Computing Welding Distortion: Comparison of Different Industrially Applicable Methods

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Keywords: simulation, welding, distortion

Abstract. Welding distortion is one of the major concerns of the industrial joining practice. In order to obtain optimal welding parameters many experiments have to be carried out. Numerical simulation enables a virtual examination of the welding distortion without performing expensive experiments. In this contribution some industrially applicable methods of weld modeling are discussed. They enable the fast distortion assessment in the pre-development stage. The application of these methods on a complex automotive part is conducted followed by a comparison of computed distortion with measured values. Furthermore, aspects of integration of weld modeling into the virtual product chain are addressed.

Introduction

Welding is the primary joining technology in the automotive industry. For example, complex chassis parts can possess dozens or hundreds of weld seams and spot welds. If resulting distortion exceeds admissible tolerances, additional compensation measures are necessary. This causes increasing development costs and takes time.

In the automotive industry the welding production planning generally starts with the prototype stage (Fig. 1). The welding plan defines an initial set of welding parameters, sequences and clamping conditions. The aim is to control the most important functional dimensions of the part. First prototypes are welded according to this plan and the distortion is evaluated. If needed, the distortion will be minimized by different measures. When it is within admissible tolerances, the development of the series welding device is started. Before the start of production the welding tests are performed again using the series welding device and the welding parameters are fine-tuned.

![Fig. 1. Production planning of welding in the automotive industry](http://www.scientific.net)
The welding process, power and velocity are usually specified by technical aspects like weld geometry and weld robot characteristics. Therefore these parameters are almost always fixed for a certain production process and cannot be freely changed. The practical approach to minimize distortion consists generally in varying the welding sequence, direction and clamping conditions. This is achieved by practical experience and numerous trial and error tests. If the distortion cannot be minimized sufficiently in this way, then the last resort is to change the geometry of the part to comply with required tolerances. This implies a new iteration of the product development process which significantly influences the production of single parts, tools and technologies.

Welding simulation enables the virtual examination of the distortion without performing expensive experiments. The global influence of welding sequence and direction or change of clamping conditions on the distortion can be numerically evaluated. Then minimization measures can be tested at an early stage thus saving time and money in the development process. Especially at the prototype stadium welding simulation delivers considerable advantages.

In this contribution some industrially applicable models for simulation of welding distortion are discussed. In the following a classification of available approaches to the welding modeling is presented. Then the physical background and the possibilities of three simplified models are discussed. They were implemented and tested on a number of representative small and large parts. In this contribution these methods are applied on a transverse control arm. Then an outlook on the integration of welding models into the virtual production chain is given. Finally, the major results are summarized and conclusions are stated.

Classification of FE models of welding distortion

Permanently increasing CPU performance and progress in the numerical methods has greatly stimulated the research on welding simulation models during the last decades [1]. They cover a wide spectrum of the physical processes occurring during and after welding as melt pool dynamics, heat transfer, solidification, phase transformations and changes of the mechanical material properties.

The range of currently available models for welding distortion simulation is described by Fig. 2. Complex models take more phenomena into account but are very time consuming. Simplified models are less accurate but considerably faster [2]. All models have to be calibrated and require knowledge about the physics of the weld process.

![Fig. 2. Models for welding distortion simulation](image)

Thermomechanical-metallurgical models. Starting from the bottom of the pyramid from Fig. 2 the most extensive modeling level is represented by thermomechanical-metallurgical models. In these models different physical phenomena during welding are taken into account as there are
elastoplastic material behavior in the part, viscous behavior in the molten zone, phase transformations in the weld and heat affected zone (HAZ), thermal and phase dependent material properties, heat transfer in the material, heat losses at the surface, etc. For example, the commercial software package SYSWELD (Fig. 3) provides such thermomechanical-metallurgical models [3].

![Thermomechanical and Metallurgical Simulation Process](image)

**Fig. 3.** Structure of a thermomechanical-metallurgical simulation with SYSWELD

The computations with these models enable the detailed analysis of the material behavior during and after welding. Temperature, distortion, residual stresses, phase changes and hardening can be investigated with transient (time-dependent) calculations. Two major restrictions limit the applicability of these models in the automotive industry. Firstly, a very large number of material data is needed e.g. temperature and phase dependent material properties like thermal conductivity, heat transfer to the environment, CCT diagrams, thermal expansion coefficient, Young’s modulus, yield stress, etc. The determination of new data sets is very expensive and time consuming. If only a part of the required data is available, additional values are sometimes obtained via interpolation or extrapolation. That brings high uncertainty at these data and diminishes the value of the fine physical modeling. Secondly, the transient thermomechanical and mechanical computations are characterized by very high preprocessing and computation times. These models restrict the choice of the finite elements in the weld and HAZ to volume elements and require a fine mesh density along the weld and over the sheet thickness. Recent developments to reduce the computation time concentrate on the projection of the thermomechanical results from a small representative weld segment to all welds of the global model. These are known as projection methods and macro bead deposit method. Then only a final mechanical computation of the whole model has to be performed. This reduces the computation time, however the time for the preparation of the computation is higher. Therefore the thermomechanical-metallurgical models are not currently used in the industrial production process. However, these models are successfully applied for distortion assessment for research and pre-development purposes.

