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Use of additive manufacturing for high-throughput material development

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Abstract

Discovering new metallic alloys based on a high-throughput method as known from life sciences would reduce the effort of experimental investigations as well as the use of resources. The realization of reproducibly homogeneous alloy compositions is required to implement such a novel method in order to provide materials with a precisely adapted requirements profile. In this work, a process chain of two laser-based processes under the application of additive manufacturing is presented. Powdered stainless steel is applied on an unalloyed case hardening steel by selective laser melting (SLM), before base material and master alloy is remelted and mixed using a modulation form of consecutive overlaying circles. The application of different laser power and modulation speed leads to graded melt pools of different size and shape. It can be shown that micro samples can be produced with a sufficient melt pool size without pores and cracks.

Keywords: selective laser melting; laser deep alloying; material development

1. Introduction

The steadily growing demands on product properties and quality, as well as the growing global competition increasingly require innovations in areas such as energy generation and transformation, mobility, infrastructure, and safety. Metallic materials, in particular, steel, are by far the world's most widely

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used construction material. The development of new metallic construction materials specifically tailored to the requirements of the respective task is an approach to realize innovative future technologies.

Conventional material development processes require a high level of resource use and extensive effort of experimental investigations to determine the material properties. For a target-oriented, model-based bottom-up solution, a basic understanding of the relationships is necessary, for which the models are missing due to many different demands placed in today`s world of materials. Therefore, only a low number of experiments are possible, so that the procedures are mostly predictive and discovering completely new materials is made more difficult (Mädler, 2014).

A novel method based on a high-throughput method was proposed for a significantly higher efficiency in the discovery of new materials, or even material classes (Mädler, 2014). The principles of the high-throughput screening are based on heuristic search and analysis. For the development of the method, micro samples with a high-throughput are to be generated. After developing microstructure by thermal, mechanical or thermo-mechanical treatments the micro samples are examined with respect to so-called descriptors which allow conclusions about the final material properties to be drawn. Based on an evaluation function the feedback from micro samples will be used to produce samples for next generation. If a certain quality threshold is reached, a macro sample is generated for validation (Drechsler, 2016). This innovative approach is intended to provide target-oriented and resource-efficient alloy compositions and process chains for new metallic construction materials.

Laser alloying provides wide application fields. A frequent area of application is the production of high-resistant products, especially for lightweight materials (Vollertsen, 2008). The process has proved in industry its ability to modify the chemical composition and thereby the properties of the material surface (Klocke, 1996). Studies on wire-based laser alloying with beam modulation have shown that the cooling behavior of the melt pool mainly influences the metallurgical and mechanical properties of the alloy (Hofmann, 2016). Different microstructures depending on the process control could be shown in laser alloying of titanium surfaces (Filip, 2006).

To generate reproducibly alloy compositions for a high-throughput, samples with a homogeneous dilution of alloy elements are to be generated by laser deep alloying. Laser deep alloying is using the deep welding effect whereby higher penetration depths can be achieved than with laser alloying. Research is carried out on a methodology based on the use of two laser-based processes in a process chain under the application of additive manufacturing (Vetter, 2016). The principle and results on influences on the formation of the melt pool are presented in this work.

2. Experimental setup

The principle of the laser deep alloying process is shown in Figure 1. In a first step alloy element layers were pre-deposited on the base material by SLM. Afterward, the layers were remelted and mixed with the base material by a scanner - guided high-power laser. The unalloyed case hardening steel C 15 acted as base material. Melting occurs at a temperature around 1510 °C. The dimensions of the base plates were 150 mm x 150 mm x 18 mm. Powdered stainless steel X2CrNiMo17-12-2 was used as a master alloy for pre-depositing the alloy layers on the base material. The grain size was in a range from 10 µm to 45 µm.

The pre-deposition of the master alloy was carried out by using a ReaLizer SLM 250 with a Yb:YAG single mode fiber laser and a wavelength of 1070 nm. The single layers of the total layer were applied with a thickness of 50 µm. The total layer thickness was 200 µm and was applied with a laser power of 100 W and a scanning speed of 120 mm/s. Each layer for each micro sample was of a square shape with a side length of 10 mm.

