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A Modelling Approach for the Manufacturing Process Chain of Composite Lightweight Structures

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Abstract. In order to support production tasks in the automotive industry, to reduce costs due to a trial and error procedure during process design and plant construction and to secure the accuracy of frame component assemblies, modern simulation methods are applied. In production chains a row of different manufacturing techniques are established. To accompany the number of manufacturing steps with the aid of calculation methods, an interacting of each simulation with the preliminary one is necessary. Such process chains help to determine the structural properties and geometrical accuracy of components and assemblies during manufacturing of composite lightweight structures and ensure their final quality. The basic difficulty of handling aluminium composites with steel reinforcements is the high residual stress level in the reinforcing elements and the adjoining matrix. This stress state can have a significant effect on the desired machining results and the related process itself. Contemplating this reveals the importance of defining a process chain by simulation.

Introduction

For the purpose of supporting the manufacturing of light-weight frame structures in the automotive industry, the following techniques are considered within the Collaborative Research Centre SFB Transregio 10: composite extrusion, laser beam welding and friction stir welding. To cope with the task of this research centre the TR-10 is partitioned into three domains. The partial projects within the A-domain work out the scientific and technological basics of the mentioned process steps. They provide novel and modified technologies respectively for the manufacturing and processing of extrusion-moulded work pieces. The B-domain includes the projects, which simulate the manufacturing processes. Core of the B-projects is the coupling of simulation with reality. The projects of the C-domain integrate the single process steps into a real and virtual process chain. Such a holistic treatment is necessary to study the influences of preliminary processes on the structural effects of components and assemblies along their manufacturing chain. Therefore, one aspect of the project is to merge single simulation models for calculating the structural properties during the manufacturing and transfer these on a modelled entire structure. In the first instance, the chaining should enable to analyse manufacturing problems and optimise the sequence of process steps. Thus, exact information of structural effects on the profile parts, introduced by the manufacturing process, is indispensable for realising an integrated simulation system. In order to achieve these objectives, an extensive knowledge of the projects, investigating the process effects in the A-domain, is also obligatory. Within the scope of the project C7 "An Integrated Simulation of Part-Structure-Interaction for Manufacturing Process Chains", this paper introduces a general approach for the integration of simulation models and an application example as a first step for the implementation.

Objectives and definition of the project

The flexible setup of lightweight structures requires adaptability in chaining the single manufacturing processes. The objective of the project C7 is to prepare single simulations of manufacturing steps and integrate them into an entire model to estimate the loads, remaining within the machined structure. The editing and preparation pursues the concept of grading the complexity of the simulation model to lower levels with a view to reduce the modelling and computation effort. It is intended to develop an integrated model of the structural interference arising during manufacturing, which allows the variation of the input parameters. To increase the quality of computation results, physical changes have to be required as initial values for the simulation of following processes. For example, Tikhomirov [1] considered welding distortions within a virtual production chain; forming results can be taken into account in a simulation chain [2] and interlinking methods realise the integration of the preliminary forming simulation into the simulation of laser beam welding [3], [4]. Kerausch [5] developed a model to integrate preliminary process steps into a forming simulation of heat treated tailored blanks. By using SYSWELD and ABAQUS an interface was implemented, which realised the transfer of structural properties subsequent to a sheet metal pretreatment by laser processes into a deep drawing simulation. Bessert [6] elaborated applications to transfer IT-based data in his research activities. He used so-called mapping-functions to provide structural properties and geometrical characteristics of thin assemblies to subsequent simulation steps. Thus, the manufacturing history of the assembly is integratively considered in the following operations. A representative application of mapping-functions for transferring the characteristics of a forming model onto a crash specific FEM-mesh is described by Zöller [7]. In addition to the structural properties he transferred also complex material interrelations. The mapping of 3D-elements in simulations of material machining with multistage manufacturing processes was investigated by Ranatunga [8]. He introduced techniques and methods to determine the changes in the assembly's geometry during one manufacturing step and with this the associated process parameter, e. g. the strain rate and hence the stress field. Within this research project methods and models should be elaborated to simulate an entire process-chain for different manufacturing techniques, for example the composite extrusion of aluminium profiles reinforced with steel wire elements.

