Basics of Welding Simulation and Heat Treatment Simulation
Applications and Benefits

Infotag Schweißen und Wärmebehandlung
Zürich

Dr.-Ing. Tobias Loose
Ingenieurbüro Tobias Loose, Herdweg 13, D- 75045 Wössingen
loose@tl-ing.de www.tl-ing.eu
Numerical Simulation for Welding and Heat Treatment since 2004

- Consulting
- Training
- Support
- Software Development
- Software Distribution

for Welding Simulation and Heat Treatment Simulation

Internet:
- DEutsch: www.loose.at
- ENglisch: www.tl-ing.eu
- ESpañol: www.loose.es
Motivation

and Examples
Welding of a T-Joint

- Double sided T-Joint  $a = 4 \text{ mm}$
- Plate S355 thickness 8 mm
- 3 Tacks double sided
- Travel speed 80 cm/min
- Current: 390 A
- Voltage: 30 V

- Start Time Tack 1: 0 s
- Start Time Tack 2: 20 s
- Start Time Weld 1: 1000 s
- Start Time Weld 2: 1023 s
- Weld 1 and Weld 2 have the same travel direction
Process Simulation with SimWeld

Input-Parameter SimWeld

<table>
<thead>
<tr>
<th>Workpiece parameters (Ctrl + 1)</th>
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<tbody>
<tr>
<td>Geometry</td>
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<tr>
<td>EN ISO 9692-1: 2003 (D)</td>
</tr>
<tr>
<td>Joint type</td>
</tr>
<tr>
<td>Square edges (3:1:1)</td>
</tr>
<tr>
<td>width</td>
</tr>
<tr>
<td>40.00 [mm]</td>
</tr>
<tr>
<td>height</td>
</tr>
<tr>
<td>1.000 [mm]</td>
</tr>
<tr>
<td>t1</td>
</tr>
<tr>
<td>8.000 [mm]</td>
</tr>
<tr>
<td>t2</td>
</tr>
<tr>
<td>8.000 [mm]</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>0.000 [mm]</td>
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<tr>
<td>radius</td>
</tr>
<tr>
<td>-1.000 [mm]</td>
</tr>
<tr>
<td>e</td>
</tr>
<tr>
<td>-1.000 [mm]</td>
</tr>
<tr>
<td>alpha</td>
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<td>90.000 [']</td>
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<tr>
<td>Material</td>
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<tr>
<td>Plates</td>
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<tr>
<td>S355</td>
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<tr>
<td>Position</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Custom</td>
</tr>
<tr>
<td>across</td>
</tr>
<tr>
<td>45.000 [']</td>
</tr>
<tr>
<td>along</td>
</tr>
<tr>
<td>0.000 [']</td>
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<table>
<thead>
<tr>
<th>Process parameters (Ctrl1 + 2)</th>
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<tbody>
<tr>
<td>Process parameters</td>
</tr>
<tr>
<td>Welding speed</td>
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<tr>
<td>80.00 [cm/min]</td>
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<tr>
<td>Initial temperature</td>
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<tr>
<td>20.00 [°C]</td>
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<tr>
<td>Simulation Options</td>
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<tr>
<td>Consider gap</td>
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<tr>
<td>Calculation length</td>
</tr>
<tr>
<td>User defined</td>
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<tr>
<td>Calculation length</td>
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<td>100.00 [mm]</td>
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<tr>
<td>Mesh density</td>
</tr>
<tr>
<td>normal (1.0x)</td>
</tr>
<tr>
<td>Resources: medium</td>
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<tr>
<td>Accuracy: medium</td>
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<th>Torch parameters (Ctrl + 3)</th>
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<td>Wire</td>
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<td>Diameter</td>
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<td>1.6 [mm]</td>
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<td>Material</td>
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<tr>
<td>SG-Fe</td>
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<tr>
<td>Contact noz. t.</td>
</tr>
<tr>
<td>20.00 [°C]</td>
</tr>
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<table>
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<th>Position</th>
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</tr>
<tr>
<td>Y</td>
</tr>
<tr>
<td>0.000 [mm]</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>20.000 [mm]</td>
</tr>
<tr>
<td>R</td>
</tr>
<tr>
<td>20.000 [mm]</td>
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<table>
<thead>
<tr>
<th>Angle</th>
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<tbody>
<tr>
<td>Along</td>
</tr>
<tr>
<td>0.000 [']</td>
</tr>
<tr>
<td>Across</td>
</tr>
<tr>
<td>0.000 [']</td>
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<table>
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<tr>
<th>Equipment</th>
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<td>Select...</td>
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<tr>
<td>Process type</td>
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<tr>
<td>Normal</td>
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<tr>
<td>Wire feed</td>
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<tr>
<td>7.000 [m/min]</td>
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<tr>
<td>Voltage</td>
</tr>
<tr>
<td>30.000 [V]</td>
</tr>
<tr>
<td>Choke</td>
</tr>
<tr>
<td>30.000 [%]</td>
</tr>
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</table>
SimWeld Results

