NUMERICAL ANALYSIS OF SUPPORT STRUCTURES' REMOVAL FROM ADDITIVELY MANUFACTURUED COMPONENTS

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Abstract. The finite element analysis (FEA) of components' build-up has recently proved to be a valuable tool for accompanying the product and process development during additive manufacturing (AM). In this numerical method a first key aspect is the heat input modelling of laser scanning for building-up AM products of industrial relevance, as close to reality as possible, by applying equivalent heat source models. Based on these reduction models the stress distribution in a successive thermo-mechanical simulation is calculated approximating the sum of thermal, elastic and plastic stresses during processing and the remaining elastic and plastic stresses after cooling. A further key aspect is, thereupon, to predict the final shape of the additively manufactured component by means of the FEA after its removal from the substrate or the support structures. This work aims to analyze the development of stresses in components during their additive laser processing and cooling to ambient temperature as well as after post-processing cutting operations. Moreover, the associated to stress development simulated final part shape is evaluated with the aid of 3d measurements on an additively manufactured twin cantilever of industrial relevance. Finally, based on the rendered simulation results a compensation of the undesired shape distortions is proposed based on reverse engineering approach.

1 INTRODUCTION

Modeling and simulation methods have recently proved high potential in accompanying additive manufacturing process and product development. In the frame of the AMable Project [1] these potentials have been identified and captured in form of potential services which can be adopted by innovative technology carriers and industrial manufacturers operating in additive manufacturing related business. The increasing knowledge and apparent benefits as well as the flexibility of modeling and simulation methods and tools allows their utilization not only in large-scale enterprises but also in small and middle-sized companies (SMEs). The major reasons motivating companies to apply modeling and simulation raise from the increasing demands and challenges during product development when using additive manufacturing techniques, e.g. application of new powders, manufacture of novel and complex shapes or functionalities, new machines etc. Additionally, the increasing required product quality and the need for reducing processing times are further reasons which encourage companies to use modeling and simulation solutions.

The main key aspects which are identified in which modeling and simulation can provide useful support for developing products with additive manufacturing processes are following:

- weld pool shape prediction by means of analytical high performance models, i.e. quasi real time, in order to assist process control [3-5],
- thermo-mechanical models with reduced equivalent heat sources for shape distortion and residual stress computation [6],
- facilitation of pre-deformed geometry shapes to limit shape inaccuracies by applying reverse engineering strategies [7],
- path planning optimization to reduce processing times and unnecessary heat input [3,8],
- modeling of post-processing operations, i.e. cutting and support structures' removal with comparison of the simulated component shape with the 3d geometry of real additively manufactured components [9,10],
- thermodynamical and kinetical models for alloy, microstructure and powder tailoring and design, such as phase field changes [11,12],
- determination of mechanical material properties based on crystal plasticity and micromechanical evaluation of resistance to fatigue, i.e. fatigue performance indicators [13], and
- further specific modeling and simulation aspects under the umbrella of integrated computational materials engineering (ICME).

However, occasional lack of specific knowledge for certain complex modeling aspects or the need for specific software or high performance computing (HPC) recourses increase the necessity for regular update, training and know-how exchange among the modeling and simulation experts [1]. Besides providing an overlook of the potential use of modeling and simulation in the additive manufacturing business, this paper focuses specifically on the finite element analysis (FEA) of post-processing operations, i.e. support structures' removal, after components' manufacture by means of selective laser melting (SLM).

2 THERMAL MODEL WITH REDUCED EQUIVALENT HEAT SOURCE

In literature several numerical approaches exist which account for the heat effects occurring during additive manufacturing processes, especially SLM [3-9]. In author's previous work a systematic modeling approach was introduced for the realization of a simulation solution with reasonable time durations for practical industrial applications based on a reduction heat input during the build-up process with metallic powders [6]. Hereby, a transient temperature profile is applied on whole model layers or multi layers, representing the total heat load per volume, based on powders melting point and the SLM process parameters (processing time, scan speed, hatch distance, laser powder etc.) for industrial relevant examples [2]. In this paper a twin-cantilever geometry is used to demonstrate the heat effects and thermo-mechanical modeling as well as the structural results, i.e. stress and deformation development, after the component creation and its cut-off from the support structures. Figure 1 illustrates the main dimensions of the twin-cantilever geometry with the support structures and the heat loses to substrate and sounding powder due to conduction as well as the convection and radiation on the upper, currently processed layer.

