IMPROVEMENT OF NUMERICAL SIMULATION MODEL SETUP AND CALCULATION TIME IN ADDITIVE MANUFACTURING-LASER-METAL-DEPOSITION COMPONTENTS WITH AN ADVANCED MODELLING STRATEGY

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ABSTRACT

Rapid localized heating and cooling during additive manufacturing using laser deposition method (LMD) lead to loss of dimensional accuracy as well as cracking of built parts. Finite-Element welding simulations allow prediction of geometrical deviations and accumulated residual stresses as well as their optimization before conducting experiments. Due to the great length of stacked welds, calculation times for fully transient thermomechanical simulations are currently long, the calculation stability suffers from the high number of contact bodies in the model and the modelling effort is high, as the geometries need to be sliced and positioned layer-wise.
In this contribution, an integrated modelling approach is demonstrated for a thin-walled LMD component made from 30 layers of 1.4404 (316L) stainless steel: Instead of the layer-by-layer modelling strategy commonly found in the literature, the whole component mesh is kept in one piece and the fully transient, layer-by-layer material deposition is implemented via element sets. In contrast to prior simulations, nonlinear contact between the layers does not have to be considered, significantly decreasing calculation times. The calculated distortions are compared to recently published, in-situ digital image correlation (DIC) measurements as well as numerical simulations conducted with the established layer-wise modelling strategy to judge result quality. Finally, the improvement in calculation time and ease-of-use is compared between both modelling approaches and conclusions regarding future usage for industrial-scale components are drawn.

Keywords: Additive Manufacturing, Laser metal deposition, Calculation time, Distortion simulation, Directed energy deposition, Efficient modelling

INTRODUCTION

Recently, additive manufacturing (AM) techniques have gained widespread attention in the industry. Laser Metal Deposition (LMD) is an AM technique that allows the build-up of 3-dimensional geometries by locally stacking wire- or powder-feedstock welds onto a substrate [1]. A broad range of materials can be processed, including titanium alloys and stainless steel [2] as well as nickel super alloys [3]. During the process, the pre-existing and already-deposited materials are repeatedly heated and cooled as multiple layers are stacked. The periodic reheating leads to complex effects such as inhomogeneous thermal strains, local re-melting, multiple phase transformations and annealing. When producing industrial-scale AM-LMD parts like excavator arms [4] or turbine housings [5], the build needs to be set up experimentally and iterated a number of times because of the interlocking nonlinear effects. For instance, welding parameters, path planning and pause times need to be optimized experimentally – with each build taking machine- and personnel-time – before a satisfactory result quality can be achieved.

Numerical simulations have the capacity to decrease the experimental effort for build-planning, parameter search and distortion reduction in AM-LMD by substituting experimental trials with virtual tests. To qualify numerical simulation tools for industrial practice, difficulties regarding long calculation times and the availability of reference measurements for validation of the model need to be overcome.

In a recent study by the authors [6] and studies from the literature for distortion prediction [5, 7, 8] and stress prediction [9, 10], fully transient FE analyses were compared to experimental results in LMD and good agreement between simulation and experiment was reported. With the predictive capabilities of numerical approaches regarding temperature flow, stress development and distortion-prediction being well-documented, further emphasis needs to be directed towards the reduction of the modelling effort and long calculation times. The high calculation times in AM originate from the comparatively long welding times and the need to resolve their transient evolution in order to predict the process. In addition, layer-wise, nonlinear contact needs to be calculated in each increment, leading to high computational cost especially for large models. Although the computational time is a key factor in the introduction of LMD simulation into industrial practice, they are rarely discussed in-detail in the literature:

Heigel et al. [11] and Denlinger et al. [7] use the CUBIC solver especially developed for additive manufacturing in their LMD simulation studies and find good agreement between the simulations and experiments. Utilizing a computational weld mechanics (CWM) approach they do not detail the calculation times or modelling efforts arising from stacking of single layer welds for their wall builds. Salonitis et al. [12] heated each layer simultaneously in their simulation of a LMD hollow cylinder. Presumably, this simplification is implemented to reduce the transient increments necessary for the simulation but the gains in process time were not evaluated in their publication. Marimuthu et al. [13] simulated the substrate distortion in an aero-engine component. They approximated the transient heat input by dividing the part into 954 subsections that were heated individually and instantaneously at the times corresponding to the process. The resulting transient temperature field was then used to conduct an uncoupled mechanical simulation. By neglecting the fully transient heat source movement, they were able to reduce calculation times by 80% to 7 h but the effect on result quality of the simplification

is not discussed. A similar approach was utilized by Papadakis et al. [5] for a cylindrical engine-case: The authors substituted the deposition path by introducing an equivalent heat quantity as thermal load on a whole layer and reduced the model by utilizing its symmetry. The geometry they investigated was too large to conduct fully transient simulations, so that the loss-of-accuracy of their simplification could not be addressed.