To achieve the described objectives, a three-phase concept should be pursued as shown in Fig. 1. This enables to achieve the complex requirements on the result accuracy and the required flexibility of the modelled process chain. The concept includes a cascade of three intertwined methods to meet the requirements for an efficient simulation of the manufacturing process chain.

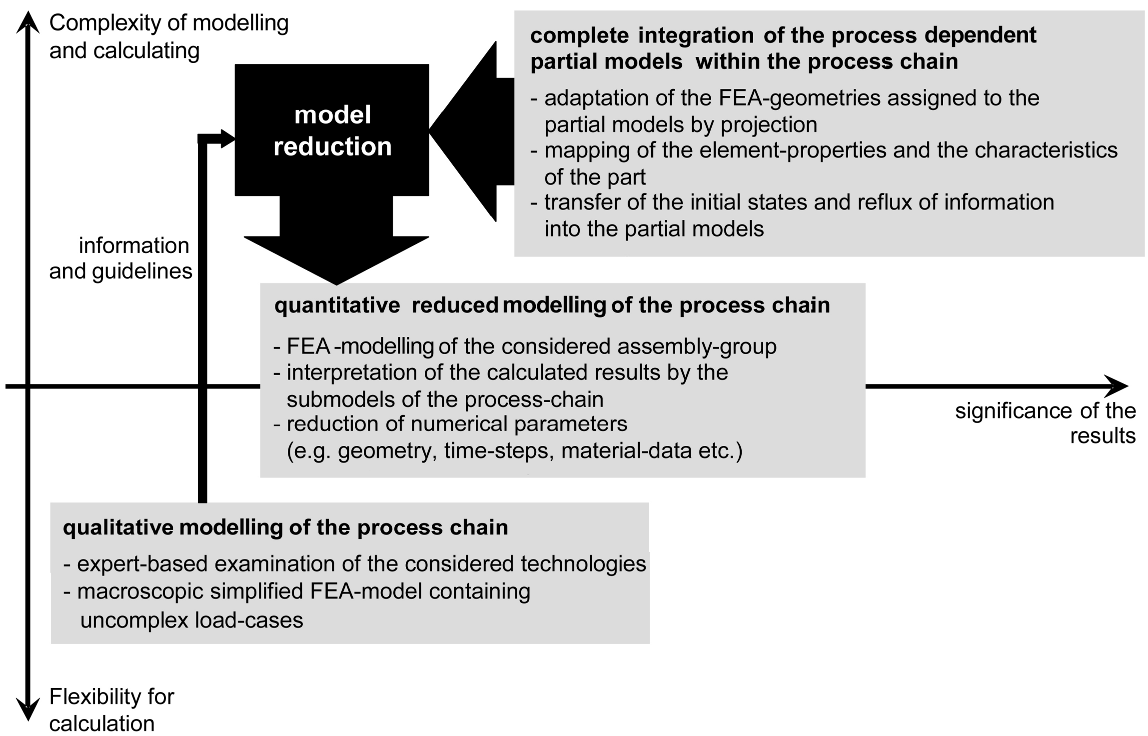

Fig. 1: A three-step-portfolio for an adaptive reduction of the modelling effort within an integrative simulation of the manufacturing chain

