Numerical Modeling of Heat Effects during Thermal Manufacturing of Aero Engine Components

Loucas Papadakis, Gregor Branner, Alexander Schober, Karl-Hermann Richter and Thomas Uihlein

***Abstract*— In production of aero engine components innovative advance manufacturing techniques, i.e. selective laser melting (SLM) and electron beam welding (EBW), are currently being developed. Structural properties and geometrical accuracy of aero engine structures can be determined in advance of manufacturing steps by means of simulation methods in order to ensure their final quality. For supporting this effort, reduced models were chosen for performing tests and simulation analyses on the development of the form accuracy and residual stresses in the structure. In this contribution an approach is introduced which includes the numerical abstraction of the real problem, so that feasibility and clarity of the developed models are attained. The rendered results will provide for an improved process design for the future manufacture of low shape distortion aero engine components.**

***Index Terms*— electron beam welding, finite element analysis (FEA), laser additive manufacturing, process-structure interaction,**

I. BACKGROUND AND MOTIVATION

IN recent years models of various manufacturing processes have become increasingly important in modern industries, which are based to a large extent on computer aided techniques. Such models supported by numerical methods, accompany not only the development phase of the product life cycle but also the manufacturing itself [1], [2]. During manufacturing it is essential to achieve product accuracy and to follow and specify structural properties by means of computational methods [3]–[5]. Furthermore, manufacturing processes and production systems can be pre-designed and optimized prior to prototype production for the needs of the production lines with the support of simulations. This can improve the quality of the final product, shorten process duration and minimize costs by avoiding trial-and-error during the process and plant design, attain useful information about the behaviour of material during manufacturing, and supply valuable findings on the interaction of process and structure.

Numerical methods may contribute to the improvement of the quality of structures in relation to their geometrical and structural properties. Especially in the aircraft industries, where product quality, process approval and safety are significant issues, computer aided techniques are expedient. Advance simulation methods may help to improve structural properties and provide for the shape accuracy during the stage of manufacturing [6]. Besides the constructive characteristics and material definition during the product development phase, manufacturing processes influence the material strength and the stability of the structure, particularly due to heat treatment. Such effects can, on the one hand, improve structural properties (due to the increase of the yield stress in case of friction stir welding and laser forming) and, on the other hand worsen them (due to the undesirable development of cracks) [7]–[9].

Available research works provide a wide spectrum of modeling methods and their applications for different manufacturing methods. The various influencing phenomena are considered in different modeling steps within the simulation. The significance of the modeling and process parameters are discussed for the processes of laser additive layer manufacturing and electron beam welding on practical reduced demonstrating examples.

Different aspects of the process-structure interaction within the simulation methodologies are introduced in this contribution, i.e. heat source definition, process sequences, clamping conditions etc. Based on these findings, the main goal of this paper is to suggest and validate simulations methods for supporting manufacturing processes for future applications in aircraft industries.

II. THERMAL MANUFACTURING PROCESSES FOR AERO ENGINE COMPONENTS

Metal based Selective Laser Melting (SLM) and Electron Beam Welding (EBW) are gaining an increasing market share in the field of production technology [10], [11]. Two main technological advantages are responsible for the increasing success of these innovative technologies. First, the growth can be referred to the process flexibility and the possibility to produce parts with high geometric complexity.

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Second, the capability to manufacture components of high shape accuracy and structural quality is a further decisive advantage. Today, the so called layerwise fabrication of parts is feasible with a lot of different materials, e.g. aluminium alloys, hot forming steel, tungsten carbide or titanium [12]–[15]. Hence, numerous industries with miscellaneous requirements are interested in SLM. Especially parts with a high complexity and internal structures, e.g. cooling channels, are economically realisable by SLM. Representative applications for the aircraft industry [16], which are manufactured with an Inconel® alloy, are illustrated in Fig. 1.

