RAPID GENERATION OF TEMPERATURE FIELDS FOR SIMULATION OF WELDING DISTORTIONS

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ABSTRACT

Distortion optimisation of welded parts by means of numerical simulation is expected to be one of the most efficient tools for reducing the costs in automotive engineering in the future. However, the high computational effort of a mechanical finite element analysis limits the application of such simulations nowadays. The numerical reproduction of the correct transient temperature field is one of the most time consuming and demanding tasks. The subject of the current paper is the use of a unique hybrid simulation technique (HST) as a fast and simple method for the calibration of the underlying heat transfer model.
The accurate description of the temperature field in the range up to 0.7 T_m is an essential prerequisite for a simulation of distortions with standard accuracy. So far, there are two common ways of tuning thermal models of commercial finite element codes: a) iterative manual methods and b) the usage of self-consistent heat source models. While manual best-guess approaches are extremely time-consuming (in the range of days up to weeks) and require experienced users, self-consistent mathematical models are mainly validated for standard cases. A cost-efficient alternative for the computation of the temperature fields is the hybrid model approach which combines neural networks with knowledge-based models representing the physics of the welding process. It exploits recorded experimental data characterising the heat transfer (thermal cycles or transverse weld macro-sections) which is usually already available in form of screening experiments. Calibration and execution of such hybrid models of heat transfer is extremely fast (in the range of minutes), requires no expert knowledge and is independent of individual modelling patterns of the simulation engineer.
In principle, HST can be used for any combination of welding technique, material and joint geometry. Exemplarily, a hybrid model is applied to the generation of a temperature field required as input data for the distortion calculation of a laser beam welded DP-W 600 plate of 2 mm thickness. This temperature distribution is compared with one calculated with a manually calibrated standard heat source model. Based on the thermal data, finite element simulations of the transient distortions are performed. The results achieved with the classic and the alternative approach proof that HST allows essential cost benefits while ensuring a comparable precision of the predicted distortions. All numerical simulations are validated with experimental results.

1 INTRODUCTION AND MOTIVATION

Distortions due to welding heat input are a major problem in almost all branches of manufacturing industries. The adjustment of distorted parts in order to meet the quality demands leads to unnecessary time and cost efforts. Consequently the early optimisation of such distortions is a prime target in the development phase of a new product[1]. The use of numerical simulation techniques is expected to become one of the most efficient approaches to reach this ambitious target.

The general application of FEA welding simulation by engineers without expert knowledge presupposes a couple of requirements. Firstly, the calculated result must not depend highly on the user's experience. Secondly, the whole analysis procedure for the prediction of the distortion of a single part should not exceed a maximum of 2-3 days and the sole numerical calculation should be executed in an overnight period.

Currently, the average period of time needed for a high quality set up and a single transient distortion calculation of a component with a medium complex geometry and weld plan is about 2-3 weeks provided that the operator is an expert user. If more complex assemblies like an automotive door sill with more than 20 weld seams are considered, the needed time is typically in the order of months. **Fig. 1** shows examples for parts with different levels of complexity.

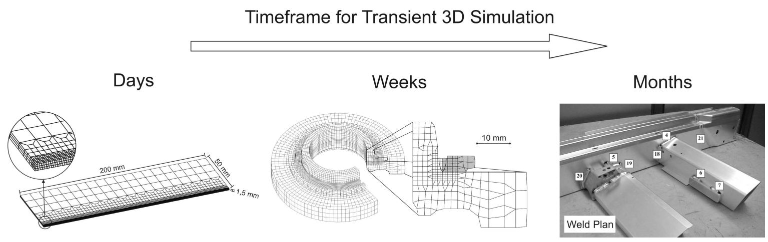

Fig. 1 Examples for specimen with different levels of complexity for numerical welding simulation, left: flat plate (half model, simple), middle: automotive gearwheel (full model, medium size and complexity), right: automotive door sill (big size and high complexity)

The most challenging task in the set up of such welding simulation is the generation of the temperature field with a sufficient precision. The accurate description of the temperatures in the solid material up to 0.7 T_m is an essential prerequisite for a simulation of distortions with standard accuracy[2]. While being only the necessary input data for a mechanical analysis this step normally consumes most of the time needed for the preliminary work (about 90%). Besides, the extensive iterative character of the procedure of model calibration requires a lot of experience in order to achieve a sufficient model accuracy needed for high quality distortion calculation[3]**.** Furthermore, the calibration against multiple experiments requires intense interference by a human operator considering today's FE codes. In order to overcome this unsatisfying situation, a time efficient and automated way of temperature field generation without the need for expert knowledge is desired.

