Lasers in Manufacturing Conference 2019

Additive Manufacturing of 3D Polymer Structures by Laser Cladding

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Abstract

Additive manufacturing is progressively establishing itself in various industries and users are constantly looking for materials to open new fields of application. Polymers are mostly processed in stereo lithography with UV-lasers and selective laser sintering using CO2-lasers. Typically, laser cladding is solely used to process metal powders and is known as laser metal deposition (LMD), but in this study the same principle was successfully demonstrated for thermoplastic polyurethanes (TPU). For the usability with a solid state laser the absorption in the material was increased by additives. TPU powder was deposited with a powder nozzle on TPU substrate as well as on a stainless steel component, which was initially generated by LMD. Various 3d-structures were generated from this polymer, promising a high potential for new applications. In this way a hybrid structure of polymer on metal was also produced with an NIR laser and in the same cladding experimental setup.

Keywords: Additive manufacturing; thermoplast; polyurethan; solid-state laser; laser polymer deposition; laser metal deposition; 3D hybrid structure;

1. Introduction

In the 80s the manufacturing of polymer parts for prototypes in the automotive industry was the first industrial application of additive manufacturing based on the stereolithography (SLA) process. Since then additive manufacturing techniques have experienced an impressive development. Starting from single unique parts, manufactured for prototype cars, additive manufacturing has found its way into the production of small series [1]. Polymer materials were the first materials used for those additive

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manufacturing processes, but additive manufacturing of metallic materials has outperformed the polymer applications in the meantime. The reasons for this development are complex. One main drawback of the

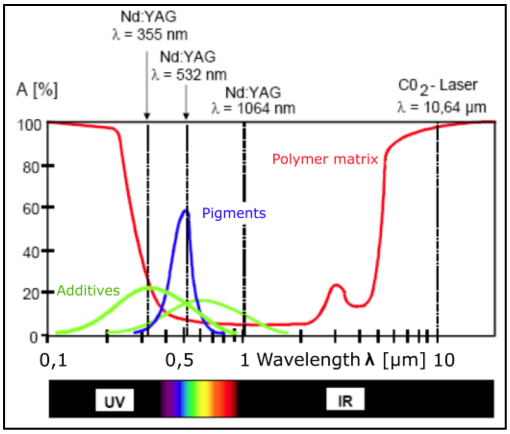

Fig. 1. Absorption spectrum of a polymer matrix, additives and pigments for laser processing [7].

polymer processing is that only few polymers are available for SLA and as powders suitable for the so-called selective laser sintering (SLS) process [2], which is the main process to manufacture complex polymer structures. Today about 88 % of all polymer powders used for SLS are polyamides (PA) of which PA12 dominates the market with about 60 %. The other 12% are used for niche applications [3]. Due to these material limitations and costs of about 50 to 100 €/kg powder, the dissemination of industrial polymer parts, manufactured with an additive approach, is restricted. The costs of polymer powders are at least one order higher than the basic polymer costs that have to be considered for injection molding [4, 5].

In SLS three-dimensional parts are produced by adding layers of polymer powder. Due to absorption of the radiation of a CO_2 laser, the polymer particles are locally remolten among each other as well as with the solid layer beneath the powder layer. CO_2 lasers are used in SLS because of their favorable emission wavelength of ~ 10 µm that matches high absorption of the polymer matrix (see Fig. 1).

Although CO_2 lasers are well established in material processing of polymers, they show disadvantages compared to modern solid-state lasers (SSL) with wavelengths around 1 µm (diode laser, disc laser, fiber laser). The beam guidance of CO_2 lasers is limited to mirrors which is less flexible and more difficult to handle (prone to faults) than optical fiber beam guidance [6].

