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On the design of an asymmetric temperature control platform towards the influencing of the heat balance of the DED-LB process

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Abstract

During the laser based directed energy deposition (DED-LB) process, a large quantity of heat is introduced into the substrate or work piece geometry resulting from the melting process. The relatively high build-rate leads to various complex thermal mechanisms. In particular, the rapid cooling of the deposited structures has a significant impact on the process.
Since DED-LB is an additive process, geometry can vary, ranging from the buildup of complex structure to repair applications. Therefore, the thermal conditions also change depending on the geometry. As a result, controlling the heat balance during the process is important, and it is necessary to locally cool or heat areas in one substrate work piece to prevent possible defects, geometric deviations or to influence the mechanical properties.
In this paper, the design towards an asymmetric cooling and heating platform is demonstrated. This was done by DED process simulation to determine a range of values of the required heating and cooling energy depending on different deposition geometries. Based on these results, single combined heating and cooling units were designed in a modular way to achieve a scalable solution. In simulations, this approach already shows promising results in terms of reduced geometric deviation. Finally, the platform is mechanically designed to incorporate subsequent process steps on the same system and proof of concept is delivered.

Additive Manufacturing, Directed Energy Deposition, substrate tempering, cooling behavior, geometric deviation

1. Introduction

With the help of the laser-based Directed Energy Deposition (DED-LB) process, complex components or additive manufactured (AM) structures can be created on existing components. The DED-LB process combines the fundamental principles of welding and coating. In the powder-based DED-LB process, a laser beam is focused onto the substrate surface to create a melt pool. Within the melt pool, a portion of the substrate surface and supplied powder material are melted and structures are created. [1]
The thermal history of the DED-LB process involves a series of thermal phenomena, including rapid heating, melting and cooling of the melted powder material and the substrate with cooling rates ranging from 10^3 to 10^4 K/s [2]. This results in a structure with a characteristic microstructure, arising from numerous phase transformation within a single geometry. The thermal properties, such as the maximum temperature, the position of the maximum temperature, as well as the cooling rate can vary significantly within the deposited structure. These local changes in the cooling rate can occur due to heat accumulation, for example in thin-walled structures [1]. A characteristic of thermo-mechanical manufacturing process like the AM-processes is the generation of residual stresses within the microstructure. In case of the DED-LB process, rapid heating and cooling of the structure lead to the initiation of thermal stresses. These thermal stresses occur along the grain boundaries due to the higher contractions between the upper, hotter layer and the underlying colder layer or the substrate material [3].

The cooling behavior is determined by process parameters such as laser power, scanning speed and the deposition rate. Additionally, the cooling behavior is influenced by the geometry and size of the deposited structure and of the substrate work piece [2]. By adjusting the process parameters, the thermal balance can be influenced. However, the process parameters cannot be arbitrarily adjusted, as the process would otherwise become unstable. The cooling behavior of the deposited structure can be influenced by heating or cooling the substrate. This enables an influencing of the microstructure and properties. Additionally, the substrate tempering can prevent the formation of defects. Heating the substrate leads to a reduction of the cooling speed, while cooling results in a higher cooling speed. Due to the extended cooling time during the preheating, fewer residual stresses are initiated in the microstructure. This serves to mitigate the occurrence of cracks within the microstructure and in the interlayer bonding zone. Furthermore, preheating can improve the dimensional accuracy of the work pieces [4].
Substrate cooling helps to avoid geometric defects, such as warping of the topmost layer of a deposited structure. This effect is often observed in thin-walled structures. [5]. The use of substrate cooling allows for more precise contours with reduced geometric deviations, especially in thin-walled geometries. Overheating can occur in this kind of structures due to impaired heat dissipation into the substrate [1].
Various concepts for the temperature control of the substrate work piece are found in the literature. In addition to the use of resistance [6] and induction heaters [3] the laser of the DED machine can also be used for preheating [7]. Substrate cooing is commonly achieved with the help of water cooling systems [8]. The effect of substrate heating and cooling on the entire deposited structure has been discussed in the literature. Within the scope of this work, an asymmetric temperature control platform is designed for the investigation of the local tempering of the substrate work piece. The design of this device is based on a concept of a multi sensor platform, developed for monitoring the

laser-based powder bed fusion process (PBF-LB) [9]. The objective of this work is the design of a platform that enables localized control of the cooling rate within a deposited structure. This device is intended to enable further investigations in which asymmetrical and local substrate tempering is achieved by combining heating and cooling processes.