Core of the investigations within C7 is to use and to enhance the techniques in Fig. 1 to successively reduce the modelling and computation effort in order to get results that vary in the level of detail. The qualitative modelling of the process chain implies the knowledge integration of the individual processes of the manufacturing chain into an abstract entire model. Thus, a first estimation of the effects on the entire structure is possible. The collaboration with the A-projects should enable to identify tendencies of manufacturing effects on the entire structure. This approach provides a basis to detect the structural loads during the manufacturing phase and to estimate the effects on the assembly. The complete integration of the process dependent partial models in the process chain gives the feasibility to derive the state of the assembly at the beginning of the process specific simulation of the respective B-projects. For example, computed residual stresses should be considered as the initial state in a subsequent welding or drilling simulation. Within this research project the following part-specific values should be provided for the integration task:

- residual stresses as a result of the manufacturing processes
- transient deformation behaviour
- plasticizing
- transient temperature field

The integration of these values and the refeeding of the results should be realised by the master model, which integrates all the aspects of the partial models from the specific process simulations to transfer them as information data. On the basis of the FEM-programme ANSYS all the results of the B-projects can be transferred by capable interfaces. The transfer data is written in *.ASCII-format (text format), which is easy to interpret. Also the times between the manufacturing processes (e. g. cooling phases), which are modelled by the B-projects, can be integrated by means of the chaining model unless their structural influence is negligible for subsequent processes. Thus, the relevant structural influences of the specific processes can be considered along the entire process chain. The transfer of the unequally meshed geometry models from the B-projects can be realised by several mapping-systems, which facilitate the integration of unequal element types (e. g. shells, volumes), sizes and formulations (e. g. linear, quadratic, cubic) between different FEM-systems. Compared to the complete integration of the process dependent partial models as described above, the objective of the reduced modelling of the process chain is to reduce the computation and modelling effort. This approach of minimising effort allows varying the sequence of the manufacturing process models, which in turn supports the process chain optimisation. Otherwise, when using the described complete integration of results and geometries from the B-projects, the computation of variations would be too complex. Therefore, possibilities should be found that reduce the model complexity of the process chain without loosing the significance of the simulation results. Potentials for reduction are the idealising of the process-structure-effects, the coarsening of time lags within the FEM-computation, the coarsening of the FE-mesh or the homogenisation of anisotropic and temperature depending material data. With a view to a minimum effort of modelling the process chain, the reduction of the model is an important task within this project. Particularly, the number of independent parameters should be kept as small as possible when data is transferred or created respectively. This will assure a medium-term economic use of the method. However, the quality of the simulation results should not be decreased significantly for the considered use case. To ensure this, the simulation results will be validated by experiments.

Approach

To reach the discussed objectives, various steps are considered in the following. As already mentioned, a profound technology comprehension of the projects within the A-domain is fundamental to be able to include the results of the process simulations. Therefore, the processes, which are involved in the process chain will be analysed at their corresponding project location.

The influencing factors on the machined work pieces from the different manufacturing processes (e.g. stress state, temperature, distortion, local microstructure, changes in hardness) should be identified and related to each other. The disturbances may tend to global or local structural effects. Thereby, the transition between global and local influences can be smooth. For example, a drilling causes a local impact. Whereas, the residual stress from the composite extrusion is a characteristic global influencing value. The residual stresses are mainly caused by the different thermal expansion coefficients of the matrix material and the reinforcements. This leads to different elongations when the profile cools down and, thus, into a residual state of stress. These stresses interact with those that result from the complex interaction of the welding chamber geometry, the process parameters and the material flow. The calculation of this complex stress situation in the composite by analytical methods is difficult to perform. Because of this reason, it will be determined by measurement techniques. To detect residual stresses in structural parts several techniques are implemented in practise. These include the following non-destructive test procedures: radio graphical techniques [9], neutron diffraction [10], hole-drilling strain-gauge methods [11], ultrasonic tensile testing via transversal waves [12] or the Barkhausen noises [13]. In the near future it is planned to determine the residual stresses in the reinforcing elements and in the transition zone between the reinforcement and the composite using the neutron diffraction.

