Using LS-DYNA for Simulation of Welding and Heat Treatment

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DYNAmore GmbH
Motivation – Process chain

- For modern processes and materials, the mechanical properties of the finished part highly depend on the fabrication chain.

- Numerical simulations of the complete process chain necessary to predict finished geometry and properties.

- Welding stages particularly important:
  - Locally very high temperature gradients
  - Large distortions
  - Changes in the microstructure of the material in the heat affected zone

- Compensation for springback and shape deflections.
Motivation - Example

1 Deep drawing
2 Clamping
3 Welding
4 Springback

alignment points
Motivation - Example

5 Deep drawing

6 Clamping

7 Welding hollow seams

8 Welding flanged seams

9 Springback (left) vs. measurement (right)
Motivation - Conclusions

- Need a powerful multi-physics solver to simulate the welding process

- As stand-alone process welding is most often simulated with solid discretizations

- In automotive industries, welding is only one stage in the process chain
  - Seamless transition of data from one stage to the next
  - Typically, forming and spring-back analyses are done using shell discretizations

- All new developments are to be done for solid and shells!
Necessary developments

- Realistic description of the heat source applied to the weld seam
  - For curved and deforming structures (thermal expansion during welding)
  - For different processes and different discretizations (particularly shell discretizations)

- Material formulation with microstructure evolution
  - Phase changes due to heating and cooling alter mechanical and thermal properties
  - Transformations induced strains and plasticity
  - Strain rate and temperature dependent plasticity
  - Valid description for a wide range of steel and aluminium alloys

- Special contact capabilities
  - Material fusion due to heating
  - Thermal contact at T-joints for shells
CONTENT

■ Motivation

■ *BOUNDARY_THERMAL_WELD_TRAJECTORY

■ *MAT_GENERALIZED_PHASECHANGE / *MAT_254

■ New contact options in LS-DYNA

■ Remarks on Simulation Strategies
*BOUNDARY_THERMAL_WELD*

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- Defines a Goldak type heat source
- Weld source motion possible, follows motion of node NID
- Only applicable to solid parts
Modelling a moving heat source

- Useful keyword: *CONTACT_GUIDED_CABLE

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- It forces beams in PID onto the trajectory defined by nodes in NSID

- Possible solution
  - Select a trajectory on the weld seam
  - Define contact between this trajectory and a beam B1 (N1 and N2)
  - Define a second trajectory and a beam B2 (N3 and N4) following it in a prescribed manner
  - Welding torch aiming directions from N3 to N1 (*BOUNDARY_THERMAL_WELD)
  - Define local coordinate system N1,N2,N3
  - Use *BOUNDARY_PRESCRIBED_MOTION_RIGID_LOCAL to move heat source
Movement of the heat source - example

LS-DYNA keyword deck by LS-PrePost
Movement of the heat source - example

DynaWeld
Time = 28.349
Contours of Temperature, middle
min=293, at node# 99000011
max=3144.52, at node# 9751
**BOUNDARY_THERMAL_WELD - Summary**

- Only Goldak-type equivalent heat source available

- Weld source motion possible, follows motion of node NID
  - Structure solver necessary
  - Weld path definition not straight-forward for curve geometries
  - Compensation for part deformation requires complex pre-processing

- The incremental heating leads to element distortion when the used timestep is too large.

- No heat entry to shell elements

Need a more flexible and easier to use boundary condition for welding!
A new heat source - approach

- Move the heat source motion to a new keyword.