2. Effect of the asymmetric substrate tempering

For the investigation of the effect of the local and asymmetric substrate tempering, a simulation model based on Ansys Mechanical was created. The DED-LB process was modelled using the Ansys Additive DED extension. Within this extension, individual elements are generated and activated at a process temperature of 1750°C, which corresponds to the melt pool temperature of the available DED machine. The material used for these investigations was 316L for the powder material and structural steel for the substrate material. Table 1 shows the parameters used for the simulation. The deposition of a simple single thin wall structure was considered with a length of 175 mm and height of 30 mm. The track width corresponds to the diameter of the powder nozzle available for future experiments.

Table 1 Simulation parameters of the DED-LB process

process temperature	1750 °C
deposition rate	24 mm³/s
element size	3 mm
layer height	3 mm
scanning speed	1000 mm/min
track width	3 mm
thin wall dimensions	175 x 30 mm

The model is based on a thermomechanical simulation, where first the thermal behavior of the deposition was determined, and afterward the mechanical behavior in form of the deformation was examined. For the investigation of the asymmetric tempering, two different temperatures were used: 150 °C and 300 °C. These temperatures were applied during the deposition at the center and end of the thin walls. During the deposition, the heat transfer between the deposition process and the tempering process is calculated. Furthermore, an idealized temperature control is assumed, ensuring that the specific temperatures at the respective locations remain constant throughout the deposition process. Figure 1 shows an exemplary simulation result of the deformation with the geometric model used in the simulation.

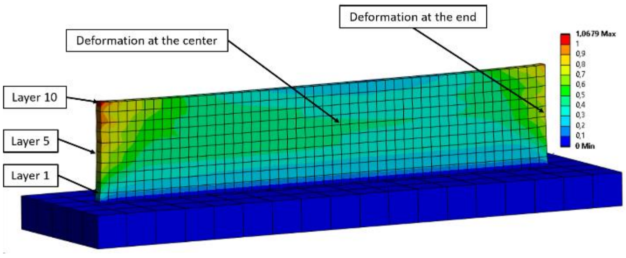


Figure 1. Geometric model of the deformation simulation

In Figure 2, the deformations at the center of the thin walls in each layer are illustrated for different tempering strategies documented in Table 3. The impact of local substrate tempering is clearly evident in this deception of the deformation. In the parameter set without local substrate tempering during deposition, a variation in deformation across different layers is observed. The deformation in parameter set two is lower, but an increase in deformation can be observed in the top layer. For parameter sets three and four with substrate temperatures of 300 °C, a broader distribution is noticeable. In some layers, the deformation is significantly below and above the initial state in parameter set one. Parameter set three, where the substrate work piece temperature was set to 150 °C at the center of the wall, shows a narrower distribution with the lowest deformation values, compared to the non-preheated substrate.

