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ADDITIVE MANUFACTURING PROCESSES IN FLUID POWER – PROPERTIES AND OPPORTUNITIES DEMONSTRATED AT A FLOW-OPTIMIZED FITTING

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Abstract:
In recent years, additive manufacturing (AM) techniques have gained in significance. For example, geometries can be produced which, years ago, could only be produced economically with original forming processes, for example due to undercuts or their geometrical properties. AM techniques enable a design of component and machine in which the function fulfilment determines the construction and not the manufacturing possibilities. Components manufactured by AM are increasingly being used in series production and, for example in the aerospace sector, are enabling considerable weight reductions. While other industries have already made efforts and progress in the application AM processes, comparatively little progress has been made in the hydraulics industry. For example, enormous increases in power density could be achieved with this novel approach of manufacturing.
The aim of this publication is to present additive manufacturing processes for processing metals which are suitable for use in hydraulic applications and to show ways of making them usable. At first, the methods are presented and their properties and special features are dealt with. Subsequently, the achievable properties are also discussed. Following, an overview on the state of the art for the hydraulics industry is presented and classified with regard to the possibilities of additive manufacturing. Finally, an example is used to illustrate the possibilities offered by AM where a rectangular fitting is presented which has a significantly reduced line resistance thanks to AM and flow-optimization. The design is presented as well as results which allow a classification of the achieved loss reduction.

Keywords: *Additive Manufacturing, Hydraulics, Fittings*

1. Introduction

In recent years, additive manufacturing (AM) has become one of the most revolutionary and promising technology application in manufacturing. The process of making a product layer by layer instead of using traditional molding or subtractive methods is often referred to also as 3-D printing. Once employed purely for prototyping, AM is now increasingly used for spare parts and small series production. So far, adoption of AM has been highest in industries where its higher production costs are outweighed by the additional value AM can generate improved product functionality, higher production efficiency, greater customization and shorter time to market. Currently, AM's market penetration is still hindered by lack of design knowledge, high production cost and limited production scale. But as the AM industry is currently growing exponential [1], it is essential for each technical domain to evaluate the potential benefits from AM and leverage those. Since fluid technology has paid little attention to this technology and its research is still focused on increasing efficiency, this paper aims to highlight the opportunities for fluid power arising through AM.

2. Introduction to Additive Manufacturing

In this chapter, a short definition of the general principle as well as the shared advantages and disadvantages of many AM processes are given. The available AM processes for the manufacturing of metallic parts are then introduced with process principle, specific characteristics and available materials.

2.1 Overview

In recent years, many different processes have entered the manufacturing world under the label of Additive Manufacturing (AM). According to ASTM, an AM process is defined as a “process of joining materials to make parts from 3D model data, usually layer upon layer” [2], as opposed to subtractive (e.g. milling) or formative (e.g. bending) manufacturing [3]. Most AM processes share common characteristics and thus common advantages and disadvantages due to the manufacturing, joining and subsequent stacking of layers.

One of the biggest advantages of AM is the high possible part complexity due to the reduction of a 3D part to a 2,5D manufacturing issue. Even undercuts and internal structures are possible, with the complexity limited by the process resolution and the amount of data. Also, the “tool-less” (the tool is the same for all parts) manufacturing directly from 3D data leading to short lead times and cost savings. On the downside, parts manufactured layer-by-layer by AM processes usually exhibit anisotropies in the material properties and a staircase effect on slanted surfaces. When the slanted surface is facing downwards it is commonly called an overhang and, when exceeding a critical angle, cannot be manufactured by many AM processes without support structures (see **figure 2**).

2.2 Available Processes

AM processes are commonly classified into the following categories [2]:

- **Binder jetting**: AM process in which a liquid bonding agent is selectively deposited to join powder materials
- **Directed energy deposition**: AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited
- **Material extrusion**: AM process in which material is selectively dispensed through a nozzle or orifice
- **Material jetting**: AM process in which droplets of build material are selectively deposited
- **Powder bed fusion**: AM process in which thermal energy selectively fuses regions of a powder bed
- **Vat photopolymerization**: AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
- **Sheet lamination**: AM process in which sheets of material are bonded to form a part

An overview of the most important AM processes for the production of metal parts is given in **table 1**.