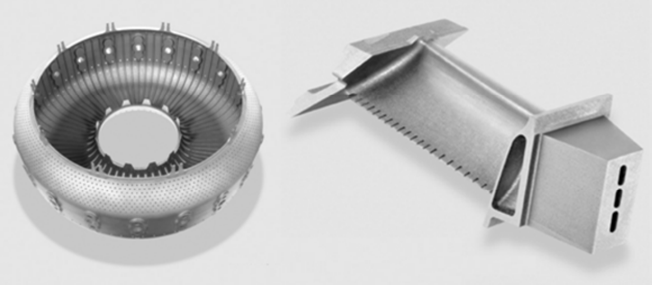

Fig. 1. Aero engine structural components (combustion chamber, turbine blade) produced by SLM [16]

Even if extensive technical progresses have been made in recent years compared to conventional manufacturing technologies, SLM and EBW still comprehend several process deficiencies [17]. Especially the temperature gradient mechanism (TGM) as a result of the locally concentrated energy input leads to residual stresses, crack formation and part deformations, as shown in Fig. 2 [18], [19]. Primarily these residual stresses contribute to a crack formation or a disconnection of parts from the building platform in case of SLM [20]. Furthermore the shape accuracy as well as the mechanical strength of parts is influenced thereby [21]. To cope with these challenges, numerical solutions by means of the FEA comprise adequate algorithms [22], [23].

Fig. 2. Laser based consolidation of metal powder, residual stresses and crack formation in SLM

The presented work contains different approaches to investigate residual stresses and shape deformation within the SLM and EBW process. First, a numerical method, considering a coupled thermal and mechanical simulation based on a three-dimensional model including temperature dependant material properties for powder and solid is described [24]. Within this simulation, specific requirements (e.g. the activation of fused powder layers, weld gab definition) and boundary conditions (e.g. convection and radiation) of the thermal manufacturing technologies are considered [19]. In order to evaluate the achievable process stability and the structural part properties, the investigations in case of SLM are containing additionally variable building platform temperatures T_{BP} and support lattice parameters (e.g. the support lattice distance d_{SG},). Representative studies indicate, that these parameters imply the largest influence on the resulting residual stresses adjacent to the scanning strategy [19]. In the other hand during EBW the clamping conditions play a decisive role along with the exact modelling of the weld pool geometry.

III. SIMULATION APPROACHES FOR THERMAL MANUFACTURING PROCESSES

So far, in the field of thermal manufacturing processes various heterogeneous simulation approaches exist for solving single physical phenomena. The approaches are structured on the basis of the sub areas process, structure and material. Due to analogies among the simulation of beam based welding technologies, relevant basic methods [25] are being adopted and specifically extended to the application in the thermal manufacturing processes including SLM. Fig. 3 shows an appropriate subdivision of the numerical simulation of layer based processes. Moreover, coupling respectively interfaces between the specific objectives of simulation are possible.

A. Process Simulation

According to the process simulation of welding technologies, the underlying numerical algorithms can be adapted in order to investigate the absorptivity or the mechanisms of powder solidification also in SLM. Within these considerations, the density change during solidification of the powder is as important as the melt pool stability. In comparison to welding technologies, SLM technologies inherit additional complexity. Since the process stability and the solidification of the powder material depend on the layer thickness and the process parameters, accordant influences are necessary for the simulation. In addition, the process and material specific mechanisms of solidification are relevant. An exemplary application field for the process simulation in SLM is the analysis of the so called balling-effect [26].

B. Material Simulation

The obtained results of the process simulation can be used in order to investigate the microstructure, which is influenced through several heat effects, by means of the material simulation. Beyond the hardness of structures, especially the metallurgical phase transformations and considerations concerning crack susceptibility are relevant. Thus, node temperatures and the melt pool composition are exchanged between the process and the material simulation. Contrary, the specific enthalpies and the thermo-physical material properties are useful for the process simulation. During multi-layer welding technologies as well as additive manufacturing technologies the structure is underlying alternating heating and cooling cycles. Hence, the material simulation is challenged by adequate algorithms for the prediction of the microstructure kinetics.

C. Material Simulation

Analogue to the process and material simulation, the structure simulation of thermal manufacturing processes constitutes a combination of available techniques. First, the layer dynamics and the attendant density changes during the solidification are relevant in modeling. Second, metallurgical phase transformations affect the structure deformations as well as the residual stresses. Furthermore, there is a need for applicable measurement techniques, since the occurring temperature gradients are at about 100 K/s [6], [19]. Thus, the structure simulation is challenged by the development of adequate methods for the calculation of residual stresses and deformations due to the plasticization in the heat affected zone. Beyond the transient temperature field, particularly predictions concerning the layer delamination or the strength of supports are essential. In addition, the influence of the transformation plasticity on deformations and residual stresses has to be considered. As a representative example for the use of simulation approaches in SLM, the structure based method is described in detail.

