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Laser plastic welding of additively manufactured components – surface treatment and process adaption for improving the welding result

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Abstract

Additive manufacturing (AM) of thermoplastic components is a growing market, used in prototyping, small-scale production or in mass production of customized parts because of its high flexibility and form freedom. The laser-based powder bed fusion of polymers (PBF-LB/P) is a process variant where the part is formed out of a powder bed, leading to a rather uniform structure. In order to manufacture composite parts, a flexible joining technique, that leads to strong and tight weld seams is needed, making the laser transmission welding (LTW) a perfect match.
The SLS parts' heterogeneous microstructure, rough surface and resulting optical properties make it a rather challenging process. Through a surface treatment with a 1940 nm thulium laser the surface roughness and crystallinity and thus the transmission are improved. Different welding principles are tested and the weld seam strength is investigated as well as cross sections in order to verify a cavity-free weld seam.

Keywords: "Laser transmission welding; Additive manufacturing; Selective laser sintering; Polyamide 12 (PA12); Surface treatment"

1. Motivation

Because of its flexibility and customizability additive manufacturing (AM) is commonly used in prototyping or small batches. Multiple process variants are available, one that is common in industry is the Laser-based powder bed fusion of polymers (LBF-LB/P). One of the most important advantages of additive manufactured parts is the high form freedom. In opposite to injection molded (IM) parts, it is for example possible to produce undercuts or light weight structures. Even more flexibility is gained by the possibility of creating composite parts with a reliable but also flexible joining technique. As the laser welding of polymers is already a well-established process for injection molded parts, leading to very good results, it is also a well-suited technique for joining additive manufactured parts. It is a highly flexible and toolless process, which makes it a very suitable addition for the as well toolless additive manufacturing. However, the rather heterogeneous microstructure of laser sintered (LS) components leads to internal scattering of the laser light in the laser transparent part, thus a lower transmission than comparable injection molded parts. In the laser sintering process, additional powder layers are put over the finished component in order to allow uniform cooling and prevent warping (Drummer et al. (2019)), leading to a loosely adhering powder layer. Despite cleaning the component, this layer is still partly remaining, resulting in a rough surface which is prone to burnings, thus needs a special treatment before welding.

For welding AM parts, two cases can be differentiated. Dependent on the application AM components can be joined with AM components or with IM ones. The latter may be advantageous for the customization of mass production parts, where a customized AM part is welded to an IM standard component (Wolf et al. (2020)).

Laser welding is a standard process for joining polymers. Based on the application different process variants are available, like for example contour welding, where the laser moves over the welding contour once or only a

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few times with a relatively low velocity. Opposite to this, when welding with a quasi-simultaneous process variant, the contour is overrun several times with a high velocity. The processes for laser transmission welding all have in common, that the parts consist of a laser transparent upper joining part and a laser absorbing lower joining part. In the welding process, the parts are held together with a specified clamping force, leading to a good contact of the joining parts in the welding area. The laser transmits through the upper joining part and is absorbed at the surface of the lower joining part. Because of the thermal contact, the upper part is warmed up as well via heat transfer, thus both parts plasticize in the welding area and form the weld seam. Welding parts with uneven surfaces is problematic as gaps between the surfaces can hardly be bridged. This is in particular challenging when using a contour welding process, as the contour is only overrun once. In quasi-simultaneous welding the weld is overrun with a very high velocity, so the whole weld seam plasticizes quasi-simultaneous, leading to a better gap bridgeability. Therefore, the quasi-simultaneous welding process is the most suitable technique for welding AM parts. Small gaps, attributable to the rough, powdery surface of LS components can be levelled in several overruns of the laser, until a full thermal contact is obtained. (Fahrenwaldt et al. (2014))

Studies were already carried out covering the welding of LS components to LS or IM parts with ultrasonic, heat element or infrared welding (Heilig et al. (2018), Bastian et al. (2018), Wolf et al. (2020)), as well as via fused deposition modeling AM components to AM components (Kuklik et al. (2020)). However, until now because of the technical challenges mentioned before, the laser welding of LS parts still needs to be investigated.

