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Development of a laser beam deflection system for hybrid large scale additive manufacturing

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Abstract

The granule extrusion based so called Large Scale Additive Manufacturing (LSAM) has been under constant development during the last years. Although granule extrusion technologies enable the processing of a huge variety of materials, they also introduce new challenges in printing parts with enhanced mechanical properties. Especially due to the emerging strand geometry, process related voids occur, leading to an orthotropic behaviour of the generated components. A promising approach to diminish this characteristic is the use of carbon dioxide laser (CO_2) radiation. Its wavelength of 10.6 µm is mainly absorbed by the surfaces of polymers, so a remelting of generated strands can be achieved. In order to reduce voids as well as improve lateral bonding quality the laser beam must be aimed at the gap between an already deposited- and its adjacent, subsequently printed strand.
For generating three-dimensional parts, LSAM strand deposition is governed by a defined tool path. The used setup provides a fixed extruder nozzle and a build platform that is moveable in x-, y- and z-direction. Depending on the deposition direction, the laser beam needs to be redirected in order to reach the area between two adjacent and consecutively printed strands. Therefore, an optomechanical design for multidirectional laser beam propagation becomes necessary.
Initially several concepts of deflection systems were systematically developed, compared and evaluated according to the desired requirements. A preferred solution was found based on a combination of a fixed elliptical tube-like mirror and an rotating plane deflection mirror. Different variations of the principle were simulated regarding ray propagation and reflection behaviour. The final design solves the addressed task by covering > 90 % of the nozzle's circumference. Since a defined angle of the rotating plane deflection mirror is required, a suitable dimensioning of the mechanical components as well as an elaborate part arrangement for precise alignment steps become necessary.

Optomechanical Mirror Setup, Laser Beam Deflection System, Elliptical Cylinder Mirror, Large Scale Additive Manufacturing (LSAM), Hybrid Additive Manufacturing

1. Introduction

Additive Manufacturing (AM) describes a wide area of technologies and processes for industrial applications. Therein, Large Scale Additive Manufacturing (LSAM) has been introduced during the last years. Such systems realize parts by melting polymer granules through a heated extruder and the material deposition on a platform, according to the desired geometry. Especially in the last years knowledge about the process behaviour has been continuously extending [1, 2] and experimental setups have been evolving to huge manufacturing systems for industrial applications such as Big Area Additive Manufacturing (BAAM) [3].

Even though LSAM provides huge potential for fast build rates and the processing of a huge variety of materials, common drawbacks of extrusion-based AM are present as well. Probably, the most dominant issue are the remaining cavities between deposited strands [4]. These process related defects become even more obvious and bigger in shape, when enlarged diameters of strands are used to generate large scale parts [5]. As a consequence, orthotropic part behaviour is intensified and mechanical properties are strongly depending on external load orientations.

2. Background and state of the art

In extrusion-based AM fracture resistance is primarily affected by inter- and intra-layer adhesion as well as void occurrence and size [4, 6]. Investigations reveal that voids can be minimized by increasing printing temperatures, although distortion and part deformation occur as a negative side effect [4, 7, 8]. Especially in LSAM this effect is intensified since void size is increased with bead width [9]. Hence, a suitable compromise between nozzle temperature and resulting meso structure needs to be found. Furthermore, additional energy treatments become necessary to remelt deposited strands and solidify the parts.

In order to mitigate the mentioned characteristics, several laser beam heat treatment approaches have been developing for FLM during the last years, e.g. [10-12]. Laser radiation is directed onto deposited strands in order to reheat defined areas locally and increase interlayer as well as intra-layer bond. Since polymers provide wavelength-dependent absorption properties [13], laser selection is also associated with the chosen materials as well as necessary additives. On the other hand, there are materials such as styrene-acrylonitrile-copolymer (SAN - TYRIL 790 - Trinseo) and poly(methyl methacrylate) (PMMA – Altuglas VSUVT) which provide perfect properties regarding a carbon dioxide laser (CO_2) beam treatment of unmodified raw material [14]. However, strand deposition direction is changed based on the part's geometry and the manufacturing routine, so the laser beam needs to be redirected as well. Thus, especially when CO_2-laser radiation is used, a mirror based, optomechanical design for multidirectional laser beam propagation becomes necessary. Such a setup has not been demonstrated in LSAM, yet.

