

# Recent Updates for the Heat Transfer Solver in LS-DYNA® with focus on computational welding mechanics

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## Abstract

*Even though welding is a well-established production process in manufacturing industries and it has a significant influence on the finished geometry as well as on the material properties of the processed part, it is still often neglected in the virtual process chain. In this contribution novel developments for the heat transfer solver in LS-DYNA® are presented, which are designed to close this gap in the virtual process chain. In order to ensure a seamless data transition between stages without complex procedures, all new developments are applicable to solid and shell discretized geometries.*

*First of all, the new keyword \*BOUNDARY\_THERMAL\_WELD\_TRAJECTORY is presented that provides an easy and flexible input structure for a heat source moving along a prescribed and, possibly, geometrically complex path for thermo-mechanically coupled and thermal only simulations.*

*Due to high temperatures, temperature gradients and temperature rates present in welding applications, phase transformations in the microstructure of the material play a crucial role in the process. The new material model \*MAT\_GENERALIZED\_PHASE\_CHANGE/#254 allows to distinguish up to 24 different phases in the microstructure. For each of the possible phase transitions the user can choose from a list of generic and well-established transformation models making the model applicable to a wide range of steel and aluminum alloys.*

*Depending on the process of interest, the transfer of heat and momentum between the welded parts is either implemented numerically by a special filler material in the weld seam or by a tailored contact formulation. The former can for example be realized with the new material formulation \*MAT\_254. The latter features a peak temperature induced switch between a sliding and tying contact and heat transfer across shell edges.*

## 1 Introduction

Over the last decades the mechanical and functional requirements put on the parts produced by the manufacturing industry has increased tremendously. In order to meet these requirements, the complexity of manufacturing processes has increased likewise. Therefore, numerical process simulation, which aims to accurately predict the shape and properties of the finished part, has gained importance.

Many of the processes used today incorporate characteristics of different physical regimes. Naturally, the coupling between different physical fields makes a numerical handling more complex and a powerful multi-physics solver such as LS-DYNA® is indispensable to simulate and solve such complex non-linear coupled problems.

From a numerical point of view, a particularly challenging process step is fusion welding. It is a well-established technology, in which the material is locally heated above the melting point and the molten regions are joined together during subsequent cooling. It usually results in comparably high deformations that have to be compensated for. Within the heat affected zone the material properties are often significantly altered as compared to the base material. This effect is due to phase transformation in the micro-

structure. Consequently, the main objective of the numerical simulation is to predict the deflection of and microstructure composition in the welded structure.

It is common practice to model the heat input of the weld torch by an equivalent heat source that is described by a power density distribution. For arc welding processes, the Goldak double ellipsoid heat source is considered to be the standard, see Goldak et al. [1]. In LS-DYNA an implementation of this distribution has been available for a couple of years (keyword: \*BOUNDARY\_THERMAL\_WELD). In thermo-mechanical coupled simulations the movement and the aiming direction of the weld torch has been associated with the movement of a beam. For curved and possibly deforming structures, an a-priori definition of the movement might be very complex or even impossible.

To address this issue and additionally to provide more flexibility in terms of energy rate distributions a new implementation for equivalent heat sources has been added to LS-DYNA. The keyword \*BOUNDARY\_THERMAL\_WELD\_TRAJECTORY can be used to simulate a weld torch moving along a path defined on a (possibly moving and deforming) part in coupled but also in thermal-only analyses. In the next section some key feature such as easy definition of trajectories and weld aiming directions, a list of pre-defined weld pool geometries and the possibility of thermal dumping will be discussed.

If the user is mainly interested in the deflection of the part after the welding stage, the LS-DYNA material \*MAT\_CWM/#270 is a suitable choice to model the welded parts as well as filler material that is sometimes used in welding processes. Here a ghosting approach, i.e. a thermal activation of material, plays a crucial role. The material is briefly reviewed in section 3.

Many applications, however, necessitate an additional knowledge of phase transformations in the heat affected zone and, consequently, of the resulting material properties. In order to provide a suitable model for a wide range of metals, a new material \*MAT\_GENERALIZED\_PHASECHANGE/#254 has been implemented. The material distinguishes up to 24 different microstructural phases. For each possible phase transformation between the phases the user can define a specific phase transformation model by choosing from a list of generic transformation models.

Based on the current phase concentrations the mechanical and thermo-mechanical parameters are evaluated. The material features a temperature and strain rate dependent plasticity algorithm. More details on this material can be found in the third section of this contribution. Beside a brief introduction of the keyword input, basic equations of the phase transformation models and the most important structure mechanical features are presented.

