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Review

Review and New Aspects in Combining Multipoint Moulding and Additive Manufacturing

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Abstract: Additive manufacturing has become a very important manufacturing method in the last years. With additive manufacturing, a higher level of function integration can be achieved compared to traditional manufacturing technologies. However, the manufacturing of larger parts leads to long construction times. A possible solution is the combination of multipoint moulding with additive manufactured form elements. This article reviews the state of technology for multipoint moulding and additive manufacturing. Moreover, the state of technology is analysed to outline the possibilities and challenges of combining both technologies. The review shows that there has been research on different challenges of the new production process. On the other hand, it turns out clearly that there are many open points at the intersections of both technologies. Finally, the areas where further research is necessary are described in detail.

Keywords: additive manufacturing; multipoint moulding; fused filament fabrication; vacuum assisted multipoint moulding; technology combination; silicone made build platform

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1. Introduction

In recent years, additive manufacturing has become a very important manufacturing method. The components are built up in layers of a pre-material. Therefore, additive manufacturing allows function integration within a component. This function integration enables components with better mechanical properties and lower weight to be produced. In addition, time-consuming joining operations can be avoided. The currently used additive manufacturing methods have the disadvantage that increasing component sizes lead to massively increasing construction times.

On the other side, there may be the possibility to mould larger parts. In the production of individual parts or small batches, the fabrication of moulds is a main cost factor. It can be avoided by using vacuum-assisted multipoint moulding (VAMM). The possibility of dispensing mould making not only leads to a reduction in costs, but also to an improved environmental balance sheet, as the disposal of moulds that are little or only used once is no longer necessary. On the other hand, vacuum-assisted multipoint moulding is limited regarding the resolution and the possible part shapes.

A possible solution is the combination of additive manufacturing with vacuum assisted multipoint moulding. Thereby, the whole process could gain from the speed and flexibility of vacuum-assisted multipoint moulding with an increased resolution and higher shape flexibility offered by the additive manufactured attachments.

Possibilities of this combination for a new process called enhanced vacuum-assisted multipoint moulding with additive attachments (EMMA) and resulting advantages will be examined in this paper. Therefore, the literature review in the next sections will discuss the actual state of the art of multipoint moulding and additive manufacturing. For this purpose, the article will review the different additive manufacturing technologies and analyse if they accomplish for the combined process and what challenges remain. In the next step, this paper reviews the actual research topics which could be related to these challenges and possibly provide evidence to solve them. The main objective of this article is therefore to provide an overview of the existing evidence and the further research needed to implement the enhanced vacuum assisted multipoint moulding with additive attachments process.

The next section will discuss the actual state of technology in vacuum-assisted multipoint moulding and show the possibilities and restrictions of this technology.

2. Vacuum Assisted Multipoint Moulding

2.1. Definition and Historical Development

Multipoint moulding (MM) is based on the idea of creating a mould that can be adapted to the part to be produced and thus it is not necessary to produce a mould for each individual part. MUNRO AND WALCZYK [1] define a multipoint mould also called a reconfigurable tool: "A reconfigurable tool is defined as a machine that can be repeatedly configured by a user for shaping mechanical parts in a manufacturing setting. Although most machines are reconfigurable by virtue of their replaceable cutting bits, dies, moulds, rollers, and the like, the machines [. . .] are reconfigurable pin-type tools with a variable surface similar to the popular 3-D pin art or PinPressions™ toy, [. . .]. To be clear, the machines discussed here are not fixturing devices, nor are they used for secondary cutting or finishing of parts." Figure 1 shows the schematic of such a 3D pin art. As shown in Figure 1, the toy consists of a set of needles behind glass. The needles are mounted in two plates with open ends at the back. The image is then created by the movement of the pins, e.g., pressing a hand on the back and thereby creating a three-dimensional image behind the glass.

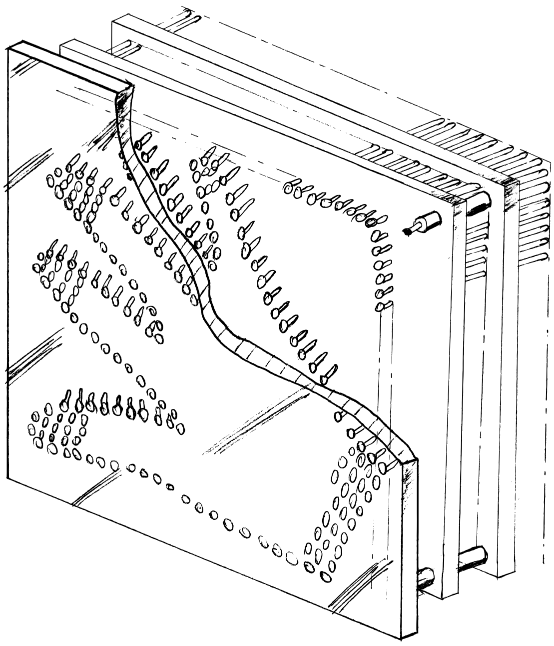


Figure 1. Schematic drawing of 3D pin art (based on the work in [2]).

The first known approaches to multipoint moulding date back to a patent of COCHRANE [3] from 1862 who developed a device for sheet metal forming with adjustable pins (see Figure 2). After inserting the sheet metal, the pins should be adjusted by hand and thus the shaping should be realised. Figure 2 shows the structure of the device. It consists of a set of pins with rounded heads and a studding which mounts the pins in the backplate and allows the adjustment in the forming process. The raw material is placed on the pinheads and is then pressed against the counter-pins on the other plate to be transformed.

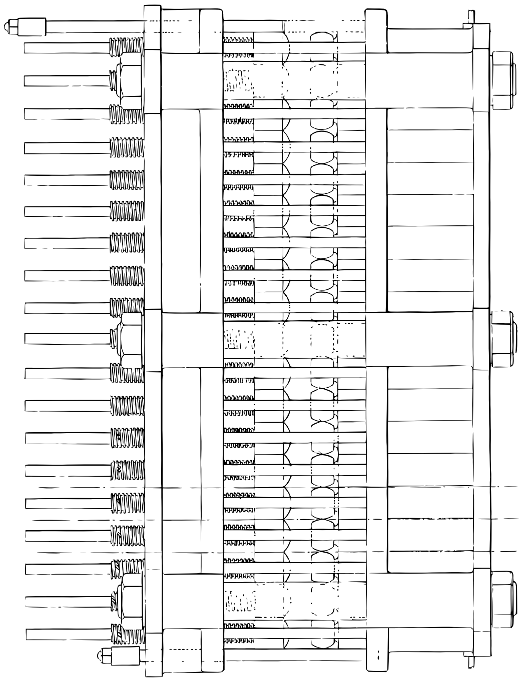


Figure 2. Schematic drawing of the first multipoint mould (based on the work in [3]).

The further development of multipoint moulding with the main contribution of the authors is shown in Table 1 in a chronological order.

Table 1. Chronological development of multipoint moulding.

Authors	Year Published	Main Contribution
Cochrane [3]	1862	development of multipoint moulding for sheet metal forming
Walczyk and Hardt [4]	1998	examination of pin shape and matrix structure
Valjavec [5]	1998	closed loop automatic adjustment control
Walczyk and Im [6]	2000	implementation of closed-loop automatic adjustment control for hydraulic actuation
Walczyk and Longtin [7]	2000	separated pins at larger distance and extension as a fixing device on CNC machine tables
Walczyk et al. [8]	2003	densely packed pins with interpolation layer and a single vacuum chamber for CFRP parts
Owodunni et al. [9]	2004	fully computer-controlled adjustment by a commercial CNC system
Wang and Yuan [10]	2006	forming of very large aluminium sheet metal in several working steps mainly for large spherical objects
Tan et al. [11]	2007	forming of perforated titanium sheets for individually formed plates for skull reconstruction
Hagemann [12]	2008	studies on multipoint moulding in injection moulding with the technical implementation
Walczyk and Munro [13]	2009	second vacuum circuit under the interpolation layer for concave shapes
Koc and Thangaswamy [14]	2011	adjustment and configuration for use in injection moulding

