Multi-Material Processing in Additive Manufacturing

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Abstract

One of the most important advantages of additive layer manufacturing (ALM) is the ability to produce parts with high geometric complexity in a very economical manner. However, only little effort has been taken in order to enhance aspects of material flexibility of ALM. A modified manufacturing process was developed and different stages concerning the dimensions of multi-material complexity are defined. The technological base being selective laser melting, two varying metallic materials were fused within each layer. Therefore, a new recoating mechanism for non-cohesive powders has been developed. To increase lifetime of tools with abrasive wear environment, hot work steel and tungsten carbide/cobalt have been combined. A tooling insert has been chosen as an example of application.

Introduction

ALM has many advantages in comparison to conventional manufacturing technologies (e. g. milling). By using ALM, it is possible to fabricate highly complex parts (Fig. 1). Hence, this benefit can be used to produce customized parts (e. g. bone structures) or tooling inserts with conformal and form-fitting cooling channels [1]. Besides the high geometric complexity, ALM allows to assimilate any meltable material, e. g. metals, ceramics or composite powders [2]. Only singular approaches have been taken to make use of this flexibility [3].

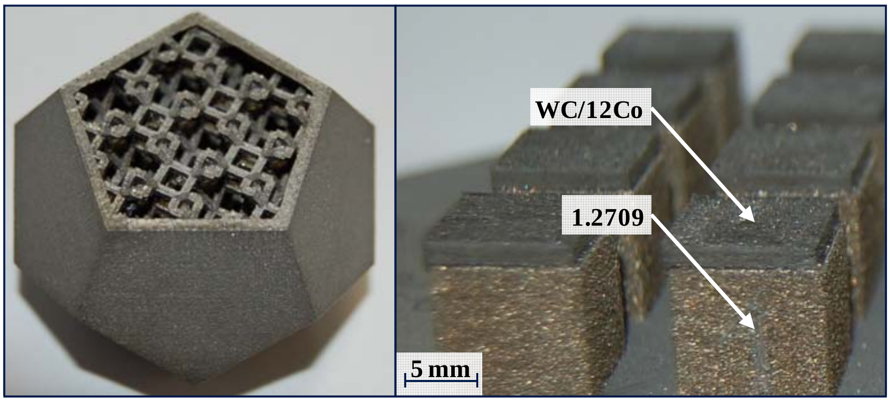


Fig. 1: Complex geometric parts produced by selective laser melting; a dodecahedron with internal structures (left) and a one dimensional multi-material structure (right)

Mostly, the whole part is completely made out of one substance. By combining two materials, new applications can be found [4; 5] and in order to enable complex multi-material structures, a modification of the existing process is necessary.
Different approaches are shown in literature, how multi-material parts can be built [6; 7; 4]. In general, the combination of at least two materials can be defined as a multi-material part. By manufacturing layer by layer, parts with a material change in the direction of built-up can be realized quite easy by exchanging powder. This procedure enables only little technological advantages. A one dimensional multi-material part as shown in Fig. 2 (left hand side) can be generated with current machine equipment. ALM has a lot more potential, concerning multi-material structures. The aim of this research activity is to enable fully three dimensional multi-material parts as shown in Fig. 2 (right). Variation of materials in each layer can only be achieved by a new recoating mechanism, which has the ability of positioning powder selectively.

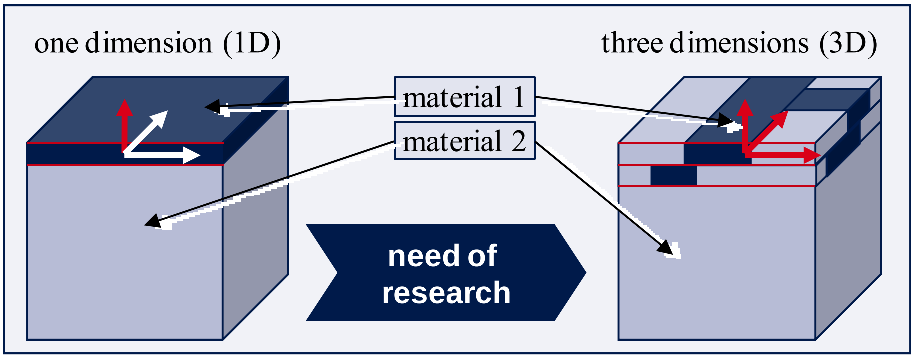


Fig. 2: Need for research approaches for multi-material parts

State of the art

To generate a powder layer containing several materials, a new recoating mechanism needs to be integrated into the fabricating system. The fact that powder grains can have quite different attributes leads to various solutions, how to handle this formless materials. Miscellaneous research teams have developed approaches for this matter, which will be presented below.
One possibility for the above shown issue is to use the physical effect of electrostatic charging [8], as it is applied e. g. in laser printers. The geometric shape of the electrostatic element can be a cylinder or a plate, which should be selectively dischargeable. By placing the element on top of the powder reservoir, the grains are attracted to the charged surface areas. This procedures (charging and discharging) need to be repeated for each substrate. If all materials adhere to electrostatic element, the powder grains can be released to the working level at once [9]. In the following process step, the powder layer is sintered with pressure to a multi-material solid freeform part. The layer height and hence the build-up rate can be controlled by varying the electrostatic charging.
The flowability is another powder characteristic, which enables to vary materials in one layer by using a nozzle mechanism. The precision of this mechanism depends mostly on the bore hole diameters [10]. The opportunity of minimizing the bore hole dimension is limited. As Al-Jamal has shown, powder flow can be realized with a nozzle diameter of 0.4 mm [6]. This also depends on the grain size as well as on the particle distribution. To enable multi-material coating in ALM

processes, nozzles must be integrated into the existing recoating mechanism [11] or replace it [12].

