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Influence of initial powder layer thickness and focus deviation on the properties of hybrid manufactured parts by Laser Powder Bed Fusion

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Abstract

In hybrid-additive manufacturing using powder bed fusion with laser beam (PBF-LB) conventionally manufactured base-bodies are overprinted with an individual geometry. In this paper, the influence of deviations of the initial layer thickness, and the focal plane on the component properties are investigated. For separate consideration of the individual effects, purely additive (AlSi10Mg) and hybrid-additive (AlSi10Mg on EN AW6082) test specimens were manufactured. The layer thickness was varied from 0 to 200 µm, and the focal plane between 0 and -8 mm. The influence on the microstructure due to the altered induced energy input is analyzed. These findings are correlated with respect to the tensile strength and material hardness. The highest strength is achieved with an initial layer thickness of 50 µm. A hardness decrease of 8 % due to hot stress cracks in the interface is avoided by targeted shifting of the focal plane.

Keywords: Selective laser melting; hybrid additive manufacturing; focus deviation; initial layer thickness; AlSi10Mg; EN AW6082

1. Introduction

Product lifecycles and the demand for customized products are increasing [1]. As a result, purely conventional mass production using casting processes is not economically possible. An innovative approach is to combine conventional processes and additive manufacturing. The key is to identify the part of a product which has no need of being customized. This part still has to be manufactured economically with mass production. The customer-specific or highly complex part is then built up additively [2]. This approach reduces the low productivity and high costs for the time-consuming layer-by-layer process of a part without having to forego the advantages of design freedom in additive manufacturing. Hence, this approach increases the attractiveness of additive manufacturing in all mechanical engineering sectors [3].

Manufacturing layer-by-layer directly on top of a conventional base body is a non-joining method of manufacturing hybrid metallic parts. Using powder bed-based laser melting (PBF-LB), the base bodies must be clamped onto a platform and the free space between parts must be filled with powder equaling the height of the base bodies. The metal powder is then partially melted by a laser, the platform is lowered and new powder is applied by a coater lip. The process is repeated until the component is completely manufactured. This procedure results in two possible errors that can affect the boundary layer between the base body and the additively manufactured part. In full additive manufacturing, components are usually built on support structures. This compensates for manufacturing tolerances of the machine and platform, as well as deviations between the adjusted coater lip height and the initially set platform height. Deviations of up to 150 µm are possible in the first layer. On the other hand, there may occur deviations in the focal position of the exposed area. During the maintenance of additive systems, the position of the laser focal length is also adjusted. The reference point within the system

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is unknown. The coater lip must then be aligned with this point. The negative influence of a focus deviation on the decreasing component density and surface quality was demonstrated by Emminghaus et al. for the material TiAl6V4 [4].

The aim of this work is to investigate the influence of both described deviations on the density, strength, hardness and microstructure deviations in the boundary layer of hybrid aluminum test specimens.

2. Materials and Methods

The specimens were manufactured on an SLM280HL machine with a layer thickness of 50 µm without platform preheating. The system is equipped with a 1070 nm ytterbium fiber laser from IPG. The laser beam is focused in the plane to w_0: 81 µm with a Varioscan system. The beam has a Rayleigh length of z_R: 3.57 mm. To avoid oxidation effects, the build chamber is flooded with argon. The AlSi10Mg powder was purchased from m4p material solutions GmbH, figure 1.

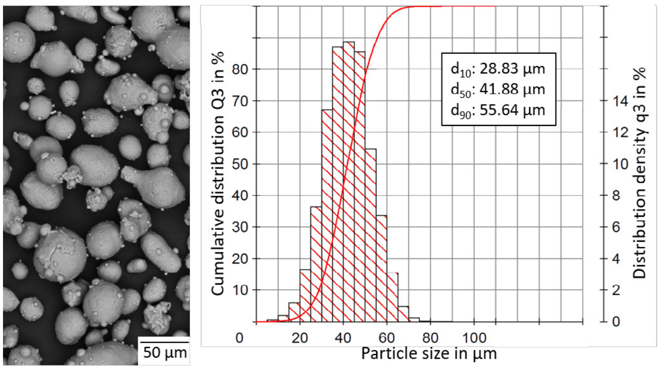

Fig. 1. Properties of AlSi10Mg, particle SEM image left, and particle size distribution right

In order to clearly resolve the deviation of the layer thickness on the mechanical properties of hybrid test specimens, these were built up purely additively (AM/AM). This compensates for any tolerances and setting variations at the interface. The layer deviation was programmed in the center of the specimen made of AlSi10Mg. The specimen were manufactured with the parameters laser power 350 W, scan speed 1150 mm/s, hatch distance 0.17 mm, focus 0. To investigate the influence of a focal plane offset, the focus is just varied for the upper half of the specimens. The focal plane offset was adjusted by permanently shifting the Varioscan scattering lens.