In addition, the lower focusing ability, resulting from the large wavelength, constrains the geometrical resolution of the additive process. Cutting edge fiber lasers, which are used in all selective laser melting (SLM) machines for metals, exhibit multiple technical and economic benefits. They enable a better focusing due to a high beam quality and lower wavelength. The electro-optical efficiency is 2 – 3 times larger which significantly reduces the cooling effort/hardware and leads to a compact design. Furthermore, the life time is longer, maintenance of laser components is nearly negligible and overall costs are less [8]. Nevertheless, low absorption of state-of-the-art polymers in the visible and near-infrared (NIR) spectral range is the main drawback of SLS with SSL. In order to process polymers with these lasers they have to be modified. For example, Wang et al. have shown SLS with a 445 nm diode laser and carbon black modified PA12 powder [9]. Presently, optimized polymer stock powders for SLS with SSL are neither used nor available [1, 2, 10, 11].

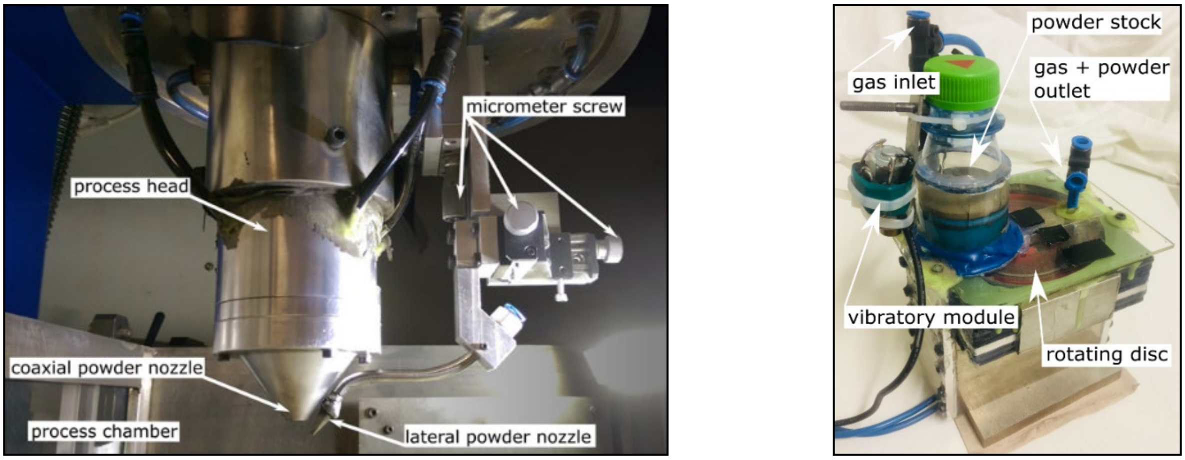

Fig. 2. (a, left) Experimental setup with a lateral powder nozzle on the right side; (b, right) Powder feeder setup with additional vibratory module.

In a LPD process a melt pool or softened zone is generated with a focused laser beam on a substrate surface. Polymer powder is locally added with a gas stream through a lateral nozzle, as shown in Fig. 2(a). The particles stick to the melt pool, where they melt because of heat conduction as well as absorption of the laser beam. The process head moves on (laser and nozzle have no relative movement to each other) and the 3D structure is built track by track and layer by layer. In comparison to SLS LPD can be applied on existing structures and the powder material can be changed to produce hybrid components (see chapter 3.2).

Building space is not limited to an enclosed powder bed but defined by the movement range of the process head (up to several meters) [12]. LPD is particularly suitable to test small amounts of new powder types because there is no powder bed. This is advantageous to effectively screen the influence of additives like nanoparticles and its concentration that can be applied after polymer powder synthesis.

This paper shows successfully produced 3D structures from modified TPU by using a new cladding technique called LPD with a laser wavelength of 1 µm. Additionally, a hybrid structure from metal and TPU is built to give an outlook on a new application field with the LPD technique

2. Experimental procedure

LPD was performed with a pulsed Nd:YAG SSL with a wavelength of 1.06 µm and 300 W maximum average power. The system includes a focusing optic with a focus length of 200 mm and a spot diameter of 400 µm. However, the laser beam was defocused for the experiments to increase the spot diameter to 2 mm to decrease the intensity. The first samples were produced on a stainless steel plate with a size of 30 x 30 mm² and 1 mm thickness with the parameters shown in Table 1. Prior to the LPD process the steel plate was coated with a 500 µm layer of modified TPU in a furnace (170 °C for 15 minutes). This layer is used as an interface between the metal plate and the welded structure, because the melt pool temperature of the metal is higher than the thermal decomposition temperature of the polymer. The applied layer is therefore used as a substrate.

