A FINE MODIFICATION OF THE DOUBLE ELLIPSOID HEAT SOURCE

O. MOKROV*, M. SIMON*, A. SCHIEBAHN* and U. REISGEN*

*RWTH Aachen University, ISF – Welding and Joining Institute, 52062, Aachen, Germany, mokrov@isf.rwth-aachen.de

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ABSTRACT

The analysis of residual stresses or distortion of welded structures uses the prediction of the local temperature field. The calculation of the temperature field requires the definition of heat source. The double ellipsoid Goldak equivalent heat source (EHS) is the most used heat input model for arc welding. This model distributes the heat of the arc welding process in a volume, which is equal to a melted weld pool. The heat flow calculation with the EHS reaches a compliance of the experimental and the calculated temperature field, which is far from the weld seam. Close to the weld seam and especially at the fusion zone these results are hardly reachable with the Goldak model. Another disadvantage of Goldak's EHS is a very high non-physical energy density in the centre of the heat distribution. The reasons behind these disadvantages are analysed. It is shown how to modify the equation of the double ellipsoid heat source to secure the benefits of EHS and simultaneously eliminate the disadvantages of the model. A comparison between real experiments, calculations with Goldak's EHS and the modified EHS Modification-R^{10} (EHS MR10) shows a significant improvement of the results using EHS MR10. The distribution of power density is described in the modified EHS by a function of the tenth power and therefore referred to as MR10.

INTRODUCTION

Welding processes lead, because of the strong time-dependent and locally concentrated heat input in real components, almost always to a deformation of the structure. This deformation is generally unwanted and causes problems on the orientation and adaptation tolerance with neighboring structures. These problems are especially pronounced on comparatively heat-intensive welding procedures like electric arc welding. Detailed research projects have been already carried out in order to reduce the appearing welding warpages.

In this context, simulation offers a good opportunity to calculate and study the residual stresses and warpages as well as the structure transformations. The simulation of the residual stresses distortion, according to Radaj [1, 2], is defined as a structure simulation or welding simulation due to heat input, Fig. 1. The most important requirement for calculating the heat input via FEM-based simulation packages is an appropriate heat source description, which guarantees a good agreement of the numerical simulation results with the real temperature relationships in electric arc welding. Based on this, reasonable boundary conditions for the welding structure simulation can be defined.

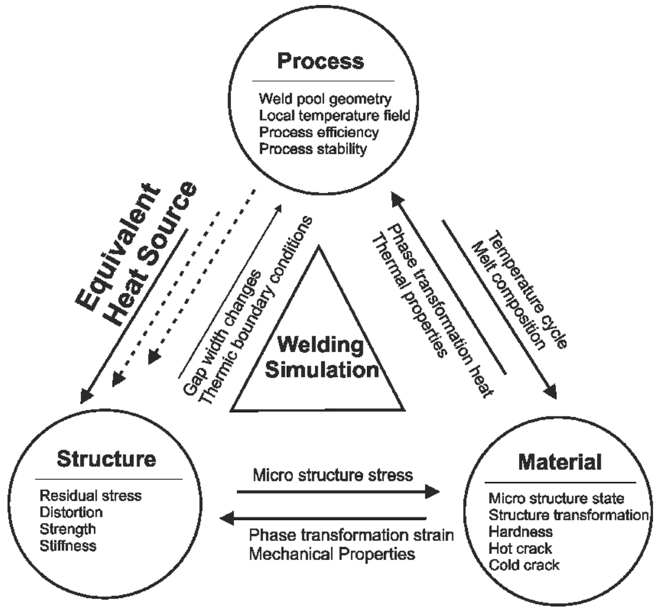

Fig. 1 Welding simulation areas according to Radaj [1,2].

Usually different models for the heat sources are used: unidimensional point heat sources, two-dimensional superficial distributions and tree-dimensional volumetric distributions as well as combinations of these. The application of these models for the simulation of residual stresses and warpage requires, in the corresponding FEM-programs, usually an elaborate calibration procedure.