Table 1: Overview of metal AM processes

Process	**Laser powder bed fusion (L-PBF)**	**Electron beam melting (EBM)**	**Binder jetting**	**Laser metal deposition (LMD)**
ASTM category	Powder bed fusion	Powder bed fusion	Binder jetting	Directed energy deposition
Principle	Laser-induced heat selectively melts metal powder in powder bed	Electron-beam-induced heat selectively melts metal powder in powder bed	Liquid binder is selectively applied to metal powder in powder bed by inkjet print head	Laser-induced heat melts metal powder as it is deposited
Materials	Fe, Ni, Ti, Al, Cu, CoCr, TiAl, Au, Ag, CoCr, …	Ti, CoCr, Inconel 718	Polymers, sand, ceramics, metals	Ti, Fe, Cu, Ni, Al, Co, …
Application / industry	Aerospace, Turbomachinery, Automotive, Dental/Medical, Tooling	Aerospace, Turbomachinery, Medical	Tooling, Automotive, Medical	Turbomachinery, Tooling
Machine suppliers (examples)	Aconity3D, EOS, Trumpf, SLM Solutions, Concept Laser, Renishaw, GE Additive	Arcam, Freemelt	ExOne, 3DSystems, Desktop Metal, Digital Metal	Trumpf, DMG Mori, Optomec, Okuma

2.3 Laser Powder Bed Fusion

Laser powder bed fusion (L-PBF) is one of the most common AM processes for the production of dense parts from metal powder [4]. Example applications are in aerospace for the production of lightweight parts and in turbomachinery for the production of parts from heat resistant superalloys. The process principle is shown in **figure 1**. In an iterative process, a thin (30 – 50 µm) layer of powder is applied on a b by a recoating mechanism. The areas of the powder later constituting the solid part are selectively melted by focused laser radiation. The build plate is then lowered by the amount of the layer thickness. The cycle is repeated until the part is finished. A detailed description of the process can be found in [5]. The powder is almost fully melted, parts with a relative material density near 100 % can be manufactured. Unused powder is fully reconditioned and reused, making the process resource efficient. The process is shielded by an inert atmosphere and gas flow, usually Argon or Nitrogen, to protect the material from oxidation and for removal of process byproducts from the laser beam.

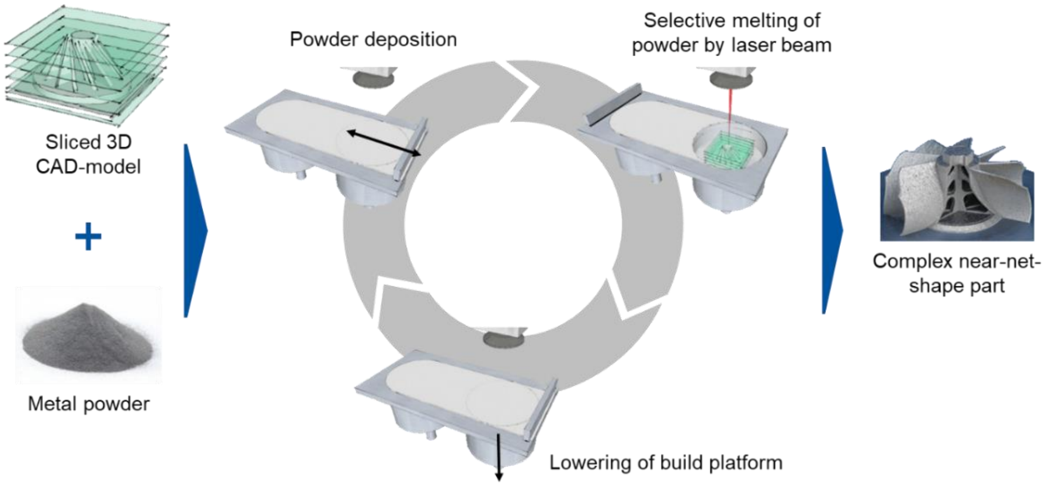

Fig. 1. L-PBF process principle [6]