By means of the obtained findings and in extended consultation with the partners of the technology projects, the limits of the process feasibilities should be exposed. Within these bounds a structure for demonstration purposes (called demonstrator) is defined, which gives the possibility to integrate exemplary manufacturing steps in a process chain. The relevant demonstrator is shown in Fig. 2, where a quadratic hollow profile is joined with a pipe. Both aluminium profiles (EN-AW 6060) are reinforced with steel elements. To fit the profiles together, a circular recess, which is commensurate to the pipe, can be machined into the quadratic profile by the application of circular milling (see Fig. 2).

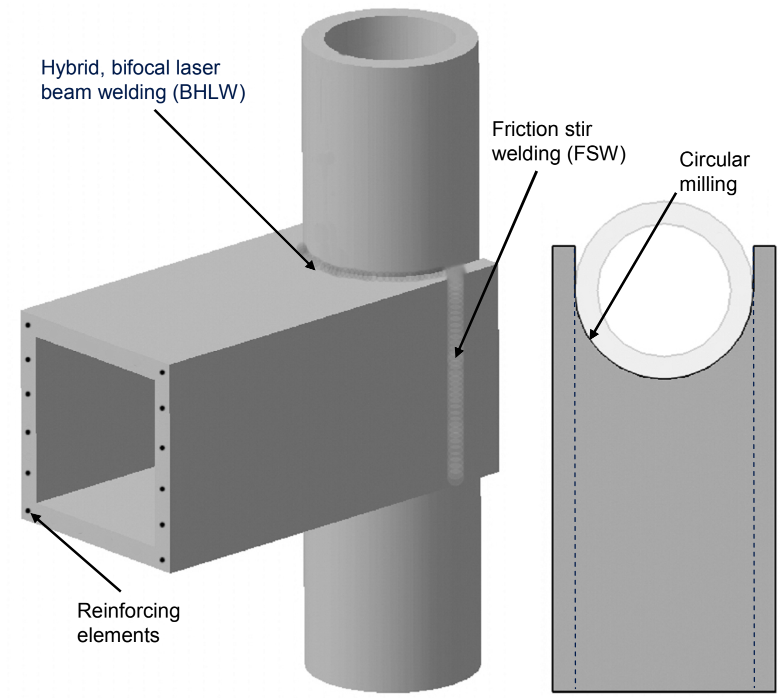

Fig. 2: Example for a demonstrator: T-joint of a round and square hollow profile with embedded reinforcing elements

The friction stir welding (FSW) [14] and the hybrid, bifocal laser beam welding (BHLW) [15] are intended to realise the joining. The semicircular weld line proves to be a huge challenge. Further difficulties for the BHLW are the different absorptive capacities of the laser light as well as the unequal melting points of aluminium and steel. Thus, the analysis of the processes and the consultation with the partners of the technology projects at first is a really important factor for technical feasibility.

The different joining techniques cause various requirements for the respective clamping. For example, in spite of the high processing loads coming up with FSW the exact position of the parts relative to each other and to the tool must be provided. The implementation of an appropriate clamping device for the joining using FSW or BHLW is also a task within this project. Subsequently, several welding tests will be performed. Measuring the geometry of the demonstrator before and after joining should give information about the welding distortions. Furthermore, the residual state of stress in the assembly will be analysed using a method mentioned above.

Another important point of this project is to gain the knowledge concerning the simulation projects within the B-domain. The basis for integration is to have detailed information about the activities, which have already been carried out or are planned within the partial projects B1 to B4. B1 is engaged in the simulation based optimization of composite extrusion and B2 in the simulation of five axis milling. The B3-project analyses the machining with cutting tools using the FEM and B4 simulates the BHLW to optimize the properties of the process and the product. The interaction between the B-domain and C7 is shown in Fig. 3.

