# Design-Opportunities and Limitations on Additive Manufacturing Determined by a Suitable Test-Specimen

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Karlheinz P. J. Hoeren[1], Gerd Witt[1]

[1]University Duisburg-Essen, Department of Mechanical Engineering,
Chair of Manufacturing Technologies
{karlheinz.hoeren, gerd.witt}@uni-due.de

**Abstract.** The key-feature all additive manufacturing processes have in common is parts being built up in layers. Due to this tool-less build-up principle, the degree of freedom in design is huge compared to conventional manufacturing processes. For instance rear sections, inner cavities, conformal cooling-channels and lightweight-structures can be realized without a significant rise of manufacturing-costs. However there are some specific limitations coming along with the layer-wise build-up. Depending on layer-thickness and the orientation of a surface, the so-called stair-step effect occurs with different levels of intensity. Furthermore some additive manufacturing processes have to use support-structures. These structures are used to hold the part in place or to lead the pro-cess heat away from the melting-zone. In order to convey these limitations and to show how de-tailed and filigree parts can be generated, a test-specimen has been designed that suits processes with- and without support-structures.

The geometry of the specimen`s bottom side contains chamfers and notches, so the amount of necessary supports is kept as low as possible and the specimen can be separated from its build-platform without complications. Furthermore, the specimen is designed as a web of test-areas, connected by bars. This way the curling effect that often leads to aborts in additive manufacturing processes is prevented and thus cannot have an influence on the geometries tested on the speci-men. The presentation is about showing first test results of Laser Beam Melted, Laser Sintered and Fused Layer Modeled specimens that have been evaluated by sight test and measured by a coordinate measuring machine. In addition the content of the individual test-areas will be ex-plained.

**Keywords:** Additive Manufacturing, Laser Beam Melting, Fused Layer Modeling, Laser Sintering, test-specimen

## 1 INTRODUCTION

Additive manufacturing can be described as a direct, tool-less and layer-wise production of parts based on 3D product model data. This data can be based on Image-Generating Measuring Procedures like CT (computed tomography), MRI (magnetic resonance imaging) and 3D-Scanning, or, like in the majority of cases, a 3D-CAD construction. Due to the layer-wise and tool-less buildup-principle, additive manufac-

adfa, p. 1, 2011.

turing offers a huge amount of freedom for designers, compared to conventional manufacturing processes. For instance rear sections, light weight constructions or inner cavities can be built up without a significant rise of manufacturing costs. However, there are some specific limitations on the freedom of construction in additive manufacturing. These limitations can partly be attributed to the layer-wise principle of buildup, which all additive manufacturing technologies have in common, but also to the individual restrictions that come along with every single manufacturing technology. [1] [2] [3]

Following, after a short description of the additive manufacturing technologies Laser Beam Melting (LBM), Laser Sintering (LS) and Fused Layer Mod-eling (FLM), the geometry of a test-specimen that has been designed by the chair of manufacturing technologies of the University Duisburg-Essen will be introduced. Based on this geometry, the design-opportunities and limitations of the described tech-nologies will be evaluated.

### 1.1 LASER BEAM MELTING (LBM)

Besides Electron Beam Melting, LBM is the only way of directly producing metal parts in a powder-based additive manufacturing process. [4] [5] In course of the LBM process, parts are built up by repeatedly lowering the build-platform, recoating the build-area with fresh powder from the powder-supply and selective melting of the metal powder by means of a Laser-Beam. For the schematic structure of LBM-Machine see Figure 1. [6]

Melting metal powder, a lot of energy is needed. Therefore a huge amount of thermal energy is led into the build-area. In order to lead this process-warmth away from the build-plane, and in order to keep the parts in place, supports (or support-structures) are needed in Laser Beam Melting. Sup-port-structures are to be placed underneath every surface that is inclined by less than about 45° to-wards the build-platform. They are build up simulta-neously with the part and consist of the same mate-rial. Thus parts have to be mechanically separated from their supports after the LBM-process, for ex-ample by sawing, milling or snapping off. As a re-sult, the surface-quality in supported areas is significantly reduced and LBM-parts are often reworked with processes like abrasive blasting, barrel finishing, or electrolytic polishing. [7] [8]

