Recent Developments in LS-DYNA to close the virtual process chain for forming, press hardening and welding

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Abstract. Forming, press hardening and welding are a well-established production processes in manufacturing industry, but predicting the finished geometry and the final material properties of the processed parts is still a major issue. In particular, deformations caused by welding are often neglected in the virtual process chain, although they have to be compensated for in order to fulfill the requirements on shape tolerance. This presentation will give an overview on novel features of LS-DYNA implemented particularly for welding simulations.

To begin with, new keywords will be presented that allow applying the heat generated by the weld torch. LS-DYNA offers a very convenient way to define the well-known Goldak heat source, but it is also possible to define arbitrarily shaped torch geometries.

In order to obtain a predictive model for welding simulations, specific material models have been devised in LS-DYNA. The properties of filler material in weld seams are accounted for by a ghost material approach. Material is initialized as ghost material and is activated, i.e. it is given base material properties, when the temperature reaches the melting point. This approach has been implemented for a relatively simple thermo-elasto-plastic material formulation *MAT_CWM as well as for the more complex material law *MAT_UHS_STEEL. The latter has initially been implemented for press hardening simulations and is able to predict the microstructure of steel alloys including phase transformations and the resulting mechanical properties.

In this contribution, details of the material formulations and novel features are presented. Examples will demonstrate how these features can be applied to multistage processes including several forming and welding stages.

Introduction

Predicting the finished geometry of a part is a major objective for the manufacturing industry. Of particular interest are processes with multiple process steps and several different process types. Here, the complete manufacturing process has to be included in the simulation in order to obtain accurate results. For sheet metal forming, this is already state-of-the-art. However, as the mechanical and functional requirements put on the produced parts increase, more complex process steps have to be considered in numerical analysis.

For example, welding has gained importance recently; cf. for example Schill and Odenberger [1]. Due to the extremely high temperatures evolving in the structure, significant macroscopic deformations and internal stresses are induced within the welded part. Moreover, the process locally changes the microstructure of the metal alloys.

So far, this effect of microstructure evolution in steel alloys had only been of interest for hot stamping (press hardening) processes. The main objective of those is to systematically manipulate the microstructure of the material (mostly boron-alloyed steel 22MnB5) 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, there exist several methods that can be used to influence the cooling rate of the part locally. Regions with high cooling rates show a purely martensitic microstructure, whereas a lower rate results in a mixture of ferrite, pearlite, bainite, and martensite. Consequently, the latter has a lower macroscopic strength and higher ductility.

To choose process parameters to obtain optimal part properties for an individual task, numerical simulations are indispensable. In the Finite Element software package LS-DYNA, material model *MAT_UHS_STEEL (*MAT_244) has been implemented for the application in hot form simulations. The formulation is based on the work of Åkerström et al. [2,3]. Based on the chemical composition of the alloy, the micro-mechanical characteristics for phase kinematics and, consequently, the overall macro-mechanical properties are determined for a coupled thermo-mechanical simulation.

To be applicable in welding simulations, this material formulation has been extended and enhanced. In contrast to hot stamping applications, the heating process has to be taken into account resulting in a still more complex phase kinematics description. As temperatures above the melting points are locally obtained, annealing is also to be considered. Additionally, the material formulation should be suitable for the usage as filler material in the weld seams, which are usually discretized with solid elements right at the beginning of the simulation. However, as long as the welding torch has not reached the material it is not to influence the result of the simulation. In analogy to the recently introduced LS-DYNA material *MAT_CWM (*MAT_270) a ghosting approach has been implemented.

Prior to a more detailed discussion of material *MAT_CWM and extensions to *MAT_UHS_STEEL, possibilities to simulate heat sources for a welding process are demonstrated. LS-DYNA does not only allow for a convenient definition of the Goldak heat source introduced in [4] but also for a very flexible input of arbitrarily shaped welding torch geometries.

Definition of Heat Sources

In many applications the Goldak double ellipsoidal heat source is a reasonable choice. Within LS-DYNA a specific keyword *BOUNDARY_THERMAL_WELD has been defined. 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 weld source origin is defined in a node that moves by a prescribed displacement.

