

Equivalent energy method for welding structure analysis

Tobias Loose¹, Jens Rohbrecht¹

¹DynaWeld GmbH & Co. KG, www.dynaweld.eu

1 Motivation

Simulation means real physical processes are calculated on computers with numerical methods. The real world is substituted by a virtual world. The benefits on welding are:

- predict the state before manufacturing
- complex high costly physical tests are replaced by low costly virtual tests,
- visualization of states of work pieces, which are not or hardly able to be measured,
- automation of analysis and evaluation, which cannot be realized by physical tests,
- explanation of formation processes as basis for the design of optimization tasks,
- training and education.

Simulation for welding started before more than 20 years [1, 2, 3] and is meanwhile in use for all welding processes. Experience has to be elaborated for new materials, new processes or new design. Welding simulation helps to achieve this experience rapidly [4, 5].

Two topics are required for industrial applied welding simulations:

- The simulation has to be performed economically.
- The setup of the simulation has to be founded on process data.

The welding procedure specification (WPS) contains all data being relevant for the welding process. This paper explains how to use this information as input for a welding

Large simulation models as well as thick parts with multilayered welds lead to a special challenge. Welding simulation for this kind of specimens becomes economic only under use of simplified approaches: the metatransient method for 3D or 2D models. The authors developed the equivalent-energy-method (EEM) which is based on the data from the WPS. This method postulates that the energy input per unit length in the simplified model is the same than in the detailed model. Additionally a temperature field calibration guarantees for the simplified method, that the heating of the area next to the weld, which is mainly driving the distortion, is estimated correctly.

2 Definition

2.1 Welding process analysis

In the welding process analysis the evolution of the heat generation is calculated. The welding process analysis for fusion welding uses the CFD method taking into account fluid of molten material or air. The welding process analysis for resistive welding uses the FEM method with electrical-thermal-mechanical coupled analysis. The welding process analysis usually takes into account the region next to the weld but not the whole assembly. Welding process analysis usually only considers one weld process.

2.2 Welding structure analysis

The welding structure analysis takes into account the whole assembly with a sequence of many welds. Different welding processes are possible within one welding structure analysis. The welding process analysis does not calculate the heat input itself, but instead uses an equivalent heat source with the approach, that this heat source applies the same heat and local heat distribution than the real process. Welding structure analysis usually uses the Finite Element Method (FEM). The scope is on the calculation of temperature, distortion and stresses calculated over the whole assembly. Microstructure evolution and effects on phase calculation can be taken into account.

2.3 Hardness calculation

The calculation of hardness is a postprocessing procedure evaluating the temperature sequence and the phase proportion. Hardness calculation is not a result on the mechanics thus the hardness calculation cannot be used to verify a welding structure analysis.

2.4 Equivalent heat source

The equivalent heat source is an engineering model to apply the heat in a welding structure analysis. The equivalent heat source shall consider fluid effects but it does not calculate these effects. The equivalent heat source consist on a geometrical distribution and an intensity distribution.

2.5 Transient method

In the transient method a moving heat source is applied according to the movement of the weld torch or laser beam. The transient method requires a fine time stepping during the welding time. The welding is modeled with real time schedule. The transient method is the method most close to reality and always requires a 3D Analysis.

2.6 Metatransient method

The metatransient method is a simplification of the transient method by neglecting the temperature gradient in weld direction. This method has no moving heat source. A part or the whole layer of a weld is heated simultaneous. But on the contrary to other simplification methods, the metatransient method considers the heating and cooling and also the temperature sequence in the area next to the weld. The metatransient method can be subdivided in thermal cycle approach and heat input approach. In the thermal cycle approach a prior calculated welding thermal cycle is applied as thermal load on nodes in the weld area [7]. In the heat input approach heat energy is applied to the elements in the weld area [6].

2.7 LS-DYNA

LS-DYNA is a Finite-Element Code with many solvers for different fields like thermodynamic, electro-magnetism or structure mechanic and best suitable for welding simulation.

2.8 DynaWeld

DynaWeld is a pre-processor for welding and heat treatment simulation with the LS-DYNA code. It contains an environment to drive necessary auxiliary software and supports special post processing routines for welding and heat treatment.

