High Power Selective Laser Melting (HP SLM) – Upscaling the Productivity of Additive Metal Manufacturing towards Factor 10

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Abstract

World market competition boosts trends like mass customization and open innovation which result in a demand for highly individualized products at costs matching or beating those of mass production. One of the manufacturing technologies with greatest potential to meet those demands is Selective Laser Melting (SLM) due to its almost infinite freedom of design and the provision of series-identical mechanical properties without the need for part-specific tooling, downstream sintering processes, etc. However, the state-of-the-art productivity is not yet suited for series production. Hence, a new machine prototype including a kW laser and an optical multi-beam system is developed and set up. Experimental findings and first applications demonstrate the capability of the new system.

Introduction

The market competition originated from countries with low-cost work forces exerts pressure on companies world wide and leads to a focus on innovation. Besides this, the increasing competition is also compelling industries to improve the efficiency of production processes, e.g. increasing the automation level or improving process productivity.

Considering industrial production in high-wage countries today, these trends can be cut down on two dilemmas that are closely related to each other (see Figure 1). [1] The first dilemma refers to the "value-oriented vs. planning-oriented" production. The former approach focuses on value adding processes (without consideration of planning-, preparation-, handling- and transport processes) while the latter focuses on extensive planning in order to optimize value-adding (modeling, simulation, information gathering). The second dilemma is related to the "scale-scope" dimension. Either the production system is designed for high scale output without variances in the product design (critical masses, business and manufacturing process decomposition, mastered processes) or it is designed for individual products down to a production batch of a unique product (one-piece-flow, complex and highly integrated processes). The resolution of this production-related polylemma is the main target of the Cluster of Excellence "Integrative Production Technology for High Wage Countries" (see Figure 1).

Especially the scale-scope dilemma is boosted by global trends like mass customization and open innovation which result in a demand for highly individualized products at costs matching or beating those of mass production. One of the areas of greatest potential for the resolution of this dilemma are Additive Manufacturing (AM) technologies due to their almost infinite geometrical variability and freedom of design without the need for part-specific tooling. Selective Laser Melting (SLM) is one of the AM technologies for metallic parts that additionally provides series identical mechanical properties without the need of downstream sintering processes, etc. which predestines it for individualized manufacturing. However, the state-of-the-art process and cost efficiency is not yet suited for series production and thus have to be improved.

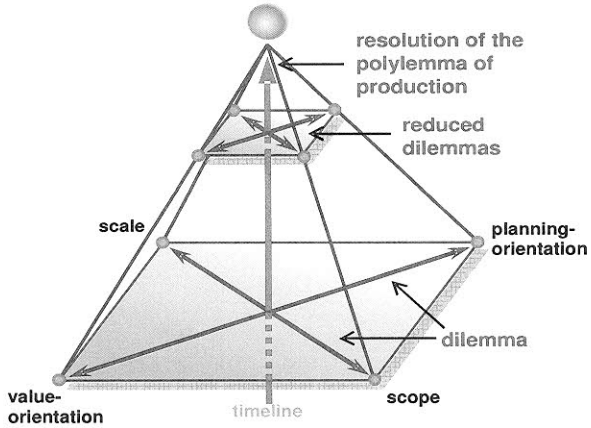

Figure 1: Polylemma of production

SLM Process

The ILT-developed SLM process is an Additive Manufacturing process that fabricates metallic components – layer by layer – directly from 3D-CAD data. This process enables the production of nearly unlimited complex geometries. The material used in the SLM process is a metallic or ceramic powder which is deposited as a thin layer (approx. 50 µm) on a substrate. The powder is selectively melted under an inert atmosphere by a laser beam according to the CAD model (see Figure 2).

Subsequently, the substrate is lowered by one layer thickness and a new powder layer is deposited above. Again, this layer is selectively melted and metallurgically bonded to the layer below. The scan direction is alternated after each layer in order to deter imperfections, which may occur during the melting process, from growing throughout several layers. Hence, the final component is built of many single layers. The use of standard metallic powders and the complete melting enables a density of approximately 100% which in turn assures mechanical properties that match or even beat those of conventionally manufactured parts.

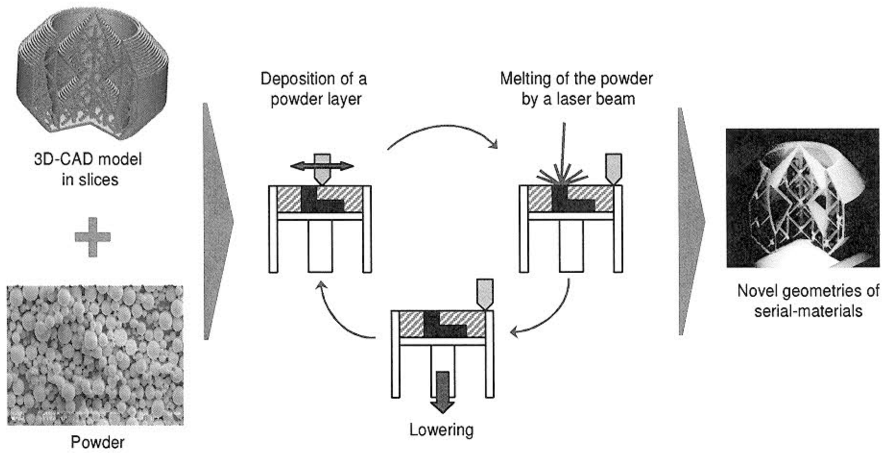

Figure 2: Schematic representation of the SLM process

In sum the SLM process enables a single component to combine the benefits of high geometrical freedom and functional integration with series suitable mechanical properties.