The same investigations were also carried out for hybrid manufactured specimens (Hybrid). The setting of the deviations was increased based on the results of the purely additive findings. This allows to show further effects which normally not occur by setup deviations. For this purpose, round rods with a diameter of 10 mm were prepared using high-strength, weldable aluminum EN AW6082. The material has a similar yield strength to AlSi10Mg. These bodies were then clamped onto a special building platform and milled to ensure parallelism between the platform support surface and the rod surface. The height deviation between the individual rods was measured directly in the milling machine CMX 600v from DMG MORI with a Renishaw OMP40-2. The deviation was 14 µm. Tactile surface roughness measurement has been performed with a MarSurf GD perthometer from Mahr GmbH. 25 randomly selected rods resulted in Ra 0.27±0.09 µm and Rz 1.85±0.44 µm. The construction platform was then installed, the free space manually filled with powder and the zero position set with a straight edge.

Tensile test specimens were turned after the additive manufacturing so that the interface is in the middle of the specimens, figure 2. By removing the surfaces layer, the effects of surface roughness and edge porosity, which occur in additive manufacturing, on the test results are excluded.

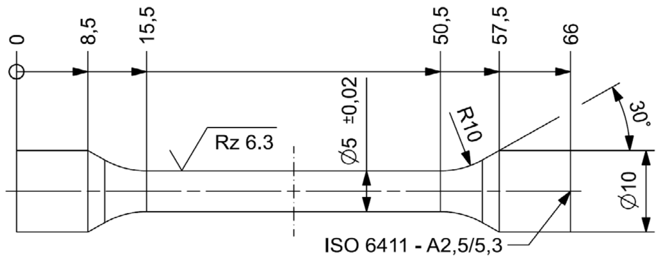

Fig. 2. Design of tensile test specimen

The tensile test was carried out according to DIN EN ISO 6892-1 on a tension-compression testing machine from Zwick Roell GmbH & Co. KG equipped with a 200 kN load cell.

The Vickers hardness test HV0.1 was carried out according to DIN EN ISO 6507-1 on a Falcon 600 from Innovatest Deutschland GmbH. For this purpose, 3 hardness curves were recorded in each polished and etched sample, consisting of 7 measuring points with a distance of 0.2 mm in between, aligned horizontally to the interface. The middle measurement was aligned in the interface. Two further interface measurements were taken at the same distance above and below of the measurement line.

Changes in density were determined image-based from the micrographs.

For statistical validation, all tests were set up 8 times (5 times for tensile tests, 3 times for micrographs and hardness profiles). The error bars in the figures are given as minimum and maximum measured values to the calculated average value, without outliers proved by a Grubbs' Test (significance level α: 0.05). Without outliers, at least 4 samples per setting are available for the calculation. The indication of the standard deviation is not chosen due to insufficient number of experiments. An ANOVA (α: 0.05) test was performed to demonstrate the significance of the factors combined with a Tukey's test to prove the significant difference between the varied factor levels. The probability value p is given in the charts. An overview of all tests is shown in table 1.

Table 1: Experiments overview

Test sample type	Focal plane offset z in mm	First layer thickness in µm
AM/AM	0	0*/ 50/ 100/ 150
AM/AM	0/ -0.1/ -0.2/ -0.5/ -1/ -2	50
Hybrid	0	0*/ 50/ 100/ 150/ 200
Hybrid	0/ -2/ -4/ -6/ -8	50

*no powder recoated

3. Results

Negative influence of a deviating layer thickness could only be significantly demonstrated in the purely additively constructed samples. The Tukey's test and the similar error bars of the yield strength comparing 50 µm and 100 µm show no significant difference. With further increasing layer thickness, the yield strength drops by 10 %. Analyzing the tensile strength, there is a steady negative influence of up to 9 % when comparing 50 and 150 µm. If the layer thickness is lower (0 µm) than the ideal initial level (50 µm), the yield strength drops by 14 % and the tensile strength by 4 %. Therefore, a deviation to higher initial layer thicknesses, up to 100 µm is recommended. While samples with a layer thickness of 0-100 µm failed at various points along the measurement section, samples with a layer thickness of 150 µm only failed in the interface, figure 3.