2.9 Nomenklatur

| | |
|--|--|
| x,y,z | global coordinates |
| u,v,w | local heat source coordinates, DynaWeld convention [fig 1] |
| r,s,t | local heat source coordinates, LS-DYNA convention [fig 1] |
| a,b,c | raddi of equivalent heat source elipsoid |
| r ₁ ,r ₂ ,r ₃ | raddi of equivalent heat source double conus |
| b | hight of equivalent heat source double conus |
| f | Heat distribution factor |
| k _f | calibration factor for heat input |
| Q | Energy per unit time |
| q | Energy density per unit time: $q = Q/V$ |
| E | Energy per unit length |
| e | Energy density per unit length $e = E/V$ |
| U | Voltage |
| I | Current |
| t,t _r | Time, Runtime |
| v _t | welding velocity, travel speed |
| v _w | wire feed speed |
| D _w | Diameter of wire |

| | |
|-----------|---|
| A | Area, cross section of deposit material of single layer |
| $f_{1,1}$ | index for front, upper |
| $r_{1,2}$ | index for rear, lower |

Heat input and energy are equivalent but heat input means the efficient part of energy which is entered to the workpiece.

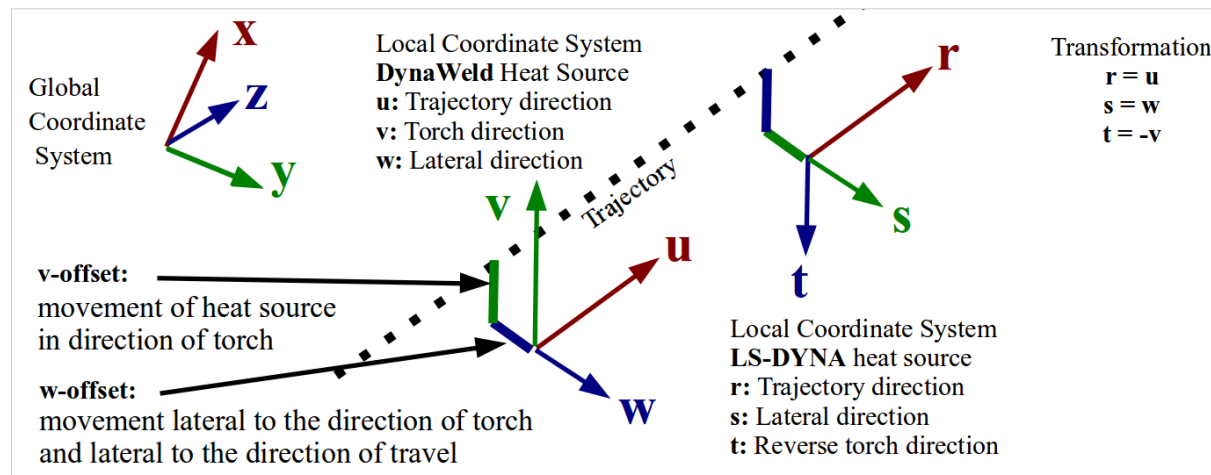


Fig.1: Convention of local heat source coordinate system

3 Equivalent Heat Source for transient Analysis

For the welding structure analysis we use equivalent heat sources. Equivalent, because neither we describe the physics that lead to the heat input, nor we describe the real distribution of heat input. What we describe is a function of geometry and intend a heat input, that is equivalent to the real heat input. The function of the heat input has no special rules but to fit the heat input. The equivalent heat source covers local effects like the fluid movement in the melt pool which leads to a nearly homogenous distribution of the heat. In some prior publications [8] a Gaussian distribution of energy density is propagated which comes from the idea, that the heat of the arc or the laser beam has a Gaussian distribution. Regarding the effects of fluid movement to be covered in the heat source too, the Gaussian distribution becomes obsolete because a constant distribution is sufficient and closer to reality of the total approach. Another point is the mesh density. For distortion analysis a coarse mesh with two Elements in the width of molten zone is sufficient [9] so that a constant distribution better matches to such a coarse mesh.

Besides the distribution of the density of heat input, the geometric shape is the other part of the heat source. To apply a heat load that leads to an equivalent melt pool, it is recommended to choose a geometric function which is similar to the melt pool geometry. Because of the movement of the heat source at least the cross section of the heat source geometry should match to the cross section of the molten zone.