State of the Art

Former research into Additive Manufacturing mostly focused on the qualification of new materials and their industrial application. However, only little, if any research concerning SLM's process efficiency and therefore its build rate has been conducted yet. In order to come to a better understanding of the SLM process efficiency, the SLM process cycle time is divided into primary and auxiliary process time. The main process time only consists of the time that is needed to melt each single layer of a component whereas operations like substrate lowering and powder deposition are part of the auxiliary process time. With regard to this work the focus is on the primary process time because for a large volume that shall be additively manufactured this part of the total manufacturing time amounts to more than 80%. Large volumes can either consist of one large volume part or several low volume parts which are placed on a single substrate and manufactured simultaneously. Especially the latter one refers to the manufacturing of small or medium series production which shall be addressed with this work. The main influencing variables of the primary process time are layer thickness (D_s), scanning velocity (v_{scan}) and scan line spacing (Δy_s). The process related build rate is calculated according to the following equation:

(1) $\dot{V}_{process} = D_s \cdot v_{scan} \cdot \Delta y_s$

Scanning velocity and layer thickness are limited by the laser power available whilst scan line spacing is limited by the focus diameter ($\Delta y_{s,max}$ typically equals approx. 0.7 times the beam diameter). [2] Table 1 exhibits a comparison of the above mentioned process variables and the build rates published to date.

Yet, it was not stated in all papers mentioned in the table below if fully dense components were fabricated. Furthermore some authors investigated (two-component) sintering processes while others focused on melting processes but only investigated binding mechanisms within single layers and compared different materials.

Source	Material	Laser source	Max. Laser-power*	beam diameter (scan line spacing)**	scanning velocity	layer thickness	theoretical build rate***
			[W]	[mm]	[mm/s]	[mm]	[mm³/s]
[2]	stainless steel (X2 CrNiMo17 12 3, X2 CrNi24 12), tool steel (1.2343), nickel	Nd:YAG (cw)	105 W	0.2 (0.14)	< 200	< 0,1	< 2.8
[3]	tool steel (X38 CrMoV 5-1), titanium (TiAl6V4)	Nd:YAG (cw)	120 W	0,2	< 250	< 0,1	< 3.5
[4]	aluminium (AlSi25, AlSi10Mg, etc.)	Nd:YAG (cw)	330 W	< 0.4	< 250	< 0,1	< 7
[5]	stainless steel (1.4404), hot-work steel (1.2714), ni-base alloy (IN718)	CO_2	200 W	0,1	50	0.05 - 0.1	0.5
[6], [7]	stainless steel (X38 CrMoV 5-1 & X40 CrMoV 5-1)	no information	no information	~0.4	no information	< 0.4	—
[8]	Titan (TiAl6V4)	no information	no information	< 0.5 mm	no information	0.13 - 0.38	—
[9]	tool steel	Nd:YAG (pulsed)	550 (150)	0.9 (0.6)	< 10	0,4	< 2.4
[10]	WC-Co	Nd:YAG (cw)	60	0,8	30	0,2	2.5
[11]	Cu, Ni,Fe3P	CO_2	60	0.3 (0.2)	< 100	0,2	< 4
[12]	stainless- & tool steel (1.4404 & 1.2343)	Nd:YAG (cw)	250	0.2 (0.15)	160	0,05	1.2

* If pulsed laser radiation was used, the 2nd number denotes the average laser power

** If no scan line spacing is given, the relation scan line spacing ≅ 0.7 x beam diameter is used

*** according to formula 2-1

Table 1: Summary of influencing variables and build rates concerning the additive manufacturing of metallic powders.

Hence, the depicted values of the parameters, especially the theoretical build rate (last column), assign a kind of limit value. By contrast, the last row depicts a set of parameters that originates from industrial applications and has been approved in own investigations on a series SLM machine (Trumaform LF). The materials investigated are series-identical high alloyed steel (1.4404) and hot work tool steel (1.2343) respectively. The same materials were investigated in a benchmark conducted by "Laserinstitut Mittelsachsen" in close collaboration with "Fraunhofer-Allianz Prototyping" and "LBC GmbH". This investigation points out that the build rate of the same SLM machine amounts to 3 – 5 cm³/h, which is 0.8 -1.4 mm³/s. [13] Thus, the last-row value of the build rate is taken as benchmark for the following investigations.