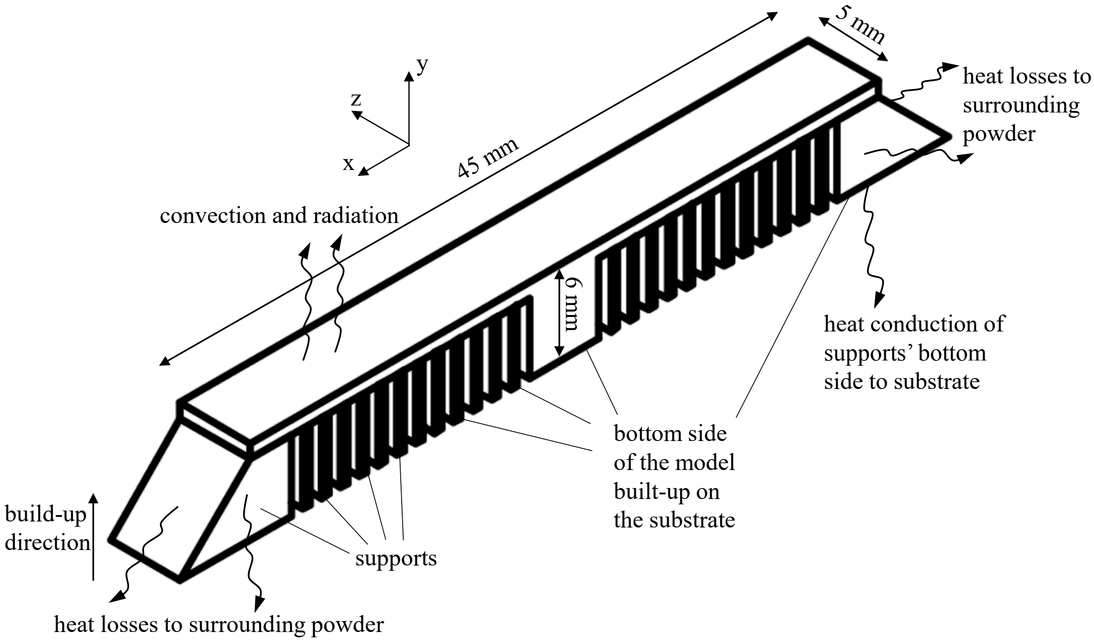


Figure 1: Twin-cantilever geometry with support structures with defined heat loses as considered in the transient thermal finite element model approximating the build-up process during SLM

The equivalent heat load within the transient thermal simulation of the twin-cantilever was adjusted accordingly in each volume layer of elements in the form of temperature-time function as illustrated in Figure 2. In the FE mesh of the twin-cantilever each element layer has a thickness of 90 μm corresponding to the threefold of the powder layer thickness of the real SLM process. This trade-off was made in order to reduce time-consuming simulation duration and enormous amount of data storage. Between each process layer the real process sequences were considered, i.e. approximately 10 s for the powder layer deposition prior to the processing of the subsequent overlying layer. Table 1 summarizes the SLM process parameters used by Fraunhofer ILT on SLM®280 HL machine with IN718 powder for the manufacture of the twin-cantilever [2]. The laser scanning was performed longitudinally to the twin-cantilever with no hatch angle increment.

Table 1: SLM process parameters in IN718 powder for the manufacture of the twin-cantilever [2]

Process parameters	Value	Units
Laser power	300	W
Scan speed	1600	mm/s
Laser beam diameter	90	μm
Layer thickness	30	μm
Hatch distance	80	μm
Hatch angle increment	0	º degrees
Time interval for powder deposition	10	s