In powder bed additive manufacturing, where the length of weld paths is even longer than in LMD, a number of studies exist that focus on efficient modelling to reduce calculation time: Plotkowski et al. [14] described a semi-analytical approach to rapidly calculate the heat distribution in electron beam melting. Li et al. [15] used a multiscale model that predicted temperature flow on a micro-scale, mapped it to a layer hatch model in meso-scale for the body heat flux and finally calculated the macro-scale part distortions and residual stresses from the temperature flow. Afazov et al. [16] predicted the distortion of an industrial-scale selective laser melting (SLM) component by solving the heat input analytically and grouping it together for a set number of layers. The distortion due to the heat input for these layers is then calculated on the macro-scale part in a mechanical simulation. This approach is also used in commercial softwares like Simufact Additive.

Denlinger at al. [17] conducted a fully transient structural welding simulation to calculate base plate distortion for a SLM cube. In order to reduce the computation times, dynamic mesh coarsening was used to reduce the element count by roughly 98 % for the top layer. Irwin et al. [18] proposed longer heat sources to reduce the amount of increments needed to model additive manufacturing. They showed that the simplification of the heat input in SLM simulations does not significantly reduce the result quality because the speed of heat flow is in a similar order of magnitude as the laser scanning velocity.

In comparison to selective laser melting, where model simplifications in heat input and techniques to reduce calculation times are established in the literature, little published data exists for LMD. Due to the differences in scanning speed and the more localized heat input in LMD, formulations established for SLM cannot be readily transferred [19]. Hence, this work aims to increase the knowledge in LMD simulations by investigating ways to improve the calculation time while keeping the fully transient simulation approach. In contrast to the layer-by-layer approach commonly found in the literature [5, 6], the component is meshed in one piece and the layer-wise element activation is implemented via element handles. The calculated distortions are compared to in-situ validation experiments to ensure that the changed models do not introduce additional error.

METHODS

SIMULATION MODEL

The model for this investigation is comprised of a baseplate and a thin-walled AM-LMD geometry that represents a turbine blade. The baseplate has a dimension of 100x100x6 mm³. The blade is generated layer-wise with 1.4404 stainless steel powder (Fig. 1 (a)). According to a previous study reported in [6], each layer is considered to have a square shaped cross section of 1.2 mm width and 0.6 mm height (Fig. 1 (b)). Hence the deposit is considered as flat. The material properties (see also [6]) are temperature dependent, changes in

microstructure due to multiple heating cycles, however, are neglected. The density and Poisson's ratio are constant. The weld pool is modelled as a low-stiffness solid and the occurrence of weld pool dynamics is neglected.

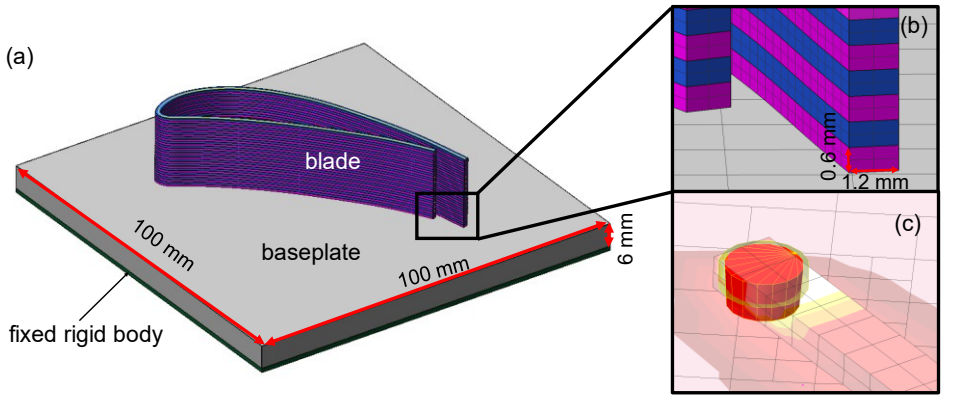

Fig. 1: Numerical model of the AM-LMD process. (a) Model geometry with baseplate (grey) and AM-LMD blade geometry made with 30 layers (blue/purple). A fixed rigid body (green) is glued to the lower surface of the baseplate to constrain movement. (b) The cross section of each layer has a simplified rectangular shape. The blade is modelled with individual bodies (and meshes) for each layer. (c) Heat input is modelled with a three-dimensional conically shaped volume heat source that moves transiently along the weld path (see also [6]).

