material class typical 700°C [7] and if at the same time and location tensile stresses are acting [7][9]. A third necessary condition for LME is the presence of zinc, which was respected by the fact that only surface elements can undergo LME crack initiation. For the same reason further LME crack extension is only possible if the investigated material point is connected to an already damaged position.

The model consists of the two electrodes and two steel sheets of 1.6 mm thickness. Since the zinc coating is very thin compared to the sheet thickness it is not modelled as a physical entity in the FE model. Nevertheless, the effect of the coating is respected in the contact conditions between the electrode and the sheet as well as between the two sheets.

As long as no lateral forces e.g. from the clamping act the RSW process can treated as an axial-symmetric problem. Since Abaqus only supports 3D elements for coupled electric, thermal and mechanical problems, a 3D wedge model with an opening angle of 3° and axial-symmetric boundary conditions was built. Thermal, electrical and structural coupled elements of the type Q3D8 are assigned to the whole model except the element row near the axis of the model where Q3D6 wedge elements were used for geometrical reasons. The model consists of approximately 5000 elements. In the relevant zone near the zinc coated surfaces a mesh with an element height of 0.04 mm and an aspect ratio of 2:1 was assigned.

Different boundary conditions need to be assigned to the model. In order to supress any displacement in axial-direction in the model the degrees of freedom of the nodes at the bottom surface of the lower electrode were fixed. The initial temperature of the whole model was set to 25 °C and a fixed potential of 0V was defined for the bottom of the lower electrode. The welding force and the welding current were applied to the top of the upper electrode. The water cooled inside of the electrodes was modelled using a convection boundary condition with a heat transfer coefficient of 7.5 mW/(mm² K) and a sink temperature of 25 °C. For the heat exchange between the zinc coated sheet surfaces to the environment an ambient temperature of 25 °C and surface radiation with an emissivity of 0.2 [20] was used. The mechanical, thermal and electrical contact conditions between sheet/sheet and electrode/sheet play an important role on the Joule heating and thus on the entire solution. The contact properties for electrical conductivity and thermal conductivity were specified as a function of the temperature and the contact clearance based on literature [14][21]. When clearance reaches 0.1 percent of the element height of the sheets, conductivity is set to zero. The temperature dependency of contact conditions plays an important role for the formation and the shape of the FZ.

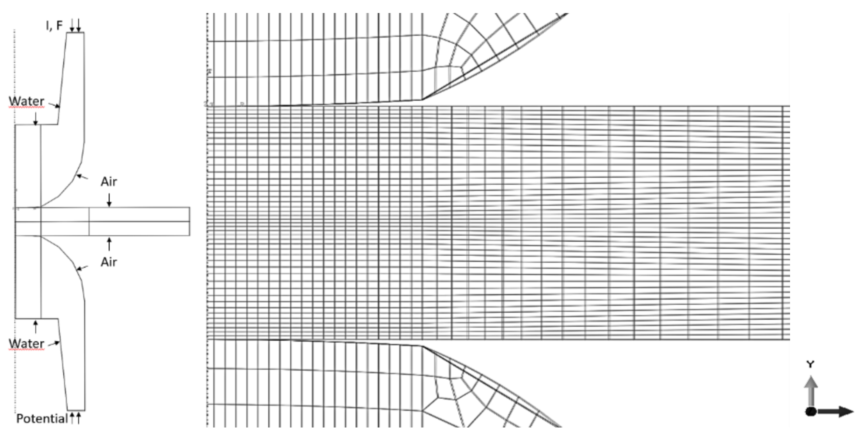

Fig. 4 left: whole RSW model with symmetry axis; right: mesh in the spot welding zone

The simulation is segmented in four different steps: In Step 1 the contact between the electrodes and the sheets is established by a small displacement controlled movement of the upper electrode. In step 2 the full mechanical load is applied. In step 3 the current is introduced while the mechanical load is kept constant. Finally, in step 4 the current is set to zero again but the welding force is kept constant until the end of the step.

RESULTS

The model allows to calculate a great variety of different results such as current density distributions, temperature fields, phase fields, stresses, strains and a first and simple LME cracking risk indicator. In Figure 5 the different temperature fields for the four investigated RSW cases are compared to the micrographs of real weld spots. The upper limit of the scale was set to 1500 °C, which is about the temperature where the material should be melted and the lower limit is set to 700 °C which is approximately the austenitization temperature. Hence, the upper limit corresponds roughly to the limit line of the FZ and the lower limit to the limit line of the upper-critical HAZ. The simulated shape of the FZ and the upper-critical HAZ and the qualitative tendencies between the different RSW cases agree quite well with the experimental findings, but the calculated temperatures seem to be too low or the assumed austenitization temperature is too low in this rapid heating case. This is also obvious judging from the penetration depth of the electrode, which is much bigger in the experiment than in the simulations. This is most likely due to the lack of reliable material data and missing information on the contact conditions at the current stage of the project. Due to less generated heat in the model, plastic conditions do not change as much as in the experiments and therefor the penetration depth is lower. The presented model describes the overall phenomena and trends quite well although the material data and LME risk indicator need further improvement. This is part in the ongoing work and will be presented in future works focusing not so much on modelling but on material and process aspects.