Increasing the Build Rate

The experiments conducted to date indicate that there is only limited scope to increase the build rate based on higher laser power and a corresponding increase in the scanning velocity at a constant beam diameter. [15] Increasing the laser power while maintaining a constant beam diameter has the effect of increasing the intensity at the point of processing. This in turn leads to a higher evaporation rate resulting in a higher incidence of spattering which has a negative effect on the process as a whole. To avoid this, the beam diameter has to be enlarged. Schleifenbaum et al. showed that satisfactorily results can be achieved with regard to Selective Laser Melting of series-identical metallic powders by means of increased laser power (up to 500 W) and the correspondent adaption of the beam diameter to approximately 0.8 mm. [15] Yet, the accuracy and detail resolution of additive manufactured parts are negatively influenced by larger melt pools which, as a general rule, grow with larger beam diameters and layer thicknesses. [2]

In order to avoid this negative influence of larger melt pool geometries the so-called skin-core strategy has to be taken into consideration. According to this strategy the part to be built needs to be divided into an inner core and a skin which forms the outer contour of the part (see Figure 3). Thus, different parameters for the outer skin and the inner core of a component can be chosen. Both, skin and core must have a density of approximately 100% to assure the same mechanical properties as conventionally manufactured components. However, the core does not have strict limitations and/or requirements concerning accuracy and detail resolution. Hence, the core can be fast manufactured with a large beam diameter whilst the skin is manufactured with a small beam diameter in order to assure the part's accuracy and detail resolution.

Setup of a New SLM Machine

As discussed above an increase of the build rate by means of increasing the beam diameter and layer thicknesses needs to be supported by higher laser power. Besides that, the new prototype plant must be equipped with a variable focus diameter in order to assure the accuracy of additively manufactured components.

To realize this new concept a Trumaform LF250 was completely rebuilt, both in terms of hard- and software. In order to increase the process related build rate beyond [15] the maximum laser power should be extended to more than 500 W. To date, the maximum laser power in commercially available SLM machines is limited to some 200 W - 400 W. [14] Therefore, the integration of a new laser source (1 kW) is combined with the redesign of the optical system.

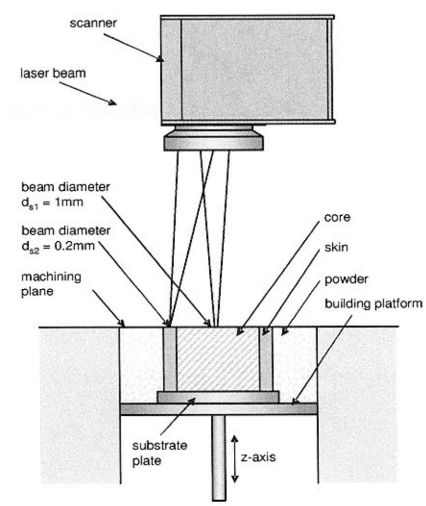

Figure 3: Schematic representation of the skin-core concept

Investigations have shown that there is only limited scope to increase the build rate by means of high power lasers with a (single mode) Gaussian beam profile that causes an extremely high intensity in the beam centre. [17] Hence, the desired intensity distribution (i.e. uniformly or top hat shaped) [17] has to be taken into consideration when designing the new optical system. As a general rule, a top hat intensity distribution is boosted by the superposition of many transversal electromagnetic modes during the propagation through an optical multimode fibre. Therefore, a fiber coupled high-power laser (1kW) is opted for the integration into the SLM machine. The focus diameters realised with this setup can be changed between 193 µm and 1050 µm.

Since the optical fibres should not be exposed to mechanical forces, like distortion, sharp bending, etc. the fibre switch is realized by a movable tilted mirror. This mirror can be moved into the course of beam by means of a pneumatic linear axis. The tilted mirror has to be moved parallel to the mirror plane in order to assure concentricity of the different beams in both end positions of the slide. Figure 4 depicts the new designed optical system that enables the automated change of optical fibres for the realisation of different focus diameters at the machining plane. The principle shown is patent by Fraunhofer ILT.

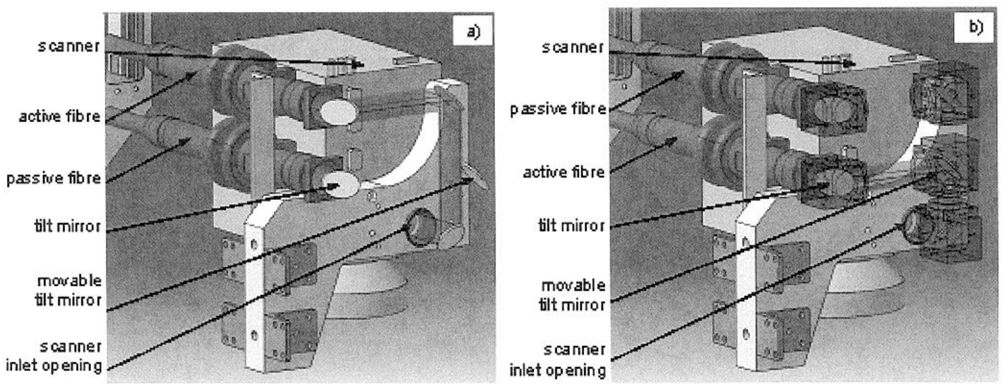

Figure 4: Optical system according to the multi-beam concept, a) upper fibre active b) lower fibre active, beam deflector cubes visible

Test Methodology

For the manufacturing of multi-layer components each single layer is melted according to the 3-D CAD model. Each layer is subdivided into several areas in order to keep the scan vector length (L) within certain boundaries. Concerning state-of-the-art SLM processes (e.g. 1.4404), L is 5 mm. In order to smooth the component's outer surface, the contour of each layer is remelted after the hatchure (sum of the scan vectors of a single layer) is completed (see Figure 5).