The objective of this research paper is the comparison of two approaches for gathering of temperature fields by means of a) an iterative manual method as the current state of the art workflow and b) the Hybrid Simulation Technique (HST) as a fast and robust automated method based on a combination of neural network technology and knowledge based models. The HST generated temperature field is compared with the manually tuned results for a laser beam welded flat plate. The qualitative and quantitative performance of both techniques is discussed and the results of the subsequent distortion calculation are interpreted. The numerical calculations are validated with experimental data. The welding experiments and the measurement of the needed data are described in the following section.

2 EXPERIMENTAL DATA

The specimen used for the experiments is a 200 x 100 x 2 mm³ flat plate made of the high strength dual phase steel DP-W 600 (1.0936). Preceding X-ray diffusion measurements show no significant residual stresses before welding.

The welding heat source is a 3 kW Nd:YAG solid state laser. The energy input per unit length is adjusted via the welding speed, here 4.0 m/min. A bead-on-plate weld is made on the top of the plate that is supported on three points in a specially made frame and statically determined. Nevertheless free movement without any constraints is guaranteed as indicated in **Fig. 2**.

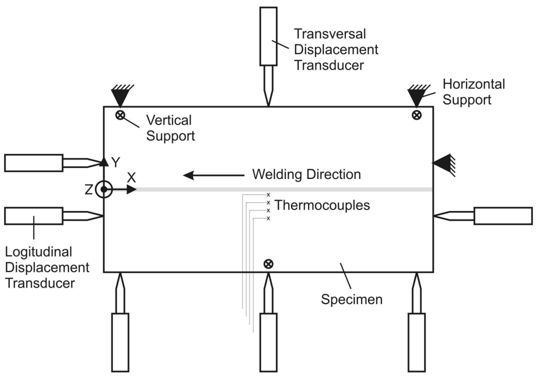

Fig. 2 Experimental set-up for recording of validation data

The transient temperature field is measured with Ni/CrNi thermocouples (type K) with a wire diameter of 0.1 mm. Four thermocouples are spot welded on the top and the bottom face of the specimen close to the expected weld seam. The weld seam cross section is characterised via multiple macrosections perpendicular to the welding direction. They do not show significant differences in their shape or surface area indicating a stable and quasi steady state welding process.

The transient longitudinal and transverse distortions are recorded isochronous to the temperature field with seven displacement transducers mounted in the frame supporting the specimen. On account of the concentrated heat input from the laser beam and the symmetric shape of the weld pool (full penetration) the angular distortions are extremely small and are therefore neglected.

The welding experiments are repeated four times with identical parameters. All recorded data shows only minor deviations between the single experiments with a very small scatter band. The measured thermal data is used to validate the numerical temperature field calculations as described in the following two sections.

3 SIMPLIFICATIONS AND ASSUMPTIONS

The welding process is characterised by an intense interplay of a multitude of physical and chemical effects. It is often observed that a rising complexity of the process is connected to an increasing degree of chaos, for instance it is impossible to exactly reproduce the weld seam shape when repeating a welding experiment with an identical process parameter set. In contrast to that, knowledge based models of the welding process, derived from conservation principles, are fully deterministic and therefore cannot consider chaotic elements of the real process. This discrepancy causes the need for a calibration of all welding models against the results of multiple experiments in order to compensate unknown process details, inaccuracies of measured material properties and simplified mathematical models. Consequently, the scatter band width of the recorded experimental data defines the required degree of model complexity to secure the accuracy and reliability of the predictions.