Any geometric function is valid. But some geometric functions have become standard. For arc welding processes an ellipsoidal geometric function and for beam welding processes a double conical geometric function is used. The heat input may be weighted between the front and the rear part (ellipsoid), or the upper and lower part (double conus). In this case f is the weighting factor with f_f / f_r for the front / upper part and f_u / f_l for the rear / lower part and $f_f + f_r = 2 / f_u + f_l = 2$. The ellipsoid may degenerate to a sphere and the double conus to a cylinder.

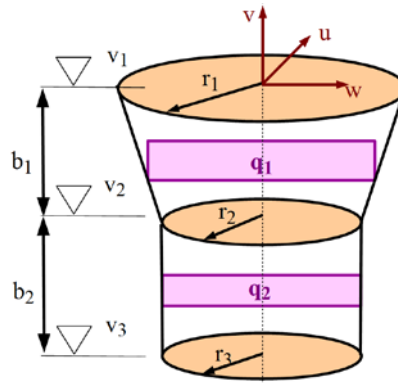


Fig.2: Double conical equivalent heat source with constant heat density distribution

Fig. 2 shows the double conical equivalent heat source. Eq. 1,2 gives the volumetric heat density and Eq. 3,4 the condition if the point is in the conus and heat is applied.

$$q_1 = Q_1 \frac{3f}{2\pi b_1(r_1^2 + r_1 r_2 + r_2^2)} \quad q_2 = Q_2 \frac{3f}{2\pi b_2(r_2^2 + r_2 r_3 + r_3^2)} \quad (1,2)$$

$$q = q_1 \quad i \quad v_2 < v \leq v_1 \quad a \quad \sqrt{v^2 + w^2} \leq \frac{r_1 - r_2}{v_1 - v_2}(v - v_2) + r_2 \quad e \quad (3)$$

$$q = q_2 \quad i \quad v_3 \leq v < v_2 \quad a \quad \sqrt{v^2 + w^2} \leq \frac{r_2 - r_3}{v_2 - v_3}(v - v_3) + r_3 \quad e \quad q = 0 \quad (4)$$

The double ellipsoidal heat source with constant heat distribution developed by Loose is drawn in Fig. 3. The geometry between front and rear part of the ellipsoid is only differed by the longitudinal radius a . The mathematical functions of the heat source are shown in Eq. 5 up to Eq. 7. The approach of this heat source is to cover the effect of melt pool flow by the constant heat density over the geometric shape.

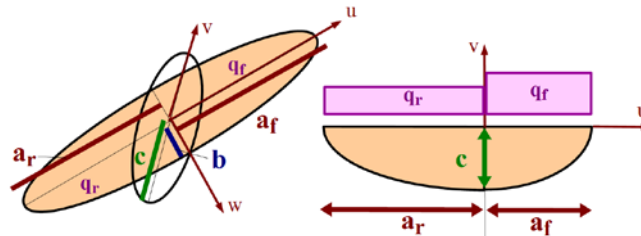


Fig.3: Loose: double ellipsoidal equivalent heat source with constant heat density distribution

$$q_i = Q_i \frac{3\pi f}{a_i b_i c} \quad w \quad i \in \{f, h\} \quad (5)$$

$$q = q_f \quad i \quad uf \geq 0 \quad a \quad 1 - \sqrt{1 - \left(\frac{u}{a_f}\right)^2 - \left(\frac{v}{b}\right)^2 - \left(\frac{w}{c}\right)^2} \quad e \quad (6)$$

$$q = q_r \quad i \quad uf < 0 \quad a \quad 1 + \sqrt{1 - \left(\frac{u}{a_r}\right)^2 - \left(\frac{v}{b}\right)^2 - \left(\frac{w}{c}\right)^2} \quad e \quad q \neq 0 \quad (7)$$

The SimWeld heat source [10] is also double ellipsoid but the nearly constant distributed heat density is described by a super-Gaussian function. Thus the intensity function of this heat source overcomes the mathematical discontinuity of the Loose function. The shape of the SimWeld heat source is shown

in Fig 4 and its equation are written in Eq. 8 and Eq. 9. The Loose and SimWeld heat source can share the same parameter.

