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Investigations on the transmissivity and scattering behavior of additively manufactured components for laser transmission welding applications

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Abstract

Additive manufacturing (AM) of thermoplastic parts is a common technique for prototypes, small batches, and mass customization products. A widely used AM process is the fused deposition modeling (FDM), which generates parts with an inhomogeneous volume structure, because it is build up line by line and layer by layer.
An industrial established joining technology is the laser transmission welding (LTW), e.g. for joining injection molded parts in the automotive sector. For this technique, the transmissivity of one joining partner has a high influence on the resulting weld seam quality and the welding process itself. In order to use LTW for joining AM parts, the influence of transmissivity and scattering behavior of AM parts were investigated. The optical properties were analyzed with spectroscopy and shear tensile tests were performed with welded samples to enhance the knowledge about the relationship between the FDM process, the optical behavior, and the weld seam strength.

Keywords: Laser transmission welding, additive manufacturing; fused deposition modeling; transmissivity; polylactide

1. Introduction

The additive manufacturing is grown up from a production process for rapid prototyping to small batches and customized mass production. One popular manufacturing process for thermoplastics is the fused deposition modeling (FDM). To prepare a 3D-CAD part for the deposition process, the part has to be converted into a format that describes the outer surface, such as the STL format. At the next process step, which is called

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slicing, a software cuts the surface model in defined layers with a description of each layer infill and generate a machine-readable code such as G-code. Within this process, the deposition parameters such as layer thickness, layer infill pattern, print velocity or line width are defined. Finally, the FDM-printer uses the G-Code to form the 3D object. A thermoplastic material, provided as a filament, is melted up by the print head, extruded through a fine nozzle and laid up line by line to form a layer in the X-Y plane. After solidification, the Z-axes moves the value of the layer thickness and the next layer will be deposited. After additional layers are deposited on each other, the 3D object is created.

Because the deposited filaments have a circular cross section, they create voids in between the adjacent filaments of an FDM part. In recent years, many authors have investigated the influence of process parameters and manufacturing strategies on the anisotropic material behavior and voids. To increase the bonding strength between line intersections, Torres et al. used annealing for FDM parts made of polylactide. The parts had increased strength after the annealing but a decreased ductility. Rodriguez et al., 2000, investigated the influence of FDM process parameters on the void generation. Ahn et al. developed in 2004 a post process for thicker walls, where they infiltrated a manufactured part made of ABS with an epoxy-resin to increase the translucent behavior.

Laser transmission welding (LTW) is an established industrial technique to join thermoplastic parts. It is based on the optical transmittance of thermoplastic material for near-infrared radiation (NIR). For joining two parts, the radiation has to pass through the transparent part to reach the surface of the second part, which absorbs the radiation. After absorbing, the optical energy is transformed into thermal energy. Heat conduction transfers the heat to the transparent part, so both parts melt at their interface. After cooling and solidification, the two parts form a bond. For the heat conduction a sufficient surface contact is necessary, which requires constant joining pressure and a smooth surface at the parts' interface, Potente, 2004.

Kuklik et al., 2019, demonstrated a fundamental study of laser transmission welding for additively manufactured parts. They investigated the influence of additive manufacturing process parameters on the transmissivity as well as the weldability of natural polylactide parts. For the highest weld seam strength, an energy per unit length of 4.0 J/mm at a weld velocity of 2.5 mm/s was recommended. In cross sections of the weld seams cavities were observed, which resulted in an inhomogeneous weld seam width and so weld seam area in the joint. This was also reflected in the high standard deviation of the weld seam strength. The authors suggested that voids from the additively manufacturing process and the surface roughness resulted in small gaps between the parts caused these cavities.

Vazques-Martinez et al., 2020, investigated a laser welding process with a pulsed fiber laser system and a large welding area of 5 x 5 mm². The authors also observed the formation of gaps and cavities between the additively manufactured components and described that a high energy of the laser pulses resulted in shrinking marks on the upper surface of the transparent part too. They suggested that the high energy density of the focused beam leads to a melting of the transparent part at the point of entry and thus to the collapse of the upper surface.

Kuklik et al. demonstrated in 2020, that the cavities inside the weld seam of laser welded FDM components could be avoided by using a bar on top of the absorbent part. During the welding process, the bar melts down and supports the heat transfer to the transparent part. This resulted in weld seams without cavities.

In this study, additive manufacturing parameters are changed in a fractional screening design of experiments in order to investigate the influence of these parameters on the transmissivity behavior compared to a standard manufacturing parameter set. Tensile shear tests are performed with welded samples and cross sections perpendicular to the weld seam are prepared and analyzed with a microscope. The authors assume that the change of the additive manufacturing parameters will influence the transmissivity and the scattering behavior, which will result in a change of the weld seam width.