Therefore a necessity arises for a heat source and its adaptation procedure, which facilitates a higher precision for the simulation of the heat input and a reduction of the calibration effort.

HEAT SOURCE APPLICATION IN WELDING SIMULATION

The first to accomplish a mathematical description of welding heat sources were Rosenthal [3, 4] and Rykalin [5]. The power density distribution of electric arc welding was described by means of an adaptation of the Gauss equation with the application of an intensity parameter to ensure that the whole power is inputted within the arc affected area. The phenomenological explanation for the application of the Gauss function in the construction of the heat source models is based on the original idea of the electric arc process as a combination of stochastic, physical processes.

The EHS by Goldak[6, 7, 8] is an extension of this concept to the case of volumetric heat input. The goal was to account for metal flow within the weld pool. Here the intensity parameter assures too that the whole power is inputted within both quarter-ellipsoids (fourths of the ellipsoid). A quick overview over different approaches for heat source modelling is shown in Table 1.

Table 1 Overview over approaches for Equivalent Heat Sources.

Name	Method
Rosenthal [3, 4], Rykalin [5]	Function-analysical solutions by linearization of the heat conduction process in a homogeneous and isotropic continuum with the neglection of the convection in the weld pool
Rykalin [5]	Plane heat density distribution, based on the Gaussian distribution
Goldak et al. [6, 7, 8]	Distributed volumetric heat sources
Radaj [1]	Solidus surface as an equivalent heat source
Schwenk et al., Pittner et al. [9, 10]	Synthetical approach by decomposition of the process model into an empirical part, which is based on neuronal networks, and a phenomenological part, which describes the physical phenomena
Karkhin et al. [11]	Detailed description for the function-analytical creation of a volumetric heat source

The following examples show a few of many applications of the equivalent heat source (EHS) by Goldak in welding simulation. In a work of Schenk et al. [12], the impact of clamping technology on the appearing deformations were examined both experimentally and also through simulation. The necessary clamping technology for welding causes, in practice, substantial costs to some extent. For this, the choice of the clamping points and the resulting influences on the deformation have to be researched. In this work, the GMA welding of T-joint components of steel (S355) were examined for different clamping configurations. Measured welding temperatures and the resulting deformations were determined for two clamping configurations and compared with the simulations. For the modelling of the heat input, a two-dimensional simplification of the Goldak heat source was used. The work emphasizes, for a good agreement between simulation and experiment, the influence of the clamping configuration on marked-ness and shape of the appearing deformations.

Another work of the same group [13] presented a thermo-mechanical, metallurgic, microscopical model for steel, which well describes the material behavior in welding. The model is based on an existing model, which was extended for non-isothermal behavior in combination with phase transformation. The model and its numerical implementation in ABAQUS are described with vector notation for the stress and load tensors. In order to model the heat input, a Goldak heat source was implemented in ABAQUS in the user-subroutine DFLUX. Model parameters were presented for the steels DP600 and S355. Thermo-mechanical model parameters for DP600, namely hardening and stretching rate, were kept by adapting the temperature and stretching rate. A metallurgical model was implemented with help of the data gathered from the phase field models for the austenite-growth and the continuous cool-down transition diagrams for phase transformations from austenite. The model was applied to the welding simulations of DP600 for lap joint and S355 in T-joint geometries. The final warpage was compared with the experimental results and it was shown, that the presented model is capable of reproducing the experimental results very well.

This and many other examples show that for the illustration of the volumetric heat distribution in electric arc welding, here for the example of gas metal arc welding (GMAW), typically the double ellipsoid equivalent heat source model by Goldak is used. It is comparatively easy to determine and yields higher agreement (e.g. for the external boundaries of the heat affected zone when welding metallic materials) than other heat source models [6, 14].

The EHS by Goldak serves as de-facto standard for a model of heat input for the FEM-based welding structure simulation in the case of gas metal arc welding (GMAW). On SYSWELD or Simufact Welding is, for example, the EHS, one of the predefined heat sources. This applies also for comparatively complex calculation cases.

