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Optimization of laser welding process for laser additive manufactured aluminum parts by means of beam oscillation and process-oriented component design

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Abstract

This paper deals with laser beam welding of laser additive manufactured (LAM) aluminum components. Experimental results are presented, as by means of beam oscillation, the increased seam porosity can be reduced during the laser beam welding of such components. Furthermore, due to the layered manufacturing process, LAM components have particular geometric and surface properties. The second part of the paper presents how this affects the laser welding process.

Keywords: Additive manufacturing, laser welding

1. Introduction and motivation

Due to the currently limited machine productivity as well as their size, laser additive manufactured (LAM) components are still limited in their dimensions. Joining processes are therefore required in order to integrate these LAM components into overall constructions. The laser beam welding is characterized by a low heat input compared to arc welding processes and therefore ideally suited for joining filigree LAM components. However, investigations of the iLAS already showed a significantly increased pore formation, shown in figure 1, during welding of laser additive manufactured aluminum (AlSi12) compared to the cast material of the same alloy. [1] The reason for this high porosity is a sevenfold higher hydrogen content of the base material, which is separated in the form of pores in the melt pool during welding due to a solubility drop during solidification. [2]

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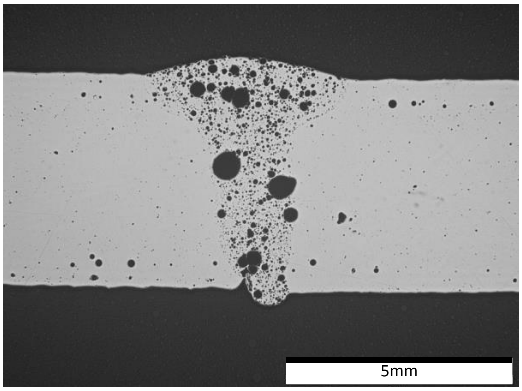

Fig. 1. Laser weld seam in laser additive manufactured AlSi12

The three factors of material, process and construction are generally decisive for the weldability of a component. The material has already been analyzed in [2] and possibilities for optimizing the weldability are shown. In this paper, we will discuss the optimization of the welding process by means of beam oscillation in Chapter 2 and the influence of the design or component preparation on the welding result.

2. Laser beam welding with beam oscillation

Previous studies carried out by the Institute for Laser and Systems Engineering (iLAS) show that a large melt pool, which is kept open for a long time, helps the pores to rise in the still liquid melt during the laser beam welding of laser additive manufactured aluminum and partially degas or collect in the upper seam area so that they emerge from the seam with a new melting down at low power. However, the objective is to weld as quickly as possible in order to be able to produce economically. Furthermore, a large melt pool has the disadvantage of a high necessary energy input and consequently an increased thermal distortion of the component as well as a sagging of the weld seam through the difficultly controllable liquid aluminum melt. The beam oscillation is an approach to expand the seam without having to increase the laser focus. Thus, the energy input need not be increased to the same extent as in a defocusing, proportionally to the seam width. This fact minimizes warpage. The choice of the oscillation amplitudes also allows defined melt bath widths to be set even at higher welding speeds. Furthermore, it is expected that the rising and the outgassing of the pores will be positively influenced by the beam oscillation and the resulting melt bath dynamics. At low welding speeds, tests without pendulum show an accumulation of large pores immediately below that of the near surface. The beam oscillation is expected to influence the surface tension of the seam in such a way that these pores can now outgas. A publication by Weberpals demonstrates the positive influence of beam oscillation in the conversion of process-stable seams with defined seam widths on aluminum sheets in automotive engineering. [3] Dittrich shows a pore reduction by beam oscillation during the laser beam welding of aluminum die-cast components with welding depths of approx. 1 mm. [4] The welding parameters used are not named in either work.

The results of the study on laser beam welding with beam oscillation for the welding of 3 mm thick LAM aluminum components are presented in this paper. Two opposing approaches are used: the use of a highly focused single-mode laser and the use of a multi-mode laser with a 400 µm focus diameter and additional defocusing.