The model was set up in the commercial FEA structural welding software Simufact Welding utilizing the direct FEA-solver sfMARC. The governing differential equations for the thermal and mechanical analysis are given in detail in [6]. A thermo-mechanically coupled transient simulation is considered using three-dimensional equivalent heat sources that move along a predefined path (Fig. 1 (c)). The so-called quiet-element method is used to model the molten powder addition by activating elements transiently on the basis of the moving source. With this approach the thermal and mechanical properties of the a-priori defined deposit geometry are drastically scaled down at the beginning of the simulation (quiet state) before getting "activated" by the propagating heat source via an element-birth formulation. The activation is done in two steps: a virtual activation box surrounding the heat source geometry activates the quiet elements and their nodes thermally once they get inside the box. Mechanical properties are then scaled up to full stiffness after the nodal temperature has reached melting temperature again after cooling down from a higher temperature.

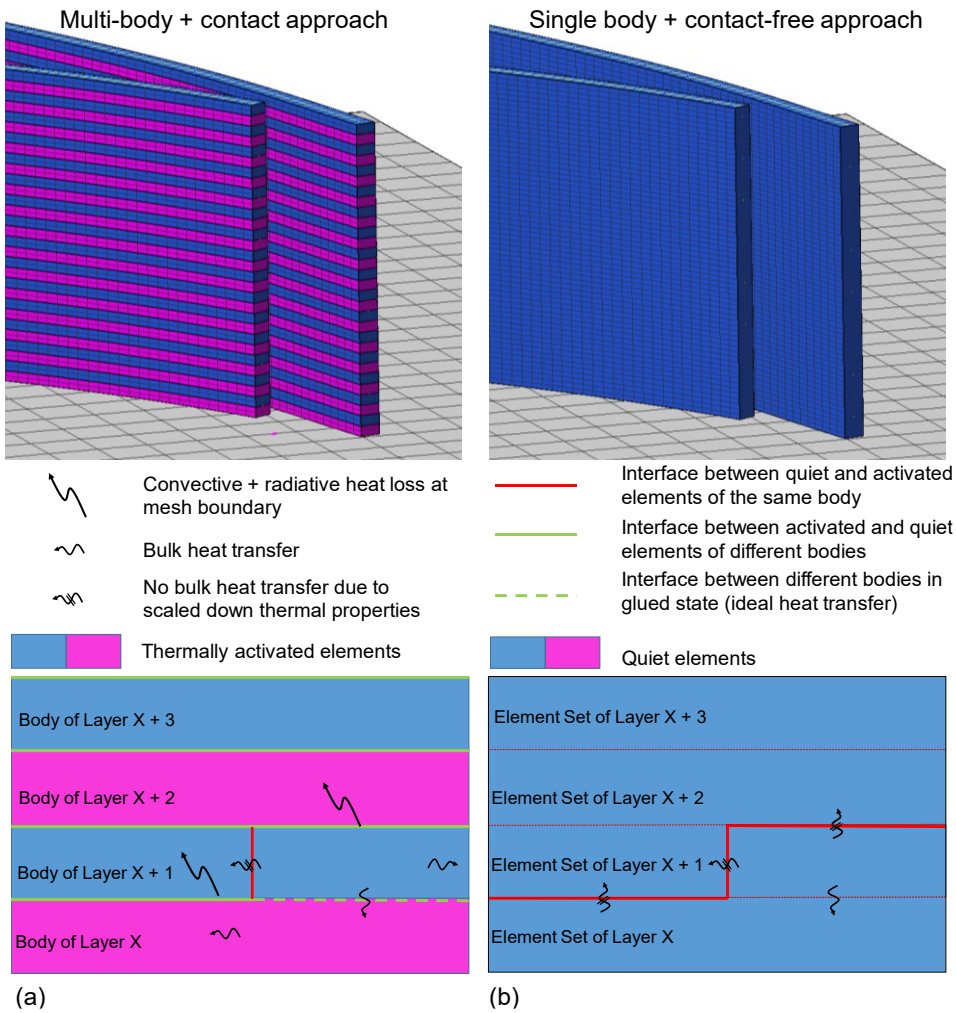

Fig. 2: Handling of thermal properties in multi-body and single body approach. (a) multi-body + contact approach: radiative and convective heat loss between activated and quiet elements is handled with boundary conditions. (b) single body + contact-free approach: No heat loss considered between the layers. Energy transfer between activated and quiet elements is neglected due to scaled down thermal conductivity and only takes place at outside surfaces.