2. Experimental

For the investigation of laser transmission welding of additive manufactured components, samples were manufactured with an Ultimaker FDM desktop printer of the 3rd generation. This printer has a heated build plate and a resolution of 12.5 µm in the X-Y plane and 2.5 µm in Z direction. The used nozzle has a diameter of 0.4 mm.

The material of the transparent part and the absorbent part is polylactide in transparent and black, respectively. The software Cura from Ultimaker was used for slicing of the CAD models. This software provides default profiles for the process parameters. The "fast" profile can be used for faster manufacturing by reducing the resolution of the parts. With the default profiles "fine" and "extra fine" the layer height and the printing velocity are reduced to achieve better printing results in complex structures. To minimize the production time the laser absorbent samples were sliced with the "fast" profile of Cura. Transparent samples with the "fast" profile were manufactured to examine the laser transmission welding process. The parameters layer height, line width, the layer infill pattern, the material flow, the printing velocity and the printing temperature were changed in a fractional screening design of experiments (DOE) on two levels ("+" and "-") as shown in table 1. For the screening, more than one parameter is changed at a time during the additively manufacturing to reduce the number of experiments and to determine the influence of the manufacturing parameters on the transmissivity. Samples made with the "fast" profile were used as reference.

Table 1. Manufacturing parameters to investigate the transmissivity of additively manufactured components

Manufacturing parameter	Levels of the fractional screening DOE		Reference "fast" profile
	-	+	
Layer height	0.1 mm	0.2 mm	0.2 mm
Layer infill pattern	Lines	Concentric	Lines
Line width	0.3 mm	0.35 mm	0.35 mm
Printing temperature	195 °C	215 °C	205 °C
Material flow	120%	100%	100 %
Printing velocity	35 mm/s	70 mm/s	70 mm/s

For the lap shear tests and the investigations of the transmissivity samples with 50 mm length and 25 mm width were produced. The thickness of the samples were 2 mm.

For the laser welding experiments, a diode laser with a maximum power of 300 W and an emission wavelength of 940 nm was used. The laser beam was guided with an optical fiber to a scanner optic. This generated a focal diameter of 2 mm and maximum scanning speed up to 5 m/s.

To fix the alignment and generate a clamping pressure for the welding, the parts were pressed together with an overlap of 12 mm between a glass plate and a pneumatic cylinder. The samples were welded together in a contour welding process with scanning speeds from 2.5 mm/s to 15 mm/s and laser powers of 10 W to 30 W.

3. Results and discussion

Three transparent samples of the parameter sets developed from the DEO were measured with a spectrometer Lambda 1050 from Perkin Elmer. The spectrometer measures in range of 200 to 3000 nm with a resolution up to 0.1 nm. To collect all the transmitted light an integrating sphere was used for the detection.

Figure 1 shows the effects of the manufacturing parameters on the transmissivity. In reference to the "fast" profile the adjustment of a smaller layer height, a concentric layer infill, a lower printing velocity, and a higher mass flow results in a higher transmissivity of the parts. A higher and lower printing temperature leads to a higher transmissivity in comparison to the reference. The fact that the transmissivity is higher for a higher and lower printing temperature could be an overlap of influences of the other manufacturing parameters, since for the fractional screening DEO more than one parameter is changed at a time during the additively manufacturing.