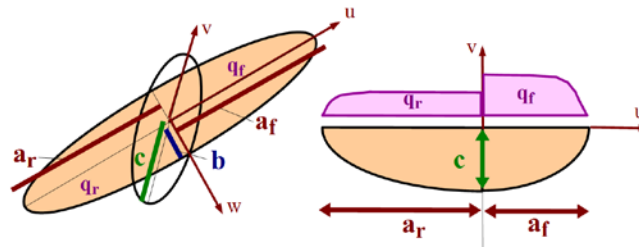


Fig.4: SimWeld: double ellipsoidal equivalent heat source with super Gaussian heat density distribution

$$q_i = Q_i \frac{2^{2.5}}{0.6 a_i b \pi^{1.5} 8} w \quad i = \{f, r\} \quad (8)$$

$$q = q_i e^{-\left(\frac{2u^2}{a_i} + \frac{2v^2}{c} + \frac{2w^2}{b}\right)^5} \quad w \quad i = f \quad u \geq 0 \quad \text{at} \quad v \leq 0 ; n = r \quad u < 0 \quad \text{at} \quad v \leq 0 \quad (9)$$

In order to achieve a more precise consensus between simulation and reality, Mokrov [10] developed a new approach of the double ellipsoidal heat source for gas metal arc welding processes, where the rear heat input is on the top of the heat source center, so that the heat input is placed in the weld reinforcement of the pass. The Mokrov heat source is drawn in Fig. 5. All parameter of the ellipsoid a, b, and c are different in the front and the rear part: Eq 10 and Eq. 11.

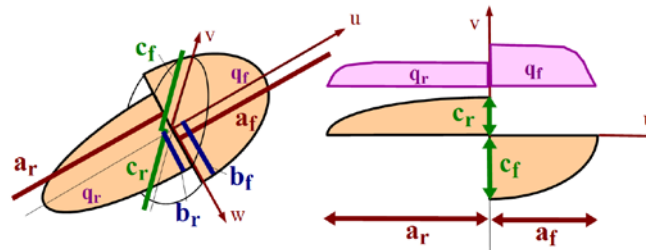


Fig.5: Mokrov: double ellipsoidal equivalent heat source with super Gaussian heat density distribution with upper and lower part

$$q_i = Q_i \frac{2^{2.5}}{0.6 a_i b \pi^{1.5} 8} w \quad i = \{f, r\} \quad (10)$$

$$q = q_i e^{-\left(\frac{2u^2}{a_i} + \frac{2v^2}{c_i} + \frac{2w^2}{b_i}\right)^5} \quad w \quad i = f \quad u \geq 0 \quad \text{at} \quad v \leq 0 ; n = r \quad u < 0 \quad \text{at} \quad v > 0 \quad (11)$$

The total heat input per unit time (Q) is the significant value for the heat source which has to be in accordance with the real heat input.

4 Equivalent Heat Source for metatransient Analysis

For the metatransient analysis elements are heated with constant heat density multiplied by function of time: $q = f(t)$. With the part heat source (fig. 6) all elements of the part are heated simultaneously. 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: $Q = Vq$

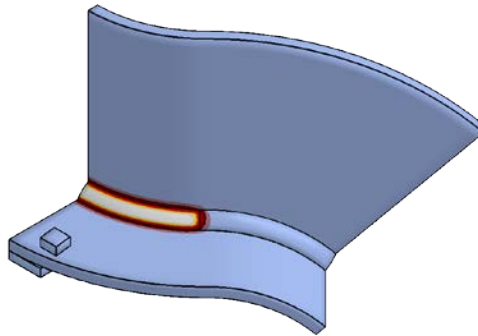


Fig.6: Weld heated with part heat source for metatransient analysis

The use of thermal cycle to define the heat input is possible but not recommended because in this case the heat input cannot be determined and adjusted.

5 Heat Source Adjustment

5.1 Heat Source Adjustment by Macro Section

The procedure applicable for all weld types is the heat source adjustment by macro section. The given parameters are the travel speed (v_t) and a macro section. The approach is to adapt the geometrical function of the equivalent heat source to the real weld pool diameter of the macro section and increase or decrease the energy per unit time in the simulation model until the isothermal of melting temperature from simulation fits together with the shape of the melt pool in the macro section (Fig 7). For some weld processes like laser or electron beam welding it is today the only way of heat source calibration because the efficiency of these processes is unknown. Thus the emitted energy is known, the applied energy, which is the needed parameter for the simulation, is unknown.