2. Experimental Setup

For this study rectangular parts as can be seen in Fig. 1 were made out of white PA12 powder (PA2200, EOS GmbH Electro Optical Systems, Germany) at an EOS P 385. The scanning velocity is set to 4500 mm/s with a scanning pitch of 0.3 mm to 0.4 mm and a laser power of 35 W. In order to achieve a sufficient absorptivity of the laser absorbing part in the welding area, an absorber fluid (Clearweld LD940C) is applied locally on the surface (Fig. 1). This is a well-known and easy and effective way to convert a laser transparent part into an absorbing one. Manufacturing all the parts out of the same powder is advantageous, as the powder in the machine does not need to be changed and all parts can be printed in one step. Since PA2200 has a relatively low water absorption (0.52 % at 23 °C and 50 % relative humindity, EOS (n.d.)) and the samples are processed promptly, they are not dried prior to further processing.

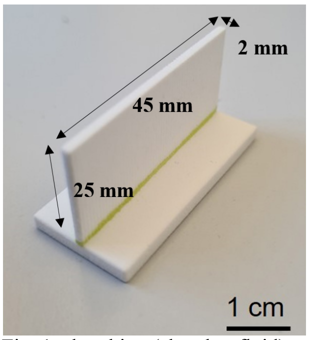

Fig. 1. absorbing (absorber fluid) + transmissive part

In order to improve the transmission and reduce the surface roughness of the laser transparent parts, the surface of the parts is pre-processed with a thulium fiber laser. For the wavelength of this laser, λ = 1940 nm, the absorption of the parts is higher than at a wavelength of λ = 980 nm, which is used for welding. By irradiating at 1940 nm the uppermost, loosely adhering powder layer is remelted to obtain a smoother surface and enhanced transmission. P = 4.2 W to 8.9 W were chosen as laser power for this process, the scanning speed is varied between v = 5 mm/s and 16 mm/s with a beam diameter d = 2 mm and a hatch distance of 0.6 mm. To evaluate the benefit of this process the surface roughness of unprocessed and pre-processed surfaces is measured with a laser scanning microscope. The transmission at λ = 980 nm is evaluated with a transmission measurement system (PICTOR Planar, Intego GmbH, Germany).

For the experiments, a T-joint geometry is chosen in order to weld with a collapse-controlled, quasi-simultaneous process. In this process variant the whole weld seam plasticizes quasi-simultaneously, leading to a movement of the laser transparent layer towards the absorbing part. This so-called welding collapse is the stop criterion for the process. When welding the AM parts with a rather inhomogeneous transmission, this stop criterion holds some advantages over a time or contour-controlled process, where each part is welded in the same amount of time. Because of the wide dispersion of the transmission of the laser transparent part, the time until the weld seam plasticizes and the welding collapse is reached differs from part to part. With the chosen process variant this property can be taken into account. Furthermore, through the movement of the parts the roughness of the surface can be compensated, as the plasticized material fills eventually existing voids, leading to a gap-free interface between both parts. For welding a fiber coupled diode laser with a wavelength of λ = 980 nm and a maximum power of P = 250 W is used. The parts are welded at a laser power range of P = 160 W to P = 210 W, a beam diameter of w = 2.8 mm, a feed rate of v = 200 mm/s, a clamping force of F = 210 N and a welding collapse of 0.2 mm. AM-AM parts and AM-IM parts, where the absorbing component is injection molded (Grilamid L 20 G black, EMS-CHEMIE AG, Switzerland), are welded. In order to inspect the weld seam and the proper connection of the parts, thin and cross sections of the parts are prepared and examined with a microscope. To evaluate the weld seam quality, tensile strength tests are carried out as well. The tensile strength of the AM-AM and AM-IM parts is compared to the base material strength of AM parts, which is determined with tensile test rods. A comparison to the IM parts is not made, as only a comparison to the base material of the weaker component, in this case the AM material, is useful. The tensile strength of the IM part is taken from the datasheet (EMS-GRIVORY (n.d)).

3. Results

The surface treatment with a thulium laser leads to very good results. The transmission at a wavelength of $\lambda = 980$ nm can be enhanced significantly as can be seen in Fig. 2, starting at 10 % transmission for the unprocessed parts. The energy density introduced into the parts correlates with the increase of the transmission and decrease of surface roughness.