3. Problem formulation

In order to provide an insight into the relations between the acting machine components a short overview about the collaborating parameters of the hybrid printing process is given in Figure 1.

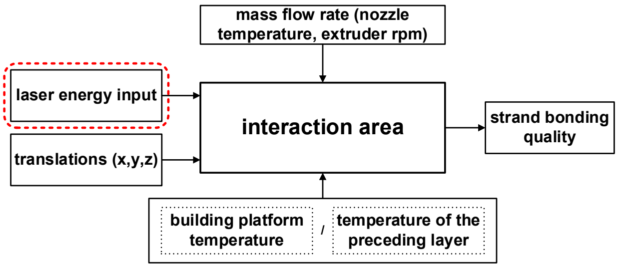


Figure 1. In- and output values of the interaction area with focus on the laser energy input

An interaction area (IA) is defined having four input values: mass flow rate, translational movements (x, y, z), building platform temperature and preceding layer temperature, respectively as well as laser energy input. With the addition of the latter component the process is transferred into a hybrid additive manufacturing application. The nozzle is fixed and therefore, the part solely is generated by a movement of the platform. As a result of the interaction of these variables a certain strand bonding quality is achieved, defined by the inter-layer and intra-layer bond.

Under consideration of the spatial orientation of the components (Figure 2) it is obvious that the direction vector of the incorporated laser radiation ($\overrightarrow{V_L}$) needs to be linked to the vector of the deposition direction ($\overrightarrow{V_{vf}}$) under a certain angle α.

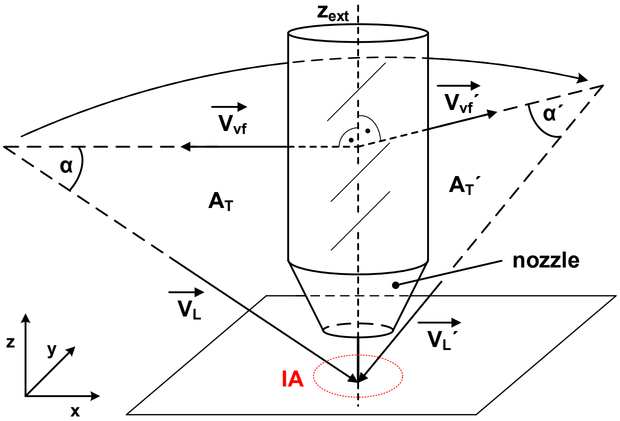


Figure 2. Working principle demonstrating the laser beam movement from $\overrightarrow{V_L}$ to $\overrightarrow{V_L}'$ when deposition direction is changed from $\overrightarrow{V_{vf}}$ to $\overrightarrow{V_{vf}}'$

Otherwise it is impossible to guarantee an unhampered heat treatment of the interaction area. At the same time, the z-axis of the extruder (z_{ext}) as well as $\overrightarrow{V_L}$ and $\overrightarrow{V_{vf}}$ create a plane A_T. Only under the condition of the constant angular relationship $\overrightarrow{V_{vf}} \perp z_{ext}$ and α = α', a defined coupling of the laser radiation into the interaction area can be achieved by rotating A_T around z_{ext}. Thereby the orientation of $\overrightarrow{V_L}$ is always depending on the direction of $\overrightarrow{V_{vf}}$.

4. Approaches

Based on the problem formulation, different principles have been developed as part of the conceptional phase. The following solutions require a laser beam radially shifted to the extruder axis. Its propagation direction and beam shape have been defined previously. There are no dependencies between beam shaping and beam guidance at the principle synthesis. All depicted illustrations are not true to scale.

4.1. Version 1 – radially arranged 4-mirror-system

The first concept for variable laser beam deflection comprises a system of four plane mirrors (M_1 – M_4), radially arranged to each other by 90° (Figure 3) and possessing a degree of freedom (DOF) of six.

