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Study of process window development for high deposition-rate laser material deposition by using mixed processing parameters

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For several years, the interest in additive manufacturing is continuously expanding, owing to the paradigm shift that new production processes, such as laser material deposition (LMD), provide over conventional manufacturing technologies. With LMD, three-dimensional, complex components out of a wide range of materials can be manufactured consecutively layer-by-layer. However, aiming for the production of large components with LMD, the currently achieved deposition-rates of approximately 0.5 kg/h remain a major concern in regards to processing time and economic feasibility. In this respect, an experimental setup for high-deposition rate LMD is built up in the current work. Furthermore, an approach for developing a process window for resource efficient, high-deposition rate LMD is investigated in this paper. For the production of sound layers with LMD, the processing parameters need to be considered in an appropriate relation. Thus, by setting the main processing parameters: powder mass flow, traversal speed, laser power, and laser spot diameter into proportion, the mixed processing parameters: energy mass density and energy area density can be defined. Based on the metallographic investigation of laser deposited Inconel 718 single tracks regarding dilution, aspect ratio of track (ratio of track width to track height) and level of porosity, upper and lower limits for these two parameters can be set which represent process window boundaries. With this approach, a processing parameter field can be defined, to deposit sound Inconel 718 single tracks with a deposition-rate of approximately 5 kg/h and powder capture efficiency higher than 90%. © *2015 Laser Institute of America*. [http://dx.doi.org/10.2351/1.4919804]

Key words: additive manufacturing, laser material deposition, Inconel 718, high-deposition rate, process window, energy mass density, energy area density

I. INTRODUCTION

Laser material deposition (LMD) is a laser cladding based free form additive manufacturing (AM) technology that can be used to fabricate functional, three-dimensional components. During LMD, a melt pool on a thin surface of the substrate or a previous layer is generated by high power laser radiation. Simultaneously, metal powder is injected into the melt pool with a powder feeding nozzle and melted completely. By moving the working table and/or the laser head, a metallurgical fused bond is formed. LMD provides remarkable benefits over conventional welding processes through defined heat input, leading to an accurate control of solidification. Due to a very small heat affected zone and nonequilibrium rapid solidification, a fine microstructure can be obtained, leading to superior mechanical properties. However, if a careful tuning of the processing parameters is not performed, material defects can be systematically formed either at the interface separating two adjacent clad layers or within the bulk of the layer. Despite the technological advantages of the LMD process, currently achieved deposition-rates of approximately 0.5 kg/h for Inconel 718 (IN718) are causing a deferred use in the AM of large scale components.

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Thus, the increase of the deposition-rate in LMD is coming more and more into research focus in the course of the last years.

Tuominen *et al.*[1] showed that deposition-rate of LMD of Inconel 625 (IN625) can be improved by the use of a rectangular, wide beam off-axis nozzle and a 15 kW CO_2 laser source. By depositing approximately 18 mm wide single tracks, a deposition-rate of approximately 15 kg/h and a powder capture efficiency of approximately 73% could be achieved. As an off-axis nozzle, the wide beam nozzle is not suitable for additive manufacturing applications because on the one hand, both the optic and the nozzle need to rotate around the vertical axis frequently to change scanning directions in order to form the certain structure of the desired component, resulting in problems such as the increase of processing time, difficulties in scan pattern designing and complexity in programming. Fraunhofer-Institute für Werkstoff- und Strahltechnik (IWS) (Ref. 2) used a coaxial powder nozzle with an integrated module for additional inductive heating during LMD of IN625. With this setup, the deposition-rate could be increased to approximately 15 kg/h in the application of cladding of the fixed size metal pipe by using an 8 kW laser source and a 12 kW induction power together. In this case, an inductive heating device, which is designed to heat up the pipe with certain dimensions and has a fixed structure, needs to work together with the whole setup. This setup can only be used to cladding pipes or adding structures on pipes. In both studies, the LMD deposition-rate could be increased significantly. However, the range of applications of these setups is limited due to relatively low process flexibility, which is one of the primary considerations for the AM of complex components. Witzel *et al.*[3] showed that the deposition-rate of IN718 can be increased to approximately 3.9 kg/h, using a coaxial powder nozzle and a laser spot diameter of 4 mm and increased traversal speeds of up to 4 m/min.