- $a = 4.4 \, \text{mm}$
- $I = 390 \, \text{A}$
- $V = 29.2 \, \text{V}$
Temperature

Tack 1

Weld 1

Tack 2

Weld 2
z-Distortion at Evaluation Path
transformed to flat left side
Curved Hollow Section Beam

Length 4,00 m
8 2-layered Welds
12 single layered Welds
Curved Hollow Section Beam
Autobody Sheet
Welding

z-displacement 5-times scaled
Weld of a Pipe with 40 mm Wall Thickness
made of Alloy 625

60 Layer - GMAW

93 Layer - TIG
Weld of a Pipe with 40 mm Wall Thickness made of Alloy 625 - 60 Layer GMAW

Temperature Layer 44

Equivalent Plastic Strain
Temperature Field Multilayered Weld
2D Metatransient
Multilayered Weld T-Joint with large Plate Thickness
2D-Analysis LS-DYNA

2D plain strain
Plate: 300 x 80 mm
Stiffner: 150 x 24 mm
Fillet Weld: a = 13 mm
Material: 1.4301

Tack a = 1,4 mm
with failure on strain KFAIL = 0,25 m/m

Initial gap between stiffner and plate: 0,1 mm

Symmetry boundary conditions on left and right side.
Multilayered Weld T-Joint with large Plate Thickness
2D-Analysis LS-DYNA – plastic strain
Prediction of Weld Quality
Microstructure and Mechanical Properties

Material Specification
Chemical Composition

WeldWare®

WPS
Welding Procedure Specification

SimWeld®

W355

S690

• Weld-Pool
• HAZ
• Microstructure
• Yield Strength
• Ultimate Strength
• Hardness
• Ultimate Elongation

Martensite
$t_{8.5,5}$-time of view-point

High energy per unit length

Ultimate stress

Yield stress

Martensite
$t_{8.5,5}$-time of view-point

High energy per unit length
Quenching of a Gear made of S355
Temperature Curve

Quenching Gear # www.loose.at

Edge
Middle
Quenching of a Gear made of S355
Results of Heat Treatment Simulation

Martensit (right)
Hardness HV (bottom left)
Yield (bottom right)
Plate with the dimensions 270 x 200 x 30 mm³ with V/U-shaped notch
Austenitic stainless steel (316LNSPH, Re = 275 MPa)
2 Layer welding of the notch with same material: 316L
TIG Welding with U = 9 V, I = 155 A, v = 0.67 mm/s

Validation
IIW Round Robin Versuch

Mesuread and calculated results
Longitudinal residual stresses

In: Cherjak, H. (Ed.); Enzinger, N. (Ed.): Mathematical Modelling of Weld Phenomena Bd. 9, Verlag der Technischen Universität Graz, 2010
Validation
IIW Round Robin Versuch