A wide range of materials can be processed by L-PBF. Standard materials commercially available from many suppliers include, among others, Aluminum alloys (AlSi10Mg, AlSi12), Stainless and Tool Steels (1.4404, 1.4542, 1.2709), Nickel-based alloys (Inconel 718 and 625) as well as pure Titanium (Titanium Grade 2) and Ti6AlV4 [7,8]. Due to the rapid solidification rates of the molten material, reaching up to 7x10^{6} K/s, the materials generally exhibit a very fine and homogeneous microstructure throughout the whole part [9,3]. This results in high strength comparable to the standard cast and sometimes wrought material properties, albeit often with anisotropies in the build direction. Heat treatments are available for reduction of anisotropies or sometimes necessary for reaching the standard material properties.

The cooldown and shrinkage of the bonded consecutive layers leads to a buildup of residual stresses in the material, as shown in **figure 2**.

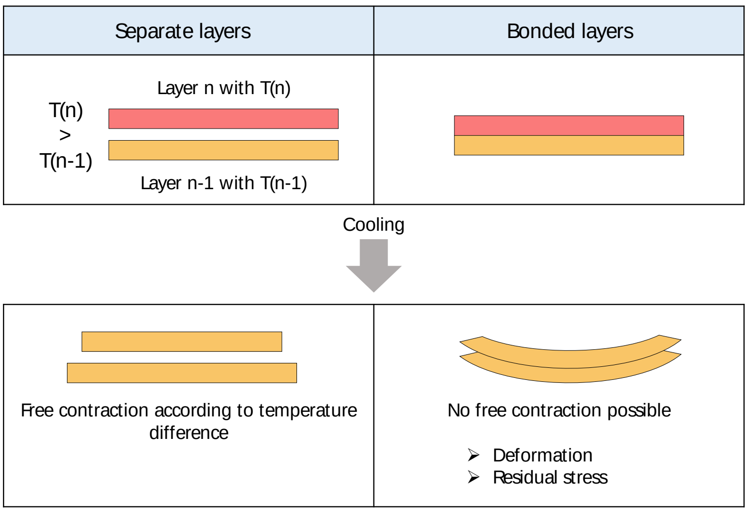

Fig. 2. Buildup of residual stresses

When overhangs are produced, the residual stresses result in deformation and, when the critical overhang angle is reached, in failed builds. Support structures are therefore needed to counteract the stresses. The support structures and the typically rough surfaces of L-PBF-parts covered with partly melted powder particles (R_a = 10 – 20 µm) generally require post-processing of the parts, consisting at least of (manual) removal of the support structures, abrasive blasting and, in case of functional surfaces with high quality requirements, machining. The need for support structures and thus for post-processing can be greatly reduced by a part design taking into account the process restrictions.

2.4 Electron Beam Melting

The basic cyclic process for EBM is very similar to L-PBF: Powder is applied in thin layers (thickness 50 – 200 µm) and selectively melted to form solid areas. The main differences arise from the use of an electron gun as the source of thermal energy. The electrons transmitted to the powder particles may lead to a buildup of charge inside the particles due to the insulating property of the oxide layers. The resulting electrostatic forces can displace powder out of the powder bed in a phenomenon known as “smoke” [10]. To avoid the buildup of charge and to hinder the movement of the particles, each powder layer is heated before the melting step by the defocused electron beam, sintering the particles slightly into a “cake”. The EBM process thus being a high-temperature process with powder and part temperatures reaching up to 1100 °C leads to two main differences to the L PBF-process: As an advantage, the temperature gradient between subsequent layers is small and the parts are consequently almost free from residual stresses, leading to excellent mechanical properties and a reduced need for support structures. As a disadvantage, the sintered powder is difficult to remove from internal structures, hindering the usage in fluid technology. A comprehensive overview of the process can be found in [10].