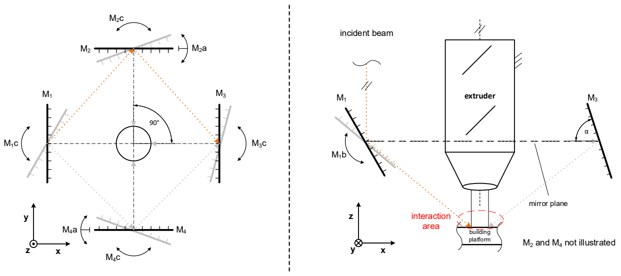
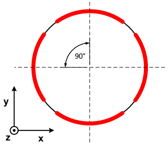


Figure 3. Working principle radially arranged 4-mirror-system as top view (left) and side view (right)

Initially, the incident beam hits M_1 and is directly reflected into the interaction area. Furthermore, a deflection onto M_2 or M_4 is possible. For this, M_1 is moved along M_1b and guides the beam into the mirror plane of the 4-mirror-system. At the same time a shutter blocks the beam for a brief moment to avoid any damage of the extruder. A swivel-movement along M_1c enables a reflection to M_2 or M_4. Besides directly deflecting the laser beam into the interaction area, either M_2 or M_4 needs to be able to pass the radiation onto M_3. Hence, one of these elements needs to provide another degree of freedom (M_2a or M_4a). Consequently, and analogous to the deflection principle at M_1, the laser beam is projected to M_3, parallel to the mirror plane. Whether M_2 or M_4 is extended by a further DOF is insignificant regarding the functional principle.

Table 1 Parameters of the radially arranged 4-mirror-system

Heat treatment area at the nozzle – top view	Remarks
	- 80% of the circumference - option for scanning - 7 necessary controls - moderate costs

The described principle requires two of the four elements providing a degree of freedom of two. Again, the rotation about the mirrors' local z-axes makes a laser beam treatment of a small interaction area as well as little scanning fields possible. The setup realizes a heat treatment along all main deposition directions (positive and negative x- and y-direction) but cannot handle diagonal movements. As a result (Table 1), six rotations of four plane mirrors become necessary to cover approximately 80% of the nozzle's circumference. The expenses for this setting are expected to be moderate.

4.2. Version 2 – cone-shaped-mirror system

A further approach utilizes the combination of a plane and a cone shaped-mirror, known from quasi simultaneous laser material applications, e.g. laser soldering [15]. Due to the present part arrangement, a concentrically orientation of the incident laser beam is not feasible. Consequently, the principle incorporates two plane swivel-mirrors (M_1, M_2) as well as a cone shaped-mirror (M_3). M_1 and M_2 have a defined distance a to the middle axis of the extruder. As depicted in Figure 4, the incident beam needs to be switched in order to gain two different rays.

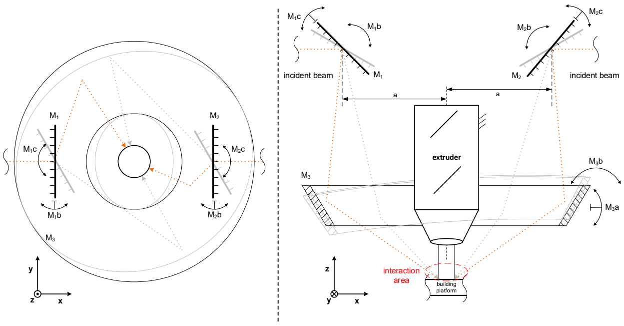
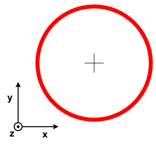


Figure 4. Working principle cone-shaped-mirror system as top view (left) and side view, with cone-shaped-mirror as sectional view (right)

For this separation two additional shutter become necessary. Since, the configuration of beam shaping and -separation is not relevant for the working principle, further details are not considered at this point. The incident laser beam strikes on mirror M_1 and is reflected onto M_3 by a swivel-movement of M_1b and M_1c. Due to the radial deviation a, the beam deflected at M_3 is not guided into a defined interaction area beyond the cone shaped mirror. Therefore, a tumbling motion, achieved through a superimposition of M_3a and M_3b, is needed in order to correct the offset. The principle works analogous for M_2. Additionally, M_1 and M_2 are able to achieve deflections at more than one half of the cone shaped-mirror's circumference (Figure 4 left).