Table 1. *Cont.*

Authors	Year Published	Main Contribution
Bayerische Forschungsstiftung [15], Simon et al. [16], Simon et al. [17], Zitzlsberger [18], Simon et al. [19,20]	2011–2014	forming of plastic sheets with wide apart pins and a thick interpolation layer without vacuum for car prototype windows
Su et al. [21]	2012	forming of thermoplastic resin sheets without interpolation layer
Zitzlsberger [18]	2014	dimpling evaluation method for transparent multipoint moulded plastic sheets
Hundt et al. [22]	2014	variable pin distance for CFRP parts without vacuum support
Wimmer et al. [23]	2016	densely packed pin field with silicon made interpolation layer and two vacuum circuits for CFRP parts, research of the influence of the thickness of the interpolation layer on dimpling
Suzuki et al. [24,25]	2018	system for combination of small cuboids with magnets to larger objects as a faster alternative to additive manufacturing, the object creation is very similar to multipoint moulding

An actual further development was made by Wimmer et al. [23] relying on a densely packed pin field with vacuum support to enable forming of concave carbon fibre-reinforced plastic (CFRP) components (see Figure 3). Figure 3 shows that the concept used by Wimmer et al. [23] follow the classical idea of multipoint moulding by mounting rounded pinheads on studdings. Moreover, they combine this classical approach with a silicone made interpolation layer and mount it inside a vacuum chamber. This allows the manufacturing of concave parts but there is a risk of transferring dimpling from the interpolation layer to the component. As it can be seen in Figure 4a,b, the thinner interpolation layers cause a clearly markable dimpling at the top side. The thicker interpolation layers in Figure 4c,d eliminate the dimpling, but also worsen the shape reproduction. Overall, the thickness of the interpolation layer is one major effect in the shape reproduction, but there also several other influences. Therefore, predicting the behaviour of the interpolation layer and the corresponding control of the system remains an issue to be dealt with [23].

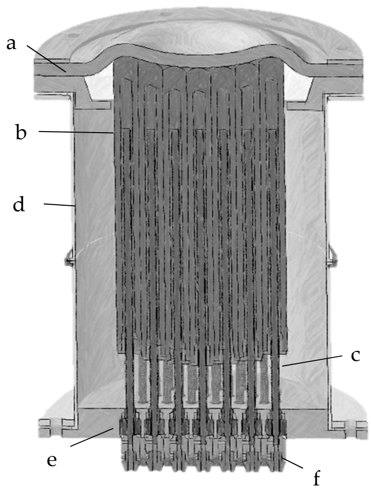


Figure 3. Principle of vacuum-assisted multipoint moulding (VAMM), shown in a smaller test setup. The setup from top to bottom: (**a**) interpolation layer, (**b**) pin array, (**c**) threaded rods, (**d**) vacuum container, (**e**) base plate and (**f**) actuator couplings [23].

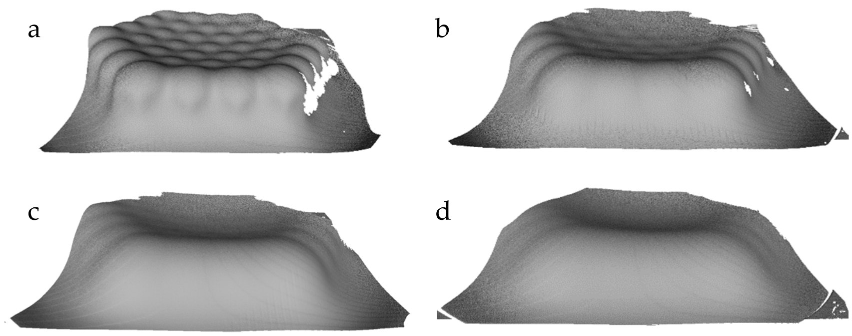


Figure 4. 3D scans of bowl shape created with a silicon rubber interpolation layer (40 Shore-A) with varying thickness ((**a**) 5 mm, (**b**) 10 mm, (**c**) 15 mm and (**d**) 20 mm) at a vacuum of 100 hPa [23].

Vacuum-assisted multipoint moulding according to WIMMER et al. [23] constitutes the basis for the further analysis as being the actual state of technology.

2.2. Restrictions and Solutions

Overall, it was shown that this technology has a broad field of application in various forming processes. Particularly in single-part and small-batch production, the time-consuming and expensive production of moulds can be dispensed. On the other hand, there are still various restrictions.

WIMMER et al. [23] show that size and shape of the pins as well as the interpolation layer used result in a certain resolution of the system. This means that, depending on these parameters, the structure manufactured on the plant must have a minimum size. Another limitation results from the maximum deformability of the interpolation layer, therefore two adjacent pins must not exceed a certain maximum height difference in order not to damage the interpolation layer. This in turn means that sharp-edged transitions cannot be represented.

Figure 5 shows a schematic part made of carbon fibre reinforced plastics including a detail which is not producible with vacuum-assisted multipoint moulding. Real components that correspond to the schematic in Figure 5 could be, for example, doors of cars with a door handle recess. The vacuum-assisted multipoint mould can be configured for the slightly curved section of the part, but not the buckle in the centre. On one hand, this buckle may be too small for representation with the pins of vacuum assisted multipoint mould. On the other hand, there are sharp edges which cannot be configured with the silicone made interpolation layer without damaging the interpolation layer. Naturally, other components are also a possibility, for example, with an additional negative form element.

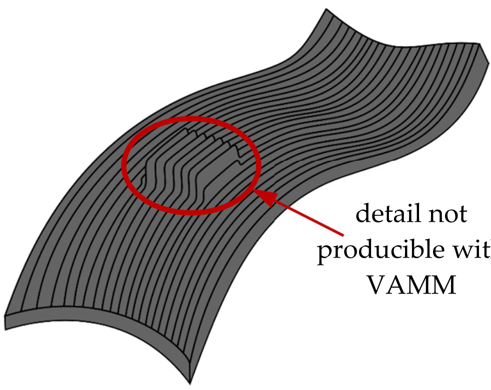


Figure 5. Schematic of a CFRP-part including a detail not producible with VAMM in the central part.

To solve this problem, LUŠIĆ et al. [26] propose the application of attachments to the interpolation layer. These attachments are to be used in areas representing geometries that cannot be mapped on the vacuum-assisted multipoint mould. As shown in Figure 6, this concept consists of the classical vacuum-assisted multipoint mould approach with the pins mounted in a vacuum chamber and a flexible interpolation layer at the top. On top of the interpolation layer an additive manufactured attachment is mounted to build the detail which cannot be represented by the vacuum assisted multipoint mould. The fixing of the externally manufactured attachments on the interpolation layer is identified as a problem. Three different solutions are presented, two of them are types of vacuum mounting and the third is a needle mounting system.

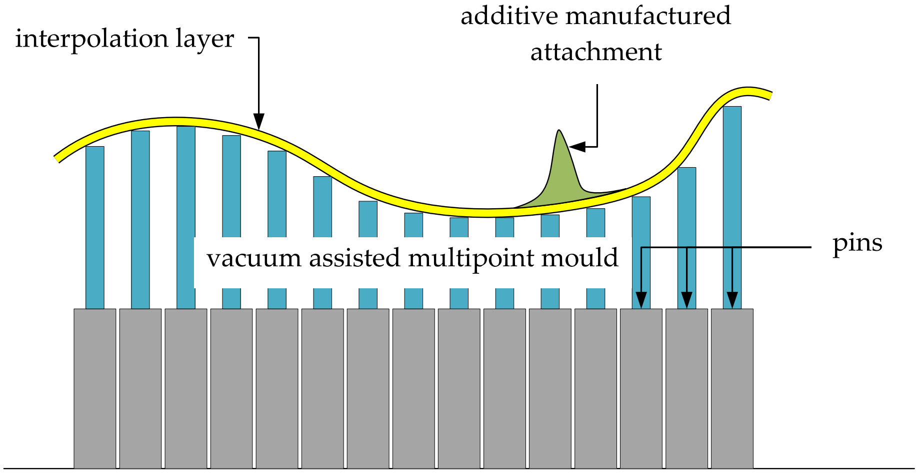


Figure 6. Enhanced vacuum-assisted multipoint moulding with additive attachments, consisting of the vacuum-assisted multipoint mould with pins and interpolation layer and the additive manufactured attachment mounted on top of the interpolation layer.