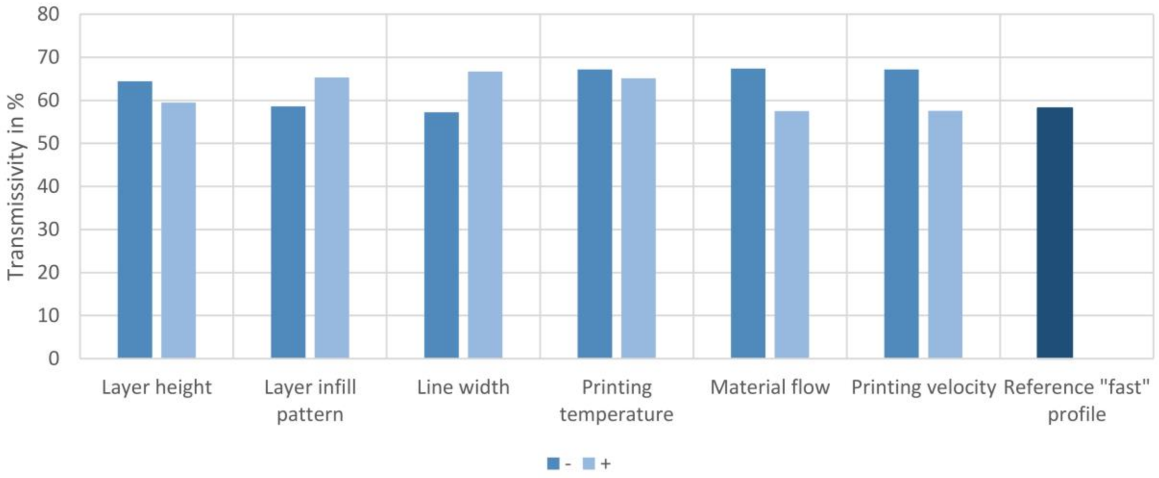

Fig. 1. Effects of the additive manufacturing parameters on the transmissivity

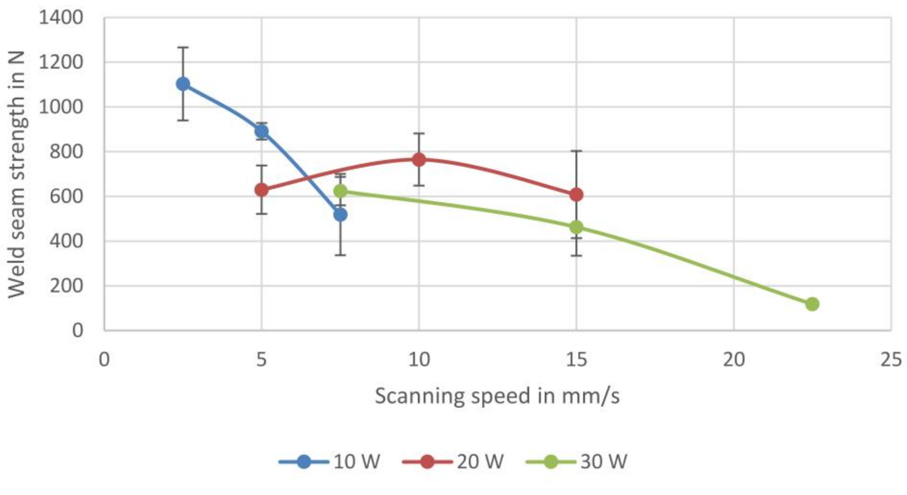

Fig. 2. The average weld seam strength as a function of laser power and scanning speed

Transparent samples with the “fast” profile parameter set were welded in overlap configuration for lap shear tests in order to study the influence of welding parameters on the respective weld seam strength. The welding was performed with different scanning speeds and three laser powers.

The average weld seam strength, together with the respective standard deviation as a function of laser power and scanning speed is shown in figure 2. The welding with less laser power of 10.0 W and a scanning speed of 2.5 mm/s determine the highest strength in the welding seam of 1100 N. For experiments with a laser power of 20.0 W the average weld seam strength reaches a maximum of 767 N at a scanning speed of 10.0 mm/s. With a laser power of 30.0 W the average weld seam strength decreases with higher scanning speed like the results with a power of 10.0 W. Nevertheless, the maximum reachable weld seam strength at a laser power of 30.0 W is 625 N, which is about the half of the maximum strength obtained at a laser power of 10.0 W. The results of the lap shear test within each welding parameter spread over a wide range, which results in a high standard deviation.

The results of the lap shear test demonstrate that a low scanning speed and therefore a long time were the material is molten enhance the weld seam strength. Further, with higher laser power and low scanning speed the molten material decomposes and the weld seam strength decreases.

To get further information of the weld seam quality, cross sections through the weld seam have been prepared and analyzed by a microscope. Figure 3 (a) presents the cross section perpendicular to the weld seam orientation through a weld seam of samples manufactured with the “fast” profile parameter set and welded with a laser power of 10.0 W and a scanning speed of 2.5 mm/s. In equal distances, small triangles can be seen. These triangles are the cross section of channels formed between two single lines, laid up at the additive manufacture process. The blurred structures between the triangles are the extension of the triangle shaped channels inside the image plane. These small channels are defects in the material and they are filled with air. In the absorbent part only the triangles are seen. The blurred structures cannot be seen, because the material is not transparent. The weld seam is in the middle of the picture with a cavity in the center. The cavity has a big extension inside the absorbent part up to the third manufacture layer. Within the transparent part, the weld seam and the cavity just reach to the first manufactured layer.