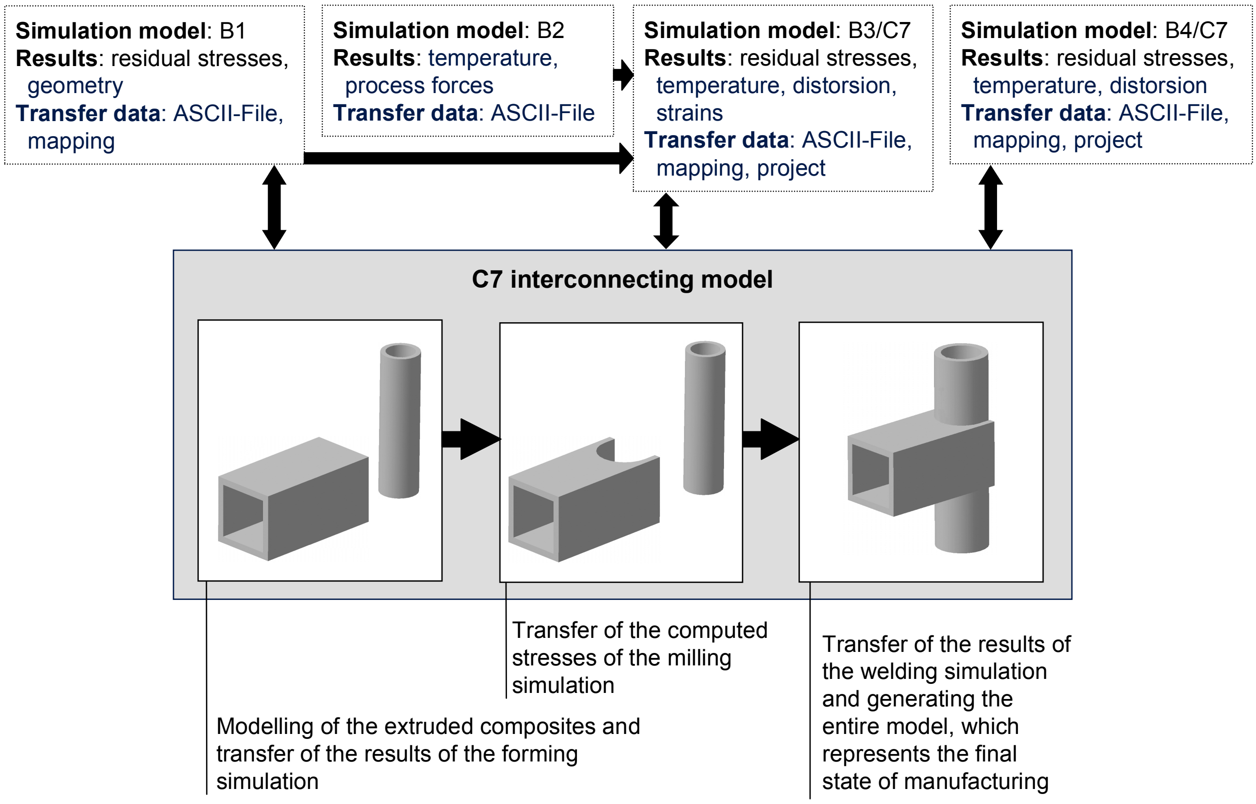

Fig. 3: Exemplary process chain for realising an integrated process simulation

A special collaboration exists between the projects B2 and B3. Therein B3 is supported by B2 with data generated by algorithms, which are not primarily based on the finite element method (FEM). The mainly used computation systems are the inverse kinematics [14], the finite difference method [15] or the discrete dexel model [16]. Therefore, the system provides a function to map the results and model characteristics on an FEM structure. The changes in geometry and properties may be transferred by using special project and mapping functions. These functions provide the process-specific shape of the FE-model, e.g. a fine mesh in the heat affected zone in a welding or machining simulation. Project functions are used to transfer element characteristics between geometries of an identical position and dimension. For example, a temperature field can be transferred on a coarsened or refined mesh structure by inter- and extrapolating the characteristics. Advanced possibilities are provided by mapping functions. These functions include the transfer of geometry changes (e.g. deformation as a result of a heat impact) between two process steps.