2.5 Binder Jetting

Similar to the L-PBF and the EBM process, Binder jetting is a powder bed process, in which powder is applied in thin layers and selectively joined to form solid areas. Differently to these processes, the joining is not achieved by melting particles, but by applying a liquid binder selectively in small droplets with a print head similar to an inkjet print head. As no thermal energy is involved, the layers don’t shrink due to cooling and thus the material is free from residual stresses. As a result, parts can be produced without support structures and “nested” within the build chamber to make best use of the available volume. The principle of joining particles with binder leads to a much bigger range of material types than in other AM principles. It is possible to process powders made from metal, polymers and ceramics as well as sand for the production of molds and cores for casting. Also, full-color models can be produced by using colored binders, similar to inkjet printers.

Directly after the printing process, parts produced by Binder jetting exhibit low strength and low ductility. This may be sufficient for the production of sand molds or colored design prototypes. For the production of functional prototypes or end-use parts, the parts can be sintered or infiltrated with low-melting alloys (typically bronze) after the additive manufacturing step, resulting in denser parts with higher strength and hardness [11].

2.6 Laser Metal Deposition

Unlike most AM processes, LMD is not limited to layer-by-layer production. Material can be deposited on freeform surfaces, only limited by the degrees of freedom of the handling system on which the processing head is mounted and the accessibility. In conventional LMD, in order to deposit material, a melt pool is generated on the surface of the part by thermal energy from the absorption of focused laser radiation. Metal powder is then blown into the melt pool either from a lateral or coaxial powder nozzle. Alternatively, in a process called Extreme High-Speed Laser Material Deposition (EHLA), the powder is melted in the flight phase, minimizing the size of the melt pool and the heat affected zone [12] and increasing the area deposition rate. In both processes, the material is metallurgically bonded with the substrate with minimal mixing of the components. The process principles are shown in **figure 3**.

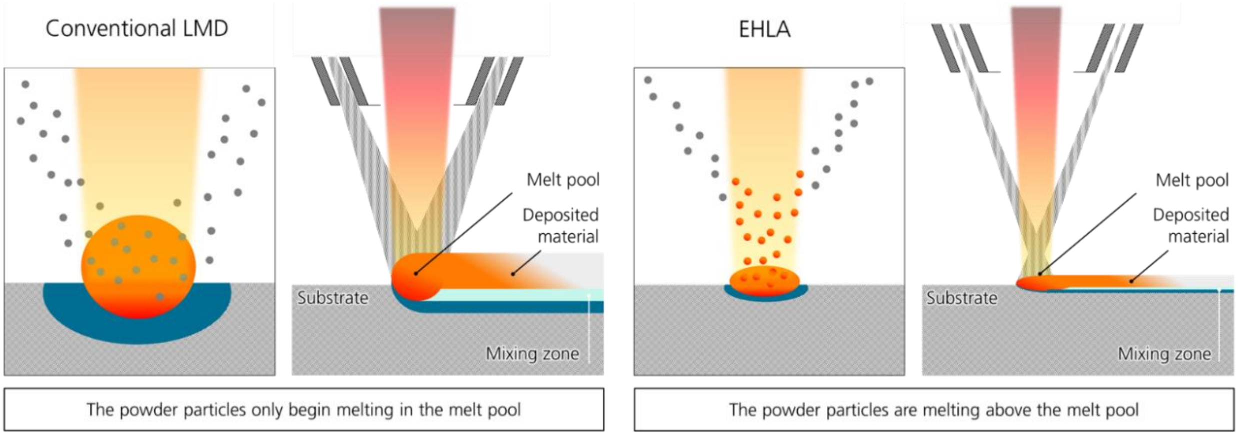

Fig. 3. Process principle of LMD and EHLA [12]

The process may be used for the additive manufacturing or repair of parts by stacking layers, or for the coating of parts with wear and corrosion resistant layers. In case of EHLA, the main application is the production of coatings on rotationally symmetric parts like hydraulic cylinders. This is due to the high deposition rates only usable on lathes. The heat transfer into the substrate is small, resulting in small thermal deformation of the substrate. The composition of the powder can be influenced during the process, making it possible to produce layers with material combinations or gradients difficult to produce with conventional processes [12].

