NEW METHOD FOR FAST PREDICTIONS OF RESIDUAL STRESS AND DISTORTION OF AM PARTS

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Abstract

A new multi-scale approach based on the method of finite elements is developed in order to enable much faster predictions of residual stress and distortion for AM parts. The approach includes the calibration of the heat source, the analysis of scanning strategies, the generation of the so-called "mechanical layer equivalent" (MLE) and its integration into a fast structural analysis. The use of MLE determined on the micro-scale and mapped into the large-scale structural analysis reduces computational time in comparison with the conventional thermo-mechanical simulations from months to hours while saving the same accuracy of numerical predictions. The new method is realized in newly developed powerful AM software. Simulation results are in a very good agreement with experimental measurements of distortion and residual stress. The potential of the new method to compensate the expected distortion using pre-deformation of parts is demonstrated by numerical experiments of a near-net-shape AM fabrication.

Introduction

In additive manufacturing processes (AM) components are build up layer by layer. Most common processes, like laser or electron beam melting (LBM, EBM), are powder based, i.e. the complete part is generated out of a powder bed by build-up micro-welding process. Other varieties are laser cladding or powder deposition welding. However, most of AM technologies for metals are based on the same principles like the melting of a material and its solidification. High local energy density and speed of the heat source lead to high cooling rates and temperature gradients during the build-up process. Hence, high thermal strains and residual stresses are generated in the manufactured part. The release after the clamp removal, like cutting support structures after LBM process, leads to a deformation of generated shape and a redistribution of the internal stresses and strain [1]. For the prediction of distortions, numerical investigations based on the method of finite elements (FEM) are conducted in order to optimize scan strategies, build-up directions or support structures.

Usually complex thermo-mechanical simulations for the prediction of distortions are carried out by use of commercial software. The size of the simulated part as well as the simulated number of layers are strongly limited by the required calculation times which are in the range of hours up to days, weeks or even months. In order to enable a practical usage of a FEM based method for AM process simulation, calculation times must be reduced radically. In present work, a new approach for fast predictions of residual stress and distortion is developed, which allows replacing the time consuming thermo-mechanical simulation by a static mechanical one. This method aims the estimation of distortion within minutes or hours. The presented experimental investigations are made on a 316L stainless steel, processed by powder based LBM on a Concept Laser machine M2. Simulations have been conducted using the FEM Solver MSC.Marc.

State of the art

For the prediction of residual stress in conventional thermal processes like welding, the thermo-mechanical FEM simulation is a common and validated tool. Complex material behavior like the non-linear temperature dependent material properties and further effects like hardening or creep strains can be considered. Coupled simulations for single weld paths can take hours to days, depending on the FE mesh and time steps. On the other hand AM processes for metallic parts like LBM can also be understood as a series of micro-welding processes; therefore the theory of welding can also be applied [2]. However, the direct simulation of the AM process is not feasible, since the process consists thousands to millions of weld seams.

Most approaches for the prediction of distortion and deformation of additively manufactured parts are based on the exposure of full layers at once [3-5]. In addition layers have to be combined, since components normally have up to 10k layers [5]. Although the simulation of components can be enabled by these approximations, and even complex material behavior can be considered, most influences of the process itself (like scanning strategies) are neglected. Furthermore, simulations of even macroscopic components still take several days. Figure 1 shows the estimated calculation time of the conventional simulation method. The simulation of macroscopic AM parts requires calculation times in the range of weeks what strongly limits the practical usage of the conventional simulation methods [6].

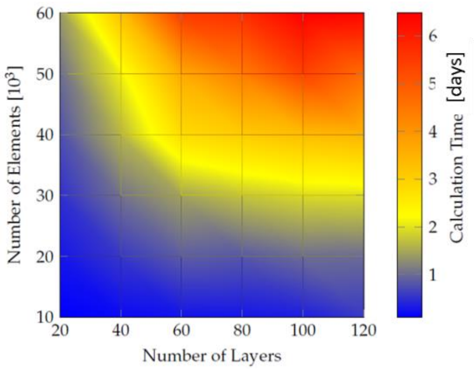

Figure 1: Expected calculation times for conventional thermo-mechanical simulations of AM process

Approach

Three different simulation models are developed in order to investigate different physical effects by LBM process on their respective scale. On each scale a non-linear material model is used. Temperature dependent material properties are estimated using the commercial software JMatPro.