- The heat source follows a node path (*SET_NODE) with a prescribed velocity
  - No need to include the mechanical solver
  - In case of coupled simulations the weld path is continuously updated

- Automatically compute weld aiming direction based on surface normal

- Provide a list of pre-defined equivalent heat sources

- Use “sub-timestep” for integration of heat source for smooth temperature fields

- Implementation for solid and thermal thick shells
Interlude – thermal thick shell in LS-DYNA

- LS-DYNA features a twelve node thermal thick shell element formulation
  - Bi-linear shape functions in-plane
  - Quadratic approximation in thickness direction

- User only specifies the standard four node shell element
  - LS-DYNA automatically generates top and bottom virtual nodes, using right hand rule
  - Activated with TSHELL=1 on *CONTROL_SHELL

- Top/bottom surfaces can be addressed in thermal boundary conditions

- Different temperature values at different locations transferred to the mechanical solver
*BOUNDARY_THERMAL_WELD_TRAJECTORY*

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- **NSID1**: Node set ID defining the trajectory
- **VEL1**: Velocity of weld source on trajectory
  - LT.0: |VEL1| is load curve ID for velocity vs. time
- **SID2**: Second set ID for weld beam direction
  - GT.0: S2ID is node set ID, beam is aimed from these reference nodes to trajectory
  - EQ.0: beam aiming direction is (Tx, Ty, Tz)
  - LT.0: SID2 is segment set ID, weld source is orthogonal to the segments
- **VEL2**: Velocity of reference point for SID2.GT.0

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Information Day Welding and Heat Treatment, T. Kloeppe
Aachen, Sept. 27th 2016
Example: Trajectory definition
**BOUNDARY_THERMAL_WELD_TRAJECTORY**

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- **NCYC:** number of sub-cycling steps

**temperature field, NCYC = 1**

**temperature field, NCYC = 10**

*Information Day Welding and Heat Treatment, T. Kloeppel*
Aachen, Sept. 27th 2016
**BOUNDARY_THERMAL_WELD_TRAJECTORY**

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- **RELVEL:** Use relative or absolute velocities in coupled simulations

RELVEL=1

Increasing rotational speed
**BOUNDARY_THERMAL_WELD_TRAJECTORY**

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**RELVEL:** Use relative or absolute velocities in coupled simulations

RELVEL=0

Increasing rotational speed
*BOUNDARY_THERMAL_WELD_TRAJECTORY*

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- **IFORM:** Geometry for energy rate density distribution
  - EQ.1. Goldak-type heat source
    (double ellipsoidal heat source with Gaussian density distribution)
  - EQ.2. double ellipsoidal heat source with constant density
  - EQ.3. double conical heat source with constant density
  - EQ.4. conical heat source

- **Pₓ:** Parameters for weld pool geometry
For IFORM=1 (Goldak)

- P1: $a$
- P2: $b$
- P3: $c_f$
- P4: $c_r$
- P5: $F_f$
- P6: $F_r$
- P7: $n$

\[
q = \frac{2n\sqrt{nFQ}}{\pi\sqrt{\pi abc}} \exp\left(-\frac{n x^2}{a^2}\right) \exp\left(-\frac{n y^2}{b^2}\right) \exp\left(-\frac{n z^2}{c^2}\right)
\]

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For IFORM=2 (double ellipsoid)

- P1: $a$
- P2: $b$
- P3: $c_f$
- P4: $c_r$
- P5: $F_f$
- P6: $F_r$

$$q = \frac{3FQ}{2\pi abc}$$
For IFORM=3 (double conus)

- P1: $r_1$
- P2: $r_2$
- P3: $r_3$
- P4: $b_1$
- P5: $b_2$
- P6: $F_1$
- P7: $F_2$

\[ q = \frac{3FQ}{2\pi b(R^2 + r^2 + Rr)} \]
For IFORM=4 (frustrum)

- P1: \( r_1 \)
- P2: \( r_2 \)
- P3: \( b_1 \)

\[
q = \frac{3Q}{\pi b(R^2 + r^2 + Rr)}
\]
*BOUNDARY_THERMAL_WELD_TRAJECTORY

IFORM=1

IFORM=2

IFORM=3

IFORM=4
**BOUNDARY_THERMAL_WELD_TRAJECTORY**

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- **LCID**: Load curve ID for weld energy input rate vs. time
- **EQ.0**: use constant multiplier value $Q$
- **Q**: Curve multiplier for weld energy input
- **LT.0**: use multiplier value $|Q|$ and accurate integration of heat
- **DISC**: Resolution for accurate integration. Edge length for cubic integration cells
- Default: $0.05 \times (\text{weld source depth})$
**LCROT**: load curve defining the rotation ($\alpha$ in degree) of weld source around the trajectory as function of time.

