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Experimental Investigation of Temperature Distribution during Wire-Based Laser Metal Deposition of the Al-Mg Alloy 5087

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Abstract. Wire-based laser metal deposition enables to manufacture large-scale components with deposition rates significant higher compared to powder-based laser additive manufacturing techniques, which are currently working with deposition rates of only a few hundred gram per hour. However, the wire-based approach requires a significant amount of laser power in the range of several kilowatts instead of only a few hundred watts for powder-based processes. This excessive heat input during laser metal deposition can lead to process instabilities such as a non-uniform material deposition and to a limited processability, respectively. Although, numerous possibilities to monitor temperature evolution during processing exist, there is still a lack of knowledge regarding the relationship between temperature and geometric shape of the deposited structure. Due to changing cooling conditions with increasing distance to the substrate material, producing a wall-like structure results in varying heights of the individual tracks. This presents challenges for the deposition of high wall-like structures and limits the use of constant process parameters. In the present study, the temperature evolution during laser metal deposition of AA5087 using constant process parameters is investigated and a scheme for process parameter adaptions in order to reduce residual stress induced componential distortions is suggested.

Introduction

The concept of adding material layer-by-layer is the key methodology in additive manufacturing (AM) and opens a large degree of freedom from design point of view [1, 2]. Since its development, predominately powder-based techniques such as selective laser melting (SLM) were investigated [3, 4]. Using AM it is possible to build parts with an increased degree of freedom and material utilization compared to conventional subtractive manufacturing techniques [3]. The deposition rate of powder-based AM is lower compared to wire-based laser metal deposition (LMD). Using wire raw material instead of powder enables deposition rates of more than 2 kg/h in case of aluminum, which is an immense increase compared to powder-based approaches working with around 200 g/h. Therefore, and because of its easy adaptability on well-known industrial manufacturing systems such as robots, wire-based LMD continuously gained importance during the last decades. Indeed, manufacturing additive parts using high deposition rates also induces new challenges. Higher laser inputs in order to process high throughput AM are required. For this reason laser powers of several kilowatts in case of wire-based LMD in contrast to only a few hundred watts for powder-based AM have to be used [3, 6]. AM of metallic parts is very sensitive to temperature with respect to aspects such as distortional behavior as well as microstructural development. Due to this, temperature monitoring turned out to be a very important tool in AM. In case of high process temperatures and temperature gradients during the process, side effects such as heat accumulation and residual stress induced part distortions can occur. These challenges, which were already known from powder-based AM [6], impair drastically for LMD using wire-material. Therefore, the necessity of a deeper understanding in order to develop effective counteractive measures is underlined. Object of the present study is the investigation of temperature profiles during wire-based LMD of wall-like Al-Mg alloy structures using three constant process parameter sets as well as the development of an approach to reduce occurring distortions.

Experimental Setup

For the experiments an 8 kW continuous wave ytterbium fiber laser YLS-8000-S2-Y12 integrated with an optical head YW52 Precitec and implemented in a CNC-supported XYZ-machining center (IXION Corporation PLC) was used. The aluminum alloy AlMg4.5MnZr (EN AW-5087) as wire material with a diameter of 1 mm and AlMg3 (EN AW-5457) as substrate material with a thickness of 3 mm were processed using three process parameter sets. The parameters are shown in Table 1, whereas Fig. 1 shows a schematic visualization of the unidirectional LMD process using local argon shielding. The time between the depositions of two layers was kept constant to 60 seconds. This ensured a sufficient cooling of the structure in such a way that the deposited track was completely solidified and able to remain its shape during the deposition a following layer.

Table 1: Process parameters used in LMD experiments.

Parameters	Set 1	Set 2	Set 3	Unit
Rayleigh Length	24.55	24.55	24.55	mm
Focus Position	+23	+23	+23	mm
Spot Diameter	1.6	1.6	1.6	mm
Laser Power	4000	4500	4500	W
Deposition Rate	1.27	1.91	2.55	kg/h
Travel Speed	1	1	1	m/min
Shielding Gas Flow Rate	10	10	10	l/min
Number of Layers	3, 5	3	3	-

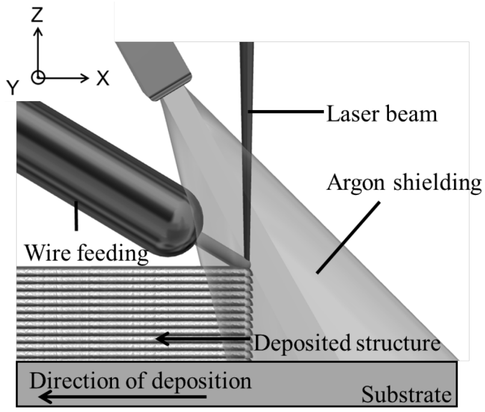


Figure 1: A schematic drawing of the deposition of a wall-like structure.