1. Heat source model (microscopic scale)

For the calibration of the heat input, a thermal Finite Element Analysis (FEA) is used to determine the parameters of the heat source and the energy absorption coefficient η of the material. To approximate the energy absorbed by the material, the weld pool shape is derived using the calibration of the experimentally measured micro-cross-sections of the weld pool and parameters of a Goldak heat source. Figure 2 represents the correspondent simulation model and boundary conditions.

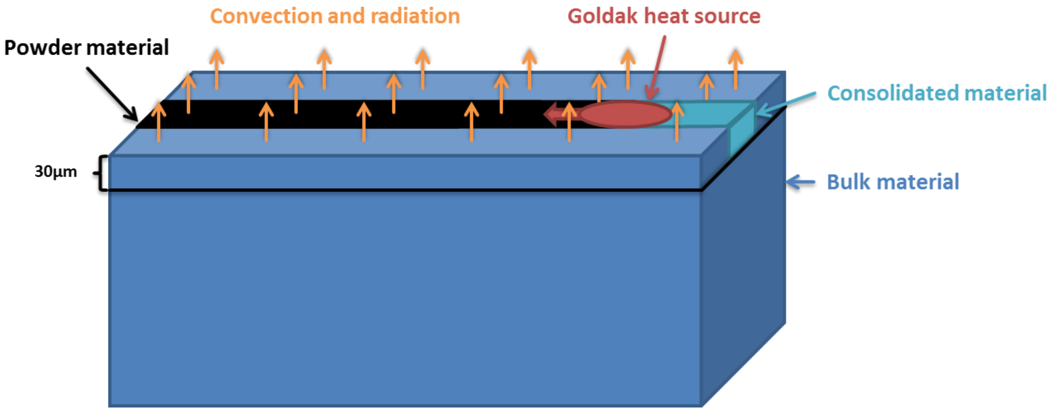

Figure 2: Boundary conditions of the heat source simulation model

For the simulation of powder, an effective powder material is considered whose very low heat conductivity is calculated using the Zehner-Schlünders equation [7]. The heat capacity and density are equal to the solid material since the volume is not changed due to the gas loss and the law of conservation of mass applies. When the effective powder material reaches melting temperature, the material properties are changed to those of the solid material. For the laser spot a Goldak heat source is used, whose parameters have to be determined by the calibration with experimental measurements of the weld pool size. Furthermore, standard radiation and convection boundary conditions are taken into account.

2. Hatching Model (mesoscopic scale)

For consideration of the trajectory of the laser spot, a thermo-mechanical, elasto-plastic simulation model is developed. The energy absorption coefficient η, determined in the heat source model, is used for estimation of the heat input. Since the element sizes is large compared to the laser spot dimensions, the total estimated energy is distributed within the cubic element. Figure 3 shows the FE model and boundary conditions.