As shown above, ALM offers the opportunity to increase its production advantages, e. g. high geometric flexibility, by enhancing the existing single material manufacturing process.

Multi-material coating mechanism for SLM

Conventional recoating mechanisms consist of a flexible or a stiff blade, which enables an even and homogeneous powder layer by movement of the blade. As expounded in the state of the art, further powder handling approaches have been proposed. Recoating of multi-material layers requires more process time, as layers containing only one kind of material. Therefore, a timesaving and economic recoating mechanism is necessary. As shown in Fig. 3, the developed recoating mechanism is a combination of nozzle mechanism and coating blade.

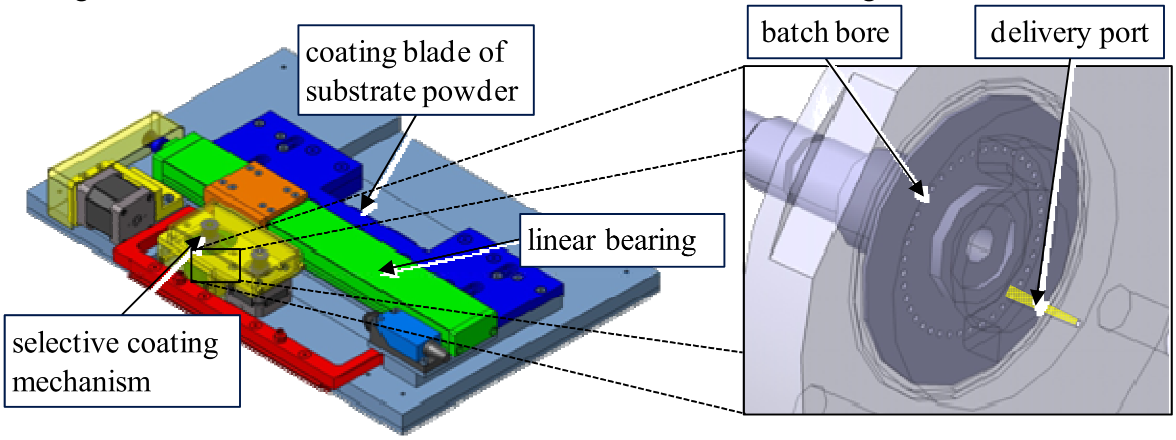


Fig. 3: Recoating mechanism for multi-material manufacturing

The selective recoating mechanism can be positioned with an accuracy of about 5000 dpi on the base plate. Therefore, a kinematic module consisting of two linear bearings has been integrated. The selective coating mechanism (Fig. 3 right hand side) can handle non-cohesive powders and operate without any additives (e. g. fluids). This enables a lean production process, because no further process steps, e. g. drying slurry, need to be executed [13]. The dosing principle is based on a small batch bore holes, which have a diameter of 0.4 mm and a volume of 0.038 mm^3 (cf. Fig. 3). Generating a part including a coated functional wear-resistant area, the surface will have a smaller volume as the inlay of the part. In conjunction with a modified process sequence, at least two powders can be melted within each layer. The associated process model will be presented in the following chapter.

Development of a multi-material process model

Adding a second material to the additive layer manufacturing process requires an adapted process sequence. Powder recycling ensures an economical process. Hence separation of materials is an important criterion in developing the process model. Putting all process steps (micro process model) in the right order a macro process model will be introduced (Fig. 4).

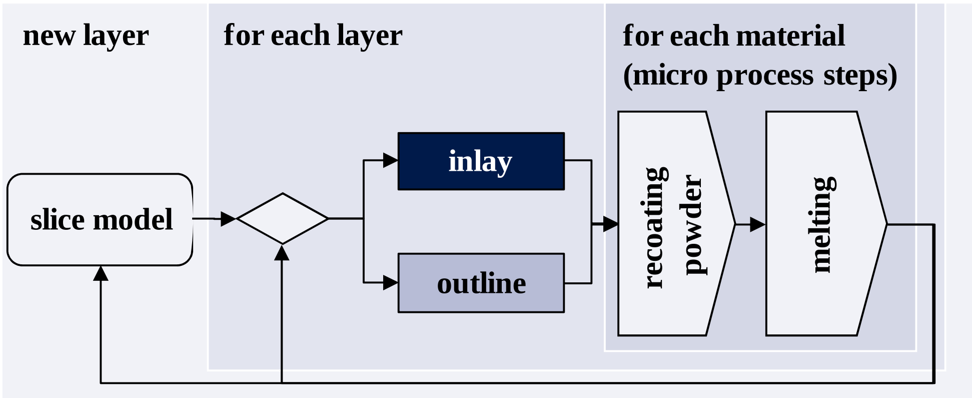


Fig. 4: Macro process model for multi-material SLM part containing a coated surface

