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Temperature generation of different travel path strategies to build layers using laser metal deposition

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Abstract

Laser Metal Deposition offers the chance to build near net shape parts. The temperature evolution within the process has an influence on track and layer geometries. There are special travel path strategies required to produce near net shape components and reduce shape deviation resulting of error propagation.
This paper deals with the temperature progression of individual layers and the maximum heating of deeper substrate regions. Spiral and zig-zag strategies are examined. The investigations are carried out using S235JR as substrate and 316L as powder material. The influence of different strategies on temperature evolution is discussed.
The results from the experiments show that various production strategies are associated with different temperature fields. Furthermore, the extent of the temperature variations of layer strategies and layer position are strongly dependent on the production direction. These results demonstrate the importance of developing suitable build-up strategies for parts of complex shape to ensure a stable process with constant temperature as well as even layers.

Additive Manufacturing; Temperature behavior; Laser Metal Deposition; Stainless Steel, 316L, edge effects

1. Introduction

Additive manufacturing technologies enable companies a fast and cost-effective development process. Tool-free manufacturing of components allows new design possibilities, but also forces engineers to rethink their design [1], [2]. Laser metal deposition (LMD) as one of these methods is currently used for repair and coating of components in the areas of tool making, turbine construction and mechanical engineering, but is increasingly being found in the area of additive manufacturing of new components [3]–[6]. This new technology extends the necessary knowledge about the process flow and the process control by a multiple, which is why previous experiences are no longer sufficient to ensure a controlled process and high quality components. For this reason, current research projects deal with the challenges of this new application spectrum.
In the case of LMD, a laser beam melts a base material and powder as filler material, which is fed by a powder nozzle. After solidification of the material, a layer with metallurgical bonding without pores and cracks is formed. The process is characterized by a small weld pool, resulting in a low dilution of base material and filler material. Furthermore, the heat input and thus also the heat affected zone is small and the cooling rate is high, resulting in a fine-grained structure [6]. The main parameters are laser power, powder feed rate, welding speed and laser spot diameter. These allow prediction of the track geometry. The laser power and the welding speed having a substantial influence on the track width, while the track height is mainly influenced by the powder feed rate and the welding speed [7].

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The manufacture of components by means of LMD takes place in layers, which is why a prior slicing of the component into individual layers is necessary. For the production of such layers, individual tracks are placed next to one another. In order to obtain a uniformly flat surface, an overlap of the tracks is necessary, which is often in the range between 30 - 50% [8], [9]. Layers can be created using different strategies. Zig-zag and spiral movements are typical layer strategies, whereas an additional contour tool path is often necessary for higher volumes [10]–[12]. New software packages to support tool path planning are already available on the market, but are constantly being further developed, since there are no consistent predictions of the material due to the different environmental influences during the manufacturing process [13]. The adaptation of build-up strategies makes it possible to influence the layer structure and predict constant manufacturing sequences [10], [14]. At the same time, the build-up strategies have an influence on the welding distortion and the residual stresses [15]. These interactions must be taken into account by the design of layer strategies in order to be able to derive an optimal compromise.

2. Experimental

This article examines the temperature behavior of different build-up strategies, which are used in additive manufacturing with LMD. Four types of strategies, namely transversal and longitudinal zig-zag strategies as well as inward and outward directed spiral strategies are studied. They are illustrated in Fig. 1 on the left side. All strategies are covering an area of 15x30 mm^2 and are used with the following parameter set: laser power P_L = 800 W, welding velocity v = 600 mm/min, spot diameter d = 1.2 mm and powder mass flow m_P = 4.4 g/min. These parameters lead to a track width of 2 mm.