DOUBLE ELLIPSOID EQUIVALENT HEAT SOURCE MODEL BY GOLDAK

The EHS by Goldak (Fig. 2) is described by six parameters (four geometrical and two energetical) and is based on the equation of Rosenthal and Rykalin for the superficial heat distribution in electric arc welding.

In the distribution by Rykalin and Rosenthal leads the intensity parameter of 3 to almost the whole supplied energy to be within the affected zone of the welding area. The EHS by Goldak underlies the same concept. Here the intensity parameter assures that the whole power is inputted within both quarter-ellipsoids (fourths of the ellipsoid), which corresponds to the normal conditions of electric arc welding.

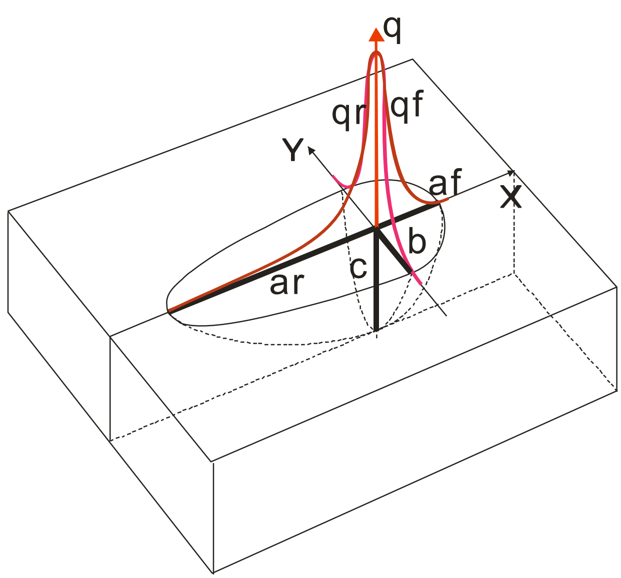

Fig. 2 Schematic illustration of the distribution of the EHS by Goldak [6].

The four geometric parameters are normally defined before the calibration through experimentally defined or through simulation-aided prediction of the weld pool shape. They represent in detail the width and depth of the weld pool as well as the maximum distance between the broadest spot of the pool to the melt front and to the solidification front. The two energetic parameters represent the inputted energies in both quarter-ellipsoids. These were measured experimentally or estimated. Additionally, a measured, calculated or estimated efficiency factor is defined.

$$q_f(x,y,z,t) = \frac{6\sqrt{3} f_f Q}{a_f b c \pi \sqrt{\pi}} exp\left(-3\frac{\left(x+v(\tau-t)\right)^2}{{a_f}^2}\right) exp\left(-3\frac{y^2}{b^2}\right) exp\left(-3\frac{z^2}{c^2}\right) \qquad (1a)$$

$$q_r(x,y,z,t) = \frac{6\sqrt{3} f_r Q}{a_r b c \pi \sqrt{\pi}} exp\left(-3 \frac{\left(x+v(\tau-t)\right)^2}{a_r{}^2}\right) exp\left(-3 \frac{y^2}{b^2}\right) exp\left(-3 \frac{z^2}{c^2}\right) \tag{1b}$$

$$f_f + f_r = 2 \tag{1c}$$

$$2Q = \left(q_f(x,y,z,t) + q_r(x,y,z,t)\right) dxdydz \tag{1d}$$

$$Q = Heat, [W]$$

Although the Goldak-EHS shows a better agreement for the heat affected zone (HAZ) compared to other heat source models, the precision is less satisfying in the area of the weld seam. In order to increase the precision, numerous experiments are carried out [1, 2, 7]. These serve for the calibration, the goal is thereby to achieve maximal agreement with the melt boundary and the weld pool shape, as well as the time-temperature cycles. As a rule, the achieved accordance comes with a calculated temperature that is too high, usually above the evaporation temperature, in the center of the EHS, as well as with a too low temperature on the edge of the EHS.