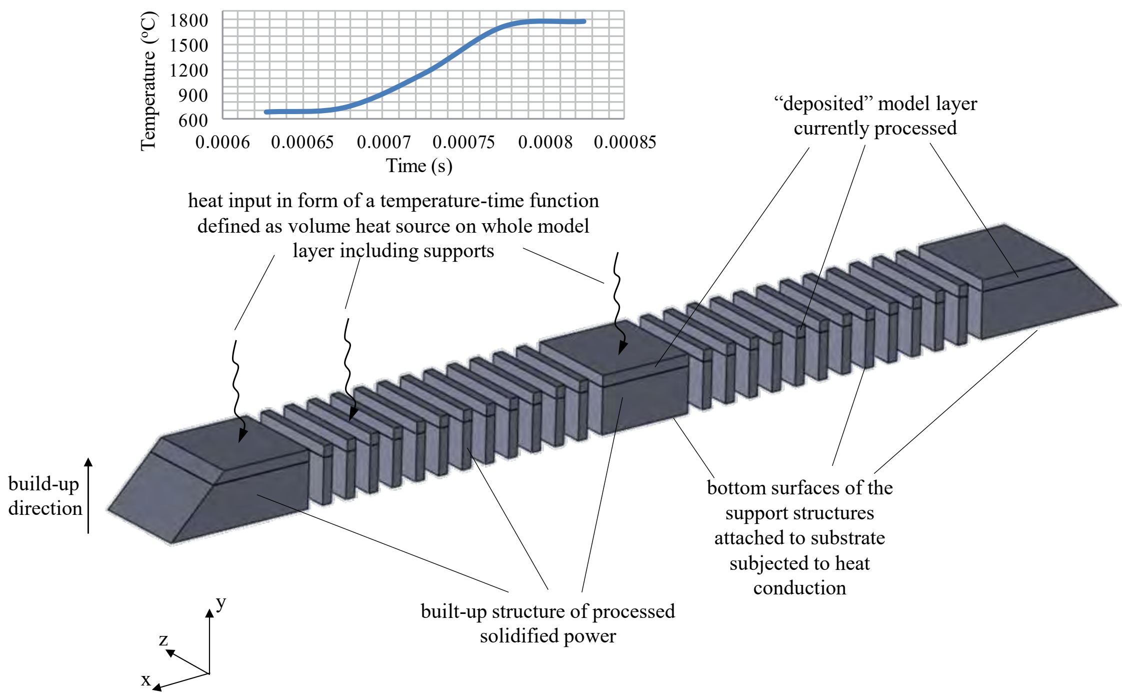


Figure 2: Twin-cantilever geometry with support structures with heat loses as defined in the transient thermal finite element model approximating the built-up process during SLM

During the "build-up process" of the twin-cantilever within the transient thermal and the successive thermo-mechanical numerical analysis, overlying, i.e. not yet deposited, elements in the FE mesh were assigned with negligible thermal and mechanical properties, i.e. were deactivated. They were assigned with the powder material properties, i.e. activated, once the layer they represented was to be processed. During processing, i.e. heating, and after reaching the melting point the powder material was assigned with the material properties of the solid IN718 with the aid of a phase transformation model implemented within the thermal analysis [11,12]. The thermal and mechanical material properties used for IN718 were temperature and phase dependant and were taken from the literature [2]. The thermal material properties for IN718 powder were induced according to the work of Biceroglu et al. [14]. The model layers were processed one after the other until the whole twin-cantilever was built. In order to ensure the "binding" of the processed model layer to underlying solid material, a partial re-melting of the underlying element layer was undertaken, similar to the real SLM process. After each layer build-up, i.e. the phase change from powder to liquid and finally to solid, and the cooling to ambient temperature, the model attained its final thermal and mechanical equilibrium.

The results of the temperature field during the model layerwise "build-up process" is shown in Figure 3 for exemplary model layers. The whole simulation time including the cooling time intervals for a new powder layer deposition and the final cooling of the complete twin-cantilever to ambient temperature equals to 850 s. The calculated transient temperature field of each model layer including the change of phase from powder to liquid and finally to solid was used as a load for a sequential thermo-mechanical numerical analysis.

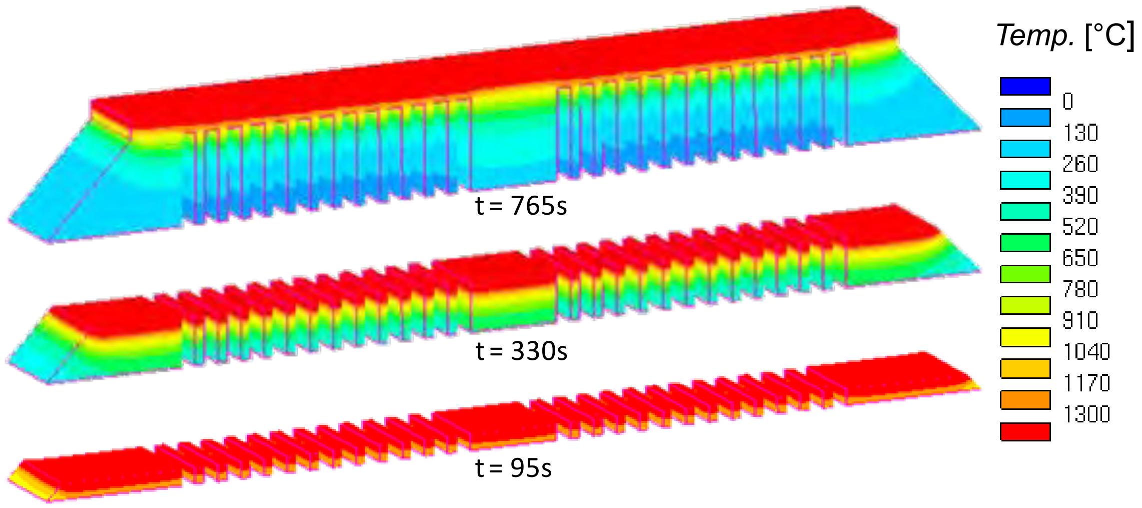


Figure 3: Temperature field results of exemplary successive element layers during the model “build-up process”

3 RESIDUAL STRESS AND DEFORMATION COMPUTATIONAL RESULTS

The thermal analysis presented in the previous section, based on a reduced heat source model replicating the real SLM process of the twin-cantilever, provided the transient temperature field of successive processed model layers as result. This transient temperature field was thereafter applied as a thermal load in an uncoupled thermo-mechanical analysis. For this numerical calculation, an isotropic elastic–plastic material definition with temperature dependant mechanical values for the Young’s modulus, yield stresses and strain hardening was employed. Additionally the change of phase from powder to melt and finally to solidified material was considered in the earlier transient thermal analysis by applying a phase change model in the finite element program SYSWELD carrying temperature and phase dependant mechanical properties of the nickel based steel alloy IN718 [2,12].