In order to analyze the temperature distribution during the LMD process at different positions, three thermocouples were employed for temperature assessment. They were inserted from the backside of the substrate material located at a depth of 0.5 mm. The temperature measurement was conducted for a layer length of 100 mm. For this purpose, the thermocouples were positioned directly under the deposition track and had an interspacing of 35 mm starting 15 mm after the beginning of the deposition of the layer. To conclude a relationship between the temperature distribution during the process and resulting distortions, laser triangulation using a Micro-Epsilon optoNCDT measuring device was used for assessing the specimen geometry after the process. Prior to LMD, a clamping on all four edges of the substrate was applied, which was removed after the process, leading to distortions due to releasing residual stresses.

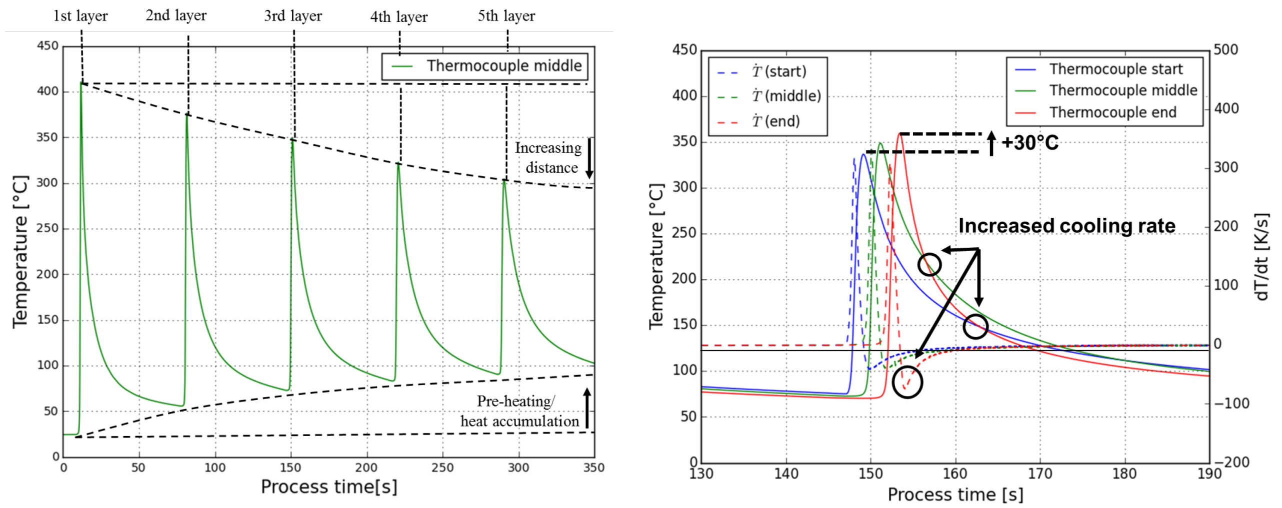
During the deposition, the wire but also the substrate were partly molten. By this, the wire material was joint to the substrate, yielding in a very high bonding such as in an as-welded configuration. Because of the contraction of the material during solidification, high tensile stresses especially within the LMD structure predominately along the deposition axis occur. These stresses also affect the substrate. When these stresses exceed the yield stress of the material, plastic deformations of the structure as well as the substrate material occur. This so-called temperature gradient mechanism resulting in componential distortions is already long time known from laser beam welding and used in laser forming processes [7]. With respect to the process stability, these distortions impede the accurate positioning of the wire during the deposition of a subsequent layer.

An additional phenomenon is that the tensile stresses show its highest values in the beginning and ending regions of the deposited layer [6]. Due to this, the deposited material may partly separate from the substrate in those regions, which is known as delamination effect. In case of multi-layer deposition, these effects may accumulate for each additional layer on top of the structure.