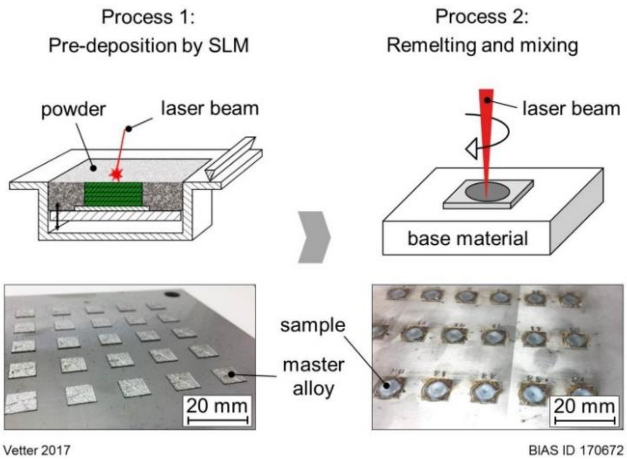

Fig. 1. Schematic setup for laser deep alloying process

The remelting and mixing of the element layers with the base material were carried out with a disk laser Trumpf TruDisk12002 with a wavelength of 1030 nm and a maximum power of 12 kW using a 3D-Scanner-Optic Trumpf PFO 3D with an f-theta lens and a focal length of 450 mm. Figure 2 a) illustrates the experimental setup. The spot diameter of 650 µm was kept constant. Argon shielding gas was provided at a rate of 6 standard liters per minute laterally at an angle of 45° using a nozzle with a diameter of 13 mm. The laser beam was modulated circularly by the scanner optics applying a form of 14 consecutive overlaying circles of different sizes and a total modulation path of 115 mm as shown in Fig. 2 b). After the mixing, the sample shape was circular with a diameter of 8 mm. The laser power was varied in steps of 1 kW within a range from 3 kW to 7 kW. The modulation speed was varied in six steps from 5 m/min to 30 m/min. The measured values were determined by means of metallographic cross sections taken in the center of the samples. The penetration depth was measured from the original surface to the deepest penetration of the melt pool. All values in the diagram are an arithmetic average of three measurements with the standard deviation.

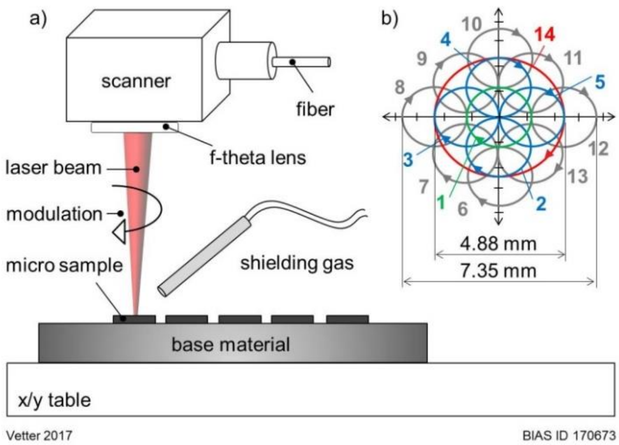

Fig. 2. a) Principle of the laser deep alloying process; b) Modulation form with a pathlength of 115 mm for remelting and mixing the pre-deposited layer with the base material

3. Results and discussion

Figure 3 shows the influence of the laser power and the modulation speed on the generation of deep alloyed micro samples. With increasing laser power the penetration depth also increases in a nearly linearly increasing course. This applies to all modulation speeds, even though the laser power has a higher effect on the penetration depth at a high modulation speed than at a low one. Doubling of the laser power from 3 kW to 6 kW at a modulation speed of 15 m/min leads to an increase of the depth by 166% from 1.14 mm to 3.03 mm. At a modulation speed of 5 m/min, the increase of the depth is by 99% from 2.95 mm to 5.86 mm. However, at a low laser power of 3 kW, a significant change in the penetration depth occurs only at a speed of 15 m/min. The standard deviation of the values has only a small spread.

