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INFLUENCE OF THE SUBSTRATE SIZE ON THE COOLING BEHAVIOR AND PROPERTIES OF THE DED-LB PROCESS

The laser-based Directed Energy Deposition (DED-LB) process involves a complex thermal history which strongly de-pends on the geometry of the deposited structure and substrate. The thermal mechanisms of the process are highly influenced by key process parameters like laser power, powder mass flow and scanning speed. Additionally, the size of the substrate influences the cooling behavior. The cooling behavior can be externally influenced and controlled by tempering the substrate, for example using a laser preheating method. The control of the cooling rate is crucial to ensure consistent properties and maintain constant conditions for subsequent finishing processes, irrespective of the size and geometry of the deposited structure and substrate. In this work, the influence of the substrate size on the cooling behavior and the properties of DED-LB manufactured structures is determined. The deposition of a cube with an edge length of 30 mm on different sized substrates and different cooling rates was simulated and executed. The impact of the different cooling behavior is evident in the hardness and the residual stresses of the deposited structures. Furthermore, the effect can be observed during a subsequent milling process. This work enables the creation of a model for the determination of the cooling rate and part properties depending on the substrate size.

1. INTRODUCTION AND STATE OF THE ART

Additive manufacturing processes (AM) facilitate the production of intricate three-dimensional structures that are difficult to produce using traditional, subtractive methods. The laser—and powder-based Directed Energy Deposition process presents an appealing and adaptable solution for manufacturing such components. Beyond the generation of complex part geometries, DED–LB finds application in repair and coating tasks. In contrast to powder bed-based manufacturing processes (PBF), the DED–LB process exhibits a higher build rate, rendering it suitable for larger industrial applications. In the DED–LB process, a focused laser beam is melting the surface layer of a substrate workpiece while also melting a metallic powder material that is being deposited into the created melt pool. In addition to the production of complex three-dimensional parts, the DED–LB process is also used for repair and coating applications [1].

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This deposition process is a highly complex thermal process. The rapid melting of the substrate surface and the powder material is followed by the rapid solidification and cooling of the generated structure, with cooling rates ranging from 103 up to 104 K/s. During the build process in layers, the cooling behavior of the deposited layers is affected by the heat input of the subsequent layer. This alternating thermal process results in the creation of a distinctive microstructure, resulting from numerous phase transformations during the deposition. [2]

The thermal mechanisms of the DED-LB process are strongly influenced by key process parameters, such as laser powder, powder mass flow and the traveling speed of the deposition head. Furthermore, the geometry of the deposited structure and the size of the substrate workpiece have a large influence on the cooling behavior.

Silveira et al. [3] identified different heat cycles, which are significantly responsible for the microstructure development during the melting of the powder and substrate material and the subsequent reheating of deposited layers. The thermal equilibrium and varied cooling rates within the structure affect these heat cycles and the generation of the microstructure. The transformation mechanisms of a microstructure can be controlled by regulating the heat balance and the cooling rate within the deposited structure. A characteristic of thermomechanical manufacturing processes is the generation of residual stresses within the microstructure. These thermal stresses occur along the grain boundaries due to the higher contraction between the upper, hotter layer and the underlying colder layer, or substrate material [4].

The thermal history, particularly influenced by parameters such as the heating and cooling rate and the temperature gradient, plays a pivotal role in determining the morphology and grain size. Saboori et al. [2] highlight the importance of these parameters for microstructural features and mechanical properties. The most effective parameters include the local solidification rate, the temperature gradient and the growth rate of the grains. The optimal values of temperature gradient and growth rate are affected by the component geometry, environmental conditions, and material properties. During further investigations, the impact of the heat balance on the microstructure was examined. The variation in microhardness along the build direction highlights the significant role of the cooling rate in the microstructural development. Farshidianfar et al. [5] observed the influence of the cooling behavior on the microstructure of 316L stainless steel. Both the size of the solidification structure and the type of the solidification mechanism are determined by the cooling rate, according to the study. Due to different cooling rates in the deposited structure, the hardness varies over height in the conventional DED–process. In this investigation, a uniform hardness profile could be achieved in a deposited structure by influencing the cooling rate.