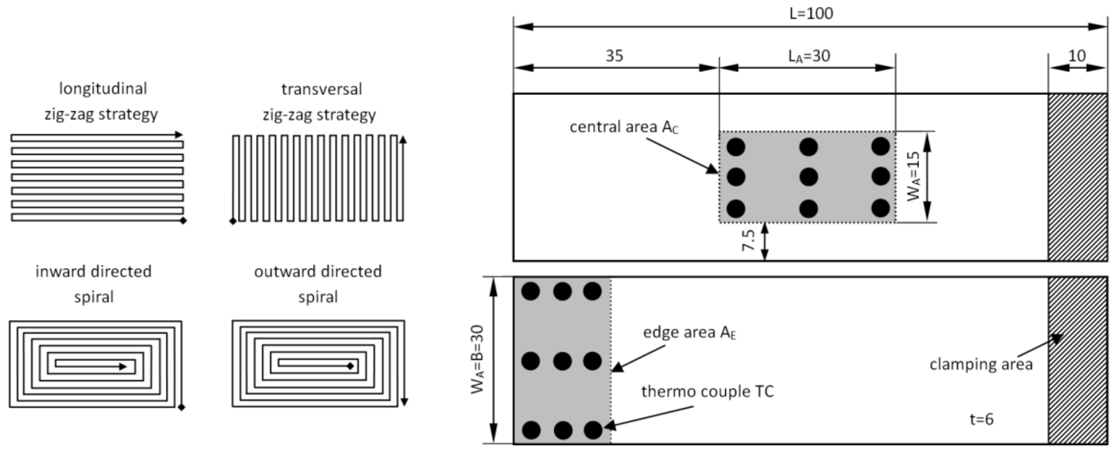

Fig. 1. Build-up strategies for individual layers

6 mm thick sheets of S235JR are used as substrate material. The strategies are welded on the central area (A_C) as well as on the edge area (A_E) of the test piece, in order to investigate influences on the temperature by using build-up strategies at different boundary conditions. The dimensions of the test piece and the position of the areas A_C and A_E are shown on the right side of Fig. 1.

The powder Metco™ 41C is used as a filler material and corresponds to 316L (stainless steel). The exact chemical composition is shown in Table 1.

Table 1. Chemical composition of Metco™ 41C

Product name	Weight in %					
	Fe	Cr	Ni	Mo	Si	C
Metco 41C	Bal.	17	12	2.5	2.3	0.03

The temperature is measured with thermocouples (TC) and two-color pyrometer. Nine thermocouples of type K measure the temperature on the bottom of the test piece, while the pyrometer determines the temperature on the surface near the weld pool. The measuring range of the pyrometer Metis MQ22 extends from 350 °C to 1300 °C. Since the melt pool temperature is above 2100 °C during welding, the measurements are performed at a distance of a_{TP} = 2.3 mm and the spot of the pyrometer is always adjusted on the test piece itself. Furthermore, the influence of the welding direction for zig-zag strategies in center direction and in edge direction are examined.

3. Results and Discussion

3.1. Central area:

Fig. 2 shows qualitative temperature graphs of the zig-zag strategies in the central area, which are recorded with the pyrometer. Both zig-zag strategies resemble an asymptotic course.

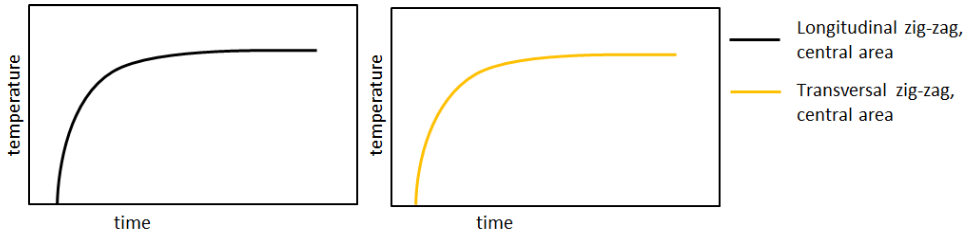

Fig. 2. Qualitative temperature graph of zig-zag strategies in the central area

Zig-zag strategies: Fig. 3 shows the longitudinal strategy $ZZ_{long, cent}$ and the transversal strategy $ZZ_{trans, cent}$. The annealing colors of both strategies are at the end of the welded layer. The highest temperatures were measured in the middle thermocouple of the last group. The longitudinal strategy shows a higher maximum temperature than the transversal strategy, because the 7.5 mm distance to the edge results in a heat accumulation.

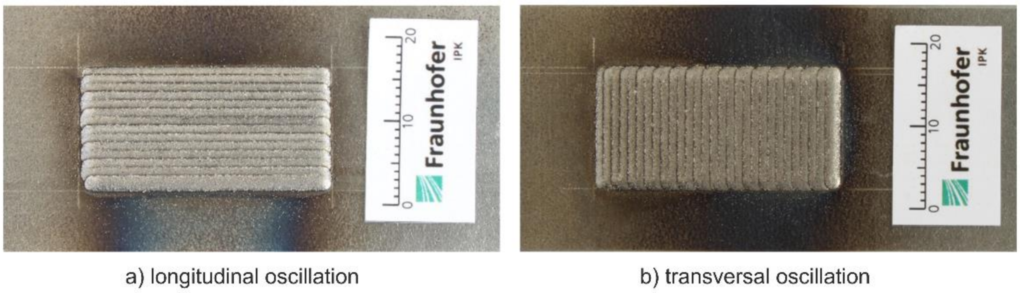

Fig. 3. Longitudinal (a) and transversal (b) zig-zag strategies with annealing colors, central area

Spiral strategies: The TC of spiral strategies can be categorised by the dictance to the center of the spiral (COS). Group 1 has the largest distance to the center point and the thermo couples are located in the corners of the spiral. The next nearest distance shows group 2 with two thermo couples attached to the middle of the transverse sides, while the group 3 is located at the middle of the longitudinal sides. The last group 4 consists of one thermo couple and lies in the COS.

