Equivalent Energy Method for Welding Structure Analysis

***

From the manufacturing specification to the simulation model

Dr.-Ing. Tobias Loose
Dipl.-Ing. Jens Rohbrecht

European LS-DYNA-Conference 2017, Salzburg
Automation as far as possible - input by hand as less as possible
Information of manufacturing specification provide the data for the simulation model
**LS-DYNA:**
- Finite-Element-Code with many solvers and methods but one Code
- Enables continuous process chain simulation within one data-structure
- Welding Simulation uses thermal, mechanical and electromagnetic solver

**DynaWeld:**
- Preprocessor for welding and heat treatment analysis with the LS-DYNA Code
- Environment to launch auxiliary software needed for simulation setup
- Provides automatisations to speed up the model setup and post processing
Definitions

Welding Process Analysis:
- predictive calculation of heat input
- predictive calculation of weld pool evolution
- for fusion welding uses CFD approaches
- for resistive welding uses FEM thermal-mechanical-electromagnetic coupled analysis
- Scope of analysis → **weld pool**

Welding Structure analysis:
- heat input by equivalent time-space function of heat density
- heat input as equivalent load but not predictive calculated
- uses FEM thermal-mechanical coupled analysis
- Scope of analysis → **entire assembly**
Definitions

**Transient:**
- Moving heat source
- Temperature gradient in three dimensions and time
- 3D Analysis
- Takes into account heating, cooling and the temperature - time evolution

**Metatransient:**
- Simplified approach to speed up simulation time
- Heat input of a discrete length of the weld pass simultaneous
- No moving heat source
- Temperature gradient in weld direction neglected
- 3D Analysis or 2D Analysis
- Takes into account heating, cooling and the temperature - time evolution
Welding Procedure Specification (WPS):
- Manufacturing specification for welding
- contains all process parameter to define the process

**Travel speed** $v_t$:
- velocity of the moving torch or beam.
- Equivalent to the velocity of the moving heat source

**Wire feed speed** $v_w$:
- velocity of the welding wire exiting the torch for gas metal arc welding processes

**Heat Input / Energy per unit time** $Q$:
- energy per unit time which enters the workpiece: $Q = U \times I \times \eta$ with:
  - $\eta = 0,7$ for WIG,
  - $\eta = 0,8$ for GMAW
  - $\eta = 1,0$ for SAW

**Heat Input / Energy per unit length** $E$:
- energy per unit length which enters the workpiece: $E = Q / v_t$
The equivalent heat source is a function of space and time for the heat input density with geometric shape and density distribution joined to a local coordinate system moving through the simulation model according the path of the heat source and does not describe the physics of the heat input but its impact correctly.

Equivalent heat source = Approach of heat input

Heat source for beam and laser welding: double conus with constant heat density (Loose)
The elipsoidal shape of heat source is mostly choosen for arc welding processes. She is divided in a front and rear part with different heat input. The spherical heat source is a trivial form of elipsoidal heat source.

The **Loose** approach is a constant distributed heat density considering the heat convection by flow in the melt.

The **SimWeld** approach uses for this a super gauss function. Compared to Loose the SimWeld function provides a steady mathematical function.

The **Mokrov** approach considers an upper heat input in the rear part. This fits better the real melt pool shape for GMAW.

The heat input per unit time is the integral of heat density over heat source geometry: \( Q = \int_V \cdot q \)

Vice versa the heat density is determined by the heat input per unit time and the distribution function.
For the metatransient analysis elements are heated with constant heat density multiplied by function of time: \( q = f(t) \).

With the part heat source all elements of the part are heated simultaneous.

The part represents one layer, one pass or sections of it to achieve a successive closing of the weld.

The heat input per unit time is the product from part volume and heat density: \( Q = V \cdot q \)
In case of unknown heat input the only way of heat source adjustment is the adjustment by macro section or known shape of the melt pool. For laser or beam weld the heat input is mostly unknown because of unknown variety of efficiency.

**Workflow:**
- Set heat source geometry similar to melt pool shape
- Calculation of temperature field with start value of heat input.
- Adjustment of heat input till the calculation fits the target.
As the process simulation is the determinant calculation to predict the heat input a special postprocessing may provide the parameter of the equivalent heat source.