The fourth section addresses developments in the thermal contact formulations in LS-DYNA. Naturally, the assumption of added material in welding processes is not always justified and the ghost element approach not always feasible. In order to enable the user to simulate for example laser welding, a novel contact formulation has been implemented for both solid and shell discretized models. The key characteristic is a peak temperature driven switch from a sliding to a tied contact formulation.

The heat transfer for shell element in contact with other shell elements or solids is a well-established feature in LS-DYNA for some years, but up until recently, it has only been applicable between surfaces. For a more convenient modelling of T-joint geometries with shell elements and easy connections of sheet metals to solid weld seams, a novel contact formulation has been added to model the heat transfer between shell edges to surfaces.

## **2 A New LS-DYNA®-Keyword for Heat Source Modelling**

In case of the well-established \*BOUNDARY\_THERMAL\_WELD implementation the movement of a heat source is always identified with the movement of two nodal points in the simulation. This firstly implies that a moving heat source can only be modelled in a thermo-mechanically coupled simulation. Secondly, defining the movement and orientation of the heat source on curved parts has often required a significant pre-processing effort. Due to the extremely high temperatures and temperature gradients during welding,

the processed part will undergo significant deformations. As this naturally affects the welding path, an accurate a-priori prediction of the path is only seldom possible.

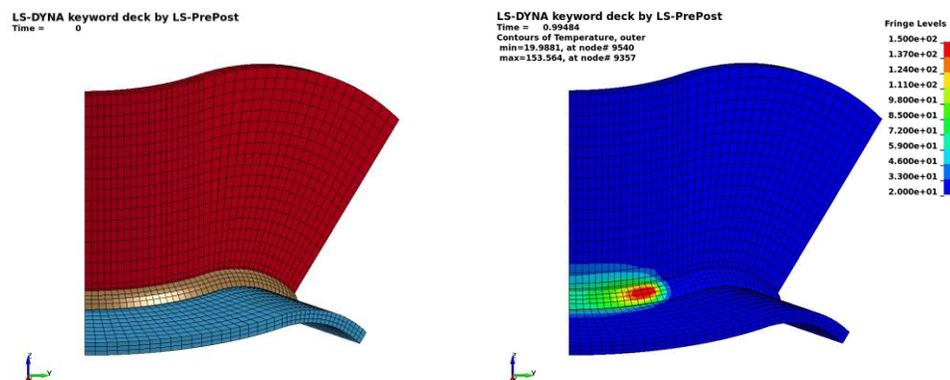
These drawbacks of the implemented boundary condition motivated the development of a novel keyword for moving heat sources called \*BOUNDARY\_THERMAL\_WELD\_TRAJECTORY. Its keyword input consists of four cards that read:

```
*BOUNDARY_THERMAL_WELD_TRAJECTORY
  PID      PTYPE      NSID1      VEL1      SID2      VEL2      NCYC      RELVEL
  IFORM    LCID       Q         LCROT     LCMOV     LCLAT     DISC
  P1       P2         P3        P4        P5        P6        P7        P8
  TX       TY         TZ
```

The boundary condition is based on the observation that in most line welding processes the weld torch moves with a prescribed velocity on a pre-defined path. In the numerical representation this trajectory of the root of the weld torch is defined by a node set with the id NSID1. The torch velocity is given by VEL1 and can also be input as load curve defining the velocity as function of time. If the nodes are part of the welded structure, the position of the weld path will be updated automatically with deformation of the structure in a coupled simulation. In that case the velocity can either be defined in a fixed frame of reference (set RELVEL to 0) or with respect to the moving welded structure (set RELVEL to 1).

Besides the position of the root also the orientation of the heat source is to be defined. The new keyword features three different methods to describe it in order to make the input for many different applications as convenient as possible. The parameter SID2 defines the method to be used by the solver. If it is set to 0, a constant beam aiming direction (TX,TY,TZ) is assumed, defined in the fourth, optional keyword card.

For curved welds as shown in Figure 1, a constant orientation is probably unrealistic. One possibility to simulate a more reasonable, varying orientation employs a second node set (with SID2 as id), which defines a second path. The weld torch is always orientated from points in this path to the root of the torch. The position within the second path is automatically updated using a prescribed velocity (VEL2).