The influence of the layer thickness on the properties of the hybrid-manufactured components was not verifiable. This is not attributed to deviations in the overall system setting, but to the lower yield strength and tensile strength of the wrought material EN AW6082 [5]. The specimens exclusively failed in the wrought material.

The decrease in strength at higher layer thicknesses can be attributed to an increase in porosity, pore size and frequency in the interface due to incomplete melting measured in the last three layers before and six layers after the interface, as shown in the histogram, figure 4, and in the microscopy images, figure 5 left. The decrease at a layer thickness lower than 50 µm can be attributed to an increase in porosity and more small pores, figure 4. The further decrease instrength at double exposure of the interface (thickness 0 µm) is attributed to the reduction of the Si network around the submicron primary Al cells by reheating. The Al cells grow by taking up the Si which leads to a kind of "grain growth" and connection of the Al cells. Therefore, the grain boundary strengthening effect decreases, which was also observed by Casati et al. [6], figure 5 right.

The influence of the focal plane offset and thus the focal diameter enlargement can only be shown for the hybrid-manufactured samples. Until a focal plane offset of -6 mm, no correlation with the strength values can be observed, as revealed by the Tukey's test and shown by the overlapping error bars. At a focal plane offset of -6 and -8 mm, a decrease in mean strength values and a significant increase in scatter up to 400 % can be observed, figure 6. This is due to the fact that the fracture increasingly occurs in the additive area despite the weaker base material. At the -6 mm setting, one specimen and at -8 mm, three out of five specimens fractured in the additive area. As a focal plane offset due to machine setting deviations greater than 0.15 mm is not realistic, this deviation is less important than the initial layer thickness for setting up hybrid build jobs.

An identical trend can also be seen in the analysis of the density. From a focal plane offset of -6 mm, the density decreases and the scatter increases, Figure 6 left. The sharp increase in porosity and the simultaneous scattering explain the result of the tensile tests. Due to the focal plane offset, the diameter of the focal point increases, which decreases the energy concentration. This leads to a reduction of the melt pool

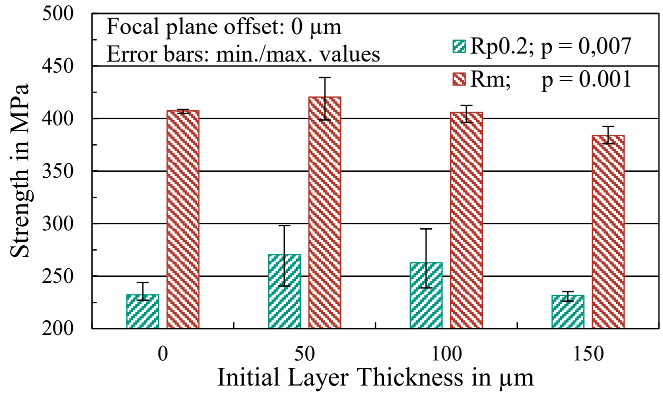

Fig. 3. Yield and tensile strength of full additively built specimens.

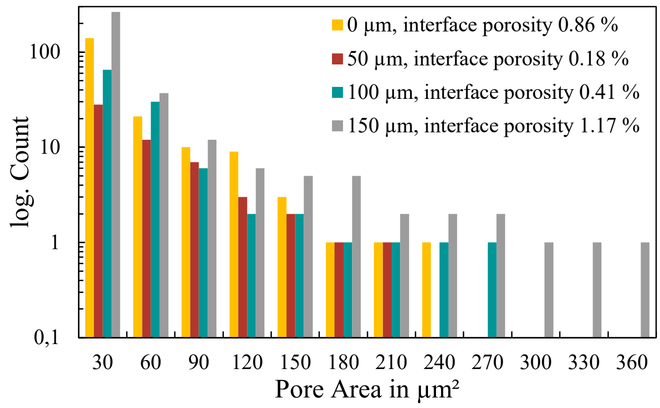

Fig. 4. Pore size and frequency of full additively built specimens and porosity in the interface measured from microscopies