The processable materials include standard alloys from a wide range of material types, like Ti6AlV4, 1.2344 and Inconel 625. Also, by mixing of powders, metal matrix composites containing carbides and nitrides can be manufactured. The deposited material exhibits a relative density near 100 % and excellent mechanical properties [12,13].

3. Classification of additive manufacturing processes for hydraulics

In the following chapter AM is being classified for the hydraulics industry. Starting from the status quo of traditional production technology in hydraulics, the possibilities arising from AM are shown. Based on a selection of previous investigations regarding AM for use in hydraulics, the utilization of AM potential is estimated. The chapter concludes with a few example applications which make use of AM.

3.1 Influence of traditional manufacturing processes on hydraulic components

Components of hydraulic components have been manufactured in the past decades and are still mostly produced today with milling machines, lathes, electric discharge machining, laser cutting or casting. These are predominantly CNC-supported manufacturing processes, which allow high economies of scale in series production with well-coordinated process control. On the other hand, there are high start-up times for setting up the machines in production lines for series production of new parts, which are usually 30 days or more. This makes it more difficult to implement small batches quickly. In addition, the design freedom of a component is severely restricted by these processes, since each process has its own requirements for accessibility to the component such as lathing which is only possible orthogonally or coaxially to the lathing axis. Additionally, each process might need its own clamping surfaces. For example, valve blocks are hydraulic components whose shape is largely determined by the production process. Except by means of original forming processes, which are frequently used in standardized valve blocks for mobile machines, it is not possible to manufacture internal connecting lines, so each channel must be led out of the component, at least at one point. All channels must be placed in such a way that no unwanted connections occur and sufficient compressive strength is guaranteed at all points. Since the components are milled from the solid, this results in unnecessary material expenditure as well as weight. The removal of unneeded material by means of subtractive procedures is, however, not economical. Since these manufacturing processes have not undergone any far-reaching innovations in recent decades the design of hydraulic components has hardly changed. A production-oriented rather than function-oriented design is still the predominant paradigm in the industrial sector.

3.2 Possibilities of additive manufacturing techniques for hydraulic components

A decisive design parameter of hydraulic components is the efficient guidance of the fluid through the component, taking into account the restrictions imposed by other functional surfaces and the manufacturing possibilities. Compared to traditional manufacturing processes, additive manufacturing processes entail significantly fewer restrictions, whereby process-specific restrictions also exist here. Strong overhangs can only be produced using support structures that are difficult to remove within cavities. In addition, high surface qualities are difficult to produce. Taking these restrictions into account, however, additive manufacturing technology allows great freedom of design. Orthogonal channels often occur in classical valve blocks, as these are drilled in as few clamping operations as possible. These hard flow deflections often lead to energy and thus efficiency losses. Usually the complete borehole is not required, which leads to unnecessary dead water areas, which represent unwanted capacity and areas for deposits. AM processes, on the other hand, make it possible to optimize flow control. Flow-optimized channel guidance allows the flow losses and the stresses introduced into the material at the points of flow deflection to be significantly reduced [14]. Within the same installation space, a higher volume flow with lower energy loss can be achieved using less material. Cooper et al. compared the flow profile of an additive block with a conventional block using Particle Image Velocimetry (PIV). In the additive block, the flow velocities are partly 250 % higher compared to the conventional block due to less strong flow deflections which results in lower losses. Test channels with heat treatment increase the strength of the component from ~350HV to ~500 HV [15]. Semini et al. also investigated the effects of the fluid on the surface, whereby the components are treated by shot-peening before the flow test was conducted in order to remove production residues from the surface. No significant effect of the flow on the surface even after a longer loading time were reported [16]. Weight savings are achieved with components redesigned for AM, where the scope is 30% and more. In addition to the gains from a design of the components that is function-oriented, further advantages can be achieved. For complex hydraulic drive components, Guerrier et al. consider the achievement of a shorter development cycle, reduced storage costs for material, better and new repair possibilities to be promising [17].