First the shape deformation and residual stresses of the twin-cantilever while still attached on the substrate and support structures (i.e. prior to cut-off operation) were computed. After cutting-off the twin-cantilever support structures in the experiment by means of electrical discharge machining (EDM) as illustrated in Figure 4, a spring-back, i.e. elastic recovery, is observed with a maximum measured deformation of approximately 0.8 mm on the edges.

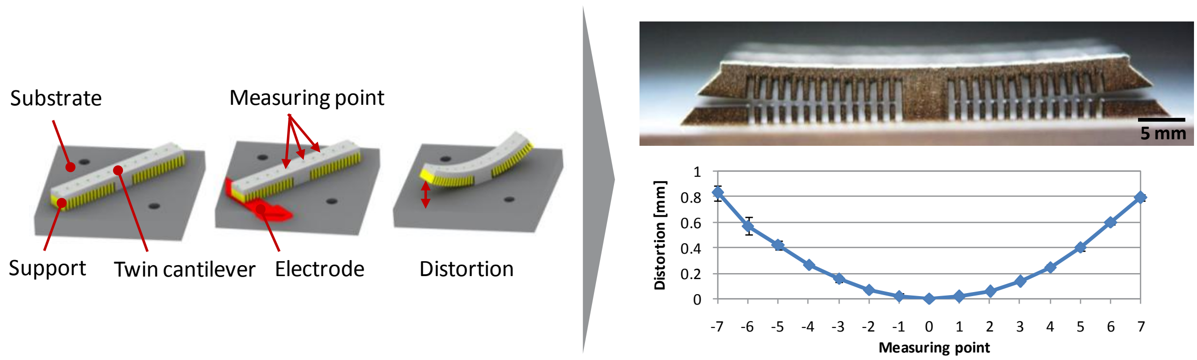
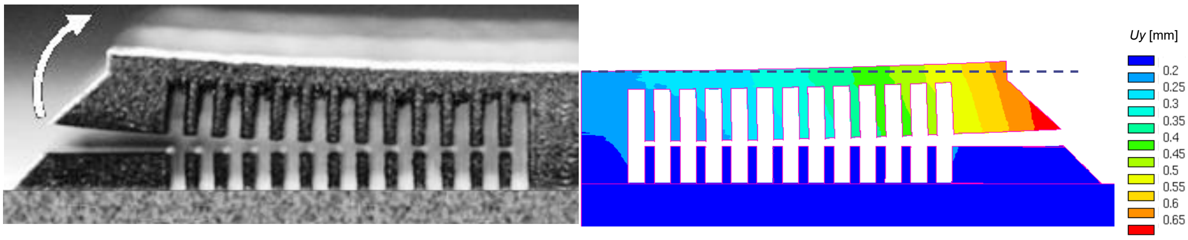


Figure 4: Support structures’ cut-off process and final deformation of the twin-cantilever geometry

Due to the nature of the SLM process in conjunction with the twin-cantilever geometry, the component was manufactured with support structures which were cut-off after manufacturing and cooling to ambient temperature. It was significant to include this process step in the simulation chain, in order to replicate the spring-back, i.e. geometrical changes and final stress state equilibrium of the component's structure after elastic recovery. In order to calculate the component's final shape after the material removal the final state of equilibrium, i.e. elastic recovery, was considered. After the thermo-mechanical simulation of the main build-up process and the cooling to ambient temperature, the elements in cutting area were removed in the FE model, whilst the stress state and final temperature at the end of the thermo-mechanical simulation were maintained with the component still attached to the support structures. At a subsequent step the simulation was restarted and the mentioned solid element removal in the support structures forced the component to its final shape providing an elastic recovery and, thus, a relaxation of the total stresses and a final state of equilibrium. The final distortion in the vertical build-up direction as calculated after the spring-back by the numerical model is demonstrated in Figure 5 providing a visual comparison with the experimental result of the real twin-cantilever geometry. The defined mechanical boundary conditions, i.e. constraints, did not allow any displacement on the bottom of the substrate, i.e. the substrate was mounted on the working bench.



experimental final shape | computational result of shape deformation

Figure 5: Experimental (left) and computational final shape (right) of the twin-cantilever in the build-up direction after the support structures' removal

The computed residual stresses variation before (left) and after cut-off (right) are presented in Figure 6. A significant relaxation, i.e. reduction, of the von-Mises residual stresses after the material removal is observed. The residual stresses' decrease is more perceivable in the upper area of the twin-cantilever and in the support structures.

