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Automatic changing of weld deposit for additive manufacturing of hybrid metal-glass components using direct laser deposition

Marius Lammers [a,b,*], Kai Biester [b], Nick Schwarz [a,b], Jörg Hermsdorf [b], Stefan Kaierle [b], Henning Ahlers [a]

[a]Hochschule Hannover – University of Applied Sciences and Arts, Ricklinger Stadtweg 120, 30459 Hannover, Germany
[b]Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany

Abstract

Direct Laser Deposition is a manufacturing process, that enables Additive Manufacturing of nearly any fusible material ranging from metal to glass feedstock. For generating hybrid components out of steel and fused silica, system technology with coaxial beam guidance using different laser beam sources can be used to enable the direct manufacturing of optical, structural and thermal elements. To suit both processes, a wide velocity range regarding the weld material feed from 0.1 to 5 m/min is required. In this paper a prototype machine for material feeding and changing is presented, that is capable of processing both metal wire and glass fiber. In order to determine process-critical parameters, preliminary tests are carried out to determine the requirements for the system. The paper also shows how the prototype system performs in terms of changing and feeding the wires as well as fibers with a focus on wear and changing cycles.

Keywords: laser glass deposition; laser metal deposition; weld material feed; metal-glass hybrid components; automatic material changing; wire; fiber

1. Introduction

1.1. Motivation and objectives

Coaxial Direct Laser Deposition is used as an Additive Manufacturing process for the production of individual parts and small series, the manufacturing of complex geometries and the processing of special

* Corresponding author. Tel.: +49 511 2788-227; fax: +49 511 2788-100.
E-mail address: m.lammers@lzh.de.

materials. The GROTESK innovation network is researching the use of integrative generative manufacturing to produce novel optical, thermal and structural multi-material components. GROTESK comprises the requirements analysis of materials and workpieces, the development of design guidelines for 3D printing, a process development and the machine concept. The objective of the GROTESK subproject, which is being carried out at University of Applied Sciences and Arts Hannover, is to develop a machine for the Additive Manufacturing of optical, thermal and structural components. Based on the components, materials and processes developed in the other subprojects of the GROTESK project, this machine shall enable the production of an optical bench in a machine environment. For this purpose, various Additive Manufacturing processes have to be combined within the machine environment, for example to build up structural and thermal functional elements of the optical bench from a metal material. Furthermore, it should be possible to manufacture the optical components from polymers or glass materials in the same environment. The processed feedstock can be provided in powder form, but also as wire (metal), filament (polymer) or fiber (glass). To achieve this goal, the subproject will analyze Additive Manufacturing processes with regard to their possibilities for changing materials and validate them according to the processes developed in the GROTESK project. On the other hand, based on this, a machine head is being developed that maps the corresponding processes and enables processing of the three selected application materials metal, polymer and glass in the forms powder and wire/filament/fiber. The control and handling technology required for the use of the machine head will also be developed as part of this subproject.

1.2. Coaxial Laser Deposition head for metal and glass materials

A special processing head is used for the coaxial laser deposition welding of metal wires and glass fibers (see Fig. 1). It has a centrally arranged welding material feed and four individual laser beams that coaxially surround the welding filler material and meet at a common focal point below the welding nozzle tip. The coaxial design enables direction-independent processing. The individual beams are generated from the focused beam using a reflectively coated, four-sided pyramid. The four individual beams are then directed into the process zone via deflection mirrors. This beam guidance allows the filler material in the form of a metal wire or a glass fiber to be fed coaxially into the process zone.

The reflectively designed beam guiding elements allow the usage of a wide range of laser wavelengths. For example, the system technology for processing metal materials can be operated with a laser wavelength in the range of 1 µm, while a CO_2 laser with a wavelength of 10.6 µm is used for processing glass. Due to the design of the processing head, the filler material can also be fed between the partial beams and inserted perpendicular to the workpiece surface into the common focal point of the partial beams. This permits a direction-independent welding result. The feed of the respective filler material describes an S-shaped curve.