3.3 Use of additive manufacturing technology in the manufacture of hydraulic systems

Currently, additively manufactured hydraulic components are often substitutes for existing traditionally manufactured components. Schubert and Kroll propose a six-stage redesign process for the production-ready redesign of such components using additive processes. This begins with the analysis of the functional structure of the existing component. Once all the basic elements have been identified, they can be individually optimized. An example of this is the adaptation of the shape so that surfaces of high quality are built up in a vertical direction or a flow optimization. This was followed by the iterative determination of the position of all basic elements. All connecting channels were then created. This offers further optimization potential such as flow optimization or the use of a channel as a support structure for another element. Finally, the design of secondary structures such as stiffeners or mountings [18] is carried out. A similar approach is also proposed by Sossou et al. While final designs determined by topology optimization can be produced with AM, it is often more practicable to give a rough shape starting with the functional surfaces, similar to the design process using traditional manufacturing techniques, and then refine this design by topology optimization [19].

At present, many hydraulic components cannot be installed immediately after additive manufacture. In many cases, printed functional surfaces do not have the necessary surface properties. Valve seats, for example, require machining to achieve the necessary surface quality at the sealing seats or running surfaces. Additive manufacturing processes are usually carried out outside line production. This makes it more difficult to integrate additively manufactured components into production, especially for small quantities. However, this problem does not only affect the hydraulics industry. Machine tools or cells, which master additive as well as subtractive processes, are of great interest across industries and in development and are expected to be ready for use within the next years [20].

3.4 Existing Advanced Solutions of Hydraulic Additively Manufactured Systems

The implementation of additive systems has increased progressively in recent years. More and more industries are concerned with harnessing the advantages of AM for their products. The annual Wohlers Report 2017 states that of those industries that are particularly relevant to the hydraulics industry, especially the aerospace industry is concerned with AM not only to save on weight [4]. As can be seen in **figure 4,** it is the second largest sales market for AM products after industrial/business machines which includes office supplies, computers and printers but also automation equipment and parts for robotics.

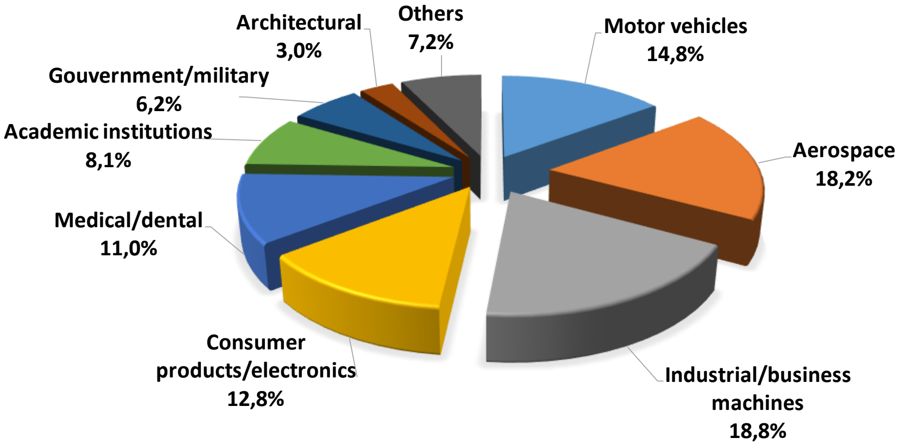

Fig. 4. Sales AM industry by sales market [4]

The first hydraulic additive manufactured component and used worldwide in a commercial aircraft is a valve block from Liebherr Aerospace (see **figure 5**). The valve block is part of the spoiler actuator of the A380 and is important for primary flight control. The block is made of titanium powder and is just as powerful as a conventional valve block made of a titanium forged part, but consists of fewer individual parts and is 35 percent lighter. The valve block has been in use since the first quarter of 2017.