2.1. Experimental setup

The LAM samples to be welded are printed on a SLM 250 laser additive manufacturing machine with standard parameters from AlSi12. Two samples of the size 25 mm x 60 mm x 3 mm are welded along the 60 mm edge in the butt joint. In order to remove dirt as well as the oxide skin, the weld joint as well as adjacent surfaces are abraded with abrasive paper before welding.

For the experiments the setup shown in Figure 2, a CNC-guided welding cell, is user. The components are fixed with clamping strips to insure technical zero gap as well as free root. The fumigation is carried out close to the upper surface via a protective gas flute with 20 l / min of argon.

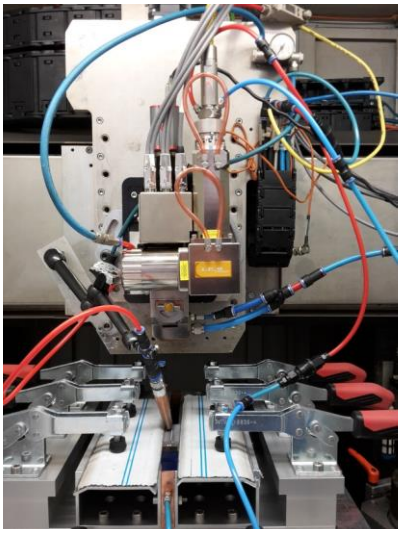

Fig. 2. Experiment setup for laser welding tests

Two laser systems are compared. On the one hand, a YLS-1000 SM single-mode laser from IPG with IPG D 30 W Wobbleoptik. The focal length is 200 mm at an imaging ratio of 1: 2. This results in a focus diameter of 28 µm which is used with a focal point on the sheet metal surface. This is compared with an IPG YLS-5000 multi-mode laser with IPG D50 wobble optics, a 300 mm focus length and a 400 µm focus diameter, which is additionally defocused by 6 mm.

The variation of the following parameters will be examined:

- Single-Mode vs. Multi-mode laser (24 µm focus diameter vs. 400 µm focus diameter)
- Shape of oscillation (o -> / - -> / | -> / ∞ -> / 8 ->)
- Pendulum frequency (150 Hz, 300 Hz, 500 Hz, 1000 Hz)

- Amplitude (0.5 mm, 1 mm, 1.5 mm)
- Weld speed (1 m/min, 1.5 m/min, 2 m/min, 3 m/min)

2.2. Experimental results: Comparison single-mode vs. Multi-Mode

The direct comparison of single-mode and multi-mode lasers with identical oscillation parameters shows in Figure 3 that the defocused multi-mode laser can achieve significantly lower seam porosities.

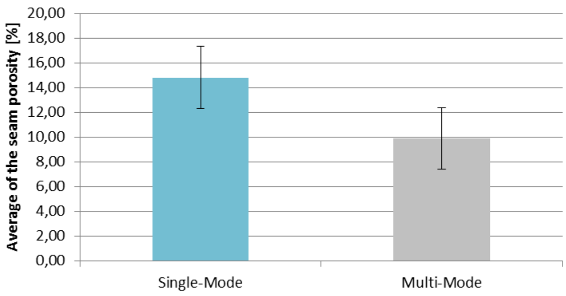

Fig. 3. Direct comparison of the averaged seam porosity as well as their standard deviation of single-mode and multi-mode laser. (v_s=1m/min, frq= 300Hz, A= 1 mm)

Similar results are shown in Figure 4, where the porosities were compared at different amplitudes and frequencies. However, it should be noted that the speed of the single-mode laser was reduced to 1 m/min due to the limited laser beam power, while the experiments with the multi-mode laser were performed at a feed rate of 2 m/min. A direct comparability is thus not given, but the tendency in all experiments always shows less porosity in the multi-mode system, so that all further experiments on this system have been carried out.