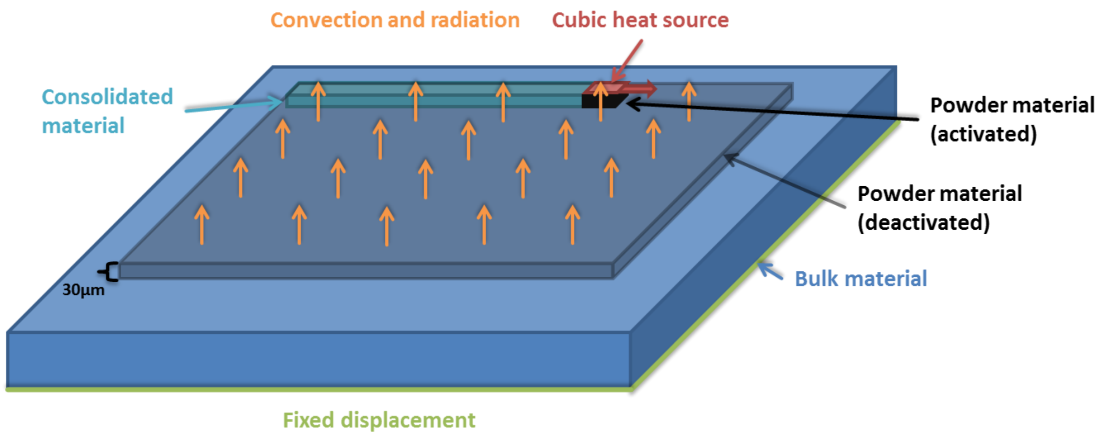

Figure 3: Boundary conditions of the hatching simulation model

At the beginning all elements representing the powder layer are deactivated, i.e. they cannot physically interact with other elements. When the heat source starts its movement, elements at the current heat source position are activated. As far as integration points in powder material elements reach melting temperature, the properties are changed to those of the bulk material (like in the heat source model). The mechanical properties of the powder are as follows: the yield stress is zero (representing an inelastic behavior), the thermal expansion is zero (powder is loose), and the Young's modulus is something above zero (it cannot be exactly zero due to back-stress calculations for plasticity). Furthermore, standard convection and radiation boundary conditions are also taken into account. A fixed displacement boundary condition is applied on the bottom of the substrate plate.

In theory an entire powder layer has to be activated at once and partially consolidated by the heat source. Since the thermal strains lead to high deformation of the deactivated elements, this activation procedure is not feasible due to numerical problems. However, the heat conductivity of the surrounding powder is neglected in this model but mechanical consolidation is considered. The missing thermal expansion of powder material until the melting temperature is reached results in higher strains which represent the difference between the processes of "pure" welding (as re-melting process) and deposition welding.

3. Layer Model (macroscopic scale)

Conventional thermo-mechanical FEM simulations show that distortion of AM parts tends to be a macroscopic phenomenon, which is mostly dependent on the hatching strategy and the geometry of the manufactured part [8]. Although stress and temperature of a certain point in a layer are affected by approximately 10 previous layers, displacement values alter (depending on the macroscopic part geometry) until the end of the built-up process. All AM parts are extremely large compared to the size of the micro-weld and each weld seam experiences an identical or comparable thermo-mechanical history. This fact is used to reduce the time consuming transient thermo-mechanical problem for the prediction of geometrical distortion to a fast solution of the mechanical problem on the basis of the method of inherent strain. For this purpose, the strains determined in the hatching model are applied as inherent strain in the macroscopic layer model. The similar approach has been successfully applied and validated for the calculation of welding distortion of large parts [9]. Figure 4 shows the simulation model that is used for the fast calculation of distortion of AM parts.

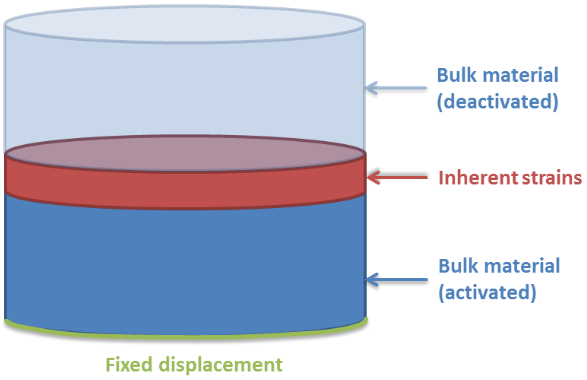

Figure 4: Boundary conditions of the layer simulation model

Initially, all elements of the mesh are deactivated. The build-up process is represented by layer wise activation of elements. In each activated layer the inherent strains calculated by the hatching model are applied. The orientation of the so-called "scanned islands" can also be considered by the corresponding rotation of the strain components. The base plate of the LBM process is represented as a fixed displacement boundary condition at the bottom nodes of the manufactured part. For the simulation of parts with complex geometries, an in-house developed mesh generator is used, which creates a layer based FE mesh on the basis of the CAD or slice data [6].

Results

1. Heat source model

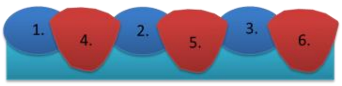

Figure 5: „Resorted“ weld paths

For the calibration of heat source, cross-sections of the micro-welds were investigated. The specimen is generated from 316L stainless steel. The laser power is 200W, with sweep speed of 800mm/s. The layer thickness is 30µm and hatch distances are 100µm. The order of the tracks is chosen from as shown in Figure 5. This order makes possible to exclude the difficulties of determination of the weld seam shape connected with the overlay of the multiply tracks and to investigate the undistorted weld seam profile. Figure 6 shows the cross-section at the surface of a specimen, which is built with such “resorted” weld tracks.