The energy density E is calculated by formula (1) with power P, scanning velocity v and beam diameter d:

$$E = \frac{P}{v * d} \tag{1}$$

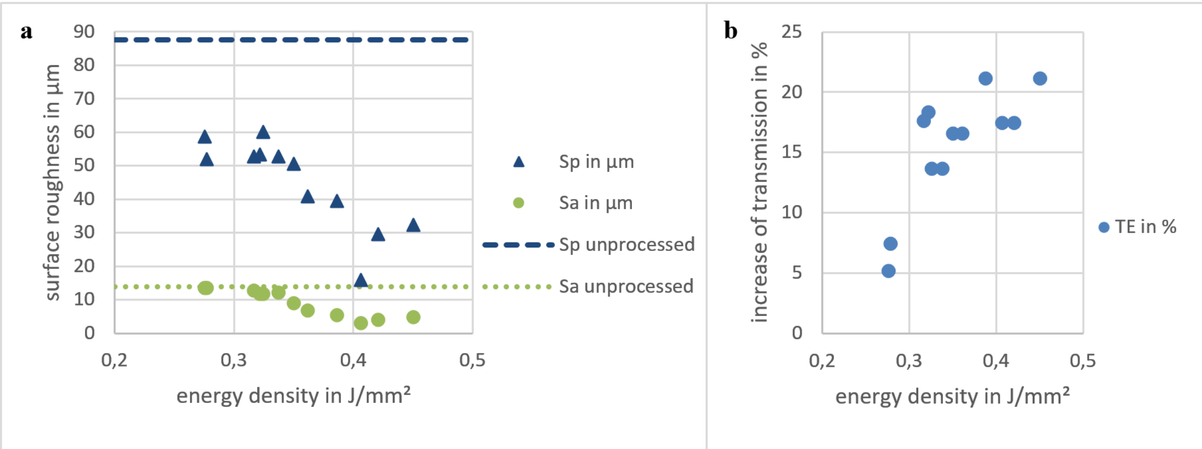

Fig. 2. (a) surface roughness, Sa - arithmetic mean roughness and Sp - maximum profile peak height and (b) increase of transmission as a function of introduced energy density

In microscope images, the influence of the irradiation on the loosely adhering powder layer becomes obvious. In Fig. 3 (a), the surface of an unprocessed part is shown. Fig. 3 (b) shows the surface of a part, processed with an energy density of 0.317 J/mm². Smaller powder particles are remelted, while larger ones stay intact. The transmission is increased by 17.6 % compared to a). With even more energy density, 0.450 J/mm², most of the powder particles are remelted, forming an almost continuous surface as can be seen in Fig. 3 (c). Compared to the unprocessed part, the transmission is increased by 21.3 %.

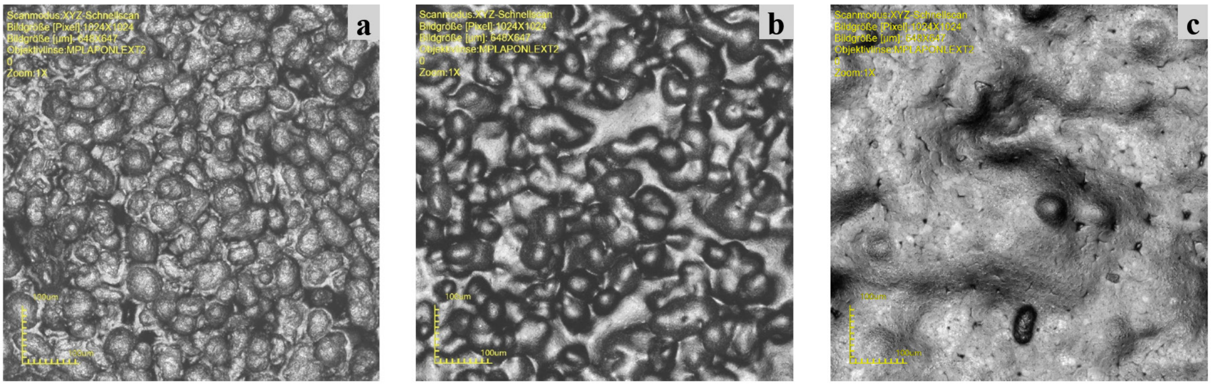

Fig. 3. Laser scanning image of (a) the unprocessed surface; (b) the surface after irradiation with 0.317 J/mm²; (c) the surface after irradiation with 0.450 J/mm²