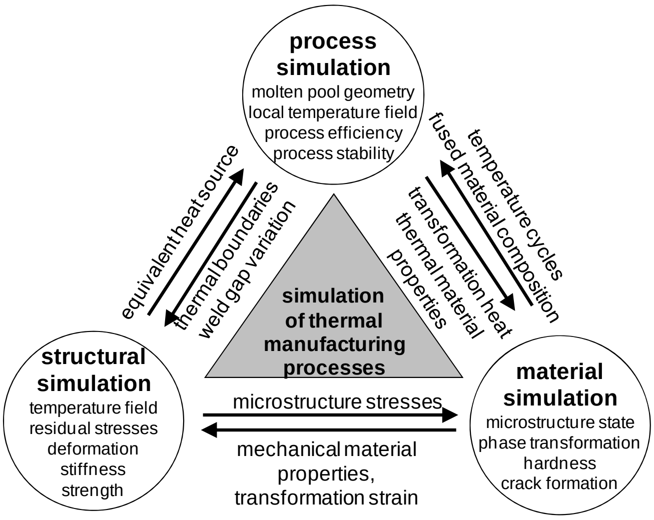

Fig. 3. Classification of simulation approaches in thermal manufacturing processes according to Radaj [25]

IV. MODELING OF TRANSIENT PHYSICAL EFFECTS IN STRUCTURAL SIMULATION

A. SLM Process

To account for the numerous physical effects within SLM, different strategies for an industrially useful structure simulation are mandatory. Due to the available computing power, it is not always feasible to model every single scanning vector within the energy application. Hence, the following chapters describe a specific model designed for the investigation of whole parts [20]. Contrary to a more specified layer based model [22], which considers the exact scanning strategy, it is the aim of the applied model to substitute the scanning vectors of every layer by so called scanning areas. Thus it is in principal possible to calculate the residual stresses and deformations of entire parts.

To evaluate the process stability in dependence of several parameters with a thermo-mechanical simulation, the manufacturing process of a twin-cantilever is considered. The tool steel cantilever (alloy 1.2709, X3NiCoMoTi18-9-5) has overall dimensions of 70 x 15 x 12 mm³ and is positioned on the building platform (see Fig. 4). Beneath the so called cantilever wings, support structures with the dimensions of 30 x 15 x 8 mm³ are located. In order to quantify the residual stresses of the cantilever, eight measuring points for the simulation and the experimental validation with the neutron diffractometry along a horizontal path are defined.

For the geometry generation in the FEA, a specific interface between the SLM manufacturing system and the numerical simulation in ANSYS Multiphysics is used. Thereby, the scanning pattern serves as a base for the selection of corresponding nodes and elements. Accordingly, the underlying method allows the representation of the exact part orientation and the single layers due to the direct access to the manufacturing system's control unit. Hence, supports are recognized as well through the algorithm.

Within the simulation, the considered twin-cantilever is sectioned in finite elements with dimensions of 1.0 x 1.0 x 0.5 mm³ (cp. Fig. 4). The boundary conditions are distinguished for the thermal and the mechanical calculation. In the thermal simulation, especially the convection coefficients to the environment largely affect the cooling cycles of single fused layers and thus the residual stresses. In order to achieve a high accuracy according to the real process conditions, specific convection coefficients for the surrounding powder $\alpha_{C,TC}$ (twin-cantilever) and $\alpha_{C,S}$ (support), the solidified surface $\alpha_{C,TC,O}$ and the building platform $\alpha_{C,BP}$ are defined. The mechanical simulation is