SimWeld provides the parameter for SimWeld or Mokrov ellipsoidal heat source for gas metal arc welding:

SimWeld MR10 equivalent heat source
8074.89890  //Q [W]
5348.47510  //Qf [W]
2726.42380  //Qr [W]
3.25000  //af [mm]
21.87500  //ar [mm]
4.30674  //b [mm]
5.95269  //c [mm]
3.01596  //x0 [mm]
3.01596  //z0 [mm]
45.00000  //ay [degree]
60.00000  //vy [cm/min]
1.32472  //factor_front
0.67528  //factor_rear
The heat source parameters can be developed from the welding procedure specification (WPS) for the following welding processes:

- arc welding
- gas metal arc welding (GMAW)
- tungsten inert gas welding (TIG)
- submerged arc welding (SAW)

The WPS is the technical description of the weld process and its parameter specified in ISO 15609. The parameters to be extracted from the WPS are:

- Current (I),
- Voltage (U),
- travel speed \(v_t\),
- shape or dimension of the pass,
- wire feed speed \(v_w\) used to calculate the area of the additional material.

Rule of thumb for the parameter of elipsoidal heat source:

- weighting between front and rear: \(f_f = 1,2\) and \(f_r = 0,8\)
- weighting between the longitudinal radii: between \(a_r = a_f\) and \(a_r = 2 a_f\)
- the elipsoid of the heat source should get the same dimensions as the melt pool.
- \(b\) (half width) and \(c\) (depth) \(\rightarrow\) filler geometry or the specified dimension of the pass.
- \(a_f > b, a_f > c\) and \(a_i\) has to be larger than one element length.
Example

Given is the WPS for a V-shaped multi pass butt weld of a tube with 12 mm wall thickness.

- Gap $b = 4 \text{ mm}$
- Root face $c = 1 \text{ mm}$

The groove weld pass has the following parameters (GMAW):

- Travel speed: $v_t = 19,2 \text{ cm/min} = 3,2 \text{ mm/s}$
- Voltage: $U = 19 \text{ V}$
- Current: $I = 80 \text{ A}$
- Wire feed speed $v_w = 3,5 \text{ m/min} = 58,3 \text{ mm/s}$
- Wire diameter $D_w = 1 \text{ mm}$

The heat input $Q$ is calculated as:

$$Q = U \cdot I \cdot \eta = 19 \text{ V} \cdot 70 \text{ A} \cdot 0,8 = 1216 \text{ W}$$

The area $A$ of the weld pool is calculated using the formula:

$$A = \frac{v_w \pi D_w^2}{v_t} = \frac{58,3 \text{ mm}}{3,2 \text{ mm/s}} \frac{\pi (1 \text{ mm})^2}{4} = 14 \text{ mm}^2$$
Heat Input Control

![Energy input per time in W vs Time in s graph with two target types](image-url)
The **Equivalent Energy Method** postulates:

- the heat input in the metatransient simulation is the same as in the transient simulation and the same as in reality.

As the transient evolution is neglected not the **heat input per unit time** \( Q = U \times I \times \eta \)

but the **heat input per unit length** \( E = \frac{Q}{v_t} \)

comes in force to determine the overall heat input.

The heat input is designed on the volume of deposit material of the pass.

For the design of the heat source parameter \( q \) (heat input density per unit time) the heat input per unit length and the area \( A \) of the pass is needed, the runtime \( t_r \) has to be calibrated.

Heat input density per unit length: \( \frac{e}{A} = \frac{E}{A} \)

Heat input density per unit time: \( \frac{q}{t_r} = \frac{e}{t_r} \)
Example:
U-grooved longitudinal weld of a tube
Inconel, Alloy 617 / Nicrofer 5520
GMAW with 60 passes
Metatransient analysis, 2D

The area $A$ of each pass has to be considered:

$A = 14.3 \text{ mm}^2$

$E = 750 \text{ Ws/mm} = 7.5 \text{ kJ/cm}$

$$e = \frac{E}{A} = \frac{750 \text{ Ws}}{14.3 \text{ mm}^2} = 52.4 \frac{\text{ Ws}}{\text{ mm}^3}$$
Adjustment runtime
Simulation - Measurement

\[ q = e / t_r = \frac{52.4 \text{ Ws}}{3 \text{s}} = 57.5 \text{ W/mm}^3 \]

Runtime \( t_r = 3 \text{ s} \)

Temperature in °C

Time in s
Comparision Transient - Metatransient

Transient Simulation

Metatransient Simulation

Temperature in °C

1500
1350
1200
1050
900
750
600
450
300
150
0