Table 2 Parameters of the cone-shaped-mirror system

Heat treatment area at the nozzle – top view	Remarks
	- 100% of the circumference - no option for scanning - 8 necessary controls - high costs

The cone-shaped-mirror systems' parameters are shown in Table 2. Each of the components provides a DOF of two. Due to the wide deflection angle of M_1 and M_2, the entire circumference of the nozzle can be reached by the laser beam. The incident beam direction is selected by the shutter in dependency to the deposition direction. In addition, the tumbling motion of M_3 needs to be synchronized to every deflection angle position of M_1 or M_2. Because of the system's inertia only a very slow scan field movement can be realized. The overall design requires eight controlled units of three mirror elements and achieves a 100% heat treatment of the nozzle's circumference. High expenses are expected for a realization.

4.3. Version 3 – elliptical mirror system

The third concept of laser beam deflection combines a rotating plane mirror (M1) and an elliptical mirror (M2). M1 is located at the left focal axis (F') of the elliptical mirror, so the local z-axis of M1 and F' are concentric. When the laser beam, which is also concentric to the focal axis at F', strikes onto M1, it can be deflected onto the right focal axis (F) by a rotation along M1c. This is due to the general deflection behaviour of an elliptical mirror [16]. Based on a certain configuration of M1 and M2 the laser beam is directly coupled into the interaction area on the building platform (Figure 5 right). This requires the middle axis of the extruder being concentric to the focal axis at F, too. Due to the elliptical mirror the laser beam can be deflected to most of the nozzle's circumference, except the area shadowed by the extruder (Figure 5 left).

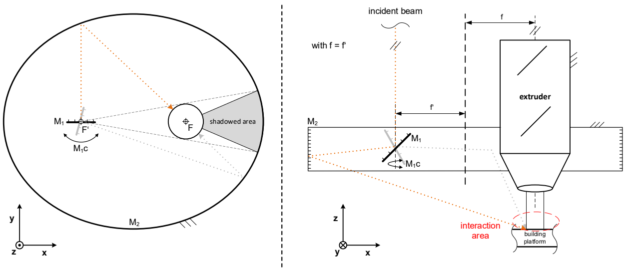
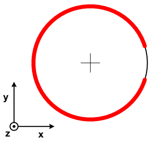


Figure 5. Working principle elliptical mirror system as top view (left) and side view, with elliptical mirror as sectional view (right)

The elliptical mirror system utilizes a combination of a rotational plane mirror (M1), having a DOF of one and a fixed elliptical mirror (M2). Consequently, only one component needs to be controlled by software. There is no synchronization between the used elements necessary. A scanning procedure of M1 can be realized through a repeated swivel-movement within an angular range. Considered holistically (Table 3), the laser beam heat treatment can be applied onto approximately 90% of the nozzle's circumference. Nonetheless, due to the none conventional shape of M2, high costs for this setup are expected.

Table 3 Parameters of the elliptical mirror system

Heat treatment area at the nozzle – top view	Remarks
	- 90% of the circumference - only 1 necessary control - limited option for scanning - high costs

5. Evaluation of the approaches

The developed approaches provide different properties which have been described at the principle synthesis.

Table 4 Evaluation of the approaches

Evaluation criteria	Ver 1	Ver 2	Ver 3
Number of beams	++	o	++
Number of deflections	o	+	+
Required control effort	– –	– –	++
Number of needed optical elements	o	+	++
Covered treatment area	o	++	+
Estimated costs	o	–	–
Result	–	o	+

++ excellent + good o satisfactory – sufficient – – insufficient

The evaluation (Table 4) contrasts advantages and disadvantages and leads based on the evaluation criteria, to version 3 – elliptical mirror system. Nevertheless, it will take huge effort of realization due to the new development of this setup and its introduction into the LSAM process.