The inward directed strategy $S_{in, cent}$ starts at the lower right corner of the layer. The TC group 1 is reached first, while the test piece is right on low temperature. The maximum temperature is reached at the end in the center of the spiral. The outward directed strategy $S_{out, cent}$ starts in the center, where the thermo couple with the highest temperature of the inward directed strategy lies. The highest energy input in this region is, while the test piece is cold. The heat dissipation has a high value at this level. The maximum temperature of this strategy were measured with the TCs of group 2, which are near to the center and the edge, where the heat accumulates.

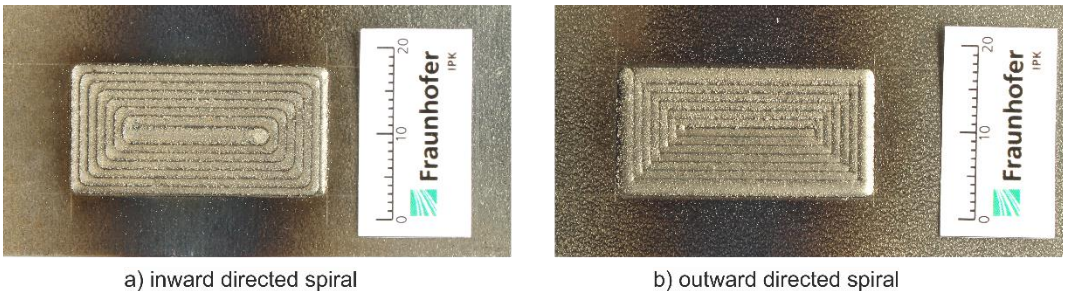

Fig. 4. Inward directed (a) and outward directed (b) spiral strategy, central area

A comparision of the different strategies in the center area shows, that $S_{out, cent}$ has the smallest maximum temperature. This results in a lower thermal influence on deeper substrate regions. Therefore, it is advisable to use outward spirals in central manufacturing areas.

3.2. Edge area:

Zig-zag strategies: The zig-zag strategies are considered in the following. The longitudinal zig-zag strategy with offset in center direction $ZZ_{long, cd}$, the longitudinal zig-zag strategy with offset in edge direction $ZZ_{long, ed}$ and the transversal zig-zag strategy $ZZ_{trans, edge}$. The temperature profile recorded by means of a pyrometer is shown in Fig. 5. A different course in the curves of the individual strategies is recognizable. $ZZ_{long, cd}$ has an asymptotic course similar to the zig-zag strategies in the center area. $ZZ_{long, ed}$ and $ZZ_{trans, edge}$ show a temperature rise followed by a constant course and a renewed increase at the component edge. Heat accumulation occurs in the edge area, since the heat input cannot be dissipated to surrounding material. This increases the temperature at the end of the welding process.

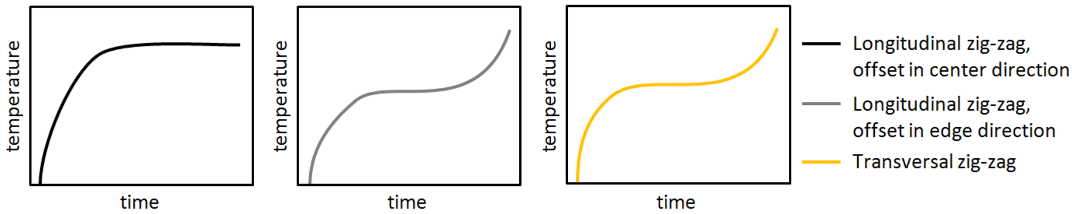

Fig. 5. Qualitative temperature graph of zig-zag strategies in the edge area

The evaluation of the thermocouple measurement reveals clear differences in the maximum temperatures among the longitudinal zig-zag strategies as well as in comparison with $ZZ_{trans, edge}$.

Because of heat accumulation at the edge strategy $ZZ_{long, ed}$ as well as strategy $ZZ_{trans, edge}$ shows higher values than $ZZ_{long, cd}$, at which the heat can dissipate in the direction of the center. All three strategies show higher temperatures than the zig-zag strategies in the central area.

Spiral strategies: The spiral strategies at the edge of the test piece are less influenced by the distance to the center than to the position in edge or center direction. The highest temperature is measured in the inward directed strategy by the thermocouple on the longitudinal side on the edge, which is not in the ending position of the laser. Similar results have been identified in the outward directed strategy, where the highest temperature is on the corner of the test piece, which is the penultimate TC before the laser stops.

The different maximum temperatures for the strategies of the edge area are listed in Table 3. The highest value of strategy $ZZ_{long, cd}$ is 34 % lower than the maximum temperature of strategy $ZZ_{trans, edge}$. It can be seen, that a different strategy has the lowest temperature in another area. This shows the high influence of a correct strategy choice for influencing the temperature development.