The problems are known to both engineers and scientists as well as developers of simulation programs. Different solutions were suggested, among others e.g. the variation of the intensity parameter (1 or 2, instead of 3) in the Goldak equation with the corresponding modification of the first normalization multiplier or an automatic calibration of the EHS in SYSWELD. These measures bring, however, only limited improvements and lead to an implausible form of the heat input. The problems, which appear during the calibration of the EHS by Goldak come as a consequence of the fact that the mathematical equation is based on the Gaussian distribution, which has in combination with the intensity parameter a strong maximum in the center of the distribution and the integration of the equation yields 1 as a result. This particularity is very helpful for analytical solutions and allows for an easy normalization for any powers.

The equation yields values, which decrease exponentially depending on the distance to the center. The approach of the distribution brings often a high accordance for the solid phase for the temperature calculation. The maximum value in the center of the distribution corresponds also to the idea of the maximal heat input in the center of the heat source for electric arc welding, which is not necessarily always the case. The model idea for the heat input in this form does not sufficiently consider the hydrodynamics in the weld pool, which could significantly decrease the heat input and the temperature gradient in the weld pool. The maximal temperature in the center follows from the balance between the heat input and the heat dissipation, so for example an even volumetrically distribution in the simulation causes also a maximal temperature in the center of the distribution. Also, hydrodynamics in the weld pool and their impact are, not stochastic processes and therefore don't follow a Gaussian distribution, but on the contrary tend to smooth out the power density gradients. It is therefore plausible to develop a volumetric distribution equation with decreased gradients in the center of the heat source distribution, but at the same time higher power density at the edge of the weld pool.

The development of a modified EHS followed in this application based on the approach by Goldak allows for an increased precision in the representation of the real heat source with a significantly lower calibration effort.

MODIFICATION IDEA

Through a mathematical modification of the distribution equation, the compensation of the temperature gradient through hydrodynamics in the weld pool is considered. From the FEM-simulation with the modified EHS, a decrease of the maximum calculated temperature in the center of the EHS and at the same time an increase of the temperature at the edge of the EHS are expected. This leads to a better representation of the physical reality and simulation precision of temperature-time-cycles and weld seam geometry without increasing the number of parameters for the description of the heat source.

The main idea for the modification of the EHS by Goldak is the replacement of the underlying normal distribution equation, Fig. 3 (a), so that the heat density is decreased in the center of the heat source (flat-topped curve) and increased at the edge (provisory model of the weld pool surface), Fig. 3 (b).

The class of exponential symmetrical distributions can be described with a common equation (Eqn. 2) according to [15]:

$$f(x) = \frac{\lambda}{2\sqrt{2}\theta_1 \Gamma(1/\lambda)} exp\left(-\left(\frac{|x-\theta_0|}{\sqrt{2}\theta_1}\right)^{\lambda}\right) \tag{2}$$

In this, the expected value for the energy distribution in electric arc welding corresponds to the value at the center of the distribution and the standard deviation is the Gamma function, for example.

The form parameter λ is important here. A form parameter of λ = 1 represents, for example, the Laplace distribution and a parameter of λ = 2 represents the Gaussian distribution, Fig. 3.

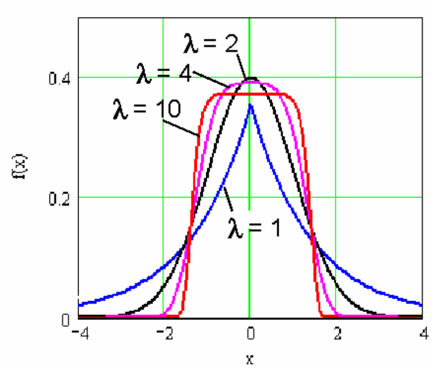

Fig. 3 The class of exponential symmetrical distribution, as well as the distribution function for different parameters λ [15].

The function from this class

$$f(x) = \frac{1}{\sqrt{2\pi}\theta_1} exp\left(-\frac{1}{2}\frac{(x-\theta_0)^2}{{\theta_1}^2}\right) \tag{3}$$

usually underlies the models of heat density distribution in electric arc welding, among others in the two-dimensional Rykalin-Rosenthal distribution or the three-dimensional Goldak-EHS.