**Figure 1: Welding of a curved T-joint. Geometry (left) and temperature field (right)**

The usage of a second node set to define the orientation of the weld torch at any given position of the trajectory provides the utmost flexibility for complex welding processes. A possible disadvantage of this method lies in the significant pre-processing effort. A remedy is provided by the third orientation definition that has been implemented into the new boundary condition. It only requires knowledge of the position of the torch and the geometry of the welded structure and is invoked for a negative parameter SID2. The input requires a segment set with an id of -NSID2 and the weld beam is always assumed to be orthogonal to the segments in this set. For many applications in fusion welding the third method seems to be the most suitable choice in terms of pre-processing effort and accuracy.

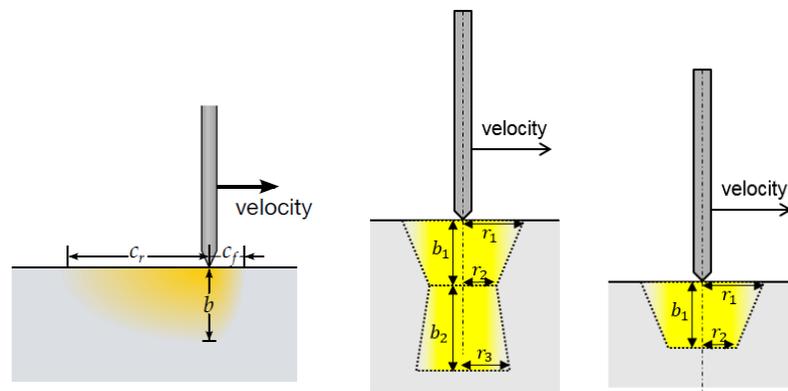
To gain even more flexibility and to make variation of process parameters easier, position and orientation of the heat source can be adapted by time-dependent load curves. The values given in curves LCROT, LCMOV and LCLAT define a rotation around the trajectory, a displacement in weld beam direction and a displacement in lateral direction, respectively.

The novel keyword does not require the presence of a structure solver for modelling a moving heat source due to the particular definitions and functionalities described above, since the motion of the weld torch is not necessarily linked to the motion of a structural part. Therefore, moving heat sources can be simulated in thermal-only analyses.

The motion of the heat source frequently becomes the limiting factor for the admissible time step size depending on mesh size and torch velocity. Too large time steps result in an unevenly heating with often unphysically high maximum temperatures, since the solver does not compute intermediate positions and the heat source “jumps” across whole elements. Since the motion of the welding heat source has been transferred from the structure to the thermal solver and due to the definition with a trajectory, a kind of sub-cycling becomes possible. The solver uses NCYC sub-time steps for any time step. This can be shown to smooth the temperature distribution and equally important the mesh distortion along the trajectory considerably. Moreover, a thermal dumping can be realized to reduce simulation times.

Although being widely used in industries, the Goldak equivalent heat source might not be the best choice for all applications. The parameter IFORM enables the user to choose between four different equivalent heat source geometries, the parameter of which are P1 to P8. If IFORM is set to 1, the Goldak heat source is defined, with a Gaussian power density distribution on a double ellipsoidal.

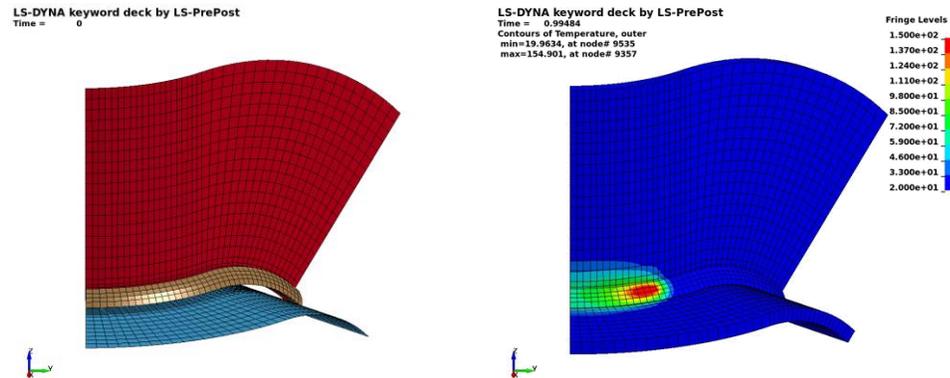
For an IFORM value of 2 the same double-ellipsoidal region as for the standard Goldak heat source is considered. In contrast a constant power density distribution is assumed instead of the Gaussian distribution. For laser welding simulations, on the other hand, often double conical or conical heat sources with constant power density distributions are thought to be most suitable. In the keyword they are referred to with IFORM 3 and 4, respectively. The different shapes are sketched in Figure 2. In all cases, the overall power of the weld torch is given by parameter Q possibly varying over time following load curve LCID.