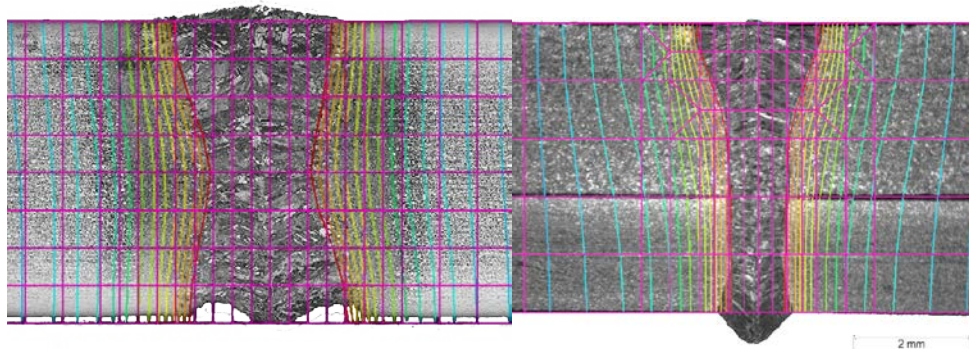


Fig.7: Macro section laser weld with isothermals of thermal analysis with adjusted heat source

5.2 Heat Source prediction by Process Simulation

The process simulation calculates the heat input. This analysis can be used to determine the equivalent heat source parameters for the structure simulation. For gas metal arc welding the process simulation software SimWeld is available to predict the parameter of the equivalent heat source. Furthermore the process simulation is the only applicable way for a real determination of the weld pool length. The SimWeld heat source and the Mokrov heat source are predestinated results from a welding process analysis with SimWeld. The input parameters from this analysis are printed in the welding procedure specification.

5.3 Heat Source Adjustment from Welding Procedure Specification (WPS)

For arc welding, gas metal arc welding (GMAW), tungsten inert gas welding (TIG) and submerged arc welding (SAW) the heat source parameters can be developed from the welding procedure specification (WPS). The WPS is the technical description of the weld process and its parameters specified in ISO 15609. The parameters to be extracted from the WPS are: Current (I), Voltage (U) travel speed (v_t) and the shape or dimension of the pass. The wire feed speed (v_w) can be used to calculate the area of the additional material.

The efficiency η of the processes are nearly equal at:

$$\eta = 0,7 \text{ for TIG}$$

$$\eta = 0,8 \text{ for GMAW and arc welding}$$

$$\eta = 1,0 \text{ for SAW}$$

The heat input per unit length is:

$$Q = U \cdot I \cdot \eta \quad (12)$$

And the heat input per unit length is

$$E = \frac{Q}{v_t} = U \cdot I \cdot \eta \cdot \frac{1}{v_t} \quad (13)$$

For these weld processes usually an ellipsoidal heat source (Loose, SimWeld) is used. The weighting between front and rear may generally be estimated with $f_f = 1,2$ and $f_r = 0,8$. The weighting between the longitudinal radii of the ellipsoid is well estimated between $a_f = a_f$ and $a_r = 2 a_f$. The ellipsoid of the heat source should get the same dimensions as the melt pool. The parameters b (half width) and c (depth) may be extracted from the modeled filler geometry or the specified dimension of the pass. The parameters all need some assumptions. If nothing is given: $a_f > b$, $a_f > c$ and a_f has to be larger than one element length. If a test weld is given, $a_f + a_r$ can be estimated as length of the end solidification pool.

Example:

Given is the WPS for a V-shaped multi pass butt weld of a tube with 12 mm wall thickness. The groove weld pass (Fig. 8) with GMAW process has the following parameters:

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 $D_w = 1 \text{ mm}$

Gap $b = 4 \text{ mm}$

Root face $c = 1 \text{ mm}$

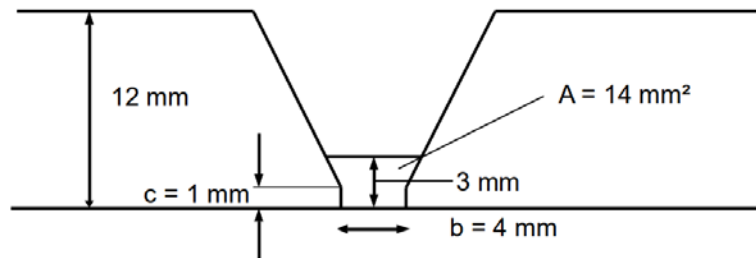


Fig.8: Sketch of the groove path of the weld

The area of filler material is given by the wire diameter and the travel speed:

$$A = \frac{v_w}{v_t} \cdot \frac{\pi}{4} D_w^2 = \frac{5,38 \frac{m}{s}}{3,2 \frac{m}{s}} \cdot \frac{\pi}{4} 1,0^2 \text{ m}^2 = 1,0 \text{ m}^2 \quad (14)$$