Transversal Stress

Longitudinal Stress

SYSWELD

LS-DYNA

Welding direction
Validation Nitschke-Pagel Test

Distortion w:
- Experiment: 0.34 mm
- Sysweld: 0.32 mm
- LS-DYNA: 0.34 mm

Makrosection
Temperature: 100 .. 1500 °C
Result
Benefits
Results from Simulation of Welding and Heat Treatment

• Process simulation welding (SimWeld)
  – weld pool formation
  – heat input / heat generation
  – local temperature field, cooling time in the weld and heat affected zone

• Structure simulation welding (DynaWeld)
  – temperature field in the whole assembly during welding, cooling time
  – distortion during welding and cooling
  – clamping forces and bearing reactions
  – plastic strains, strain hardening
  – residual stresses, elastic or plastic reserves
  – microstructure / areas with change of microstructure

• Heat treatment simulation
  – temperature during quenching
  – carburization and depth of carburization for case hardening
  – microstructure and hardness
  – distortion / distortion after hardening
Benefits from Simulation of Welding and Heat Treatment

- Adjustment of Process Parameter
- Design of Geometrie
  - optimization of geometry concerning acceptable distortions
  - determination of invers distorted geometry for the design of forming
  - design of gap for laser welding
- Heat Management
  - preheating temperature, intermediate temperature
  - design of desired microstructure
- Design of Clamps
  - predeformation
  - clamp forces
- Design of the Order of the Welds
- Observation of the State of Stresses
  - prestressed zones / tension zones
  - delimitation of plastic strain
- Special Tasks ...
More Benefits of Welding and Heat Treatment Simulation

- Simulation is available in early stage of design.
- Simulation is available without any fabrication place.
- Simulation is helpful for the analysis of damages.
- Simulation helps to understand the process and its events.
- Simulation is helpful for education and training.
- Welding and heat treatment simulation provides the state of the assembly for further simulation analyses.
Sources of Material Data for Welding and Heat Treatment

• Experiment
  – Execution of tests

• References
  – Papers with test results for material data
  – Material data sheet

• Software / Material Simulation
  – WeldWare®
  – JMatPro
  – MatCalc
Depending on Temperature

Elasticity-Modul

Elasticity-Modul in N/mm²

Temperature in °C

1. Austenit
Ferrit
Perlit
Bainit
Martensit
Base Material
Filler Liquid
Tempered Martensit
Tempered Bainit
Depending on Microstructure

![Graph showing Yield Stress (Re) depending on temperature for different microstructures]
Description of phase transformation (ZTU, ZTA)

CCT-Data
WeldWare®

Microstructure Simulation with LS-DYNA *MAT_254
Thermal strain

![Graph showing thermal strain vs temperature]

Thermal Strain in m/m

- **ALPHA**
- **GAMMA**

Temperature in °C

0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500
Transformation effects

Graph showing the relationship between temperature and deformation in °C and mm/mm, with lines representing calculated deformation, thermal deformation martensite, thermal deformation austenite, and austenite content.
Simplified Approach

Graph showing the relationship between temperature in °C and deformation in mm/mm, with lines indicating heating and cooling processes.
Deactivation of not yet deposited material

Deactivated material (blue)
Aktivation criterion: Temperature

Peak Temperature
Reset of plastic strain

Above „Annealing“-Temperature the equivalent plastic strain is kept zero.
Heat Input
Simulation with SimWeld

Process Simulation GMAW

Numerical Prediction of Equivalent Heat Source
SimWeld Preprocessing

- Definition of:
  - weld preparation
  - geometry and geometric parameter
  - work position
  - material
SimWeld Preprocessing

• Definition of:
  – wire: feed, diameter, material,
  – stick out
  – travel speed
  – angle of torch, stabbing, slabbing, skew
  – shielding gas
  – machine settings U, I
  – process type normal, pulsed U/I, pulsed I/I
  – pulse parameter
SimWeld Results