However, due to its design, the transport section has at least two radii of curvature that have to be overcome. These radii lead to higher feeding forces and can possibly deform the filler material or hinder the accurate wire feeding. An appropriate wire feeding unit is used to convey and feed the filler material from the coil to the process zone. The handling of the filler material is a particular challenge for the entire system technology. A uniform feed movement of the filler material is particularly important during the welding process.

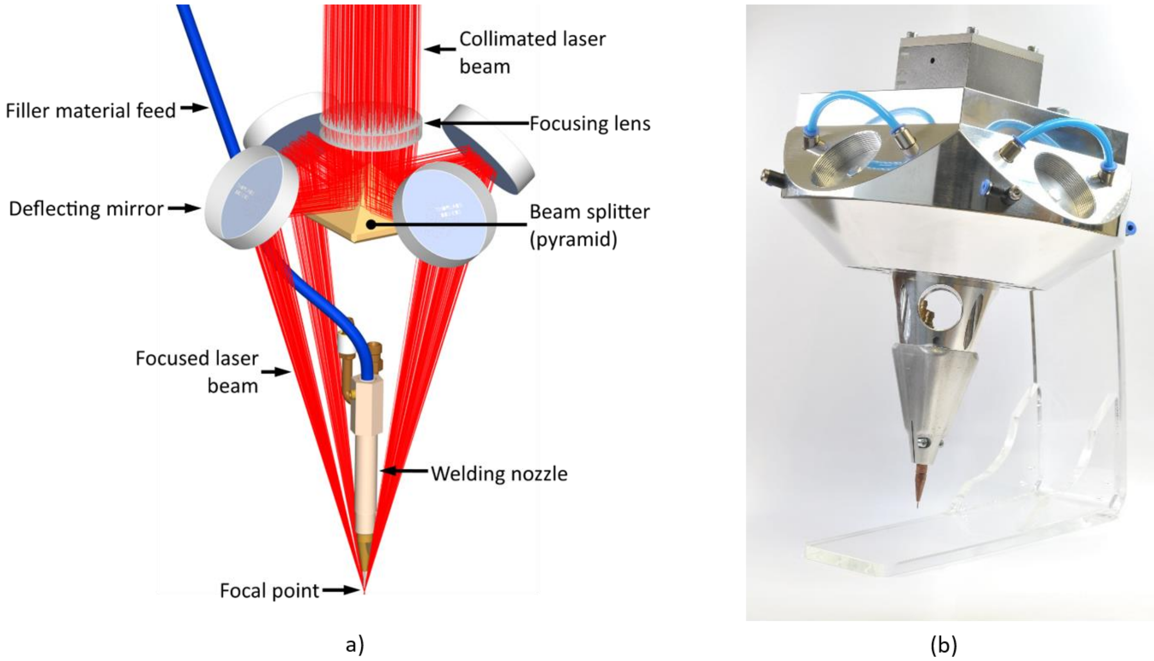

Fig. 1. (a) Working principle; (b) Photo of the coaxial processing head

2. State of the Art

2.1. Coaxial Wire Laser Metal Deposition (W-LMD)

Coaxial Wire Laser Metal Deposition (W-LMD) is an Additive Manufacturing process that uses laser radiation to melt and deposit wire-shaped filler material onto a substrate. For metal materials, comprehensive data is already available on wire feeding in connection with Additive Manufacturing [1]. Process variants with cold or hot wire are used [2]. The feeding method for the weld deposit can be realized either in a coaxial or lateral manner [1]. Coaxial feeding is required to achieve uniform welding results. This type of feeding ensures that the result is independent of the feed direction and the type of wire [3]. Different coaxial systems are used that can be categorized into two general principles of coaxial W-LMD. The first one uses a single beam that is split into multiple beams inside the processing head to avoid the wire feeding nozzle [4]. The single beams are guided and shaped to form a single focal point enabling the system to melt the wire feedstock. Principle 2 uses several fiber coupled laser diodes that are connected to the processing head. There the single beams are collimated and focused to form a common spot. While being limited to the maximum output power of the single diodes, the system offers the opportunity to control each laser beam individually [5]. An important component for W-LMD welding is the wire feeding unit. Furthermore, the parameters related to the wire feeding unit, have a great importance for the welding process.