**LCMOV**: load curve for offset of weld source in depth ($t'$) after rotation as function of time

**LCLAT**: load curve for lateral offset ($s'$) after rotation as function of time

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$\mathbf{r} = \mathbf{r}'$

$\alpha$

$\mathbf{s}'$

$\mathbf{t}$

$\mathbf{t}'$

$\mathbf{r}$

**welding torch**

velocity

**trajectory**
*BOUNDARY_THERMAL_WELD_TRAJECTORY

Example: Influence of oscillations for...

...LCROT

...LCMOV

... LCLAT
Example 1

- New Keyword is applicable to thermal thick shells / mixed discretizations
- Three-dimensional curved T-Joint, thermal-only analysis

![Solids](image)
![Solids and shells](image)
![BC on all solids](image)
![BC on solids only](image)
![BC on solids and shells](image)
Industrial examples

- Forming and clamping usually done with shell structures
- Additional filler discretized with solids

- Very smooth temperature distribution across discretization boundaries
Industrial examples

- Welding simulation can be used to investigate optimal welding strategy
  - Different welding orders one weld seam at a time
  - Simultaneous welding of multiple weld seams
CONTENT

- Motivation

- *BOUNDARY_THERMAL_WELD_TRAJECTORY

- *MAT_GENERALIZED_PHASECHANGE / *MAT_254

- New contact options in LS-DYNA

- Remarks on Simulation Strategies
Material tailored for hot stamping / press hardening processes
- Phase transition of austenite into ferrite, pearlite, bainite and martensite for cooling
- Strain rate dependent thermo-elasto-plastic properties defined for individual phases
- Transformation induced plasticity algorithm
- Re-austenitization during heating
- User input for microstructure computations is chemical composition alone

Added:
- Transformation induced strains
- Welding functionality
- Different transformation start temperatures for heating and for cooling

*MAT_244 is only valid for a narrow range of steel alloys!
Heuristic formulas connecting chemistry with mechanics fail otherwise!
Example

- A gear is heated, quenched, welded to a joint

Temperature field

Martensite concentration
*MAT_254

- Started the implementation of *MAT_GENERALIZE_PHASE_CHANGE

- **Features**
  - Up to 24 individual phases
  - User can choose from generic phase change mechanisms (Leblond, JMAK, Koistinen-Marburger,…) for each possible phase change
  - Material will incorporate all features of *MAT_244
  - Phase change parameters are given in tables and are not computed by chemical composition

- Will be suitable for a wider range of steel alloys and aluminum alloys

- Parameter of the material might come from a material database or a microstructure calculation
Special welding card not needed. Liquid filler can be accounted for by an additional phase

Damage and failure modelling, latent heat, grain growth modelling yet to be implemented
**MAT_254** / **MAT_GENERALIZED_PHASE_CHANGE**

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- **N:** Number of phases in microstructure
- **E:** Young’s modulus
  - LT.0: |E| is load curve ID/table ID for E vs. temperature (vs. phase)
- **PR:** Poissons’s ratio
  - LT.0: |E| is load curve ID/table ID for PR vs. temperature (vs. phase)
- **MIX:** Load curve ID for initial phase concentrations
- **MIXR:** LC / TAB ID for mixing rule (temperature dependent)
**TASTART:** Reset of history variables start temperature

**TAEND:** Reset of history variables end temperature

**TABCTE:** coefficient of thermal expansion (CTE)
- LT.0: |TABCTE| is load curve ID/table ID for CTE vs. temperature (vs. phase)