Results and Discussion

The temperature profile of a 5-layer deposition using parameter set 1 is depicted in Fig. 2(a). It shows a peak temperature of around 400°C during the deposition of the first layer. The resulting deposition height of a single layer is 2.5 mm, which is the additional distance per added layer between the thermocouples and the deposition position, respectively. Due to this increasing distance, the peak temperature in Fig. 2(a) decreases for each added layer. This measurement configuration reveals information about the thermal history of the LMD structure during the deposition of additional layers. This allows the gain of deeper knowledge about the development of occurring temperature gradients within the LMD structure, which have a strong influence on the residual stress development.

During multi-layer LMD, the distance between the substrate and the actual deposited layer increases for each additional layer. By this, the heat transfer condition change. Whereas the heat predominantly conducts into the substrate for the first LMD layers, this reduces for increasing number of layers. The heat has to transfer more material for each additional layer, which takes more time and supports the phenomenon that the structure did not cool down to room temperature before the next layer is added. This effect is additionally intensified by the fact that the thermal conductivity of aluminum decreases for higher temperatures [8]. By this, the structure heats up for each additional layer and a heat accumulation especially in the center of the structure results. This heating effect during multi-layer LMD decreases the temperature gradient and the resulting residual stresses do not exceed the yield stress of the deposited material anymore. Therefore, low or no additional distortions of the LMD structure after the deposition of several layers occur. This also implies that the highest distortions develop after the deposition of the first LMD layers, if no external pre-heating is applied. Additionally, it was found that LMD of aluminum using pre-heated material is also beneficial in terms of the reduction of porosity and hot tearing, which improves the stability of the LMD process using a continuous deposition. As also shown in Fig. 2(b) the peak temperature slightly increases to the end of the deposition. This is basically reasoned in the increased absorptivity of aluminum for higher temperatures [9].



(a) (b)

Figure 2: Temporal temperature profile for a 5-layer deposition using parameter set 1 at the middle of the deposition layer (a), as well as a magnified section of the temperature profile during the deposition of the third layer including the heating and cooling rate (b).

A further analysis of the temperature profile along the deposition direction of a single LMD-layer shows that the cooling conditions are not homogeneous. It stands out that the thermocouple at the end of the deposited track shows a significantly increased cooling rate.

This effect is explained by the changing heat transfer conditions along the deposition track. Fig. 3(a) illustrates schematically that at the start of the new layer, the heat mainly conducts into the subjacent structure and the substrate, respectively. As the process progresses, the laser beam moves along the deposition direction but still affects the temperature of the prior deposited material, Fig. 3(b, c). Since at the end of the deposition track, no additional heat is provided from the laser heat source, the cooling rate is significantly faster compared to cooling rates at the beginning and the middle of the deposition track, Fig. 3(d).

Another important aspect regarding the locally different cooling of the structure is the changing thermal convection conditions along the LMD structure, which is schematically shown in Fig. 3(e) to (g). It is visualized that the heat transfers to the atmospheric air by convection through a higher outer surface of the structure in the beginning and the end of the LMD structure. In the center of the structure this surface is smaller and the cooling is reduced, Fig 3(f). By the combination of these phenomena, the locally different cooling conditions as well as their impact on the cooling rates can be explained. However, changing thermal conduction conditions are assumed to have a significantly higher impact compared to thermal convection with respect to cooling of the structure. Furthermore, this explanation may clarify occurring heat accumulation in the center of the structure. Generally the cooling rate within the LMD process reach an order of magnitude around 10^2 K/s, which is significantly lower compared to powder-based LAM of aluminum reaching between 10^5 K/s to 10^8 K/s [10].

