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A Method for the Prediction of Process Parameters for minimal Distortion in Welded Frame Structures using a FE-Simulation

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Abstract

Welded frame structures are often subject to unintended distortions due to the thermal joining process. In order to precisely quantify and reduce the distortion of welded frame structures using Finite Element (FE) simulation, a fast and reliable method is required, especially for industrial applications. This paper presents a methodical, simulation based and time optimised framework for the prediction of appropriate process parameters for minimal component distortion of complex welded frame structures by means of e.g. a variation of the process parameters or the weld seam sequences. To achieve a minimal distortion of the final structure, different optimisation algorithms will be used in combination with a database.

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Keywords: welded frame structures; FE-simulation; component distortion; optimisation algorithms

1. Introduction

A major advantage of laser beam welding is its low overall energy deposition into the welding zone due to the strong local concentration of the heat input. However, the welding process can still be a problem for the manufacturing of lightweight frame structures, because of the unwanted component distortion. A challenge is posed if the amount of weld seams and the potential of component distortion respectively increase. As a consequence a higher force is required to close the frame structure prior to the final welding step. Hence residual stress is induced. With the aid of appropriate welding strategies, e.g. a variation of the weld seam sequence or a variation of the process parameters, the component distortion can be minimised and thus additional straightening can be avoided. So far, the FE-simulation is mainly used to compute the component distortions for the comparison with the experimental results. Whereas it is time-consuming to investigate an appropriate welding strategy on an experimental or a numerical level, a new methodical, simulation based and time optimised approach can be advantageous in order to predict the appropriate process parameters for minimal distortion of the whole complex frame structure.

Even though an FE-simulation with little simplifications leads to very good qualitative and quantitative results, the simulation of a complete frame structure will in most cases require a high computing time. There are several well known techniques to decrease the computational effort. The most obvious improvement of the computation can be achieved by a reduction of the degrees of freedom by using 2D shell elements [1] or an adaptive meshing technique [2,3]. It is also possible to combine these two techniques to a so-called hybrid meshing technique [4]. A common form of hybrid meshing is the local-global method [5]. It suggests calculating only the distortion of the heat affected zone in a 3D FE-simulation. The distortion of the global structure is investigated in a 2D FE-simulation using the local deformation fields obtained in the 3D simulation. These above described techniques are used, in the context of a complex frame structure, not only to get fast and reliable results, but also to reach a minimal distortion of the whole structure. Since it takes a lot of time to set up models for all possible variations of the welding task, an optimisation approach is necessary.

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Langhorst et al. [6] carried out investigations by combining an FE-simulation with artificial neural networks. They were able to predict a minimal component distortion of a square-shaped pipe structure with just 16 simulation runs instead of 64. In this case only the variation of the starting angle of the four weld paths was considered as a variable input. In contrast to that approach there is a special advantage within the framework of this paper: In order to avoid the computation of distortions with different welding parameters and different weld joint types in each case of application, a database is used to store this information. As soon as the required thermal information for a specific welding operation is available in the database, only a mechanical FE-simulation is conducted. This new approach and the appropriate method for the minimisation of distortion of a complex frame structure by combining the FE-simulation with optimisation algorithms are presented in the following sections.

2. Overview of the method

The proposed procedure to reduce the computational effort for the identification of the target value, i.e. the minimal distortion for a complex frame structure, primarily consists of two sequences.

In the first sequence the aim is to create an extendable database for different weld joint types (Fig. 3a) and their corresponding component distortions (Fig. 1). Once a single joint type of a complex frame structure was calibrated for a set of parameters, there is no need to compute this location again. Additionally, in contrast to common FE-approaches no thermal simulation of the total complex frame structure needs to be conducted.

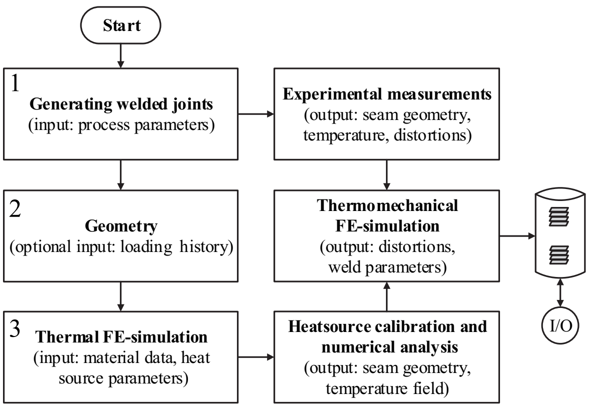

Fig. 1.First sequence: Computation of component distortions for different joint types

In the second sequence the computed component distortions are used to identify minimal distortions for each weld joint type. As the component distortions are computed in the first sequence, only a mechanical simulation of the complete frame structure is necessary (Fig. 2). Once an optimisation loop was executed, the information for each computed step is stored in the database. Finally, to get the minimal distortion of the whole frame structure, the FE-simulation is coupled with the database and with an optimisation algorithm. Once the minimum distortion of the whole structure is determined, the corresponding process parameters can be transferred to production.