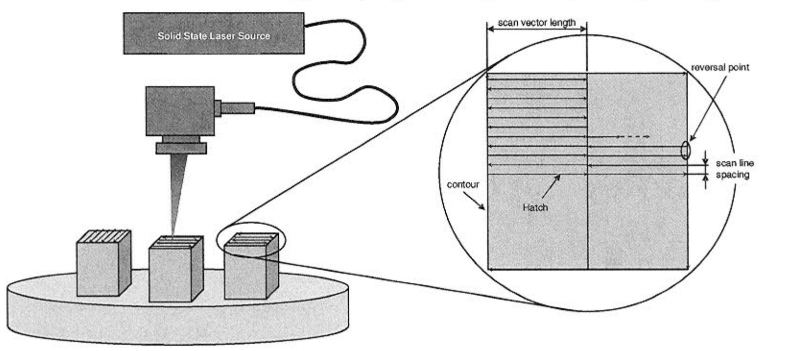

Figure 5: Schematic representation of layer wise building technique

The prerequisite for manufacturing dense components are suitable sets of parameter values that can be identified on the basis of the smoothness of the generated layers, which permit an even application of powder. The density of the additively fabricated components is a crucial factor for their mechanical properties. Hence, an increase of the build rate without maintaining the density and thus the mechanical properties would cause serious problems for the industrial application of additive manufactured components.

For the determination of the density, cross sections of the components are investigated by means of light microscopy, see Figure 6.

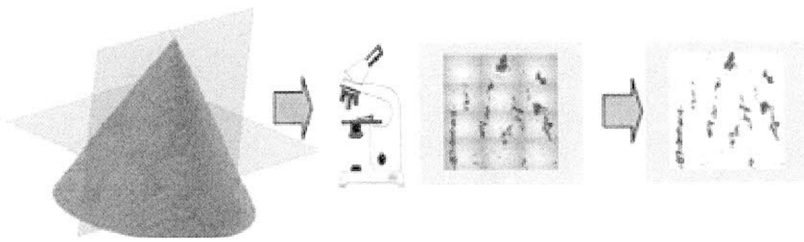

Figure 6: Fabrication of cross sections and evaluation of density

The resulting pictures are statically filtered to suppress noise and segmented afterwards into molten material (white) and pores along with sinkholes, etc. (black), see Figure 6 right.

Experimental Results - Core

As discussed in chapter 3, the crucial factors for increasing the build rate are scan line spacing, scanning velocity and layer thickness. Whereas the former is limited by the beam diameter (approximately 0.7 times the spot diameter regarding 1.4404) [2], investigations by Schleifenbaum et al. gave evidence that there is only limited scope in increasing the build rate by means of increasing the scanning velocity. [15] Hence, the main driver for increasing of the build rate can be found in the increase of the layer thickness. Therefore the scanning velocity was kept fix during the investigations discussed below.

In order to evaluate the influence of a layer thickness variation on the density, cubic specimen were manufactured and analysed according to Figure 6. In order to cope with the dilemma of incoupling the "right" amount of energy at a certain place in a certain amount of time, it is possible to vary the scan vector length. A short scan vector length causes the laser beam to alter its direction more often. I.e. the number of reversal points is increasing with a decreasing scan vector length. Within the area of those reversal points an increase of temperature can be observed since the energy source "rests" much longer on the reversal area than on a conventional hatch area. This superheating causes more powder particles to evaporate which result in the process instabilities described above. Therefore, decreasing the number of reversal points (i.e. increasing the scan vector length) decreases evaporation, spattering and process instabilities which is favourable for thinner layer thicknesses.

Figure 7 exemplifies the density as a function of the layer thickness and different scan vector lengths.

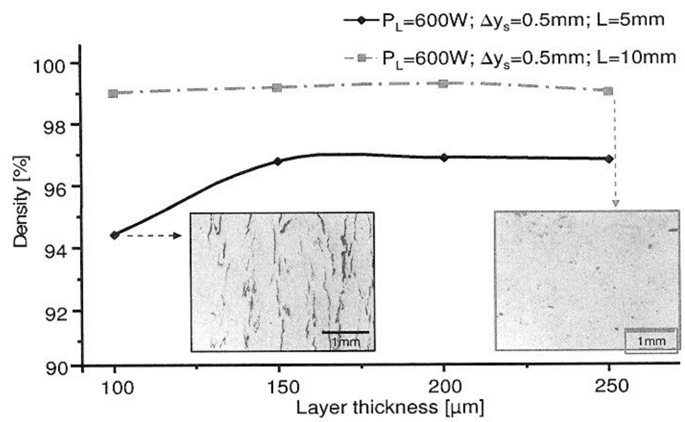

Figure 7: Density vs. layer thickness, comparison of scan vector length, beam diameter: 1.05 mm

Regarding the black graph (600 W, 5 mm scan vector length) the density increases from approximately 94% at 100 μm layer thickness to approximately 97% at 150 μm due to higher amount of energy that is needed to melt the powder mass per scan line. Consequently superheating, evaporation and spattering decrease and the process becomes more stable. Yet, even with higher layer thicknesses, the amount of evaporation and process instabilities (especially in reversal points) is too big to assure the manufacture of dense components. The density of the manufactured specimen remains at approximately 97% up to 250 μm layer thickness.