To achieve this area the height of the groove pass needs to be 3 mm. Now the geometric parameter of the heat source can be determined: $c = 3 \text{ mm} =$ height of the pass. $b = 2,75 \text{ mm} =$ half width with small extension. $a_f = a_f = 4 \text{ mm}$. The heat input per unit time is calculated by:

$$Q = U \cdot I \cdot \eta = 19 \text{ V} \cdot 80 \text{ A} \cdot 0,8 = 1216 \text{ W} \quad (15)$$

The Loose double ellipsoid heat source with constant heat density distribution is chosen and weighting of the heat to $f_f = 1,2$ and $f_r = 0,8$ as default parameter. The temperature field of the simulation is shown in Fig. 9.

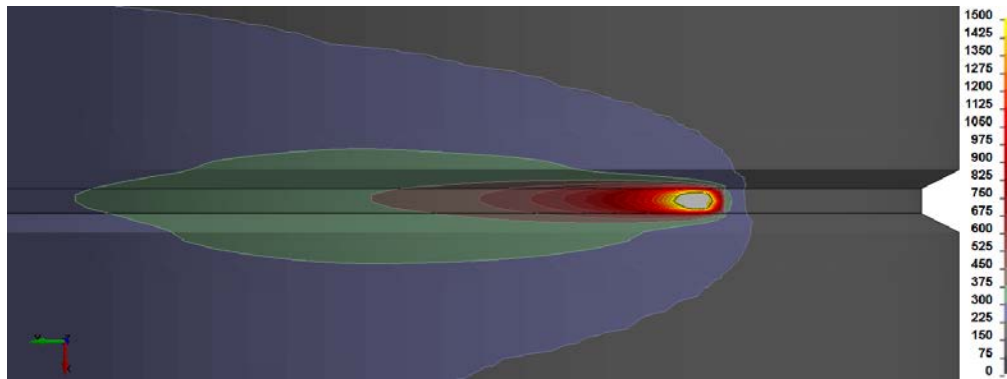


Fig.9: Temperature field of groove weld

5.4 Heat Input Control

Most important for a welding structure analysis is to match the correct heat input. Apart from the heat source adjustment as described above, a check of the heat input by a previous run of a thermal analysis is mandatory. Fig. 10 shows the DynaWeld graph of the heat input evaluation for 13 welds with 2 types of WPS parameter. The target heat input is drawn for both types. Now the calibration factor k_f can be calculated for each weld by the proportion between target and actual heat input. The calibration factor is added in the process sheet for each heat source and the next run of the thermal analysis will correctly match the heat input.