**Figure 2: Sketch of different power density distributions: Ellipsoid heat source (left), double conical heat source (middle), conical heat source (right)**

The respective power densities have to be integrated not only in time but also in space to determine the energy input into the structure. If the input value of Q is a positive number, standard Gaussian quadrature is employed. The computation is fast, but due to geometrical non-linearity in the energy rate distribution, the obtained accuracy is often not satisfactory. A negative parameter Q invokes a more accurate integration that is based on a subdivision of the elements into cubes with edge length DISCR. Per default a value of 5% of the weld depth is used, but can in most cases be significantly increased to speed-up the simulation without loss of accuracy.

As already mentioned in the introduction welding is in most cases only one of many links in the process chain. Today it is state of the art to use solid discretizations for welding simulations, whereas most of the other process steps are simulated using shell meshes. The new keyword extends the welding functionality in LS-DYNA to shells for an easy transition of data between different process stages. Best accuracy can be obtained by using the thermal thick shell formulation, which enables a temperature gradient across the shell thickness of the elements, while any shell formulation implemented in LS-DYNA can be used to solve the mechanical problem.



**Figure 3: Welding of a curved T-joint discretized with shell elements. Geometry (left) and temperature field (right). Only to visualize the temperature gradients in shell normal direction, the shells are shown as volume elements in post-processing.**

The Figures 1 and 3 show equivalent solid and shell meshes for a curved T-joint. In both cases the welded parts and the weld seam are connected with a tied contact formulation and the geometry of the weld pool was chosen such that it exceeds the solid discretization of the weld seam. The resulting temperature fields show an excellent agreement. If the heat input into the shell elements is neglected, the maximum temperature drops by almost 20%. This demonstrates that the new implementation has been necessary to simulate weld processes using shell elements.

### 3 Material Models for Welding Simulations

In LS-DYNA, the user can choose from a long list of thermo-mechanical material models. As welding simulations features certain singular characteristics, a few of them have been devised or at least adapted especially for computational welding mechanics (CWM). The most basic and numerically most efficient of these materials is \*MAT\_CWM/#270. It is a thermo-elasto-plastic material model based on the von-Mises yield function with isotropic, kinematic or mixed hardening. Moreover, a table input for the coefficient of thermal expansion allows the parameter to be defined as function of current and maximum temperature. This serves as a very simplistic model for the phase change in the microstructure.

The first key feature of \*MAT\_CWM with respect to its use in welding mechanics is the annealing functionality. Above a certain limiting temperature, history variables such as effective plastic strain and back stresses are re-initialized. The material will show an ideal plastic flow behavior but does not accumulate internal plasticity data.

Welding materials should be applicable not only to the welded structures but also to the weld seams. In those, the material has two different states: until its activation by the weld torch it is in a ghost state, thereafter it is in the solid state as the welded structure. In the ghost state, the material is characterized by negligible thermal and mechanical properties. This reflects the fact that in the real process the filler material is added to the weld seam at the same time the weld torch reaches the specific region. Details on this modelling technique can be found in [2] and [3]. For a validation against experimental data the reader is referred [4].

Phase kinetics is represented in \*MAT\_CWM only in a very simplistic manner that suffices to accurately predict the deflection of the processed part. For detailed studies of the material properties in the heat affected zone more complex material models have to be used. In LS-DYNA, material models \*MAT\_UHS\_STEEL/#244 and \*MAT\_PHS\_BMW/#248 contain elaborate phase kinetics models, c.f. Åkerström et al. [5], [6] and Hippchen et al. [7], [8]. Both materials expect the input of the chemical composition and the thermo-mechanical properties of the individual phases of the microstructure. Unfortunately, the heuristic formulas that are internally used to map the chemical to thermo-mechanical parameters are only valid for 22MnB5 steel grades and the material formulation only poorly describes other frequently used steel grades or even different material classes such as aluminum. To be applicable to a wider range of metals, a direct input of the transformation parameters as well as the thermo-mechanical parameters seems indispensable.