Regarding the same process parameters, only varying the scan vector length from 5 mm to 10 mm, a significant advancement can be observed. Almost independent from the layer thickness (100 μm to 250 μm) the density of the specimen investigated remains unchanged. At a layer thickness of 100 μm the gap between 5 mm and 10 mm scan vector length amounts to approximately 5 %. Due to the stabilization of the process with an increasing layer thickness this gap decreases down to approximately 2% at layer thicknesses between 150 μm and 250 μm. Hence a significant rise of the process stability and thus the part's density can be achieved by the implementation of longer scan vectors.

Summing up, the experiments discussed above give evidence that an increase of the build rate by means of higher laser power and larger beam diameters needs to be backed by the implementation of longer scan vectors, especially if the layer thickness is comparable "thin", i.e. less than 150 μm. The maximum build rate achieved within these experiments reaches up to 20 mm^3/s. Considering the current state of the art (see "State of the Art") the build rate can be increased by more than 1500% while maintaining a density superior to 99%. Yet, accuracy, detail resolution and surface roughness are not tolerable for the manufacture of near net shape components. In order to avoid these disadvantages of an increased build rate by means of larger beam diameters and layer thicknesses, the outer part of the specimen can be manufactured by a smaller beam diameter (0.2 mm) at layer thicknesses inferior to 100 μm, e.g. 50 μm or 30 μm. The investigation of the influence of higher laser power at a beam diameter of 0.2 mm on the build rate and the surface roughness is discussed in the following section.

Experimental Results - Skin

In order to build dense components, it is important that the melt pool does not consist of different subareas but is cohesive and self-contained. [2] On the one hand the energy per unit length decreases with an increase of the scanning velocity. On the other hand the productivity of the SLM process is positively influenced by the scanning velocity. Hence, the laser power has to be increased if the scanning velocity increases. However, the augmentation of the laser power at a constant beam diameter increases the intensity at the point of processing which causes superheating and thus spattering and process instabilities. Thus, the laser power can not be increased to values stated in the preceding section

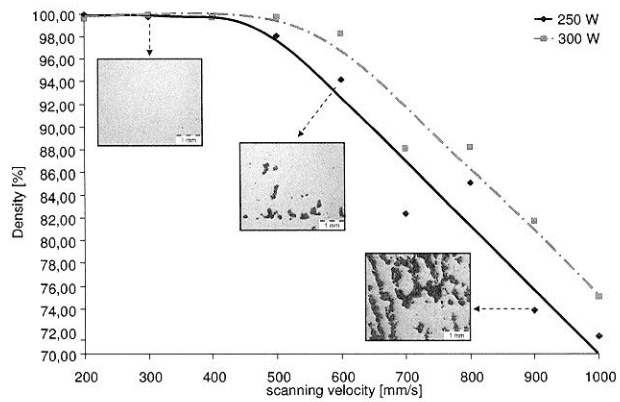

Figure 8: Density vs. scanning velocity, comparison of different laser power, beam diameter: 0.2 mm, layer thickness: 50 µm

Considering a laser power of 250 W the production of components with a density of approximately 100% is possible at a scanning velocity up to 400 mm/s. With regard to the current state of the art for 50 μm layers, i.e. 160 mm/s (see section 3.1), an increase of around 250% (2.8 mm³/s) can be achieved. If the scanning velocity is further increased the energy per unit length is not sufficient anymore to fabricate dense components. Regarding a laser power of 300 W dense components can be manufactured at a scanning velocity up to 500 mm/s. Hence, the build rate can be augmented by more than 300% (3.5mm³/s) considering the current state of the art. For higher scanning velocities the density decreases comparable to the 250 W graph.

Hence, an increased laser power can partly be transformed into higher build rates by means of higher scanning velocities. Yet, the increase is comparable small regarding the increase by means of larger beam diameters and layer thicknesses since the laser power is limited by the intensity at the point of processing. Therefore the part of a real-life component that is manufactured with this set of parameters (i.e. the outer shell or skin) should be kept as small as possible in terms of increased process efficiency.

Besides the build rate the surface roughness and detail resolution of the outer shell should be optimised, too. As a general rule, the melt pool size increases with an increased laser power if the other process parameters (e.g. scanning velocity, etc.) are kept constant. Consequently, the detail resolution decreases and the surface roughness increases with an increased laser power. Figure 9 exemplifies this effect by the comparison of the surface roughness of specimen manufactured at different scanning velocities and laser power.

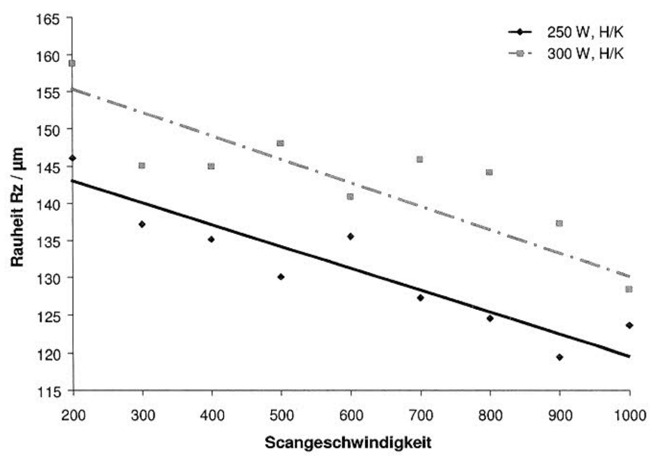

Figure 9: Surface roughness R_z vs. scanning velocity, comparison of different laser power, beam diameter: 0.2 mm