4. Conclusion

This paper deals with the influence of different build-up strategies on the resulting maximum temperatures. Zig-zag as well as spiral strategies were examined in a central and an edge area. The measurements were made using thermocouples on the underside of an 8 mm thick workpiece. A comparison of the strategies shows clear differences of the strategies as well as the same strategy in different areas.

An outward-directed spiral strategy $S_{out, cent}$ shows the lowest maximum temperature in the central area of the examined workpiece, while an inward-directed spiral strategy $S_{in, cent}$ has the highest maximum temperature of spiral and zig-zag strategies.

Investigations in the edge area show increased maximum temperatures in all strategies compared to the same strategies in the central area. Owing to the restrained heat transfer, the heat accumulation of the strategies are differently strong. A comparison of the zig-zag strategies makes it clear, that there is a strong increase in the maximum temperature when welding in the edge direction

The investigations illustrate the need for adapted build-up strategies by different boundary conditions in order to ensure low maximum temperatures and low temperature differences.

Acknowledgments

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References

[1] B. Graf, M. Schuch, R. Kersting, and A. Gumenyuk, "Additive Process Chain using Selective Laser Melting and Laser Metal Deposition," *Lasers Manuf. Conf. 2015*, 2015.

[2] B. Vayre, F. Vignat, and F. Villeneuve, "Designing for Additive Manufacturing," *Procedia CIRP*, vol. 3, pp. 632–637, Jan. 2012.

[3] DMG MORI, "Hoedtke GmbH & Co. KG - Generative Komplettbearbeitung in Fertigteilqualität." [Online]. Available: http://de.dmgmori.com/fachpresse/advanced-technologies/hoedtke-gmbh---co--kg---generative-komplettbearbeitung-in-fertigteilqualitaet/385532.

[4] DMG MORI, "Additive Manufacturing eröffnet neue Designmöglichkeiten in der Herstellung von 3D-Bauteilen." [Online]. Available: http://de.dmgmori.com/fachpresse/advanced-technologies/additive-manufacturing/441798.

[5] B. Graf, A. Gumenyuk, and M. Rethmeier, "Laser Metal Deposition as Repair Technology for Stainless Steel and Titanium Alloys," *Phys. Procedia*, vol. 39, pp. 376–381, Jan. 2012.

[6] S. Kaierle, A. Barroi, C. Noelke, J. Hermsdorf, L. Overmeyer, and H. Haferkamp, "Review on Laser Deposition Welding: From Micro to Macro," *Phys. Procedia*, vol. 39, pp. 336–345, Jan. 2012.

[7] B. Graf, S. Ammer, A. Gumenyuk, and M. Rethmeier, "Design of Experiments for Laser Metal Deposition in Maintenance, Repair and Overhaul Applications," *Procedia CIRP*, vol. 11, pp. 245–248, Jan. 2013.

[8] Y. Cao, S. Zhu, X. Liang, and W. Wang, "Overlapping model of beads and curve fitting of bead section for rapid manufacturing by robotic MAG welding process," *Robot. Comput. Integr. Manuf.*, vol. 27, no. 3, pp. 641–645, Jun. 2011.

[9] Y. Li and J. Ma, "Study on overlapping in the laser cladding process," *Surf. Coatings Technol.*, vol. 90, pp. 1–5, 1997.

[10] T. Petrat, B. Graf, A. Gumenyuk, and M. Rethmeier, "Build-up strategies for generating components of cylindrical shape with laser metal deposition," *Lasers Manuf. Conf. 2015*, 2015.

[11] M. Rombouts, G. Maes, W. Hendrix, E. Delarbre, and F. Motmans, "Surface Finish after Laser Metal Deposition," *Phys. Procedia*, vol. 41, pp. 803–807, Jan. 2013.

[12] I. Tabernero, A. Lamikiz, S. Martínez, E. Ukar, and J. Figueras, "Evaluation of the mechanical properties of Inconel 718 components built by laser cladding," *Int. J. Mach. Tools Manuf.*, vol. 51, no. 6, pp. 465–470, Jun. 2011.

[13] Siemens Industry Software GmbH, "NX Hybrid Additive Manufacturing - The new art of manufacturing – going beyond 3D printing." [Online]. Available: https://www.plm.automation.siemens.com/de_de/products/nx/for-manufacturing/cam/hybrid-additive-manufacturing.shtml.

[14] T. Petrat, B. Graf, A. Gumenyuk, and M. Rethmeier, "Laser metal deposition as repair technology for a gas turbine burner made of inconel 718," *Phys. Procedia*, vol. 83, pp. 761–768, 2016.

[15] E. Foroozmehr and R. Kovacevic, "Effect of path planning on the laser powder deposition process : thermal and structural evaluation," pp. 659–669, 2010.