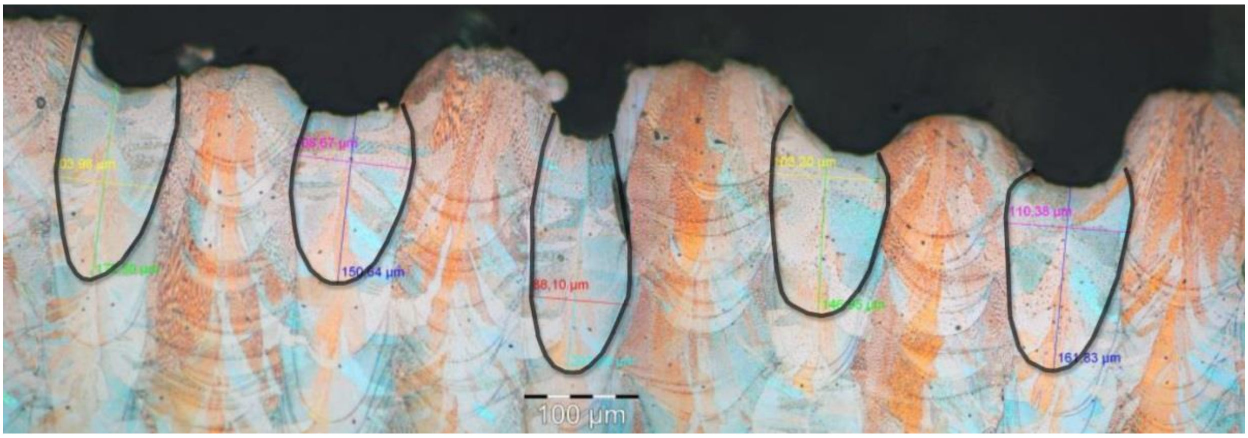

Figure 6: Cross-section at the surface of a 316L stainless steel specimen with “resorted” weld tracks

The experimental measurements of weld seam sizes carried out on the microscopic photographs of the specimen cross-sections exhibits the following values:

Weld seam width	(102.87 ± 8.80) µm
Weld seam depth	(167.18 ± 22.88) µm

In the thermal FEA a convection of 50W/m²K and an emissivity of 0.68 are assumed as thermal boundary conditions. Calibration with the experimental weld seam dimensions results in the following parameters for the Goldak heat source:

Forward length	20µm
Rear length	40µm
Width	55µm
Depth	270µm

The determined value of the energy absorption coefficient η is 86%. This value is used as the input for the hatching simulation model. Figure 7 shows the temperature distribution of the calibrated heat source, which leads to a weld seam width of 100µm and a depth of 165µm. The simulated profile of the weld seam is in a good agreement with the experimentally measured one.

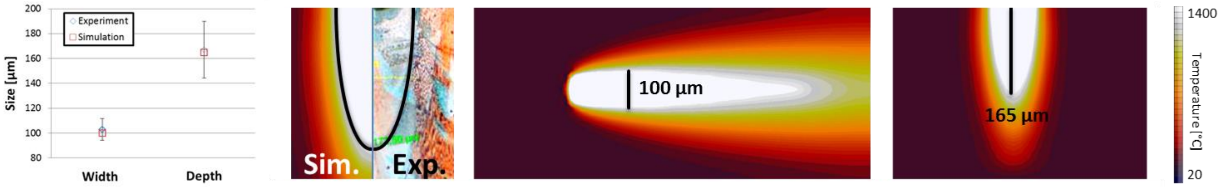

Figure 7: Temperature field of the simulated heat source and comparison with experimental results

2. Hatching Model

The simulation of scanning strategies is used to calculate the strain distribution within the one "scanned island". The energy applied by the cubic heat source used in the hatching model is equal to the energy that has been determined using the heat source model. For the dimensions of the heat source the following parameters are determined:

Height	100µm
Width	100µm
Depth	165µm

A typical island with a size of 5mm x 5mm is simulated using the cubic heat source, those trajectory follows a meandering pattern. The results of numerical analysis show a complex distribution for the components of thermal and plastic strains with as expected relatively large stationary regions. It makes possible to define an inherent strain vector for one specific material and one set of scanning parameters (not for scan strategy!) by evaluating averages of the corresponding strain components. For the inherent strain vector the following strains can be approximately calculated for the 316L material:

$$\varepsilon^{\text{inh}} = \begin{pmatrix} -0.01 \\ -0.001 \\ -0.03 \end{pmatrix}$$

This estimation of strains within a scanned island is applied as the inherent strain for the fast macroscopic simulations of distortion of AM parts in frame of the layer model.

3. Layer Model

The inherent strain vector is the basis for determination of a so-called "mechanical layer equivalent" (MLE) for each generated layer. For the certain layer, the MLE depends on the applied scan strategy (the order and orientations of generated micro-welds in a certain layer). By rotation of the strain vector, any orientation of each single micro-weld or scanning islands can be taken into account.

Based on the total MLE, the inherent strain method is used to calculate the stresses and distortions of AM parts. Three different scan strategies have been investigated by simulation and experiment on the cantilever specimens. Figure 8 shows the bending of the cantilever specimen measured and simulated for the three types of exposures (scanning directions): *x*-direction (meandering pattern), islands strategy with rotated islands and *y*-direction (meandering pattern).

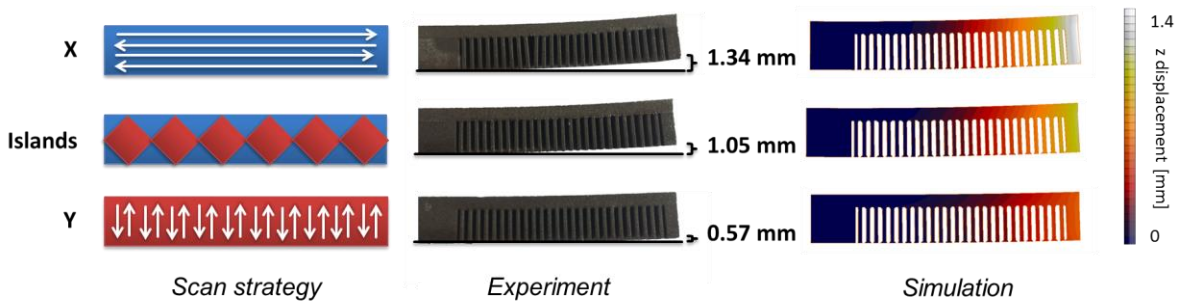

Figure 8: Results of experimental investigation and simulation of thermal distortion of a cantilever specimen

The numerical values for the distortions of the cantilever specimens are shown in Figure 9. By the use of the inherent strain vector, calculated for the 316L stainless steel material, simulation results are in a very good agreement with experimental measurements.

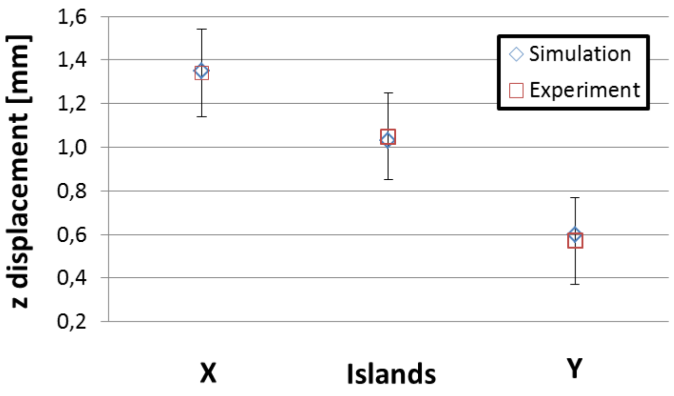

Figure 9: Comparison of simulated and measured distortions

For the cantilever specimen, the exposure in *y*-direction leads to the lowest deformation, since it is perpendicular to the preferred direction of distortion. The island strategy leads to a medium distortion while exposure in *x*-direction with long scanning vectors shows a maximum displacement.