The combination of the vacuum-assisted multipoint moulding and the additive manufactured attachments has the opportunity to combine a fast moulding process with the possibility for smaller details without producing a mould. Building the whole part with additive manufacturing processes would consume a lot of time, although the parts are thin-walled. On the other hand, the construction and milling of a mould needs even more time, even if the moulding process itself is fast. When combining the vacuum assisted multipoint moulding with additive manufactured attachments on one side the additive manufactured parts are relatively small and thus can be manufactured in a short period of time. On the other side, when using the vacuum-assisted multipoint mould there is no mould-milling necessary which significantly reduces the time required. The positioning problem of these attachments on the vacuum assisted multipoint mould is not completely solved. If a manual positioning is carried out, deviations in dimensional accuracy can be expected. In addition, trained employees are needed for manual steps, which generally reduce the efficiency of the technology. A further aspect is the need to pick up the surface in order to be able to produce precisely matching attachments. It is therefore desirable to aim for a continuous production process directly integrated in one plant and delivering a finished mould, based on the digital computer-aided design (CAD) model. Consequently, this paper will only focus on production processes matching these requirements.

Figure 7 shows the process flow chart for the proclaimed enhanced vacuum-assisted multipoint moulding with additive attachments process. It starts with the CAD model of part to be manufactured followed by the separation of the geometries in the parts which are manufacturable by the vacuum assisted multipoint moulding itself und the parts where additive attachments are needed. In the next steps, the data for the adjustment of the vacuum-assisted multipoint mould have to be calculated followed by the adjustment itself. If the vacuum-assisted multipoint mould is adjusted accordingly to the target geometry the manufacturing data for the additive attachments can be calculated and sliced, followed by the manufacturing of these attachments the part can be moulded.

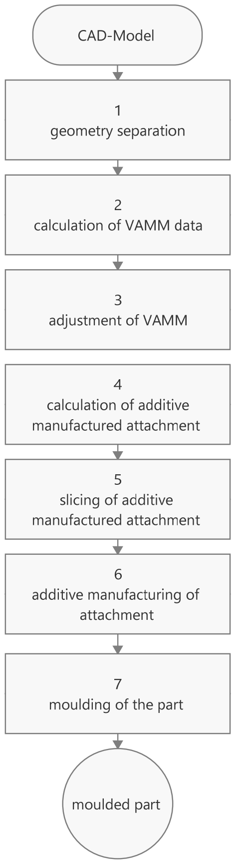


Figure 7. Process flow chart for enhanced vacuum assisted multipoint moulding with additive attachments.

Therefore, the next section will provide an overview of the actual state of the art in additive manufacturing technologies and discuss them in respect to combine both technologies.

3. Possible Additive Manufacturing Methods

According to Brans [27], additive manufacturing processes have been known for a long time and were already used in special applications and in prototype construction in the past. However, it has not become possible to use additive manufacturing in component production until the further development of the technology and its expansion to various materials.

The additive manufacturing processes, commonly known as 3D printing, are in most cases not based on a true three-dimensional production of the components, but use a 2.5D approach. With this approach, the three-dimensional component to be created is cut into individual layers with a constant thickness. These layers are stacked along the building direction (see Figure 8). A change of the geometry, for example, the wall thickness, can only take place in the transition of two layers. As it can be seen in Figure 8, this approach leads to a loss of details on one hand and to a staircase effect in the other hand. However, this method makes it possible to produce components with geometries that cannot be produced using conventional fabrication methods and therefore would have to be joined from several parts. In turn, this functional integration makes it possible to save joining processes and thus reduce production costs [28].

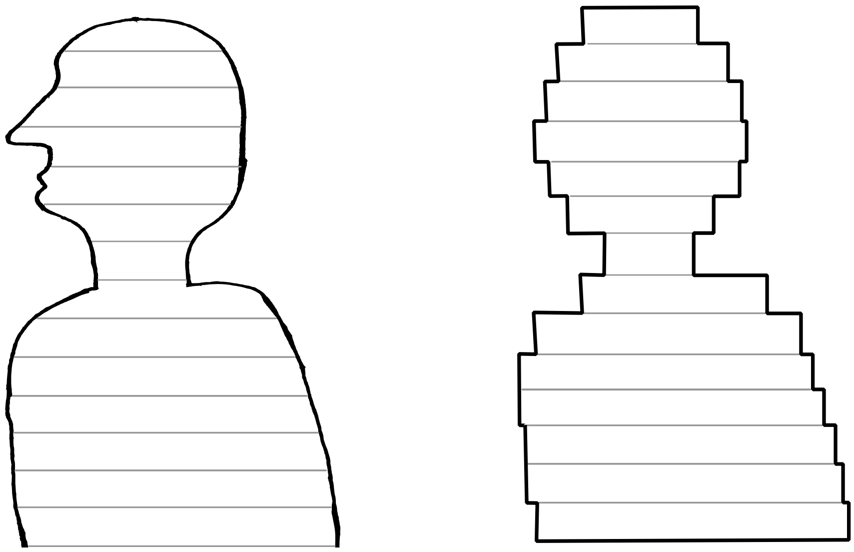


Figure 8. Slicing scheme for flat layers in additive manufacturing. Model with marked layers (**left**) and derived layer model (**right**).

In this section, the most common processes are presented and their suitability for the new enhanced vacuum-assisted multipoint moulding with additive attachments outlined in this paper is assessed.

3.1. Metal Based Processes

The historically newer group are additive manufacturing processes that use metals as manufacturing material. FRAZIER [29] already offers a comprehensive overview of the current opportunities of these processes, so that only a brief overview is to be provided here.

In this group, commonly used systems are based on a powder bed. The main principle is to build up a powder bed and fuse the powder using a laser beam directed by X-Y scanning mirrors. The component is then covered with a further layer of powder by the powder levelling roller that is fused to the underlying layer by the laser beam (see Figure 9). These processes are called laser powder bed fusion respectively selective laser melting [30].

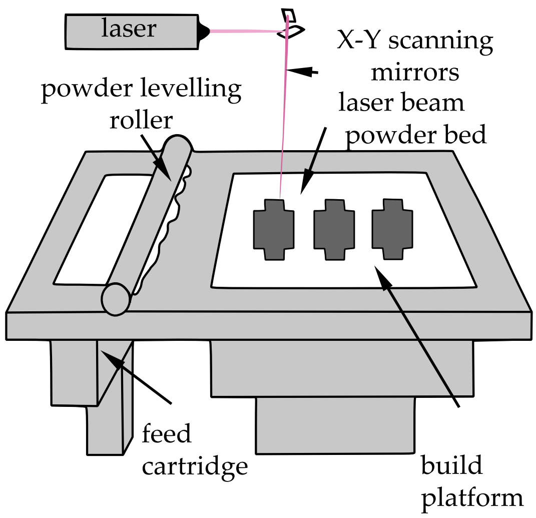


Figure 9. Schematic representation of laser powder bed fusion (based on the work in [30]).

A similar process is directed energy deposition, in which a laser beam is guided along the contour of the component while a nozzle is used to blow metal powder to the laser beam continuously (see Figure 10). The laser beam melts the powder and the component can be built up. At the same time, a powder bed is not necessary, reducing powder consumption. However, there is a high energy input into the build plate [31,32].

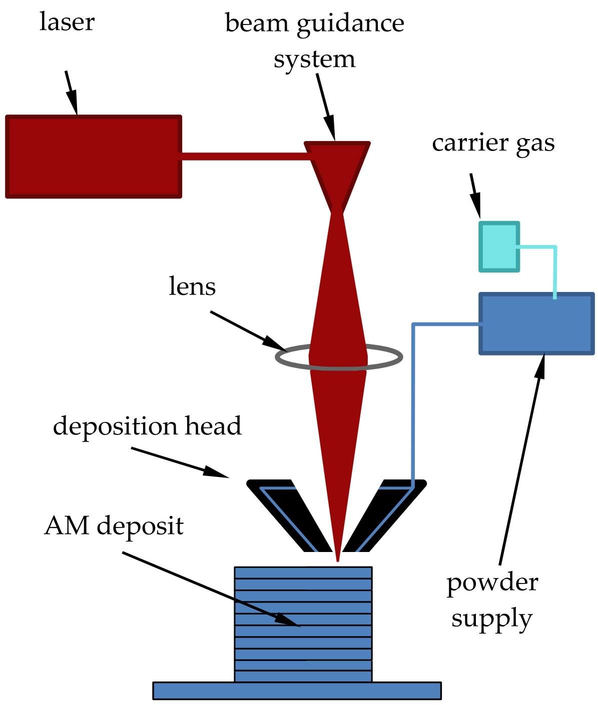


Figure 10. Schematic representation of directed energy deposition (based on the work in [29]).