Regarding the modelling of the heat input in welding, the heat distribution can be regulated with the help of the parameter λ without changing its integral value. For electric arc welding, parameters of $\lambda > 2$ lead to a more realistic representation of the heat source. These functions have often been called Super-Gauss distributions, see Fig. 4 where the integral value is the same for each half.

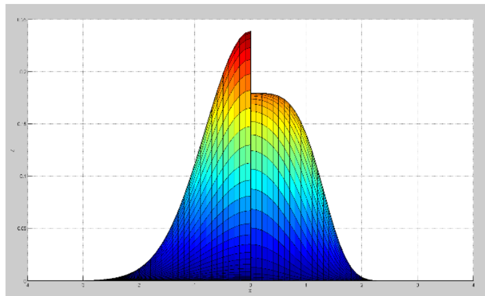

Fig. 4 Comparison of the Gauss distribution (λ=2, left half) and Super-Gauss distribution (λ=4, right half).

The superficial two-dimensional heat density distribution, which can be described with a parameter $\lambda = 4$ in equation (2) yields, in comparison with the normal distribution, a better accordance in the simulation of the temperature field and of the weld pool in the program SimWeld [16, 17].

The same methodology is applied for the modification of the equivalent heat source by Goldak.

FIRST MODIFICATION: ENERGY DENSITY DISTRIBUTION

The goal of the first modification is to reach a more equally distributed heat source in the area which can be described by the distribution radii. The equations (1a) and (1b) can be formally described as:

$$f_{Gol}(x,y,z,t) = KG\ exp\left(-\left(\left(x_0 + v(\tau - t)\right)^2 k_x + y^2 k_y + z^2 k_z\right)\right)$$
$$c = 3;\ k_x = \frac{c}{r_x^2};\ k_y = \frac{c}{r_y^2};\ k_z = \frac{c}{r_z^2}; \qquad (4)$$
$$b = \left(r_x \cdot r_y \cdot r_z\right)\pi^{1.5};\ KG = \frac{2c^{1.5}}{b};$$

Analogously, the modified equation can be written as follows

$$f_{MR10}(x,y,z,t) = KM\ \exp\left(-\left(\left(x_0 + v(\tau - t)\right)^2 k_x + y^2 k_y + z^2 k_z\right)\right)$$
$$c = 2;\ k_x = \frac{c}{r_x^2};\ k_y = \frac{c}{r_y^2};\ k_z = \frac{c}{r_z^2}; \qquad (5)$$
$$b = \left(r_x \cdot r_y \cdot r_z\right)\pi^{1.5};\ KM = \frac{2c^{1.5}}{b \cdot 0.691368};$$

The comparison between the three-dimensional power density distribution with the equation of EHS by Goldak and the modification MR10 is shown in Fig. 5. The color represents the intensity of the power density. For equal distribution parameters and fully distributed power of EHS, the EHS MR10 (right) shows an almost even density inside the distribution area and a sudden decrease at its borders. That kind of distribution significantly corresponds to the conception that the intensive mass fluxes redistribute and average out the heat fluxes in the weld pool. The attempt to reach a deeper melting depth in simulation by increasing the depth distribution parameter is shown in Fig. 6.

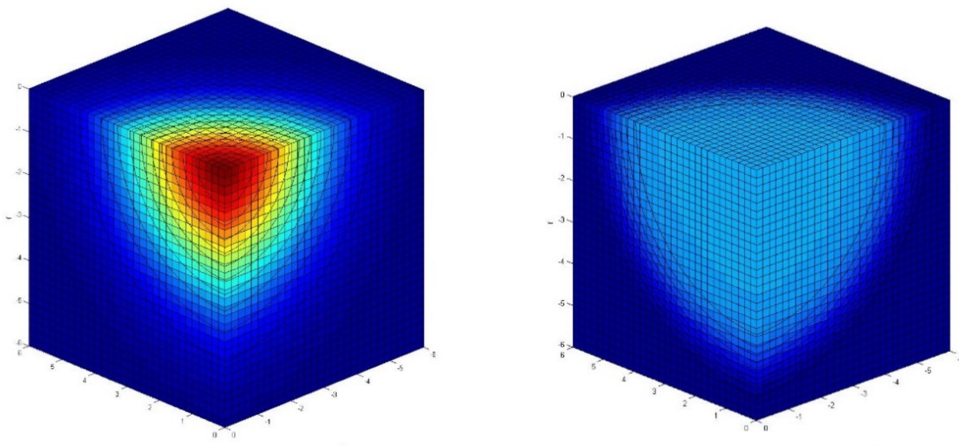

Fig. 5 Comparison between the power density distribution of the EHS by Goldak (left) and modified EHS MR10 (right) .