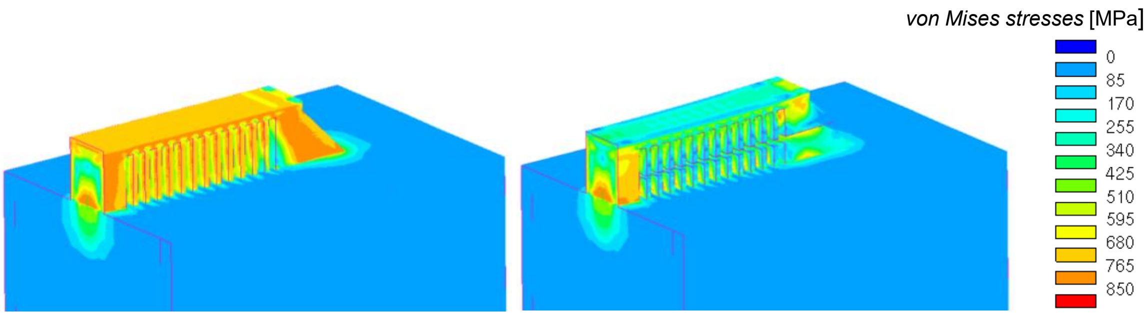


Figure 5: Residual stresses variation before (left) and after support structures' removal (right)

Not only are the computer capacity requirements and computational times of significance but also the reliability of the introduced method, which can essentially be applied in the design phase of SLM products for future industrial applications. The reliability of the applied numerical method was appraised with a model validation using deformation measurements on the manufactured twin-cantilever. The vertical displacements were measured on a path at the top of the twin-cantilever with a step of 2.5 mm, from the symmetry plane to the right side of the component as illustrated in Figure 7. As observed there is a 26% maximum discrepancy in the results on the far right edge of the component. This is acceptable, since it is related to the modeling reduction approach, and the fact that three powder layers are being “fabricated” simultaneously in the numerical model.

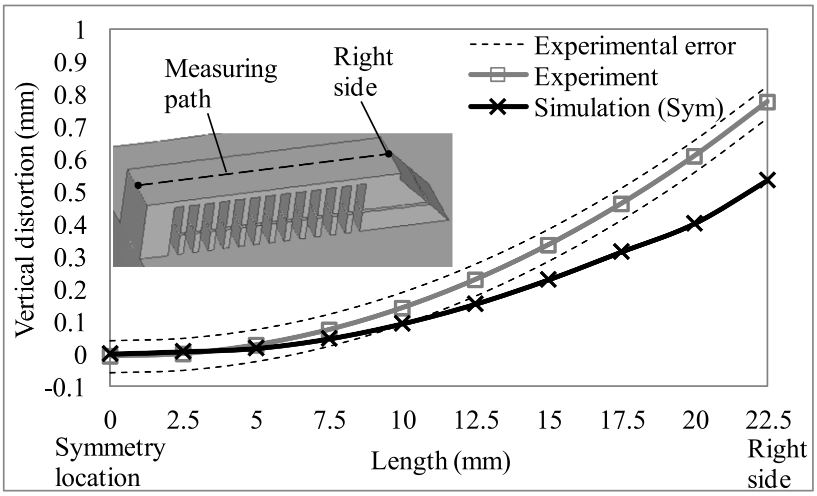


Figure 7: Comparison of experimental and numerical deformation results of the twin-cantilever after cut-off

In addition, a parameter study on the twin-cantilever component was perform in order to investigate the sensibility of the proposed modeling method. This was done by running simulations of thicker horizontal part thicknesses of the twin-cantilever geometry. The supplementary simulations included thicknesses of 1.5 mm, 2.0 mm and 3.0 mm. This has added a +0.5 mm, +1.0 mm and +2.0 mm respectively to the reference model of the 1.0 mm thickness. The computed deformation behavior for increasing component thickness was verified with the measurements on real SLM manufactured components with the corresponding thicknesses by Fraunhofer ILT [2]. The provided measurements indicate a shape distortion decrease for higher component thicknesses. Figure 8 presents the comparison of the distortion results between simulation and measurements on real components. It is observed that the model managed to provide reliable results with an accuracy improvement for increasing component thickness. This is associated with the used mesh discretization of 90 μm per layer of elements, which appears to be more sufficient for increasing component thicknesses. An attempt to lower the model thickness proved to be quite sensitive in terms of the computed deformations, i.e. unstable deformation trend was observed, due to insufficient FE mesh degree of descritization through the reduced twin-cantilever thickness resulting to even less number of element layers along the build-up direction.