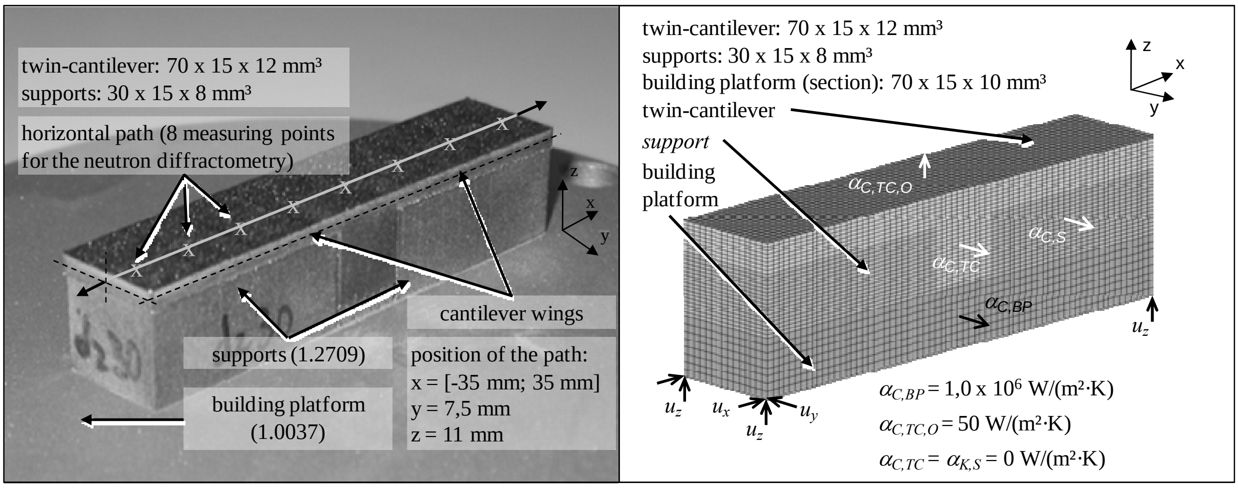

Fig. 4. Twin-cantilever for the process stability analysis and FE-geometry with thermal and mechanical boundary conditions

based on realistic clamping conditions, which comprehend a fixation of the building platform in defined orientations u_x, u_y and u_z. According to the boundary conditions, numerous different material properties for the varying process conditions, distinguished between building platform, support and twin-cantilever, are necessary. In order to simplify the simulation and to gain efficiency, the support is defined as a continuum with specific adjusted material properties. Therefore, the density, the thermal conductivity, the elastic (Young's) and shear modulus as well as the thermal expansion coefficient have to be modified according to a special developed and qualified method [20].

B. *EBW Process*

Analogue to the afore mentioned modelling method for SLM the modelling of EBW of a simplified geometry was performed by means of the FE-Software SYSWELD. The experimental setup and FE-model are shown in Fig. 5. Particular attention was given to the definition of the temperature depending material properties of Inconel 718, the clamping conditions, the welding sequences and their direction, the weld pool formation during EBW and the weld gap existing in experiment prior to joining.

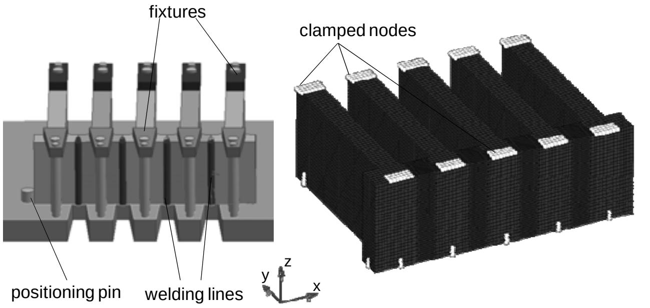

Fig. 5. Experimental setup o for the shape distortion analysis and FE-geometry with mechanical boundary conditions

V. SIMULATION RESULTS AND EXPERIMENTAL VALIDATION

In addition to the scanning strategy, which was identified as a major influence on the structure in earlier investigations [8], especially the building platform temperature T_{BP} and the support lattice parameter d_{SG} affect the development of residual stresses and deformations in SLM. Hence, these representative effects are varied within the simulation model based on the numerical formulation of occurring transient physical effects, e.g. the TGM. After solving the simulation problem of the layerwise manufacturing, another simulation step allows to visualize the cantilever geometry after cutting the no longer required support, e g. by means of wire-electro discharge machining (EDM). Therefore, the corresponding elements near the building platform have to be deactivated in the FE-Model and a subsequent solving process is done. This approach enables a relaxation of the residual stresses and a further development of deformations as it is also observed in reality. In the following chapter, the results of the numerical simulation concerning longitudinal residual stresses are compared to experimental investigations using the neutron diffractometry.