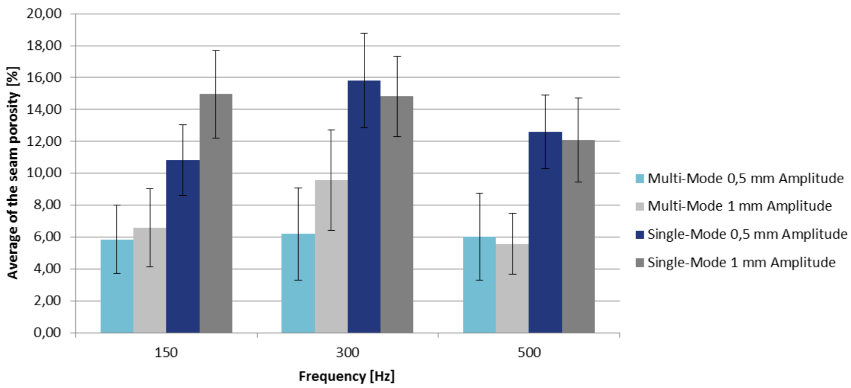

Fig. 4. Comparison of the averaged seam porosity and their standard deviation of single-mode (v_s = 1 m/min) and multi-mode lasers (v_s = 2 m/min) at different frequencies and amplitudes.

2.3. Experimental results: Influence of frequency and amplitude

The evaluation of different frequencies and amplitudes of the multi-mode system shows the best results according to figure 5 with a low oscillation amplitude of 0.5 mm. This can be explained by the significantly narrower molten bath, in which the pores, which are initially small, have less time to join together and form large pores. In fig. 6, finely distributed small pores can be seen at the low amplitude of 0.5 mm, whereas these have joined together at the amplitude of 1.5 mm to form large pores which accumulate in the upper region of the seam. The effect that these have sufficient time for the outgassing due to the wider seam and the consequently slower solidification does not occur at this welding speed.

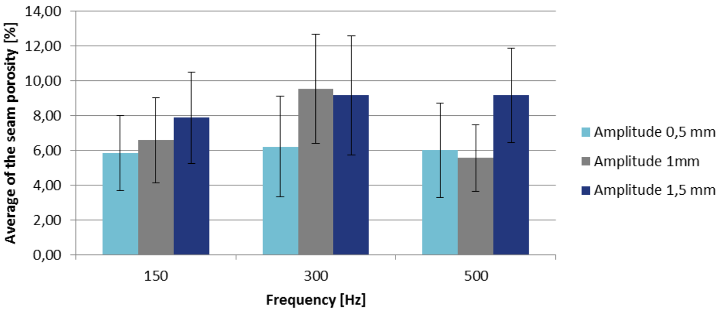

Fig. 5. Comparison of the averaged seam porosity as well as their standard deviation using the multi-mode-laser at different frequencies and amplitudes. Constant are the oscillation shape “o” and v_s= 2 m/min

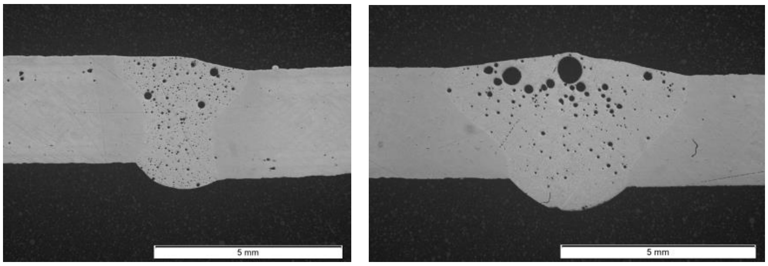

Fig. 6. Comparison of cross sections with 0.5 mm oscillation amplitude (left) and 1.5 mm oscillation amplitude (right). Constant: v_s = 2 m/min, frq = 150 Hz, oscillation shape “o”

2.4. Experimental results: Influence of the welding speed

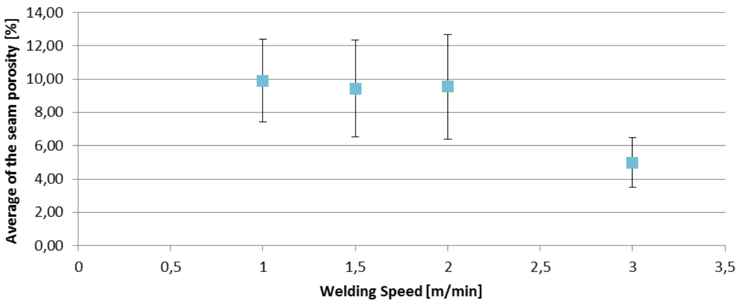

Fig. 7. Influence of the welding speed on the averaged seam porosity and standard deviation. Constant: frq = 300 Hz, A = 1 mm, oscillation shape "o"

