Parametric analysis of 1.2709 maraging steel manufactured by LPBF

Jessica Schober

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Schober Jessica
Material technology
Technical University of Applied Sciences Amberg-Weiden
Kaiser – Wilhelm – Ring 23, 92224 Amberg, D
J.Schober@oth-aw.de

Abstract— **The lack of standardisation in handling LPBF processes (Laser Powder Bed Fusion) requires the creation of a material-specific knowledge base. Resulting material and structural properties as a function of variable process parameters have to be investigated in the handling of new powder materials based on steel.**

The material 1.2709 is one of the promising powder materials used in laser additive production and serves as the experimental material for this project work. In connection with an Nd:YAG laser system of the, the quality-relevant process parameters scanning speed, laser power and line offset are quantified in a simplified test setup. Additionally the influence of an angular offset on the component quality is investigated.

Keywords—LPBF Laser Powder Bed Fusion, Parametric analysis, 1.2709

I. INTRODUCTION

The generative process of additive manufacturing enables industrial companies to take a new approach on component production. Additive technologies allow the production of function- and geometry-optimized components in an efficient manufacturing process. In particular the production of additive functional components from metal powder in connection with a laser beam as energy source increasingly arouses the attention of the industry. [1], [2]

This comparatively new manufacturing process is used in the aerospace industry, in prototype construction or in the manufacture of individual parts. Due to their lack of reproducibility and the resulting differences in properties, does additive manufactured components considered unsuitable for series production. Only the further technical development of laser additive manufacturing, also known as Laser Powder Bed Fusion (LPBF) makes it possible to generate components with high specific component densities. As a result of a metallurgical fusion of the adjacent individual tracks and layers, an almost 100% component density with material properties comparable to conventional processing methods can be achieved and generate the inception for the industrial series production. [3], [4], [5], [6]

This technology is based on the cyclic, step-by-step build-up of individual layers of powder material. As a result of the laser energy applied, the powder particles are selectively melted according to a three-dimensional computer data set and the already solidified powder layer underneath is additionally melted. The sequence of individual melting lines generates the desired component geometry line by line.

The lack of standardization in the handling of metallic powder materials complicates the introduction as an industrial manufacturing method. The lack of understanding in handling metal powders, limited knowledge of selected process parameters and their influence on component quality [1] require the creation of a material-specific knowledge base. The aim of this work is to quantify the resulting material and structural properties as a function of the process parameters in an experimental procedure.

II. INSTABILITIES DURING THE LPBF PROCESS

Process instabilities during the manufacturing process increase the risk of premature component failure. Defects in the microstructure minimize the hardness and strength properties of additive manufactured components. Unwanted pore formation in the microstructure is encouraged by the selection of an incorrect energy supply and an incorrect hatch distance.

A low energy input per length, from a certain boundary point, to an interruption of the melt bath and finally to an inhomogeneous material bond. The incompletely melted powder material, the increased melt viscosity and the resulting increase in surface tension, force the melt to change to its energetically most favourable state and form droplets. In this undesirable formation, the melt finally solidifies and causes incomplete powder melting as well as incomplete covering of the surface. In turn, excessive energy input per length leads to local overheating of the melt bath and thus to evaporation of the material. The reduced melt viscosity promotes the formation of splashes due to the outflowing metal vapours. These melt drops solidify in flight and deposit in the form of spherical particles along the melt path in the powder bed. The increased energy required to melt these splashes disturbs the process equilibrium and causes unwanted defects or inclusions in the component structure.

Furthermore, the choice of a large hatch distance leads to an incomplete melted powder material. The free powder particles form defects in the microstructure and thus increase the component porosity. If the hatch distances are too small, the melt paths are superimposed. The renewed heating of the melt increases the heat input and promoted the formation of heat cracks in the microstructure. Furthermore, the productivity of the laser additive manufacturing process is minimized due to prolonged build up rates. [1], [2]

To avoid these instabilities during the building process, it is necessary to quantify the expedient parameters.

III. EXPERIMENTAL PROCEDURE

A. *Experimental set-up (Fig. 1)*

The building process of a sophisticated LPBF system can basically, divided into three modules: laser system, powder feed and height-adjustable construction surface. This additive manufacturing process can be simulated for the purpose of this parametric analysis using conventionally available and cost-effective means.

A Nd:YAG high-performance laser is used for the tests. With a constant wavelength of 1070 nm, the laser system is operated in continuous wave mode (CW). The sealed construction chamber beneath with a maximum height of 300 mm is flooded with argon as inert gas.