Besides these aspects, the current limitations in computer capacity confine the number of physical effects taken into account. Finally, not all effects have to be considered for each calculation because of their different impact on the results[1]. These facts request simplifications and assumptions which have to be defined before the actual calculation is set up. They do not only make the FEA simulation possible but also help to minimise the computational costs. The most important ones for the current investigation are:

- ideal specimen geometry
- weak coupling between temperature field and mechanical calculation[4]
- only for iterative manual method:
    - measured homogeneous and isotropic material properties[3]
    - constant convective and temperature dependent radiative heat transfer to the surrounding area
    - 3D conical Gaussian heat source with constant heat flux rate
- only for Hybrid Simulation Technique:
    - neglect of phase transformations
    - no consideration of weld pool geometry as an optimisation target
    - heat input of the laser beam is reproduced by superposition of the analytical solutions for two point and one line sources in an infinite flat plate[5,6]
    - given thermophysical material properties serve as initial guess and are subject of calibration, see section 4

The manual calibration of the temperature field and all subsequent calculations of the distortions are carried out as a transient 3D approach with the commercial FEA code “Sysweld” from ESI, Inc., France. The HST based temperature field generation is performed with the HST code from Hybrid Simulation Technologies, Denmark. The FE mesh of the specimen is designed in accordance to the high temperature gradients of the welding process with a minimum element length in the weld seam of 0.37 mm, see **Fig. 3**. The whole model consists of about 38,000 nodes and 46,000 elements and is identical for both methods.

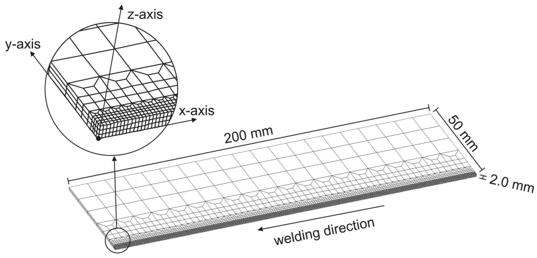

Fig. 3 Example of one half of the meshed FE model for the welding simulation of a laser beam bead-on-plate weld on a flat plate, enlarged part shows the mesh in the weld seam area

4 GENERATION OF TEMPERATURE FIELDS

As stated above, welding models based on known fundamental physical mechanisms have to be calibrated against measurements in order to compensate simplifications of the model or inaccurate material properties.

The iterative manual method uses a standard volumetric heat source for the energy input into the meshed model of the specimen. The mathematical parameters of the heat source are adjusted by hand in order to resemble the measured temperature field. The main aspects for the validation of the iterative tuning process are:

- temperature cycles
  - peak temperature
  - $t_{8/5}$-time
  - temperature gradient during cooling to ambient temperature
- weld seam cross section
  - shape
  - surface area

All five aspects have to match the experimental data and have to be inside the scatter band of the measurements. The needed adjustment time for the correct manual generation of the temperature field is in the range of 2-3 days for a first coarse result and in the range of 2-3 weeks for a very accurate result, both timeframes presupposing an expert user.

As an alternative, the software tool HST is used for the generation of the temperature field. The four tuning parameters

- thermal efficiency
- point source share with respect to the net heat input
- scaling of the Y-axis
- thermal conductivity

are subject to calibration. Every tuning parameter range is divided into 10,000 intervals. Characteristic results used for measuring the quality of the calibration are the peak temperature of the thermocouple measurements and two additional temperatures characterising the cooling phase.

The basic idea of the underlying algorithm is to decompose the model into a phenomenological part that describes the physical aspects and a calibration part based on artificial intelligence that is capable of managing recorded data acquired from multiple welding experiments.

The given task for the HST is to fit the temperature cycles at the discrete points where the thermocouple measurements are done. The molten pool geometry is not defined as an optimisation target and can therefore differ from the measured data. Considering the main aspect of the investigation, the fast and easy generation of a temperature field for the calculation of the distortions, this simplification is admissible as long as the calculated distortions match the measured data correct enough. For further information about the theory behind the HST see Ref. 7.

The main similarities and differences between both methods for the temperature field generation are listed in **Table** 1.