2.2. Laser Glass Deposition (LGD)

LGD is a process for laser-based Additive Manufacturing of glass materials based on filaments or fibers. The weld deposit is fed into the process zone in the form of a fiber, that is guided laterally or perpendicularly to the substrate surface. The thermal energy required to deposit a weld seam is provided by a laser beam source.

In general, CO and CO_2 laser beam sources with laser powers of up to 150 W in continuous wave mode (cw) are used. The process is capable of producing structures consisting of several individual seams, as well as depositing fibers on surfaces and forming droplet-shaped elements [6 - 12].

The glass fibers are fed from the corresponding material store, usually a coil, to the processing head via feeding units, similar to those used in the welding of metal materials for feeding the wire-shaped welding filler materials [9, 2]. Glass fibers are commonly fed in Additive Manufacturing using a 1+1 feeding unit with rollers made of an elastic material. More extensive studies on process-integrated feeding are not known at this time [6, 9, 11].

2.3. Automatic changing of wire shaped filler material

For Additive Manufacturing, an automated wire changing system from the company *DIRECTED METAL 3D SL* is commercially available under the trademark *Meltio M450 Dual Wire.* This system enables the usage of two wire materials with diameters from 0.8 to 1.2 mm sequentially with automated wire changes. The connected processing head uses multiple direct diode lasers with a wavelength of 976 nm and a total laser power of 1,200 W to manufacture structures made of stainless and carbon steel as well as titanium alloys and Inconel [12].

There are automatic changing systems on the market for joint welding in MIG/MAG applications, which will be briefly described below: The company *Trumpf GmbH & Co. KG* welds machine frames of a press brake in an automated robot cell, using a prototype of an automatic wire changing station from *Fronius GmbH*. The aim of the changing system is to weld both steel and stainless steel components with different filler materials in one cell and with only one torch [13]. The system, that was introduced in 2009, uses only one hose pack, requiring automatic threading and unthreading of the wire from the hose pack during the process. An auxiliary drive is used to perform these steps [14].

In 2014, the company *SKS Welding Systems GmbH* introduced an automated wire changing system that takes a different approach to wire feeding. The system is equipped with two hose packages and uses only one torch. Each hose package has its own wire feeder, which transports the wire to the torch. The hose assemblies are fed to the torch where the filler material change takes place. Fig. 2 shows the system installed on a standard industrial robot on the right side. The left side of Fig. 2 shows the Y-piece where the hose assemblies are brought together at the torch. The picture in the middle of the same figure illustrates the wire change. At the point marked (1), the last wire used is cut by a wire cutter before the wire is pulled back into

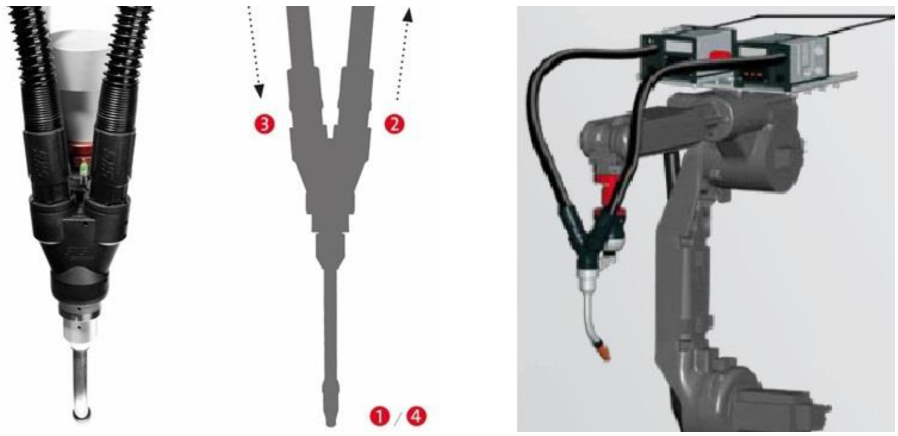

Fig. 2. Wire changing system of the company SKS Welding Systems GmbH [15].

the hose assembly, which is symbolized by number (2) in the picture. Subsequently, the wire from the second hose package is automatically threaded into the torch, that is marked with (3). Finally, the wire is cut again (4) and the wire change is completed. The system is characterized by the fact that the wire change is done in a few seconds and that it can be mounted on any commercially available industrial robot [15].