The novel material formulation \*MAT\_GENERALIZED\_PHASECHANGE/#254 aims to implement a generic approach for modelling phase transformations and, thus, to provide a suitable material formulation for a large range of metals used in welding and heat treatment applications. The formulation accounts for up to 24 phases and it is important to note that the phases are not hard-coded to represent a certain microstructure. The user can decide which of the possible phase transformations is to be considered and what transformation law from a list of well-established transformation laws is most suitable for the respective transformation. Each of the models requires a different set of parameters. Such a generic approach provides great flexibility, but goes along with a more complex material parameterization.

The implementation is available for shell and solid elements as well as for two-dimensional axisymmetric simulations. The material can be applied for explicit and implicit time stepping schemes. The keyword of the material consists of up to eight input cards:

```
*MAT_GENERALIZED_PHASECHANGE
  MID      RO      N      YM      PR      MIX      MIXR
TASTART   TAEND   TABCTE                                DTEMP    TIME
  PTLAW    PTSTR   PTEND   PTX1   PTX2   PTX3   PTX4   PTX5
  PTTAB1   PTTAB2   PTTAB3   PTTAB4  PTTAB5
  PTEPS    TRIP
  LCY01    LCY02    LCY03    LCY04    LCY05    LCY06    LCY07    LCY08
  LCY09    LCY10    LCY11    LCY12    LCY13    LCY14    LCY15    LCY16
  LCY17    LCY18    LCY19    LCY20    LCY21    LCY22    LCY23    LCY24
```

The thermo-mechanical formulation features a von-Mises plasticity depending on temperature, strain rate and phase concentrations. Parameters YM, PR and TABCTE for Young's modulus, Poisson's ratio, and coefficient of thermal expansion, respectively, can be given as functions of phase and temperature. The temperature and strain rate dependent yield curves for the individual phases are defined using the parameters LCY<sub>i</sub>. The number of phases to be considered is given by N and the initial concentrations by the load curve MIX. From the micro-structure composition, the thermo-mechanical properties are calculated using a possibly temperature dependent linear mixture rule defined by MIXR.

As discussed above, reset of history data for the plasticity algorithm is an important feature for any material model to be applicable in welding simulations. In the new formulation, the corresponding temperature range can be defined with parameters TASTART and TAEND. The material formulation does not necessitate a distinguished ghost state since inactive material can just be identified with one of the microstructure phases and is transformed into an active phase during heating.

For the calculations of the micro-structure evolution a new concept has been implemented. Phase changes are controlled by the two-dimensional transformation matrix PTLAW, where the first dimension is the base phase and the second the generated phase. This implies that for any phase to be transformed a load curve is specified in the \*DEFINE\_TABLE(\_2D). The load curve defines the phase transformation

law as function of the resulting phase. For any of the defined transformations starting and end temperature have to be defined in the same matrix form in PTSTR and PTEND.

In the current state of the implementation, four different micro-structure models are accounted for. If the phase transformation laws 1 (cooling) or -1 (heating) are chosen in the respective load curve, the so-called Koistinen-Marburger model, see [10], is used. It is widely accepted for diffusionless processes. It calculates the generated phase concentration  $x_b$  as function of the current temperature  $T$  and the transformed phase  $x_a$  using the formula

$$x_b = x_a (1.0 - e^{-\alpha \kappa (T_{start} - T)}) \quad (1)$$

In this equation the parameter  $\kappa$  is 1.0 for cooling and -1.0 for heating. Equation (1) requires only the scalar-valued Koistinen-Marburger factor  $\alpha$ . It is defined in the appropriate spot in the table referred to by PTX1.

The second transformation model implements one of the most widely used laws for diffusive phase transformations: the extended Johnson-Mehl-Avrami-Kolmogorov (JMAK), see for example review in [11]. Based on an temperature depending equilibrium concentration  $x_{eq}(T)$  and a relaxation time  $\tau(T)$  the differential form

$$\frac{dx_b}{dt} = n(T)(k_{ab}x_a - k'_{ab}x_b) \left( \ln \left( \frac{k_{ab}(x_a + x_b)}{k_{ab}x_a - k'_{ab}x_b} \right) \right)^{\frac{n(T)-1.0}{n(T)}} \quad (2)$$

$$\text{with parameters } k_{ab} = \frac{x_{eq}(T)}{\tau(T)} f(T), k'_{ab} = \frac{1.0 - x_{eq}(T)}{\tau(T)} f'(T)$$

defines the transformation from  $x_a$  to  $x_b$ . The functions  $f(T)$  and  $f'(T)$  are correction functions accounting for temperature rate effects. For a constant exponent  $n(T) = 1$  equation (2) reduces to the so-called Leblond model [12]. The model is applicable for heating (law -2) and cooling (law 2). It requires the input of the temperature and temperature rate dependent parameters  $n, x_{eq}, \tau, f, f'$ , which are defined in this order by three-dimensional tables PTTAB1 to PTTAB5.