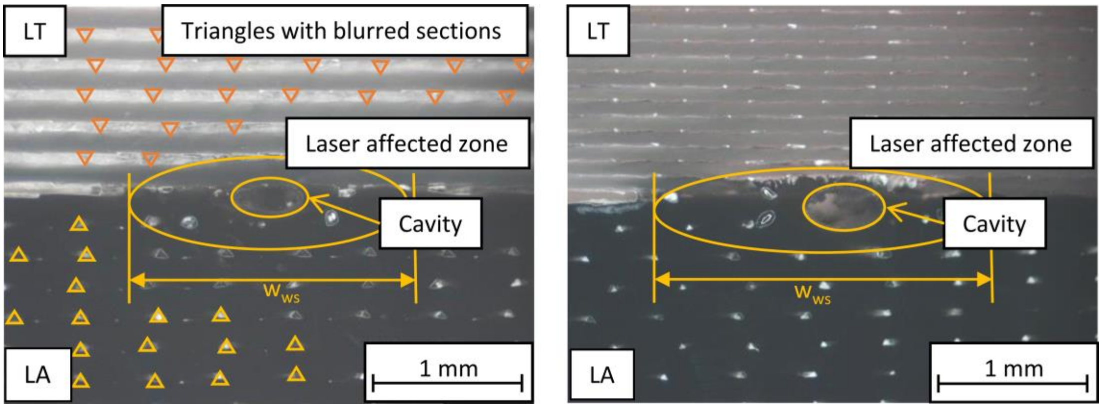

Fig. 3. Cross sections of the weld seam of samples manufactured with the “fast” profile (a) and a reduced layer height of 0.1 mm (b)

To both sides of the cavity regions are found, where the two parts are welded together. Referred to figure 3 (a), it appears that the clamping device cannot bring the parts into sufficient contact, so the heat cannot be transferred to the transparent part by heat conduction due to the missing surface contact. Conclusively during the process, more absorbent material is molten, up to the third layer, as in the transparent part. The big amount of air, which forms the cavity, is caused by the gap between the parts and the air inside the material (triangle channels). During the welding process, the air is bound inside the molten material. When the material cools down from the outside to the inside, the air is unbound, collected in the middle of the weld seam and build the cavity. The low heat conduction and the air inside the weld seam result in an inhomogeneous weld seam width over the weld seam length. Therefore, the welded area of the samples is very different, resulting in a high standard deviation of the measured weld seam strengths.

Figure 3 (b) presents the cross section of a transparent sample manufactured with a layer height of 0.1 mm and a black sample manufactured with the “fast” profile parameter set, welded together with a laser power of 10.0 W and a scanning speed of 5 mm/s. The cross section of the transparent part presents the difference between the additive manufacture parameter layer height compared to the referenced “fast” profile. Further, the triangle shaped channels between the laid lines get smaller and more layers are seen in the cross section because of the reduced layer thickness.

The width of the weld seam w_{ws}, defined by the fused area between the transparent and absorbing parts, is 1.9 mm for the samples manufactured with the “fast” profile parameter set and the w_{ws} is 2.3 mm for the samples manufactured with the lower layer height of 0.1 mm. The transparent samples manufactured with the lower layer height of 0.1 mm show less transmissivity and it seems that the higher amount of voids results in scattering of the transmitted radiation. Therefore, a wider weld seam results for the samples with the lower layer height.

4. Conclusion

This paper provides a study of laser transmission welding for additive manufactured components made in a fused deposition modelling process with the material polylactide. For the investigations, the additive manufacturing process were considered and the effects of the process parameters on the optical transmissivity were evaluated. Furthermore, the contour welding parameters were determined for various laser powers and scan velocities for a standard additively manufacturing parameter set.

The results of the transmission measurement depict, that a thin layer thickness, a wide line width, the concentric infill pattern, a higher mass flow and a lower printing velocity increase the transmission of NIR.

With a laser power of 10.0 W and scanning speed of 2.5 mm/s an average weld seam strength of 1100 N could be reached for samples additively manufactured with a standard parameter set (“fast”). By increasing the laser power or the scanning speed, the weld seam strength is reduced. Conclusively for laser transmission welding of additively manufactured components, low laser powers at slow scanning speeds are recommended. The cross sections of the samples show cavities in the middle of the weld seam, which extend more in the absorbent part. These cavities can be caused by trapped air during the additive manufacturing process. Maybe the cavities are formed by outgassing bounded water or other components during the welding process. However, the cavities cause in an irregular weld seam width and connected area in the joint. This is also reflected in the high standard deviation of the lap shear tests.

In further studies, the optical scattering effects in the transparent part should be combined to the width of the bars on the absorbent part to avoid cavities inside the weld seam. Because of a better gap bridging capability a quasi-simultaneous welding process should be probed.

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