The thermal behavior, the temperature gradient and the growth rate can be influenced by the process parameters. However, this adjustment is not possible arbitrary, as otherwise an unstable deposition process may occur. Once the potential for adjusting the process parameters has been maximized, external measurers like tempering the substrate can influence the cooling behavior. Heating the substrate slows down the cooling rate by minimizing the temperature difference between the substrate and the deposited structure. Apart from resistance [6] and induction heating [4], the laser of the DED machine is also used to for substrate preheating [7]. Water cooling systems are typically used to cool the substrate workpieces [8].

The influence of the process parameters on the microstructure has been widely discussed in the literature. In the industry, process parameter combinations are specified independently of the substrate size. However, the substrate size has a significant influence on the cooling behavior and, therefore, on the workpiece properties. The larger the substrate workpiece, the more the thermal losses during deposition and the higher the cooling rate. With constant process parameters, different workpiece properties can therefore arise depending on the substrate size.

Additively manufactured components often lack the necessary geometric precision and surface quality, necessitating subtractive post-processing. Möhring et al. [9] showed that in the additive-subtractive process chain, the thermal behavior of the deposited structures has a significant influence on subsequent machining operations. In order to ensure the quality of the subsequent machining processes, the properties of the deposited structures must be known. Within the scope of this study, an examination of the impact of the substrate size and the resulting varying cooling rates on the workpiece properties and the additive subtractive process chain is investigated.

2. A SIMULATION-BASES VIEW ON THE INFLUENCE OF THE SUBSTRATE SIZE ON THE COOLING BEHAVIOR

The influence of the size of the substrate workpiece on the cooling behavior of the DED LB process was considered as part of a model analysis at the beginning of the investigation. The DED–LB process was modeled as part of a thermal simulation in Ansys Mechanical. The material deposition was simulated using the DED extension. This extension is based on the same "death/birth" model as documented in [10]. The material deposition is modeled via the generation and activation of individual elements with the process temperature. The buildup of the elements follows a predefined G-Code. The process temperature at which the individual elements were activated was 1750°C. A value of 3 mm was used for the width of the tracks. The process temperature and the width of the melted tracks correspond to the melt pool temperature and the diameter of the powder nozzle of the deposition process discussed in the following chapter. Overlapping of the individual melted tracks, which is required in the real DED process for sufficient fusion of the melted tracks with each other and to produce components with a high density, cannot be considered in this simulation model. Therefore, a layer height of 3 mm was specified instead of the 1.6 mm used in the actual process. The parameters utilized in the simulation of the DED process are listed in Table 1. These parameters remained constant throughout all subsequent simulations.

For the simulation of the thermal behavior of the DED process with different sized substrate workpieces, a deposition geometry in the form of a cube with an edge length of 30 mm was viewed. The deposition of the cube was simulated for two different-sized substrate workpieces. A substrate workpiece with dimensions of 100 mm × 100 mm × 10 mm is often used for the development of process parameters. An example of a structural component undergoing a deposition process as part of a repair process is a substrate workpiece measuring 200 mm × 200 mm × 100 mm. For the boundary conditions of the substrate plate, thermal losses in form of heat conduction were neglected. This made it possible to generate equivalent cooling conditions in the simulation, and for the real deposition tests documented in Chapter 3 because the heat conduction into the complex structure of the table of the DED machine did not have to be modeled. During the deposition and cooling process, thermal losses in the form of convection and thermal radiation were considered.

Table 1. Parameters of the DED simulation

process temperature	1750°C
deposition rate	24 mm^3/s
layer height	3 mm
scanning speed	1000 mm/min
track width	3 mm
edge length of the cube	30 mm

Figure 1 illustrates the models of the thermal simulations of the deposition process of a cube with an edge length of 30 mm on the two different substrate sizes, immediately after the deposition. The images of the thermal solution show that the temperature immediately following the deposition process of the small substrate, Figure 1 is significantly higher than that of the larger one. A temperature difference between the cubes is also visible. During the simulation, the temperature profile at the center of the cube is measured for each of the 10 layers. Figure 2 shows the temperature profile of the 10 deposited layers over time, as well as the trend curve of the temperature of the first layer.