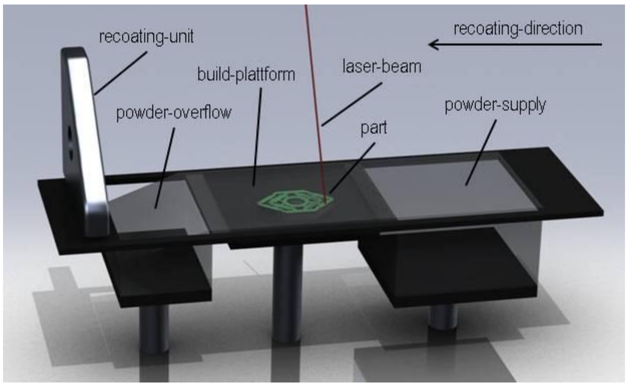


**Fig. 1.** - schematic illustration of the LBM process

## 1.2 LASER SINTERING (LS)

In Laser Sintering, unlike LBM, plastic powder is used as basic material. Regarding the procedure, LBM and LS are very similar (see Figure 2). One of the main differences is that in LS no support-structures are necessary. This is because in LS the powder bed is heated to a temperature just below the melting point of the powder, so the energy that has to be introduced by the laser for melting the powder is very low. Therefore only little additional heat has to be led away from the build-area. On the one hand, this amount of energy can be compen-sated by the powder, on the other hand, due to the smaller temperature gradient, the curl-effect is less pronounced to occur. The curl-effect is the effect that causes a part to bend inside the powder bed and become deformed or even collide with the re-coating-unit. Latter would lead to a process break down. [9] [10] [4]

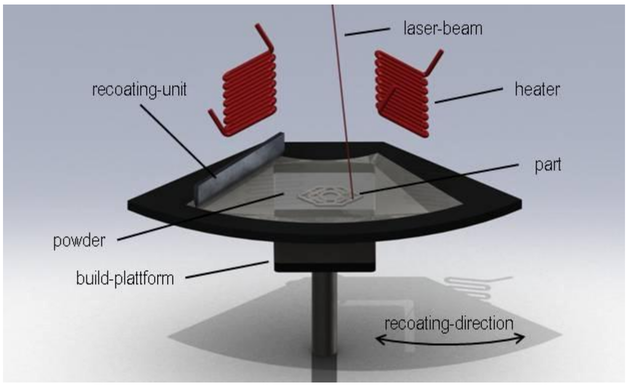


**Fig. 2.** - schematic illustration of the LS process

### 1.3 FUSED LAYER MODELING (FLM)

In FLM, slices of the part are built up by extruding an ABSplus wire through the heated nozzles of a movable printing head (see Figure 3). The printing head is moved in the x-, y-plane of the FLM ma-chine to build up a layer. When a layer is finished, the build-platform is lowered by a layer-thickness and the next layer is built up. [4] [1]

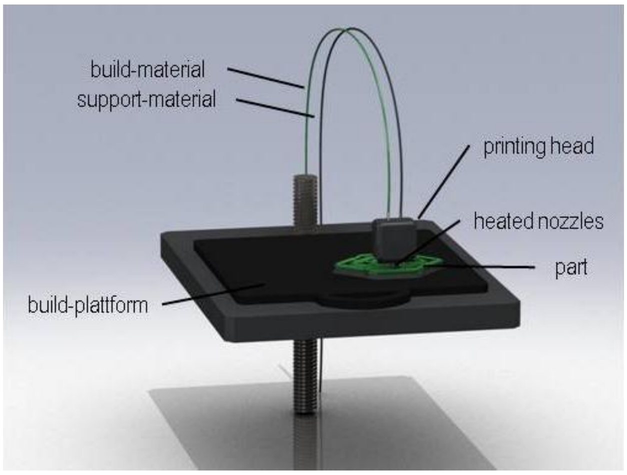


**Fig. 3.** - schematic illustration of the FLM process

Since FLM is not a powder-based procedure, like LS, or LBM, there is no powder to prevent the heat-ed ABSplus from bending up or down inside the build-chamber. Therefore in FLM, supports are needed. In contrast to supports used in LBM, these supports only have the function, to hold the part in place. One special thing about supports in FLM is that a second, acid material is extruded through a second nozzle in order to build up supports. This way, when the FLM process is finished, the part can be put into an alkaline solution and the supports are dissolved. As a consequence, supports are not the main reason for the low finish-quality of parts pro-duced by FLM. However, the high layer-thickness, which is one of the factors that make FLM cheap, compared to other additive manufacturing technolo-gies, impacts the finish-quality in a negative way.

## 2 DESIGN OF THE TEST-SPECIMEN

The chair of manufacturing technologies of the Uni-versity Duisburg-Essen has de-veloped a test-specimen to convey the limits of additive manufac-turing technologies. This specimen is designed to illustrate the smallest buildable wall-thicknesses, gap-widths and cylinder and bore diameters de-pending on their orientation inside the build-chamber. Thus diameters/thicknesses between 0.1 and 1 mm are built up at intervals of 0.1 mm and diameters/thicknesses between 1 and 2 mm are built up at intervals of 0.25 mm (see Figure 4).