Another system, presented by *Panasonic Industry Europe GmbH* in 2016, is based on the same principle: Two hose assemblies are used, which are guided to the torch serving as the end effector. A separate wire feeder is used for each wire electrode. The changeover takes place at the torch by pulling the wire back to a defined point and threading the other wire into it. Furthermore, different process gases can be used with this system [16].

3. Development of a system for automatic changing of wire shaped weld deposit

3.1. Materials used

The following weld deposits are used in the experiments to simulate the change from a glass to a metal material, see Table 1: The glass material used is a coreless fiber from the manufacturer *Fiberware GmbH* made of fused silica. This has a diameter of 0.4 mm and is provided with a polymer coating with a thickness of 50 µm, resulting in a nominal diameter of 0.5 mm. A commercially available steel wire of type *G3Si1* is used for the metal material. This has a diameter of 0.8 mm and is coated with copper. Both welding materials are provided on coils.

Table 1. Materials used

	Glass	Metal
Name	AS 400 IR AC	G3Si1
Manufacturer	Fiberware GmbH	Linde plc
Material	Fused silica (SiO_2)	Mild steel (1.5125)
Type	Coreless fiber	Solid wire
Coating	Polymer (acrylat)	Copper
Outer diameter	0,5 mm	0,8 mm

3.2. Experimental setup for automated weld material change

The setup used for the experiments is shown in Fig. 3. Two coil holders are used, as well as two commercially available wire feeding units, that find application in manual MIG/MAG welding systems. These are mounted on aluminum profile elements, which in turn are connected to each other by another profile element. From the feed units, a core runs into the Y-piece in each case. The Y-piece is followed by the funnel-shaped adapter to accommodate the filler material. Another core connects the funnel to the welding nozzle, at the end of which a contact tip is attached to guide the material in a directed manner. The pneumatic shears are provided directly adjacent to this. The functional chain is completed by a proximity sensor, that detects the material and stops the wire feeding. The components Y-piece, funnel-shaped adapter and the welding nozzle are fixed in alignment on profile elements. Likewise, the pneumatic shears and the proximity sensor are mounted on profile elements. A more detailed view of the wire change components is shown in Fig. 4.