SAENDIG et al. [33,34] and TECHEL et al. [35] introduce a process in which the layers of individual metal plates are cut out by laser and then get welded together. According to GEBHARDT [28], this form of laminating object modelling was not successful on the market.

An alternative method is the bonding of the powder by a binder in the binder jetting process, which was introduced by SACHS et al. [36] for metallic and ceramic parts. A powder bed is built up in layers similar to laser powder bed fusion. However, the individual grains are not joined by welding with a laser, but by bonding. The adhesive is sprayed onto the powder layer by layer to build up the geometry. The nozzles used are identical or very similar in construction to the print heads known from inkjet printing, which are usually guided and moved via a portal. Synthetic resins are often used as adhesives, which are available not only colourless, but also in various colours, making multi-coloured components possible. In case of using metal powder in the first step, a green part is built. In a second process step, the green part is debindered and infiltrated into a dense metal component [28].

3.2. Plastic-Based Processes

In addition to additive manufacturing processes using metals, there is the very widespread group of processes based on plastics. These processes can be classified according to the shape of the starting material. They can be divided into powder bed processes, extrusion processes, resin bath processes and processes using plate- or film-like starting materials.

In the field of powder bed processes, selective laser sintering is available in analogy to laser powder bed fusion with metals. However, the construction chamber is heated and maintained just below the melting point or the glass transition temperature of the plastic powder. This significantly reduces the energy to be introduced by the laser and prevents distortion. To suppress oxidation processes and the associated degradation of the material, the process is carried out in a nitrogen atmosphere. The layer thickness is about 0.1 mm [30].

The widely used fused layer modelling originates from the field of extrusion processes. This method is often mistakenly referred to as fused deposition modelling. Due to the comparatively simple design of the devices and the possible placement at the workplace, this procedure has become established for home users. Nevertheless, there are also devices for commercial use with an extended range of functions. In most cases, the solid thermoplastic raw material is pressed through a heated nozzle and liquefied. This liquid extrudate is placed next to each other on one level to produce the individual layer and in several layers on top of each other to produce the actual component. In most cases, a filament is used as the raw material, which is fed directly from a coil to the nozzle. Therefore, the more specific name fused filament fabrication (see Figure 11) is often used. Rarely pellet raw material is applied, which is liquefied in a screw extruder. In most cases, fused filament fabrication is used with a heated build plate to reduce warping, deformation and facilitate a better adhesion between the first layer and the build plate. Whereas other additive manufacturing technologies are very material specific there are many materials available for fused layer modelling [28].

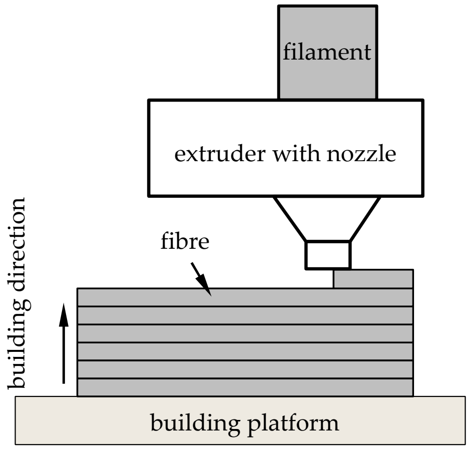


Figure 11. Schematic representation of fused filament fabrication (based on the work in [37]).

In addition to the often-used plastics, also gel-like or liquid materials are used, for example, in medical applications. LI et al. [38] present such a procedure for direct skin reconstruction.

Despite the relatively high degree of diffusion of the technology, many questions still need to be clarified scientifically. These are often questions concerning the optimisation of process parameters to improve production quality. DONG et al. [39] optimise the main process parameters to enable and improve the production of lattice structures. They show a clear influence on the manufacturability of the components, on the one hand, and on the mechanical properties of the component on the other. Apart from that, ERTAY et al. [40] address the problem of sharp directional changes in the extrusion path. These changes in direction lead to accumulation of material if the extrusion rate remains unchanged as the tangential speed of the die is greatly reduced relative to the build platform. Therefore, ERTAY et al. [40] develop a control algorithm that leads to a more uniform material deposition rate and thus to more precise components by influencing the extrusion parameters. LUZANIN et al. [41], on the other hand, optimise process parameters for polylactide (PLA) components with the aim of achieving the greatest possible bending strength.

Another major factor influencing the component strength of fused filament fabrication components is the connection between the individual extrusion strands within the layer or between the layers. Based on empirical data COOGAN AND KAZMER [37] clearly show that the component strength along the extrusion strands is significantly higher than the strength across extrusion direction. For a better prediction of this anisotropic behaviour, COOGAN AND KAZMER [42] develop a simulation model of the connection between the extrusion strands. CANTRELL et al. [43] and KELEŞ et al. [44] can also determine a clear dependence of the mechanical characteristics on the position of the component in the building space.

SEIDL et al. [45] compare the mechanical properties of the components produced by fused filament fabrication with those of components produced by injection moulding. The conclusion is that the additively manufactured components achieve strengths close to those of the injection-moulded components along the extrusion strands. In contrast, components produced using fused filament fabrication perform significantly worse under bending stress. RAUT et al. [46] extend the strength approach by the aspect of construction costs and try to derive an optimum from it. LIU AND YU [47] make targeted use of this anisotropy and show a formalism for the targeted reinforcement of highly stressed areas by corresponding planning of the extrusion paths. MOHAMED et al. [48] identify not only the screen angle, but also the layer thickness, the nozzle spacing and the number of contour paths as important factors influencing creep resistance. PRATER et al. [49] show that components produced in weightlessness have significantly better mechanical properties than those produced on earth. The exact reasons for this behaviour remain unclear.

The group of stereolithographic processes (SLA) rely on a liquid and light-sensitive resin as a base material. As shown in Figure 12a, one option is to use a laser beam for exposing a construction chamber filled with liquid resin along the component contours and thus activating the solidification of the polymer in these areas. Alternatively, the contours of an entire layer are exposed to light and thus cured by a mask process, as shown in Figure 12b. In the next step, the construction platform is lowered and the next layer is created. This process achieves very high accuracies and especially the mask processes achieve good production speeds. The downside is that in the first process step only green parts are produced which have to be cured afterwards [28,30].

The laminated layer manufacturing (LLM) or laminated object modelling (LOM) (see Figure 13) has to be mentioned as a process with plate- or film-shaped raw materials. For each layer of the part, a new film layer is glued to the lower layer and cut out along the component contours. The produced part can be removed from the waste material hackled by a crosshatch after all layers have been produced [28,30].

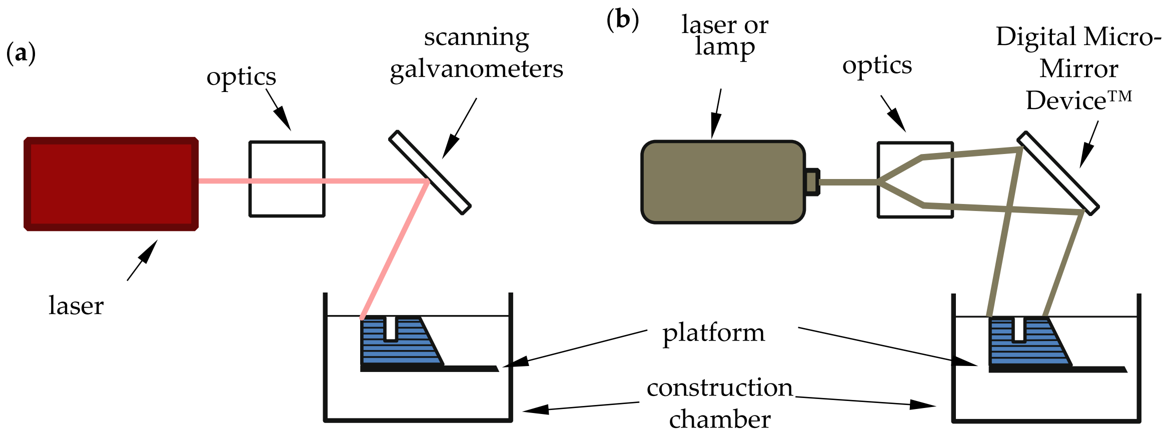


Figure 12. Schematic representation of stereolithographic processes: (**a**) vector scan SLA, (**b**) mask projection SLA (based on [30]).