In addition, the test specimen contains walls with different angles towards the build-platform (x-, y-plane), in order to show the change in surface-quality of down-skin surfaces with increas-ing/decreasing angles. Furthermore a bell-shaped geometry is built up in order to give a visualisation of the so called stair-effect. This effect characterises the lack of reproduction-accuracy due to the fact that parts are built up layer-wise depending on the orientation of a surface towards the x-, y-plane.

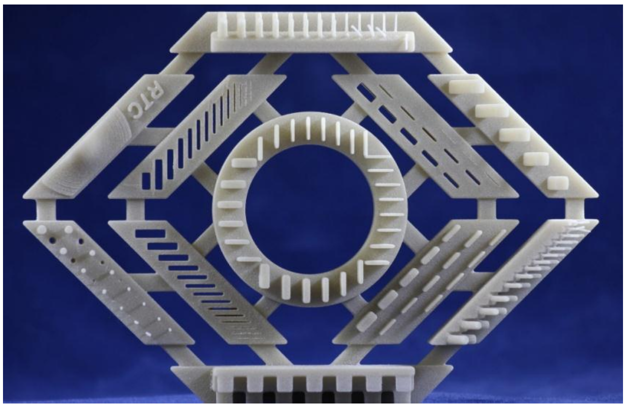

**Fig. 4.** - test-specimen made of glassfilled polyamide 12 by LS

For a further evaluation of the test-specimen, be-sides visual inspection, the distances between indi-vidual test-features are constructed large enough to enable the use of a coordinate measuring machine. However, the chief difference concerning the design of the test specimen compared to other test-specimens of the chair of manufacturing technolo-gies [11] [12] is that this specimen is designed to suit the special requirements coming along with an additive manufacturing by technologies using sup-ports (especially LBM). Besides the features de-scribed earlier, these special requirements result in the following problems:

## 2.1 CURL-EFFECT

The curl-effect, which already was mentioned in the description of LBM, needs special focus. Since the production of large surfaces inside the x-y-plane is directly connected with a stronger occurrence of the curl-effect, this has to be avoided. Therefore the test-specimen is divided into eleven platforms, con-taining the individual test-features. The platforms are connected by small bridges, positioned in a z-level below the unpskin-surfaces of the platforms. This way, a large test-specimen can be produced without melting up large surfaces, especially in a z-level that may have an influence on the features to be evaluated.

## 2.2 SUPPORTS

As described before, in some additive manufactur-ing processes, supports have to be built up with the parts for several reasons. Since supports often have to be removed manually, the geometry of test-specimen should require few and little massive supports. This way production costs for support material and post-processing requirements can be kept at a low level.

In most cases the critical angle between build-platform and a surface to be built up is at about 45 degrees. Thus the downskin surface of each plat-form of the test specimen is equipped with a 60 degree groove. This way the amount of support that has to be placed under the platforms is significantly reduced without lowering process-stability (see Fig-ure 5).

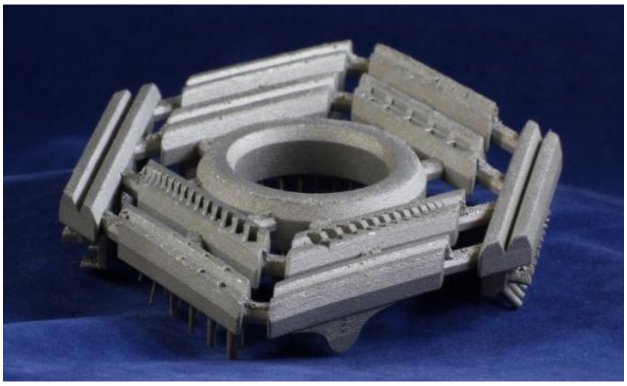

**Fig. 5.** - downskin-surface of the test-specimen produced by LBM after support-removal

Additionally there are two kinds of test-features on the test-specimen which require supports. Since walls and cylinders that are oriented parallel to the build platform cannot be built without supports, the platforms containing these features are placed at the outside of the test specimen. By this means, the features are accessible for manual post-processing and visual inspection.