The moving direction of the process head was parallel to the lateral nozzle. Laser pulse peak power was adjusted to achieve softening and melting of the TPU particles without inducing thermal decomposition of the polymer matrix. The process chamber was never heated at any time. A rotationally controlled disc powder feeder (see Fig. 2(b)) and nitrogen gas was used to transport the material to the lateral powder nozzle. The flowability of the powder was not measureable because of the crushed shape of the particles and congestion of the testing funnel. Therefore, the powder feeder was successfully modified with a vibratory module on top of the powder container and permanent vibration prevented powder congestion during the process.

LPD process efficiency and stability strongly depend on powder properties. The size distribution and shape of the powder particles have high influence on the powder focus, i.e. a broad size distribution causes significant scattering of the powder. If the focus size of the powder is much larger than the laser beam focus, the efficiency decreases notably. However, the intersection area of powder flow and laser beam should be small to avoid thermal decomposition of the powder particles based on overheating, before they reach the melt pool.

Table 1. Build parameter for TPU with carbon black

Process parameter for structures	Value for TPU material
Peak power [W]	500 (system minimum)
Pulse length [ms]	0.5 (system minimum)
Pulse frequency [Hz]	200
Carrier gas pressure [bar]	0.2
Process head lifting each layer [mm]	0.1
Process head moving speed [mm/min]	240
Spot diameter [mm]	2

For the experiments an aromatic TPU powder of the Freudenberg Group company was used. In order to increase the absorption of the laser radiation, around 1 wt-% carbon black was added. The size distribution has a wide range between 20 and 500 µm. The particles (see Fig. 3(a)) have an irregularly crushed shape, leading to bad flowability.

Firstly, a wall structure was deposited with the parameter in Table 1. The moving direction of the process head was parallel to the lateral nozzle. Different building strategies were used, whereby the difference is an additional remelting step.

Secondly, a cylindrical structure was deposited with the identical parameters as before (Table 1), but without an additional remelting step. However, the cylinder was not built on a TPU coated plate, but on a stainless steel cylinder that was previously built by laser metal deposition (see Fig. 5).

3. Results and discussion

The TPU layer on the substrate, compare Fig. 3(b), was homogenous, without pores, shrink holes or other defects on the surface. The visual variation of the brightness (see Fig. 3(b)) results from a minor waviness of the surface and angular depended reflection. The layer was firmly bonded to the metal substrate and suitable as an interface as it did not come off during the experiments.

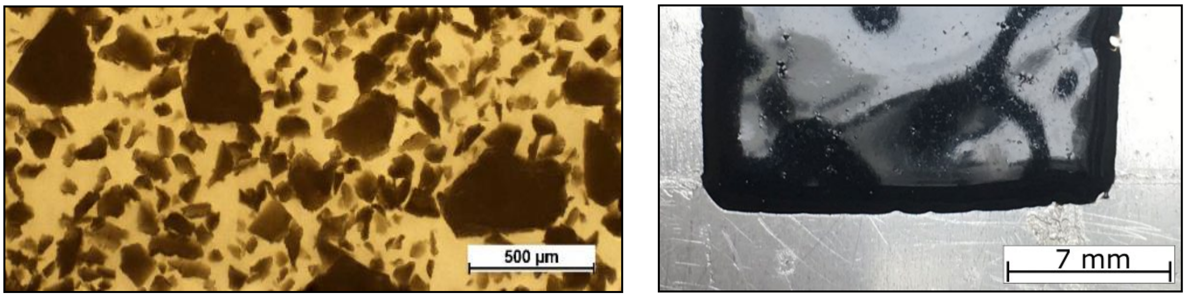

Fig. 3. (a, left) Image of the used modified TPU powder by light microscope; (b, right) Stainless steel plate, coated with carbon black modified TPU. Coating was prepared by powder remelting in a furnace.

3.1. Multi track welds

For multi track welds the parameters (see Table 1) were extended with several building strategies (compare Fig. 4(a)+(b) and 4(c)+(d)).