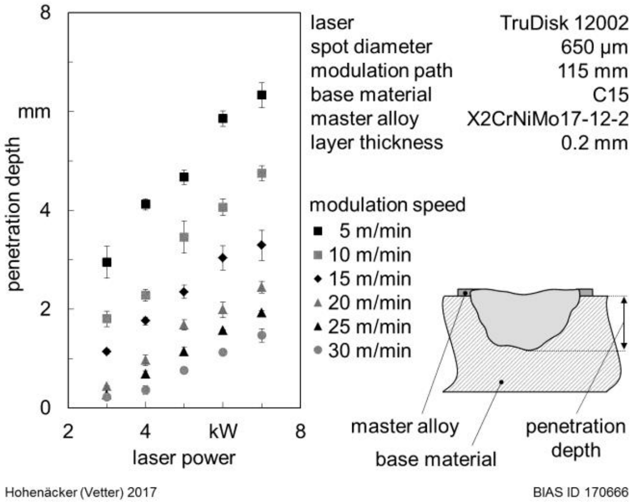

Fig. 3. Influence of the laser power and the modulation speed on the penetration depth

In Figure 4 the influence of the laser power and the modulation speed on the melt pool area is shown. Compared to the penetration depth, the size of the melt pool area provides additional information about the width of the melt pool. The melt pool area also increases with increasing laser power, however with a low scatter. High modulation speeds of 25 m/min and 30 m/min lead to melt pool areas of less than 10 mm² even at high laser power of 7 kW. With modulation speed from 20 m/min and higher, no appreciable increase of the melt pool is achieved by using laser power below 5 kW. At a modulation speed of 25 m/min, even higher laser power no longer result in a sufficient formation of a melt pool as indicated by the low melt pool area.

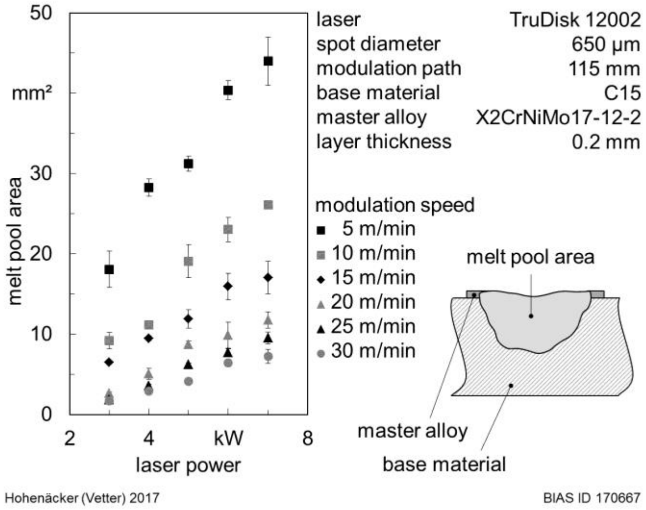

Fig. 4. Influence of the laser power and the modulation speed on the melt pool area

The comparison of cross sections in Figure 5 illustrates the enlargement of the melt pool at a higher laser power as well as at a lower modulation speed. It can be shown that high modulation speed combined with low laser power do not lead to a sufficient melt pool formation in a single application of the modulation form. However, low modulation speed with high laser power affects imperfections in the microstructure such as pores. In addition, the higher energy input due to the longer exposure time at a low modulation speed of 5 m/min not only affects the melt pool size. Rather, the entire geometry of the sample is influenced. The melt pool geometry is formed from a semicircular shape at a high modulation speed to a square shape at a low modulation speed.