In this respect, the aim of the current study is (a) set up a high-deposition rate LMD system with the high flexibility and geometrical precision of conventional LMD systems, (b) to further increase the deposition-rate of IN 718 to approximately 5 kg/h, and (c) the development of a process window. IN718 is a niobium-modified nickel-based super alloy, which is widely used in aircraft engine industries for critical rotating parts, airfoils, supporting structures, and pressure vessels as well as rocket motors, nuclear reactors, pumps, and tooling.[4,5] IN718 is known for its good strength, creep-rupture strength, good fatigue life, excellent resistance to oxidation at high temperatures up to 700 °C, and favorable weldability due to its relatively slow precipitation strengthening kinetics.[4,6]

II. EXPERIMENTAL SETUP

The high-deposition rate LMD system consists of a collimator, zoom optic, and a high-deposition rate powder nozzle. The movement of the lenses in the zoom optic and the tool axis are controlled by the NC-control of a four-axes tool machine. Using the zoom optic, the size of the round laser spot can be varied from a diameter of 3 to 9 mm. A 12 kW diode laser source is linked via a 1000 μm glass fiber. The powder is fed by the use of Argon with a powder feeder. To prevent the melt pool from interacting with atmospheric gases such as O2 and N2, Argon is used as shielding gas. The experimental setup is depicted in Fig. 1.

FIG. 1. Experimental setup for high-deposition rate LMD.

In Fig. 2, the powder-gas-jet of the high-deposition rate powder feeding nozzle is shown for a powder feeding rate of approximately 5.1 kg/h.

From Fig. 2, it can be seen that the powder-gas-jet is accumulated in a comparatively small area, forming a powder focus with a diameter of approximately 4 mm.

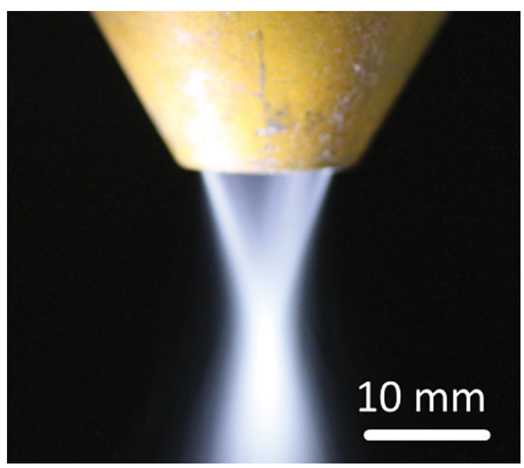

FIG. 2. Powder-gas-jet of modified ILT-Coax 50 powder nozzle with a powder feeding rate of approximately 5.1 kg/h.

TABLE I. Chemical composition of IN 718 powder in wt. %.

Ni	Cr	Fe	Nb	Mo	Ti	Al	Co
51.3	19.2	19.0	5.2	3.0	0.99	0.56	0.04

The substrate materials are IN718 plates with a dimension of 100 mm × 40 mm × 8 mm. The powder feedstock for the trials in this study is commercially available IN718, gas atomized (Argon) powder with a nominal particle size range of 45–90 μm. The chemical composition of the powder is measured via inductively coupled plasma emission spectroscopy and given in Table I.

In Fig. 3, SEM (scanning electron microscope) picture as well as optical microscopic picture of a metallographic prepared cross section of the used IN718 powder is shown.

From Fig. 3, it can be seen that a large fraction of the powder particles feature satellites, which are formed during atomization of the powder, as smaller molten particles are solidified faster and adhered to still semifluid, larger particles. In cross-sectional picture Fig. 3(a), a few particles with enclosed pores, which are also formed during the manufacturing process, can be located (hollow particles). According to the cross section, internal pores with a maximum diameter of approximately 60 μm are detected.