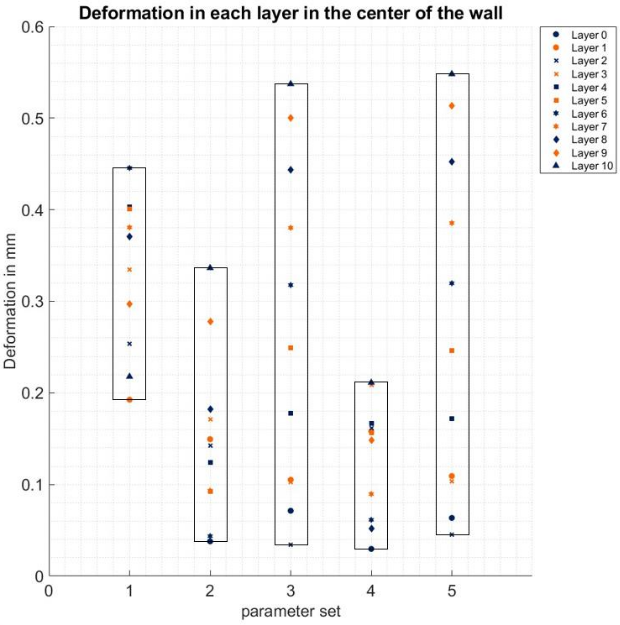


Figure 2. Deformation on each layer at the center of the wall

A similar influence was also found when examining the deformation at the ends of the walls, whereby the width of the distribution and the values of the change in deformation are significantly higher.

Table 2 Tempering strategies for the different samples

Parameter set	Center of the wall	End of the wall
1	-	-
2	-	150 °C
3	-	300 °C
4	150 °C	-
5	300 °C	-

3. Design of an asymmetric cooling

To investigate the impact of asymmetric substrate tempering on the DED-LB process, a specialized device has to be engineered to enable the implementation of asymmetric tempering within the DED-LB machine. The platform should consist of individual, modular elements whose temperature can be controlled as required to locally control the cooling rate of the deposited structures. These elements are implemented in the form of cuboids. Due to the large number of individual elements, the substrate temperature can be influenced in different local areas of the deposited structure. As part of the design of the asymmetric heating and cooling platform, the size and arrangement of these cuboid elements must be determined.

3.1 Determination of the element size and arrangement

The size and arrangement of the cuboid elements determines not only the resolution of the asymmetric tempering but also the size and geometry of the deposited structures, which are considered in the context of further investigations.