The improved accuracy of simulation results for models with increasing component thickness compared to measurements along the twin-cantilever upper area is exhibited in Figure 8. Particularly for a sufficient increase of the component thickness to 2.0 mm and 3.0 mm an adequate correlation with only marginal deviations has been achieved with the use of the introduced modeling method. This proves the reliability of the developed modeling approach especially for components with sufficient thicknesses for the adopted FE discretization.

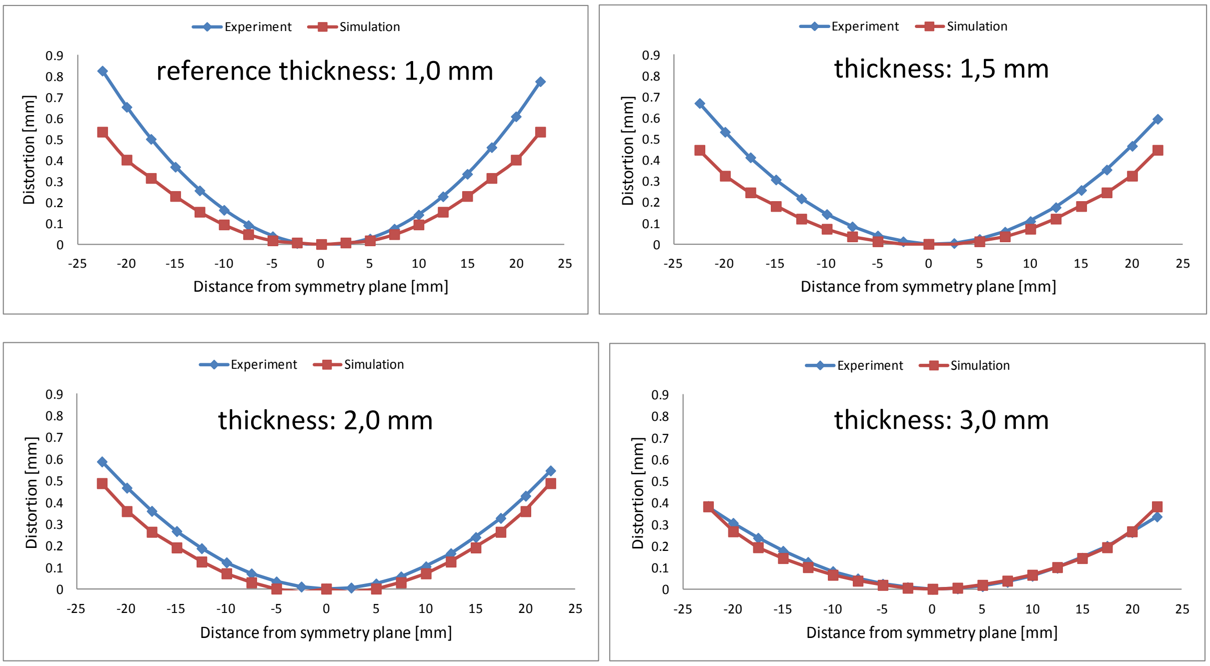


Figure 8: Improved simulation result accuracy compared to experimental measurements on real manufactured components with increasing twin-cantilever thickness

4. SHAPE DISTORTION COMPANSATION BY MEANS OF “PRE-BENT” MODEL

A further aim of this paper is to demonstrate a potential compensation of the twin-cantilever’s shape deformations after its SLM manufacture. To compensate shape distortions and counteract the resulting final deformations after the support structures removal’, a “pre-bent” twin-cantilever model with “negative geometry” was facilitated considering the already simulated deformation results, as presented in Figure. The “pre-bent” model was prepared based on the distortion results of the twin-cantilever geometry with the reference thickness of 1.0 mm. Hereby, the calculated distortions along the measuring path on the top area of the twin-cantilever (cp. Figure 5 and Figure 7) were applied in the opposite, i.e. negative, direction. Based on this deformed shape the “pre-bent” twin-cantilever geometry is remodeled with a curvature in the negative direction of the initial spring-back as demonstrated in Figure 9. The “pre-distorted” twin-cantilever is illustrated compared to the target geometry, i.e. the horizontal plane, which should be targeted after the cut-off operation.