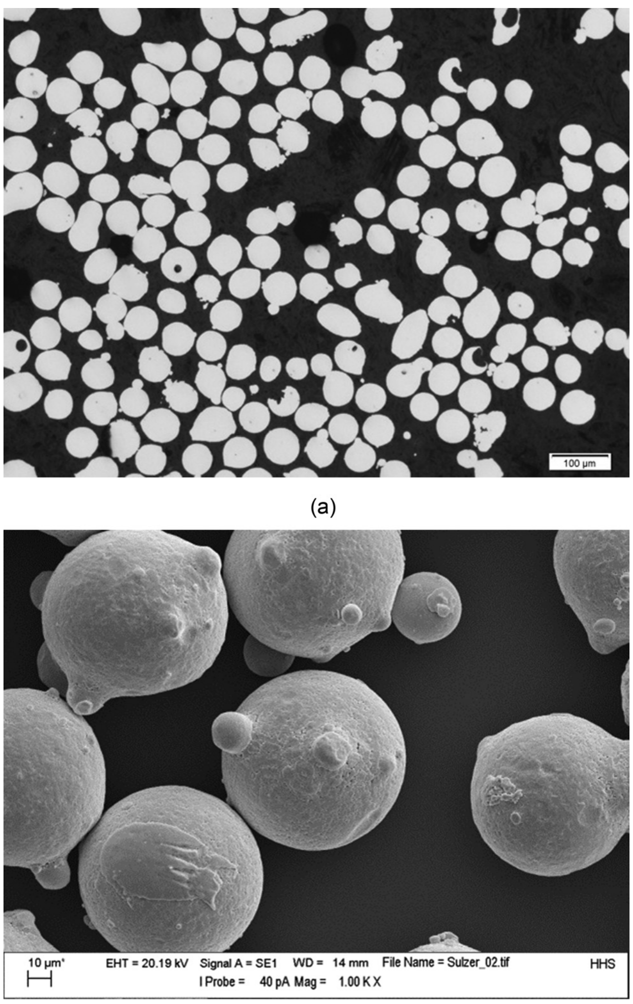

FIG. 3. Optical microscope picture of a metallographic prepared cross section (a) and SEM (b) picture of used IN 718 powder.

III. ENERGY MASS DENSITY AND ENERGY AREA DENSITY

For the definition of process window boundaries, the criteria: formation of metallurgical bonding, dilution rate, aspect ratio of track, and level of porosity are taken into consideration. During LMD, the bonding zone, which is sketched in Fig. 4, is formed on the interface between substrate or a previous layer and the clad layer when the powder feedstock material is injected into the melt pool and is mixed with the substrate material. It can be observed from the cross sections of deposited track that has been etched. On one hand, a minimal amount of energy is needed to (a) completely melt the additive material and to minimize porosity and (b) form a metallurgical bonding without bonding defects. On the other hand, the heat input should be kept as low as possible to avoid excessive distortion of the component, coarsening microstructure and undesired segregation. In Fig. 4, a schematic of a cross section of a LMD single track is depicted.

As indicator for the heat input into the substrate, the degree of dilution (dilution rate) is used. According to Eq. (1), the degree of dilution r_D is defined as the ratio of the melted cross-sectional area of the substrate A_D to the sum of the cross-sectional area of the single track A_T and A_D

$$r_D = \frac{A_D}{A_D + A_T}\,(\%). \tag{1}$$

In order to prevent bonding defects at the interface separating two adjacent clad layers, the aspect ratio r_A—the ratio of track width b and layer thickness h should be kept in a range of 4–6, as follows:

$$r_A = \frac{b}{h}. \tag{2}$$

Since the presence of pores in the laser deposited material is known to be detrimental to the mechanical properties, the porosity should be kept as low as possible. The level of

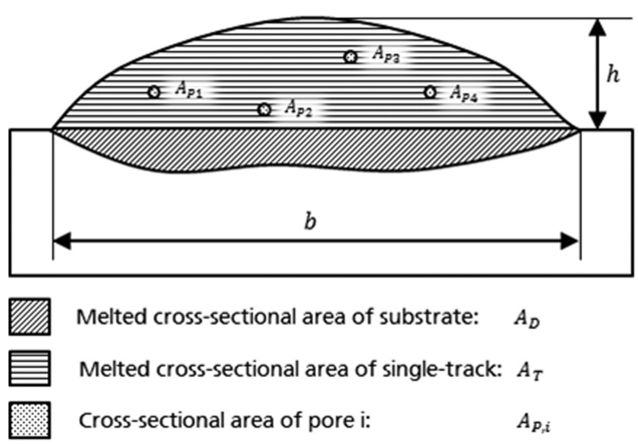

FIG. 4. Schematic of deposited track cross section.