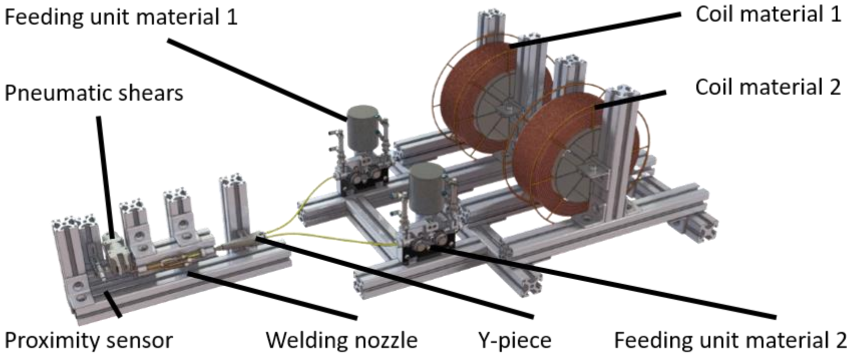

Fig. 3. CAD model of the overall test setup

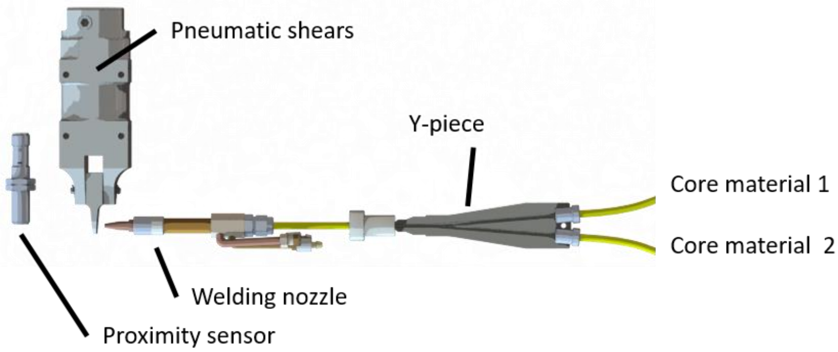

Fig. 4. CAD model of the Y-piece in sectional view

3.3. Changing cycle

The change of the filler material follows a recurring sequence, which is why the programming is implemented with a sequence control, see Fig. 5. The sequence starts with the initialization of the test sequence by the user. Following this, the first step is to cut the wire located in the system and already between the shears. Next, the wire is pulled back out of the system into the Y-piece so that the fiber can be fed into the system. After the fiber is forwarded into the pneumatic shears, the feed is adjusted and the shears cut the glass fiber. The fiber is then pulled back out of the system into the Y-piece before the wire is pushed into the system up to the pneumatic shears. Following this, the entire sequence is repeated.

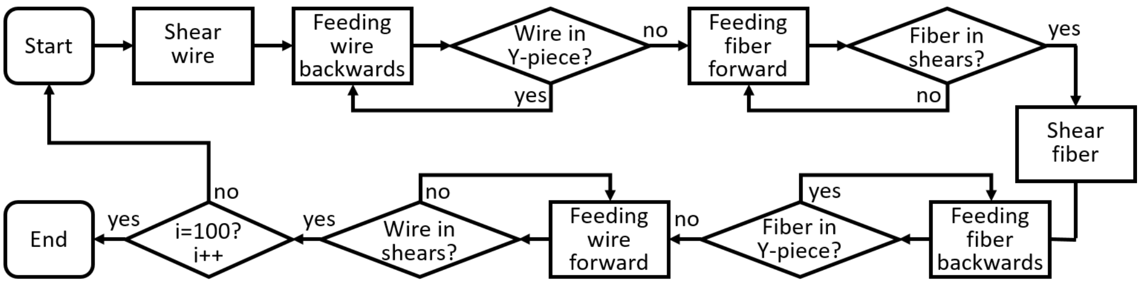

Fig. 5. Flow chart of the automated filler material change

The control and operation of the system for automated material changeover is implemented using the LabVIEW software/hardware solution from NATIONAL INSTRUMENTS CORP. The programming of the sequence control is based on a program flow chart, that reflects the sequences and queries required to check whether an action has been completed so that next one can be started. The program flow chart for the switch tests can be seen in Fig. 5. As mentioned earlier, the control is started by a user initialization. In the *LabVIEW* implementation, this step puts the program into a loop that runs through the first step of a sequential structure. The first step, which initializes another loop, triggers the wire shear and is terminated by a runtime. The next step is to feed the wire back into the Y-piece, which is also terminated by a runtime variable. For this, the knowledge of the required time for pulling back into the Y-piece is necessary.

Another possibility would be to use a proximity sensor, which terminates the loop and thus the retraction of the wire as soon as no more filler material is detected. Since there is only one sensor, this variant is not pursued. The mentioned variant reflects the first query in the program flow chart. In the following section, the wire feeding unit is switched over and the feeding direction of the wire feeding unit for the glass fiber is changed to forward. After this step is completed, the next loop is started in the next sequence. In this one, the parameters for feeding the glass fiber into the system are set. Here, the feed unit feeds the fiber until the wire is detected by the capacitive proximity sensor located behind the pneumatic shears.

