

11th CIRP Conference on Photonic Technologies [LANE 2020] on September 7-10, 2020

Distortion-based validation of the heat treatment simulation of Directed Energy Deposition additive manufactured parts

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Abstract

Directed energy deposition additive manufactured parts have steep stress gradients and an anisotropic microstructure caused by the rapid thermo-cycles and the layer-upon-layer manufacturing, hence heat treatment can be used to reduce the residual stresses and to restore the microstructure. The numerical simulation is a suitable tool to determine the parameters of the heat treatment process and to reduce the necessary application efforts. The heat treatment simulation calculates the distortion and residual stresses during the process. Validation experiments are necessary to verify the simulation results. This paper presents a 3D coupled thermo-mechanical model of the heat treatment of additive components. A distortion-based validation is conducted to verify the simulation results, using a C-ring shaped specimen geometry. Therefore, the C-ring samples were 3D scanned using a structured light 3D scanner to compare the distortion of the samples with different post-processing histories.

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Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: Directed Energy Deposition; Additive Manufacturing; Heat Treatment; Numerical Simulation; Finite Element Method

1. Introduction

Parts manufactured by directed energy deposition (DED) additive manufacturing (AM) require specific post-processing depending on their application. They are exposed to rapid localized heating during the welding and rapid cooling during the solidification, hence steep residual stress gradients appear in the part. The layer-upon-layer manufacturing causes anisotropic mechanical and structural properties. Heat treatment can be used to reduce the residual stress level of the AM part through plastic deformation [1] and to minimize the anisotropy of the microstructure through recrystallization [2]. After the heat treatment, electrical discharge machining (EDM) can be used to remove the built part from the substrate. The numerical simulation is a powerful method to reproduce these

process steps to avoid expensive experiments by conducting digital tests to determine suitable process parameters.

Nomenclature

AM	additive manufacturing
DED	directed energy deposition
OD	outside diameter
ID	inside diameter
GW	gap width

The DED AM and the heat treatment are both characterized as complex metallo-thermo-mechanical processes where the thermal state, the microstructure and the mechanical state influence each other. The structural FEM welding simulation is capable of simulating such processes.

FEM welding models predict the temperature distribution, the residual stress and the distortion. The latter was chosen to validate the simulated process steps because it can be measured easily with a 3D scanning system before and after each process step. To simplify the comparison between the simulated distortion and the measurements, a suitable specimen geometry is required.

In the field of DED AM, thin-walled samples are used to validate simulations [3, 4], whereas, in the field of heat treatment, C-rings are common specimens. They have three metrics to evaluate the deformation: the outside diameter (OD), the inside diameter (ID) and the gap width (GW) [5], as displayed in Fig. 1 (c). Those dimensions can be measured using a coordinate measuring machine or a 3D scanning system. Hardin and Beckermann [6] used C-rings as specimen to compare their heat treatment simulation results with measured distortions. This work will mainly focus on the heat treatment simulation, therefore a DED AM adapted C-ring will be used as a specimen geometry.

2. Materials and Methods

A total of six specimens were built by DED AM using the austenitic stainless steel AISI 316L as powder feedstock (Metco 41C) from Oerlikon with a grain size of 45 μm - 90 μm . The manufacturing was conducted on a “Trumpf TruLaser Cell 7020” equipped with a 2 kW disc laser and a “Trumpf” coaxial powder nozzle. The laser power was set to 600 W, the laser spot diameter was set to 0.6 mm and the forward speed was set to 600 mm/min. Between each layer, the process was paused for 30 s for cooling. 12 Layers were built with a layer height of 0.65 mm, a track width of 1.2 mm and an overlap of 30%. The parameters are summarized in Table 1. To promote an isotropic infill structure, two zigzag path strategies with different inclination angles were used alternately during the buildup. An as-built C-ring is depicted in Fig. 1 (a) and a sample after EDM is shown in Fig. 1 (b).