porosity is defined as the ratio of the sum of the cross-sectional areas of pores $\sum_i A_{Pi}$ and A_T, as follows:

$$r_P = \frac{\sum_i A_{Pi}}{A_T}\,(\%). \tag{3}$$

The economic feasibility of the high-deposition rate LMD process is significantly affected by the powder capture efficiency. The powder capture efficiency η can be calculated by the ratio of the deposited powder M_1 to the amount of fed powder M_2, which is derived from the track geometry of the metallographic cross section, the area of the single track A_T and the density of the material ρ, as follows:

$$\eta = \frac{M_{21}}{M_{21}} = \frac{A_T \cdot v \cdot t \cdot \rho}{\dot{m} \cdot t} = \frac{A_T \cdot v \cdot \rho}{\dot{m}}\,(\%). \tag{4}$$

For the production of sound layers, the processing parameters need to be considered in an appropriate relation. Therefore, the main processing parameters: powder mass flow $\dot{m}$, traversal speed v, laser power P_L, and laser spot diameter d_L are set into proportion. The relation of laser power to powder mass flow is represented by *energy mass density* (EMD) and is defined as

$$\mathrm{EMD} = P_L/\dot{m}\,(\mathrm{J/g}). \tag{5}$$

EMD can be interpreted as the amount of laser energy per unit mass of powder feedstock. Hence, a minimal EMD value ($\mathrm{EMD_{min}}$) is required to melt the powder completely and minimize porosity within the bulk of the layer. Other than that, the EMD value ($\mathrm{EMD_{max}}$) is upper limited through excessive dilution rate ($>15\%$) which indicates excessive energy input to the process. For that reason, the EMD value ($\mathrm{EMD_{proper}}$) is to be within the limits of $\mathrm{EMD_{min}}$ and $\mathrm{EMD_{max}}$, as follows:

$$\mathrm{EMD}_{min} < \mathrm{EMD}_{proper} < \mathrm{EMD}_{max}. \tag{6}$$

The relation of laser power to the product of traversal speed and laser spot diameter is represented by *energy area density* (EAD) and is defined as

$$\mathrm{EAD} = P_L/(v \cdot d_L)\,(\mathrm{J/mm^2}). \tag{7}$$

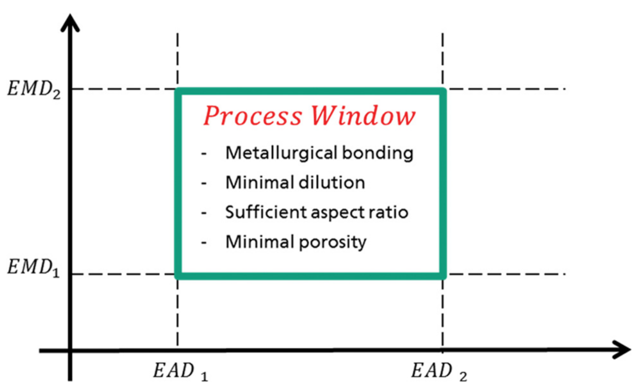

FIG. 5. Schematic view of process window, EMD vs. EAD.

TABLE II. Range of processing parameters.

P_L (W)	$\dot{m}$ (kg/h)	v (mm/min)	d_L (mm)
5058	5.1	700	9
5564	5.1	700	9
6070	5.1	700	9
6576	5.1	700	9
7081	5.1	700	9
7587	5.1	700	9
8093	5.1	700	9

EAD can be interpreted as the amount of laser energy per unit area. Therefore, a minimal EAD value ($\mathrm{EAD_{min}}$) is required to heat the substrate material such that a metallurgical bonding between additive layer and subjacent layer or substrate is formed without bonding defects. The maximum EAD value ($\mathrm{EAD_{max}}$) is limited through excessive distortion and exceeding dilution. Hence, for appropriate process conditions, the EAD value ($\mathrm{EMD_{proper}}$) is to be within the limits of $\mathrm{EAD_{min}}$ and $\mathrm{EAD_{max}}$, as follows:

$$\mathrm{EAD}_{min} < \mathrm{EAD}_{proper} < \mathrm{EAD}_{max}. \tag{8}$$

From there, a process window can be defined by the limits of EMD and EAD and visualized as schematically shown in Fig. 5 by plotting EMD on the axis of ordinate versus EAD on the axis of abscissae.

