Recent developments for thermo-mechanically coupled simulations in LS-DYNA with focus on welding processes

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1 Introduction

With increased mechanical and functional requirements put on many parts produced by the manufacturing industry, the numerical simulation of the process has gained importance within the last years. The main objective when applying numerical tools is an accurate prediction of the finished geometry. In order to allow for an efficient optimization procedure in the design phase of the process the complete manufacturing process chain has to be included in the simulation. For many processes in sheet metal forming this is state of the art.
On the other hand, welding stages are often neglected in the virtual process chain, although the deformations that are induced have to be compensated for. Furthermore, high temperatures evolving in the structure and thus induce significant internal stresses and local changes in the microstructure of the metal alloys. The combination of these effects poses many challenges on the numerical simulation tool. In this paper novel developments in LS-DYNA will be presented that allow for an accurate and efficient modelling of different welding processes.
One challenge in welding simulations is a realistic definition of the heat source including not only the correct amount of energy that is input into system but also the modelling of the power density distribution and the possibly complicated motion of the weld torch. The shape of this distribution can vary significantly between certain welding process and different choices of process parameters.
The second challenge addressed in this paper is the modelling of weld seams. In many of the line welding processes a filler material is added to connect the parts. Other approaches as for example laser welding and spot welds, on the other hand do not require an additional material. Independent of the existence of a filler material, the connection between the processed parts is only established if the temperature has reached a certain value. Only in this case shear and tensile stresses can be transferred between the processed parts.
Finally the effects of the process on the microstructure evolution in metal alloys have to be addressed. So far this issue had only been of interest for steel alloys in the hot stamping (press hardening) processes, in which the microstructure of the material (mostly boron-alloyed steel 22MnB5) is systematically manipulated in order to produce parts with ultra-high strength properties, but also to obtain areas within the same parts that have lower strength and increased ductility. In general, this is realized by locally varying cooling rates.
In contrast to hot stamping, the heating of the material is of great importance for the application in welding simulation resulting in a still more complex phase kinetic description. As temperatures above the melting points are locally obtained, annealing is also to be considered.

2 Heat Source Definition

In many applications the Goldak double ellipsoidal heat source [1] is a reasonable choice. Within LS-DYNA the specific keyword **`*BOUNDARY_THERMAL_WELD`** has been defined to provide a convenient way to define this state-of-the-art heat source. If used, the heat is applied to the integration points inside the ellipsoid region defined by the weld pool width (b), depth (c), and forward (af) and backward (ar) lengths as depicted in Fig. 1.
The orientation of this heat source can be defined with two nodes of the finite element mesh. It therefore allows the simulation of moving heat sources as well. The extremely high temperatures often result in significant deformation of the processed part during the welding. Thus, an a-priori description of the trajectory is not always possible. For these cases and for very complex curved geometries LS-DYNA provides the keyword **`*CONTACT_GUIDED_CABLE`**. This sliding contact formulation allows guiding one-dimensional elements though a list of nodes. In order to define the motion of a heat

source on a curved weld seam as in Fig. 2, a beam has to be defined to represent the moving heat source and a set of nodes has to be given to define the trajectory on the seam.