Table 1. Parameters of the DED AM process

Parameters	
laser power in W	600
laser spot diameter in mm	0.6
forward speed in mm/min	600
track width in mm	1.2
overlap in %	30
layer height in mm	0.65
number of layers	12
pause in s	30

Fig. 1 (c) shows a schematic of the C-rings of this work and its characteristic dimensions.

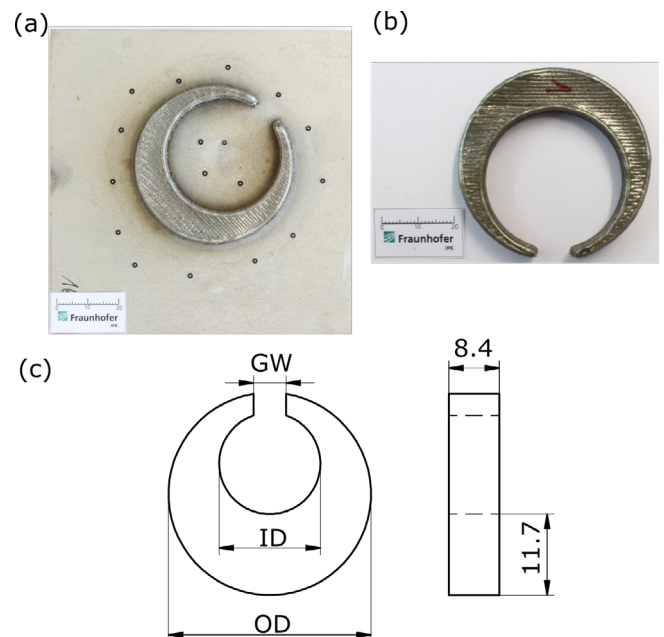


Fig. 1. (a) an as-built C-ring after 3D scanning. The dark spots are markers which were used to fit the different pictures of the 3D scanner to a 3D model; (b) a C-ring after the removal from the substrate via EDM; (c) a schematic of the C-ring and its dimensions (OD=50.9 mm, ID=31. Mm, GW = 9.3).

Table 2 shows the post-processing steps which were conducted after the buildup of the C-rings. The as-built samples were only removed from their substrates directly after the buildup, this was meant to quantify the distortion which are caused by EDM of an as-built sample without prior heat treatment. Cross-sections from an as-built C-ring and a preheated one were made to investigate the effects of the heat treatment on the microstructure.

Table 2. Post-processing history of the C-ring samples

C-ring	quantity	post process no.1	post process no.2
as-built	2	EDM	-
preheated	4	Heat treatment	EDM

The four preheated C-rings were heat-treated under an argon atmosphere using a Nabertherm LH60/13 industrial furnace at a holding temperature of 1050°C. The furnace Chamber was heated from room temperature to the holding temperature within 210 min and held for 140 min. Subsequently, the furnace was shut down and the specimens were kept in the furnace until they cooled down to room temperature within 500 min. The holding time and temperature of the heat treatment were determined in accordance with the assumptions and recommendations of the “ASM metals reference book” [7].

A structured light 3D scanner “GOM ATOS TripleScan” with a measuring volume of 100 mm x 75 mm x 70 mm, a measuring point distance of 30.6 μm and an accuracy of 2 μm to 5 μm was used to investigate the distortion after each process step. Then the dimensional changes of the specimens were determined using the software Tool “GOM Inspect” through measuring the OD, the ID and the GW at different scanned states to provide a validation dataset for the simulation.

The simulation model was discretized with 26,228 elements of hexahedral and pentahedral shape with a characteristic element length of nearly 0.7 mm. Fig. 2 shows the full finite element model during the DED AM simulation at three different stages.