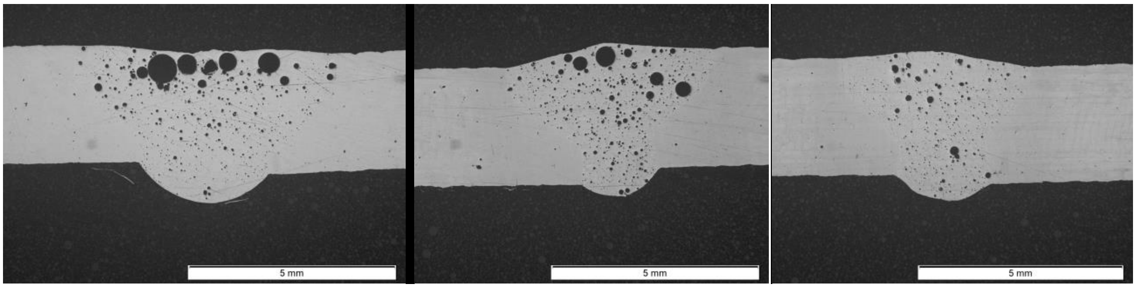

Fig. 8. Influence of the welding speed on the seam porosity. Representation of the cross-sections: left 1 m/min, middle 2 m/min, right 3 m/min. Constant: frq = 300 Hz, A = 1 mm, oscillation shape "o"

Figure 7 & 8 show the influence of the welding speed on the seam porosity at the same frequency and amplitude. As the welding speed increases, the pores are smaller and finely divided, since they do not have the time to form large pores during rapid solidification and to ascend. The welding speed of 1 m/min shows that the seam is low in pores in the lower region since these have already risen and are joined together in the upper seam region in the form of large pores. Moreover, the sample shows that the significantly larger molten bath has a larger sag. The lower the welding speed, the more necessary are therefore the measures for the control of the melt bath. Furthermore, the energy per distance was reduced by more than a factor of 2 at a jump from 1 m/min to 3 m/min, which had a positive effect on the welding delay.

2.5. Experimental results: Influence of oscillation shape

The oscillation shapes circle, eight (longitudinal and transverse to the feed direction) as well as linear oscillation longitudinal and transverse to the feed direction are compared. There are no significant differences between the different oscillation shapes. Only the circular pendulum shape shows a somewhat increased porosity and also scattering of the measuring results. Further attempts will be made to identify this influence.

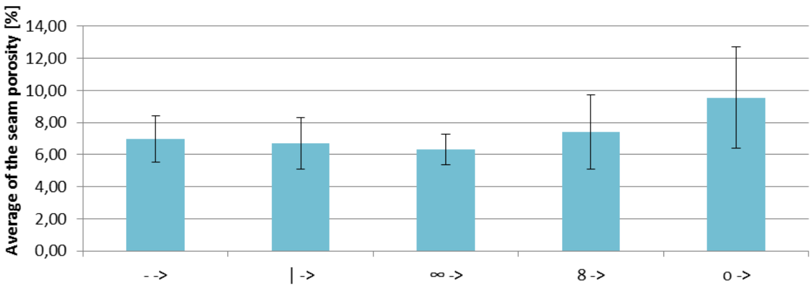

Fig. 9. Influence of the oscillation shape on the seam porosity and its standard deviation. constant: v_s = 2 m/min, frq = 300 Hz, A = 1 mm

2.6. Summary of the oscillation tests:

From the results shown above, the following statements can be summarized:

- The optical seam quality can be increased by the beam oscillation. The result is a more stable laser welding process with a smoother weld seam surface compared to processes without beam oscillation.
- With a large laser focus (> 400 µm), better welding results can be achieved than with the highly focused single-mode system (d_f = 28 µm)
- With regard to the relationship between welding speed and pore formation, two effects are apparent:
  - At low welding speeds (1 m / min), the initially small hydrogen pores agglomerate into large pores, which are enclosed in the upper seam area by the melt. Complete degassing does not occur at the welding speeds tested.
  - At high welding speeds (> 3 m / min), the seam porosity is lower because only small, well-distributed hydrogen pores are formed in the seam.
- Smaller pendulum amplitudes show a lower seam porosity

The presented results show that the surface and also the seam porosity can be significantly optimized with a well-adjusted welding process. However, pore-free seams have not been possible with any parameter set so that the combination of the welding process optimization and the optimization of the reduction of the hydrogen content in the LAM component according to [4] is necessary here.