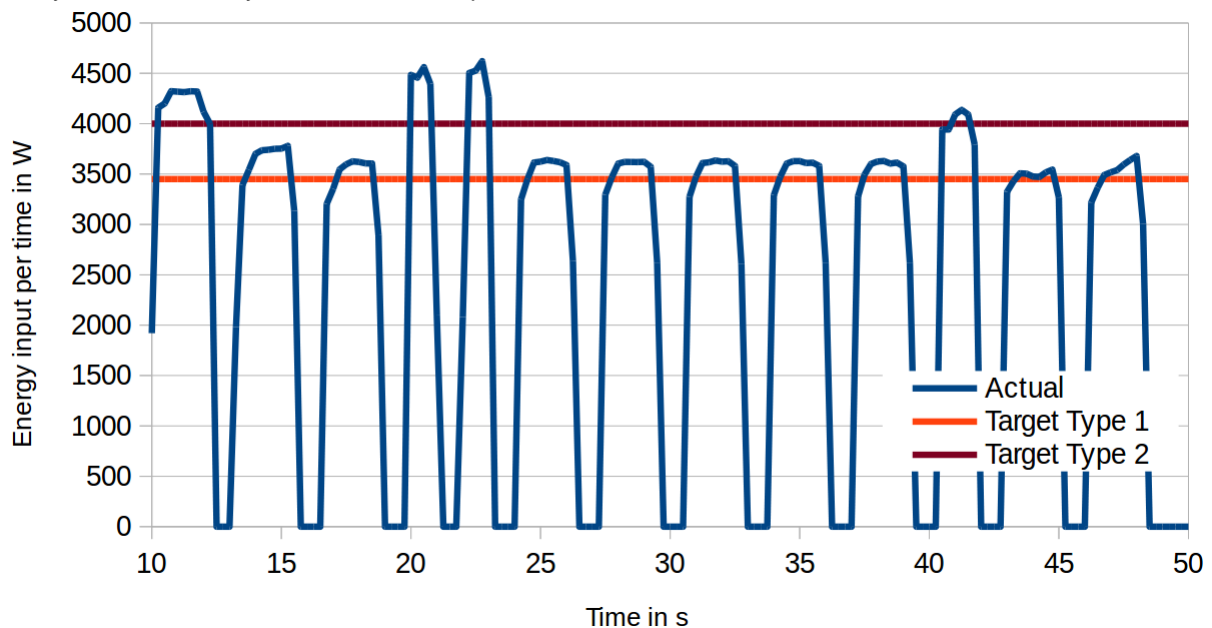


Fig.10: Graph of DynaWeld's heat input control

6 Equivalent Energy Method

The main driving parameter for distortion is the heat input. The equivalent energy method postulates, that the heat input in the metatransient simulation is the same as in the transient simulation and the same as in reality. The part heat source described in chapter 4 allows the definition of a desired heat input and is the best choice for the equivalent energy method. For the design of the heat source parameter q (heat input density per unit time) the energy per length and the area A of the filler material of the pass is needed and the runtime t_f has to be calibrated. The filler material is the material, which is the additional deposit in the current pass. Its area is calculated according Eq. 14. The energy density per unit length is:

$$e = E / A \quad (16)$$

and the heat input density per unit time is:

$$q = e/t_r \tag{17}$$

The runtime needs to be calibrated, so that the thermal cycle, calculated by the metatransient method, fits the thermal cycle of the transient method. Additionally the temperature distribution in the cross section shall become equal between transient and metatransient method. This is a big challenge because we compare the physic with 3D heat conduction with a calculation with 2D heat conduction.

The procedure of the equivalent energy method for metatransient analysis shall be illustrated by an example of multi-pass U-shaped longitudinal weld of a tube with outer diameter of 546 mm and a wall thickness of 40 mm. The number of submerged arc welded (SAW) passes is 53 (Fig. 11)



Fig. 11: Cross section with 53 passes SAW

Modeling the cross sections of the passes the area A of each pass has to be considered. For this example the following parameter are extracted from WPS according chapter 5.3:
 $A = 14,3 \text{ mm}^2$ (Area of pass according Eq. 14)
 $E = 750 \text{ Ws/mm} = 7,5 \text{ kJ/cm}$ (energy per unit length according Eq. 13)
 Now the energy density by unit length is defined according Eq. 16 by

$$e = E / A = \frac{7 \frac{\text{W}}{\text{m}} \cdot 0 \text{ s}}{1,34 \frac{\text{m}}{\text{m}^2} \cdot \frac{1}{\text{m}}} = 5,42 \frac{\text{W}}{\text{m}^3} \tag{18}$$