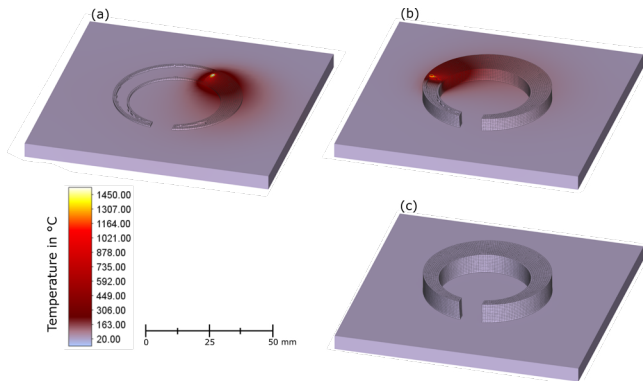


Fig. 2. DED AM simulation during the buildup; (a) simulation is building the first layer; (b) simulation is building the 8th layer; (c) simulated as-built C-ring.

The simulation of the buildup via DED is based on the papers from Biegler et al. [4, 8, 9]. They introduced a 3D coupled thermo-mechanical structural welding simulation model with a moving heat source that activates the elements of the deposition gradually. These elements represent the deposited powder feedstock, they are already in their final position before the simulation is started, but their material properties are scaled down with a factor of 10^{-5} by default. This factor is suspended when the moving heat source activates the elements by heating them above the melting temperature. Besides, the weld pool was considered as a low stiffness solid without any flow dynamics, the vaporization of alloying elements was neglected and the change in microstructure due to multiple heating cycles as well as the influence of mechanical deformations on the temperature field was neglected.

The AISI 316L powder feedstock remains austenitic at all temperatures, therefore phase transformations were not considered. The temperature-dependent material properties of standard AISI 316L were taken from [10] and applied to the simulation model. The density was fixed to 8000 kg/m^3 , the Poisson's ratio was set to 0.3, the enthalpy of melting was assumed as 256.4 J/g and an isotropic work hardening model with von Mises yield criterion was applied.

The heat treatment simulation was also done with the same thermo-mechanical coupled model as it was used in the simulation of the DED process with some differences. Flow dynamics in the furnace chamber and the contact heat transfer were neglected. Only the convective and radiative heat transfer was considered. A heat transfer coefficient to the furnace chamber was set for each process step of the heat treatment (during heating and holding: $35 \text{ W/(m}^2\text{K)}$; during cooling: $2.3 \text{ W/(m}^2\text{K)}$). Fig. 3 shows the time-temperature cycles of the simulation and the conducted heat treatment. The measured

temperature was obtained from thermocouples of the furnace chamber during the heat treatment process and it was assumed that the temperature of the furnace is approximately similar to the temperature of the samples. The temperature of the simulation was obtained from the marked reference point as labeled in Figure 3. It can be seen that the measured temperature curve during the heating and the holding stage is well represented by the simulation. The cooling of the simulation is slightly slower than the experiment. Nevertheless, both have approximately the same cooling time.

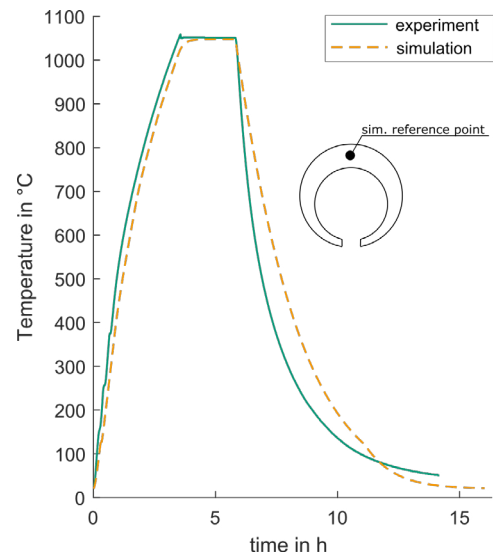


Fig. 3. Simulated and experimental time-temperature cycle of the heat treatment process.

Fig. 4 shows the heat treatment simulation during the heating, the holding and after the cooling. The DED AM simulation results, consisting of a 3D mesh, the temperature history and the residual stress distribution, were used as a starting point in the heat treatment simulation.