3. Design Guidelines for design and part preparation suitable for laser welding

In order to develop guidelines for a design and part preparation suitable for laser welding of aluminum LAM components extensive series of tests were carried out at iLAS. A 6 kW disk laser with robotized welding optics with 200 mm focusing length, 1: 1 image ratio and 300 µm focus diameter are used.

3.1. Influence of surface post processing on seam porosity

In the experiments, the thesis is to be tested that the rough LAM component surface absorbs additional environmental influences, in particular moisture, and thus leads to increased seam porosity. For testing, 3 mm and 5 mm thick welding samples are produced. The 5 mm specimens are milled on all surfaces by 1 mm in order to minimize the influence of the surface and archive also a 3 mm thickness for the comparison.

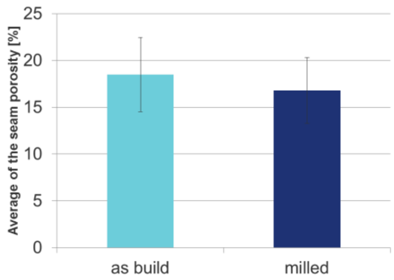

Fig. 10. Influence of the milling process on the average seam porosity

The evaluation of the results according to fig. 10 shows only a minimal difference in the mean seam porosity. This effect is not significant. The reason for this is the removal of the oxide layer on the surface, which is recommended for all aluminum components directly before welding. By means of abrasive paper, the surface is thereby also removed in the otherwise non-treated sample and similar properties are produced as in the milled sample.

3.2. Influence of processing media on the seam porosity

The aim of the investigations is to investigate the influence of processing media like cooling lubricant during milling, the water during wire cutting and the blasting material from sand blasting on the weld seam porosity compared to as build samples. The evaluations of the seam porosity also show no significant influence of the media on the seam porosity. The explanation is identical to the previous section. By the recommended mechanical removal of the oxide layer by grinding in the area of the weld seam as well as cleaning with acetone, possible impurities are removed by processing media.

3.3. Effect of surface roughness on seam formation

LAM components have different surface conditions depending on your build up direction as well as the post processing process. In the following, the influence of the surface on the weldability is analyzed. For this purpose the following typical LAM surface conditions on 5 mm thick samples are analyzed in welding tests. These are as build surfaces at a 90 ° angle as build surfaces at a 45 ° angle, which are thus affected by a stair-step effect with a rougher surface, wire-eroded component edges as well as component surfaces on which the support structures have been removed but without being smoothed afterwards.

The welding parameters have not yet been optimized with regard to pore reduction in these experiments, so that a strong pore formation results. This may be reduced by using the methods shown in chapter 3.