For this study, two different ways of handling the deposited material and its mesh in a structural welding simulation of a LMD process has been investigated. A common and often successfully applied technique is to stack up separate deposit bodies each with individual meshes layer-by-layer (Fig 2 (a)). This way, the model consists of a high number of separate deformable bodies. This enables the possibility to attach surface boundary conditions and contact properties between each body and to safely control the activation of quiet elements for each individual weld seam body. Radiative and convective heat loss can be considered at interfaces between activated and quiet elements.

Handling each weld seam, as well as the components, as individual deformable bodies has generally been proven to be a good method to cover certain structural behaviors in

typical seam welding applications such as the opening of gaps. However, non-linear contact calculation is an additional computational step in the FEM solution procedure and it gets more demanding the more complex the contact situation is. This is generally true for every FEM solver. With a very high number of different contacts, the solution procedure takes longer and the calculation usually becomes slower. Due to the huge number of layers in real-life LMD applications together with the sheer length of the weld seam up to many meters, this approach is potentially not the most practical for industrial-scaled components.

Therefore, as a second approach, a single body and contact-less modelling approach has been tested in this study. Instead of using separate bodies for each layer, the entire LMD geometry is merged into one congruent mesh (Fig. 2 (b)). This aims for reducing the numerical effort of contact calculation leaving only the contact between baseplate and the first layer of the LMD geometry. Mechanical and thermal exchange between layers is, however, no longer controlled by surface boundary conditions but entirely handled via the quiet element method. This means, that radiative and convective heat loss at the top surface of each layer (except for the topmost one) is generally neglected. In addition, the layer-wise activation of quiet elements has to be handled by defining element sets to distinguish the different layers for both the heat input and the element-birth procedure.

For this investigation four different blade, made out of 10, 20, 30 and 40 layers are simulated with both methods (multi-body and single-body approach) to compare calculation times. In addition, the result accuracy in terms of distortion behavior is investigated by comparing the displacements of the 30-layer blades with experimental measurements. Simulation is performed on a 64GB Windows machine with 2 Intel Xeon® E5-2640 v3 (@ 2.66 GHz) CPUs. The calculations are done in parallel on 15 cores (without the use of Hyper threading) using sfMARC's domain decomposition method (DDM) and shared memory parallelisation (SMP). The calculation was split into 5 domains with 3 cores used in parallel for each domain.

EXPERIMENTAL PROCEDURE

To evaluate the result quality of the developed modelling approaches, in-situ reference measurements were conducted using digital image correlation (DIC). A curved, thin-walled AM-LMD geometry was deposited from 1.4404 stainless steel powder onto a 100x100x6 mm³ 1.4404 substrate plate with the same setup used in [6]. In brief, a coaxial powder nozzle welded single tracks onto one another with 400 W laser beam power, 0.6 mm spot diameter and 7.5 g/min of powder flow. The sample geometry was the curved outline of a turbine blade (Fig. 3 (b)-(c)). 20 tracks were welded on top of one another with 30s pause time between layers and a bi-directional strategy, resulting in a wall-thickness of 1.2 mm and a height of 12.4 mm. Then the process was stopped to apply the stochastic pattern required for DIC measurements. Subsequently, 10 additional layers were deposited, while measuring in-situ displacements with the commercial 3D DIC system GOM Aramis 4m. In the optical measurements, the bright process light was blocked with narrow bandpass optical filters, suppressing all wavelengths except $810\,\text{nm} \pm 22.5$ nm. A defocused, monochromatic laser was used to illuminate the sample with 808 nm light so that the sample was sufficiently bright for the measurements [20]. The measurement setup is sketched around an in-situ frame in Fig 3 (a).

To validate the phenomenological heat source, temperature measurements were conducted with the same parameters used in the final experiments. Three thermocouples Type K were micro-welded on the substrate and a single track was welded next to them. After welding, the relative position of the thermocouples to the weld track was measured in a photograph and a cross section perpendicular to the weld was made.