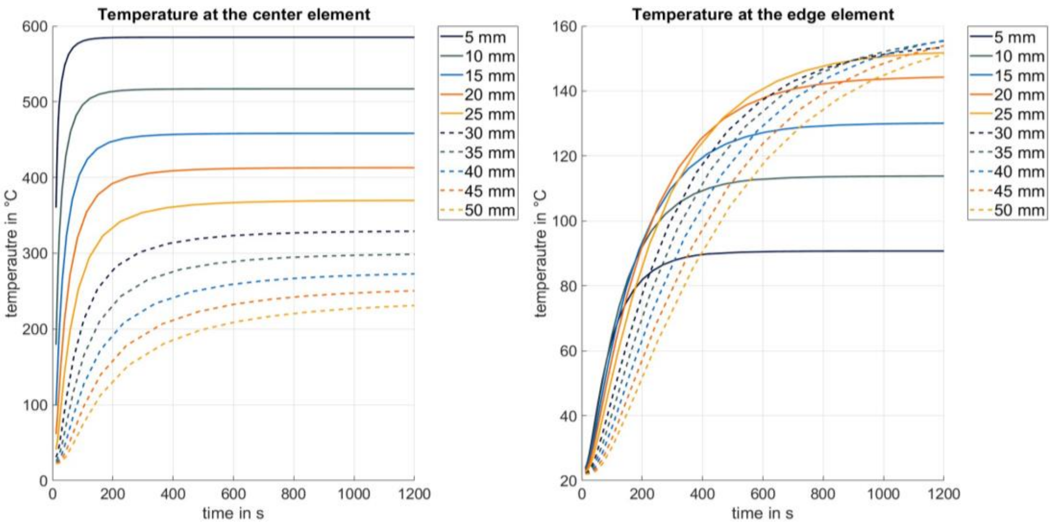


Figure 3. Temperature at the center and edge cuboid element

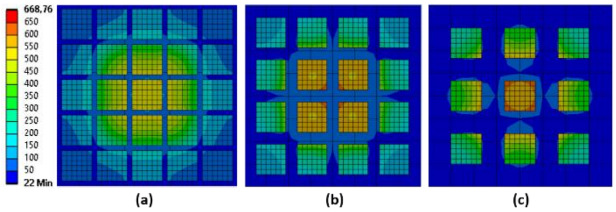
A thermal simulation of the design was carried out to determine the size and arrangement. The design consisted of a 180x180 mm baseplate on which cuboid elements with a height of 20 mm, different edge lengths and distances to each other were positioned. The edge length of the baseplate results from the requirement to achieve a system that is as compact as possible.This size limitation allows the investigation of smaller deposited structures in subsequent investigations, and thus reduces process times and powder consumption for economic reasons. Three different edge length were examined for the elements in a thermal model, 20 mm, 30 mm and 50 mm. By placing the cubes on the baseplate, the different. When placing the cubes on the given base area, the number of cubes resulted from the distance between the cubes. As part of the simulation, a square heat input was considered on a substrate plate placed on the cube. The temperature of the stationary heat input was 650 °C and the duration was 1200 seconds. The temperature results from previous simulations of the DED-process, where the temperature of the substrate surface immediately after the heat input of the laser was determined. During the simulation period, the temperature and heat flow of the individual elements were recorded. In the simulation, the cuboid elements with an edge length of 30 mm showed the best result regarding the resolution of the temperature distribution and thus the local substrate temperature control. Furthermore, this edge length provides sufficient resolution for temperature control and the accommodation of the heating and cooling technology. In terms of arrangement, three different grids of elements were compared, documented in table 3.

Table 3 Element arrangement

grid	distance between elements
5x5	5 mm
4x4	12 mm
3x3	22.5 mm

Thermal simulations with identical parameters as those used for determining the element size were conducted. The temperature and heat flux of the individual elements were recorded. In figure 4, the temperature distribution for different numbers of grid elements is shown. In the arrangement with fewer and a larger spacing between the elements, the temperature of the individual elements is higher, within the range of direct heat input. Therefore, the thermal power for the cooling and heating for each element is lower than for the grids with fewer elements.

Additionally, a higher resolution for influencing the substrate temperature is achievable with a smaller distance between the individual elements of the grid. A higher number of temperature-controllable elements not only allows for influencing the heat balance in multiple distinct areas but also enables more flexible experimental geometries. Therefore, a grid with 5x5 elements was determined for the design.



(a) (b) (c)

Figure 4. Temperature distribution (a) 5x5 grid, (b) 4x4 grid, (c) 3x3 grid

As part of additional thermal simulations, the impact of the thickness of the substrate plates on the measurable temperatures of all individual cuboid elements within the 5x5 grid was investigated. For this investigation, equal parameters were applied as in the simulations before. Figure 3 shows the temperature profiles of two of these elements, the cuboid element in the center and the edge. In the central element, the temperature rises quickly to a maximum value and remains at a constant value. The temperature can be clearly differential depending on the thickness of the substrate plate. This also applies to the edge element, although the temperature increase is lower, and no constant temperature is achieved for the thicker substrate plates during the considered simulation period. With these simulations, the heat flux of the deposition process could be documented as a function of the position of the element, regardless of the substrate thickness. This enables the localized influence of the heat flux at these individual points.

3.2 Determination of heating and cooling power

The thermal power required for cooling and heating the elements is determined by several factors. The thermal power needed for heating a single cuboid element from room temperature (22 °C) to 500 °C, the set limit temperature of the experiments, can be calculated by using the following assumptions. The thermal power required to heat an object to a certain temperature can be calculated by the following formula 1, where c_p represents the heat capacity of the used steel material, and m represents the mass of the element.

$$P_{heat} = c_p \cdot m \cdot \frac{\partial T}{\partial t} \tag{1}$$

$$P_{heat} = 434\ \frac{J}{Kg \cdot K} \cdot 0.1413\,kg \cdot \frac{(500\,°C - 22\,°C)}{60\,s} = 488.55\,W$$