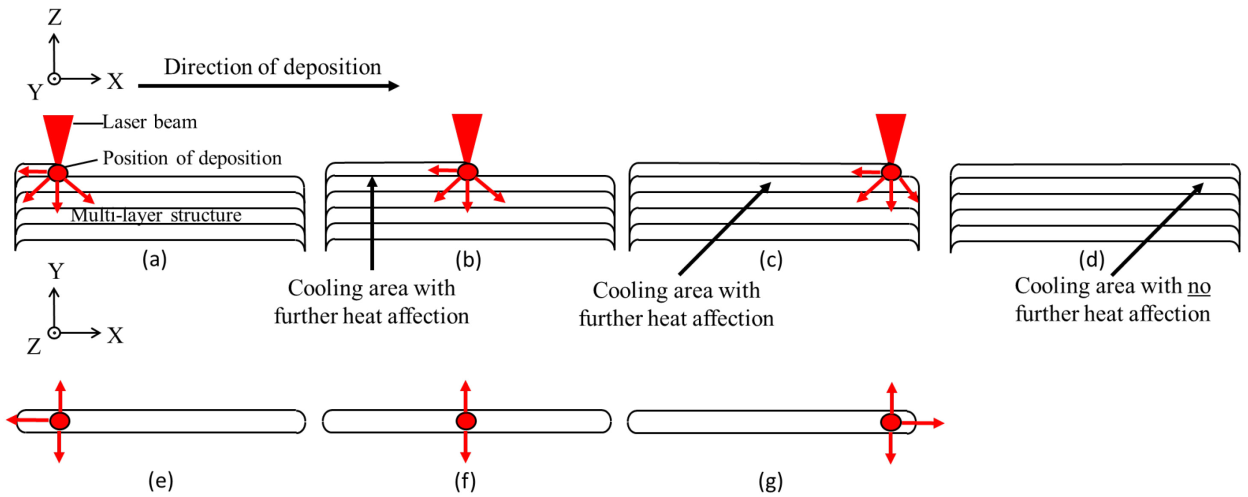


Figure 3: Schematically simplified heat transfer conditions with respect to heat conduction along the structure (red arrows) at the beginning (a) the middle (b) the end (c) and after (d) the deposition on top of a multi-layer structure. Simplified heat transfer conditions (top view) with respect to thermal convection to air along the structure at the beginning (e) the middle (f) and the end (g) of a multi-layer deposition. Changes with respect to thermal conduction are assumed to be less significant compared to the heat conduction.

As already pointed out, high residual stresses occur at the boundaries of the wall-like structure. Taking into account the results from the temperature profile analysis and cooling rate development along the deposition direction, non-homogenous residual stresses along the structure are assumed. Furthermore, different residual stress values between the beginning and the end of the structure are expected. Fig. 4(a) illustrates the resulting effect of the residual stresses. Due to the development of high temperature gradients along the structure, high distortions along the deposition direction are present. In addition, higher tensile stresses leading also to higher distortions at the end of the deposition path.

In Fig. 4(b), a top-view of a topological measurement result of a 3-layer LMD structure using parameter set 1 is shown. It is seen that the substrate and the deposited structure respectively, suffer higher distortions at the end of the deposition path as at the beginning.

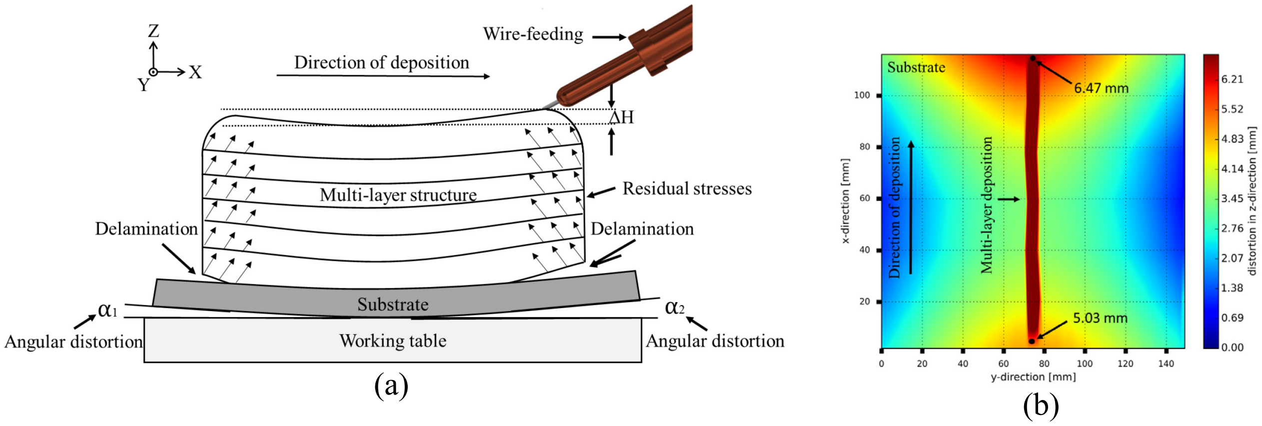


Figure 4: Schematic visualization of a multi-layer deposition and the development of non-uniform distortions along the structure which might result in partial delamination (a) as well as the topographical measurement result of a 3-layer deposition using parameter set 1 indicating non-uniform deformation along the structure with a peak in the end regions.