**Thermomechanical models.** If the full set of data including CCT diagrams and phase dependent parameters is not available, the welding simulation can be performed with thermomechanical models while ignoring metallurgical effects. Thermal and mechanical computations can be sequentially performed at each step or for the whole time interval storing the intermediate temperature values. Based on these values the actual mechanical properties are retrieved. Some commercial software packages offer a possibility of a coupled thermomechanical computation. The convergence behavior of the coupled transient simulation is more sensitive than the sequential computation. Therefore it does not bring considerable time advantage.
The total computation time and the number of the required data for these models is lower than for the thermomechanical-metallurgical models. These models have good chances to predict the correct distortion. The same cannot be said about the residual stresses in the weld because their physical background is poorer. Only the mean stress level can be evaluated. The FE mesh requirements are generally not as restrictive as for thermomechanical-metallurgical simulation. However, they are correlated with the nonlinearity of the corresponding material laws.

**Simplified mechanical models.** For fast distortion computation simplified mechanical models (Fig. 4) can be efficiently used. Simplified mechanical models neglect transient thermo-mechanical history in contrast to the previously mentioned models. They imply only a mechanical computation; no thermal simulation and also no temperature dependent material data are needed. These models are based on elastoplastic material behavior [4] and take into account material shrinkage after welding as the primary cause of distortion. There are generally no special requirements concerning the choice of the finite elements, both volumes and shells can be used. The simulations can be done using available FE-meshes, for example, from structural analysis. However, the weld seam width should be distinguishable. From our experience these models can correctly predict the distorted shape of the part. If properly calibrated, they can also be successfully applied for quantitative distortion prediction. It is demonstrated on a transverse control arm in the succeeding chapter.

![Fig. 4. Major advantages of simplified mechanical models](image)

**Thermal shrinkage model.** This model is based on the material shrinkage at the FE nodes of the welds. The initial temperature at these nodes is set to, for example, melting temperature. Then the temperature of these nodes is decreased within one step down to room temperature. The purely mechanical computation yields an equilibrium state due to this temperature induced shrinkage. This approach is repeated successively for all other welds. At the end the part is released and the final distortion is evaluated. This procedure takes into account the welding sequence. If the welding direction of separate welds is important, this can be modeled by division of the welds in segments and subsequent application of the nodal cooling for each segment. If only one FE node is cooled down within each step, the procedure corresponds to the transient mechanical simulation. However, experience shows there is no need to perform the full transient simulation, the subsequent cooling down of the welds is sufficient for the purpose of distortion evaluation.

For better quantitative prediction of distortion this model should be calibrated to adjust the influence of welding process parameters, velocity, sheet thickness and other aspects which are not covered directly by the parameters of model. Tests on simple parts suffice for this purpose where the measured distortion is used to scale the model parameters. Some of the most efficient ways of calibration comprise the scaling of the yield curve for the material of the weld. Alternatively, the weld seam width can be taken into account by distribution of the shrinkage on some rows of FE nodes parallel to the weld line.

The major advantages of the thermal shrinkage model are low computation time and the fact that only a small number of material parameters are needed. The model can easily be incorporated in any general purpose FE program. The calibration on some simple tests enables the application of the model for the distortion prediction of complex parts welded under similar conditions. If experience
in the application of this model for different materials and welding conditions is available, no additional tests are needed. The model calibration can be performed using this information.

**Prestressed truss element model.** In this model additional 1D elements connecting the nodes of the weld line are used. These elements get the initial stress which causes the shrinkage of these elements and neighboring shell or volume elements of the part. This model is aimed to describe primarily the longitudinal shrinkage mechanism. In many cases this is the dominant distortion mode. Transversal elements can also be incorporated in the weld to take into account the transversal shrinkage [1]. However, it makes the model more complex. Generally the elements of the parts to be joined must have an elastoplastic behavior and the truss elements can be elastic. The model yields also realistic distortion values, if both the part and truss elements are purely elastic. This model has no restrictions on mesh quality and element choice, demonstrates very short computation time and needs a minimal number of material parameters.

**Initial stress and strain model.** In this model the stresses and strains in each element of the weld are set prior to computing. The first equilibrium computation results in the distortion, plastic deformation and the corresponding stress state in the part. Like in the other fast models for weld distortion the parameters have to be sensibly chosen. Changing the material properties of the molten zone to the real ones helps greatly in achieving good results. Provided a proper calibration has been made the quality is very satisfying. This model is analogous to the projection methods used in SYSWELD, but no simulation on a local model is performed. This model can be applied for volume or shell meshes, needs a minimum of material data and demonstrates very short computation times.