For cooling the model proposed by Kirkaldy and Venugopalan [13] can also be employed. It has been added to the list of transformation laws (choose 3) since it is the base of microstructure evolution in MAT\_UHS\_STEEL. In a general form the formulation can be written as

$$\frac{dX_b}{dt} = 2^{0.5(G-1)} f(C) (T_{start} - T)^{n_\tau} D(T) \frac{X_b^{n_1(1.0-X_b)} (1.0 - X_b)^{n_2 X_b}}{Y(X_b)} \quad (3)$$

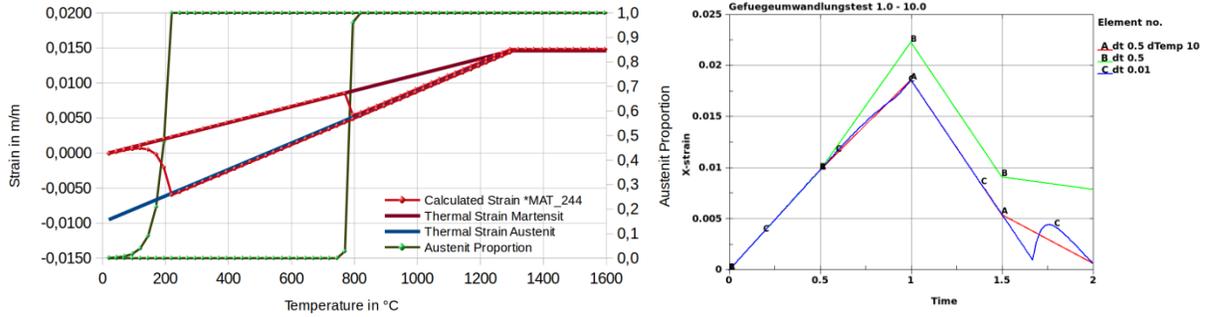
It is noteworthy that here a normalized phase concentration  $X_b$  is calculated. It has to be transformed into the total phase concentration  $x_b$  by  $x_b = X_b x_{eq}(T)$ , with equilibrium concentration  $x_{eq}(T)$ . The list of necessary parameters comprise the four scalar-valued parameters  $f(C), n_\tau, n_1, n_2$  defined in PTX1 to PTX4 and three functions  $D(T), Y(X_b), x_{eq}(T)$  defined in PTTAB1 to PTTAB3. The grain size  $G$  in equation (3) coincides with the parameter GRAIN.

The phase kinetics in \*MAT\_UHS\_STEEL during heating is governed by the model of Oddy et al. [14]. It has been added to \*MAT\_GENERALIZED\_PHASECHANGE as model -4 and uses the evolution equation

$$\frac{dx_b}{dt} = n \cdot \frac{x_a}{c_1(T - T_{start}) - c_2} \cdot \left( \ln \left( \frac{(x_a + x_b)}{x_a} \right) \right)^{\frac{n-1.0}{n}} \quad (4)$$

For usage only three scalar parameters are required:  $n, c_1, c_2$ . As before these parameters are taken from data in the two-dimensional tables PTX1 to PTX3.