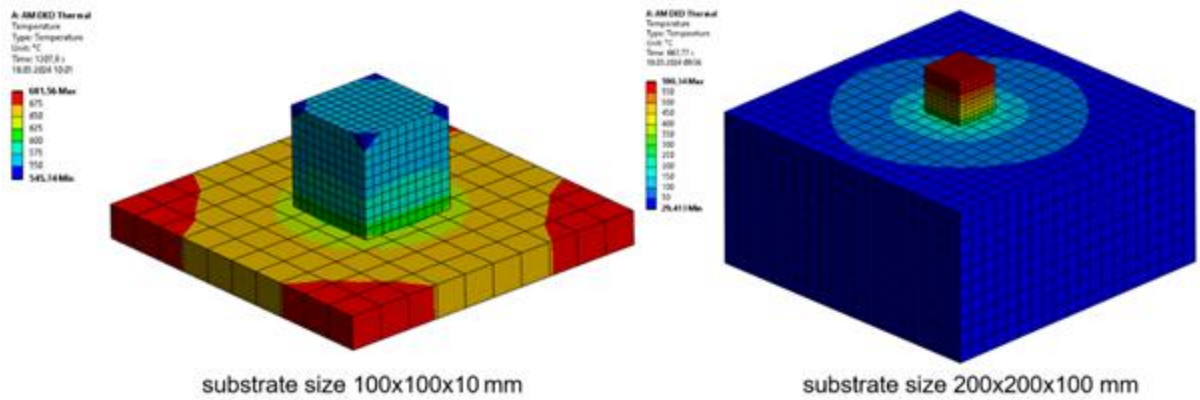

Figure 1. Thermal Simulation of the deposition process of a cube with an edge length of 30 mm

The temperature profiles of the two different substrate sizes show a clear difference in the temperature of the individual layers. While the temperature of the smaller substrate increases, the temperature of the larger substrate decreases. The decrease in temperature is attributed to the elevated heat losses that are incurred due to the larger substrate workpiece. Due to the larger amount of material present under the heat-affected zone of the deposited structure, more heat is dissipated from the melt pool, as the heat conduction depends on the thickness of the material. Furthermore, because of the bigger surface, the thermal losses in form of convection and thermal radiation are higher in comparison to the smaller substrate.

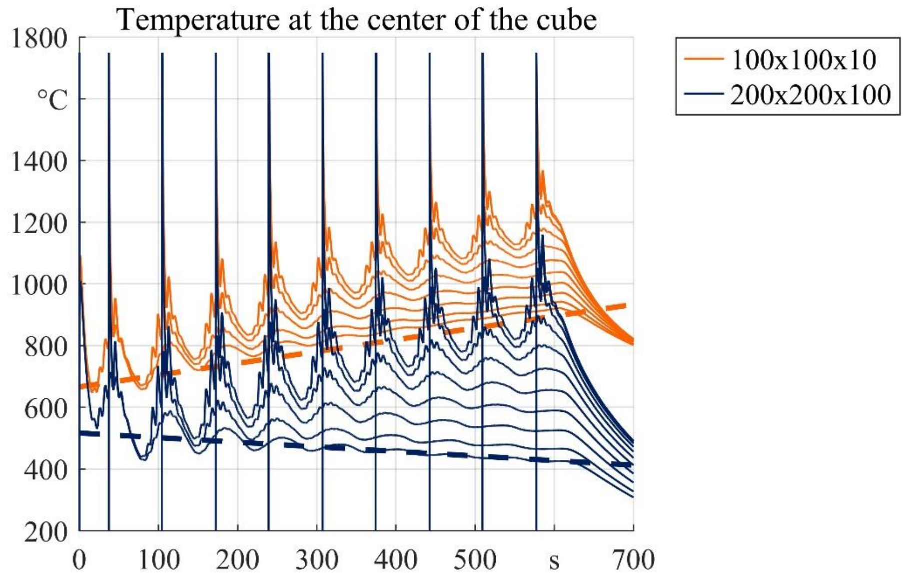

Figure 2. Temperature profile at the center of the cube in dependence of the substrate size