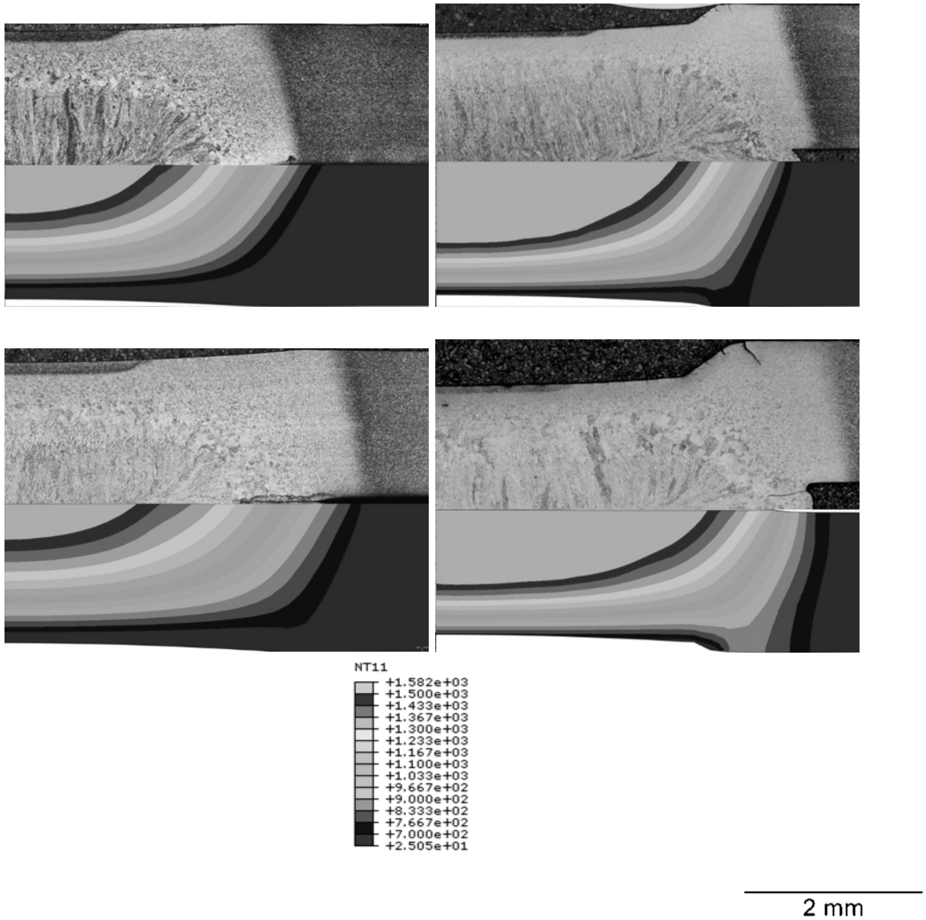

Fig. 5 Comparison of the calculated temperature distribution with micrographs of different welding conditions (top: A – B, bottom: C - D)

In Figure 6 the micrograph of the spot weld D with the harshest RSW conditions is compared to a FZ indicator, describing the area where the material was melted, to an upper-critical HAZ indicator, describing the area where the material was austenitized but not melted, and to the LME risk indicator. The calculated upper-critical HAZ zone fits for this case quite well to the micrograph but the simulated FZ is again a little too small. The LME risk indicator shows the most critical area at the shoulder of the electrode's penetration depth and represents the critical zones in general already very well. It is important to point out that LME is naturally not only a function of temperature and stress, but also of the presence of zinc. Consequently, any LME risk indicator values below the zinc coated surface only make sense if a LME surface crack penetrates that far into the sheet. Also the risk indicator describes the surface damage with crack initiation and propagation risk.

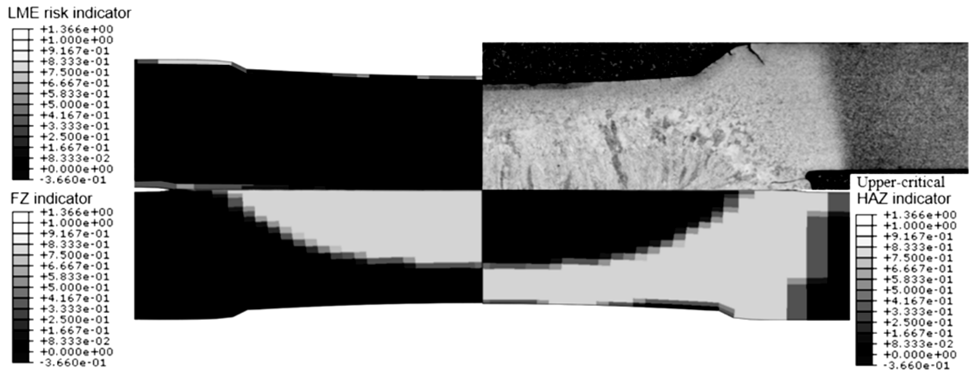

Fig. 6 Calculated LME damage parameter and calculated FZ and upper-critical HAZ indicator compared to a micrograph of spot weld D

CONCLUSIONS AND OUTLOOK

A promising multiphysics finite element model for calculating quantities like current densities, temperature fields, stress distribution and taking phase transformation into account, was set up. All necessary model equations to consider phase transformation and its related effects were implemented. The model of the investigated two-sheet DP1200 spot welds gives qualitatively correct results. However, in order to achieve quantitatively reliable results the calculations using material data mostly taken from literature on the similar steel grade DP1000 have to be repeated with measured data on DP1200. Another important value which has to be determined from instrumented spot welding tests is the electrical contact conductance that has a high impact on the temperature distribution and hence on all other results as well due to the strong interdependencies of the relevant physical phenomena.

Additionally to the fully coupled multiphysics model, a first and very simple LME cracking risk indicator was implemented. It already allows reasonable predictions of the critical zones. In a next step this LME damage indicator will be further elaborated and validated against extensive RSW testing.

The long term goal is to provide a validated and quantitatively accurate model that predicts the metallurgical and mechanical state as well as the LME cracking of spot welds. This model will then be utilized to develop new low LME RSW processes.

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