The scan strategy applied within this setup is contour/hatch. I.e. the contour vector is scanned first and all hatchure vectors afterwards. This is generally accepted to be advantageous in terms of an optimised surface roughness. [3]

The surface roughness decreases with an increasing scanning velocity. This applies for 250 W and 300 W respectively. Yet, the absolute values of the surface roughness increase with an increased laser power. At 250 W the surface roughness decreases from 145 μm at 200 mm/s scanning velocity to 120 μm at 900 mm/s scanning velocity. At 300 W the surface roughness decreases from 160 μm at 200 mm/s scanning velocity to 130 μm at 1000 mm/s scanning velocity. However, the minimum surface roughness can only be achieved by process parameters that do no assure dense components (see Figure 8). Since a density of approximately 100% is the prerequisite to assure series-identical mechanical properties, the minimal surface roughness that can be achieved with this set of parameters is 135 μm (250 W) and 150 μm (300 W) respectively (see Figure 8 and Figure 9).

In order to combine the effects of an increased build rate by means of higher laser power and enlarged spot diameter, the part to be built is divided into 2 areas - skin and core. Each area is processed with different parameters, especially with different layer thicknesses, as discussed above. Hence, process parameters and scan strategy of the skin-core interface need to be adapted in order to assure a stable bonding of skin and core. The investigation of scan strategy and process parameters on the skin-core bonding is discussed in the following chapter

Experimental Results - Skin-Core

Again, for the manufacturing of multi-layer components each single layer is melted according to the 3-D CAD model. However, for the application of the skin-core strategy the specimen is subdivided into an inner and outer shell (see Figure 10, left). The outer shell (skin), which is in this case 2 mm thick, is manufactured with the small beam diameter (0.2 mm) and according to the results discussed above with 250 W laser power, a scanning velocity of 400 mm/s and a layer thickness of 50 μm. By contrast, the inner core is manufactured with a beam diameter of 1 mm. Furthermore the core layer thickness is enlarged for a further increase of the build rate. The core layer thickness can only be sized in multiples of the skin layer thickness, i.e. considering a skin layer thickness of 50 μm the core layer thickness can only be 100 μm, 150 μm, 200 μm, etc. (see Figure 10, right).

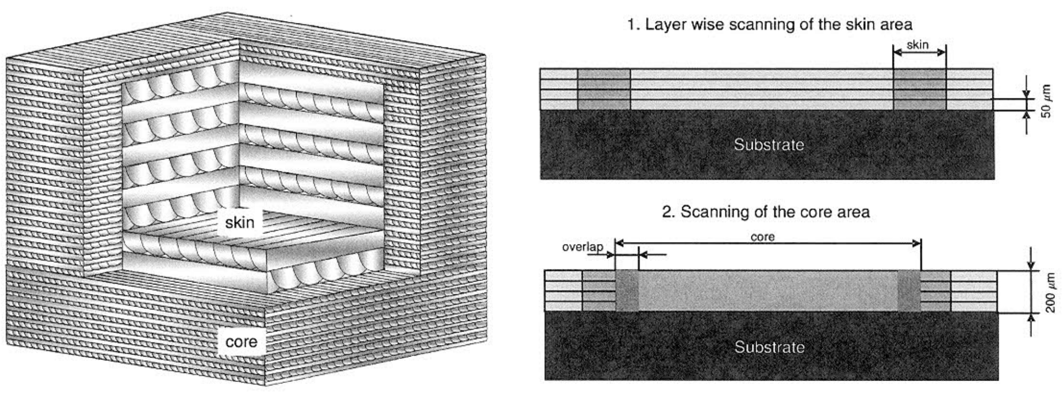

Figure 10: Schematic representation of the skin core principle (left) and procedure of skin and core melting (right)

A crucial factor for the metallurgical bonding is the overlap, i.e. the interface area that is scanned twice, of skin and core (see Figure 11, left). This overlap has to be > 0 mm. Figure 11 (right) exemplifies the manufacture of such a skin-core specimen. Again the specimen manufactured is a testing cube of the size 20x20x20 mm³. In this case, the core was manufactured with a spot size of 1 mm at a layer thickness of 200 μm, whereas the skin was manufactured with the small spot

(0.2 mm) at a layer thickness of 50 μm. After the manufacture the specimen is analysed according to Figure 6.