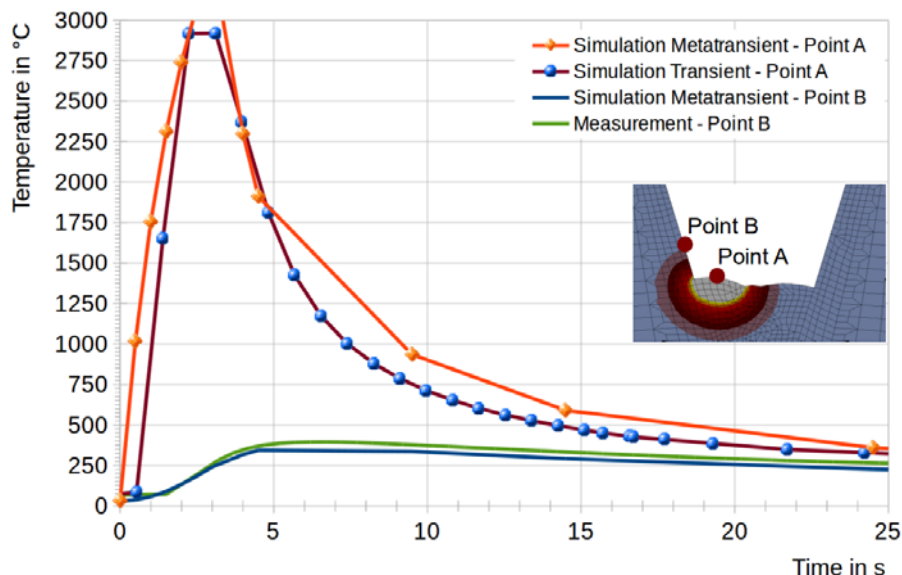


Fig. 12: Temperature Curves

Finally the runtime of the heat source needs to be calibrated that the thermal cycle in the weld pass fits between transient and metatransient method (Fig. 12. Point A). After some runs the best fit is achieved with $t_r = 3 \text{ s}$. The part heat source is hence defined by

$$q = e/t_r = \frac{5,4 \frac{W}{m^3} s}{3 s} = 5,5 \frac{W}{m^3} \quad w \quad t_r \neq 3 s \quad (18)$$

The comparison between measurement and metatransient simulation in Point B (Fig 12.), which position is a little apart from the pass, results in a good accordance. Fig. 13 plots the temperature in the cross section during the time of maximum heating for the transient simulation versus the metatransient simulation. In summary it becomes evident, that the equivalent energy method is a straight forward method in accordance with the process specification and leads to a suitable approach to calibrate heat sources for metatransient models.

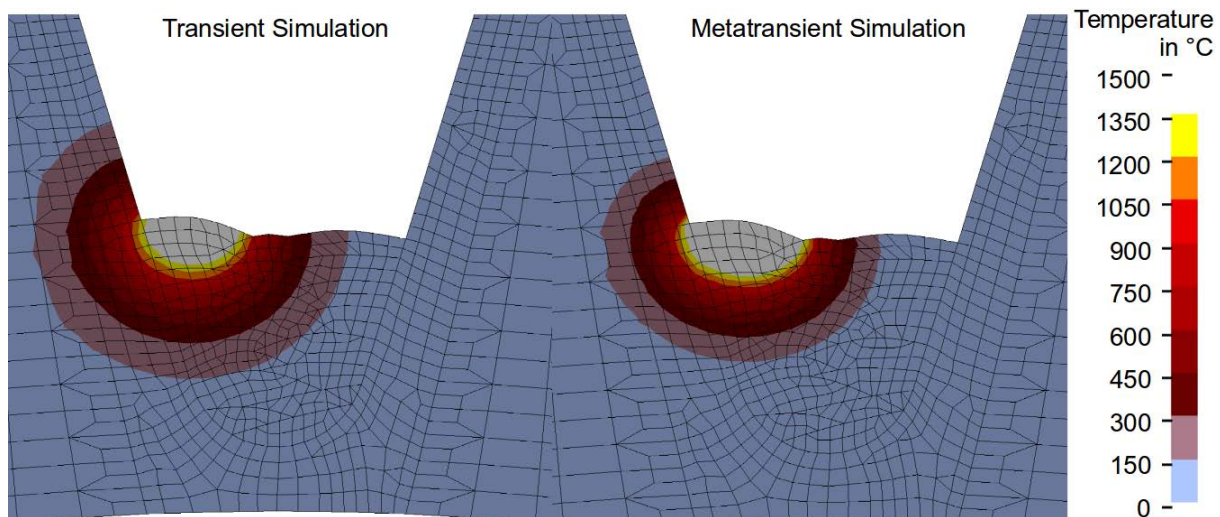


Fig.13: Temperature field in cross section at maximum heating

In the same manner as this example of a multi pass weld the equivalent energy method can be applied to calibrate heat sources for assemblies with large single layered welds to speed up the simulation using the metatransient method.

7 Summary

The simulation of welding processes requires a large amount of computation resources, especially in cases of assemblies, large device dimensions, long welding seams and many welding layers. This fact is the main motivation for the development of simplification approaches, whose deviation concerning the quality of results is still kept as small as possible.

Speed increase for optimization by multiple computations of different variations is another motivation for this.

This publication introduces the equivalent energy method as an excellent approach to do so. Before it gives a deeper understanding of all established methods for transient and metatransient analysis types, shows the difference between welding structure and welding process simulation and presents new mathematical heat source formulations for the use in welding simulations.

The general procedure of heat source adjustment is described in a practical and comprehensible way to be used as an operating instruction for simulation engineers. The same is for the introduction of the equivalent energy method as a new strong approach for the tasks mentioned above.

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