After the deposition process, at about 600 seconds, the cooling phase beings. The deposited structure is cooled at different cooling rates, depending on the size of the substrate. As a result of the higher temperature of the deposited structure resulting from lower thermal losses during the deposition, the deposited cube cools more slowly on the small substrate. Since no substrate workpiece with dimensions 200 mm × 200 mm × 10 mm was available for the subsequent real deposition experiments, a substrate workpiece with the dimensions 200 mm × 95 mm × 35 mm was used. A thermal simulation of the cube deposition was conducted for this substrate size. Figure 3 shows the temperature profile of this substrate size compared to the substrate with a size of 100 mm × 100 mm × 10 mm. The difference in size of the real substrate workpieces is significantly smaller than of the initial workpieces in the simulation. However, there is still a big difference between the temperature profile and the cooling rate. The substrate with a size of 200 mm × 95 mm × 35 mm shows only a slight difference in absolute temperature after 700 seconds, compared to the previously considered workpiece with a size of 200 mm × 200 mm × 100 mm.

During the simulations of the two larger substrate workpieces, a faster cooling behavior could be shown in comparison to the initial substrate plate with the dimensions of 100 mm × 100 mm × 10 mm. To replicate a slower cooling behavior, a simulation involved preheating the substrate plate measuring 100 mm × 100 mm × 10 mm to 500 °C. Slow cooling behavior can arise from both small substrate sizes and heat accumulation within the de-posited structure. Heat accumulations occur when the geometry of the deposited structure or the substrate does not allow sufficient heat dissipation from the deposited structure. Preheating the substrate reduces the temperature difference between the deposited structure and the substrate. The reduced temperature difference decreases the thermal losses and this slows the cooling. In Figure 4, the thermal simulation of the cube's deposition on the preheated substrate was compared to the deposition process on the non-preheated substrate of the same size. As expected, the temperature profile of the preheated substrate workpiece is higher. When looking at the cooling curves, it is clear that a slower cooling of the preheated sample can be seen.