In order to identify quantitative values for $\mathrm{EMD_1}$ and $\mathrm{EMD_2}$ as well as $\mathrm{EAD_1}$ and $\mathrm{EAD_2}$, single tracks with a fixed laser spot size of $\mathrm{d_L} = 9$ mm and a fixed powder feeding rate of approximately 5.1 kg/h are deposited with seven different laser powers ranging from. $\mathrm{P_L} = 5058$ W to $\mathrm{P_L} = 8093$ W. Based on preliminary tests, the traversal speed for these processing conditions is set to 700 mm/min so that r_A is within the range of 4–6. After every track, the substrate was cooled to room temperature prior to the deposition of next track. An overview of the processing parameters is given in Table II.

The deposited layers are cross-sectioned in four locations (a)–(d), as schematically shown in Fig. 6 and hot mounted in phenolic resin. The metallographic samples are ground and polished using 1 μm diamond-suspension. In order to analysis dilution rate, polished samples were etched by hydrogen peroxide (Ethanol 75 ml, HCl 25 ml, and H_2O_2 3 ml) for 40 s.

Microscopic pictures are recorded for all cross sections by using optical microscope and evaluated regarding

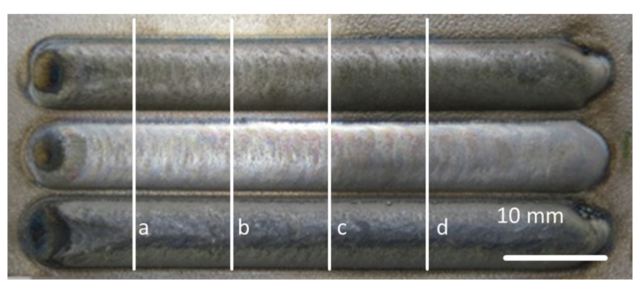

FIG. 6. Schematic illustration of the location of the cross-sectional areas.

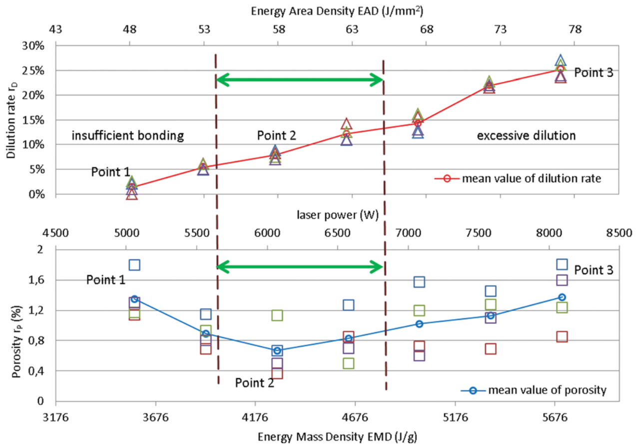

FIG. 7. Results of the investigation of dilution (upper graph) and porosity (bottom graph) vs. laser power, EAD and EMD.

bonding zone, aspect ratio of track, and level of porosity with quantitative image analysis software.

IV. RESULTS AND DISCUSSION

The results in regards to the degree of dilution and porosity are shown in Fig. 7. By the continuous line, the arithmetic means of four measurements are represented. In the upper graph, r_D in the bottom graph, r_P is plotted versus P_L on the first axis of abscissae. Since the EMD- and EAD-values are linearly proportional to P_L, EAD and EMD are plotted on the second and third axis of abscissae. As P_L is increased from 5058 W to 8093 W, the EAD-value is increased from 48 J/mm^2 to 77 J/mm^2 and the EMD-value from 3570 J/g to 5713 J/g, respectively.

The mean values of r_D are by approximation positive linear proportional to P_L, ranging from a dilution of approximately 1% at 5058 W, due to insufficient heat input to melt the powder and the substrate, to a dilution of approximately 25% at 8093 W. As P_L is increased from 5083 W to 6070 W, the mean value of r_P is decreased from approximately 1.4% to approximately 0.75%. The size of the pores in the cross sections is in the same order as the size of the internal pores

TABLE III. Processing parameters and analysis results.