The building surface is raised by the fine thread of a cylindrical hand specimen holder. The lower part of the hand specimen holder is fixed in the installation space with a screw and the outer ring is unscrewed layer by layer. This defines the layer thickness. This defines the layer thickness, which is 0.1 mm during the entire test.

The powder is applied manually. To evenly distribute the powder particles on the building surface an create a constant layer level, a rectangular plate can be used.

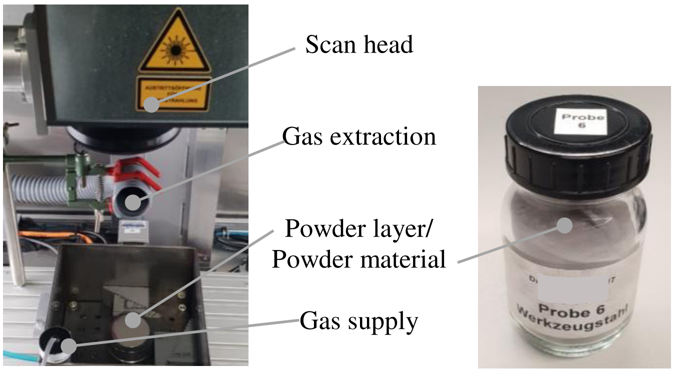

Fig. 1. Experimental set up and the powder material 1.2709

B. *Powder material 1.2709*

This parametric analysis used the powder material 1.2709. With its extremely high strength values, good welding properties and his high resistance to stress corrosion cracking [7], compared to conventional alloyed steels, this material is one of the common powder materials used in the additive production. As an iron-nickel alloy, the martensite-hardening steel with an almost carbon-free structure was mainly used in aerospace, military and toolmaking industries. The high nickel content and the low number of carbides minimize the risk of undesired cracking during thermal melt cooling. [8], [9] An internal investigation shows that the powder particles have a spherical shape with a particle size between 10 and 50 µm (see Fig. 2.).

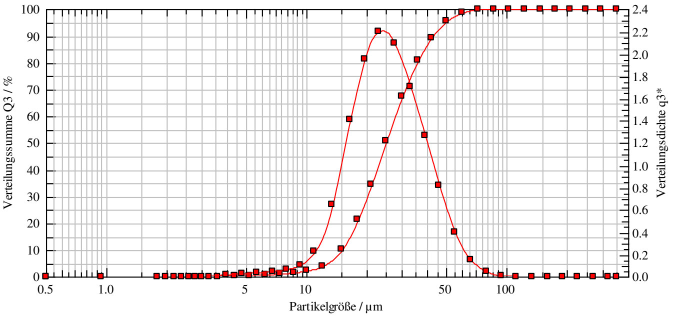

Fig. 2. Particle size distribution of the powder material 1.2709

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In addition to the high quality of the powder material, the choice of the correct process parameters is directly related to the density and thus the strength of components manufactured in LPBF [9]. In order to achieve a homogeneous microstructure during the manufacturing process, the material-dependent process parameters are determined experimentally.

The main focus of this parametric analysis lies in the experimental determination of the ideal energy per unit length, as a product of the laser power and the scanning speed, as well as the determination of the line offset based on it. Individually generated melting lines as test results of the variable parameter setting serve as evaluation samples for this work. The melt lines are examined in top view as well as in cross section according to their quality.

A. *Influence of the energy input on the first layer*

The absorbed laser energy for melting the powder material and the already solidified material below is referred as the energy input per length. The ideal energy supply varies according to the degree of absorption and the thermal conductivity of the powder material used. It is selected depending on the layer thickness. The introduced energy input per length E defines the quotient of the laser power P and the scanning speed v.

In order to find the ideal range of energy input per length, melting lines will be generated by a constant laser power with a gradually increased scanning speed. Power values of 250 W and 125 W are investigated. The amount of scanning speed is adapted to the laser power supplied in the same ratio, so that the value of ideal energy input per length can be defined.

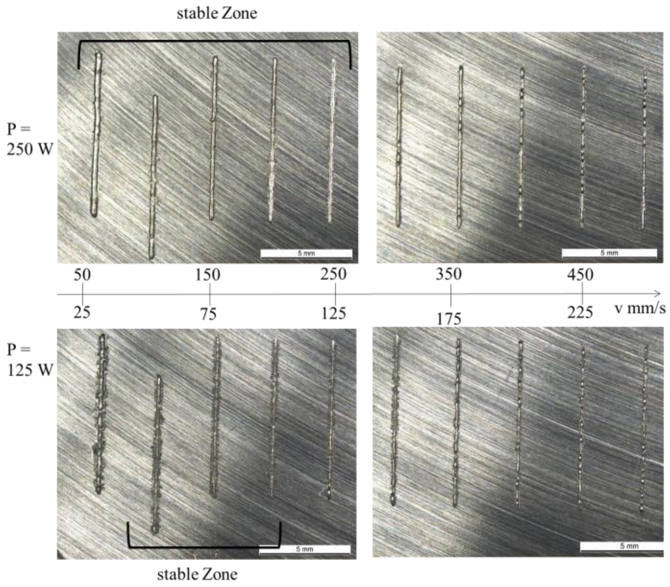

Fig. 3. Samples for defining the energy input per length with melting lines built with different laser power and scanning speed