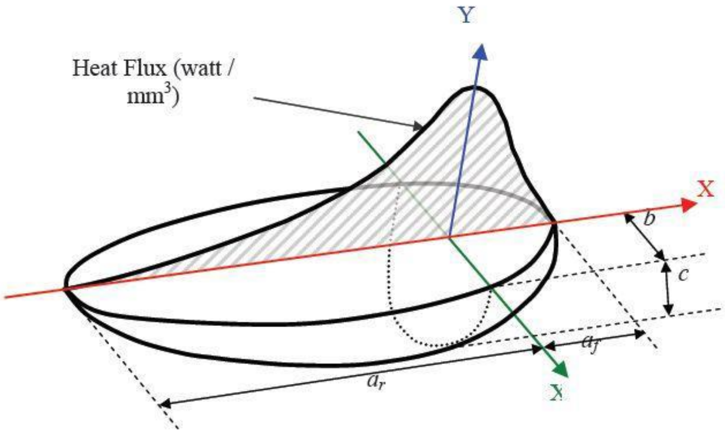

Fig.1: Schematic drawing of the Goldak double ellipsoidal heat source

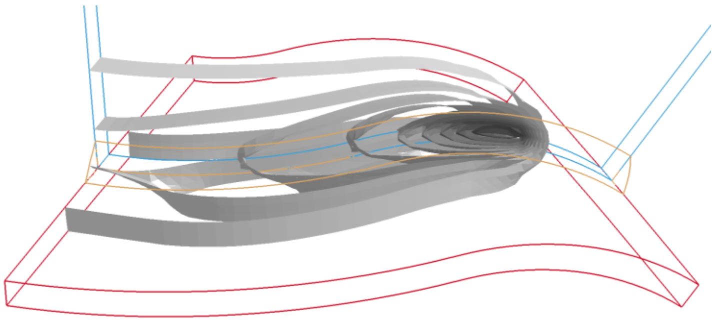

Fig.2: Temperature iso-surfaces during the welding of a curved weld seam using the Goldak double ellipsoidal heat source

If this predefined weld torch geometry does not correspond to the process parameters, a more general definition can also be incorporated in LS-DYNA [2]. The keyword **`*LOAD_HEAT_GENERATION`** accepts the input of an arithmetic expression to define the spatial power density distribution. To demonstrate the capabilities of this approach a Goldak double ellipsoidal as well as a double cone-shaped heat source moving on a curved trajectory have been exemplarily defined. The respective resulting temperature fields are shown in Fig. 3.

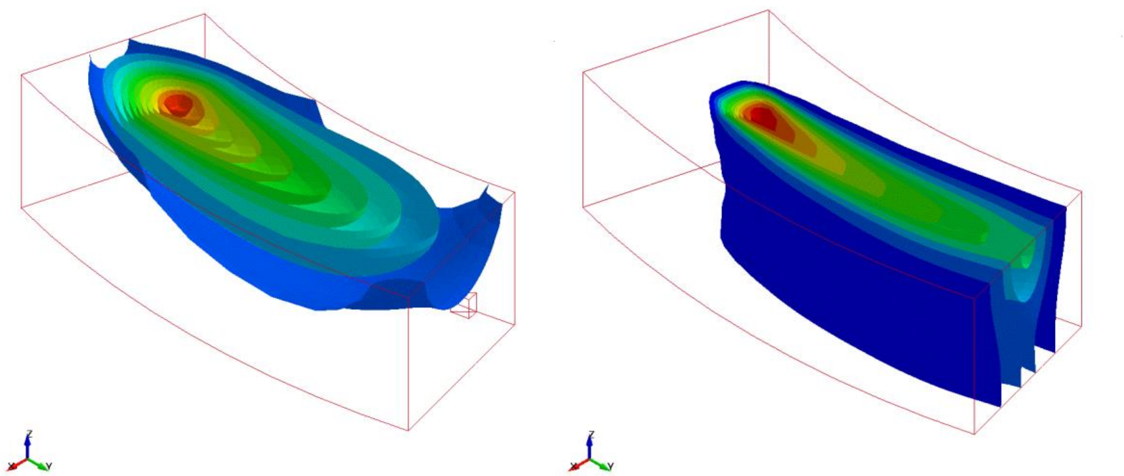

Fig.3: Temperature iso-surfaces for a Goldak double ellipsoidal (left) and a double cone-shaped (right) heat source. Both defined in LS-DYNA using an analytical expression.

3 Modeling Weld Seams with LS-DYNA

3.1 Processes with filler material

Usually, weld seams are discretized with solid elements together with the welded parts at the preprocessing stage. The connection can either be realised by shared nodes or more general by defining a contact condition between them. In both cases the elements representing the filler material are present in the model during the whole simulation. In contrast, the weld seams are filled continuously during the physical welding process and the mechanical connection is only established by those parts of the seam that are already filled and have been affected by the weld torch.
Numerically this is implemented in LS_DYNA following the ideas presented by Lindström [3,4] by material **`*MAT_CWM`** that can either be active or in a ghost state (inactive). Initially, the material in the weld seam is inactive. Although corresponding to a void, a ghost material has thermo-mechanical properties to avoid numerical instabilities. In **`*MAT_CWM`** the mechanical behaviour can be defined by Young's modulus, Possion's ratio and coefficient of thermal expansion. There exists a thermal counterpart **`*MAT_THERMAL_CWM`** in LS-DYNA, the behaviour of which is characterised by the specific heat and heat transfer coefficient.
It is important that the ghost material parameters for both material formulations are chosen carefully in order to not affect the outcome of the solution. On the other hand, a numerically stable computation has to be guaranteed for implicit and explicit time integration schemes.
Motivated by the physical process, the material is activated as soon as it is heated up above the melting point. Active material is formulated as an elasto-plastic material incorporating a von-Mises yield criterion and linear mixed hardening, for which all material parameters can be defined as functions of temperature. In order to obtain a smooth transition from ghost to active material, activation is assumed to take place within a user-defined temperature interval and the material properties are linearly interpolated in this range.
This approach allows simulating multistage welding processes. A typical discretization for such an application is shown in Fig. 4. The 17 weld seams of this example are discretized and assigned to individual parts. Resulting temperature distributions in the geometry are shown in Fig. 5 after the first and after the ninth stage have been completed. It is important to note, that the weld seams that have not yet been activated are not heated up, whereas there is a reasonable heat transfer through activated material.
The comparably low stiffness of the filler before activation naturally also affects the distortion of the finished part. This is exemplarily shown for the single-stage welding of a simple T-joint in Fig. 6 with different initialisation strategies for the weld seam. In case that filler material is activated at the beginning of the simulation, the resulting tip displacement of the part is significantly lower due to the unphysical high stiffness within the weld seam as compared to a simulation with a weld seam initialised as inactive material.