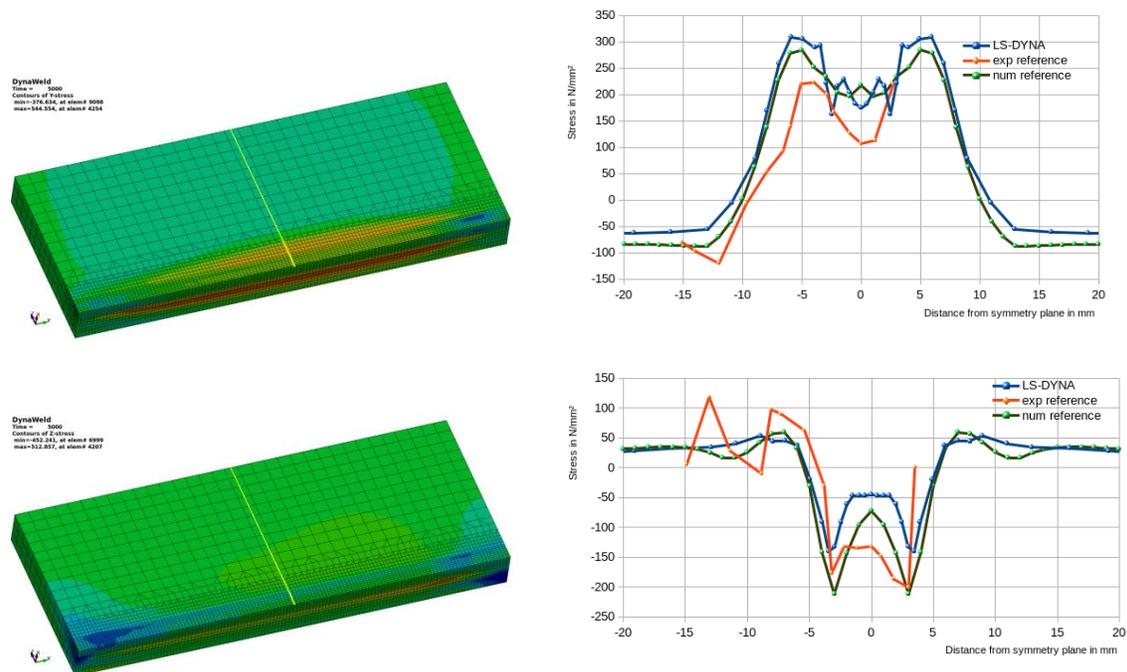
For most steel alloys, phase transition between ferritic and austenitic phases goes along with transformation induced strains. In dilatometer experiments these show as characteristic jumps in strain over temperature curves. The height of the jumps varies with temperature and with phase combination. This information about the jumps can serve as input for the new material formulation as tabular data in parameter PTEPS. As Figure 4 (left) demonstrates, the new material can capture these jumps between different dilatometer curves for the individual phases.



**Figure 4: The effect of transformation induced strains: Dilatometer experiment on the left, the effect of different time step sizes and the parameter DTEMP on the right.**

Different coefficients of thermal expansion for the phases and transformation induced strains add significant non-linearities with respect to the temperature to the system. Welding simulations usually feature locally extremely high temperature rates and temperature gradients due to the high power input of the applied weld sources. Therefore, using a reasonably large time step with respect to simulation time will lead to a temperature increase of several hundred Kelvin at some nodes within one time step. The strain results for one rapidly heated element are shown in Figure 4 on the right. The obtained curves for a large time step (B) and a very small time step (C) deviate significantly. Therefore, a parameter DTEMP has been added, that represents the temperature increase within one time step that still shows acceptable results. In case that during the material evaluation at an integration point a higher temperature rise is detected, a sub-cycling procedure is invoked assuming a constant temperature rate. The quality of the strain results can be significantly improved by this approach as curve (A) shows, whereas the simulation time is only mildly affected for realistic examples.

Phase transformations do not only induce elastic but also plastic strains. The algorithm to calculate the transformation induced plasticity (TRIP) is based on the formulation proposed by Leblond [15]. This formulation has a very high impact on the residual stress distribution of welded structures and can be activated by defining a non-zero value for the parameter TRIP.



**Figure 5: Residual stresses for Nitschke Pagel test after cooling.**

In Figure 5 (left) the simulation results of the Nitschke-Pagel [16] experiment is depicted. In this bead on plate example, a weld torch is moved along the middle of a steel block. Experimental and numerical data for the residual stresses in the structure is available in [17] and can be compared with simulation results of LS-DYNA using the new formulation `*MAT_GENERALIZED_PHASECHANGE`.

The residual stresses are shown in Figure 5. Along a line on the surface of the structure, stress data can be used for quantitative comparison with measurements from [16]. The numerical approximation obtained with `*MAT_GENERALIZED_PHASECHANGE` for both the longitudinal and the transversal component agree reasonably well with the literature data. The same investigation has been made for a specialized welding simulation code in [17]. Although the material definitions and also the formulation for the equivalent heat source slightly differ between the two numerical models, there is a good agreement between the numerical results.