Subsequently, with the consolidated knowledge of the technology and simulation projects, it should be possible to build up the FE-models of the considered processes. For the demonstrator shown in Fig. 2 the following processes have to be considered: composite extrusion, circular milling, friction stir welding and hybrid bifocal laser beam welding. Fig. 3 shows how to phase the simulation of a manufacturing process chain.

The computed distortion and residual stress state of the demonstration example have to be compared with real measurements. The next step is to analyse and optimise the manufacturing sequence. For that it is advantageous to reduce the modelling effort at the beginning. With regard to Fig. 1 the reduction can be performed by an analysis of the sensitivity of exemplary parameters (design of mesh and geometry, material data, time steps: transient vs. quasi static). After reducing the modelling effort, the order of all involved process steps along the manufacturing chain (except of the simulation of the composite extrusion as the first step) could be varied in order to support the optimisation of the manufacturing chain. As a start for the variation of the manufacturing steps, the related restrictions are secondary. To maximise the solution space, the objective is to find as many combinations of manufacturing chains as possible. Based on the numerous variants of simulations, the optimisation of the manufacturing chain can be supported with a minimum effort.

The importance of defining a process chain by simulation becomes apparent by the analysis of the results. The integration of physical values, resulting from previous steps (e. g. temperature, residual stresses), leads to a different structural behaviour as in comparison to a mere geometry-model as input data for the succeeding simulation. This is demonstrated by a first step example in the paragraph below.

An example of use as a first step of the approach

As already mentioned above, the first manufacturing step of the integrated process chain within these investigations is usually the extrusion of composite profiles. In this process, wires or wire ropes (e. g. made of steel) are inserted as reinforcements into an aluminium alloy during the profile extrusion. For this, the extrusion process is executed at temperatures up to 450 °C by heating up the chamber. Due to the different coefficients of thermal expansion of the aluminium matrix and the steel wires, the cooling to ambient temperature leads to a state of initial stress of the reinforcements and the matrix material. The proof of residual stresses in the cooled profile was already furnished in [17].

To model the extrusion process, simplifying assumptions are made. For example, one assumption is to consider merely stresses in the profile; potential damages are not considered. Furthermore, for the simulation, the entire composite extrusion is reduced to a process of transient cooling. In particular, a rectangular aluminium matrix (70 mm x 5 mm x 56 mm) with six embedded reinforcing elements (diameter = 1 mm) is cooled from 450 °C to almost ambient temperature. In the simulation the energy is transferred to ambient air over the profile surface. To cool down to ambient temperature, the section needs approximately ten minutes (Fig. 4). After cooling, a pressure stress state dominates the reinforcements and tensile stresses affect the aluminium matrix. As mentioned before, this is caused by the different thermal expansions of the matrix material and the reinforcements, which results in a lower shrinking of the steel wires with regard to the surrounding aluminium. The materials, which have to be specified for the simulation, are EN AW-6060 for the aluminium matrix and S 355 J2 for the steel reinforcements. A set of material properties is already stored in the database of the commercial software HyperMesh (Altair) and SYSWELD (ESI Group) while HyperMesh is used for the meshing tasks and SYSWELD for the computation. Concerning the materials mentioned above the database is complemented by experimental data provided by the subproject A3. For modelling the profile as a statically determinate system, all six degrees of freedom (three rotatory and three translatory) of a single node in the corner of the profile, marked as the restraint in Fig. 5, are blocked. Thus, the system is over-constrained and kinematically stable.