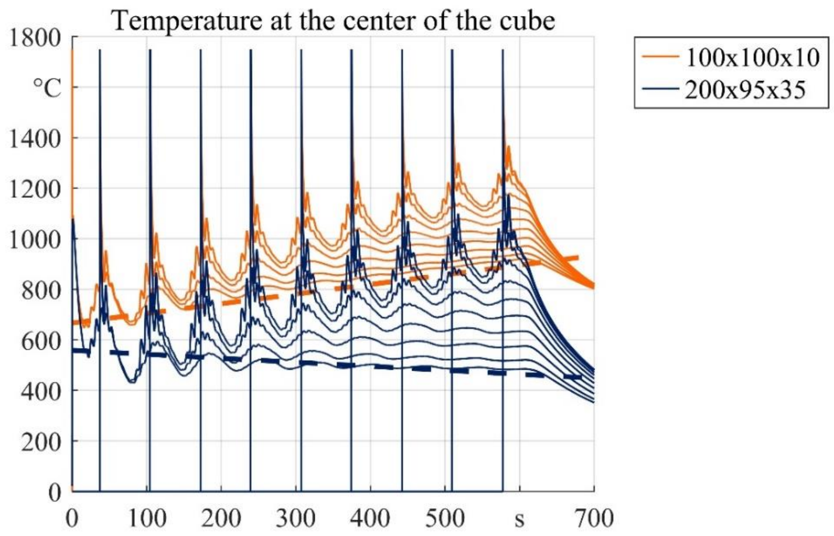

Figure 3. Temperature profile at the center of the cube for real substrate sizes

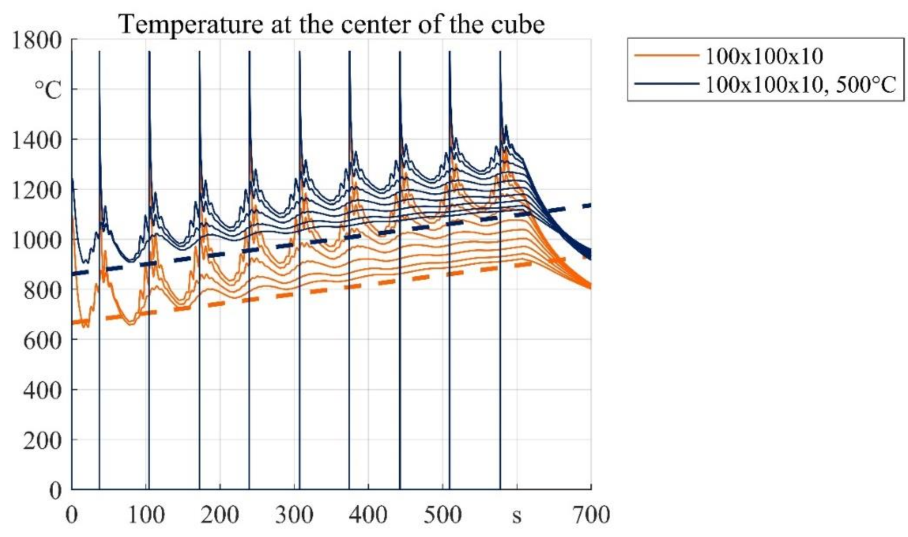

Figure 4. Temperature profile preheated and non preheated substrate

In this chapter, thermal simulations of the DED process were conducted using substrate workpieces of differing dimensions and substrate temperatures. The simulations revealed that, even with the constant DED process parameters, different temperature profiles and cooling characteristics emerge, depending on the substrate's dimension and temperature. As described in Chapter 1, the workpiece properties of the created structures are deter-mined by their cooling rate. The simulation results indicate that, despite constant DED process parameters, different workpiece properties occur in the deposited structures. When determining process parameters for the DED-LB process, the size of the substrate workpiece is usually not considered. Due to variations in cooling conditions, different ma-terial/part properties may occur in processes using identical process parameters. The cooling conditions can be influenced by factors such as differing substrate geometries and sizes, as well as the geometry of the deposited structure. Heat dissipation from the deposited structure into the substate workpiece and the machine periphery can be impeded. This creates zones in which heat accumulates, affecting the cooling rate and therefore the work-piece properties. The influence of the substrate size and temperature on the workpiece properties and subsequent finishing processes will be examined in the subsequent stage of this study.

3. INVESTIGATION OF THE INFLUENCE OF DIFFERING COOLING RATES ON THE WORKPIECE PROPERTIES

3.1. EXPERIMENTAL SETUP

For the investigation, the deposition of cubical structures with an edge length of 30 mm were conducted with the help of the DMG Mori LT 65 DED Hybrid machine. Two different materials were considered for the deposition: 316L stainless steel and a wear resistant material commercially available under trademark Ferro55.

The chemical properties of 316L are shown in Table 2. This austenitic steel is used in various applications due to its excellent corrosion resistance and versatile mechanical properties. Ferro55 is a cast steel alloy that is used where high strength, hardness and wear resistance are required. The 316L powder has a particle size distribution of 45–90 µm, while Ferro55 has a particle size distribution of 45–125 µm. The process parameters and geometric parameters for the build strategy used for the deposition process were specially developed by the machine manufacturer for this application.

Table 2. Chemical properties of 316L

C	Cr	Ni	Mo	Si	Fe
0.018%	17.8%	11.9%	2.3%	0.2%	balanced

Table 3. Chemical properties of Ferro55

C	Cr	Mo	Mn	Si	Fe
0.35%	7%	2.2%	1.1%	0.3%	balanced

For the substrate workpiece, structural steel with the sizes 200 mm × 95 mm × 35 mm and 100 mm × 100 mm × 10 mm, was used, similar to the simulation-based investigation in Chapter 2. A cube of 316L and Ferro55 was deposited on each of these substrate workpieces, shown in Fig. 5. For the deposition, the substrate workpieces were placed on a vermiculite plate. Vermiculite is an insulation material with a thermal conductivity value of 0.07 W/mK. With the help of this insulation, it was possible to create conditions equivalent to those in the simulations.

To examine the impact of the substrate temperature on the workpiece properties, 316L and Ferro 55 cubes were built on both a preheated and non-preheated substrate plate. The substrate plates were preheated to 500 °C using the laser preheating method developed by the IfW in cooperation with DMG Mori [7]. In order to avoid externally influencing the cooling behavior, it was ensured that all specimens could cool down on the machine table under the same conditions during preparation. For the subsequent investigation of the hardness and residual stresses, the top of the cubes was milled off to obtain a smooth sur-face. Hardness measurements of at the top surface were performed and calculated by the Vickers principle. The residual stresses were measured with a Stresstech DR45 X-Ray diffractometer. An electropolishing process was used to determine the residual stresses over the depth, thereby ensuring that the residual stresses from the previous milling process did not influence the measurement results.