At first a wall with a height of 11 mm was built up layer by layer (Fig. 4(a)). However, the cross-section (Fig. 6(c)) clearly shows incomplete melting and some pores. This is also indicated by the surface topography of the wall that consists of partly molten particles. The incomplete melting results from low average energy input, low melt pool temperature and insufficient melt pool size. However, further experiments with increased laser peak power (and pulse energy) caused a temporal temperature rise during the laser pulse, which led to decomposition of the polymer and smoke emission. The carbon black modified TPU powder has high absorption, but a low heat conductivity of less than 0.2 W/(mK) [13]. (Heat conductivity of steel is larger than 15 W/(mK).) Low heat conduction leads to rapid heat accumulation at the surface. Higher average laser power with lower pulse energy could not be applied, due to laser system specifications. In conclusion, no laser pulse parameters could be identified to obtain an adequate average melt pool temperature and homogeneous remelting of the polymer powder.

In a second building strategy an additionally remelting step with the same parameters (Table 1) was performed after each layer. In this step no powder was introduced and the energy input was solely used to homogenize the deposited layer. As shown in Fig. 4(d) the porosity of the surface was successfully reduced and the surface quality was improved. The side surface topography shows waviness, but very few sticking particles. With increasing wall height, the quality of the surface increases as well (compare Fig. 4(a) and (b)). The top surface is homogeneously remolten without any remaining particles. The height of the second structure is 300 µm smaller. This could be due to the result of the additional remelting step. Therefore, the density near the surface increase at the same amount of material.

Fig. 4. Multi track wall structures; (a) Surface without remelting; (b) Surface with remelting; (c) Cross-section without remelting; (d) Cross-section with remelting.

3.2. Cylindrical structures

The cylindrical structure shows a surface that is affected by the relative motion between the melt pool and the powder nozzle. The melt pool was deformed by the gas stream of the powder nozzle and pushed along, resulting in direction-dependent material deposition and surface topology. This might be reduced by the use of a coaxial powder nozzle. Nevertheless, the effect can not completely avoided since a minimum gas flow is needed to transport the powder. By pushing the melt forward, a material accumulation was formed, as it can be seen in the marked area (Fig. 5, red / white arrow). The roughness of the surface varies depending on the direction of the build-up. In Fig. 5 the powder nozzle points from the right to the left, which is why the melt is pushed towards the structure itself and creates a smooth surface. In comparison to that, powder particles adhere to the surface on the opposite side of the cylinder (right side of Fig. 5) and therefore create a rough surface. In this case the melt was pushed away from the structure so that the particles did not melt but adhered to the heated surface.

4. Conclusion

In this paper 3D structures were successfully constructed from TPU powder and by laser polymer deposition with a solid state laser. The TPU powder was modified with carbon black and shows a significant increase in absorption. In future work the amount of carbon black will be varied to increase the range of the laser parameters. Less carbon black will allow the laser beam to transmit deeper into the material resulting in a reduced risk of polymer thermal decomposition due to overheating. The additional remelting step showed good results but is not absolutely necessary if a deeper melt zone is possible.

The shape and size distribution of TPU powder need to be optimized to achieve a better flowability.

Due to the movement of the melt, the surface roughness depends on the direction of the build-up.

Finally, additive manufacturing with laser polymer deposition and solid-state laser was presented to be a promising alternative to existing selective laser sintering technology.

Using small amounts of powder in the LPD technique allows a cheap and time saving material research. It will open up new fields of application with hybrid material structures, which can be produced by laser metal deposition and laser polymer deposition on the same production facility.

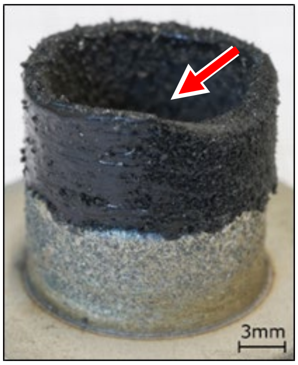

Fig. 5. Hollow cylindrical structure on a further perpetrated stainless steel substrate. Material accumulation is marked.

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