No	P_L (W)	$\dot{m}$ (kg/h)	v (mm/min)	EAD (J/mm^2)	EMD (J/g)	r_D (%)	r_P (%)
1	5870	2.4	700	56	8805	34	1.2
2	5870	5.1	1600	24	4143	Bonding defects	
3	5870	5.1	400	98	4143	11	3.4
4	5870	6.8	700	56	3108	Bonding defects	

of the hollow powder particles. If P_L is further increased to 8093 W, the mean of r_P is increased again to approximately 1.4%. With a difference of approximately factor 3 between minimal and maximal value of r_P in one single track, the scatter of r_P is comparatively large. In this respect, the mechanisms for the formation of pores during high-deposition rate LMD need to be further investigated in the future. Assumingly, the porosity can be further reduced by the use of powder with less hollow particles. In Fig. 8, metallographic pictures of the cross sections of point 1, point 2, and point 3 are shown.

According to formula (4), the calculated powder capture efficiency for the process conditions of point 2 is amounted to approximately 92% ($A_T = 13.9\,\text{mm}^2$, $\rho = 8.19\,\text{g/cm}^3$). From there, the upper and lower limits for EAD and EMD can be determined according to

$$\begin{gathered} 54\,\text{J/mm}^2 < \text{EAD} < 65\,\text{J/mm}^2 \\ \& \\ 4000\,\text{J/g} < \text{EMD} < 4800\,\text{J/g}. \end{gathered} \tag{9}$$

Within these boundaries, the aspect ratio is in the range of 4–6, the porosity is minimal and the dilution is sufficient to (a) guarantee a metallurgical bonding as well as (b) avoid excessive dilution rate ($>15\%$). To further investigate the effects of EAD and EMD separately, four additional experiments are carried out. The powder mass flow $\dot{m}$ and traversal speed v are varied independently so that the preset process window boundaries are exceeded for one mixed parameter, while the other one is kept within limits. An overview of the processing parameters and analysis results regarding mean

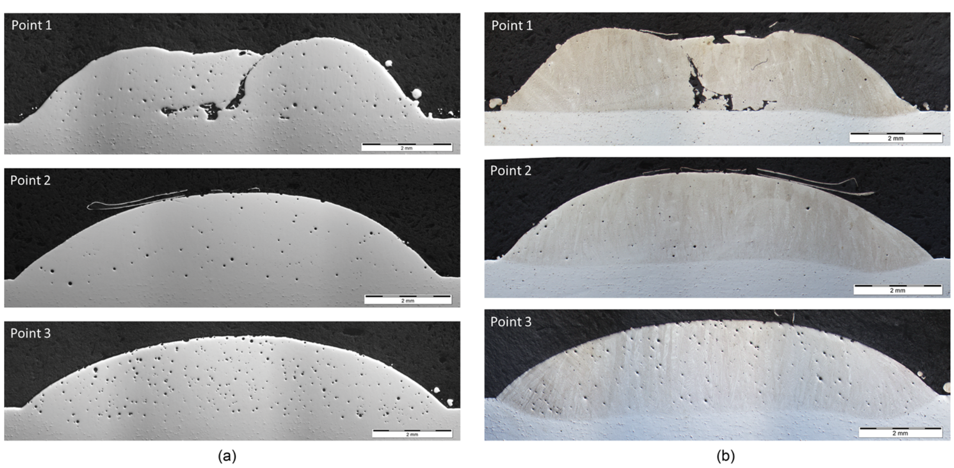

FIG. 8. Optical micrographs of polished cross sections of experimental points 1–3, before etching (a) and after etching (b).