## 2.3 RECOATING

In powder- or liquid-based additive manufacturing processes, different recoating-systems are used to supply the build-platform with fresh material. One thing, most recoating-systems have in common is some kind of blade that pushes the material from one side of the build-chamber to the other. Especially in LBM, the surfaces that just have been built up tend to have heightenings. In the majority of cases, these heightenings are the edges of the part, slightly bending up as a result of the melting-process. The combination of these circumstances can cause a scratching between the recoating-unit and the part to varying extends, depending on the build-material and the build-parameters used. In order to keep this phenomenon from affecting the features of the test-specimen, all platforms of the test specimen are oriented in an angle of 45 degrees towards the recoating-unit. This way, harsh contacts between recoating-unit the long edges of the platforms can be avoided.

However, there is another problem connected with the recoating-direction that may have an influence on the results, when small features are built up. As the test-specimen is designed to show the most filigree features that can be produced with each additive manufacturing process, the diameters and wall-thicknesses have to be decreased to the point, where they cannot be built up anymore. At this point, the features either are snapped by the recoat-ing-unit, or they cannot be built up as a connected object anymore. In both cases, fragments of the test-features are pushed across the powder-bed the recoating-unit. In order to prevent these fragments from having an influence on the build-process, by getting stuck between the recoating-unit and another area of the part or by snapping other test-features, the platforms and test-features are arranged in a suitable way. For instance, all diameters and wall-thicknesses decrease with the recoating-direction. Additionally, platforms with gaps are placed behind platforms with filigree features, so the space above them can be used as outlet zone.

# 3 PRODUCTION OF TEST-SPECIMENS WITH LBM, LS AND FLM

Following, the results of visual inspections and measurements on test-specimen, build of Hastel-loy X (LBM with an EOSINT M270 Laser Beam Melting System), glass-filled polyamide (LS with a FORMIGA P 100 Laser Sintering System) and ABSplus (FLM with a Stratasys Dimension 1200es Fused Layer Modeling System) are discussed. For inspections and measurements, the test-specimen made of Hastelloy X and glass-filled polyamide have been exempted from powder adhesions by blasting with glass-pearls (LS), respectively corundum and glass-pearls (LBM). On the test-specimen produced by FLM, only supports have been removed by putting it into an alkaline bath.

## 3.1 WALL-THICKNESSES

A look at the minimum producible wall-thicknesses conveys that in LBM the most filigree walls can be produced. Additionally walls in LBM show the slight-est deviation from the specified dimensions (see Figure 7). However, in LBM there is a considerable difference between walls oriented parallel the re-coating-unit and wall orientated orthogonal to the recoating-unit. The walls oriented parallel to the recoating-unit can only be built up down to a thick-ness of 0.7 mm. Thinner walls have been snapped by the recoating-unit (see Figure 6).

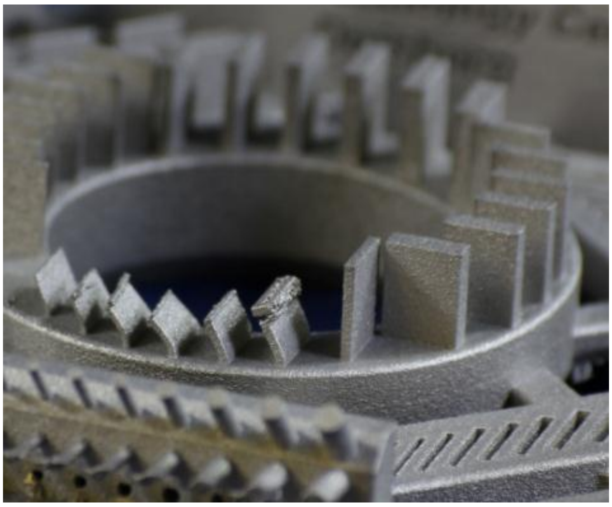

**Fig. 6.** - snapped walls, orientated parallel to the recoating-unit in LBM

Especially in FLM, but also in LS one can observe that from a certain threshold, in spite of decreasing nominal dimensions, the measured wall-thicknesses do not become any thinner. In FLM this can be ex-plained by the fact that an object that is built up at least consists of its contours. Taking into account the diameter of an ABSplus wire and the fact that it is squeezed onto the former layer, it is clear that the minimum wall-thickness is situated at about 1 mm. In LS, the explanation is very similar. However the restricting factor is not the thickness of a wire, but the focus diameter of the LS-System in combination with the typical powder-adhesions.