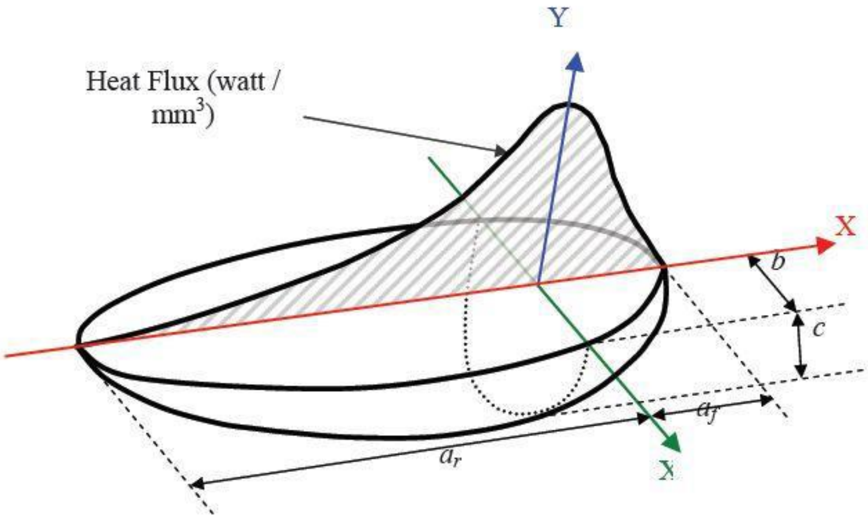


Fig. 1: Schematic drawing of the Goldak double ellipsoidal heat source.

If this predefined geometry does not correspond to the process parameters, a more general definition can also be incorporated in LS-DYNA. The keyword *LOAD_HEAT_GENERATION accepts the input of an arithmetic expression to define the geometry of the heat source. 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. 2.

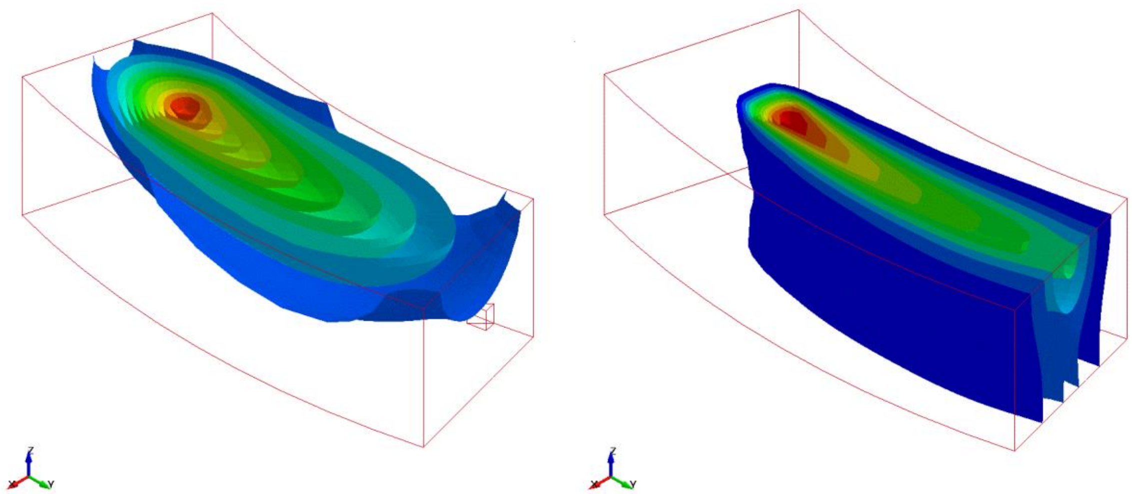


Fig. 2: Temperature iso-surfaces for a Goldak double ellipsoidal (left) and a double cone-shaped (right) heat source. Both defined in LS-DYNA using an analytical expression.

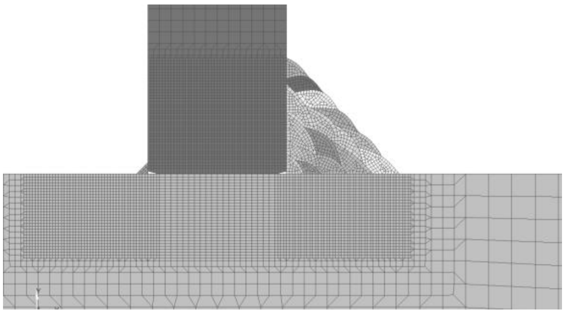
Modeling Weld Seams with *MAT_CWM

Usually, weld seams are discretized with solid elements together with the welded parts at the preprocessing stage. Therefore, these elements are present in the model during the whole simulation. In contrast, the weld seams are filled continuously during the physical welding process. Forces can only the transmitted by those parts of the seam that are already filled and have been affected by the weld torch.