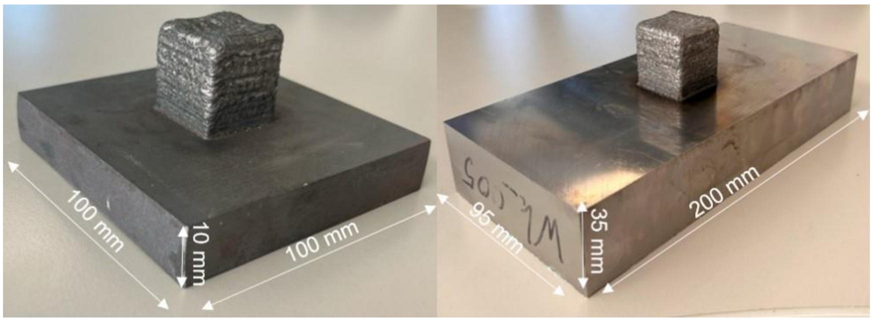

Figure 5. Deposited cubes on different sized substrates

Milling tests were carried out on the end faces of the cubes. During the milling process, the samples were placed on a force measuring platform. The experimental setup for the milling of one of the Ferro55 samples is shown in Fig. 6.

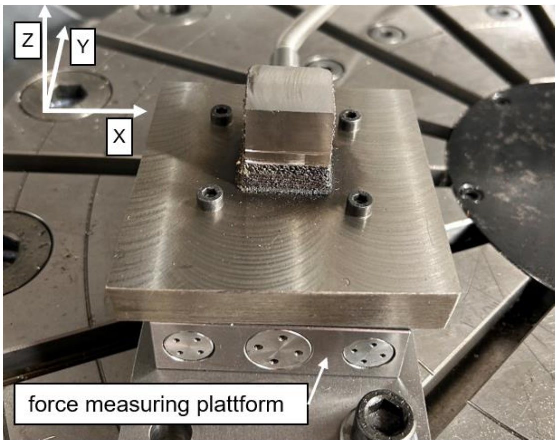

Figure 6. Experimental setup milling experiments

With the help of this device, the cutting force in Y-direction was measured during milling. The milling tests were performed with a end mill with a diameter of 10 mm and 5 cutting edges, with a cutting speed of 80 mm/min and a feed per tooth of 0.05 mm per tooth. The maximum lateral adjustment was 0.5 mm per cut. After a calibration cut in which the surface was cleaned, measuring cuts were made on each of two sides of the cube, during which the forces were recorded.

3.2. RESULTS AND DISCUSSION

Figure 7 shows the result of the hardness measurement on the surface of the milled cubes. When examine the hardness of the Ferro55 samples, a contrary effect becomes apparent. The hardness of the cube on the preheated substrate is higher. This phenomenon was also noted by Schöcker et al. [11], who observed an increase in hardness of DED manufactured Ferro55 structures up to a temperature of 575°C during their investigations of different heat treatment methods. Preheating the substrate workpiece can be seen as a type of heat treatment. This is one possible explanation for the increase in hardness. The cubes, manufactured from 316L, exhibit the expected image upon hardness examination. The cube on the big substrate shows a higher, the cube on the preheated substrate shows a lower hardness. Higher hardness is observed in the cube deposited on the larger substrate, attributed to the increased cooling rate. The degree of heat dissipation from the deposited structure increases proportionally the substrate size. The larger the substrate workpiece, the greater the thermal losses in form of heat conduction, heat radiation and convection. Compared to the initial sample, the non-preheated substrate workpiece, preheating the substrate workpiece significantly slows down the cooling of the cube. This favors grain growth and results in a structure with a lower hardness.