Fig. 5. Spoiler-actuator valve block by Liebherr-Aerospace [21]

The manufacturer Aidro is also active in the additive production of valve components. Their additive manufactured valve blocks are characterized by lower weight, more compact design and lower losses. Additively manufactured valve spools have also been tested. AM here offers great freedom in the design of the valve's control windows, so that larger volume flow rates are possible with the same geometrical dimensions of the spool and at the same pressure difference [22]. Another highly integrated solution made possible by AM is the "Integrated Smart Actuator (ISA)" developed by Moog for robotics (see **figure 6**). The cylinder housing and valve are designed as a single component and all channels are designed for optimum flow. This actuator provides an outlook on development opportunities for compact drives, which are becoming increasingly popular on the market.

Fig. 6. Integrated Smart Actuator (ISA) for Robotics Systems by Moog [23]

Also the humanoid robots of Boston Dynamics have a very advanced design, which unfortunately is not documented in scientific publications. Here, the lines are integrated into the supporting structure similar to blood vessels. Cartridge valves and actuators are placed in the support structure, whereby their housings are also integrated into the structure. It is demonstrated how functional surfaces of hydraulic components can be merged with the supporting structure, resulting in an exceptional power-to-weight ratio. Another component benefitting from AM are heat exchanger. AM allows much more compact designs at higher surface to weight ratios and less pressure drop [24].

4. Case Study – a Flow-Optimized Fitting

One of the biggest challenges for additive technologies in fluid power applications is the manufacturing cost compared to alternative manufacturing techniques. Connection elements in hydraulics can be found in every application from mobile to stationary hydraulics, see **figure 7**. The manufacturing is cost-optimized by forging and drilling. This results in sharp edges within the channel geometry. Pressure losses are of secondary interest, since an optimization would result in a change of manufacturing process.

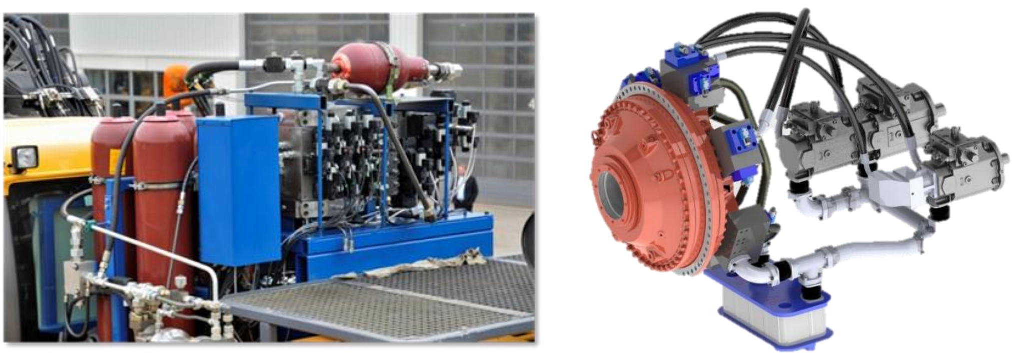

Fig. 7. Hydraulic connectors on a mobile machine (left) and for a hydrostatic wind drive (right)

Considering a stationary hydraulic manufacturing machine with parameters presented in **table 2**, an assumed 40% reduction in pressure losses, 300 l/min flow rate and 1000 hours of operation per year, one can illustrate the possible savings for the operator using equations (1) and (2).

Table 2: Estimated values for case study

Characteristic	Descriptor	Value	Unit
Flow rate	Q	300	l/min
Pressure drop 90° connector	Δp_C	0.5	bar
Pressure drop 90° connector w/ Inlay	Δp_I	0.3	bar
Energy cost per kWh	C	0.15	€/kWh
Hours of operation p/a	t_{Op}	1000	h

$$P = Q \cdot \Delta p \tag{1}$$

$$C_{total} = P \cdot C \cdot t_{Op} \tag{2}$$

With the aforementioned assumptions, the savings in energy cost per year would be above 11 € just looking at one connector. For a whole system, this amount would increase significantly.