According to figure 2, high quality melting lines can be achieved at P = 250 W with v = 50 - 250 mm/s and P = 125 W with v = 50 - 100 mm/s. The intersection of the stable zones formed, the ideal energy range from 1.0 - 1.67 J/mm. A chosen energy input per length in this range avoid process instabilities and generate a good component density.

B. Process parameters to generate a metallurgical connection (in vertical direction)

In the cross section, the melting lines of the defined, stable zone are checked for their metallurgical connection with the construction surface.

On one layer: In order to achieve a homogeneous microstructure, the applied powder not only has to be melted, but also the underlying material has to be melted, too. Ideally, the melting height should be close to the applied powder height of 0.1 mm. Due to the powder density a layer height equal to the value can never be completely achieved. According to these quality criteria, that can be recognized in the cross section of the melting lines, the process parameters for melting on layer can be define.

On four layers: By superimposing the melting lines in a horizontal direction, the influence of chosen process parameters on several powder layers is verified. It is known that the energy required for melting decreases with an increasing number of layers due to component heating. [10] Therefore, a total of four powder layers are applied in horizontal direction and melted per layer with the process parameters of the stable zone.

Taking account of the industrial goals to build a laser-additive component as quickly as possible the process parameters P = 250 W and v = 250 mm/s are the parameters which realize maximum build-up rates. With an energy input per length of 1.00 J/mm this parameters generate the best line quality, by melting one and four powder layers and thus form the basis for the following test.

C. Process parameters to generate a metallurgical connection (in horizontal direction)

To realize a three-dimensional component geometry, a melt plane is generated by overlapping the individual lines. Based on the previous test results, the powder particles are melted with a P = 250 W and v = 250 mm/s. A total of four melting lines are lined up. The line offset is increased from 0.125 mm to 0.175 mm in 10% steps, corresponding to the melt width of 0.25 mm generated.

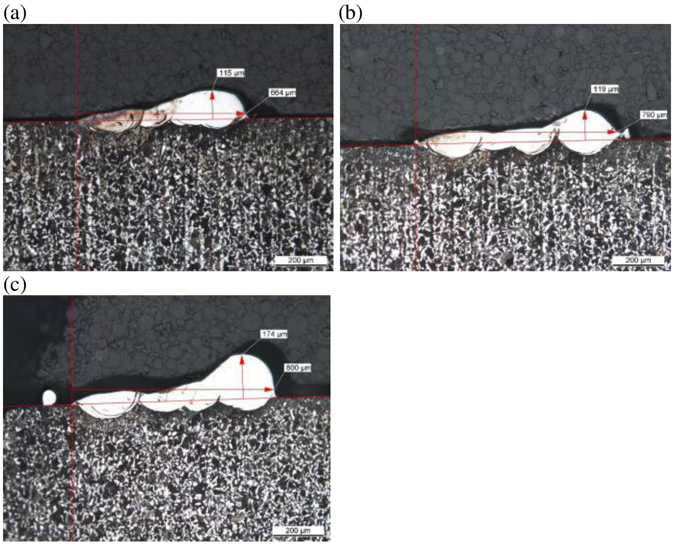

Fig. 4. Vector shifting distances (a) 0,125 mm, (b) 0,150 mm, (c) 0,175 mm on one powder layer, built with a laserpower P = 250 W and a scanningspeed v = 250 mm/s

Figure 4 shows the test result of a powder layer with increasing track distance in cross section. A hatch distance of 0.125 mm (a) leads to repeated melting and bulging of the powder layer and a line offset of 0.175 mm (c) to a rough surface quality due to insufficient powder and lack of fusion. Only (b) with a hatch distance of 0.150 mm produces a constant, even melt layer in horizontal direction and generate a metallurgical connection.

V. INFLUENCE OF THE ANGULAR OFFSET DURING THE CONSTRUCTION PROCESS

A three-dimensional, rectangular sample geometry is produced in the LPBF by stringing together several melting lines both in horizontal and vertical direction. In the following, the influence of an angular misalignment on the component quality is analyzed. Based on the parametric result obtained, two rectangular sample geometries with a height of four layers are generated in an area of 5x5 mm. In one of the two specimens, every melt layer is staggered perpendicular in an angle of 90°. Finally, the results are examined in cross section and checked for the formation of defects and the formed microstructure.