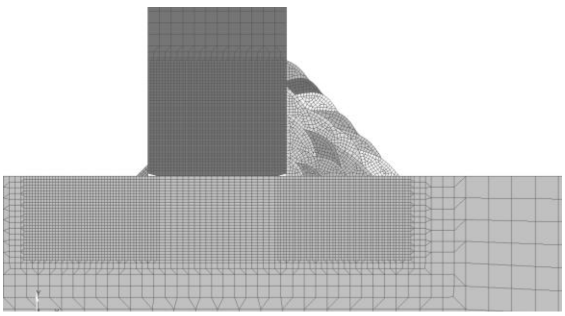

Fig.4: Discretization of a multistage welding process of a T-joint.

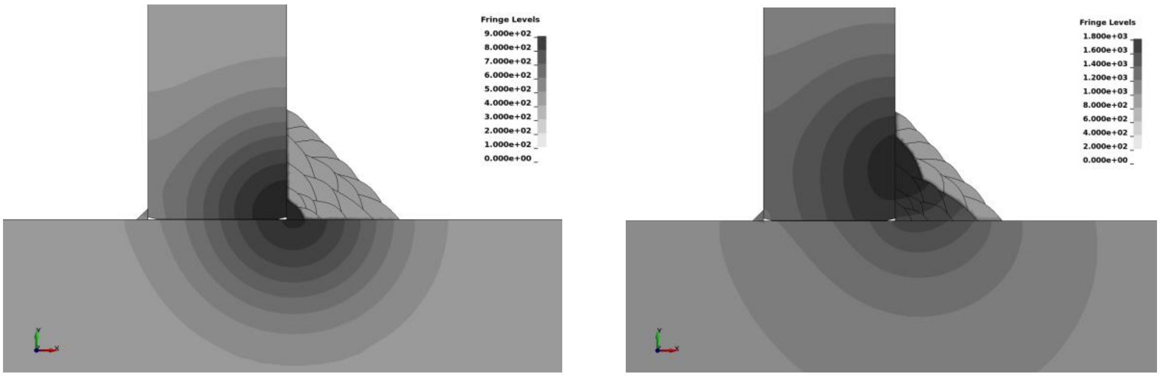

Fig.5: Temperature distribution in Kelvin during a multistage welding process after the first stage (left) and after the ninth stage (right).