**DTEMP:** Maximum temperature variation within a time step
- If temperature increase exceeds DTEMP, sub time steps locally on integration point level are used
- Important for rapid heating and cooling scenarios to resolve non-linearities

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**Card 2**

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Effect of DTEMP

- Rapid heating and cooling of a single element
- Non-linear strains as transformation induced strains and the coefficient of thermal expansion depend on the temperature

Results for small time steps can be reproduced if DTEMP is sufficiently small
**PTLAW**: Table ID containing phase transformation laws

- If law ID.GT.0: used for cooling
- If law ID.LT.0: used for heating
- \(|LAW\ ID|:
  - EQ.1: Koistinen-Marburger
  - EQ.2: JMAK
  - EQ.3: Kirkaldy (only cooling)
  - EQ.4: Oddy (only heating)

**PTSTR**: Table ID containing start temperatures

**PTEND**: Table ID containing end temperature

**PTXi**: \(i\)-th scalar parameter (2D table input)

**PTTTabi**: \(i\)-th temperature dependent parameter (3D table input)
Koistinen Marburger

Evolution equation:

\[ x_b = x_a \left( 1.0 - e^{-\alpha (T_{\text{start}} - T)} \right) \]

Parameter:
- PTX1: \( \alpha \)

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Johnson-Mehl-Avrami-Kolmogorov (JMAK):

- Evolution equation:

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

\[
k_{ab} = \frac{x_{eq}(T)}{\tau(T)} f(\dot{T}), k'_{ab} = \frac{1.0 - x_{eq}(T)}{\tau(T)} f'(\dot{T})
\]

- Parameter:
  - PTTAB1: \(n(T)\)
  - PTTAB2: \(x_{eq}(T)\)
  - PTTAB3: \(\tau(T)\)
  - PTTAB4: \(f(\dot{T})\)
  - PTTAB5: \(f'(\dot{T})\)
*MAT_254 with JMAK

First example: Phase change test for steel S420
Kirkaldy (equivalent to *MAT_244):

- Evolution equation:

\[
\frac{dX_b}{dt} = 2^{0.5(g-1)} f(C) (T_{start} - T)^{nT} D(T) \frac{X_b^{n_1(1.0-X_b)}(1.0-X_b)^{n_2X_b}}{Y(X_b)}, x_b = X_b x_{eq}(T)
\]

- Parameter:
  - PTX1: \( f(C) \)
  - PTX2: \( n_T \)
  - PTX3: \( n_1 \)
  - PTX4: \( n_2 \)
  - PTTAB1: \( D(T) \)
  - PTTAB2: \( Y(X_b) \)
  - PTTAB3: \( x_{eq}(T) \)
Oddy (equivalent to *MAT_244):

- Evolution equation:

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

- Parameter:
  - PTX1: \( n \)
  - PTX2: \( c_1 \)
  - PTX3: \( c_2 \)
**MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE**

<table>
<thead>
<tr>
<th>Card 5</th>
<th>1</th>
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<td>LCY21</td>
<td>LCY22</td>
<td>LCY23</td>
<td>LCY24</td>
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</table>

- **PTEPS:** Table ID for transformation induced strains
- **TRIP:** Flag for transformation induced plasticity (active for TRIP.gt.0)
- **GRAIN:** Initial grain size
- **LCYxy:** Load curve or table ID for yield stress vs. equivalent plastic strain (vs. strain rate vs. temperature)
Residual stresses

Nitschke-Pagel test

- Temperature
- Longitudinal stresses
- Equivalent plastic strain
- Transversal stresses
Residual stresses

Nitschke-Pagel test

- Temperature
- Longitudinal stresses
- Equiv. plastic strain
- Transversal stresses
Residual stresses

Nitschke-Pagel test

![Graph showing residual stresses](image)