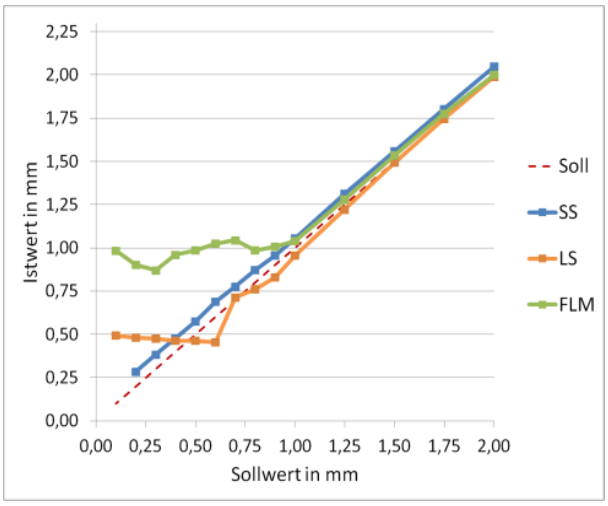


**Fig. 7.** - results of measuring minimal wall-thicknesses along the y-axis (parallel to recoating-unit in LBM)

The wall-thicknesses along the z-axis in powder-based manufacturing technologies (LBM and LS) are always slightly thicker than the nominal size (see Figure 8). This is to be explained by the fact, that melting the first layers of the walls, especially in LS, excess energy is led into the powder underneath the walls and melts additional powder particles. In LBM this effect can be observed less intense, since the manual removal of supports affects the results.

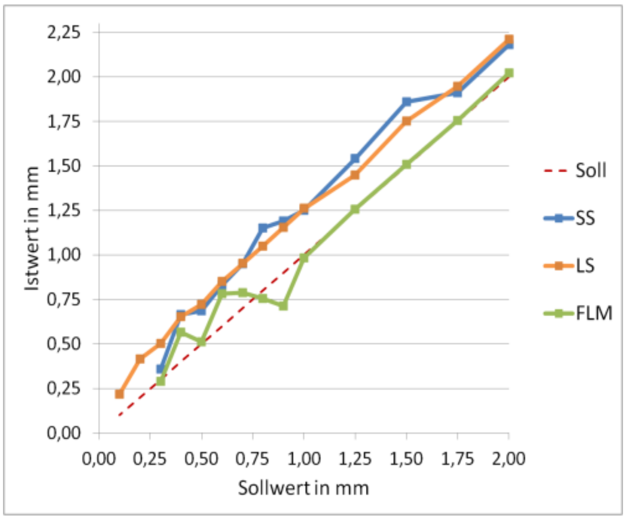


**Fig. 8.** - results of measuring minimal wall-thicknesses along the z-axis

In FLM, the course of measured wall-thicknesses is erratic within the range from 0.25 to 1.0 mm. This can be explained considering the layer-thickness in FLM. The layer-thickness in FLM is 0.254 mm. That way, a nominal thickness of 0.35 mm for example can either be represented by one, or two layers (0.254 mm or 0.508 mm). Since the resolution in FLM is very coarse, this effect can also be seen by a visual inspection of the walls (see Figure 9).

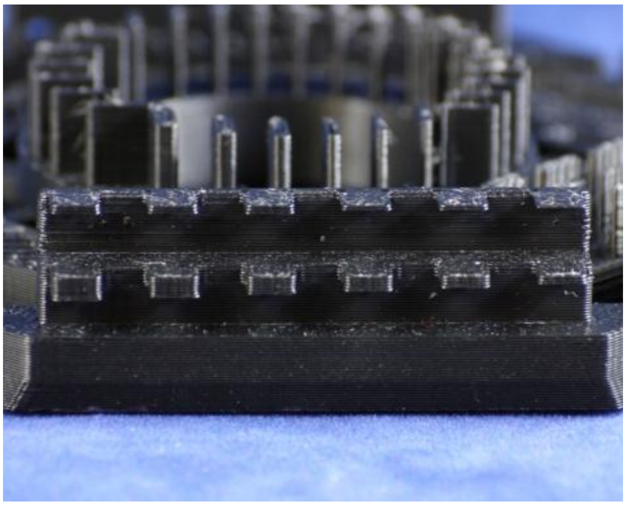

**Fig. 9.** - minimal wall-thicknesses along the z-axis in FLM

## 3.2 CYLINDERS

The test-specimen contains clinders with an angle of 0 degrees and cylinders with a polar angle of 45 and 90 degrees, each in negative x- and y- direction. The orientation along the x-axis has been chosen, since the process-stability in LBM is a lot higher, if the unsupported cylinders with a polar angle of 45 degrees dont grow against the re-coating-direction.