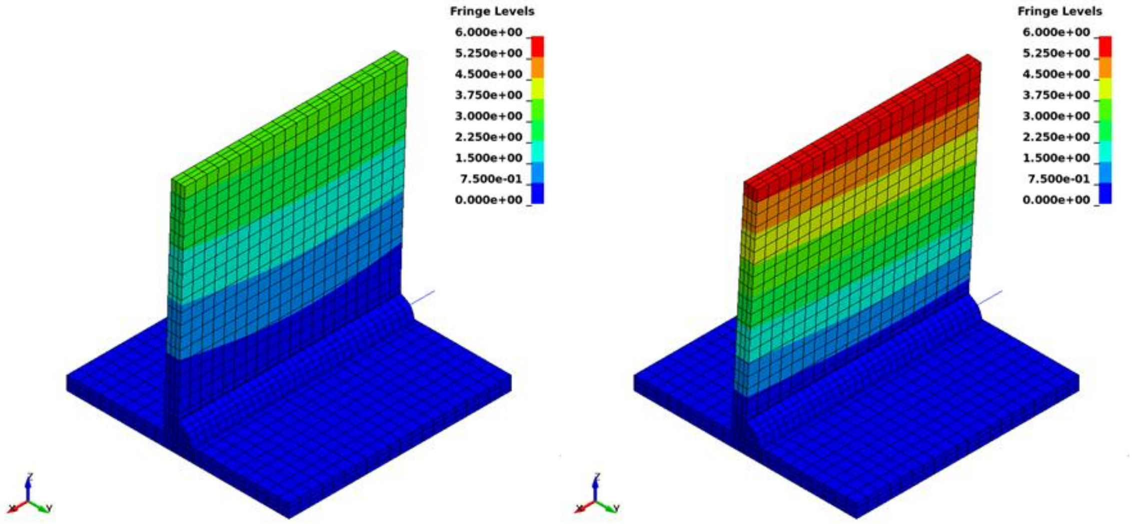

Fig.6: Comparison of the displacement field after the completed welding process. On the left, all material is activated at the beginning, on the right, ghost material is used as filler material. Color coded is the displacement magnitude.

As the temperature may rise above the melting point of the employed materials, *MAT_CWM has been given an anneal functionality. Within a user-specified temperature interval all material properties are reset to the base material. In particular, effective plastic strain data and/or the backstress tensor are zeroed out. Beyond the annealing temperature, an ideal plasticity but no evolution of the internal plasticity parameters is considered. A comprehensive study of the material for a realistic industrial process has been given in [5].

The evolution of the microstructure in the microstructure might also be of interest for the filler material in the weld seams. Therefore, the ghost material strategy described in this section as well as the annealing methodology have been included into *MAT_UHS_STEEL, which is described in some detail in section 4.

3.2 Weld seams without filler material

As already mentioned above, not all welding processes require the presence of a filler material. Here, the materials of the parts to be combined are locally heated up, e.g. by a laser beam. If the melting temperature is exceeded in the contact surface, a strong connection is established and the parts can no longer be separated.

This can be realised numerically with a new contact formulation in LS-DYNA that is defined by the keyword **`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL`**. This contact can switch locally from a sliding contact to a tied contact condition. The switch is triggered if the temperature in the contact zone reaches a certain user defined value. Of course, the contact formulation for the rest of the contact surface is not affected by this switch.

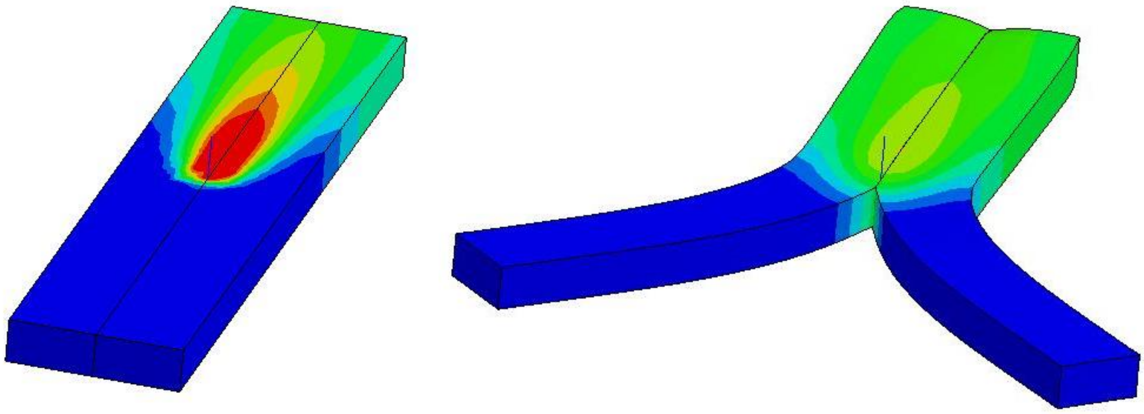

Fig.7: Welding and subsequent loading of a butt weld of two bars. Temperature field at the end of the welding step is shown (left). Loading only results in a separation of the contact areas that have not been affected by the heat.

An example application for this novel feature is the butt weld shown in Fig. 7. As depicted on the left, the weld torch only moves through one half of the contact area. After the welding, forces are applied onto two end points of the structure. The deformation shows that the parts can only separate in areas for which the contact has not been affected by the heat source. The area that is welded has been switched to a tied contact formulation and does not allow for separation of the parts.