Table 1 Main similarities and differences between the iterative manual method and the hybrid simulation technique

	iterative manual method	**HST**
required user experience	very high (welding simulation expert)	low (standard user)
required user attendance	continuous (complete process)	only for starting
time for temperature field generation	days up to weeks (depending on complexity)	seconds
needed input data	• welding speed • temperature cycles • macro sections of weld seam • temperature dependent thermophysical material properties	• welding speed • temperature cycles

5 COMPARISON OF EXPERIMENTAL DATA AND THERMAL SIMULATION RESULTS

The results of the generated temperature cycles and the corresponding transverse macro sections are shown in **Fig. 4** and **Fig. 5**, respectively.

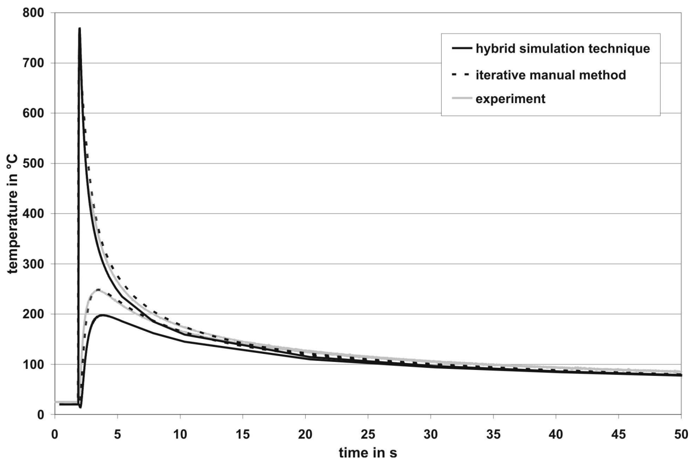

Fig. 4 Comparison of calculated temperature cycles and experimental data directly beneath the weld seam and approximately 4.5 mm away, 3 kW Nd:YAG laser beam bead-on-plate weld, v = 4.0 m/min, DP-W 600 (1.0936)

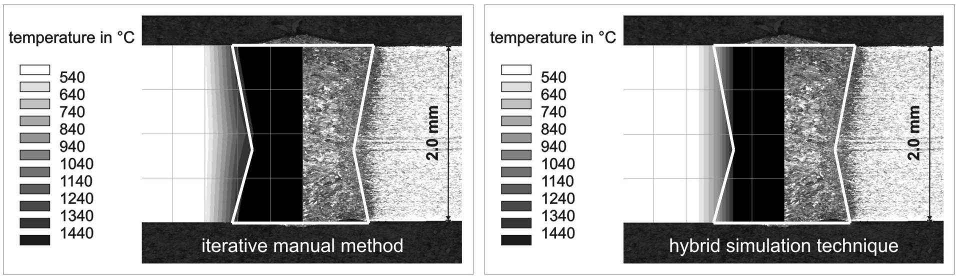

Fig. 5 Comparison of calculated transverse macro section and experimental data, 3 kW Nd:YAG laser beam bead-on-plate weld, v = 4.0 m/min, DP-W 600 (1.0936)

The temperature cycles and the transverse macro weld sections of the iterative manual method reproduce the experimental results qualitatively and quantitatively very good, see **Table 2** for detailed values.

Table 2 Comparison of important temperature field values for experimental data and both simulation techniques (iterative manual method and Hybrid Simulation Technique HST)

value	experiment	manual	HST
peak temperature	710℃ (100%)	726℃ (102%)	770° C (108%)
minimum $t_{8/5}$-time	0.88 s (100%)	0.91 s (103%)	0.67 s (76%)
surface area of the weld seam cross section	2.81 mm² (100%)	2.61 mm² (93%)	2.31 mm² (82%)

All characteristic values of the temperature cycles as peak temperature and $t_{8/5}$-time differ less than 10% for both considered distances from the weld seam. The shape and the surface area of the macro section correspond very well with the experimental macro sections, the deviations are also less than 10%.