Numerically this is implemented following the ideas presented by Lindström [5,6] as a material that can either be active or ghost (inactive). Initially, the material in the weld seam is inactive. Although corresponding to a void, a ghost material has thermo-mechanical properties. In *MAT_CWM the mechanical behavior 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 behavior of which is characterized 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 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 (von-Mises yield criterion, 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. 3. The 17 weld seams of this example are discretized and assigned to individual parts. Resulting temperature distributions in the geometry are shown in Fig. 4 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.



Fig, 3: Discretization of a multistage welding process of a T-joint.

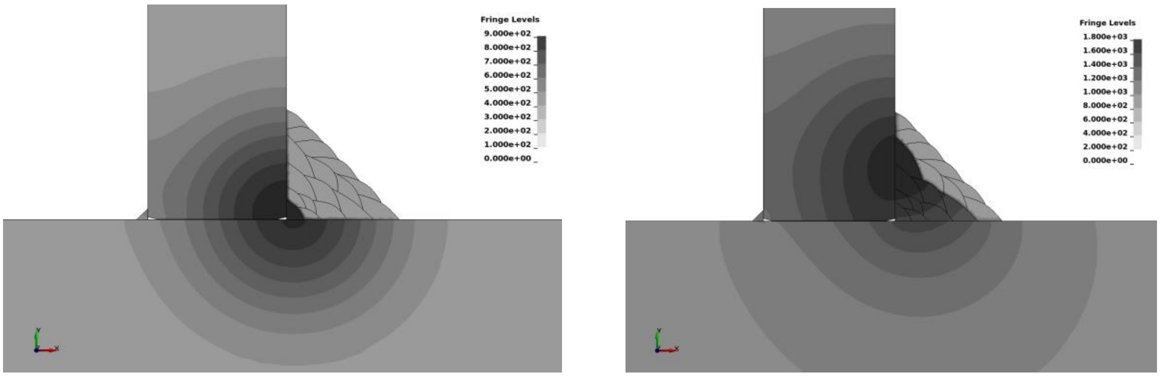


Fig. 4: Temperature distribution during a multistage welding process after the first stage (left) and after the ninth stage (right).

Furthermore, *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.

Modeling Weld Seams and Welded Parts with *MAT_UHS_STEEL

For some applications, 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. As already mentioned above it has initially been developed for hot stamping simulations. Being based on the work of Åkerström et al. [2,3], the decomposition of austenite into ferrite, pearlite, bainite, and martensite can be described, while the parameters for these phase changes are determined by the chemical composition of the material under consideration. The phase change is reversible and the material formulation also allows considering the generation of austenite from the hard phases during heating. The macroscopic mechanical properties follow from the current phase mixture and the properties of the individual phase.

The demands resulting from welding simulation necessitated some extensions to the model. First of all, the evolution of the microstructure might also be of interest for the filler material in the weld seams. Therefore, the ghost material strategy devised for *MAT_CWM was included into *MAT_UHS_STEEL as well using the same input structure. The application to the welding of a T-joint can be seen in Fig. 5. It shows a comparison of the displacement field after the process is completed between the original formulation and the enhanced version. In case that filler material is activated at the beginning of the simulation, the resulting tip displacement of the part is too low due to the unphysical high stiffness within the weld seam.