Effect of the building platform temperature TBP

Concerning the building platform temperature, Fig. 6 illustrates a comparison of the longitudinal residual stresses for $T_{BP} = 20$ °C and $T_{BP} = 200$ °C in sectional representation. Coincidentally, the simulated deformations are displayed with a tenfold scaling. In the figure, the area left to the centre line characterizes stresses for a building job at 20 °C, whereas results for $T_{BP} = 200$ °C are shown on the right side. Compared to an SLM process at ambient temperature, an explicit preheating leads to larger extended longitudinal compressive stress divisions at the lower side of the cantilever wings ($\sigma_{x,max} = -536$ N/mm²), which are connected to the supports. Beyond, the preheated structure

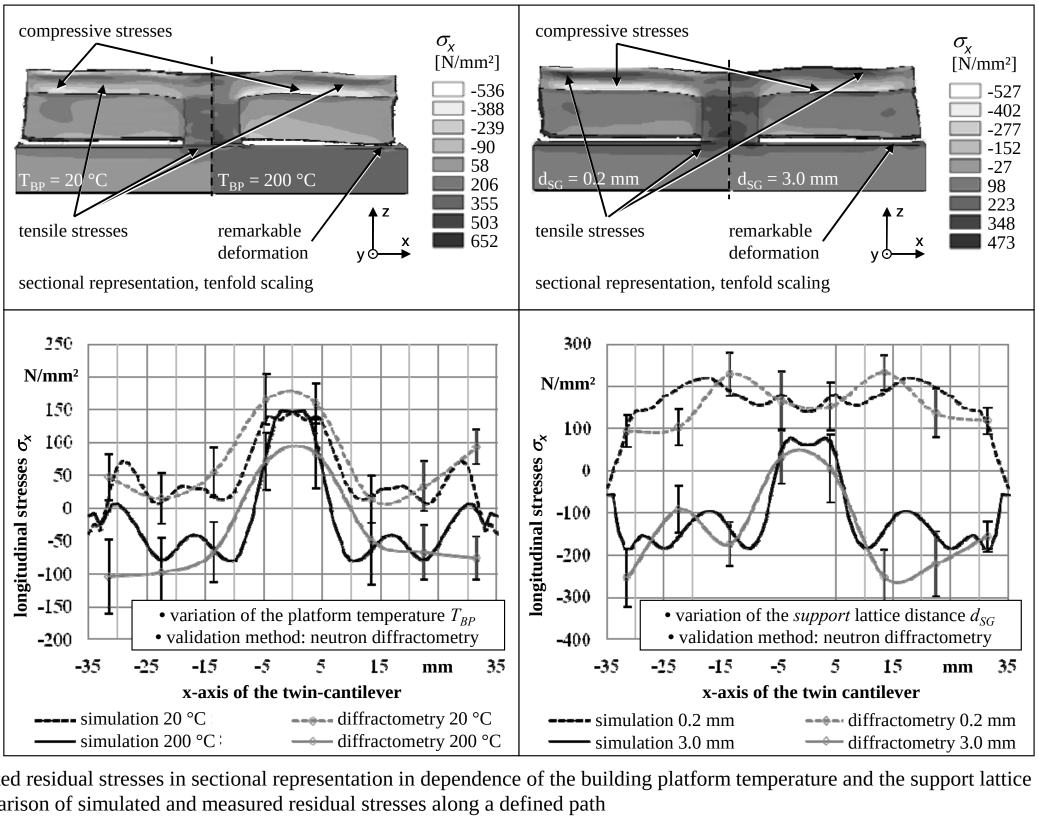

Fig. 6. Simulated residual stresses in sectional representation in dependence of the building platform temperature and the support lattice distance; comparison of simulated and measured residual stresses along a defined path

shows larger deformations of the cantilever wings in the negative z-coordinate direction. This effect especially becomes apparent through a decreasing gap between substrate and supports.

Effect of the support lattice distance d_{SG}

Concerning a variation of the support lattice distance d_{SG}, comparable results like for different platform temperatures can be derived. In Fig. 6, the centre line detaches two cantilever models with $d_{SG} = 0.2$ mm and $d_{SG} = 3.0$ mm. According to the illustration, a close-meshed support ($d_{SG} = 0.2$ mm) leads to higher temperature gradients between the process zone and the substrate and thus to larger compressive stresses at the upper and lower side of the cantilever wings ($\sigma_{x,max} = -527$ N/mm²). Contrarily, the wide-meshed support ($d_{SG} = 3.0$ mm) causes decisively higher tensile stresses at the upper side ($\sigma_{x,max} = 473$ N/mm²). Furthermore, a wide-meshed support involves larger deformations of the cantilever wings in the negative z-coordinate direction. Because of powder inclusions and a reduced heat conductivity, wide-meshed supports show a comparable influence on the structural part behaviour like an increased building platform temperature (e.g. $T_{BP} = 200$ °C).