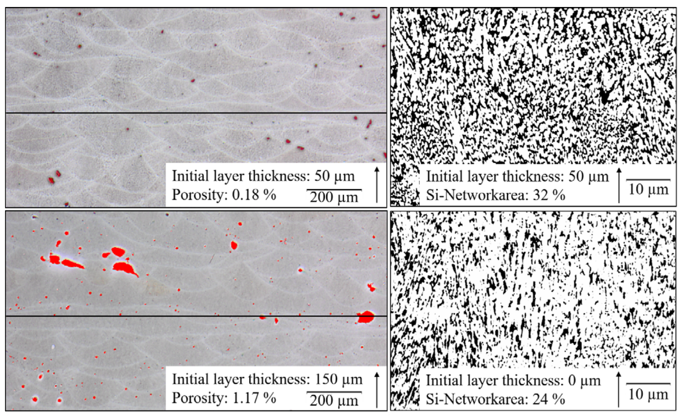

Fig. 5. Influence of initial layer thickness on interface porosity (red) left, reduction of Si-Network (black) cause of double layer scanning as a binary microstructure picture right. Building direction visualized as arrow

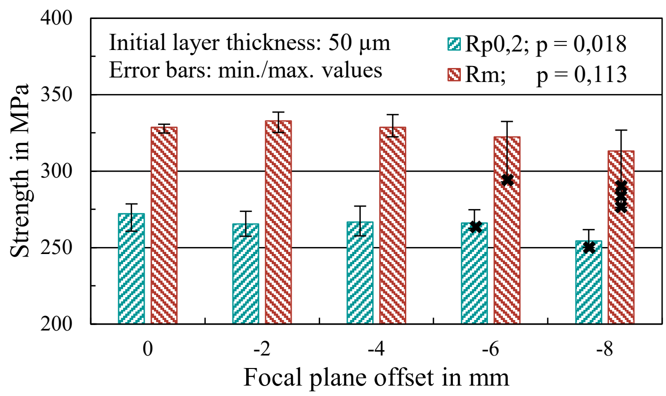

Fig. 6. Yield and tensile strength of hybrid-additively built specimens. Additive fractured specimens marked as black crosses.

depth [7]. The probability of poor layer bonding, resulting in inadequately melted areas that act as notches in the material, increases. The sudden onset of property degradation, also observed in more detail in [4] for the material TiAl6V4, is due to processing outside the Rayleigh length as well as falling below the necessary peak energy threshold of the beam to produce a sufficiently large melt pool, figure 7 right. The threshold for a dense material parameter set is defined as 43 % of the peak energy density of an ideal Gaussian spot profile. This corresponds to a focal plane offset of -4 mm, which leads to dense parts without strength decrease in these experiments. The threshold could be lower, as expected from the results of [4], but further experiments with a focal plane offset between -4 and -6 mm must first be performed for this material pairing.

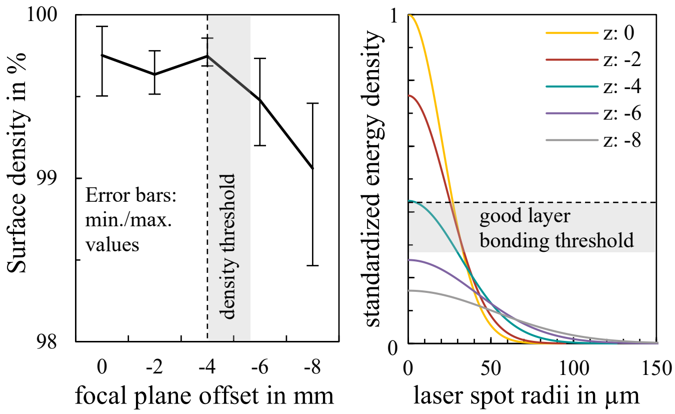

Fig. 7. Surface density of additive section of hybrid manufactured test pieces left, ideal Gaussian transversal energy intensity distribution for different focal offsets and constant power right. Possible threshold value marked as grey surface.

The hardness is more sensitive concerning changes in the process parameters. Hence, a positive effect of the defocusing in the boundary layer is found. If the boundary layer is exposed with a lens position of 0 or -2 mm, there is a significant (p = 0,005) decrease in hardness in the boundary layer of approx. 8 %, figure 8. A difference in the hardness of the additively manufactured material based on the focal plane offset cannot be calculated.