- Equivalent Heat Source
- Weld Pool Geometry
- Droplet
- Wire Temperature
- Energy, Voltage, Currency
- Temperature Curve
Estimation of Heat Source Parameter from Welding Procedure Specification (WPS) for Arc Weld, TIG, GMAW, SAW

- **Velocity**
- **Estimation of weld pool geometry**
  - length = length of heat source
  - depth = depth of heat source
  - width = width of heat source
- **Energy input per time**
  - Voltage
  - Currency
  - Energy per unit length
- **Estimation of efficiency**
  - TIG: 0,75
  - GMAW: 0,8
  - SAW: 1,0
Doppelt-Elipsoide Heat Source (Loose) with constant heat source density

*Heat Source Code DynaWeld*

**LE** Solid
**LEP** Solid Part
**TRLE** Solid trajectory reference
**TSLE** Solid trajectory surface
**SLE** Shell
**SLEP** Shell Part
**SHLE** Shell Surface
**SHLEP** Shell Surface Part

**Locale coordinate system**

**Geometry function** (double-ellipsoid)

Parameter:
- **Q**: total energy per unit time
- **qf**: source density front
- **qr**: source density rear
- **ff**: ratio front
- **fr**: ratio rear
- **af**: radius front
- **ar**: radius rear
- **b**: radius width
- **c**: radius depth

qf, qr: Wärmequelle dichte konstant:
- Wärmeeintrag qf für \((u/af)^2 + (v/c)^2 + (w/b)^2 \leq 1\)
- Wärmeeintrag qr für \((u/ar)^2 + (v/c)^2 + (w/b)^2 \leq 1\)

\[
qf = 1,5 \times Q \times ff / (af^2 \times b^2 \times c^2)
\]
\[
qr = 1,5 \times Q \times fr / (ar^2 \times b^2 \times c^2)
\]
\[
ff + fr : = 2
\]
Laser, Electron Beam, Laser-Hybrid

Adjustment due to Microsection

- Velocity
- Estimation of the geometry of weld pool from microsection
- Geometry of weld pool = geometry of equivalent heat source
- Adjustment of heat input until calculated liquidus line fits liquidus line of microsection
Double Conical Heat Source (Loose) with constant heat source density

Geometry function (double-ellipsoid)

Parameter:
- \( q_1 \): source density top
- \( q_2 \): source density bottom
- \( r_1 \): radius top
- \( r_2 \): radius middle
- \( r_3 \): radius bottom
- \( v_1 \): \( v \)-coordinate top
- \( v_2 \): \( v \)-coordinate middle
- \( v_3 \): \( v \)-coordinate bottom

\( q_1, q_2 \): heat source density constant

Heat Source Code DynaWeld
- TRLK: Solid
- LK: Solid
- LKP: Solid Part

Locale coordinate system

Heat Source

v1

v2

v3
Local Coordinate System Heat Source Moving along Trajectory

**ay:**
Rotation of the reference around the trajectory. The reference needs to be adjusted in torch or beam direction.

**v-offset:**
Movement of heat source in direction of torch.

**w-offset:**
Movement lateral to the direction of torch and lateral to the direction of travel.

For the Heat Sources with the DynaWeld Code TSxx only a trajectory needs to be defined. The Reference is automatically set normal to the surface.