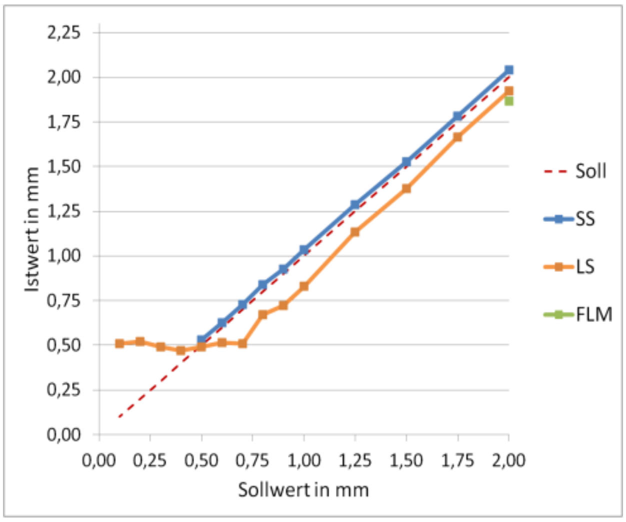


**Fig. 10.** - results of measuring minimal cylinder-diameters

Comparing the cylinders with a polar angle of 0 degrees, shows again, that in LBM the most filligree featuers can be built up with the best accuarcy (see Figure 10). However, there are breaks visible in the cylinders in a hight of about 5 mm at cylinders with a diameter of less than 0.9 mm (see Figure 11). These breaks are a result of the scratching between the cylinders and the recoater-blade. This time the blade did not snap the cylinders since the geometry is more flexible. Thus the cylinders were able to flip back into their former positions be built on.

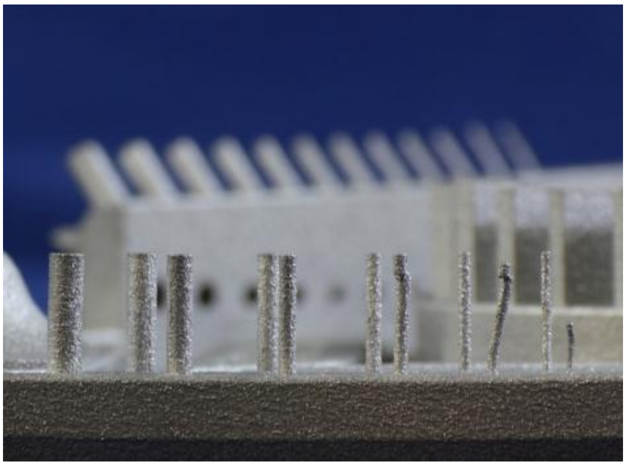

**Fig. 11.** - breaks in LBM-Cylinders

The results in LS are comparable tho those of the minimal wall-thicknesses along the x- and y- axis (see Figure 10). The smallest possible diameter in LS is 0.5 mm. In FLM, however, only cylinders with a diameter of 2 mm can be built up.

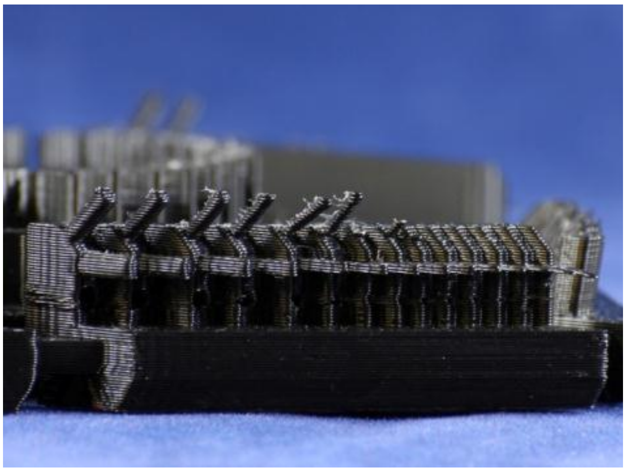

**Fig. 12.** - form deviation of FLM cylinders

The results concerning cylinders with a polar angle of 45 and 90 degrees in LBM and LS are correlating with the results of cylinders with a polar angle of 0 degees regarding their accuracy. In FLM it is striking that smaller diameters can be built with increasing polar angles (see Figure 12). At a polar angle of 90 degrees, even cylinders with 0.1 mm diameter can be built. However, with increasing polar angles the form deviation in FLM becomes more visible. Due to the coarse resolution in FLM, caused by thick layers and a thick ABSplus wire, the deviation in Form and diameter for small cylinders becomes so large that inspecting their diameter is not possible anymore from 0.9 mm downwards (see Figure 13).