The results of the HST based heat transfer model reproduce the experimental data also qualitatively and quantitatively good. The peak temperature has, like for the manually generated results, only minor deviations. The values of the cooling time and the surface area of the macro section show some differences from the experimental results, see **Table 2**. This behaviour is caused by the usage of the combined analytical formula for the heat transfer. The heat dissipation in the experiment is comparably small within the specimen volume because of the low heat flux rate to the surrounding area at the plate edges. In contrast, the knowledge based model employed by HST is defined with the assumption of a flat plate stretched to infinity in Y-direction and therefore high heat flux rates at the edges. This assumption causes a slightly different temperature field. A better matching of the experimental temperature field, including the weld seam width, could be achieved with a more complex knowledge based part of the hybrid model.

The hourglass-like shape of the transverse macro section of the weld seam is not reproduced by the HST method. As already stated in section 3 "simplifications and assumptions" the weld seam geometry is no optimisation target for the neural network. The generated temperature fields are normally not suitable for special analyses of the weld seam geometry. Considering the objective of the fast generation of the thermal load for the mechanical analysis, this limitation of the accuracy of the hybrid model is acceptable.

The good accordance of the cross section area is noteworthy. The width of the weld seam is given indirectly by the temperature gradient in transversal direction. This gradient can be derived from the measured temperature cycles in different distances from the weld seam. The HST only brings the calculated temperature cycles in accordance with the measured data; the correct weld seam width arises from the correctly reproduced temperature cycles automatically.

Considering the numerically generated temperature fields, the differences between the result quality of the manual and the automatically method are negligible. Both methods are adequate for the numerical calculation of welding temperature fields. While the manual method always requires more input data, an expert user and a lot of time for high quality results, the hybrid simulation technique gives such high quality results with less input data in an extremely short amount of time and can be used by a standard user with minimum experience in welding simulation. The subsequently calculated welding induced distortions caused by the two temperature fields are given in the following section.

6 CALCULATION OF DISTORTIONS AND COMPARISON WITH EXPERIMENTAL DATA

The distortions of the specimen are calculated with the generated temperature fields as input data. The thermal expansions are derived automatically from the transient and spatial distribution of the temperatures. They form the load values for the following mechanical analysis.

The differences between the calculated distortions for the iterative manual method and the HST method are originated by the differences in the generated temperature fields. A fully identical temperature field always leads to identical distortions; the method used for the generation has no influence on the mechanical calculation. The results of the calculated distortions in longitudinal and transversal directions are shown together with the scatter band of the experiments; see **Fig. 6** and **Fig. 7**.

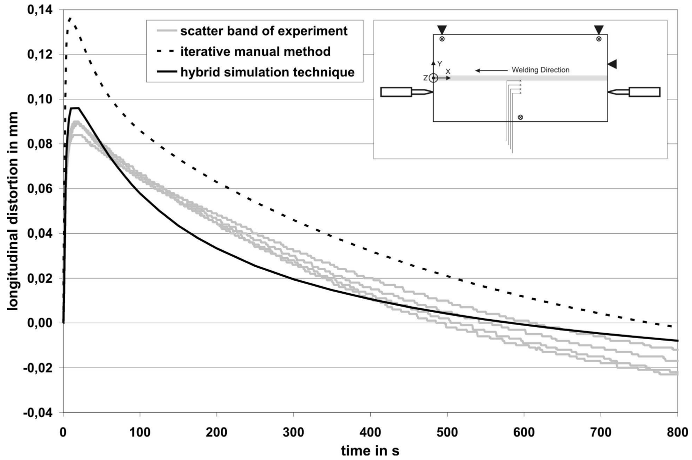

Fig. 6 Comparison of calculated longitudinal distortions and scatter band of experimental data, 3 kW Nd:YAG laser beam bead-on-plate weld, v = 4.0 m/min, DP-W 600 (1.0936)