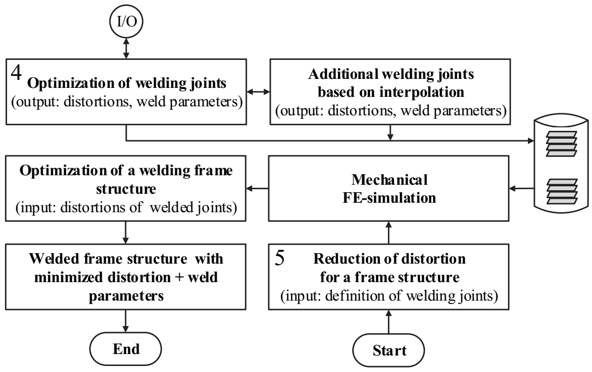

Fig. 2. Second sequence: Minimisation of distortions for a complex frame structure

3. First sequence of the method: Data preparation for the database

3.1. Generation of the weld joints

The first step in the first sequence is necessary to generate the required database entries and serves as a validation of the computed component distortion from the FE-simulation (Fig. 1, Step 1). These experimentally generated data entries are:

- the component distortions of the welded joint,
- the weld cross sections of each weld seam and
- the experimentally measured thermal distributions.

A welding process has different input values and can be classified in process parameters and parameters of the welding task. The relevant process parameters will vary according to the examined welding task. An exemplary set of input parameters is shown in table 1.

Table 1. Exemplary input values for a welding process

Process parameters	Parameters of the welding task
Laser power	Component materials
Welding speed	Wall thickness
Welding sequence	Clamping conditions
Weld filler	Joint type

Depending on the shape of the frame structure different constellations of these input values can appear. Thus, for instance, it might be necessary to carry out a series of tests with two variable parameters in order to generate enough database entries for the optimisation process in the second sequence. More precisely, if a new input value, e.g. another joint type as a function of the laser power and of the welding sequence is investigated, the new component distortions have to be stored for each variation of the laser power and welding sequence, as shown in Fig. 3b.

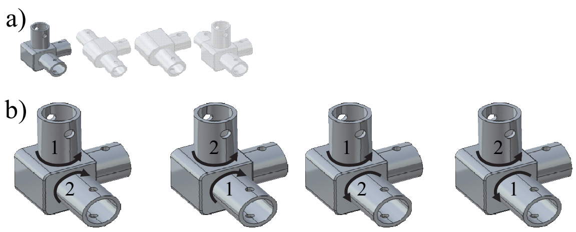

Fig. 3. a) Exemplary joint types and b) variation of the welding sequence for one joint type in order to identify minimal distortion

Since an interaction between the weld seams can have an additional effect on the component distortion, a respective series of tests for each joint type is appropriate. A time-optimised FE-simulation is based on preliminary preparation tasks, e.g. the measuring and the evaluation of the temperature around the weld seam or the contour detection of the weld cross section. Depending on the welding task and parameters, the shape of the weld cross section varies. Therefore, each weld seam contour with different weld parameters has to be captured optically. Within a series of tests it might be necessary to manufacture a high number of weld cross sections. For this reason an automated detection and an analysis of each seam contour is beneficial (Fig. 4, left).

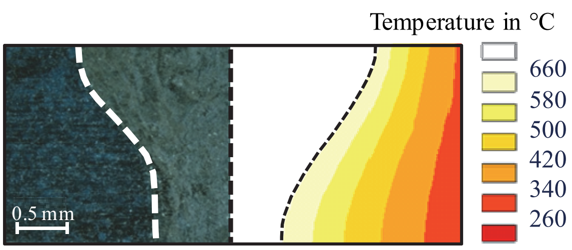

Fig. 4. Exemplary detection of the solidus line for EN AW-6060 of a butt joint (left) and the exemplary calibrated thermal distribution based on an optimised heat source (right)

In order to validate the FE-simulation with the experimental component distortions from the first sequence, there are tactile and visual ways of distortion measurement. One feasible way is the use of a 3D-camera (Fig. 5). In addition to the clamping conditions, these loads can be delivered as additional input parameters to the geometry of the joint type in the FE-simulation (Fig. 1, Step 2). However, that means that for each set of input parameters a new series of tests is needed. A detailed investigation and implementation of preliminary loads was carried out e.g. by Papadakis [7].