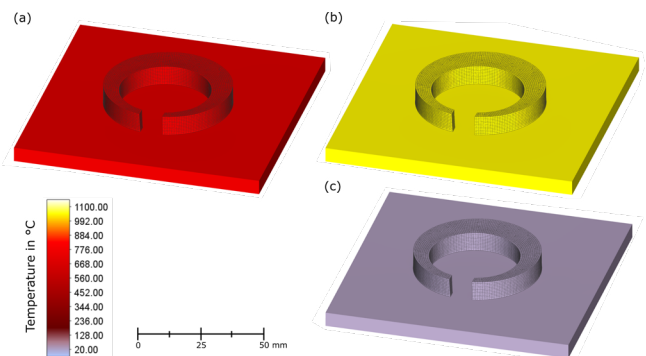


Fig. 4. Heat treatment simulation: (a) during the heating stage; (b) during the holding stage; (c) after the cooling.

During the heat treatment, the parts are held at an elevated temperature for a certain time and the residual stresses are transformed into plastic deformation, therefore it is necessary to consider creep, which commonly occurs at temperatures above 40% of the material melting temperature in Kelvin under a certain load (here the residual stresses). To simulate the heat

treatment process with the prescribed models of the DED AM process, it was necessary to expand the material model and to include a creep model. The creep power-law is a suitable constitutive equation to model the creep of austenitic stainless steel [11,12] and it is commonly used to simulate the heat treatment process. The creep power-law can be written as:

$$\epsilon = A\sigma^n \quad (1)$$

Where A is a constant related to the microstructure of the material, n is the exponent of stress and the applied stress is denoted as σ . To minimize the experimental complexity, it will be assumed that the creep behavior of additive manufactured AISI 316L is similar to conventional machined material. Therefore, the power-law parameters from the literature will be applied for the simulation of the current work. The creep parameters A and n were calculated using a linear regression model from creep parameter data obtained by [11] ($A = 1.33 \times 10^{-1}$ and $n = 4.84$).

The process of EDM is represented by deactivating the elements at the level of the EDM cutting path while the simulation calculates a new mechanical equilibrium considering the changed mechanical conditions to simulate the stress relaxation and the distortion after the removal of the substrate. This method was already used by [3] and by [4] to simulate the removal of a DED part from a substrate.

3. Results and Discussion

To investigate the distortion of the C-rings, the differences between the C-ring dimensions (OD, ID and GW) at different scanned states were calculated as follows:

$$\Delta D = D_{m-1} - D_m \quad (2)$$

Where D stands for OD, ID or GW of the C-ring and m represents the last post-processing step. For example, the characteristic dimensions which were measured after post-process no. 2 ($m=2$) are subtracted from the characteristic dimensions which were measured after post-process no. 1 ($m=1$) and the dimensional change is denoted to ΔD .

Fig. 5 shows the dimensional changes of the OD, the ID and the GW of the samples with different post-processing histories extracted from the experiments and from the simulation. The as-built samples were removed from their substrates directly after the buildup, whereas the preheated C-rings were heat-treated before the EDM. The first row of Fig. 5 shows the dimensional changes and the second row shows the absolute values of the deviations, to compare the absolute distortion between the samples with different post-processing histories. From the experimental data in the first row it can be seen, that the OD, the ID and the GW of the as-built C-rings increased after the EDM, hence the samples have widened. The dimensions of the preheated samples decreased, hence the preheated C-rings have contracted. Considering the absolute values of the dimensional changes of the samples, which are plotted in the second row of Fig. 5, it can be seen that the removal of an as-built C-ring from the substrate evokes the

largest deformations in OD, ID and GW. This is mainly caused by the relaxation of the steep residual stress gradients which are induced during the rapid thermo cycles of the DED process. The dimensional changes after the removal of the preheated C-rings from the substrate are in general smaller than the prior described ones, which is plausible, because of the stress-relieving effects of the heat treatment.