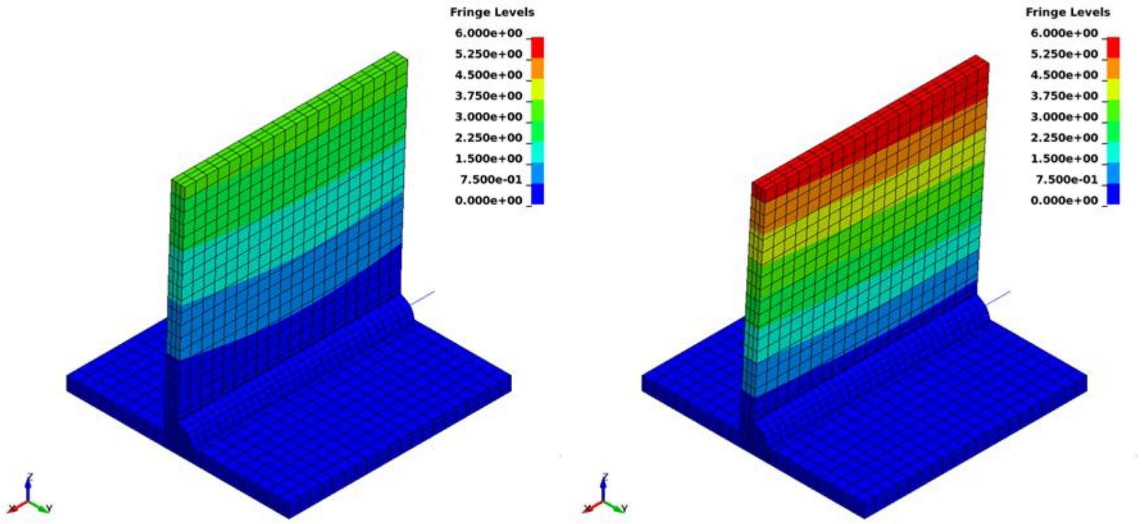


Fig. 5: Comparison of the displacement field after the completed welding process. On the left, all material is activated at the beginning, on the right, ghost material is used as filler material.

To demonstrate the interaction between welding and phase transformations, a rather academic round robin example is investigated. Into the notch of a block, two weld seams of the same material are introduced as depicted in Fig. 6 and all material is initially in a ferrite state.

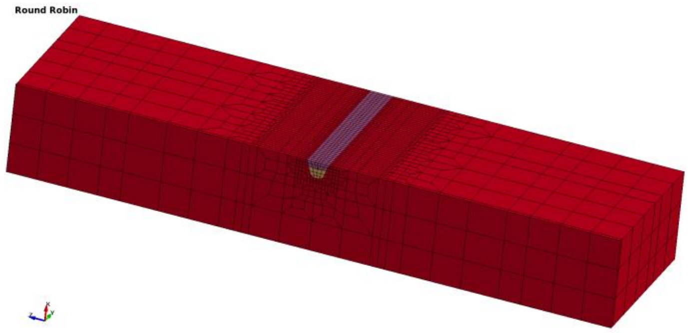


Fig. 6: Geometry of round-robin example.

For this contribution, numerical results are evaluated at two different points in time. At t=9.6 and t=28 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. 7. The smooth contour of the temperature field indicates 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.

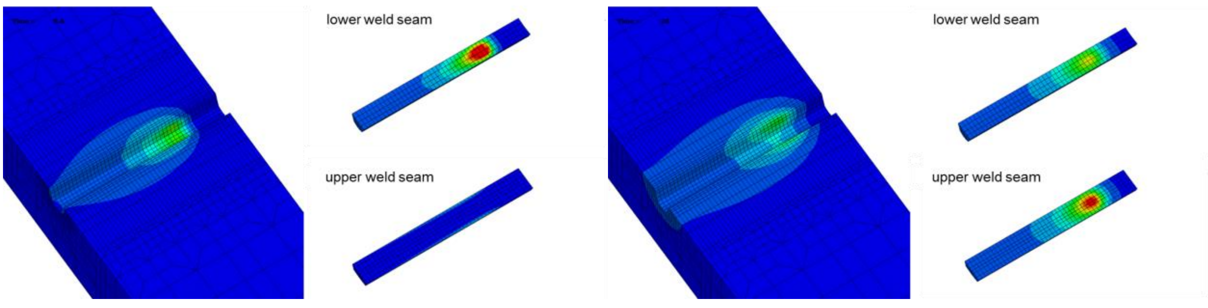


Fig 7: Temperature distribution in round robin example at t=9.6 (left) and t=28 (right). Shown temperature ranges between room temperature and 1900 K.

Close to the weld torch, temperatures locally exceed the start temperature for austenite composition, c.f. Fig. 8. According to the applied material and boundary definitions, a comparably high cooling rate is obtained in the subsequent cooling phase and Fig. 9 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.

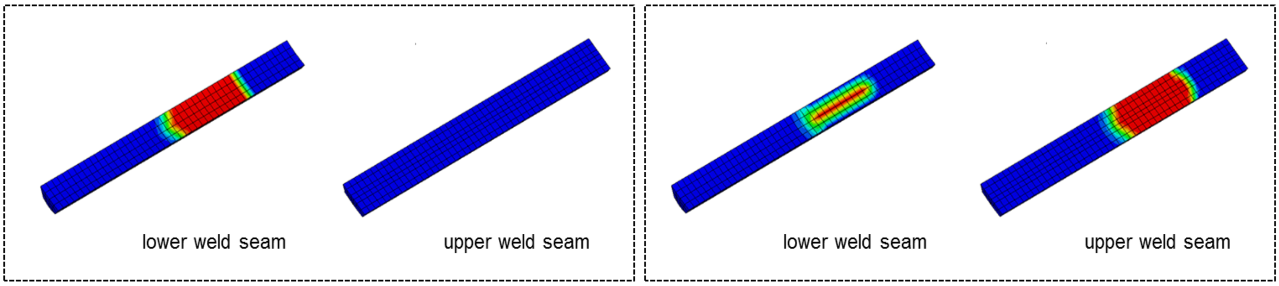


Fig. 8: Austenite concentration at t=9.6 (left) and t=28 (right).