The heat loss due to thermal radiation of the surface of the element can be calculated as follows, with formula 2 with the emissivity of the surface $\varepsilon_{rad} = 0.7$ and the Stefan Boltzmann constant $\sigma = 5.67 \cdot 10^{-8} W/(m^2K^4)$.

$$P_{Rad} = \varepsilon_{Rad} \cdot \sigma \cdot A \cdot \left(T_2{}^4 - T_1{}^4\right) \tag{2}$$

$$P_{Rad} = 0.7 \cdot 5.67 \cdot 10^{-8}\ \frac{W}{\left(m^2K^4\right)} \cdot 0.0045\,m^2 \cdot \left(500\,°C^{\,4} - 22°\,C^4\right)$$

$$P_{Rad} = 86.04\,W$$

Heat losses due to convection are calculated using formula 3, where h represents the heat transfer coefficient with stagnant ambient air, and A defines the surface of the cuboid element.

$$P_{conv} = h \cdot A \cdot (T_2 - T_1) \tag{3}$$

$$P_{conv} = 4\ \frac{W}{m^2} \cdot 0.0045\,m^2 \cdot (500\,°C - 22\,°C) = 11.162\,W$$

By adding the thermal power and the power that must be applied to compensate for the losses, a power of $P_{Heat} = 585.75\,W$ is required. To compensate for thermal losses due to heat conduction, which were not considered in this calculation, the heating power is provided with commercially available resistance heating cartridges with an output of 750 W are integrated for the heating process.

To determine the thermal power for the cooling operation, the heat flux at the center element of the platform was analyzed. The thinnest substrate plate shows a maximum heat flux in the first 200 seconds of 1.4 W/mm². To neutralize this heat flux, the central element needs a cooling power of 1440 W to bring the element down to room temperature.

3.3 Design of the asymmetric temperature control platform

Figure 5 shows the resulting design of the asymmetric temperature control platform. The platform consists of the predetermined 25 cuboid elements with an edge length of 30 mm and a height of 20 mm. The sectional view shows a hole for the heating cartridge and channels for water cooling. The individual elements are positioned on a baseplate, in which connection options for the energy and water supply are also to be integrated. Furthermore, thermocouples are integrated into the individual elements to record the thermal behavior of the process.

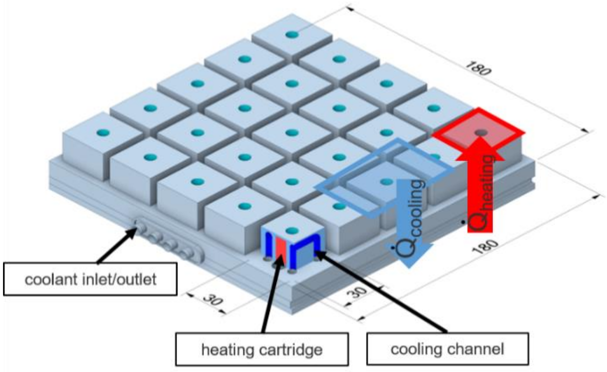


Figure 5. Final design of the asymmetric heating platform

4. Conclusion

In this work, the design process of an asymmetric temperature control platform for the DED-LB process was considered. In the course of the development process, the basic design of the platform was defined in the form of a system of modular elements, and the size and arrangement of the elements were determined. Furthermore, the required thermal performances were estimated. A grid of cuboid elements with an edge length of 30 mm was determined for the monitoring and influencing of the local heat fluxes. In further steps, the construction and manufacturing of the developed design will take place. This work serves as the foundation for further investigations into asymmetric substrate tempering. In subsequent research, the platform will be utilized to investigate the effect of locally influencing the cooling rate for simple thin walled structures. Additionally, heating and cooling strategies and a temperature control system need to be developed to influence the properties of these deposited structures.

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