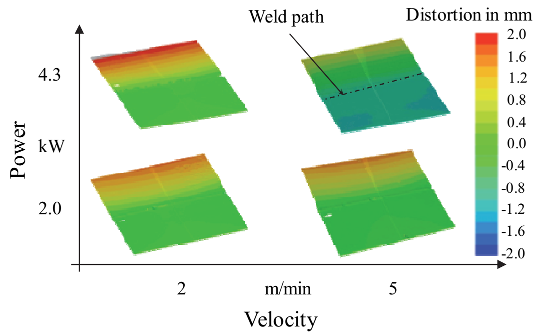

Fig. 5. Exemplary determination of the component distortion for a 3 mm thick sheet (EN AW-6060) after welding by means of a 3D-camera (COMET L3D 2M) with an accuracy of 0.1 mm

3.2. Thermal FE-simulation of the weld joints

For the computation of component distortions a transformation of the process parameters into equivalent heat source parameters is necessary. In the case of a small structure deformation a welding simulation can be performed by a non-coupled solver, i.e. a separate computation of the thermal effects and of the residual stresses and distortions is possible [7]. This simplification has the advantage that for the calibration of the heat source parameters only a thermal FE-simulation has to be performed (Fig. 1, Step 3). Just as for the consideration of the experimentally generated joints, the same computational procedure for each joint type and welding task is applied. After choosing a suitable heat source, the heat source parameters have to be adapted iteratively, until the solidus temperature corresponds to the contour of the weld cross section (Fig. 4, right). Furthermore, the computed transient temperature field is adjusted, using the experimental heat propagation that either can be measured with a thermographic camera or with thermocouples. The calibration of the thermal distribution can be done in different ways. It can be carried out manually by systematically changing each heat source parameter or by using an optimisation algorithm. An example for automated heat source calibration is given in [8]. For the calibration of the heat source either a local or a global optimisation algorithm can be used. Compared with a local optimisation algorithm, a global optimisation algorithm, e.g. a genetic algorithm, comprises an additional stochastic term that makes it possible to identify a globally optimal solution for the heat source parameters. However, a global optimisation requires more computation time. Hence, in order to identify the first output values for the heat source parameters, a global optimisation has to be done first. After that, a local optimisation for similar heat source parameters can be applied. Following a successful calibration, each set of heat source parameters and the corresponding input parameters are stored in a relational database. Thus, non available heat source parameters in the database can be determined by interpolation or a system model, based on regression or an artificial neural network (Fig. 6).

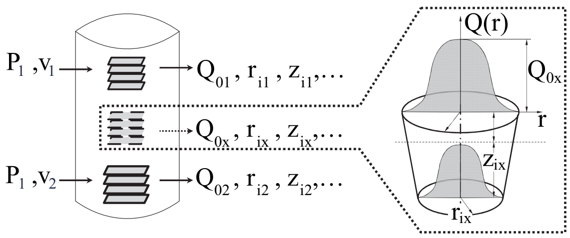

Fig. 6. Computation of the equivalent heat source parameters for a conical heat source based on already existing data entries

3.3. Thermo-mechanical FE-simulation of the weld joints

As described above, the primary goal of the thermal FE-simulation is the time-efficient calibration of the heat source parameters. In order to compute the component distortion, the thermal FE-simulation is followed by a thermo-mechanical FE-simulation with a calibrated heat source. The aim of this step is to compute the component distortions, depending on the chosen process parameters. Furthermore, due to the time-dependent interaction of each weld seam, for the optimisation process of a weld joint the component distortions of each defined time increment and for a particular location are stored in the database.

In order to achieve the same component distortions just in an equivalent mechanical FE-simulation, only the distortion at the nodes with a plastic deformation is needed for the computation (Fig. 7). The rest of the displaced nodes serve for the validation of the computed results.

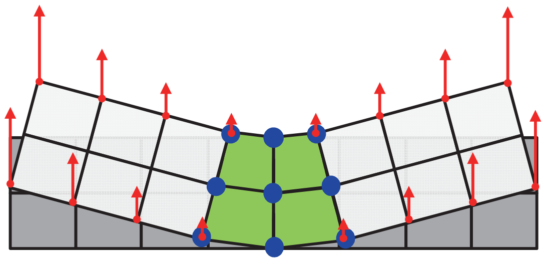

Fig. 7. Schematic representation of the induced plastic deformation (dots) and of the remaining component distortion (arrows) after a welding process

3.4. Data base management

In order to precisely predict the component distortion, it is necessary to sufficiently fill the database with the required information. The management of the already stored data and new incoming sets of process parameters is a particular challenge. If modified joining situations are investigated concerning the significance, the new input parameters, e.g. another beam source, have to be evaluated. For the evaluation there are two types of scenarios: In the first scenario, it can be assumed that the database comprises enough information for similar sets of parameters. In this case, if the difference between two existing sets of process parameters is within a predefined range of values, either a system model or interpolation can be used to generate equivalent heat source parameters (Fig. 6). Otherwise the significance of the new input parameters cannot be estimated and the second scenario is assumed. In this case additional experiments, including the calibration of the heat source, have to be carried out. The reliability of a solution for the calibration of the heat source parameters can be evaluated by an uncertainty analysis.