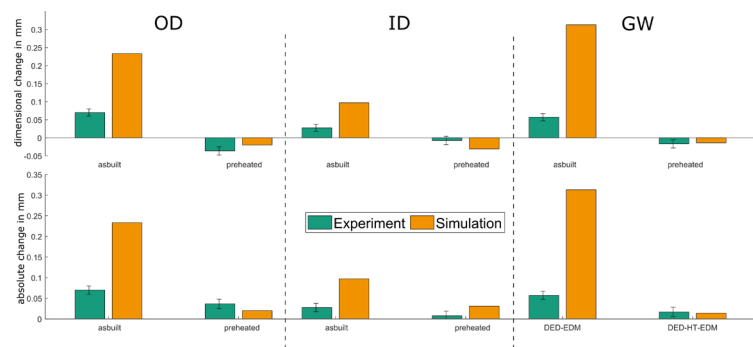


Fig. 5. Comparison of the simulated and measured dimensional changes of the C-rings. The first row shows the real dimensional changes, calculated in accordance to Equation 2. The second row shows the absolute dimensional changes.

The simulation overrated the distortion of the as-built C-rings after the EDM, because the residual stress level of the as-built part was overestimated by the DED AM simulation, therefore it would have been necessary to measure the residual stresses after the buildup to ensure a quantitative validation of the simulation model.

The disagreement between the dimensional changes of the preheated simulation and the measurements can be related to the made simplifications, e.g. the model assumed a homogeneous heat distribution in the whole part during the heat treatment process, as can be seen in Fig. 4, neglecting that the temperature history on the surface of the part can differ from the temperature history inside the part, which can have an influence on the resulting residual stress distribution. Further, the Simulation model only considered the stress relaxation through creep. Therefore, creep can be assumed as a major driver of the simulation in this paper, hence the creep parameters, from Equation 1, have a significant influence on the stress relaxation during the heat treatment. Therefore, it can be assumed, that the application of creep parameters obtained from standard material instead of additive manufactured material cannot represent the processes in the microstructure of an AM part during the heat treatment. Fig. 6 shows close-ups of the made cross-sections from an as-built sample and a heat-treated one. It can be seen that the heat treatment dissolved the weld bead boundaries and certain grain growth occurred, similar observations were made by Montero-Sistiaga et al. [1]. Hence, it is necessary to obtain creep parameters from additive manufactured AISI 316L in order to represent the prescribed microstructural processes during the stress relaxation to enhance the predictive capabilities of the simulation model.

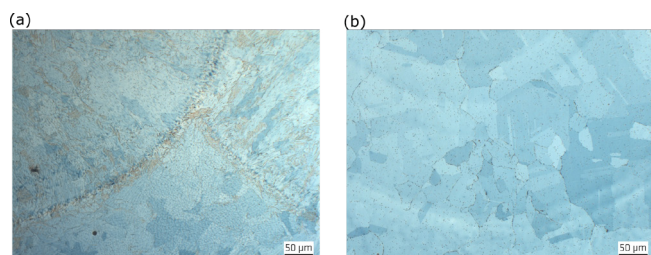


Fig. 6. close-ups of the made cross-sections; (a) Cross section of an as built sample; (b) Cross-sections of a heat-treated sample.

4. Conclusion

In summary, the simulation was able to predict the experiments qualitatively and to reproduce the observations from the experiment. The model was able to calculate the widening of the as-built C-rings after EDM as well as the contracting of the preheated C-rings after their removal from the substrates. The model was able to represent the significant distortions which were evoked by removing the as-built samples from the substrate via EDM, due to the pre-stressed state of the sample and the model showed that the heat treatment prior the removal of the substrate via EDM reduces the distortion through the stress-relieving effects of the heat treatment.

It was showed that the distortion-based validation approach can validate a simulation, consisting of DED AM buildup, heat treatment and EDM, qualitatively. A further quantitative enhancement of the predictive capabilities of the simulation model can be achieved through a validation of the residual stresses and trough the application of creep parameters obtained from AM material.

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