4 Material formulation including the microstructure evolution

By activating **`*MAT_CWM`** right from the beginning of the simulation this formulation can be used to model the welded parts. It is based as mentioned above on an elasto-plastic material formulation, for which all material parameters can be defined as functions of temperature. For a variety of problems this formulation may provide sufficiently accurate results.

For some applications though, an accurate simulation of the virtual process chain requires the microstructure of the material to be taken into account. In LS-DYNA the material formulation **`*MAT_UHS_STEEL`** serves this need. This formulation has initially been developed for hot stamping simulations. Being based on the work of Åkerström et al. [6,7], the decomposition of austenite into ferrite, pearlite, bainite, and martensite can be described. The parameters for these phase changes are determined by the chemical composition of the material under consideration. The macroscopic mechanical properties follow from the current phase mixture and the properties of the individual phase. In the material formulation a linear mixture rule is always assumed.

In general, the phase change is reversible and the material formulation also allows considering the generation of austenite from the hard phases during heating. It is important to note that there is an offset of the phase transformation start temperatures between the heating and the cooling phase. This is accounted for in the current implementation of **`*MAT_UHS_STEEL`**, as discussed in [8].

To investigate the interaction between welding and phase transformations and demonstrate the applicability of the material formulation for welding simulations, a rather academic round robin example as depicted in Fig. 8 is taken into account. Into the notch of a block, two weld seams of the same material are introduced. Here it is important to note, that this is possible only since the ghosting strategy and annealing approach that has been described in section 3.1 have been implemented in **`*MAT_UHS_STEEL`** as well. All materials have been initialized in a ferrite state.

For this contribution, numerical results are evaluated at two different points in time. At t=9.6 s and t=28 s the weld torch has moved around two third of the lower or upper weld seam, respectively. This can easily be verified from the temperature distributions shown in Fig. 9. The smooth contours of the temperature field at both simulation states indicate a realistic heat transfer across the boundary between the individual parts. It is important to note that the heat transferred to the block is too low to induce a phase change from ferrite to austenite. In the following, phase mixture is thus only evaluated for the weld seams.

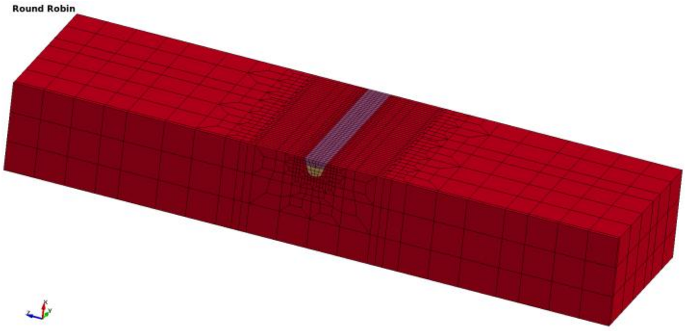

Fig.8: Geometry of round-robin example.

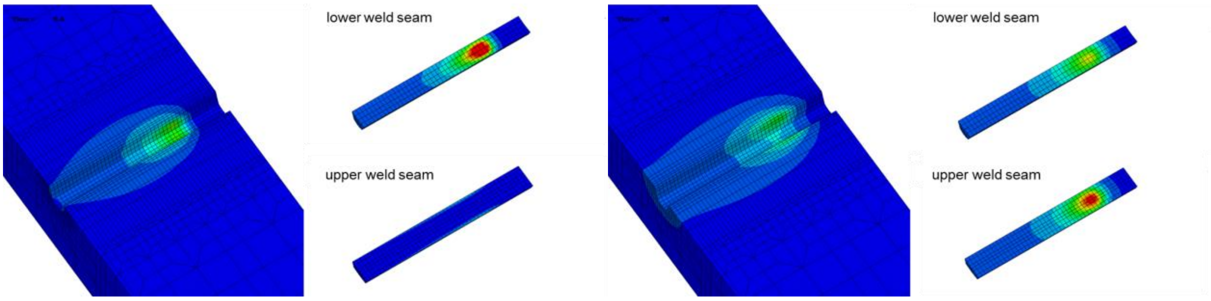

Fig.9: Temperature distribution in round robin example at t=9.6 s (left) and t=28 s (right). Shown temperature ranges between room temperature and 1900 K.

Close to the weld torch, temperatures locally exceed the start temperature for austenite composition, c.f. Fig. 10. Due to the applied material parameters and boundary definitions, a relatively high cooling rate is obtained in the subsequent cooling phase and Fig. 11 demonstrates that austenite is mainly decomposed into martensite. After completion of the first welding stage, the lower weld seam has a very high martensite concentration. The second weld stage introduces temperatures that are high enough to not only transform the ferrite in the upper seam but also the martensite in the lower seam into austenite. Again, cooling results in a high martensite concentration.