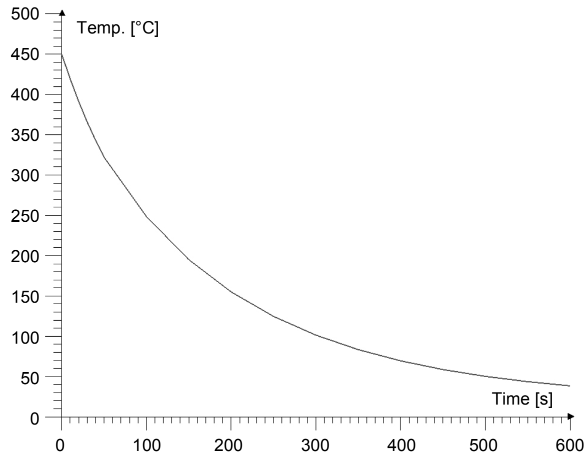

Fig. 4: Temperature development in the profile while cooling subsequent to the composite extrusion

The objective of the investigations within this project is to realise the chaining of simulations. Therefore, the simulation of the composite extrusion is concatenated with the simulation of a subsequent process step – the friction stir welding (FSW). The modelling of the FSW process is a subject matter of the project B4. In this example, the simulation includes a composite, which is friction stir welded transverse to the direction of the reinforcements. With regard to the discussed objective of reducing the modelling amount (see Fig. 1), a method to model the FSW process is to simplify the impact by defining a heat input. Thus, the deformations and the development of residual stresses can be calculated based on the heat source parameters. The specific heat input of the process is calibrated within the project B4, thus, the required parameters for modelling the heat source are supplied.

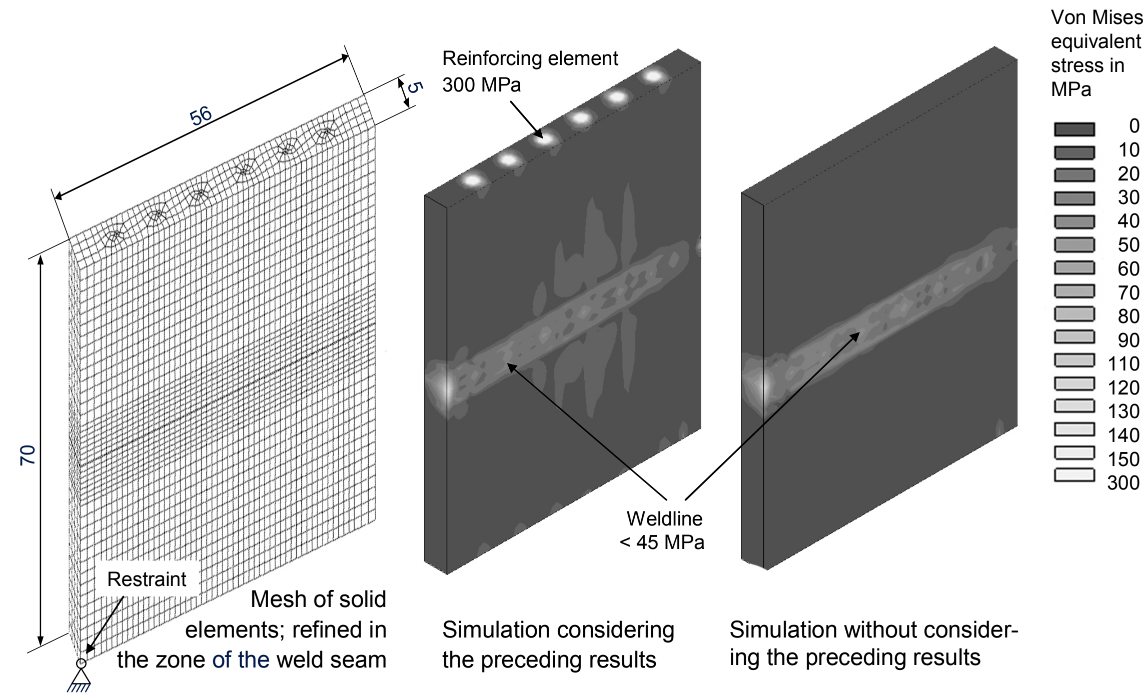

Fig. 5: Stresses in comparison with and without considering the preceding simulation results