#### 4 Recent developments in the thermal contact algorithms

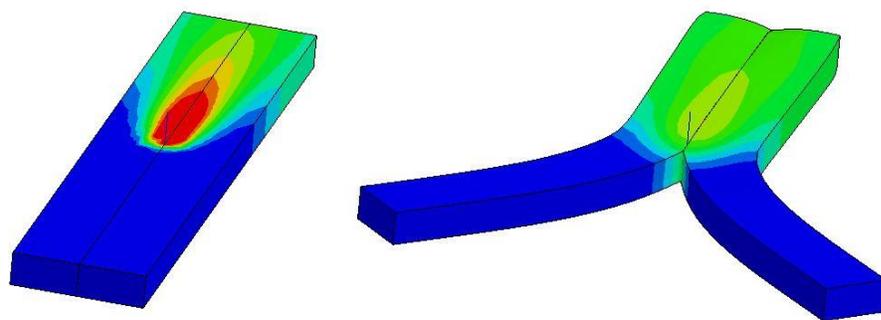
For welding processes that do not add material to the system, the ghosting approach discussed above is not feasible. Here, the materials of the parts to be combined are locally heated up. If the melting temperature is exceeded in the contact surface, a strong connection is established and the parts can 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 to a tied contact condition. The switch is triggered by the peak temperature in the contact zone. Of course, the contact formulation for the rest of the contact surface is not affected by this switch. The new contact formulation reads an additional input card of the form

```
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL
...
TEMP      CLOSE      HWELD
K         HRAD       HO          LMIN      LMAX      CHLM      BC_FLAG  ALGO
...

```

The behavior of the welding contact option is defined by the first card shown. The second card is standard LS-DYNA input for thermal contacts. The parameter `TEMP` indicates the minimal peak temperature expected and `CLOSE` the maximal gap allowed in order to initiate the tied contact. After the welding has been established, the heat transfer coefficient is set to `HWELD`.



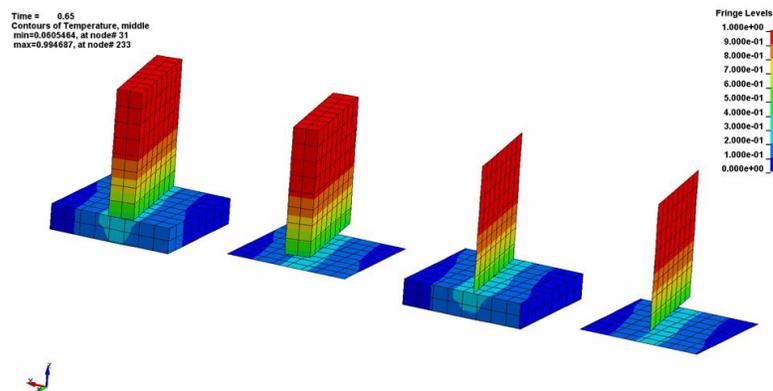
**Figure 6: Welding and subsequent loading of a butt weld of two bars. Temperature field at the end of the welding step is shown (left) as well as the final displacement (right).**

An example application with solid elements for this novel feature is the butt weld shown in Figure 6. 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

The contact formulation can also be used to simulate the laser welding of structures discretized with shell elements. One limitation at present lies in the fact, that the welding contact can only be considered between two surfaces. Thus, it is possible to simulate welding of stacked sheet metals with shell elements, but not of a butt weld similar to the example just discussed.

The heat transfer between shell element and other shell elements or solids is a well-established feature in LS-DYNA for some years. Nevertheless, it used to require a SURFACE\_TO-SURFACE contact formulation. A novel implementation enables the heat transfer across shell edges onto a shell surface or solid face. It can be activated by using a value of 2 (two-way contact) or 3 (one-way contact) for the parameter ALGO in the contact definition presented above.



**Figure 7: Heat transfer within a rotated T-Joint with different discretization strategies.**

In Figure 7 the resultant temperature field within a rotated T-joint are presented for different element types. Bringing an initially hot part in contact with an initially cold part initiates a heat transfer in the contact zone that, as the result in Figure 7 show, is independent from the discretization chosen for the individual parts.

## 5 Summary and Outlook

As welding is very important for manufacturing industries some effort has been put into novel features of the multi-physics Finite Element solver LS-DYNA for more accurate numerical simulations and easier set-up of this very complex coupled process. The development shown in this contribution will continue in order to further improve the welding capabilities of the software and still widen its field of application.

The new thermal boundary condition `*BOUNDARY_THERMAL_WELD_TRAJECTORY` will be extended by further pre-defined energy rate distribution functions but also by the possibility to input user-defined function in the local weld coordinate system.

The next step in the development of the `*MAT_GENERALIZED_PHASECHANGE` is the implementation for shell elements. So far material formulation has only been used to model steel alloys, but most of the equations discussed above also apply aluminum alloys. Adaptations to the model will be made to account for both groups of metals.

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