While the distribution density of the EHS by Goldak increases only slightly at the desired depth, the distribution of the EHS MR10 practically precisely follows the required depth of the weld seam melting zone which is equivalent to the depth parameter of the distribution.

The given examples show the benefits of EHS MR10 by enabling the possibility of a required density of power in the desired area. The dependency between the distribution parameters of EHS MR10 and the weld seam geometry are rather direct, however only if the density power is sufficient for the melting.

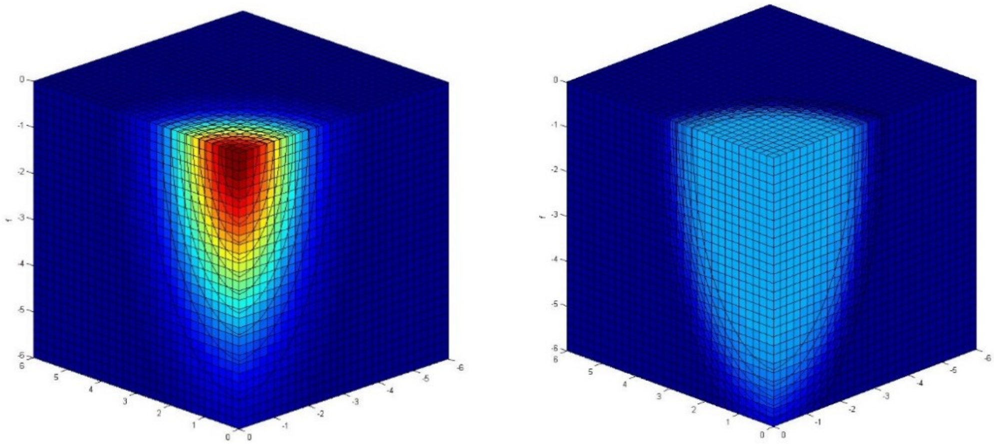

Fig. 6 Representation of the distribution efficiency in the depth direction of the EHS by Goldak (left) and modified EHS MR10 (right).

SECOND MODIFICATION: HEAT SOURCE AREA

Another fundamental problem in using the EHS by Goldak for the calculation of the heat input in FEM-simulation arises when considering the weld reinforcement, created by the additional wire metal. This consideration is necessary if the exact balance of mass and energy is to be achieved. In this case the weld reinforcement is already included in the FEM-simulation mesh. By taking the additional metal given in the mesh into account a conflict with the normalization condition (Eqn. 1d) arises. According the Eqn. (1d) both parts (the front side and the rear side) of the EHS by Goldak should be distributed onto the welding plate. In fact, the normalized conditions (Eqn. 1d) allow that only the lower parts of the distributed energy will be part of the calculation. Therefore, the upper parts of the given ellipsoids remain out of consideration.

If the weld reinforcement is included in the FEM-mesh, two cases are possible: 1. The EHS center has a trajectory (welding line) inside the mesh above the previous surface in the state before the welding (without weld reinforcement) and 2. The EHS center has a trajectory (welding line) above the surface with the consideration of weld reinforcement (top position). In the first case, it has to be guaranteed that the zone of weld reinforcement will be blocked from receiving heat. In the second case, a part of the distributed power to the left and right side of the weld reinforcement border will be lost. Additionally, it makes it difficult to reach the required depth of the melted welding zone.