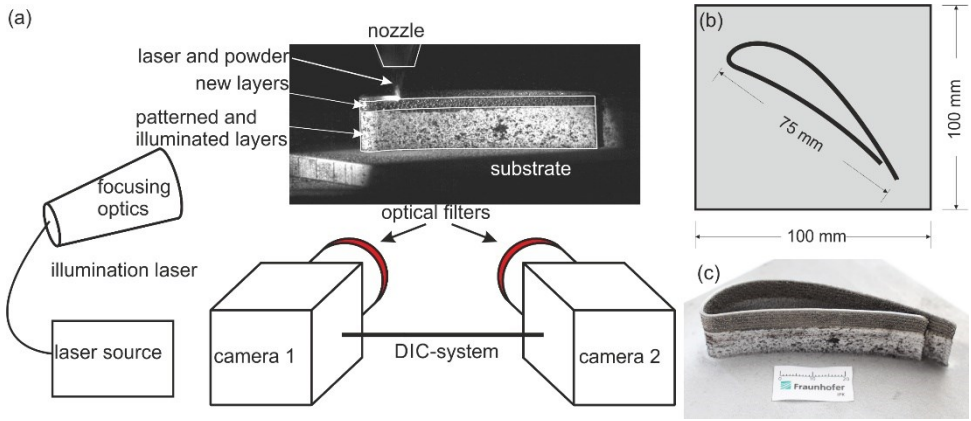

Fig. 3: Experimental setup, altered with permission from [6]. (a) In-situ image captured by the DIC-system is shown with the two cameras, optical filters and illumination laser sketched in their respective position. (b) Top-down view of the investigated, arbitrarily curved geometry. (c) Photograph taken after the process. The lower layers are patterned for the DIC measurements and the upper layers were added during the measurement.

RESULTS AND DISCUSSION

TEMPERATURE INPUT CALIBRATION

As the heat input and heat flow during manufacturing are the driving force behind distortions and residual stresses, it needs to be modelled to match the real heat input in the experiments as closely as possible. In CWM, the heat input is simplified with a phenomenological heat source and a calibration against experimental temperature measurements needs to be conducted.

The results for the thermal calibration are depicted in Fig. 4 (a), showing a very good agreement between the measured and simulated temperature development. Both the heat input – visible in the peaks – and the thermal conduction and thermal boundaries – visible in the cooling rates respectively – match well for an energy absorption efficiency of 60 % and a convective cooling of 35 W/m²K. In addition, the extent of the molten zone is compared between experimental cross section and the numerical results with good agreement in Fig. 4 (b). In Fig. 4 (c), the experimental melt pool taken from a DIC image and the simulated molten zone are compared. As effects from molten metal are neglected in CWM, the shapes do not match completely but the extent of the molten volumes match closely. With these results, the heat input is considered to match the experiments and will be used as an input in the mechanical model.

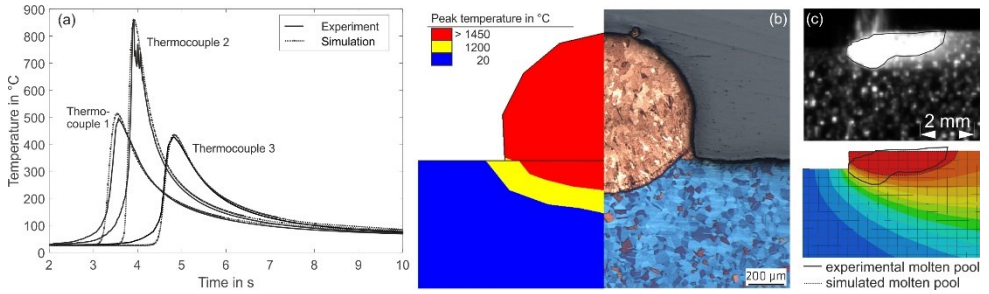

Fig. 4: Results of the heat input calibration, altered with permission from [6]. (a) The comparison between simulated and experimental temperature measurements shows good agreement. The simulated and experimental cross sections are compared in (b) with the molten area in the simulation image and the cross-section showing good agreement. In (c), the molten pool geometry from the DIC images is compared with the calculated molten zone.