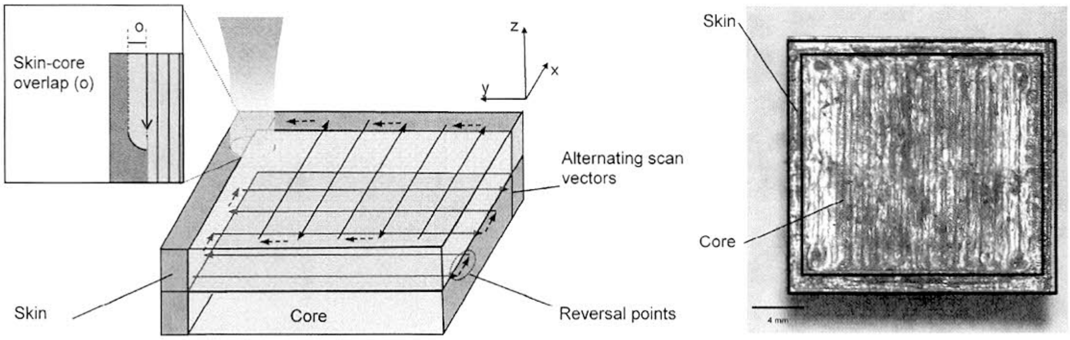

Figure 11: Schematic representation of skin-core overlap (left), Skin-core specimen, top view (right)

In order to assure the metallurgical bonding of skin and core the overlap is varied depending on the skin-core layer thickness proportion (see Figure 12).

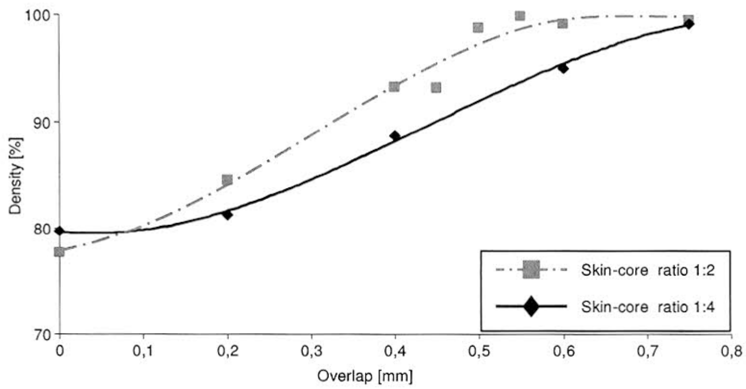

Figure 12: Density of skin-core interface vs. overlap, skin-core layer thickness ratios of 1:2 and 1:4

For both investigated layer thickness ratios (1:2 and 1:4) the number and size of defects and thus the porosity is decreasing with an increasing overlap. Considering a skin-core layer thickness ratio of 1:2, i.e. in this case 50 μm skin layer thickness and 100 μm core layer thickness, a dense metallurgical bonding (density > 99%) can be assured with an overlap > 0.5 mm. With regard to a skin-core layer thickness ratio of 1:4, i.e. in this case 50 μm skin layer thickness and 200 μm core layer thickness, a dense metallurgical bonding (density > 99%) can be assured with an overlap > 0.75 mm.

Figure 13 depicts the cross sections of such skin-core specimen with a layer thickness proportion of skin and core of 1:2 (left) 1:4 (right).

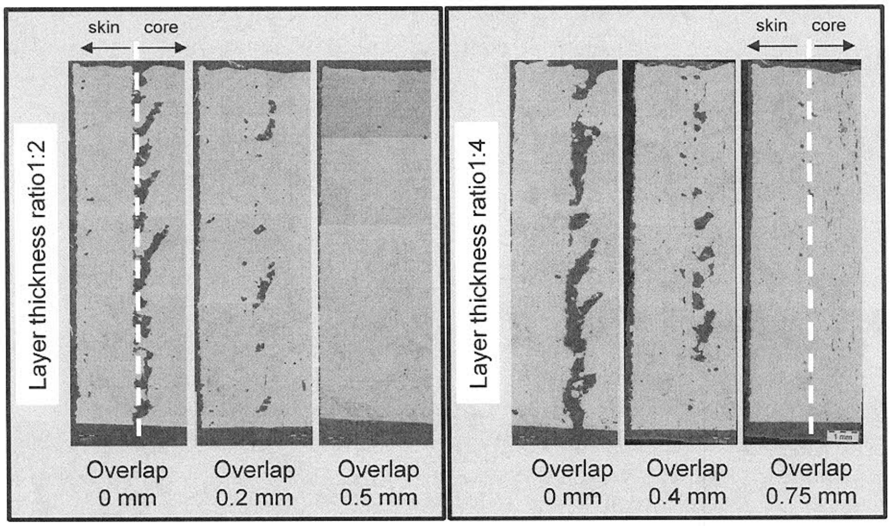

Figure 13: Cross section of skin core specimen

Though there is still some porosity detectable in the core part, the bonding of skin and core shows a density of approximately 100 % for an overlap of 0.5 mm (layer thickness ratio 1:2) and 0.75 mm (layer thickness ratio 1:4) respectively. Hence, the manufacture of at least simple cubic skin core specimen with a layer thickness ratio of 1:4 (skin: 50 μm, core: 200 μm) is possible.

Complex skin-core geometries

In order to demonstrate the potential of the skin-core strategy for the additive manufacture of complex real-life components with an increased build rate a demonstrator is build as shown in Figure 14, left.