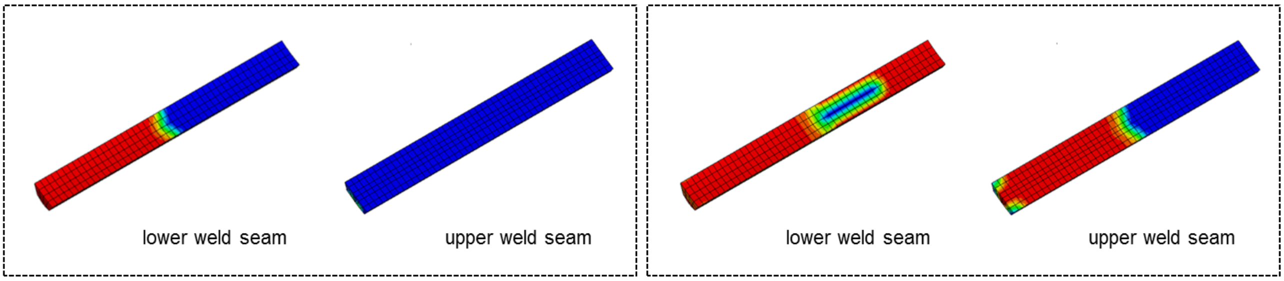


Fig. 9: Martensite concentration at t=9.6 (left) and t=28 (right).

Phases changes as they are induced by welding 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, the effect of the induced elastic strains has been implemented only recently. This feature can be calibrated using dilatation experiments, which are exemplarily shown for a dual-phase steel in Fig. 10. The transformation induced strains are represented in this graph as jumps in the curve that describes the expansion versus the temperature. The slope of this curve corresponds to the coefficient of thermal expansion which changes as the phase mixture is updated.

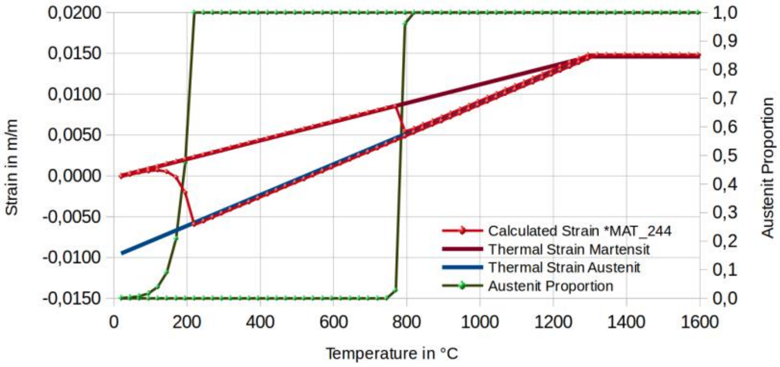


Fig. 10: Curve of strain vs. temperature for a dual-phase steel.

Finally, also the annealing functionality has been implemented in *MAT_UHS_STEEL. The numerical implementation closely follows the structure introduced for *MAT_CWM. Above the melting temperature, history variables are reset and the stresses cannot increase (ideal plasticity without evolution of plasticity parameters.

Summary

We have presented new developments in the software package LS-DYNA that enable the user to consider welding stages in the manufacturing process chain. Different modeling approaches for the heat sources have been introduced, which on the one hand allow a very simple input for standard weld torch geometries and on the other hand provide the flexibility to define arbitrarily shaped heat sources.

A ghost material approach has been discussed to model the behavior of filler material in weld seams. It has been implemented in LS-DYNA first in *MAT_CWM that provides a thermo-elasto-plastic material formulation. As the changes in microstructure of the welded material and in some application also within the filler material are of interest, the ghost approach has also been included into the complex LS-DYNA material *MAT_UHS_STEEL together with further enhancements and extension in this material.

With some simple examples the reasonable effects of these new features have been discussed. Furthermore, LS-DYNA has also been used to simulate the manufacturing 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.

References

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

[2] 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.

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

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

[5] 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).

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