SIMULATION RESULTS

In Fig. 5, the simulated distortions in x-, y- and z-direction for a 30-layer blade are depicted after cooling down to room temperature for both modelling approaches. Both methods give almost similar distortion result, however, slight differences can be observed for the x-distortion, especially around the very top of the blade structure.

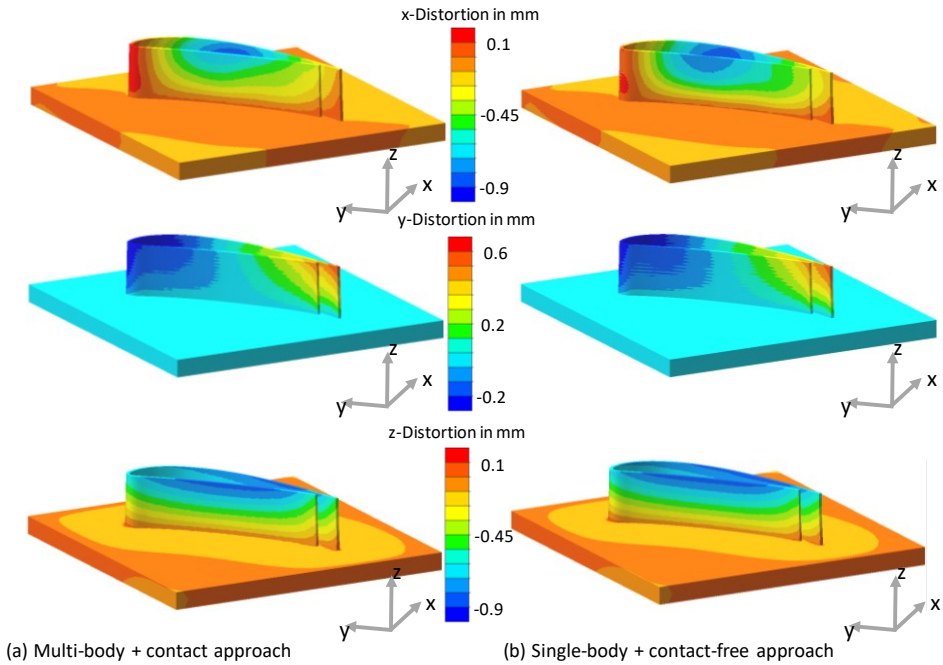

Fig. 5: Comparison of total displacement after simulation of a 30-layer blade for multi-body vs. single body approach.

In order to check the level of agreement more quantitatively and to evaluate the general accuracy of the simulation compared to experimental measurements, the out-of-plane distortion at six specific points is tracked over time and compared to the DIC measurements. The results are plotted in Fig. 6 for the out-of-plane distortions. The typical saw-tooth behaviour common in additive manufacturing can be observed in the experimental and simulated out-of-plane displacements. Only at P6, the transient movement is not as pronounced, presumably due to the relative proximity of the point to the rigid tip. In general, the simulation results are in good quantitative agreement with the DIC measurement and coincide closely with one-another. By trend, both simulation results tend to slightly underestimate the out-of-plane distortion at P1, P2, P3 and P6, while somewhat overestimating it in P4. The slight errors between simulation and experiments are likely due to the simplifications introduced in the simulation: Especially the orthotropic grain structure arising from multiple re-heating of the materials is not considered [6] and effects like stress relaxation and creep are neglected. More importantly for the argument presented in this work, there is little to no difference in the predicted distortions between both simulation approaches. Hence, the newly-developed contact-free approach does not introduce unforeseen errors.

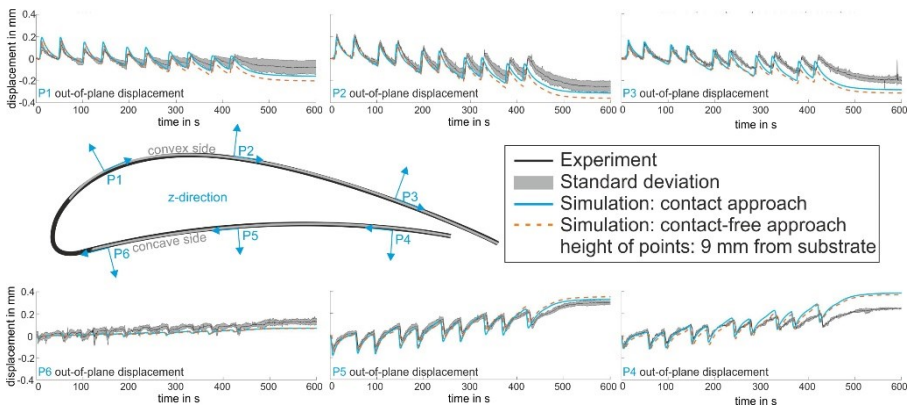

Fig. 6: Out-of-plane distortion vs. time at six distinct measure points at a height of 9 mm above the substrate for both simulation approaches and the DIC measurements (including standard deviation).