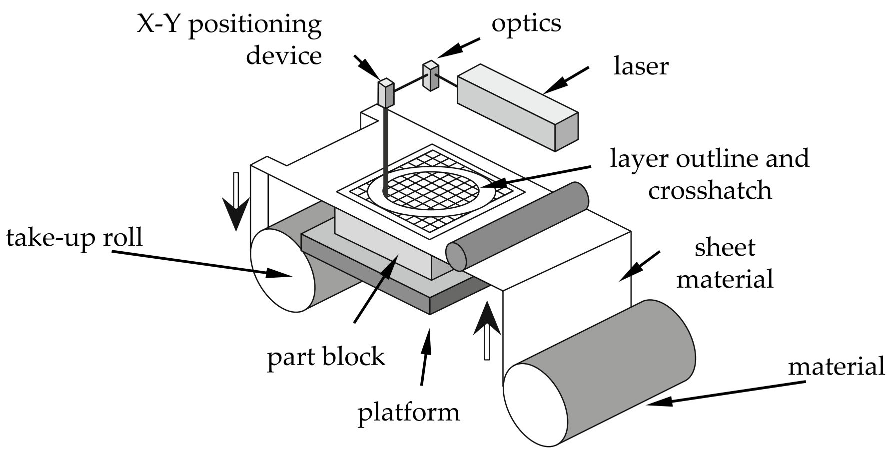


Figure 13. Schematic representation of laminated layer manufacturing (based on [50]).

However, the disadvantage is that the individual film layers create clearly visible and comparatively sharp-edged transitions between the layers on component slopes, the so-called staircase effect. For a significant increase in production speed and simultaneous improvement in surface quality HOPE et al. [51], HOPE et al. [52], LEE et al. [53] and LEE et al. [54] present a process based on thicker layers. At the same time, a cut deviating from the vertical is made possible, so that the staircase effect can be reduced.

3.3. *Processes for Other Materials*

In addition to the methods already presented, there are adapted or proprietary processes for many other materials. Binder jetting is also available for sand and other materials as base material. A special application for the sand-based process is the foundry industry, where binder jetting is used to produce cores for moulds quickly and cheaply without an expensive and time-consuming production of a mould for a core shooter [28,30].

JUNK AND CÔTÉ [55,56] also found in a comparative study that the energy balance of binder jetting is significantly better than that of fused filament fabrication. It was found that the energy consumption for building a test prototype in the binder jetting process is significantly lower. The most important factor influencing energy consumption was the construction time.

The fused filament fabrication has been further developed too. There are many versions for a wide variety of materials. LIM et al. [57] present a version of fused layer modelling for the production of large curved concrete parts. BELLINI [58], on the other hand, is developing a process for the extrusion of ceramic components. AN et al. [59] show in an overview of the current state of research that the fused filament fabrication is also interesting for the production of organic components. Current research ranges from the production of replacements for missing skin areas to the extrusion of tissue for entire organs. Medical technology also deals with additive manufacturing. The idea is usually the possibility of individual adaptation of the parts to the patient's needs. For example, COMOTTI et al. [60] show an approach for the production of a prosthesis of the lower extremities. However, an individually adapted shape is created in a multi-material approach, which can be produced in one production step by additive manufacturing.

The laminated layer manufacturing can use paper as a raw material. Thereby, the part is built from individual layers of paper, which are glued together and cut out [28,30].

Summarising the additive manufacturing processes for other materials are mostly variants of processes originally using metals or plastics.

3.4. *Process Discussion*

Table 2 provides an overview of the essential process parameters of the additive manufacturing processes presented, so that the ideal options for the integrated process can be discussed further.

Beside the technical aspects in combining both technologies there are the production costs of the process. On one hand, the plant costs and, on the other hand, the production costs have to be mentioned. With regard to the production costs of parts manufactured by the enhanced vacuum-assisted multipoint moulding with additive attachments process, the largest part is related to the manufacturing costs of the additive manufactured attachments. Therefore, the comparison of the production costs with the different additive manufacturing processes would be a very interesting topic. There is a lot of literature on this subject, for example, COSTABILE et al. [61], or DOUGLAS [62], offer an overview on calculating additive manufacturing costs. As it can be seen there, the calculation of the real costs is very complex and provides very different values depending on the specific machine manufacturer and material supplier. Therefore, this factor is excluded from the further research and should possibly be examined again in the future.

The processes for the additive production of metal components rely on metal powder. Powder residues that get into the vacuum-assisted multipoint mould can lead to the failure of the system. This would require a complex sealing against powder dust. On the other hand, the metal parts provide a good temperature stability and high temperature curing carbon fibre-reinforced plastics systems can be used. The melting temperatures of the metals are well above the decomposition temperatures of the silicone mats currently used as interpolation layers. Therefore, the application of the attachments to the interpolation layer would lead to the destruction of the interpolation layer. In contrast, using the binder jetting process resolves the temperature problem in the first step. In a second step, the green parts have to be debindered and sintered, which leads to the same temperature problem or to the removal from the interpolation layer with the need of repositioning after postprocessing. Therefore, the additive manufacturing processes using metals or alloys are not suitable for a combined integrated process.

Table 2. Main characteristics of additive manufacturing processes in respect of the combination with vacuum assisted multipoint moulding.

Process Name	Material	Form of Base Material	Field of Process Temperatures	Advantages	Disadvantages
Laser Powder Bed Fusion (LPBF)	metals, alloys	powder bed	material dependent (melting spot: 600–3500 °C)	temperature stability of parts, precision, part strength, shape options	powder bed, high fusing temperatures, residual material
Directed Energy Deposition (DED)	metals, alloys	powder jet	material dependent (melting spot: 600–3500 °C)	temperature stability of parts, part strength	powder, high fusing temperatures,
Laminated Object Modelling (LOM)	metals, alloys, plastics, paper	solid plates, film reels	depending on material (room temperature—1500 °C)	depending on material, many materials available, process at room temperature possible	staircase effect, residual material, cutting and joining of material
Binder Jetting (3DP)	metals, alloys, ceramics, sand	powder bed	room temperature	many materials available, part strength, process time, shape options	possibly postprocessing necessary, powder bed, residual material
Selective Laser Sintering (SLS)	plastics	powder bed	material dependent (building chamber: 100–150 °C sintering spot: 100–350 °C)	precision, shape options	powder bed, high fusing temperatures, residual material, heated chamber
Fused Layer Modelling (FLM) [1]	plastics, concrete, bio materials	filament, pellets, gel-like liquids	material dependent (room temperature—250 °C)	no residual material, comparatively simple, only nozzle heated, many materials	temperature stability of parts, part strength, shape options
Stereolithography (SLA)	liquid, light-sensitive resins	resin bath	25–30 °C, possibly cooling necessary	precision, process time	resin bath, temperature stability of parts, part strength, shape options, postprocessing needed

[1] More commonly known is Fused Filament Fabrication (FFF), as a special case of the process group for the use of filaments as raw material.

Accordingly, to the metal processes, powder bed processes are only insufficiently suitable for enhanced vacuum-assisted multipoint moulding with additive attachments integrated in one plant, even when using plastics. As the process temperatures are reduced and may be suitable with the interpolation layer the big advance of the high temperature stability is also no longer existent. The situation is similar with stereolithographic processes that rely on a resin bath, which can only be realised directly on the interpolation layer with great effort. In contrast, the fused filament fabrication has great potential for enhanced vacuum assisted multipoint moulding with additive attachments, since the material is only placed at the required points during production. The solid raw material can be fed from a coil, so that no special precautions are necessary on the vacuum assisted multipoint mould. Summarising in the case of plastic processes the powder bed processes and the stereolithographic processes only have little advances in regard to the integrated enhanced vacuum assisted multipoint moulding with additive attachments process. The big disadvantage is the high effort in dealing with the powder and resin residuals.