<table>
<thead>
<tr>
<th>Num. Reference</th>
<th>Exp. Reference</th>
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Information Day Welding and Heat Treatment, T. Kloeppel
Aachen, Sept. 27th 2016
CONTENT

- Motivation
- *BOUNDARY_THERMAL_WELD_TRAJECTORY
- *MAT_GENERALIZED_PHASECHANGE / *MAT_254
- New contact options in LS-DYNA
- Remarks on Simulation Strategies
*CONTACT_OPTION_THERMAL

- Works for SURFACE_TO_SURFACE type of contacts

If bc_flg = 1, turn off thermal boundary conditions for segments in contact

- If \( L_{\text{min}} < L_{\text{gap}} < L_{\text{max}} \)
  
  \[ h = h_{\text{cond}} + h_{\text{rad}} \]
  
  With
  
  \[ h_{\text{cond}} = \frac{k}{L_{\text{gap}}} \]

- If \( L_{\text{gap}} < L_{\min} \)
  
  \[ h = h_{\text{cont}} \]
  
  \[ h = h(t,T,P) \]

- If \( L_{\text{gap}} > L_{\text{max}} \)
  
  \[ h = 0, \text{ no contact} \]
Contacts in LS-DYNA – necessary enhancements

- Welding without adding material (laser welding)
  - Ghosting approach, which has been implemented in LS-DYNA in some material formulations no longer feasible
  - Significant sliding of parts before welding

- Edge contact
  - Certain scenarios require to consider heat transfer across the edge of a shell into a surface

![Coupling of a sheet metal to a weld seam](image1.png)

![T-Joint with shells](image2.png)
Welding without filler elements

- New contact formulation
  *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL
  - As regions of the surfaces are heated to the welding temperature and come into contact, the nodes are tied
  - Regions in which the temperature in the contact surface is always below the welding temperature, standard sliding contact is assumed
  - Heat transfer in the welded contact zones differs as compared to unwelded regions

- Right now, only implemented for contact in SMP (share memory parallel), MPP versions to follow
**CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL**

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<td>CLOSE</td>
<td>HWELD</td>
<td></td>
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<td>H0</td>
<td>LMIN</td>
<td>LMAX</td>
<td>CHLM</td>
<td>BC_FLAG</td>
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</tbody>
</table>

- Card 4 is read if TIED_WELD is set
  - TEMP: Welding temperature
  - CLOSE: maximum contact gap for which tying is considered
  - HWELD: Heat transfer coefficient for welded regions

- Card 5 is standard for THERMAL option
  - H0: Heat transfer coefficient for unwelded regions
Example: butt weld

- During welding the blocks are allowed to move
- Assumption: Insulation in unwelded state, perfect heat transfer after welding
Example: laser welding

- During welding the sheets are allowed to move
- A very high heat conductivity in the contact area is assumed
Thermal edge contact

- Activated for ALGO.eq.2 or 3 (one way)
- Can be used in a variety of contact types
  - SURFACE_TO_SURFACE, NODES_TO_SURFACE
  - SPOTWELD
  - TIED_SHELL_EDGE_TO_SOLID, TIED_SHELL_EDGE_TO_SURFACE
Thermal edge contact + welding contact

Example:
- Laser welding of a butt weld of a shell structure
- Welded area discretized with solids
- Shell elements tied to the solid elements
Thermal edge contact + welding contact

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■ New contact options in LS-DYNA

■ Remarks on Simulation Strategies
Remarks on Simulation Strategies

- Coupled thermo-mechanical analysis
  - Default strategy in LS-DYNA
  - Staggered approach

- De-coupled approach
  - Run thermal problem first
  - Use results of thermal run as boundary condition
    *LOAD_THERMAL_D3PLOT
  - Yields the same results, if output frequency of the thermal run is sufficiently high
  - Might be easier in terms of boundary conditions for the thermal run
  - Allows to easily test variations of the mechanical model
  - Re-implementation to accept thermal thick shell results
Thank you!