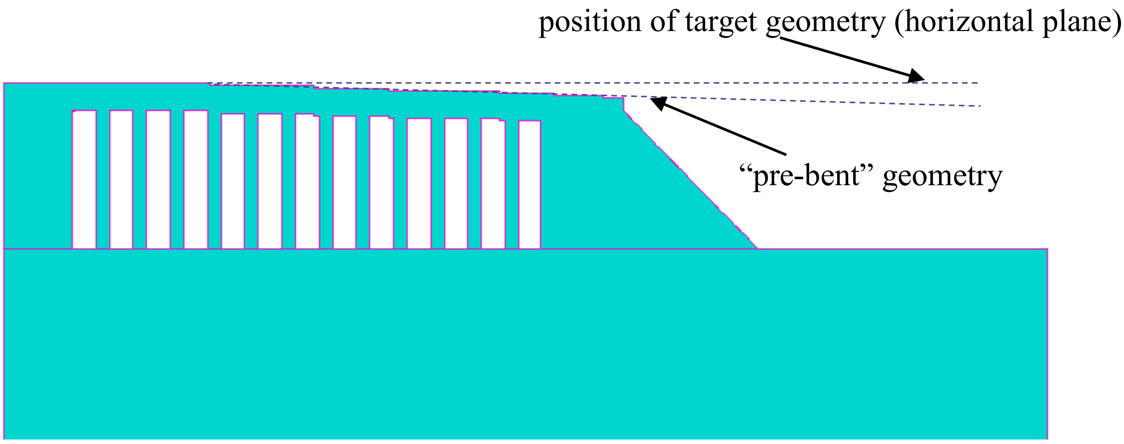


Figure 9: “Pre-bent” twin-cantilever geometry based on the original model deformation results compared to the horizontal target geometry

The overall distortion of the “pre-bent” model after the numerical analyses proved to be only slightly higher compared to the original model with approximately solely 0.1 mm of maximum discrepancy on the tip of the twin-cantilever. The final distortion of the “pre-bent” model appears to provide a sufficient improvement compared to the initial reference model approaching the horizontal plane in a very good manner as shown in Figure 10.

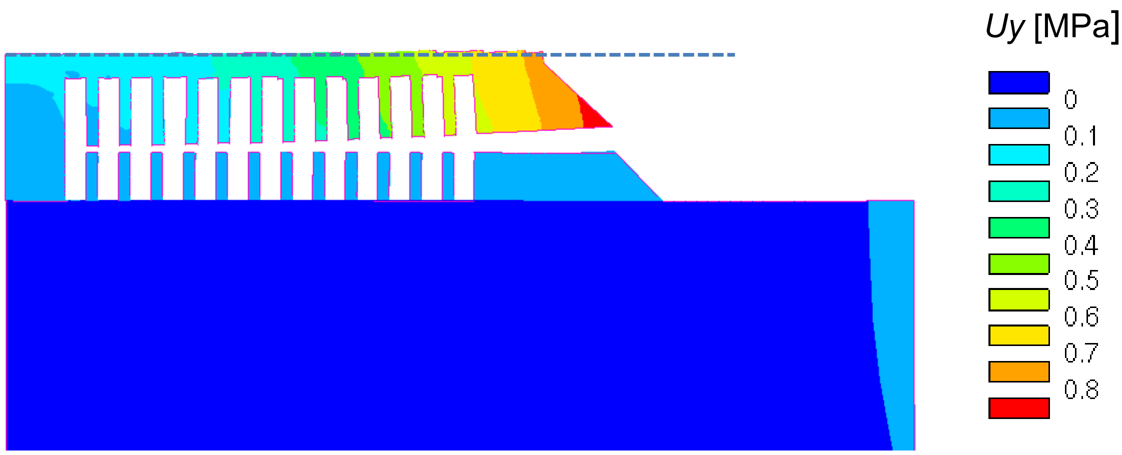


Figure 10: Final distortion of the “pre-bent” twin cantilever model compared to the target horizontal plane

To compare the original and “pre-bent” model’s final shape distortion, the distance of the horizontal part to the target geometry horizontal plane was taken into account. As observed in Figure 11, the pre-distorted model has provided improvements on the final component shape accuracy with a limitation of the discrepancies to only 0.1 mm on the right edge of the twin-cantilever.