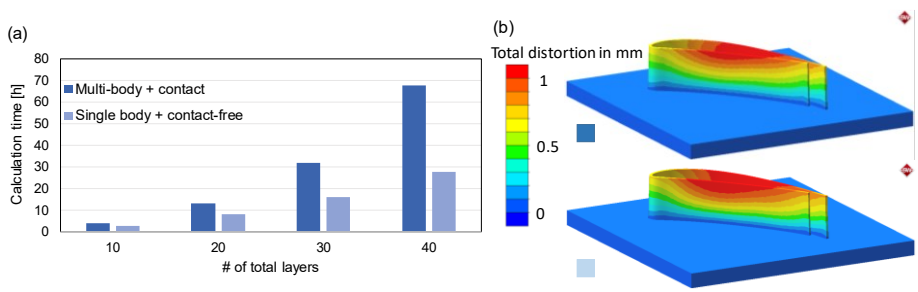

Fig. 7: (a) Comparison of calculation times (Wall time) on a 64 GB Intel Xeon® CPU E5-2640 v3 (@ 2.66 GHz) machine with the sfMARC solver. Multi-body vs. single body approach for 10, 20, 30 and 40 layers. (b) Comparison of total displacement after simulation of a 30-layer blade for multi-body vs. single body approach.

While the results of both simulation approaches are in good agreement with the experimental observation, the calculation times are very different. Fig. 7 gives an overview of the calculation times (Wall time) for blades with 10, 20, 30 and 40 layers of deposited material.

The comparison clearly depicts the advantages of a single-body, contact-free calculation approach to model the deposit. As expected the benefit increases with increasing total number of layers. Even for this relatively small model (compared a real industrial-scaled component) the calculation time for 30 layers is less than half of the multi-body simulation. Hence, the hypothesis that the contact-calculation is responsible for a large portion of the calculation time in the multi-body simulation approach is validated. Upon removal of the contacts, the calculation times improve significantly and the neglect of convective and emissive cooling at the top interface has little influence on the result quality for the investigated thin-walled part.

Especially with thick-walled LMD parts, the correct modelling of the cooling needs to be assessed in future works: For the thin-walled component, the side surfaces are far larger than the top surfaces and the heat loss is largely realized through them. In a thick-walled part, on the other hand, the top surface is larger and has an increased influence on the cooling; as this surface is part of the single-component in the contact-free approach, the heat loss to the surroundings might be underestimated for intermediate layers.

Although the calculation times were significantly improved with the new approach, they are still a major issue for large parts: In Fig. 7a, doubling the model size from 10 to 20 layers (1.5 m weld length to 3 m weld length) increases the calculation time by 300 % from 2.7 h to 8.3 h for the contact-less model. Adding another 10 layers, totalling in 4.5 m weld length, increases the calculation time by another 200 %. This hints at an almost exponential growth that might be problematic for investigating real-life parts with hundreds of layers. But with the in-situ distortion measurement results presented in [6] and in this work, future model improvements and simplifications can be easily tested for their validity.

Finally, the ease of modelling between both strategies can be compared. In the multi-body contact approach, each layer geometry and weld path need to be defined and positioned individually and manually in the FE software. This approach requires expert users and is prone to mistakes. In the contact-less approach, the whole part is meshed at once with mesh densities corresponding to the experimental layer thickness and imported into the FE pre-processor. The manual positioning of individual layers is no longer required but the weld paths and element sets still need to be defined by hand. In the long run, especially for industrial-scale parts, the model generation needs to be automated further. The ease-of-use can be improved especially by coupling the FE software with computer-aided manufacturing (CAM) tools for path planning and meshing tools to define the element sets.

CONCLUSION

A novel modelling strategy for additive manufacturing laser-metal-deposition was presented to reduce the calculation times arising from long weld paths in transient simulations. It relies on a contact-less approach that minimizes nonlinear contact calculations by defining element sets for material activation. It was shown that the new

approach does not significantly change the result quality while improving calculation times by over 50 %.

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