Fig. 6 indicates for both, the simulation and the neutron diffractometry, that the longitudinal stresses along the horizontal path are continuously tensile 100 N/mm²; 250 N/mm² in case of a close-meshed support ($d_{SG} = 0.2$ mm). Contrarily, the strains are disarranged into compressive stresses for a considerable increase of the support lattice distance to $d_{SG} = 3.0$ mm (-260 N/mm²; -50 N/mm²). Furthermore, a good accordance of the simulation and the neutron diffractometry is achieved in the centre of the cantilever. While the longitudinal compressive stresses for the wide-meshed support significantly relax in this area, the closed-meshed support causes a local minimum within the tensile stress range.

The definition of heat source model for replicating the weld pool formation and the 3-d heat distribution in structure is an essential part of the simulation procedure of thermal manufacturing processes. Fig. 7 shows the weld pool formation during thermal calculation of EBW compared with weld seam macrographs and the comparison of calculated with measured temperature cycles at specific positions on the surface of the structure.

Based on the theory regarding the development of welding distortions of the literature [21] is expected to observe a shrinkage of the structure after the electron beam welding process. This was observed in the above reduced model in the x-direction or tangential direction. Local plasticisation effects in the weld seam area, as shown in the cross section micrographs in Fig. 7, induce in combination with the overall structure stiffness (in respect to the neutral line) to a bending distortion in the y-direction (radial) and, consequently, to a shape change of the entire demonstrating structure in the tangential direction. The simulation results