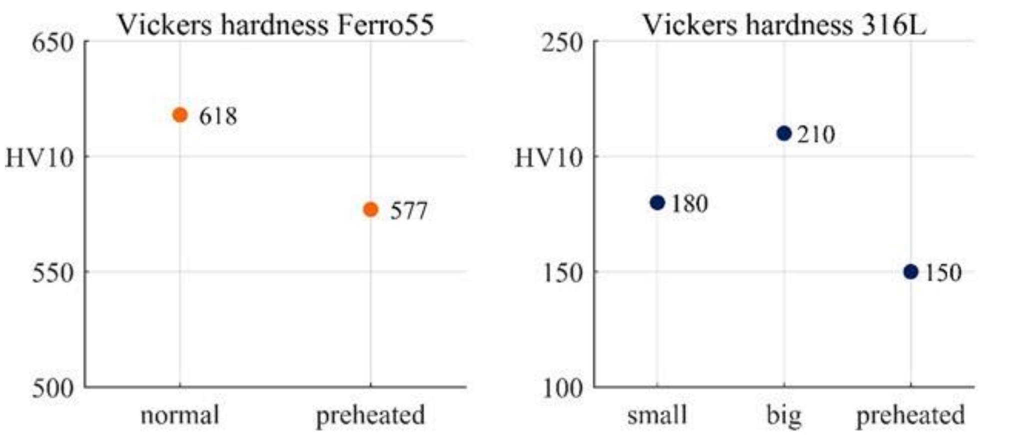

Figure 7. Vickers hardness for the Ferro55 and 316L samples

Nevertheless, the hardness measurement reveals the influence of the substrate size and the associated cooling rate on the hardness of the deposited structure. Particularly with large substrate workpieces, such as those used in repair processes, the DED-LB-generated structure can lead to areas with a significantly different hardness.

The influence of the cooling rate on the residual stresses was investigated with the pre-heated and non-preheated samples. In the remainder of this work, the non-preheated substrate workpiece ist refered in Fig. 8, the results of the X-ray diffractometer measurement for the Ferro55 and 316L samples are shown. The residual stresses were measured in 5 µm steps up to a maximum depth of 20 µm. The results show the same trend between the preheated and non-preheated samples for both materials. In the preheated samples with a lower cooling rate, the compressive residual stresses are lower. Compared to the residual stress values of the Ferro55 samples, the 316L samples show a higher scatter. This scatter results from the measurement conditions and the available chromium X-ray tube in com-bination with the high chromium content of 316L. For the Ferro 55 samples, the residual stresses between the preheated and non-preheated samples are almost identical up to a depth of 5 µm. At a depth of 10 µm, the stresses are lower in the preheated sample. At the surface of the 316L samples, the residual stresses differ between the preheated and non-preheated sample. Preheating the substrate for the 316L samples also leads to reduced residual stresses on the top surface of the cube.

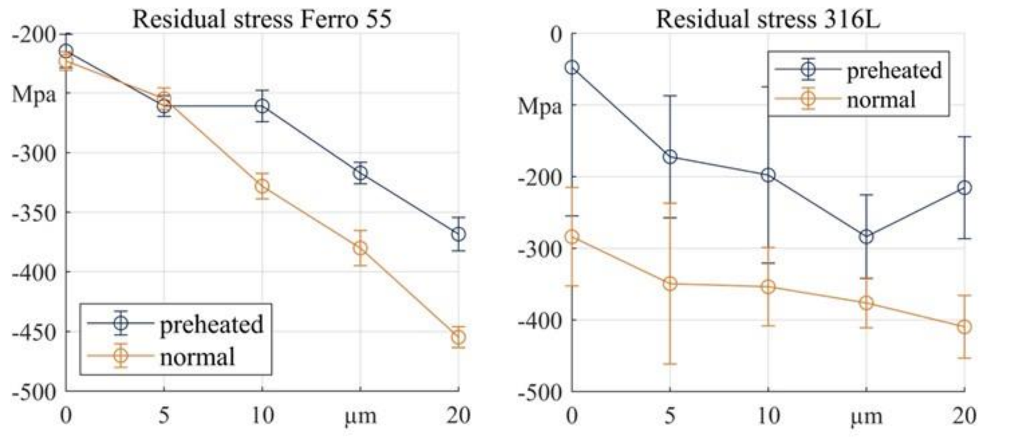

Figure 8. Residual stresses of Ferro55 and 316L samples

The results show the influence of the cooling rate on the residual stresses in the de-posited structure. A slower cooling rate s results in a decrease in residual stress. The influence of the cooling rate and the substrate size on the residual stresses must be considered when designing structures to be deposited and for subsequent machining operations. The influence of the cooling rate on the workpiece properties can also be seen when looking at the machining forces of the milling tests, shown in Fig. 9.