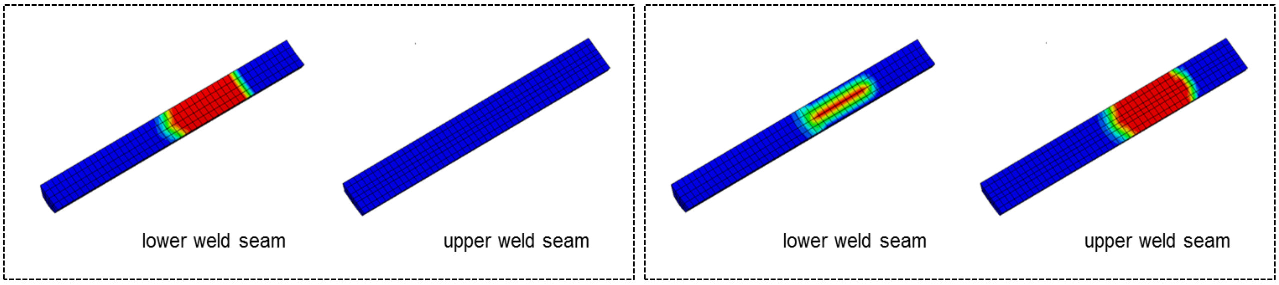

Fig.10: Austenite concentration at t=9.6 s (left) and t=28 s (right)..

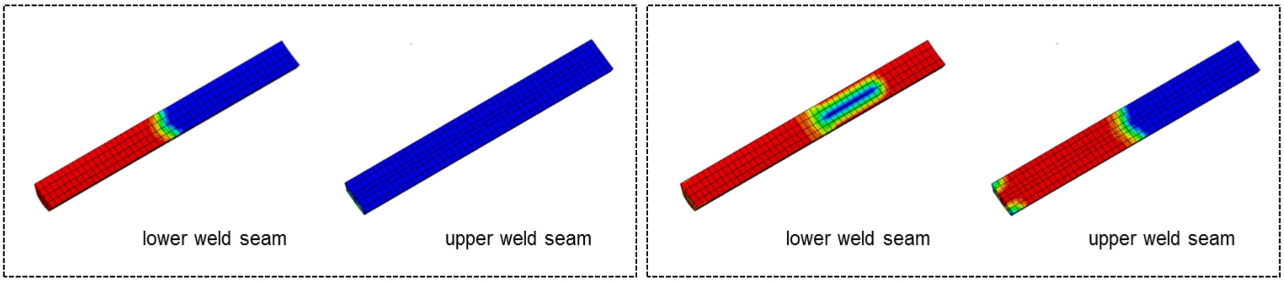

Fig.11: Austenite concentration at t=9.6 s (left) and t=28 s (right)..

Phase changes as they are induced by hot stamping and welding usually go along with transformation induced plasticity (TRIP) as well as transformation induced elastic strains. Whereas a TRIP-algorithm has been part of the original formulation of ***MAT_UHS_STEEL**, an algorithm for the induced elastic strains has been implemented only recently. This novel feature can be calibrated using dilatation experiments. The resulting curve, which is exemplarily shown for a dual-phase steel in Fig. 12, describes the expansion of the material versus the temperature. Transformation induced strains show in this graph as jumps. The slope of this curve corresponds to the coefficient of thermal expansion which changes as the phase mixture is updated. The numerical simulations show that the experimental dilatation data can be accurately reproduced.

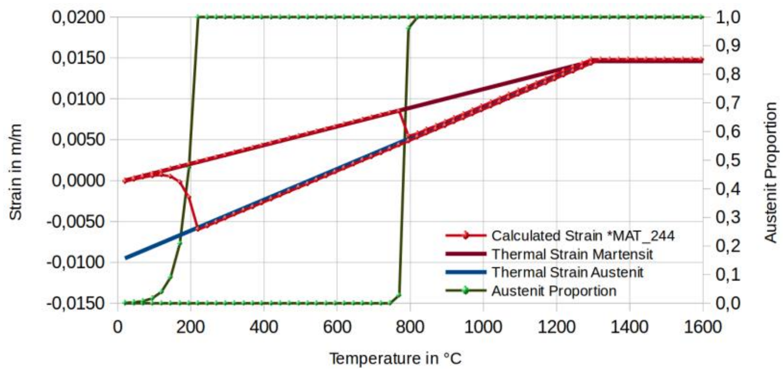

Fig.12: Curve of strain vs. temperature for a dual-phase steel.