Fig. 5 illustrates the stress situation in the composite profile as one output value. On the left side of Fig. 5, the preliminary extrusion process was considered as the initial state of the FSW simulation. The right side displays the residual stress state after the simulation of FSW without considering the structural effects of the preceding process. As mentioned above, the unequal coefficients of thermal expansion of the matrix and the reinforcements cause the resulting stress situation. The high stress level in the reinforcing elements demonstrates that the consideration of the preceding process is necessary to describe the stress state in composite structures. Thus, the chaining of the simulations (Fig. 5, left side) results in a maximum stress level that exceeds the highest stresses in the simulation without considering the preliminary process by up to five times.

In addition to residual stresses another significant output value for welding simulations is the distortion. Information about shape distortions are fundamental to cope with deviations caused during manufacturing. Subsequent to the FSW simulation and after unclamping the profile, the residual displacements are compared in Fig. 6. The comparison shows that considering the preceding process step results in a 14% lower distortion. Thus, it appears that a chaining of single process simulations is necessary to predict the structural effects more accurately along the manufacturing process chain of composite structures.

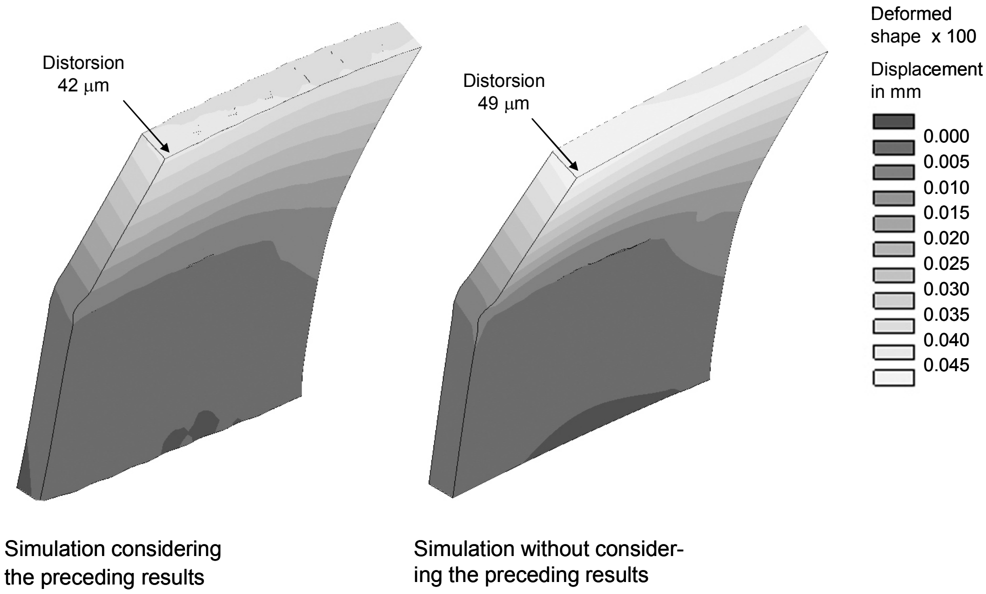

Fig. 6: Comparison of the distortion with and without considering the preceding simulation results (overstated shape: x 100)

Outlook

This contribution presents an approach of chaining two specific sub process simulations, which has been successfully realised for a basic geometry within one simulation environment. In the future, it is planned to expand the simulated process chain including the FE-programmes ANSYS (ANSYS, Inc.), HyperForm (Altair), HyperMesh (Altair) and SYSWELD (ESI Group), which are used by the projects of the B-domain. In particular, the manufacturing processes, contemplated in the context of the specific projects as part of the Transregio 10, will be integrated in an entire model. The objective is to create interfaces enabling the transfer of data between the different FE-programmes in order to calculate welding distortions considering all preliminary manufacturing processes, e.g. forming, circular milling and drilling.

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