6. Mirror geometry and simulation of beam propagation

For laser beam treatment of polymer strands, the combination of a rotational plane mirror (M_{Rot}) with an elliptical mirror goes beyond the state of the art. Consequently, it becomes necessary to develop a defined shape of the elliptical mirror's reflectional surface. Based on the principle in Figure 5 (right) shape variations were conducted at four different geometries depicted as quarter-sectional view in Figure 6. The laser beam propagation was simulated utilizing the commercialised ray tracing software TracePro®. When the plane mirror M_{Rot} is being rotated the beam intersects with the right focal axis of the elliptical mirror. But, depending on the angle of rotation, this intersection occurs at different distances beneath the mirror system when an inclined or circular shape is used. The elliptic design leads to a rotational ellipsoid which describes a special case. It achieves a beam propagation from the left to the right focal point both laying in the same working plane. Since both focal points are located inside of the mirror system a deflection into the interaction area is not possible. Therefore, the rotational ellipsoid is not suitable for the addressed task.

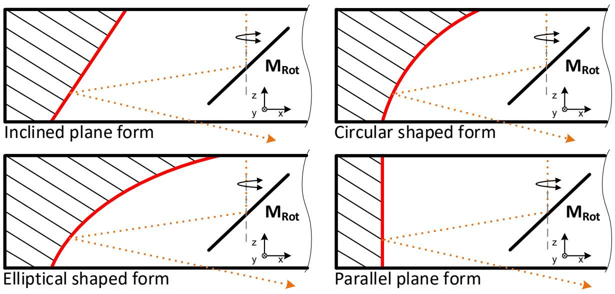


Figure 6. Sectioned segments of different mirror designs (schematic illustrations, not true to scale)

The final solution was found in a parallel mirror surface which leads to an elliptical tube-like mirror. When M_{Rot} is rotated with respect to its z-axis, the deflected beam intersects the right focal axis on a defined and fixed distance beneath the mirror system.

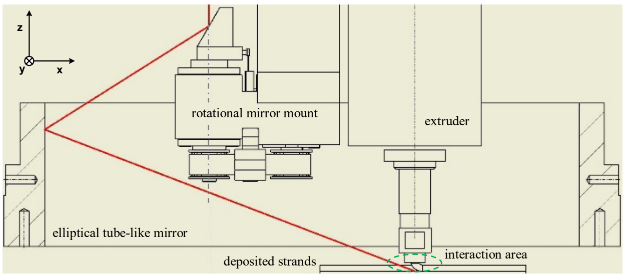


Figure 7. 2D-CAD-model of the elliptical mirror system and extruder

The developed design (Figure 7) is realized as a rotational mirror mount attached to a monolithic elliptical tube-like mirror. The deflection system is implemented into an experimental setup of a LSAM machine. Requirements regarding accessibility, lifetime and maintenance are considered in the design, too.

7. Summary

Large Scale Additive Manufacturing enables fast build rates as well as the processing of a huge variety of materials. A new approach aims onto an LSAM process improved by a laser beam treatment. The realization of such a setup requires the development of a multidirectional deflection system.

After depicting the problem formulation several concepts are described. In general, the three approaches shown are suitable to solve the task. They possess different benefits and drawbacks. In the end an evaluation of the principles leads to the preferred solution, called elliptical mirror system.

Further development steps became necessary in order to design an appropriate mirror geometry. By means of an optical simulation software four designs were investigated. The final result was found in an elliptical tube-like mirror shape. This system is well suited to realize a repeatable laser beam treatment, tailored to the LSAM process.

Future work will transfer the gained results into an experimental setup. The elliptical tube-like mirror will be manufactured under ultra precision conditions in order to minimize the alignment effort. After implementation into the LSAM machine and commissioning the hybrid process, utilizing the laser beam deflection system, will be examined.

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