<u>Fast prediction of distortion and possibilities for distortion compensation</u>

Figure 10 shows the FE mesh of a bionic Ti6Al4V aerospace bracket with the so-called tree supports that contains 100k elements. Since the number of elements is large, the conventional thermo-mechanical FEM simulation is not feasible. The mechanical simulation using the MLE method requires the calculation time of about 10 hours. The CAD and the calculated deformation are shown in Figure 11. Due to a bending of the component, a geometrical deviation of 2 mm was simulated and validated by experiments. Since the deformation can be calculated, the CAD data can be modified using the negative values of the calculated distortion for compensation.

Figure 10: FE mesh of a bionic aerospace bracket

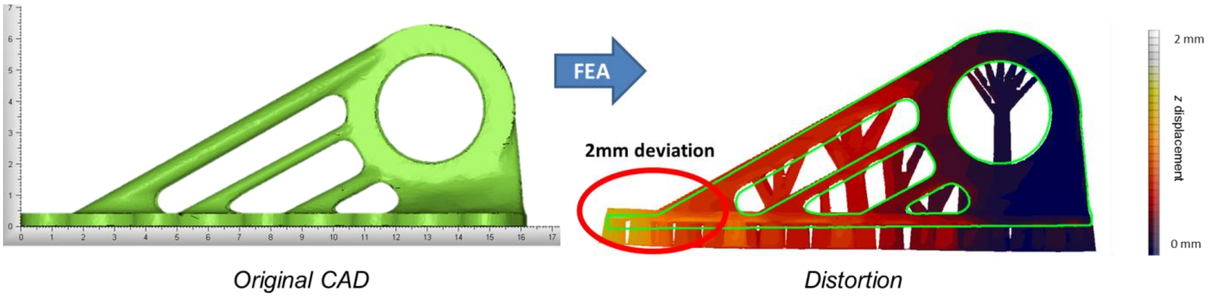

Figure 11: Initially designed part geometry and simulated distortion

Figure 12 shows the adjusted CAD shape of the component and the resulting deformation after process. The bent bottom surface of the CAD is plane after the relaxation of residual stresses. Based on this simulation model, a near-net-shape AM manufacturing can be realized without cost expensive experimental investigations.

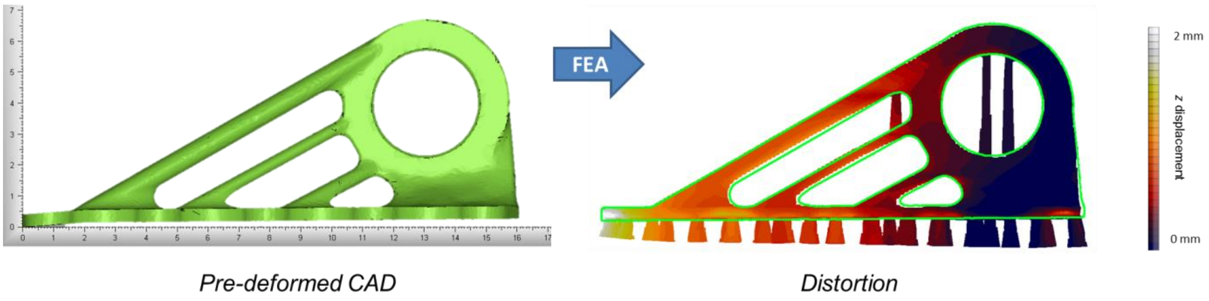

Figure 12: Redesigned part geometry leads to zero distortion after manufacturing process

Summary and outlook

A method for the fast prediction of residual stresses and deformation for AM parts is developed on the basis of the multi-scale simulations and application of the inherent strain approach for solution of the thermo-mechanical problem. The use of the multi scale approach makes possible consideration of scan strategies and complex material behavior. The application of the inherent strain approach enables the reduction to a complex thermo-mechanical problem to a simpler structural-mechanical one. The required calculation time can be drastically reduced in two or more orders of magnitude. It makes possible numerical predictions of residual stress and distortion for very complex AM parts and opens the way for application of this method in real industrial praxis.

It is demonstrated that the developed numerical method can be also effectively used for the fast predictions of the pre-deformed geometry parts in order to compensate the expected distortion. The further developments will concentrate on this important issue in order to enable the right first time near-net-shape additive manufacturing of complex parts.

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