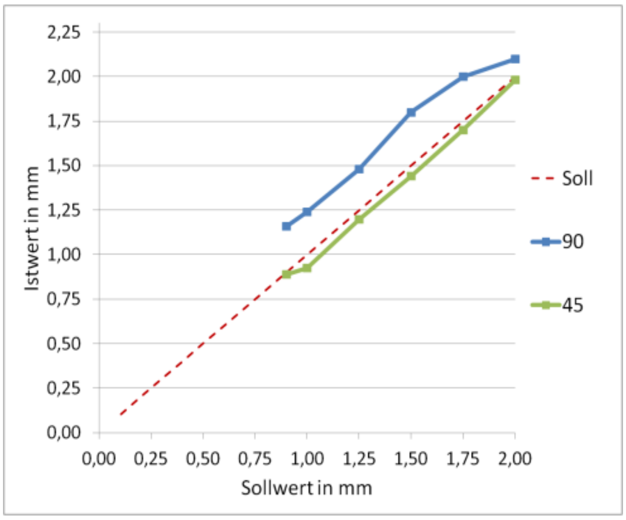


**Fig. 13.** results of measuring cylinders with a polar angle of 45 and 90 degrees manufactured by FLM

### 3.3 GAPS AND BORES

The evaluation of gaps and bores is reduced to a visual inspection. This is due to the fact that the accuracy of such filligreee bores cant be usefully inspected with a coordinate measuring machine, since the diameter of the measurement-end would be on the same scale as the diameter of the bores and the irregularities that are to be inspected. The results of the visual inspection are summarised in Table 1.

| | LBM | LS | FLM |
|---|---|---|---|
| bore along x-axis | 0.5 mm | 1.25 mm | 0.7 mm |
| bores along y-axis | 0.8 mm | 1.5 mm | 0.6 mm |
| bores along z-axis | 0.6 mm | 1.75 mm | 0.8 mm |
| gaps along x-axis | 0.4 mm | 0.5 mm | 0.3 mm |
| gaps alon y-axis | 0.4 mm | 0.4 mm | 0.2 mm |

**Table 1.** - smallest depictable bores and gaps determined by visual inspection

One striking concerning bores in LS is their quality, which is worse compared to the other mannufacturing technologies. This becomes clear either by inspecting the smallest depictable diameters, but also by taking a look at the huge form deviation of bores in LS (see Figure 14). The eplanation for both, form deviation and resolution is found in the way of energy contribution in LS. As described above, in LS, less energy is necessary to melt the powder, compared tho LBM. Thus the threshold between melting the powder and not melting the powder is much smaller. Consequently, if excess energy is led into the part, surrounding powder ist melted and form deviations will occur.

**Fig. 14.** - form deviation of bores along the y-axis in LS

### 3.4 ANGLES TOWARD BUILD-PLATFORM

The test-specimen contains five walls, inclined from 80 to 40 degrees towards the build-platform in steps of 10 degrees (see Figures 15-17). This walls serve as a visualisation of the decreasing surface quality with decreasing angles towards the build-platform. Again the walls are inclined to the negative x-direction in order to raise process stability and avoid process aborts. If possible, this walls should be built without support-structures, so deviations in form and surface quality can be displayed within the critical area.

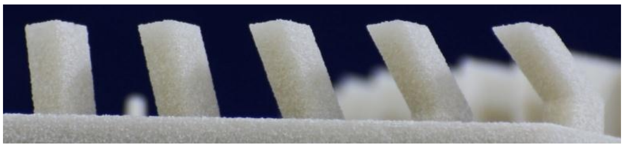

**Fig. 15.** - angles towards build-platform in LS

In LS, the surface quality appears hardly affected by different angles towards the build-platform (see Figure 15). Even with an angle of 40 degrees, the stair-effect (visibility of layers on stongly inclined walls) is not visible.

**Fig. 16.** - angles towards build-platform in FLM

Taking a look at the walls built by FLM, it becomes clear that the stair-effect in FLM is visible right from the beginning (see Figure 16). This is due to the coarse resolution of FLM. Additionally, the wall inclined by 40 degrees even has a worse surface quality then the other walls. In FLM, supports are created automaticly. Therefore users are not able to erase supports before starting a FLM process. The wall, inclined by 40 degrees, was built up with supports. Thus the lack of surface-quality results from the connection between supports and part.