5 Welding as one stage of the process chain

In manufacturing industries, welding often is only one stage of the complete process chain. Naturally, the stresses as well as other internal variables have to be transferred from one process step to the next. The approach is demonstrated with a deep drawing example of a welded blank.
The welding of a circular blank (initially in a ferrite state) is shown in Fig. 13. The process results in a significantly deformed structure that is then clamped between two rigid rings before the sheet is formed using a hemispherical punch, c.f. Fig. 14.

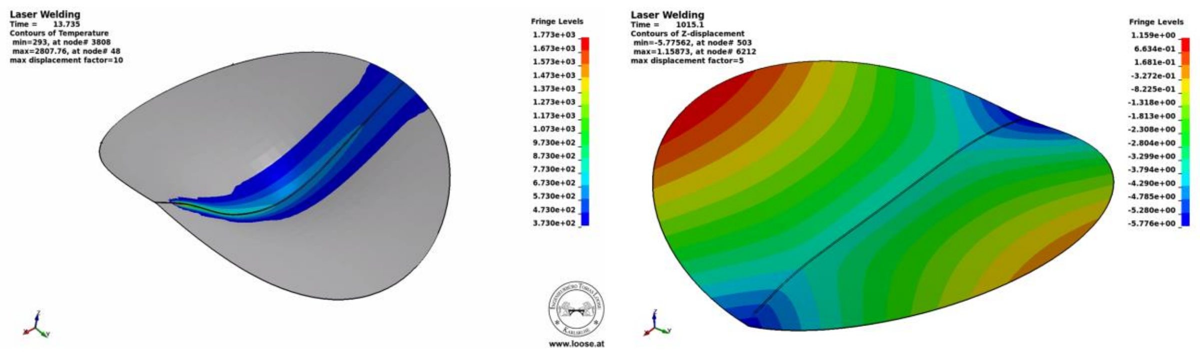

Fig.13: Welding step. Temperature field during welding on the left and contour of z-displacement on the right. In both cases the deformations are scaled by a factor of 10.

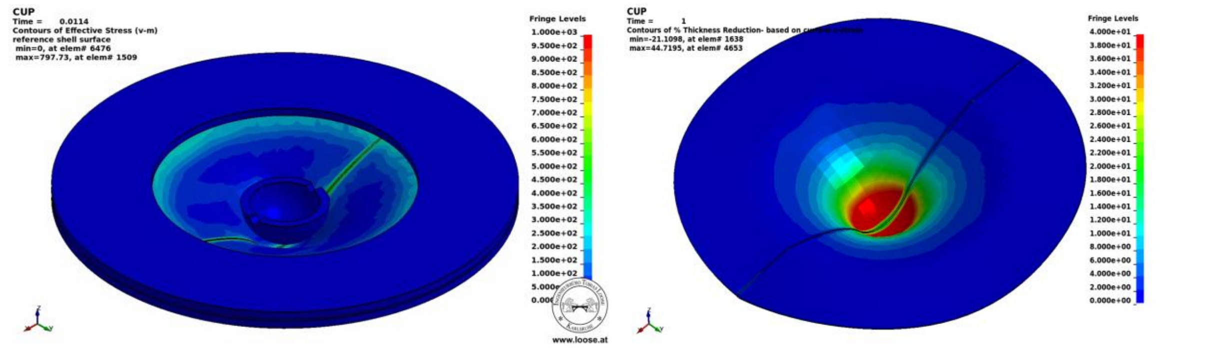

Fig.14: Deep drawing. Position of tools after the drawing on the left, von Mises stresses are colour coded. On the right the final thickness reduction of the blank is shown.

Internal variables are output at the end of welding and used as input for the subsequent forming. It is apparent from the results shown in Fig. 14 that the welding has a significant influence onto the deep drawing process. Within the heat affected zone in proximity of the weld seam, a martensite structure has developed. Due to higher stiffness of this microstructure as compared to the other phases, the residual stresses after forming are increased, whereas the thickness reduction is relatively low in this region of the blank.
A more detailed survey on this example as well as on more complex virtual process chains modelled with LS-DYNA can be found in [9].