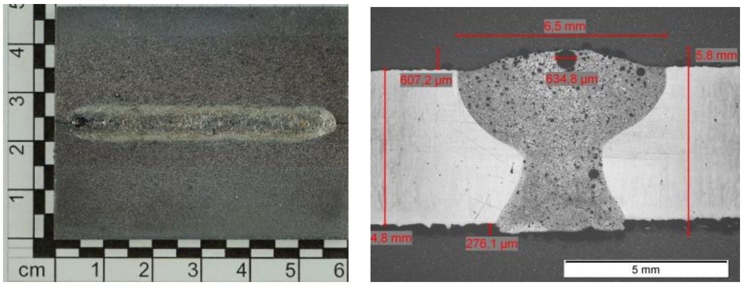

Fig. 11. Welding of as build 90° – as build 90°: surface of weld & cross section

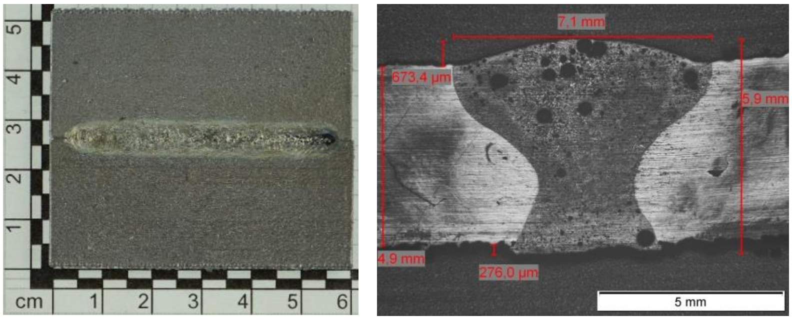

Fig. 12. Welding of as build 45° – as build 45°: surface of weld & cross section

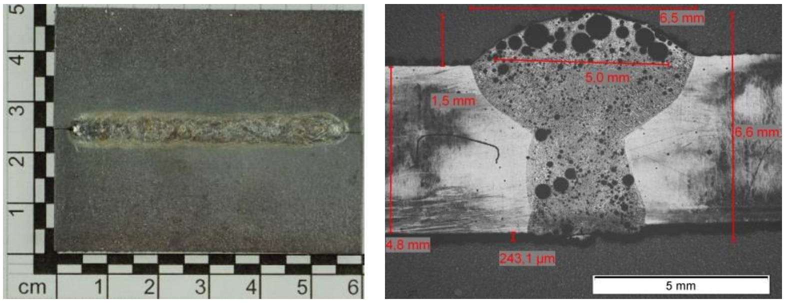

Fig. 13. Welding of wire cut – wire cut: surface of weld & cross section

Fig. 14. Welding of support – support: surface of weld (no cross section possible)

Figures 11-13 show that the as build surfaces, whether 90 ° or 45 °, as well as the wire-cut samples have good welding properties. The roughnesses are sufficiently small to ensure the necessary technical zero gap (gap <0.2 mm) when welding the specimens together. According to Figure 14, this is not the case for the samples with coarsely removed supports. This results in a gap which is too large to ensure a secure connection. The thin molten aluminum melt runs through this gap downwards out of the joining zone. Thus no cross-section can be made. From this, it can be deduced that a simple removal of the support structures is not sufficient and the corresponding surface must then be subsequently smoothed to ensure a stable laser welding process.

3.4. Derivation of design and postprocessing guidelines

The following guidelines for the preparation of the components can be derived from the investigations described above:

- There is no negative influence due to cooling lubricants of milling, the water of wire cutting or the abrasive of sand blasting on the weld seam porosity. These typical postprocessing processes of the LAM process chain can thus be used without hesitation, if the specimens are cleaned properly before laser beam welding.
- The as-build surface quality of the aluminum LAM components is sufficient for the welding process. Post-treatment for surface smoothing or particle removal is not necessary in order to achieve good weld seam quality.
- Support structures on welding joints must be removed properly and these surfaces must be smoothed (eg manual grinding) in order to ensure the optimum gap (technical zero gap) during laser beam welding.

These and other guidelines for laser welding-compatible design are summarized in a design catalog of the iLAS, which enables the process-safe welding of aluminum LAM components by means of a process-oriented design and component preparation.

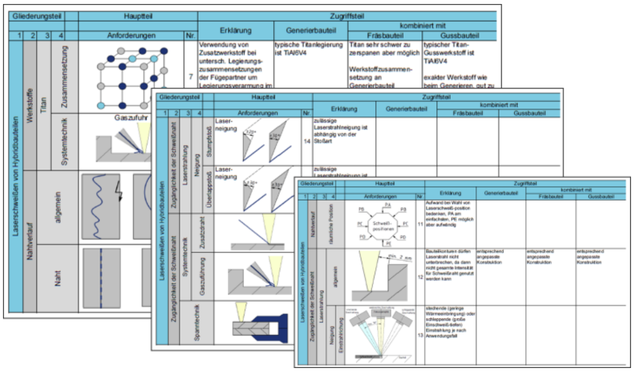

Fig. 15. Excerpt from design catalog for laser welding-compatible component design and process preparation for joining of aluminum LAM components

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