The study of the cross section of the welding pools with GMAW and SAW welding, especially under the conditions of increased welding speeds and heat input intensities, makes it possible to establish the following assumption: the metal, melted under the welding arc and mixed with the wire metal leaves the melting area as a result of hydrodynamics in the welding pool and forms the weld reinforcement. In fact, these hydrodynamics change the heat input distribution into the weld pool by convection. If the hydrodynamic flow in the welding pool is not taken into consideration during the FEM-simulation, then the process can be compensated by adding heat to the weld reinforcement.

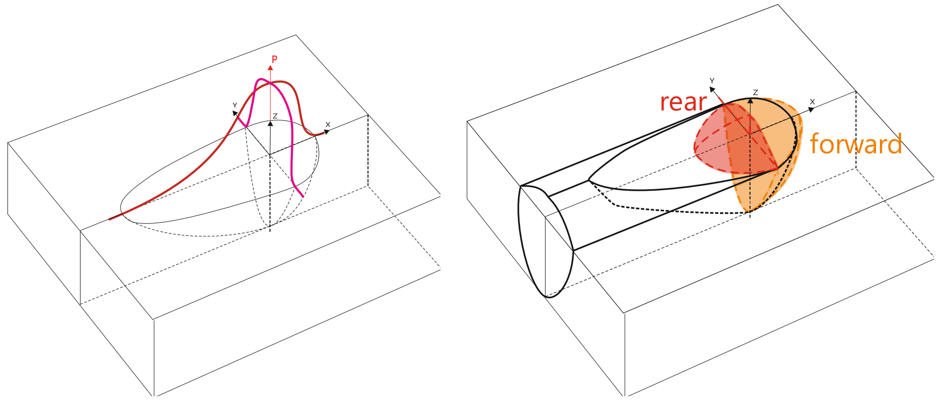

Fig. 7 Schematic representation of the second modification.

In case of a double ellipsoid EHS it is proposed to distribute the heat at the rear ellipsoid only in the metal of the weld reinforcement and block the heat entry of the lower rear part of EHS in the welded plates. The Fig. 7 shows the application of the second modification. This second modification can be used also for the „standard" EHS by Goldak, but in relation with the suggested first modification it makes it possible to reach better results with less time needed for the calibration.

APPLICATION EXAMPLES

The modifications were implemented and simulated for verification by using the tool ANSYS. The comparisons between experimentally determined and simulated geometries in the weld pool for the cases of Goldak's EHS with the 2nd modification and EHS MR10 are shown exemplary in Fig. 8.

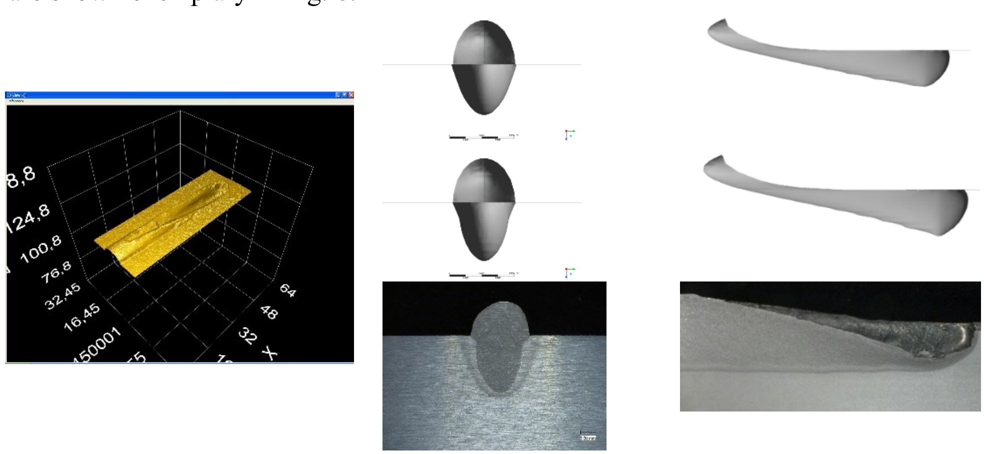

Fig. 8 The comparison between experimentally determined (left: 3D, bottom: 2D) and simulated geometries of the welding pool for the cases of Goldak's EHS with the 2nd modification (top) and EHS MR10 (middle).