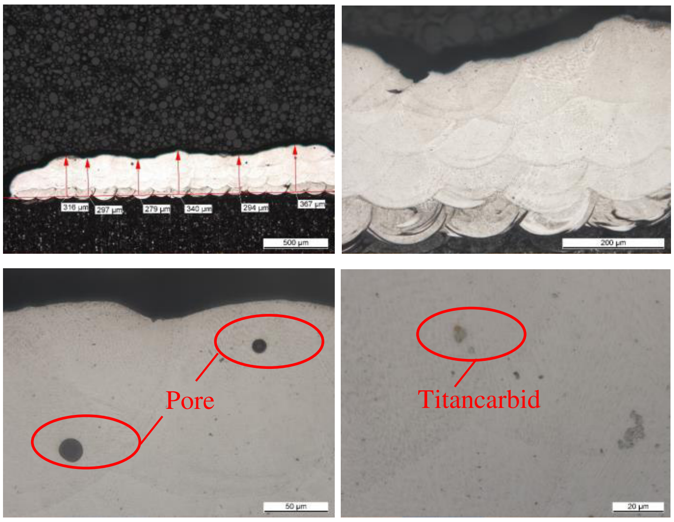

Fig. 5. Microstructure built with an angular offset of 0° (Sample 1), an laser power P = 250 W, a scanningspeed v = 250 mm/s and a shifting distance of 0.150 mm

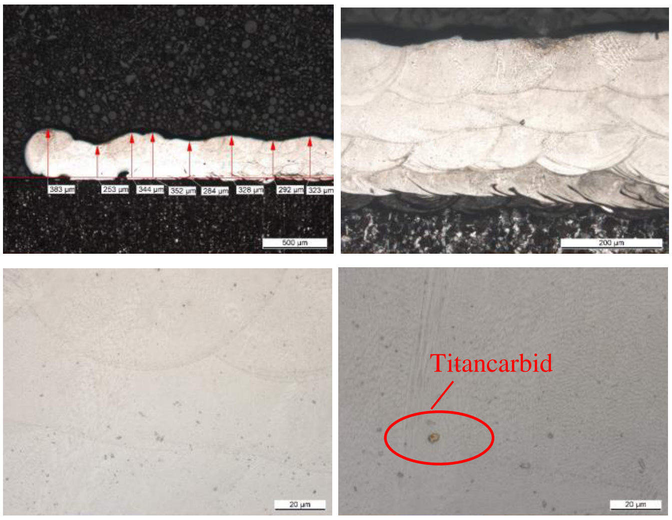

Fig. 6. Microstructure built with an angular offset of 90° (Sample 2), a laser power P = 250 W, a scanning speed v = 250 mm/s and a shifting distance of 0.150 mm

Figure 5 shows the specimen 1 assembled with an angular offset of 0°. The specimen 2, with an offset of 90°, is shown in Figure 6. Regardless of the angle offset selected, both specimens have a total height of 0.32 mm. With an applied powder height of 0.4 mm, this means a shrinkage of 0.08 mm. The surface structure of both specimens is almost constantly flat with light waves. The molten bath and the building direction are clearly visible in the cross section. In the transition area between the building surface and the first layer of powder as well as in the microstructure no hot cracks can be detected.

The microstructure essentially consists of many fine cell crystals and some coarse grains. The high cooling rates in the LPBF process of the molten bath generates the formation of a dendritic martensite. The morphology growth in form of elongated crystals perpendicular to the solidification isotherm proceeds in center direction. The crystals of the material align themselves in the direction of the solidification. Titanium carbides can occasionally be localised in the microstructure. Undesirable process instabilities in the form of pores were increased detected in test specimen 1. These defects in the microstructure increase the porosity and minimize the component properties. The microstructure of test specimen 2 does not show any of these types of defect. An angular offset of 90° achieves the desired homogeneous melt connection and seams to generate the best manufacturing results.

VI. CONCLUSION

This parametric analysis provides basic knowledge for the melting of the powder material 1.2709 in the LPBF process. In the experimental procedure, the process parameters for melting a layer height of 0.1 mm are defined using existing equipment and a simplified test setup. The ideal energy supply for a line is in the range of 1.0 and 1.67 J/mm. With a laser power of 250 W, a scanning speed of 250 mm/s and a line offset of 0.15 mm, three-dimensional sample geometry with high quality properties can be created. Furthermore, with the mentioned process parameters and an angular offset of 90° during the assembly process, an almost 100% component density without defects was created.

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