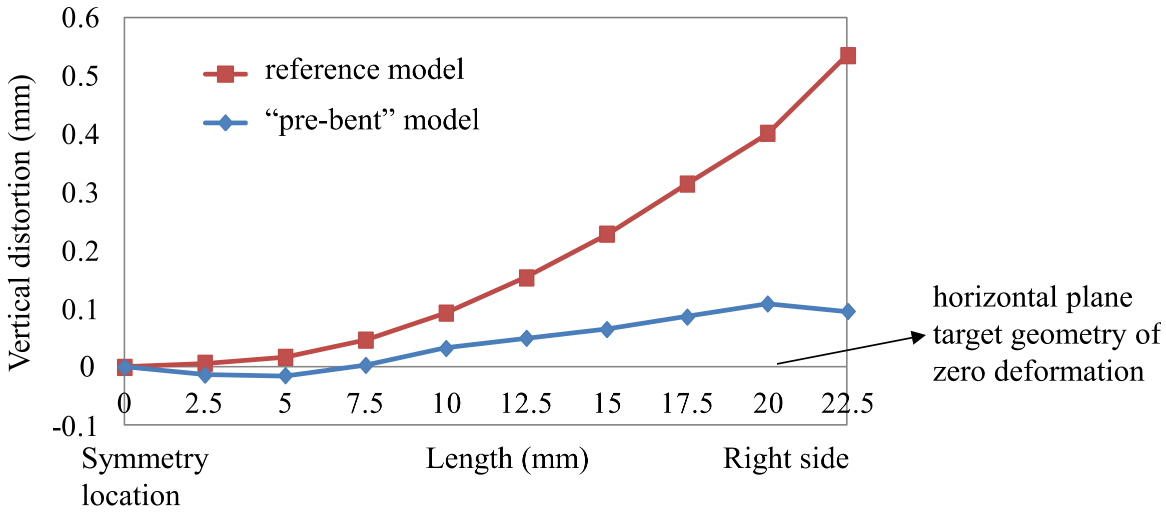


Figure 11: Improvement of the final shape accuracy for the “pre-bent” model compared to the reference model

Figure 12 shows the residual stress distribution of the pre-distorted twin-cantilever model after the build-up process (left) and after support structures’ removal (right) indicating a very similar trend to the reference model in Figure 5. This was expected as there are not any significant changes in the geometry and the build-up process apart from the trimming on the twin-cantilever’s upper area in order to approximate the negative shape distortion of the reference model after the cut-off operation.

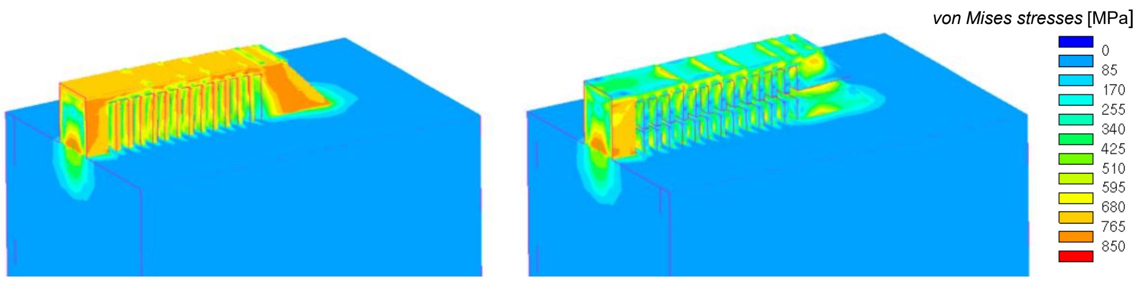


Figure 12: Residual stresses variation of the “pre-bent” model before (left) and after support structures’ removal (right) with a similar trend as the reference model.

5 CONCLUSIONS

In this paper the structural behavior of a twin-cantilever manufactured by means of SLM including the post-processing operation of support structures’ removal is presented. The thermo-mechanical effects during the build-up process as well as the “spring-back” of the created twin-cantilever after support structures’ removal were replicated by means of a numerical analysis. Based on a reduced equivalent heat source model the SLM process was approximated on a FE mesh discretized to a certain degree. Thereupon, the component’s residual stresses and deformations were computed once the component was manufactured and cooled to ambient temperature and subsequently after it was detached from the support structures. In order to draw conclusions on the reliability of the proposed computation chain, including the build-up process and the supports' removal operation, experimental measurements of the shape deformation on real twin-cantilever geometries were conducted and compared with the simulation results. The rendered results have led to following conclusions:

- After the build-up process of the twin-cantilever and its cooling to ambient temperature no significant shape deviation were observed, i.e. <0.1 mm, compared to the initial target CAD geometry, in both experiments and simulation.
- The reference experiment utilized for evaluating the numerical model demonstrated a maximum deviation between numerical and experimental results of 26% at the edge of the twin-cantilever after the cutting operation. This error was linked with the heat source reduction approach and the degree of mesh discretization which led to a less accurate computation of stress distribution in the component. However, these approximation were inevitable in order to demonstrate the structural results on a practical component with reasonable computational times and storage capacity.
- The conducted parameter study proved that the coarse mesh discretization in the build-up direction in the numerical models becomes less significant with increasing twin-cantilever thickness, since deviations to experimental deformation proved to diminish.
- The relaxation of residual stresses after the support structures' removal are closely associated with the induced deformations. This is the reason why the comparison of the twin-cantilever final shape between simulation and experiment allowed us to conclude on the quality of the computed residual stresses.
- The computed or measured shape distortions caused after support structures' removal can be used to manufacture components with negative geometries, i.e. pre-bent, so that they can compensate the induced deformations and approximate more accurately the target, i.e. ideal, final component shape after the cut-off operation.

To summarize, by applying appropriate approximation methods and simplifications along the introduced simulation chain, it was possible to compute the residual stresses and deformation behavior of components of industrial relevance after support structures' removal. The potential to reach a higher agreement with measurements increases when applying the appropriate model refinements. In this way simulation methods can assist in making the right design decisions during the development of products created by additive manufacturing processes.

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