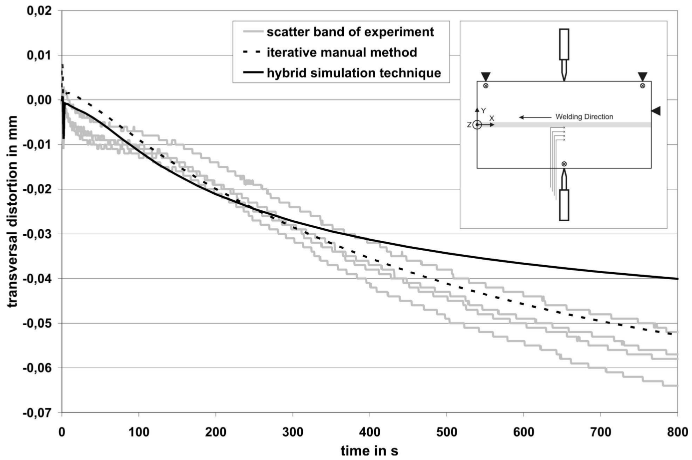

Fig. 7 Comparison of calculated transversal distortions and scatter band of experimental data, 3 kW Nd:YAG laser beam bead-on-plate weld, v = 4.0 m/min, DP-W 600 (1.0936)

A very good qualitatively correspondence between the measurements and the simulation is visible and the transient deformation behaviour of the specimen is reproduced quite accurately. The actual values of the distortions are given in **Table 3**.

Table 3 Comparison of important distortion values for experimental data and both simulation techniques (iterative manual method and Hybrid Simulation Technique HST)

value	experiment	manual	HST
longitudinal distortions after cooling down	-0.012…-0.023 mm	-0.003 mm	-0.008 mm
transversal distortions after cooling down	-0.052…-0.064 mm	-0.053 mm	-0.040 mm

The scatter band width of the measured data is chosen as the measure for the quality of the simulation results. The distance of the simulation results to this scatter band indicates the quality of the numerical representation of the real process.

The iterative manual method generates more accurate transient deformation results. While the curves for the HST method cut the experimental scatter band twice in longitudinal direction, the manual generated curve has the exact qualitatively shape as the experiments, only with an offset. The transversal distortions show an analogous result. The correct transient behaviour is evaluated to be more important than an absolute value after cooling.

However, the advantage of the HST is obvious when looking at the time needed for the generation of these results. It is only a very small fraction compared to the iterative manual method and the model creation can be performed without an expert user's knowledge. One can see that, especially with further developments that are likely to increase the result quality of the HST method (e.g. considering of weld seam width), this method is to be expected highly valuable for the rapid generation of temperature fields in order to calculate welding induced distortions.

7 SUMMARY AND OUTLOOK

The performance of the HST for the generation of welding temperature fields has been demonstrated. Focussing on the objective of the investigation, namely the rapid and robust generation of input for subsequent distortion calculations, HST can be considered a very economic and time efficient alternative to classic approaches for calibration and execution of thermal welding models. The time consumption of the classic iterative manual method for the temperature field generation is about three magnitudes greater (days instead of seconds) while the accuracy of the temperature field is in the same order.

The numerically generated temperature fields based on HST and manual calibration show only small deviations to the experimental data. Thus, they are both suitable for high quality welding simulations. The calculated distortions of the flat plates match the measured data overall qualitatively correct. The deviations of the quantitative results of the longitudinal and transversal distortions for both methods are also in the same order. However, the application of the HST allows a significant reduction of the time needed to provide the application-specific model.

Furthermore, HST makes the simulation of distortions available to engineers who have a profound understanding of the physics of the investigated welding technique but do not have resources in terms of time and money to apply complex simulation tools which require years of experience in this very special field of FEA. A commercial usage of the HST would enable a fast and accurate temperature field generation by every simulation engineer. Another economic advantage of the automated method is that the requirements with regard to the accuracy of the thermophysical material properties and definition of thermal boundary conditions are substantially lowered. Only the temperature dependent thermomechanical material properties in the temperature range up to 0.7 T_m are required for the calculation of the distortions in standard precision.

Finally, the method is independent of the used welding technique and can be applied for all fusion welding processes. So far, HST is a very useful intermediate step until fully self consistent calculation methods are able to cover not only the standard cases, but even the difficult combinations of energy input, welding speed, sheet thickness, material combinations etc.

Future development of the presented HST based temperature field generation will be focused on the creation of a library of relevant welding configurations. By interpreting already recorded measurement data, the generation of models for new welding applications can be performed with smaller sets of additional experimental data. Hence, providing of the welding model can be accelerated and experimental costs are saved. Other possible enhancements are the on-line interpretation of measured temperature cycles for control purposes or the automated checking of recorded data for unexpected deviations during experimental work.

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