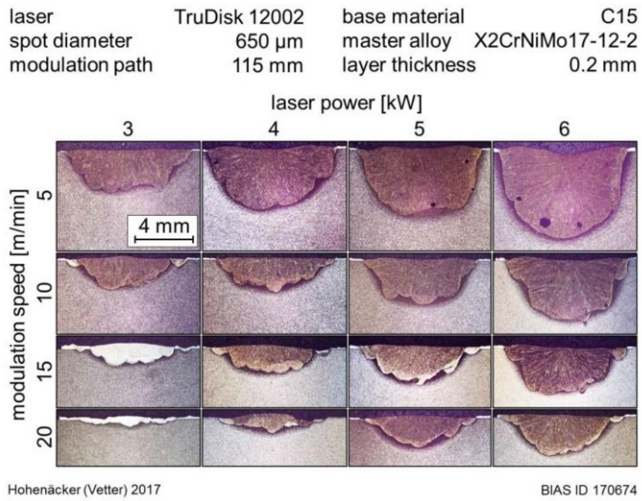

Fig. 5. Cross sections of samples produced with different laser power and modulation speed

The application of differently high laser powers and modulation speeds also influences the microstructure of the produced alloys. By applying a higher laser power a directed microstructure occurs, see Figure 6. With lower laser power, the microstructure is less directed and more homogeneous. The directed microstructure can be explained by the fact, that the cooling takes place very fast from the outside to the inside of the sample. The influence of the energy input on the microstructure is still under investigation. However, a trend of finer microstructure at lower modulation speed can be shown.

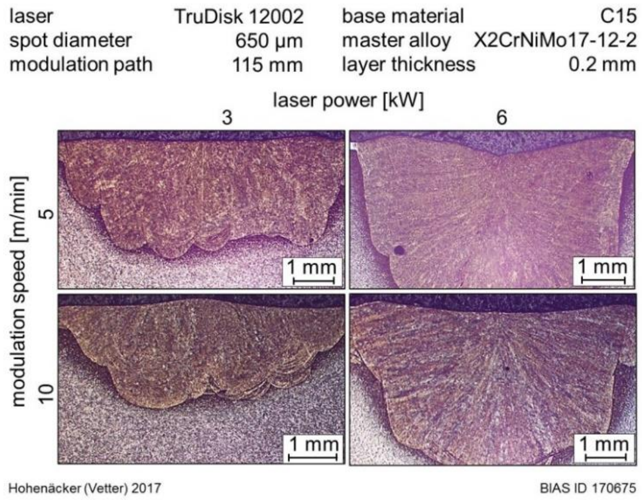

Fig. 6. Influence of the laser power and the modulation speed on the microstructure

In Figure 7 a process window for laser deep alloying with a sufficiently large melt pool and without imperfections is shown. At high modulation speed and low laser power only a small melt pool formation is achieved. High laser power and very low modulation speed, on the other hand, lead to imperfections in the microstructure such as pores and cracks.

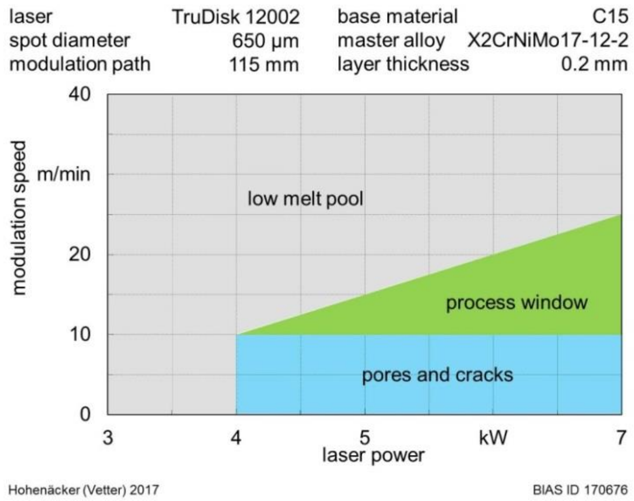

Fig. 7. Process window for laser deep alloying

4. Conclusions

The application of different laser power for remelting and mixing leads to a finely graded increase of the melt pool area and thus to a controllable increase of remolten base material as the main alloy element. By selecting suitable laser process parameters micro samples with a sufficient melt pool size without pores and cracks can be produced. Therefore, the laser deep alloying process using pre-deposited element layers combined with beam modulation is a suitable method to adjust the alloy content of alloys specifically when producing samples for a high-throughput based material development.

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