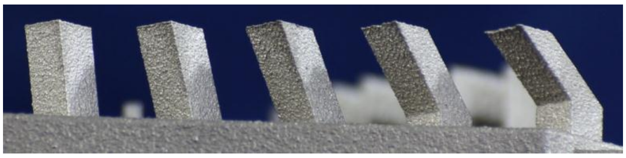

**Fig. 17.** - Anlges towards build-platform in LBM

The walls in LBM convey a strong influence of angles between parts and build-platform and the surface-quality of downskin surfaces (see Figure 17). A first discoloration of the surface can be seen on the wall inclined by 60 degrees. This discoloration is a result of process-warmth, not beeing able to leave the part due to the fact that these walls dont have support-structures. At an inclination of 50 degrees, a serious deterioration of the surface quality becomes visible. This deteroration becomes even stronger with an inclination by 40 degrees. Additionally, the edge of the wall inclined by 40 degrees appears frayed. The reason for this can be found in the fact that with decreasing angle towrad the build-platform and increasing jam of heat inside the part, the curl-effect becomes stronger. In this case, the recoater-unit starts scantching the curled edge. This is a first sign, that at this angle of inclination, process aborts may occur depending on the orientation of the part towards the recoating-unit.

### 3.5 STAIR-EFFECT

The bell-shaped feature on the test-specimen serves as a visualisation of the stair-effect. Comparing the built up test-specimens, a clear difference in surface quality can be recognised.

In LBM, steps are just slightly visible at an angle of 10 to 15 degrees towards the build-platform (see Figure 18). Due to the thin layer-thickness in LBM, the whole bell-profile apperas very fine and smooth. Taking a look at the LS-bell-profile, it becomes clear that the surfaces are a bit more rough than in LBM. The stair-effect is already visible at an angle of 20 degrees. In FLM, as mentioned above, single layers are always visible, due to the coarse resolution of the technology. In spite of this, the bell-profile conveys that, using the FLM-technology, angles of less then about 20 degrees inevitably lead to a loss of shape.

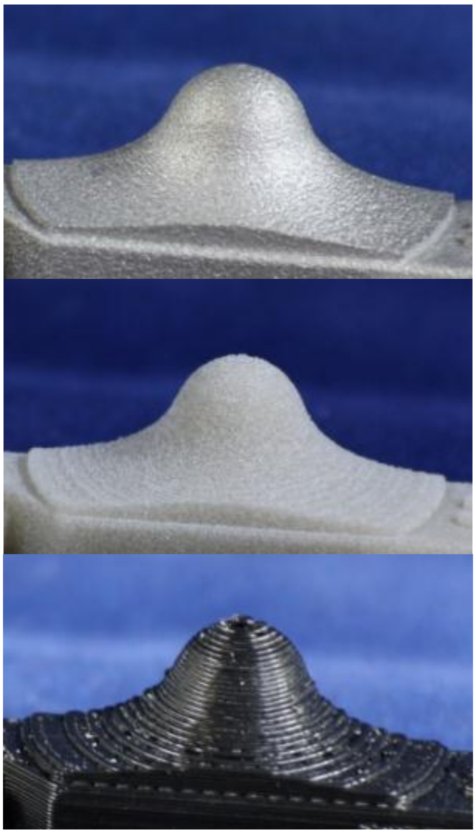

**Fig. 18.** - Comparison of bell-shaped features on the test-specimen built by LBM, LS and FLM

## 4 CONCLUSIONS

Comparing the different test-specimen, built by LBM, LS and FLM, the first thing to be recognised is that in LBM the most filigree structures can be produced with the best accuracy. However, it becomes clear that the LBM-process is much more complex than for example the FLM-process. Both, designers and operators have to be aware of the typical constrains that are connect with the process-specific characteristics of LBM. This becomes particularly obvious, considering the huge influence that part-orientation and supports have on process stability and part-quality.

As mentioned above, LS is very similar to LBM concerning the course of procedure. This similarity can also be seen, comparing the test-specimen. In LS, most features are just slightly less filigree than in LBM. Due to the fact that support-structures are not needed for LS, a lot of time and money can be saved in pre- and, as a consequence, post-processing. In addition, the process-handling is easier and process aborts are a lot less likely.

Taking a look at the FLM-process, it is obvious that this technology is way less complex and filigree than LBM and LS. Fine features often can`t be displayed and deviations in form and dimension often can be recognised. However, the FLM-process is very easy to be handled. Supports are constructed automatically and when the part is built up, they can be removed by an alkaline-bath. Additionally, no precautions have to be taken and no cleaning effort has to be done handling any powder. The FLM-technology is much cleaner than LBM and LS and therefore much more suitable for an office-surrounding. The last thing to be taken into account for this comparison are process-costs. The FLM-technology is a lot cheaper than LBM (which is the most expensive technology) and LS.

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