At ifas, this case study was used to develop a flow-optimized geometry using additive manufacturing, namely poly-jet printing of polymer. The idea was to keep the original design and manufacturing process of a 90° connector as it is and develop an inlay to optimize the flow path. **Figure 8** shows the initial design concept, see [25]. Here, the symmetry plane of the 90° connector is used to create two identical inlays that can be mounted into each channel, meeting at the plane of symmetry. This gives the inlays a defined mounting position. Detachment of the inlays is prevented by mounting tubes or pipes at each end of the connector. The flow optimization was done focusing on minimizing the losses due to the 90° bend. Introducing an additional rotational spin to the fluid flow benefits the pressure drop immensely.

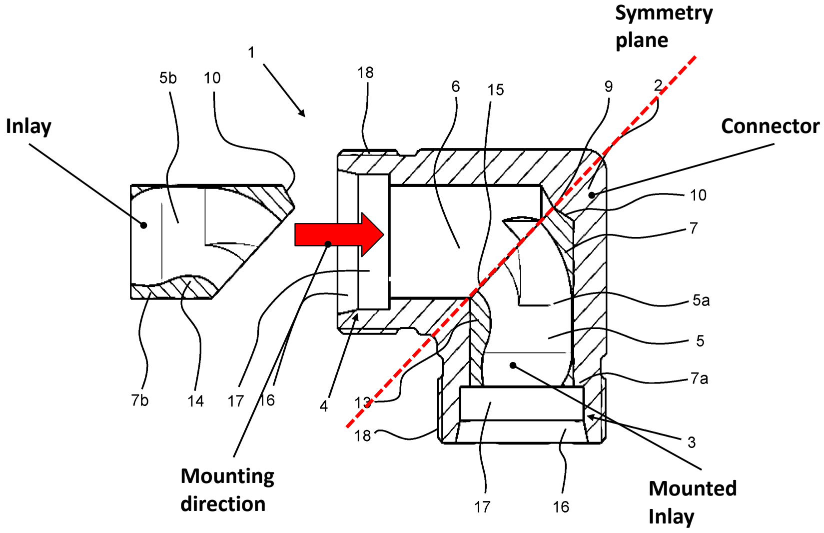

Fig. 8. Conceptual design of an additively manufactured inlay for mounting into a 90° connector [25]

It was found with the design shown in **figure 8**, pressure losses over the connector can be reduced by up to 40% depending on the flow conditions. An additional benefit is the symmetrical layout. This guarantees a bidirectional flow with identical flow characteristics.

Regarding manufacturing costs, the inlays can be manufactured using AM techniques requiring only little cost compared to the saving potential. Due to the design, these parts don't need to be pressure resistant since the connector acts as a wall.

5. Conclusion and Outlook

In this paper, the manufacturing capabilities currently offered by AM were presented with a special focus on laser powder bed fusion. The AM industry is currently growing exponentially and is constantly penetrating new markets and industries. Compared to traditional processes, it offers the possibility of aligning the design of components more closely to the functions, which is currently of particular interest for fluid components with flow channels. The channels can be optimally aligned to the expected flow conditions and higher flow rates, lower pressure losses and more compact structures can be realized in this way. In the fluid power industry, AM is currently still not well represented. For hydraulics, AM is used in the fields of aerospace, racing and robotics. This may be due to the fact that AM components are still used as substitutes in existing designs. The higher costs must therefore usually be more than compensated by a single factor from the user's perspective, for example an outstanding power-to-weight ratio, which is of interest in the aerospace sector but not in stationary hydraulics. As the case study shows, however, AM can also be interesting in other areas and, with a long-term view to costs, can already offer solutions today that enable efficiency gains and cost savings in operation through a design that cannot be realized with traditional manufacturing methods.

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