In order to inspect the weld seam with regard to cavities in the weld seam, thin sections and cross sections were prepared of AM-AM parts and AM-IM parts. Fig. 4 (a) shows a cross section of an AM-AM part under a reflection microscope. The yellow color that can be seen in the picture 4 (a) is the absorber fluid applied on the surface of the part. The welding zone is clearly visible as a completely remelted area between both parts. Although there are some smaller cavities in the AM components, there are no voids in the weld seam. Taking a closer look into the weld seam in Fig. 4 (b) shows that there is an approximately 100 µm thick melt layer, in which the material was completely melted. Through the clamping force and the relative movement of the upper part towards the lower part a squeeze flow towards the edge of the part can be observed. Although there is no equal melt layer visible in the thin sections of AM-IM parts, there is still a cavity-free connection between the parts, as can be seen in Fig. 4 (c).

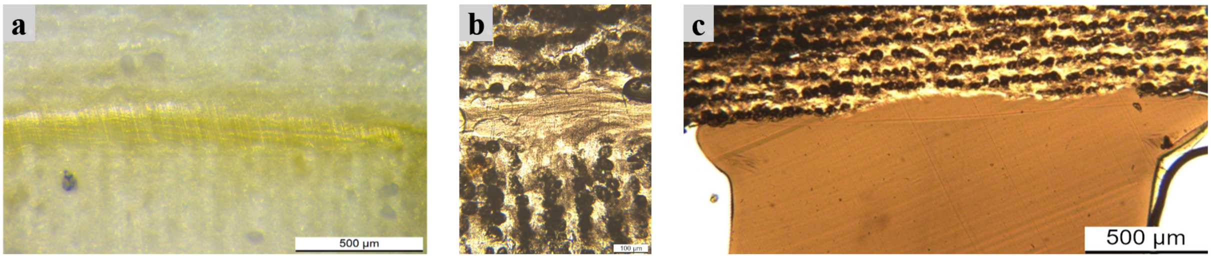

Fig. 5. (a) reflection microscope image of a cross section of the weld seam (AM-AM); (b) thin section of the weld seam (AM-AM); (c) thin section of the weld seam (AM-IM)

Tensile strength tests carried out show the high tensile strength of the welded parts. As can be seen in Fig. 5 the AM-AM parts reach up to 90 % base material strength, whereas the AM-IM parts reach tensile strengths up to 75 % base material strength.

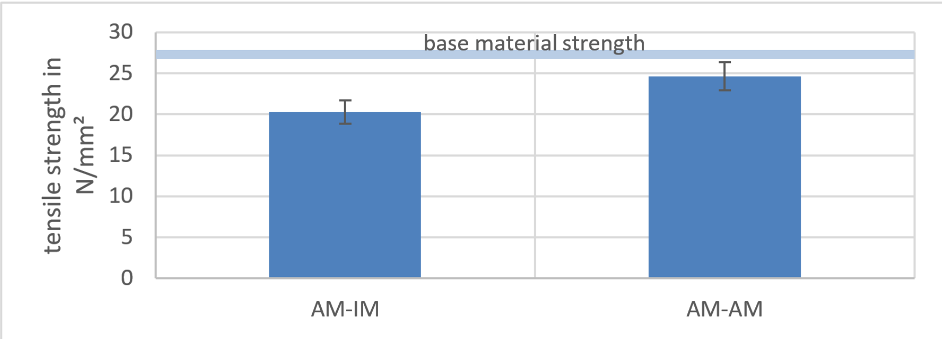

Fig. 4. Tensile strength of welded AM-IM and AM-AM parts in relation to AM base material strength, n = 3

4. Conclusion

In this study the laser welding of AM-AM and AM-IM composite parts was investigated and the suitability of this process to join AM parts was proven. PA12 components were manufactured through an SLS process and successfully irradiated with a thulium fiber laser in order to enhance the transmission and to reduce the surface roughness. This treatment can provide an increase of the transmission by up to 20 %, which leads to an enhanced weldability. When welding the parts with a diode laser in a T-joint configuration with a quasi-simultaneous process and a set welding collapse, it was possible to form strong and cavity-free weld seams, which was verified by thin and cross sections and tensile strength tests. In further studies the welding of more complex part geometries will be tested as well as composite parts, where the absorbing component is made out of black PA12 powder. Additionally, other methods of increasing the absorption of natural or white AM parts will be investigated.

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