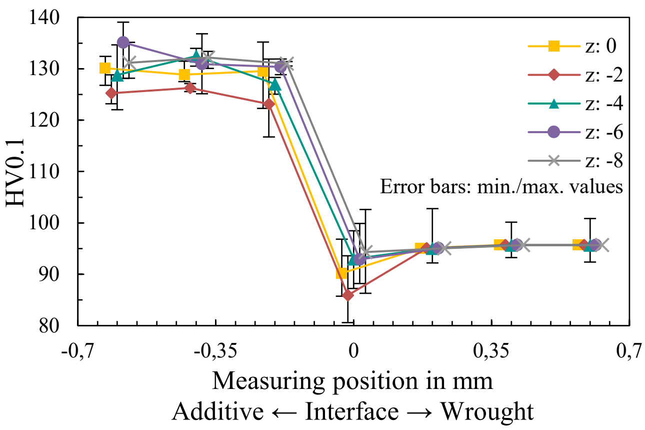

Fig. 8. Hardness profile of interface between wrought and additive manufactured material.

The decrease in hardness during focused processing of the surface layer is attributed to the overheating of the surface layer and forming of a mushy area. This leads to the formation of hot stress cracks mostly in the material EN AW6082, even the material is less susceptible to crack formation during welding than other aluminum materials like EN AW6005 or 6061 [8]. The number and severity of the cracks decrease with increasing defocusing, because the overall process temperature decreases figure 9.

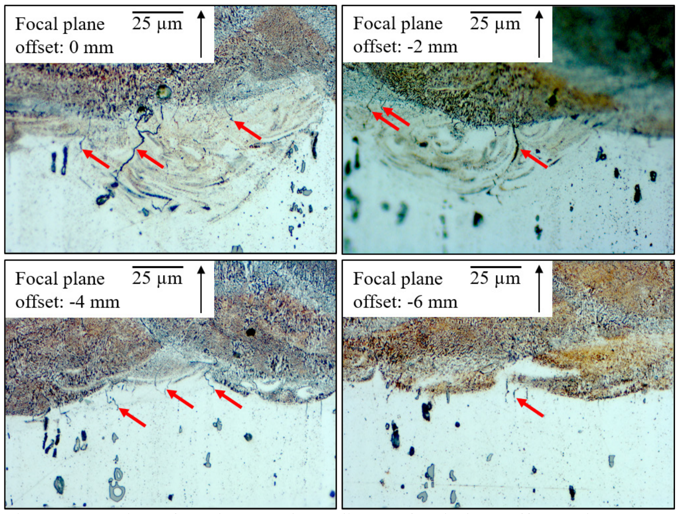

Fig. 9. Formation of mushy area depending on focal plane offset and associated crack formation marked with red arrows. Building direction visualized as black arrows

The mushy area in the boundary layer shown in figure 8 is created by a Marangoni flow in the melt pool. The temperature difference between the middle of the melt pool and the edge of the melt pool creates a surface tension gradient, which leads to shear stress in the melt pool [9]. The resulting stirring effect ensures a heterogeneous alloy distribution in the boundary layer [10]. It is observed that the size of the mushy region decreases with increasingly focal offset. Further, it is observed that the cracks mostly form through the mushy region, so the formation should be avoided in the process. This effect was also reported by Wang et al. [10].

4. Conclusion

In this work the influence of deviations of the initial layer thickness and linked the focal plane offset due to tolerances and difficulties in the machine setup were investigated. The microstructure, hardness and tensile properties were considered with the following results:

- By building up fully additive specimens the influence of the initial layer thickness could be shown. Best results in tensile properties are achieved with an ideal layer thickness of 50 µm. If deviations can't be avoided higher layer thickness, up to 100 µm, is preferred over a lower one.
- An influence of the initial layer thickness on the properties of hybrid manufactured components made of AlSi10Mg and EN AW 6082 could not be determined, due to the varying material properties.

- A negative influence of a focal plane offset in a realistic range on the tensile properties of hybrid AlSi10Mg and EN AW6082 specimens could not be found. But the adjustment of the energy input by varying the focal plane offset lead to a reduction of hot cracks in the interface and no hardness drop.

5. Acknowledgements

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