A very specific experimental weld seam was chosen for the demonstration of the modification's advantages. Such a cross section is commonly a result of the combination of a high wire feed rate and corresponding current as well as a short arc length and corresponding voltage. The cross section as well as the long section show good correspondence in the simulation for the case of EHS MR10 and also EHS according to Goldak with the 2nd modification. Usually for the calibration a cross section from the real experiment is necessary or a result from a process simulation for example from SimWeld [16, 17]. Also, for the calibration of the energy input, the thermo-cycles are necessary. For this reason the length of the melt pool conveys the whole information about the agreement, much more than the comparison with the thermo-cycles. Furthermore, the thermos-cycles far away from the fusion line are nearly not sensitive to the distribution of the input power density. Both simulations produce good results for the length of the weld pool. In the case of EHS MR10 it was even possible to reproduce the mushroom shaped seam.

This method was also validated for the cases of different welding velocities and the corresponding energy per unit length.

Fig. 9 shows further a good agreement of the comparison between experimentally determined and simulated cross sections for the cases of Goldak's EHS with the 2nd modification and the agreement further increases for the comparison with the EHS MR10 cases.

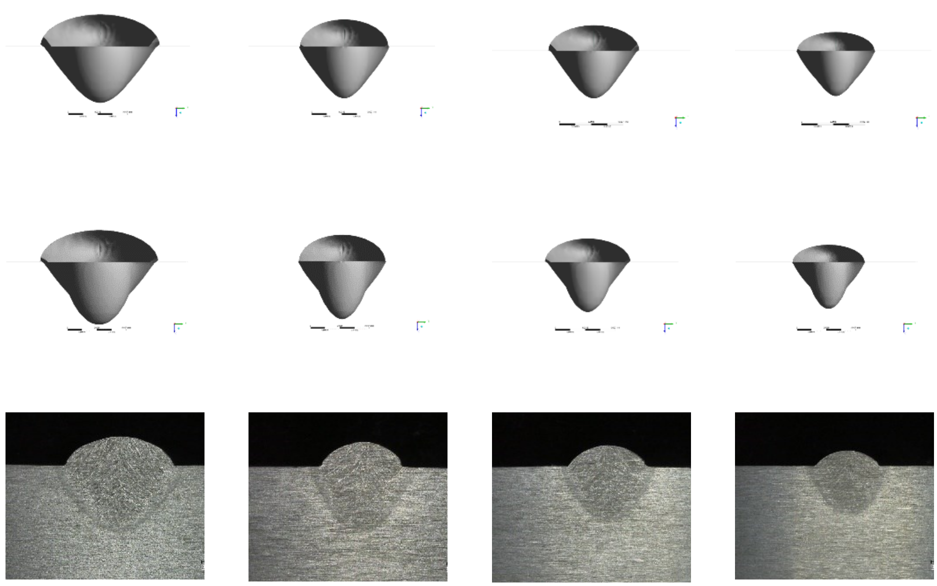

Fig. 9 The comparison between experimentally determined (bottom) and simulated cross sections of the weld seam for the cases of EHS according to Goldak with the 2nd modification (top) and EHS MR10 (middle) for different welding velocities.

The EHS MR10 is implemented as FORTRAN- subroutine for the usage by the FEM-Software SYSWELD. A similar C-subroutine is implemented for the usage by the FEM-Software DynaWeld [18].

CONCLUSION

The suggested and described modifications of the EHS according to Goldak were qualified for the calculation of the GMA welding's temperature field. Since the modifications depict the real processes of the GMA welding closer to reality, the simulation also shows better results with a significantly lower calibration effort.

However, it should not be expected that all kinds of geometries of the weld seam can be depicted by using this modification. The EHS MR10 is primarily an „equivalent" heat source, which purpose is to enable the most real heat distribution outside of the weld pool. The calculated temperature in the weld pool area can be understood as an estimation only and any predictions of the temperature distribution in the case of the EHS approach are unsubstantial.

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