6 Summary and Outlook

This contribution presented new developments in the software package LS-DYNA that enable users to consider welding stages in the manufacturing process chain. Different modelling approaches for heat sources have been introduced. For cases, in which the assumption of the standard Goldak double ellipsoidal heat source is reasonable, LS-DYNA allows a very simple heat source input using the keyword **`*BOUNDARY_THERMAL_WELD`**. It has been shown here that this implementation can also be used to define the motion of a heat source on complex, curved weld seams. As a double ellipsoidal power density distribution is not always a feasible choice, the keyword **`*LOAD_HEAT_GENERATION`** provides the flexibility to define arbitrarily shaped heat sources.
A ghost material approach has been discussed to model the behaviour of filler material in weld seams. It has been implemented in LS-DYNA first in **`*MAT_CWM`** and its thermal material counterpart **`*MAT_THERMAL_CWM`**. Material **`*MAT_CWM`** provides a temperature dependent elasto-plastic material formulation. The basic idea of the ghosting approach is to initialize the material in an inactive state with almost negligible mechanical and thermal properties. Therefore weld seams can be discretized in the pre-processing step and still do not significantly affect the outcome of the simulation.
As some processes do not necessitate the addition of filler material, the ghosting approach is not always a suitable choice. For such applications, a new contact formulation has been recently introduced in LS-DYNA. As long as the melting temperature of the material has not been exceeded within the contact area, the contact **`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL`** behaves like one of the standard contact formulations in LS-DYNA. As soon as the critical temperature is reached, the formulation is switched to a tying contact, which does not allow for a separation of the contact partners.
Often the changes in microstructure of the welded parts and possibly also within the filler material are of interest for the quality of the process. Therefore, the ghost material approach has also been included into the complex LS-DYNA material **`*MAT_UHS_STEEL`** together with further enhancements and extension in this material. This material initially has been designed for hot stamping processes, but in its current implementation can accurately predict the microstructure evolution in welding processes, taking up to five different phases into account.
With some simple examples the reasonable effects of these new features have been discussed. The set of new developments makes LS-DYNA an efficient and valuable software tool for welding analysis. This could also be shown with simulations of the manufacturing processes of real industrial parts. The

distortion as well as the local microstructure evolving during the welding stage could be predicted with a very high accuracy.

Future developments aim to increase the range of possible applications. As the name suggests, **`*MAT_UHS_STEEL`** is limited only to a certain group of materials. Currently, implementation of a more general material formulation for welding and heat treatment simulations is on the way, in particular in terms of the microstructure evolution. This formulation will not be restricted to five phases but allows for an arbitrary number of different phases. From a list of generic transformation models, the user can choose for each of the possible phase transitions individually. The current status of the implementation and as well as further possible developments for thermo-mechanically coupled simulations will be discussed.

7 Literature

[1] Goldak, J., Chakravarti, A., Bibby, M.: “A Double Ellipsoid Finite Element Model for Welding Heat Sources”, IIW Doc.No., 212-603-85, 1985

[2] Klöppel, T., Erhart, A., Haufe, A., Loose, T.: “Recent Developments in LS-DYNA to close the virtual process chain for forming, press hardening and welding”, Key Engineering Materials Vols 651-653 (2015) pp 1312-1318.

[3] Lindström, P.R.M, Josefson, L.B., Schill, M., Borrvall, T.,” Constitutive Modelling and Finite Element Simulation of Multi Pass Girth Welds”, Proc. Of NAFEMS NORDIC Conference, Gothenburg May 22-23, (2012).

[4] Lindström, P.R.M, “DNV Platform of Computational Welding Mechanics”, Proc. Of Int. Inst. Welding 66th Annual Assembly 6, (2013).

[5] Schill, M., Odenberger, E.: “Simulation of residual deformation from a forming and welding process using LS-DYNA”, 13th International LS-DYNA Conference, Detroit, 2014

[6] Åkerström P., Oldenburg M.: “Austenite decomposition during press hardening of a boron steel – Computer simulation and test”, Journal of Materials Processing Technology, 174, 2006, 399-406

[7] Åkerström P., Bergman G., Oldenburg M.: “Numerical implementation of a constitutive model for simulation of hot forming”, Modeling and Simulation in Materials Science and Engineering, 15: 105-119, 2007.

[8] Klöppel,T., Schill, M., Loose, T.: “Recent Developments for Hot Stamping and Welding Processes in LS-DYNA”, LS-DYNA Forum 2014, Bamberg, 2014

[9] Loose, T.: “Coupled Simulation of Forming and Welding with LS-DYNA for the Design of Distortion-Compensation”, LS-DYNA Forum 2014, Bamberg, 2014