The cutting forces of Ferro55 were higher for the preheated sample than for the non-preheated sample. The difference in cutting force between the two samples is 28 N. The disparity in cutting forces was greater for the 316L samples compared to the Ferro55 samples. Here, the difference equates to approximately 100 N. An unpaired t-test was carried out as part of the analysis of the cutting forces. The t-test indicates that there is a significant difference between the mean values of the preheated and non-preheated samples, and this difference is not the result of outliers in the measured cutting forces. The results of the investigation of the machining process show the influence of the slower cooling rate and the size of the substrate workpiece on the cutting force. It can be concluded, that the cooling behavior has a statistically significant influence on the cutting forces.

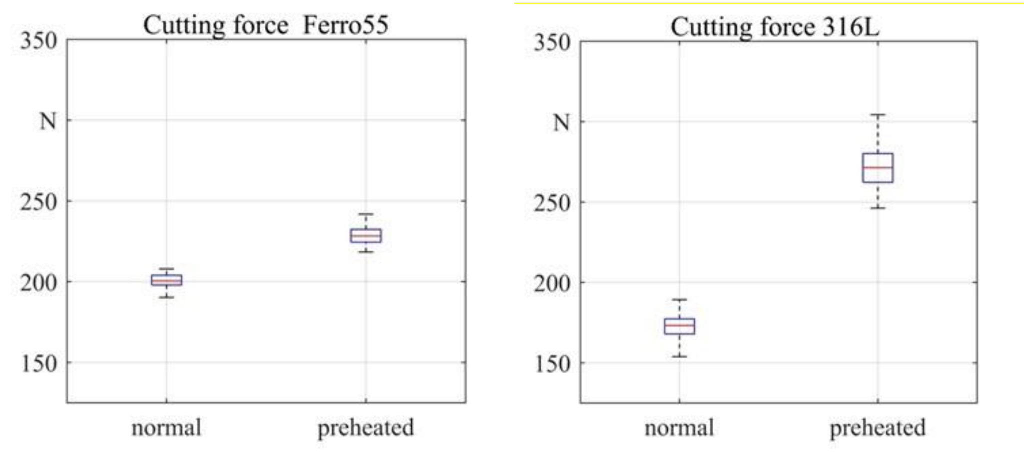

Figure 9. Cutting forces of Ferro55 and 316L samples

4. CONCLUSION AND SUMMARY

In the course of this investigation, the influence of the size of the substrate workpiece and the cooling rate on the part properties of the DED-LB process was investigated. A simulation-based observation of the deposition process of a cube on substrate workpieces of different sizes revealed varying thermal behavior during the build and the cooling process. A correlation between the substrate size and the cooling behavior could be established. Large substrate workpieces result in a higher cooling rate, when considering constant DED-LB process parameters. A similar effect was observed during the substrate preheating. With the help of substrate preheating, slow cooling behavior could be reproduced. This cooling behavior occurs, for example, with small substrate workpieces or with heat accumulations in the deposited structures. The cooling behavior becomes slower as the temperature of the substrate workpiece increases.

The effect of the substrate size and the associated influence on the cooling behavior could be confirmed in real deposition tests with two different powder materials. Investigating the workpiece properties could determine the influence of the cooling behavior on the hardness, the residual stress, and the machining forces of a milling operation. Different substrate sizes lead to different harnesses, residual stresses, and cutting forces.

The process parameters for different powder materials for the DED-LB process are often specified in the industry for different deposited geometries, e.g., for three-dimensional or thin-walled structures. The size of the substrate workpiece is not considered. The investigations carried out in this work have shown that different substrate sizes lead to different workpiece properties. Particularly in the context of repair and coating processes with the DED-LB process, when small geometries are generated to large preform parts, this can result in strongly varying workpiece properties. To achieve constant proper-ties, the cooling rate of the DED-LB process must be adjusted depending on the substrate size, either by controlling and adjusting the process parameters or by externally influencing the cooling behavior. The influence of the substrate size on the workpiece properties is still the subject of further investigations, in which particular attention will be paid to determining the cooling rates and linking these thermal parameters with specific workpiece properties. Furthermore, the external influencing of the cooling behavior will be investigated.

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