Alternatively, the loop is terminated again by a runtime variable to prevent endless feeding that could occur due to an error. If the loop was terminated by one of the two termination conditions, the fiber is cut by the pneumatic shears in the next sequence. The structure of the loop used is identical to that of the first step of the flow structure. In addition, in parallel, the feeding direction is changed independently of the described operation for the feeding unit of the glass fiber, so that in the next step the end of the fiber can be fed back into the Y-piece. As already mentioned for the feeding of the wire, this loop, and thus the feed motion, is also terminated by a runtime variable. Following this, the wire feed direction is changed and the wire feeding unit is switched over, so that finally the wire is fed back into the system until the sensor triggers or the run time has expired. After a complete sequence has been run, the condition of the parent loop is checked. In this case, the condition is the number of alternating cycles, which was previously set to 100. If the number of alternations is not reached, the sequential structure is run through again until the condition is fulfilled.

3.4. Results of the changing tests

The first tests were carried out at a feeding speed of 4 m/min. The first test was aborted after 53 cycles because the wire was no longer transported through the system to the pneumatic shears. The reason for this was wear of the welding nozzle tip. By cutting the wire with the pneumatic shears, the wire is provided with a cutting edge at each change, that releases a small chip from the welding nozzle tip when the wire is transported to the tip. The wear marks, as well as the burr created, are shown in Fig. 6. The burr is responsible for the wire being blocked and further transport to the pneumatic shears is no longer possible. The chips cause the wire to jam in the welding nozzle tip, as a result of which the glass fiber cannot be fed through the system. This error results in a breakage of the glass fiber, which means that no further change is possible. The resulting error with the glass fiber is remedied by another proximity sensor, which is placed in front of the Y-piece and only allows the medium to be fed into the system when no wire or fiber is detected by the sensor. The test was then repeated with a new welding nozzle tip. In this case, the test was aborted again after 60 cycles, since once again the wire was no longer transported to the shears due to the same error. From this it can be concluded that the contact tip, which is a wearing part, must be replaced when using metal wire material after approximately 50 changes in order to prevent an error. Observations have revealed another weak point of the system: When pulling the weld material backwards, the wire and fibers are only fed out of the feeder and not rewound, which allows the material to slip off the side of the coil. This is another possibility for a failure, especially when the distance between the Y-piece and the welding nozzle is high.

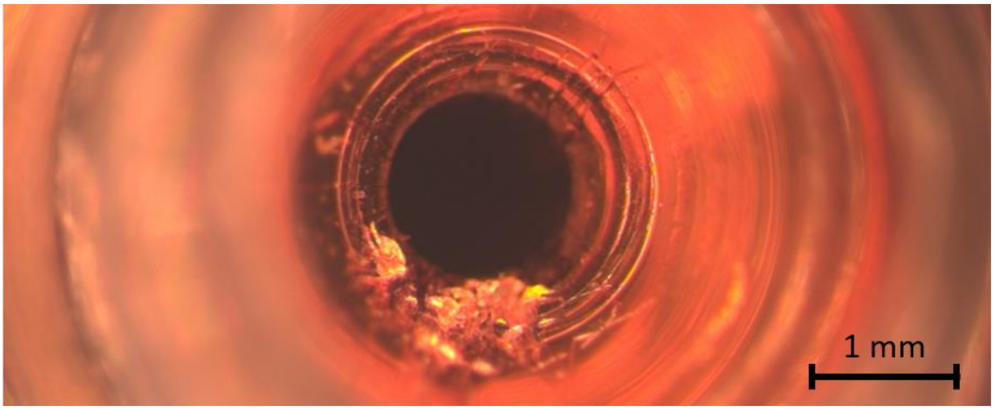

Fig. 6. View into the welding nozzle: Burr formation in the welding nozzle tip after 60 changes

The changeover time for the trials performed is 42 seconds for one changeover cycle. In this case, an alternating cycle is defined as one run of the entire process. This means the change between wire and glass fiber and the change back again. It follows that the changeover time from one material to the other is 21 seconds.

4. Switching between laser beam sources

4.1. Laser beam sources to be used

Various gas laser beam sources shall be applicable with the system for processing glass fibers made of fused silica: On the one hand, CO_2 lasers with wavelengths in the range from 9.4 to 10.6 µm shall be used. On the other hand, CO lasers in the wavelength range from 4.8 to 8.3 µm shall also be adaptable. A maximum laser power of 200 W should be usable for the gas lasers in order to enable the mapping of the Additive Manufacturing of glass materials.