Global Coordinate System

- **X:**
- **Y:**
- **Z:**

Local Coordinate System Heat Source

- **u:** Trajektory direction
- **v:** Torch direction
- **w:** Lateral direction
Final Adjustment of Heat Input
Determination of calibration factor $kf$ to achieve the target heat input

<table>
<thead>
<tr>
<th>Heat Input Adjustment:</th>
<th></th>
<th></th>
<th></th>
<th>k.f. old</th>
<th>k.f. new</th>
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<tr>
<td>Weld 1001</td>
<td>4212,63</td>
<td>5525,82</td>
<td>1,31</td>
<td>1,00</td>
<td>1,31</td>
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<tr>
<td>Weld 1002</td>
<td>5838,02</td>
<td>5525,82</td>
<td>0,95</td>
<td>1,00</td>
<td>0,95</td>
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</table>
Metatransient Heat Source
with constant heat source density in the whole part

Heat Source code DynaWeld
PH Solid Part
PHS Shell Part

Parameter:
Q: total energy per unit time

q: heat source density constant over all elements of considered part.
Metatransient Method with Energy calibration

Benefit of Energy Calibration:
Enables the application of the Metatransient Method from SimWeld simulation or WPS.
Metatransient Method with Energy calibration

MSG-023
Time = 1.25
Contours of Temperature, middle
min = 29.9797, at node # 116173
max = 1999.29, at node # 119772

MSG
Time = 13816
Contours of Temperature, middle
min = 20.4167, at node # 216659
max = 1928.86, at node # 186712
max displacement factor = 0
Process
Welding

- Heating
- Cooling
- Reheating
  - Tempering Effects
- Grinding and Rewelding
Heat Treatment

Heating
Thermal Heating
Inductive Heating

Carburisation

Quenching

Tempering
Process Chain
Manufacturing of a Box
Task and Model

Forming:
• The roof geometry is made by forming a 3 mm thick sheet (1.4301)

Assembly:
• Add the sidewall

Welding:
• Weld the sidewall to the roof

Clamp and predeformation:
• press the sidewall on measure

Assembly:
• Add the bottom plate

Welding:
• Weld the bottom plate to the sidewall

Unclamping

Model:
• Solid-element model
• Material model (*MAT_270) is used in all steps
• History variables and deformations are kept from one step to an other
• Implicit analysis in all steps
Deep-Drawing of a Cup from a Laser Welded Sheet
Task and Model

Welding:
- Two sheets (S355) with 1 mm wall thickness are laser welded

Forming:
- The welded and distorted sheet is clamped
- A globular die is pressed slow in the sheet.

Model:
- Shell-elements are used for the sheet, solid elements are used for the clamps and the die
- Same material model (*MAT_244) is used in all steps
- History variables, phase proportions and deformations are kept from one step to another
- Welding: implicit analysis, Forming: explicit analysis
Stresses and Strains in Midsurface of Shell after welding and deep drawing

top left:  
**effective stress before unclamping**  
200 .. 1100 N/mm²

bottom left:  
**effective stress after unclamping**  
0 .. 200 N/mm²

bottom right:  
**plastic strain after unclamping**  
0 .. 0.65 m/m
Microstructure during Deep-Drawing

top left:  
Ferrit proportion

top right:  
Bainit proportion

bottom right:  
Martensit proportion
Effective Stress during Forming
Influence of Material Property Change from Welding

CUP
Time = 0.0059
Contours of Effective Stress (V-m)
reference shell surface
min = 58.1917, at elem# 1630
max = 1037.41, at elem# 2204

Fringe Levels
1.100e+03
1.055e+03
1.000e+03
9.650e+02
9.200e+02
8.750e+02
8.300e+02
7.850e+02
7.400e+02
6.950e+02
6.500e+02
6.050e+02
5.600e+02
5.150e+02
4.700e+02
4.250e+02
3.800e+02
3.350e+02
2.900e+02
2.450e+02
2.000e+02
Thinning of the Sheet
Influence of Material Property Change from Welding
Process chain
Heat Treatment - Welding
Welding after Heat Treatment
Results of Process Chain Simulation
Heat Treatment - Welding

Special Contact during Welding

Equivalent Stress after welding

Martensit before welding

Martensit after welding
Thanks for your Attention!

- Forming
- Heat Treatment
- SimWeld
- DynaWeld
- Structure Analysis
- Post Weld Heat Treatment
- Crash
- Assembly