**Numerical example: simulation of a transverse control arm**

For the comparative analysis of the described models for computing weld distortion a transverse control arm is chosen. This MAG-welded part consists of two punched steel plates which are connected via a T-joint and two bushings. After welding the deviation of the center distance of the bushings was measured. All data concerning the welding process, sequence and clampings were available. The numerical simulation was performed using all three described simplified welding models. For this purpose they have been implemented into the commercial software package ABAQUS. Furthermore a SYSWELD simulation was performed [5].

Fig. 5 shows distortion results obtained by the simulation with thermal shrinkage model with ABAQUS and thermomechanical-metallurgical simulation with SYSWELD. Tab. 1 summarizes the distortion values and corresponding total computation times for different models on a 1.6GHz Itanium computer. The SYSWELD simulation was performed on a 2.2GHz PC. The distortion results are very similar indicating that all methods are viable. The number of material parameters and preprocessing time is compared. The amount of material parameters needed for the SYSWELD computation is always larger. The preprocessing time for SYSWELD is also larger, mainly because special meshes, time consuming data acquisition and preparation and heat source calibration are needed. This time depends also on the experience in the welding simulation. Since SYSWELD has a profound physical basis the results are not limited to distortion only. For example, residual stresses, hardening, metallurgical phases are accurately simulated. The simplified models are focused on the distortion prediction. The quality of other variables is less accurate.
Fig. 5. From top to bottom: transverse control arm, simulated horizontal distortion with the thermal shrinkage model with ABAQUS, simulated horizontal distortion with SYSWELD (in mm)

Tab. 1. Comparative analysis of simplified mechanical models and SYSWELD

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Thermal shrinkage model</th>
<th>Prestressed truss element model</th>
<th>Initial stress and strain model</th>
<th>SYSWELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of material parameters</td>
<td>small</td>
<td>small</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>Preprocessing time required</td>
<td>small</td>
<td>small</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>Relative distortion with respect to the experiment, [%]</td>
<td>93</td>
<td>103</td>
<td>96</td>
<td>92</td>
</tr>
<tr>
<td>Total computation time</td>
<td>41 sec</td>
<td>26 sec</td>
<td>13 sec</td>
<td>38 hours</td>
</tr>
</tbody>
</table>

**Outlook on the welding integration into the virtual product chain**

As shown, the welding simulation in itself is of great value in determining the weld distortion and the measures against this effect. But it plays also a special role in the virtual product chain. The virtual product chain comprises the simulation of every manufacturing step of a product, thus taking
into account every change of state in this process when determining the final properties. This is of course still ongoing work and will need considerable efforts.

Already now the strength of a part including the changes due to welding can be calculated [6,7]. This is important for some chassis parts like the control arm shown in Fig. 5. Parts like these have to fulfil pre-determined requirements including an upper and a lower limit for the strength to ensure sufficient stability in all driving conditions and avoid damage to other parts of the carriage in the case of abusive load.

Welding does not only lead to a higher strength of the part as compared to calculations done on the basis of the CAD-model but leads to changes of the surface geometry too. Although this is very important for the fatigue calculation there is no way yet to determine the geometrical effects. This is however only a stimulus to advance weld simulation and especially the simplified models which give also the possibility to enhance the numerical model with values from experience or measurements.

In the end the fully realized virtual process chain will make it possible to develop components completely in the computer. This is not yet possible with today's state of development. Fig. 6 outlines the virtual process chain. Essential to it is the updating of the CAD-CAM database. Thus in every new step the information gained in the previous simulations can be used.

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**Conclusions**

In this contribution three simplified models for simulation of welding distortion are presented. They have been developed to be applied prior to the start of the production process as well as prior to a detailed numerical analysis when no complete data set concerning the welding process and material used is available. It is shown that these models enable a very fast distortion evaluation of complex parts. A proper calibration of these models leads to good quantitative distortion results. The major advantages of simplified welding models are the small amount of required material and process data as well as the short preprocessing and computation times. They can also be easily integrated in any
general purpose FE software. All this makes these models well suitable for the industrial production practice. In addition, the simplified models enable the distortion minimization by changing the clamping conditions or welding sequence. In this way, many prototype weldings can be avoided and the lead time before the start of production can be reduced.

The simplified models are aimed primarily to simulate the welding distortion. Results for residual stresses and hardening are still of minor quality. Further steps of development of the simplified models include the improved accuracy of these quantities while maintaining their computational efficiency. This is especially important for the virtual product chain. The next steps of the manufacturing analysis include fatigue and crash simulation where the stress state in the welds often plays a crucial role.

Another important aspect is the systematisation of the knowledge concerning the calibration of the simplified models. More experience for different geometries, materials and welding processes has to be obtained to unify the calibration procedure and to reduce the number of the preliminary tests.

Acknowledgements

The authors are very grateful to Volkswagen AG Braunschweig for providing the data of the transverse control arm.

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