When it comes to other materials the production of sand attachments directly on the vacuum assisted multipoint mould leads to the same problem as with all powder bed processes, although sand models would ensure good temperature stability. The extrusion of concrete already shows clear advantages here since no excess material has to be removed yet the penetration of concrete into the vacuum assisted multipoint mould carries risks. Furthermore, the material cannot be stored ready for processing, but would have either to be mixed in the process or produced in advance of production. Subsequently, the components require a long setting and curing time until the actual component can be manufactured. The high temperature stability would be an advantage too. Paper models would ensure relatively easy processability, but the model must be impregnated before the infiltration of the carbon fibre part starts. Otherwise, the paper absorbs the resin of the component to be infiltrated with and adheres to them.

Summarising, there are different possible additive manufacturing methods available for the integrated process of enhanced vacuum assisted multipoint moulding with additive attachments. The fused filament fabrication is clearly the easiest way to implement the process, with just one disadvantage which is the relatively low temperature stability of the attachments. Therefore, only resin systems curing at room temperature can be used for the carbon fibre reinforced plastic parts. Hence, this paper will focus on the combination of vacuum assisted multipoint moulding with attachments produced by fused filament fabrication.

Therefore, the next chapter will focus on the different possibilities and difficulties of integrating fused filament fabrication to the vacuum assisted multipoint mould.

4. Discussion of the Process Combination in Enhanced Vacuum Assisted Multipoint Moulding with Additive Attachments

By default, the fused filament fabrication process is operated with low melting point plastics and therefore has the disadvantage that only material with low curing or forming temperatures can be used for part production. In addition, in most cases a glass plate is used as a construction platform for the fused filament fabrication, which inherits a number of differing properties in comparison to the interpolation layer made of silicone. Moreover, the building platform is usually flat. This means that the curved building ground on the vacuum assisted multipoint mould also represents a deviation from the standard process.

According to Kleespies III and Crawford [63] the discrete pins of the vacuum assisted multipoint mould cause unevenness in the part despite the interpolation layer (see Figure 4). The degree of unevenness the so-called dimpling essentially depends on the mechanical properties and the thickness of the interpolation layer. However, the use of a thicker interpolation layer results in a significant decrease of the smallest producible structure. Hence, an appropriate middle course must be chosen here. While Kleespies III and Crawford [63] detect the occurrence of dimpling in the forming of plastic sheets, Păunoiu et al. [64] show that this effect also occurs during the forming of sheet metal. Similar influencing parameters are determined in each case. According to Lušić et al. [65]

the compensation of this phenomenon would either be to make the system significantly more precise and rigid, which would cause high costs. Hence, LUŠIĆ et al. [65] develop a readjustment of the pins based on a 3D measurement of the surface. Therefore, the pins are initially adjusted followed by a three-dimensional scan of the actual shape of the interpolation layer. This actual shape is matched with the CAD model of the part to be produced with a best fit method. Based on this match, the deviations of the individual pins are determined and in the next step the VAMM is adjusted accordingly, thus the form deviations of the VAMM can be reduced.

Another problem of enhanced vacuum assisted multipoint moulding with additive attachments could arise from the layered manufacturing of the additively produced attachments. KULKARNI AND DUTTA [66] clearly show that noticeable surface defects can occur depending on the layer thickness and the construction angle of the component. Since these surface defects resemble a staircase, the effect is also called the staircase effect (see Figure 8). KULKARNI AND DUTTA [66] develop an adaptive cutting technique to reduce this effect, which adapts the layer height to the shape of the component and thus produces significantly more precise surface contours. To further improve the prediction of the staircase effect, VAHABLI AND RAHMATI [67] develop a method based on a neural network and thus achieve a significantly more accurate prediction of the expected surface roughness. KUO et al. [68], on the other hand, show an appropriate post-treatment option by filling the steps with epoxy resin. In addition to a significant improvement in surface accuracy, a massive improvement in the mechanical properties of the component can also be achieved.

Overall, the combination of the two processes in enhanced vacuum assisted multipoint moulding with additive attachments is countered on the one hand by the problems of the shape deviation of the flexible form. On the other hand, the defects of the additively produced attachments themselves could impair due to the staircase effect. Therefore, the next step is to examine whether solutions have already been found for these challenges and whether these can be transferred to enhanced vacuum assisted multipoint moulding with additive attachments.

4.1. Additive Manufacturing on Silicone Made Building Platform

The aim of current research is to develop enhanced vacuum-assisted multipoint moulding with additive attachments a continuous process for manufacturing with a vacuum assisted multipoint mould. As already mentioned, it is necessary to place additional additively manufactured attachments on the interpolation layer at certain points in order to be able to map a larger part spectrum. Moreover, it should be possible to adjust the machine without any further intervention by an employee. Therefore, the system must be able to produce the attachments directly in one plant. As the vacuum-assisted multipoint moulding for carbon fibre-reinforced plastics uses a silicone interpolation layer [23], the attachments must be manufactured on a silicone building platform.

In the literature, there are already some processes outlined which produce directly on existing components and thus deviate from the usual flat building platforms. Among the procedures of laser-sintering the method of KESHAV et al. [31,32] should be mentioned. They are developing a metal-based process that uses an inert gas jet to bring metal powder to the point of material application. The powder is melted at its destination by a laser beam and thus bonded to the underlying layer. They are reducing the laser power to minimise the temperature load on the substrate. Nevertheless, the images show a clear heat influence on the base material. Therefore, the process is ruled out for an application on silicone.

CHOI et al. [69] present a process resulting from the adaption of a standard fused filament fabrication machine. Due to the conversions made to the machine used by them, it is possible to manufacture on already existing components and to consider uneven subsoil structures. The results show that production on existing components is possible, even if these components do not have a flat surface. However, the original components also consisted of an acrylonitrile butadiene styrene (ABS) or Acrylonitrile butadiene styrene/polycarbonate (PC) mixture, which shows a certain similarity to the acrylonitrile butadiene styrene used for fused filament fabrication. For these material combinations, joining forces in the area of an industrial adhesive bond could be demonstrated. However, the shown process has clear disadvantages in the area of accuracies, which decrease significantly compared to production on a commercial fused filament fabrication plant. LI et al. [38] also show in their work on the concept study for direct printing for wound care that production on curved surfaces is possible using a robot arm. A similar concern is pursued by SUPHAMA et al. [70] with their approach to the repair of components and the associated direct production on curved components. However, they use a delta printer. In addition, the method is supplemented by real-time image evaluation for control with respect to the subsoil.

A possible approach for problems with the adhesion of the actual component to the surface of the additive attachments could be the method of KÖPPLMAYR et al. [71]. A nanostructure is applied to components produced by fused filament fabrication using a stereolithographic process. This method offers the opportunity to add different nanostructures to the part. The test results show high accuracy. This could make it possible to prevent undesirable adhesion by means of such a nanostructure. On the other hand, to use this process in terms of controlling the adhesion of the part on the interpolation layer it would require removing the part from the interpolation layer or building it in a separate machine and add the nanostructure in a separate process. This leads to an extra positioning process of the additive manufactured attachment which is challenging on a freeform surface and therefore not suitable for a fully integrated process.

GRIMMELSMANN et al. [72], on the other hand, investigate the factors influencing adhesion in additively manufactured composite materials made of textile fibres and plastics. The greatest influence can be seen in the layer thickness since increasing it leads to an incomplete coating of the fibres with the plastic. Moreover, the material used also has a decisive influence on the production result due to its properties such as viscosity during extrusion.

KUO et al. [73] develop a flexible construction platform made of silicone to facilitate removal of components and reduce the adhesion compared to conventional construction platforms. They mainly examine the manufacturability on the silicone base. KUO et al. [73] show that production on the pure building platform made of silicone cannot be repeated reliably. Therefore, various changes are made to the silicone mat. On the one hand, this leads to an increase in surface roughness due to the use of different abrasive papers. However, this also does not lead to process-safe manufacturability. The same result is achieved by flame treatment of the surface. With the additional use of transparency film, they achieve the desired repeatability. The influence of the build plate temperature is not examined, which is a field of further investigations. In NAZAN et al. [74], the influences of an improved connection of the component to the building platform by means of epoxy resin are also examined on the basis of the resulting distortion. It is determined that the different materials have different warpage tendencies, but PLA has the smallest deviations with an unheated construction platform.