4. Second sequence of the method: Global distortion compensation by optimisation

4.1. Optimisation for weld joints

The first sequence served as a generation of data entries in the database. Hence, for the second sequence the database contains the following information:

- Computed and experimentally validated component distortions for each defined time step, joint type and set of process parameters
- process parameters and the corresponding heat source parameters

Now this information can be used for the optimisation (Fig. 2, Step 1). Usually the exact set of process parameters for minimal component distortions is not contained in the database. Therefore, the component distortions for different process parameters have to be computed first. Assuming that the database has enough sets of parameters for the investigated case, the component distortions can be computed in three different methods. The first possibility includes a thermo-mechanical FE-simulation. Based on already existing database entries for the heat source parameters, a new set of heat source parameters can be estimated. Applying the second technique, the component distortions can be estimated by the use of an exclusively mechanical FE-simulation. In this case the stored distortions are imposed on the structure. The third possibility is based on interpolation of the component distortions without any FE-simulation. This approach implies a sufficiently filled database. In order to predict the reliability of the results for the component distortions, an uncertainty analysis can be conducted likewise.

Once a method to compute the component distortion is selected, several computational runs for each joint type have to be carried out. Among the investigation of these minimal component distortions, for each joint type additional computational runs with an appropriate selection of weld parameters has to be carried out and stored in the database for the last computational step, i.e. the identification of minimal distortion of the whole frame structure.

4.2. Optimisation for a complex frame structure

The final step consists of an algorithm based computation of the whole frame structure (Fig. 2, Step 5). In order to get a frame structure with a minimal distortion, only the weld locations have to be defined. Thus, already existing component distortions of each joint type are transferred to the complex frame structure. Additionally, by retrieving the stored information of the component distortions, only a mechanical simulation needs to be executed in this step. The aim of using optimisation algorithms is to find a set of parameters for a minimal distortion of the final structure so that smaller clamping forces are required to close the frame structure before the final welding step. This also means that even though the distortions of the whole frame structure might not be completely compensated, the residual stresses would be minimised by means of an optimisation algorithm.

The exact procedure of the process consists of a systematic variation of several computations with different sets of parameters and welding sequences. Similar to the approach of Langhorst et al., the optimisation relies on comparing the target value. In a loop, the optimisation algorithm has to decide, which set of process parameters has to be chosen in order to obtain a better result for the target value. The more entries in the database exist the better the conclusions about the target value will be. If a necessary set of process parameters is missing and cannot be interpolated, the component distortion of the considered joint type will be automatically computed as described in 4.1. Following a successful optimisation process, the appropriate process parameters are provided for production.

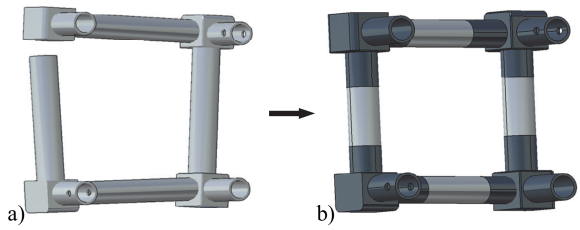

Fig. 8. Schematic results: a) Conventional thermo-mechanical FE-Simulation. b) Mechanical FE-simulation and reduction of distortions for a complex frame structure based on database entries of component distortions for each joint type (right)

5. Conclusions

A novel method for a time efficient computation as well as a reduction of the distortions of welded frame structures is presented in this paper. The basic idea behind this approach consists of the following steps:

- Generation and storage of the experimental information, i.e. the process parameters, the contour of the weld cross section, the thermal distribution and the component distortion of the joint type
- Calibration of the equivalent heat sources by thermal FE-simulation
- Computation of the component distortions by thermo-mechanical FE-simulation
- Optimisation of the component distortions for each joint type and saving the component distortion in the database
- Optimisation of a complex welding structure by utilising the stored component distortions

These steps provide an overview of the individual tasks. Especially the choice of the appropriate optimisation algorithm and the appropriate evaluation criteria have to be investigated further in order to describe the accuracy of a result. Furthermore, it has to be examined whether it is possible to incorporate the computed component distortion in a steady-state computation and to neglect the computational results for each transient computational step. That way the computation time could be reduced considerably.

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