Various solid-state lasers in the wavelength range of approx. 1 µm are to be used for processing wires made of mild steel. It should be possible to use fiber, disk and diode lasers with a maximum output power of 3 kW.

4.2. Concept for switching between laser beam sources

For switching between the beam sources, there is a concept in which the gas laser is mounted on the coaxial processing head above a mirror made of ZnSe coated with a dielectric layer (see Fig. 7). The radiation from the solid-state laser is incident on the mirror at 90 degrees to the radiation from the gas laser. The dielectric coating is highly reflective (>99.9%) for wavelengths in the range of 1 µm. For wavelengths in the range of 4.8 - 10.6 µm the coating is transmissive (>85 %). The thickness of the ZnSe mirror causes an offset in the radiation from the gas laser. To compensate this, a cross table is installed that allows linear alignment in the X and Y axes. The compensation of angular positions (A-/B-axis) is carried out through leveling elements.

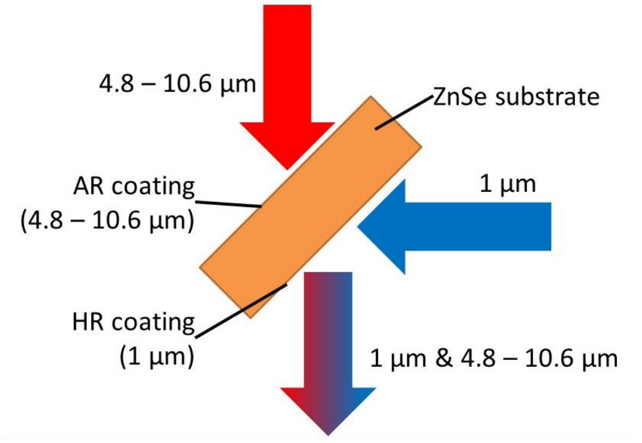

Fig. 7. Principle of the beam combiner for solid state (1 µm) and gas laser beam sources (4,8 – 10.6 µm)

5. Summary and Outlook

5.1. Summary

Coaxial Direct Laser Deposition enables Additive Manufacturing of almost all fusible materials. This paper describes the development of a system for fully automated switching between glass fibers and metal wires in direct laser deposition. In addition to feeding and switching between different welding materials, switching between different laser beam sources is also considered, since steel wires are processed with solid-state laser beam sources (wavelength 1,080 nm) and fused silica fibers are usually processed with gas lasers (wavelengths 4.8 µm to 10.6 µm). Within the scope of tests, it was shown that an automated changeover between two wire-shaped welding materials using a Y-shaped Connector and two independent wire feeders is possible. The duration of a change from wire to fiber and vice versa is 21 seconds. With the test setup used, up to 60 changeovers could be carried out before wear in form of burrs occurs in the contact tip of the welding nozzle (= wearing part), preventing an automated filler material changeover. Furthermore, a concept was developed with which both an ytterbium fiber laser and a CO or CO_2 laser can be integrated into an optical beam path.

5.2. Outlook

The system technology developed for changing the filler material and switching between the different laser beam sources is to be used later in combination with a coaxial deposition welding head to enable hybrid components made of fused silica and metal materials to be manufactured generatively with the overall system. The next step will be to test the system in combination with the existing coaxial welding head. The special feature is that the feeding distance between the merging point (Y-piece) and the welding nozzle is longer and that it has a radius of curvature, in contrast to the test setup currently used. The integration of further sensor technology to determine the position of the wire or the fused silica fiber is also to be evaluated and, if necessary, implemented. Furthermore, the system is to be extended to include powdered welding filler materials using a welding nozzle specially developed for this application.

Future research will therefore address these issues and incorporate them into the development of a multi-material processing head for Additive Manufacturing. Furthermore, the aim is to further reduce the changeover time in order to keep the non-productive times in the Additive Manufacturing of multi-matrix components low and thus also reduce the overall manufacturing time.

Acknowledgements

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