4.2. Additive Manufacturing on Curved Surfaces

As already described in the previous section, for direct production of the additive attachments on the interpolation layer of the vacuum-assisted multipoint moulding, the additive manufacturing must take place on a curved base. In the first step, the CAD data of the part must be divided into the individual layers for production using the layer construction method. There are two main methods for layering the part. Therefore, the next section examines the advantages and disadvantages offered by the various options.

4.2.1. Flat Slicing Methods

Currently, most slicing algorithms divide the component in plane layers of the same height. These layers are oriented parallel to the construction platform [28]. Therefore, the positioning of the component in the building space is an important process parameter regarding to the surface quality of the finished part, as all edges of the part that are not oriented parallel or perpendicular to the building platform, will show a more or less pronounced staircase effect [30]. ARMILLOTTA et al. [75], therefore, develop an improved calculation model to predict the surface quality more precise, depending on the position of the component in the building space. This model can be used to reduce the staircase effect and improve the surface quality. KULKARNI AND DUTTA [66] develop an improved slicing algorithm using an adaptive layer thickness. The ideal layer thickness is selected based on the current outer contour of the component. On the one hand, this makes a significant improve of the surface quality possible and at the same time allows a significant increase of the construction speed, compared to a uniform reduced layer thickness required to achieve the same surface quality. A similar approach is chosen by TATA et al. [76] but allows the user to set limits so that he can determine the required layer thickness himself. ESPALIN et al. [77] also use an adaptive slicing process, but at the same time extend it by the additional possibility of varying the width of the extrusion strand, as shown in Figure 14. Whereas in the standard process, all extrusion strands have the same width and height (see Figure 14 top). The concept proposed in ESPALIN et al. [77] has the opportunity to use different layer heights and extrusion strand widths in one part. As shown in the bottom part of Figure 14, it is possible to produce finer walls of the part in combination with relatively rough extrusion strands inside the part. This increases the surface accuracy according to ESPALIN et al. [77] by 38–55% and simultaneously reduces production times by 53%.

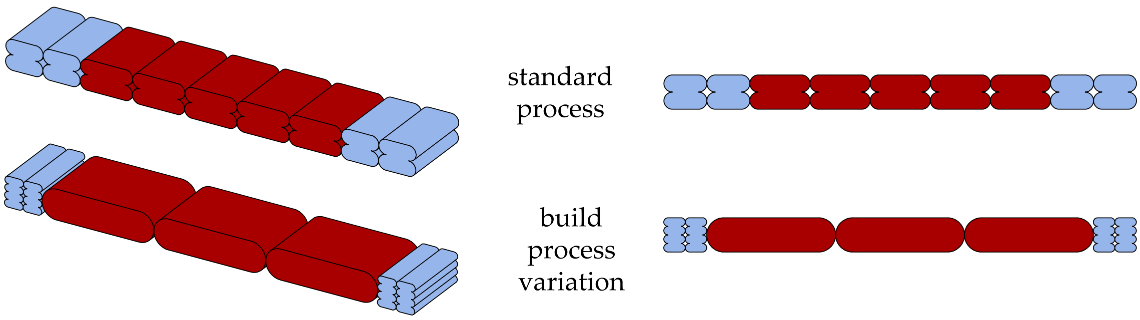


Figure 14. Layer configuration in standard fused filament fabrication and the process variation approach (based on the work in [77]).

HOPE et al. [51], HOPE et al. [52], HOPE et al. [78], and HOPE et al. [79], on the other hand, develop a system called "TruSurf". "TruSurf" in the first step cuts layer edges at an angle according to the object contour instead of straight cuts (see Figure 15). In comparison of the standard slicing (see Figure 15, left) and the "TruSurf" slicing (see Figure 15, right), a significant increase in accuracy can be achieved. Moreover, this allows significantly greater layer thicknesses and thus shorter construction times. In addition, they extend the process that not only straight, but also curved cuts are possible and thus the contour accuracy is further increased. The variable curvature of the knife proves to be problematic. The method shows significant improvements in surface accuracy but has been developed for the laminated layer manufacturing and not yet been applied to extrusion processes. NAGESHWAR et al. [80] allow the theoretical proof of these advantages. PATIL et al. [81,82] show another calculation method of the reduced form error for sloping boundaries compared to the standard way. On the other hand, KUMAR AND CHOUDHURY [83] show that despite these extensions, more layers are required to achieve the surface quality than the previous methods indicate.

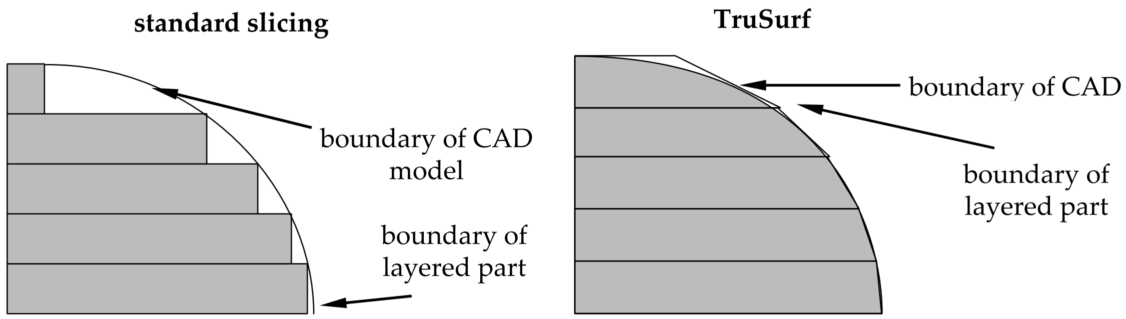


Figure 15. Comparison of the staircase effect between standard slicing and the TruSurf algorithm (based on the work in [52]).

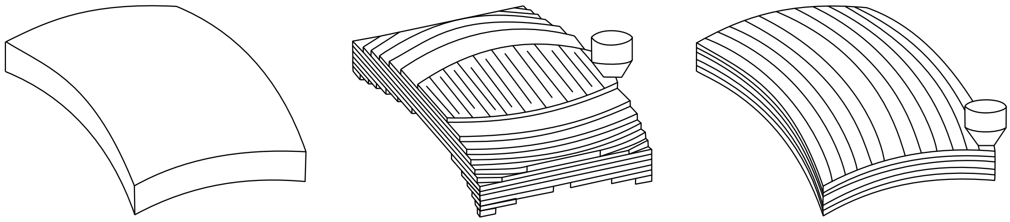
BOYARD et al. [84] show another problem: the support structures required for overhangs. Support structures lead to a higher material requirement and have to be removed after production. They develop a method for creating these support structures directly in the CAD tool. This generates a continuous process that reduces the necessary support structures. WU et al. [85,86] choose another way and mount the building platform on a 6-axis robot underneath a fixed extruder. This design makes it possible to disassemble the component into several subassemblies. The extrusion direction of these subassemblies can be chosen in a way that no support structures are required. The flat layers are always extruded in the direction of the gravitational force, but the construction platform is guided at different angles so that the application can also take place at an angle to the construction platform. In contrast, there are several support structures required using the standard process.

For enhanced vacuum-assisted multipoint moulding with additive attachments, the building platform is a curved platform. Using flat layers perpendicular to the direction of gravity may lead to a lower adhesion between the interpolation layer and the attachment. This could be due to the small contact areas only at the layer edges, because of the staircase effect. This point would have to be clarified in further investigations. If a building direction along the surface normal to the building platform is selected, support structures become necessary after a certain gradient.

The combination of the vacuum assisted multipoint mould and a 6-axis robot offers the flexibility to use flat layers on the one hand and also curved layers. Therefore, the full flexibility of both systems can be used as the robot arm can follow the build plate as it is adjusted by the vacuum-assisted multipoint mould, making no restrictions to the geometry adjusted by the mould, whereas a portal system needs the space for the extruder, the extruder can be tilted with a 6-axis robot to reduce the geometrical problems between the building platform and extruder. Furthermore, curved layers can also be used for the reduction of the staircase effect with curved top layers.