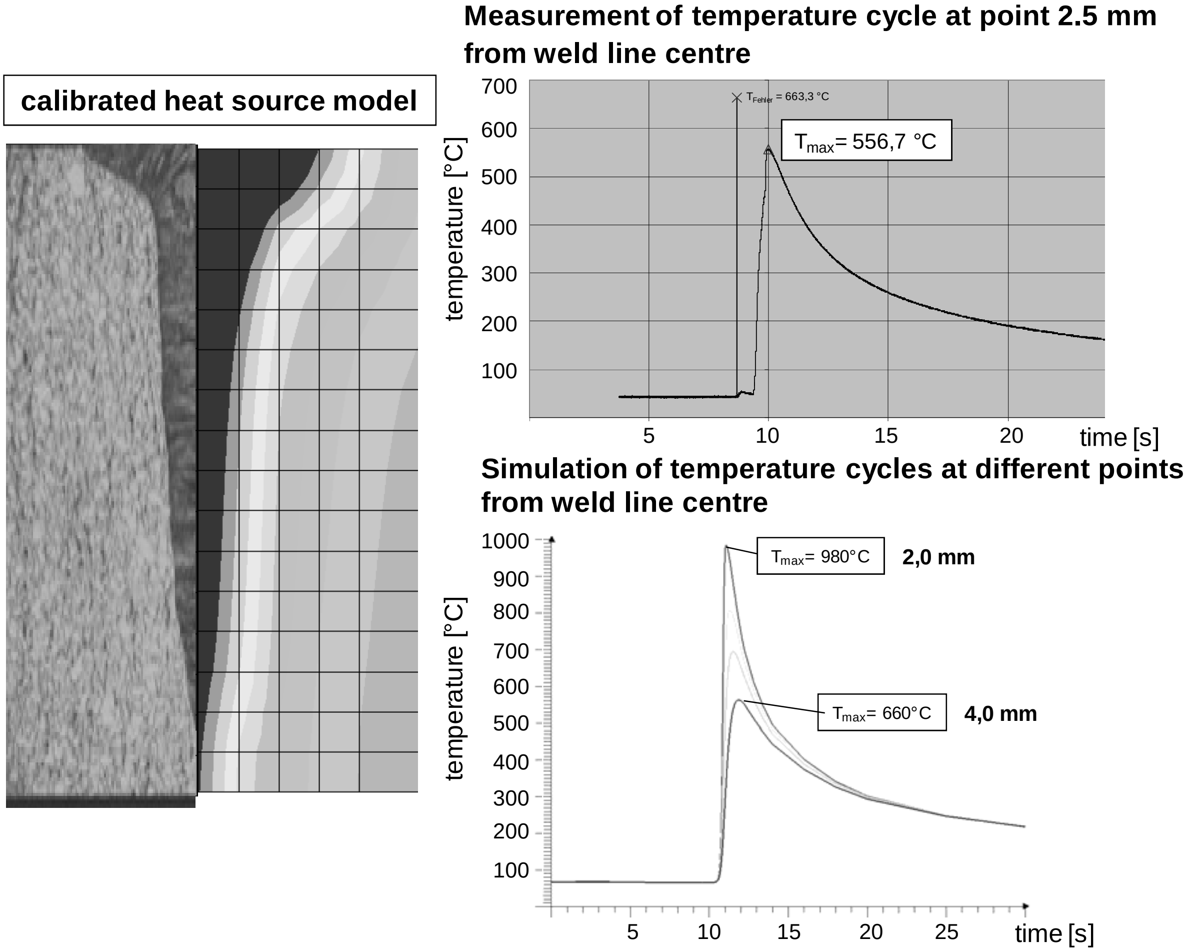

Fig. 7. Weld pool formation in thermal calculation of EBW compared to weld seam macrograph and comparison of calculated with measured temperature cycles

of the EBW model meet qualitatively the expectations and experiences from the theoretical principles, as seen in Fig. 8.

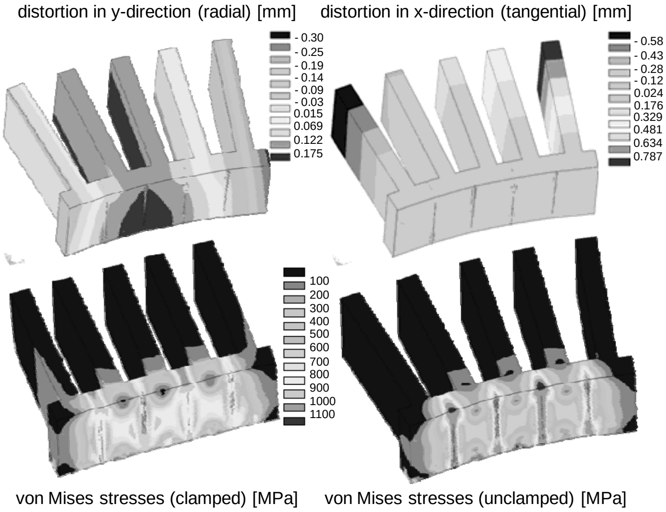
distortion in y-direction (radial) [mm]
distortion in x-direction (tangential) [mm]
von Mises stresses (clamped) [MPa]
von Mises stresses (unclamped) [MPa]

Fig. 8. Structural results of welding distortion and residual stresses after the thermo-mechanical calculation of EBW

VI. CONCLUSIONS AND OUTLOOK

On the one side, the presented investigations in SLM constitute, that both the building platform temperature T_{BP} and the support lattice distance d_{SG} affect the structural part behaviour significantly. On the other side, the investigations demonstrate the applicability of the developed numerical models by means of the FEA for the prediction of residual stresses and deformations in dependence of various process parameters. Thus, higher process stability in SLM will be achieved based on preliminary simulations. In general, the numerically calculated results for the cantilever geometry show an adequate correlation with the experimental series. Nevertheless, it has to be mentioned, that the simulation was carried out with several simplifications, e.g. the powder layer thickness was set to 0.5 mm compared to 50 µm within the real process in order to achieve a more efficient simulation

Regarding the modelling and simulation of EBW a parameter study is necessary in order to identify the weight of the influence of each simulation parameter. Furthermore, a validation of the welding distortion results is conducted and will be presented in future work. In the future, the investigations of thermal manufacturing processes will be focussed on the variation of further process parameters (e.g. the orientation of parts in SLM) and further modelling strategies and the improvement of the model accuracy. In addition, it is intended to develop specific modelling strategies for the analysis of detailed scanning patterns based on the system control of the manufacturing unit. Furthermore, industrially relevant parts, e.g. aircraft components, will be analysed based on the thermo-mechanical simulation of SLM and EBW.

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