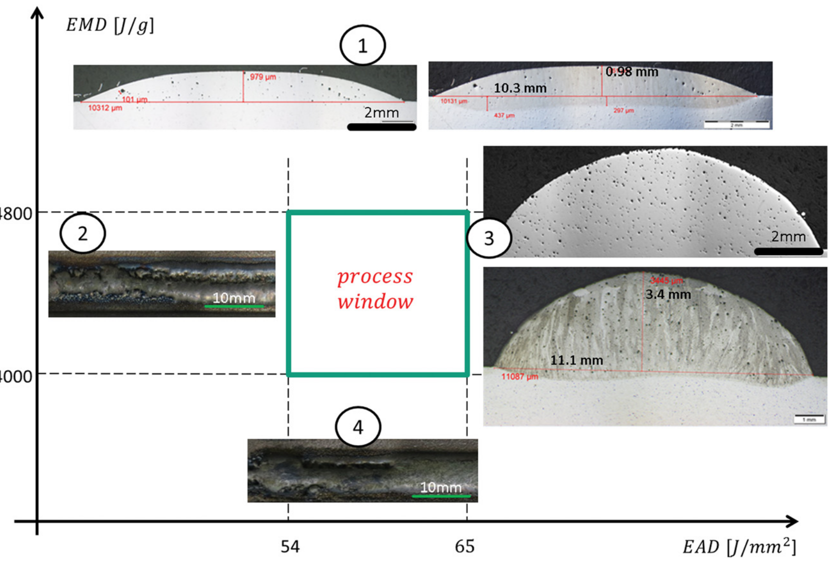

FIG. 9. Metallographic pictures of cross sections for experiments 1–4 in relation to the process window, EMD vs. EAD.

value of dilution rate, porosity, and aspect ratio of track cross section are given in Table III.

In Fig. 9, the metallographic pictures of the cross sections for experiments 1–4 are depicted in relation to the defined process window.

As $\dot{m}$ is decreased to 2.4 kg/h, the EMD-value is increased to 8805 J/g (No. 1), resulting in an unfavorable aspect ratio of approximately 10. By increasing v up to 1600 mm/min, the EAD-value is decreased to 24 J/mm^2 (No. 2), resulting in bonding defects due to an insufficient heat input to completely melt the powder and the substrate. When v is decreased to 400 mm/min, the EAD-value is increased to 98 J/mm^2 (No. 3), leading to an unfavorable aspect ratio of approximately 3 as well as high porosity inside the bulk of the layer. As $\dot{m}$ is increased to 6.8 kg/h, the EMD-value is decreased to 3108 J/g (No. 4). For this powder mass flow, the heat input is insufficient to melt the powder and the substrate completely, resulting in bonding defects.

V. SUMMARY AND CONCLUSIONS

A flexible, high-deposition rate LMD system aiming toward reduced processing times in Additive Manufacturing is set up, consisting of a high power diode laser, zoom optics, and a coaxial powder feeding nozzle. IN718 single tracks with varying laser power from 5058 W to 8093 W are laser deposited, using a 9 mm laser spot size, a powder mass flow of 5.1 kg/h, and a traversal speed of 700 mm/min. The deposited tracks are cross-sectioned, metallographic prepared and analyzed regarding aspect ratio, porosity and formation of bonding zone. Assuming that for the production of sound layers, the primary processing parameters need to be considered in an appropriate relation, the parameters: EMD and EAD are defined by setting these processing parameters into proportion. Based on the metallographic investigation, limits for these two parameters can be set such as follows, which presents process window boundaries for the case that was investigated

$$54\,\mathrm{J/mm^2} < \mathrm{EAD} < 65\,\mathrm{J/mm^2}$$
$$\&$$
$$4000\,\mathrm{J/g} < \mathrm{EMD} < 4800\,\mathrm{J/g}.$$

Within these boundaries, the aspect ratio is in the range of 4–6, the powder capture efficiency is approximately 94%, the porosity is minimal and the dilution is sufficient to (a) guarantee a metallurgical bonding as well as (b) avoid excessive heat input. To investigate the effects of EAD and EMD separately, the powder mass flow and traversal speed are varied independently so that the preset process window boundaries are exceeded for one mixed parameter, while the other one is kept within the process window boundaries. With an EAD- and EAD-value below the predefined limit, the heat input is insufficient to completely melt the powder and the substrate, resulting in bonding defects. As the EMD-value is larger than the upper EMD-limit, the excessive dilution with the dilution rate of about 34% is observed, which means a waste of energy. As the EAD-value is larger than the upper EAD-limit, the aspect ratio is decreasing to approximately 3, and the deposited track has high porosity with a value of about 3.4%.

In further investigations, the mechanisms for the formation of pores during high-deposition rate LMD as well as the influence of the degree of overlap and deposition strategy in regards to microstructure and geometrical accuracy will be analyzed.

ACKNOWLEDGMENT

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Biographies

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