4.2.2. Curved Slicing Methods

In addition to the today most commonly used methods using flat slices, the algorithms for curved layers are developed and tested in [87–92]. The method investigated there is called curved layer fused deposition modelling (CLFDM), where flat layers are replaced by curved layers that are adapted to the component contour. As shown in Figure 16, the curved model (a) is classically sliced in flat layers (b) resulting in a visible staircase effect. In order to take advantage of these curved layers it is necessary for the components to be manufactured along curved extrusion paths. In this case, a significant improvement in surface quality can be achieved, as illustrated in Figure 16c. Moreover, the components, manufactured by curved layer fused deposition modelling, show increased strength. If the number of layers can be additionally reduced due to the curved production layer, the building speed increases compared to the classic flat layer variant. HUANG AND SINGAMNENI [88] examine the influence of the building direction on the mechanical properties and find that the components where the extrusion strands oriented in the load direction can sustain approximately 500% of the load compared to strands lying transversely to them. HUANG AND SINGAMNENI [89] extend the process by combining the classic flat layer structure with curved layer fused deposition modelling for the surface strands to achieve a further advantage in construction speed. Such a combined procedure is also examined by ALLEN AND TRASK [93]. They show that the combination of the two layering techniques lead to an improvement in surface quality and at the same time also improve the mechanical properties, although a load-compatible extrusion path is only present in the outer layers. DIEGEL et al. [87], on the other hand, show another application for curved layer fused deposition modelling in electrical engineering. Here, the curved layer fused deposition modelling makes it possible to integrate conductor tracks directly into curved components and thus to create parts without circuit boards and connecting wires.



(**a**) curved model (**b**) flat layers (**c**) curved layers

Figure 16. Comparison of flat and curved layer manufacturing: (**a**) curved part to be manufactured (**b**) part sliced with classical flat layers (**c**) part sliced with curved layers (based on the work in [92]).

ALSHARHAN et al. [94] use a similar process to go further and produce the entire component from only one continuous extrusion strand. In the subsequent investigation of the mechanical characteristics, a clear improvement compared to processes using flat slices can be attributed to a better load distribution in the part. On the downside, the fracture behaviour changes from ductile to brittle fracture without warning of failure. Such an improvement of the mechanical characteristics is also demonstrated by LIM et al. [95] for the "Concrete Printing" process [57] if curved layer fused deposition modelling is used and the extrusion paths are generated according to the load paths in concrete parts.

Compared to the methods with flat layers the calculation of the extrusion paths for the curved layer fused deposition modelling presents a greater challenge, as the ideal curvature of the slices for the component surface must be determined. In addition to the algorithms already mentioned, CHAKRABORTY et al. [96], JIN et al. [97] and LLEWELLYN-JONES et al. [98] have each conducted their own investigations on the ideal layer generation and present corresponding methods and algorithms. TAM AND MUELLER [99] go further and reduce the component to a skeletal model with material only in the main load directions. Therefore, a significant material saving can be achieved compared to a full model. In terms of using this method for moulding parts, it would be necessary to adapt the process for getting a closed surface at this side of the part where the moulding should take place.

Another challenge is the production of components in three-dimensional paths. SEWELL et al. [100] are developing a process that uses the additional axes available in conventional CNC machining centres. There the construction platform itself performs a movement and at the same time, the print head is moved. This procedure can also eliminate the need for support structures. ALLEN AND TRASK [93] use a gantry machine, on the one hand, and delta kinematics on the other. The comparison of the two processes shows a simpler and faster production with the delta kinematics, due to the additional degrees of freedom. SONG et al. [101] confirm these findings and develop a kinematic similar to delta kinematic itself. Moreover, they extend it by a real-time image evaluation to compensate for positioning errors to achieve a higher building precision.

The use of industrial robots is also found in the curved layer fused deposition modelling. BROOKS et al. [102] use the robot arm to pick up a construction platform corresponding to the component contour and move it along the extrusion paths below the stationary extruder. The movement of the construction platform eliminates the need for support structures, as the material is always applied in the direction of gravity. TAM AND MUELLER [99] also use a mould for the component, but rely on a moving extruder. ZHANG et al. [103,104] and ZHANG et al. [105,106] also opted for an industrial robot and developed the software for the calculation of the extrusion paths as well as the control system. OXMAN et al. [107] further develop the process and make it possible to extrude freely into space without a form and without support structures by means of a robot arm. The extrusion without support structures is made possible by cooling the extrudate after it exits the nozzle.

A possible use of fused filament fabrication on freeform surfaces beyond the application scenario shown in this paper could also be the possibility of component repair described in BURANSKÝ et al. [108]. In addition to the completely new production of the component shown in BURANSKÝ et al. [108], a repair could be carried out at the defective location. This repair for example could be the recovery of a holder by directly printing the new on the defective part.

To sum up, the previously presented studies show that it is possible to use fused filament fabrication on curved building platforms. For the mentioned two different slicing methods, further research has to be made to determine if a flat or a curved slicing algorithm suite better for the process outlined in this paper. The general possibility of fused filament fabrication on building platforms made of silicone has already been proved by KUO et al. [73], although it is possible that more research has to be made in terms of adhesion on the building platform in a fully automated integrated process.

5. Summary and Conclusions

Overall, it could be shown that vacuum-assisted multipoint moulding adds flexibility in production of prototypes or small series, as there is no need for mould production. In addition, resources and costs can be saved in the production, as there are no low-use moulds to be recycled. At the same time, the structure of the production technology also has some disadvantages. The biggest disadvantage is the limited detail accuracy due to the necessary interpolation layer. This means that very small structures and larger structures with strong transitions cannot be produced.

The solution to this could be an integrated process called enhanced vacuum-assisted multipoint moulding with additive attachments that integrates the details that cannot be depicted in the vacuum assisted multipoint mould using corresponding attachments. These attachments are to be produced directly on the interpolation layer using additive manufacturing. It could be shown that with enhanced vacuum-assisted multipoint moulding with additive attachments a larger amount of part shapes can be depicted with this process. A number of challenges were identified in this paper. A large block of topics is the selection of the additive manufacturing process. In this study, it could be shown that the powder bed-based processes and the processes based on resin baths are not suitable for production directly on the vacuum-assisted multipoint mould. This is due to the raw materials, which could damage the existing system, as well as to the temperatures required for these processes, which can cause damage to the interpolation layer. Overall, it could be shown that the extrusion-based fused filament fabrication is most suitable for this application, although the plastics used in fused filament fabrication lead to restrictions for the component materials that can be processed.

Further challenges arise from the interpolation layer as a building platform. In contrast to the usual fused filament fabrication, which relies on a flat building platform made of glass, the interpolation layer can form a curved building platform. In addition, the interpolation layer is made of silicone. This raises the question of the adhesion of the attachments on the interpolation layer. This study has shown that the challenges of a curved building platform have already been examined in literature. It could be shown that there are two possibilities for layer generation, on the one hand the classical process with flat layers, and, on the other hand, the extrusion along curved layers. In principle, both methods are also suitable for use on curved building platforms. However, the comparisons carried out in the literature clearly show that curved layers along the outer contours of the component bring clear advantages in terms of surface quality and the tolerable load. The first tests carried out in the literature for additive production on a silicone platform showed that this is a challenge. Although a solution could be presented there using an additional intermediate layer, the actual implementation must still be verified for the application outlined in this paper.

The following investigations have to answer the question of the ideal combination of process parameters of the additive manufacturing process for production on the curved silicone platform. In this context, it should also be examined whether a corresponding intermediate layer can be dispensed by varying process parameters. In addition, the influence of the nozzle angle to the construction platform and on the component properties has to be explored. In this context, it must be clarified which design (portal or delta machine, robot arm, etc.) is ideal for the system. The achievable production accuracy of the additively manufactured attachments must also be clarified.

In the area of the overall enhanced vacuum-assisted multipoint moulding with additive attachments, this research has to be followed by investigations of the achievable component accuracy and the possible mapping of any inaccuracies in the finished component. Another important question is the limit of the hardening temperature for the component to be manufactured and the prevention of the attachments sticking to the finished component.

Another field of further investigation is the software integration between the two different processes, mentioning the fields of separating the geometry into the parts modelled by the vacuum assisted multipoint mould and the parts built with attachments. The second field is the conversion of the geometrical data to machine instructions of the both part systems.

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