Regarding the origin of the non-homogenous heat distribution, transfer and resulting componential distortions, it is supposed that an increased deposition rate may lead to an improvement with respect to the occurring distortions. It is assumed that an increased amount of deposited material will increase the structural stiffness. Besides this, the cooling conditions are assumed to be homogenized, leading to decreased cooling rates and reduced residual stresses, respectively. Therefore, three layer deposition using parameter sets 2 and 3 were conducted. Because of the increased deposition rates, the laser power had to be increased by 500 W in order to achieve defect free structures. After sufficient cooling of the structures, topological measurements to quantify the distortions were conducted. It was found that the general distortions show the same tendencies as for parameter set 1. However, the distortions are reduced for higher deposition rates as shown in Fig. 5. These results suggest that LMD using higher deposition rates is beneficial in terms of reduction of distortions.

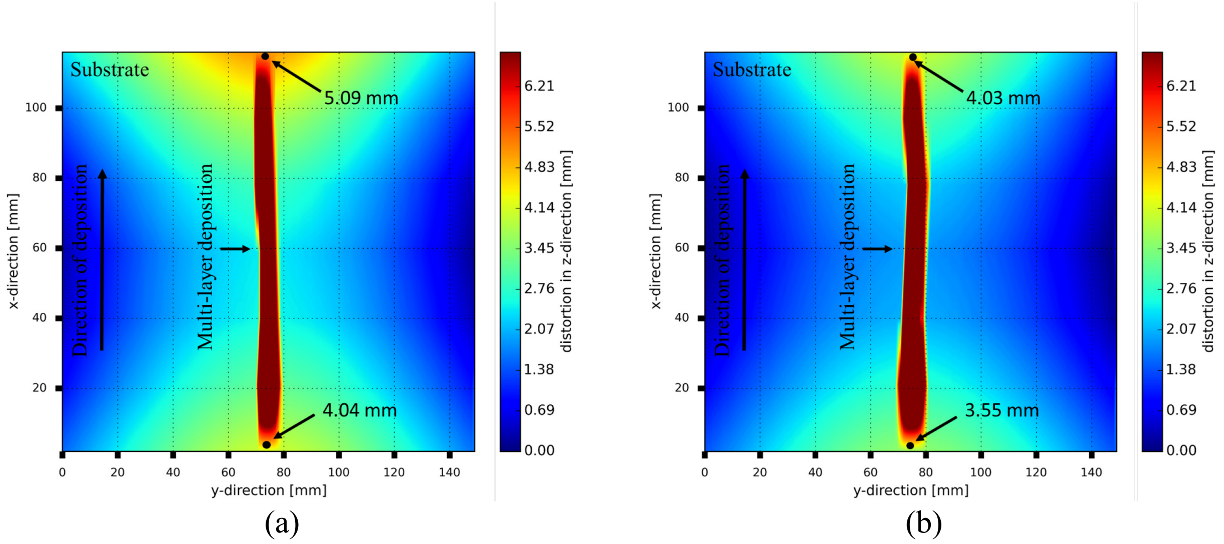


Figure 5: Topological analyses of the distortions after the deposition of three layers using parameter set 2 (a) and 3 (b) showing a general decrease in distortion for an increased deposition rate.

By increasing the deposition rate but keeping the heat input constant, the ratio between energy input to deposited material reduces. As pointed out before, this is a driving factor with respect to control the heat transfer and cooling conditions in such a way that residual stresses are reduced. This approach led to a homogenization of the heat distribution and decreased temperature gradients along the part as well as to a decrease of the distortions in the current case.

Conclusion

In this contribution, the temperature distribution during wire-based LMD of an Al-Mg alloy using constant process parameters was experimentally investigated. It was seen that the cooling conditions are not homogenous during the deposition process. An increased cooling rate as well as a slight temperature increase to the end of the deposited tracks was observed. Additionally, non-homogenous distortions along the LMD structures were detected, which could be reduced using process parameter adaptions with respect to increased deposition rates. By this, the ratio between the deposited material to the heat input was reduced. Because of the complex interlink between process parameter and residual stress development, this has to be further investigated, in order to optimize the process leading to minimum distortions as well as residual stresses during wire-based LMD. However, a first scheme for the reduction of residual stresses and componential distortion in wire-based LMD of aluminum was conducted.

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