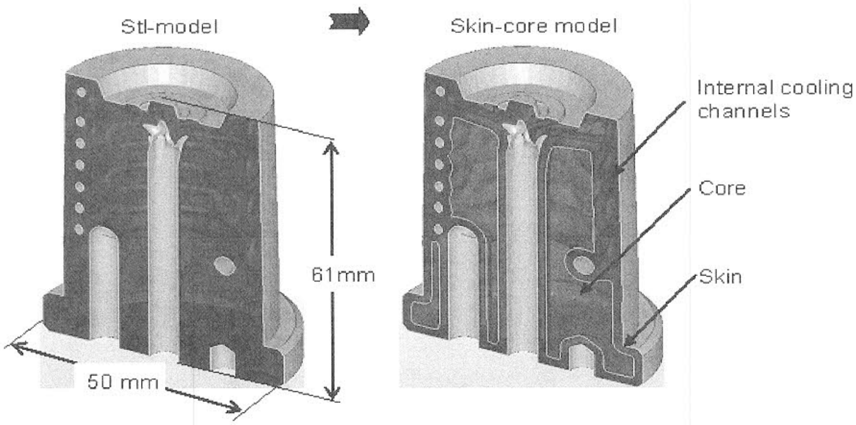

Figure 14: 3D-model of the complex tooling insert (left) and skin-core model (right)

The part shown is a tooling insert for injection moulding. Due to the internal cooling channels the tool insert can not be built conventionally. Figure 15, right exemplifies the skin-core model of the tooling insert. In order to maximize the build rate while maintaining detail resolution and surface roughness the core layer thickness is chosen to 200 μm and the skin layer thickness to 50 μm. The resulting layer thickness ratio of 1:4 determinates the overlap to 0.75 mm (see chapter "Experimental Results - Skin-Core"). The additively manufactured skin-core tool insert is shown in Figure 15, left. In order to evaluate the density of skin, core and especially the bonding of skin and core, several cross sections according to Figure 6 are made (see Figure 15, right).

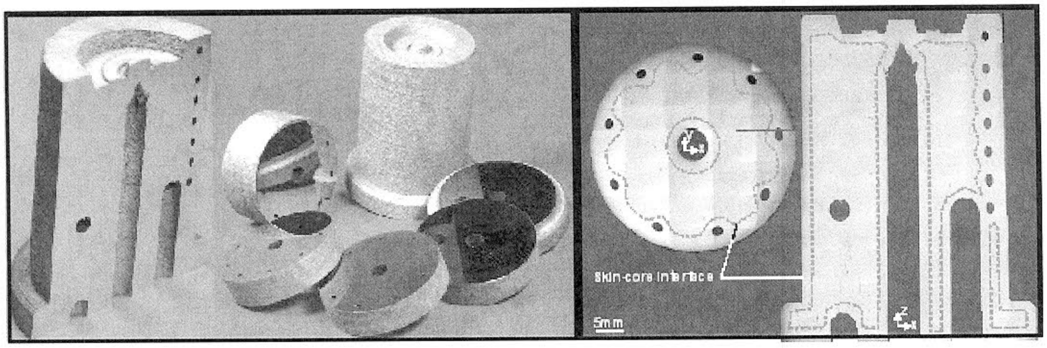

Figure 15: Additively manufactured skin-core tool insert (left), cross sections (right)

The tooling insert shows a density of approximately 100 %, i.e. the detectable porosity can be found in the range of conventionally SLM-manufactured specimen. The pores and sinkholes can not be correlated to special area, neither skin and core nor skin-core interface. Hence, the manufacture of complex shaped skin-core parts with a layer thickness ratio of 1:4 (skin: 50 μm, core: 200 μm) is possible. The core build rate amounts to 16.8 mm³/s, the skin build rate amounts to 3 mm³/s. Hence, the overall process related build rate of the tooling insert amounts to 10.2 mm³/s.

Summary and outlook

One of the key research targets in the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" concerns solving this dilemma that opposes economies of scale and scope, e.g. either the low-cost production of high quantities or the high end and thus cost intensive low volume production of individualized goods. Selective Laser Melting represents one of the areas of greatest potential to reach this target. However, the state-of-the-art process and cost efficiency is not yet suited for series production.

In order to improve this efficiency and enable SLM to enter series production a new prototype machine tool is designed and built. For the first time a kW laser system is integrated into a SLM machine. In order to transform laser power into process efficiency, i.e. build rate, an optical system is designed that enables the additive manufacturing of components with an increased build rate. In order to maintain accuracy and detail resolution of additively manufactured components while increasing the build rate at the same time the optical system includes a new multi-beam concept that enables the processing with different focus diameters, layer thicknesses, etc. dependant on the part's specifications (skin-core strategy). The experiments show that, with a spot diameter of 1 mm the core build rate of cubic geometries can be increased by more than 1000% regarding the present state of the art. However, accuracy, detail resolution and surface roughness are not tolerable for the manufacture of near net shape components. Thus, the skin-core concept is firstly applied to cubic specimen and consequently to real-life parts, in this case a complex tooling insert with internal cooling channels. With regard to a layer thickness ratio of 1:4 the density of all areas of the part - skin, core and skin-core interface - reach approximately 100%. The process combined related build rate of the tooling insert amounts to 10.2 mm³/s which represents a more than 8-fold increase with regard to the current state of the art.

Consequently, future research has to focus on developing a process conduct for even higher build rates as well in the core- as in the skin area. Furthermore it needs to be investigated if complex parts can be built with a layer thickness ratios < 1:4. This will enable at least small lot series fabrication at costs matching or beating those of mass production, while retaining the ability to satisfy market demand for individualized products at the same time and finally help to SLM to break into new markets.

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