Developing a modular framework enables a flexible process management, e. g. adding a third kind of powder material. All micro process steps consist of an initial and a final state. The included operations transform all input parameters into the output parameters. Each part will be designed by means of a computer (CAD). This three dimensional model will be separated in single layers, which already contain the local information of powder recoating. For each new layer, a mathematical algorithm is executed, which calculates all interception points for the selective powder mechanism. As shown above, the mechanism single ejects micro volumes of powder. During the process sequences of inlay and outline recoating the materials are kept strictly apart. For a part consisting of two materials, following process order is realized: First, one powder is placed selectively at all calculated interception points for the current layer. Second, the inserted material is melted to a solid part. Third, the second powder is recoated laminary. Melting the laminar powder completes the layer. All four steps are repeated layer by layer. Step no. three and no. four are similar to single material process steps. Step one and two, which are specific for multi-material structures, are explained in detail.

The flowability of bulk materials has an important impact on placing powder selectively. Low flowability makes dosing of powder difficult. Therefore, both the nozzle design (e. g. the inner diameter) and powder fraction and form need to be optimized for small volume batches. Spherical powder with a grain size distribution between 20 µm and 53 µm has a much higher ease of flow as spattered material [10]. Hence, a powder configuration of tungsten carbide (WC) and Cobalt (Co) with high flowability has been chosen (cf. Tab. 1). WC and Co can be mixed in different proportions (e. g. 88% of WC and 12% of Co).

Tab. 1: Grain size distribution of the chosen powder material

Grain size [µm]	0-20	20 - 45	45 - 53	53 - 63	63 - 71	> 71
WC/Co 88/12 [%]	0.95	73.96	20.65	4.22	0.22	0
WC/Co 83/17 [%]	0.49	75.55	21.12	2.84	0	0

The geometrical arrangements of the nozzle are limiting the powder flow (cf. Fig. 5). Therefore, mainly the following two variables are responsible.

First, the inner diameter of the nozzle (D_{nozzle}) should be at least 5 times the grain size ($D_{grain50}$). As a simplification, the arithmetic average of the given grain size distribution has been chosen. A too small ratio can cause bridging and will stop the powder flow. Second, the angle of the delivery port should be much bigger than the critical angle, which depends on the chosen powder.

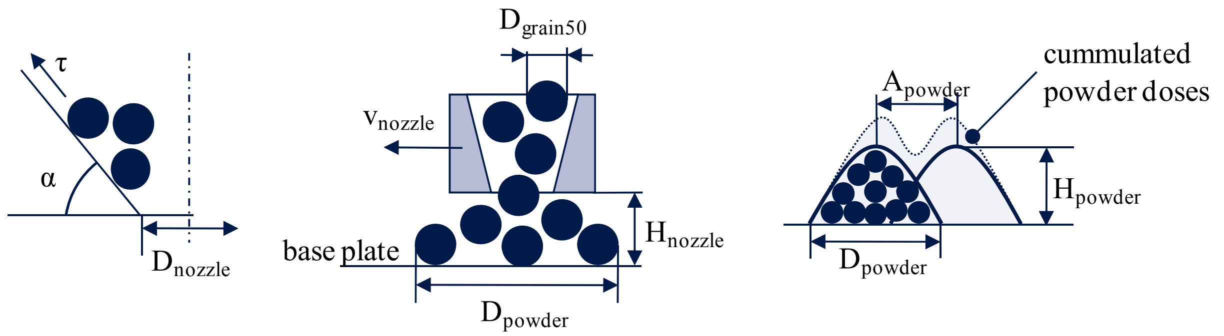
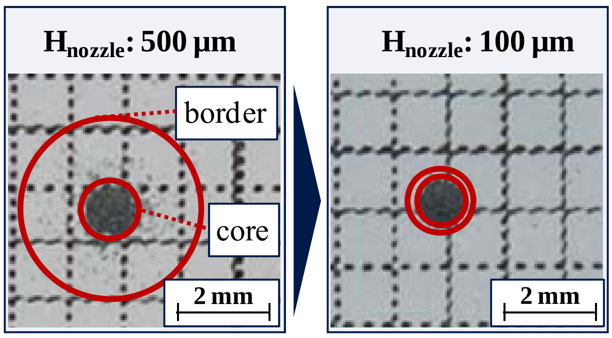


Fig. 5: Geometrical arrangements of the nozzle

The critical angle can be measured with DIN ISO 4324 and depends on powder adhesion. Hence, the friction coefficient τ between nozzle wall and powder defines the critical angle.
If powder flow is secured, the height H_{nozzle} influences the spreading of the dosed grains. In Fig. 6, the correlation between H_{nozzle} and D_{powder} can be depicted. The dose bore during this experiment had a diameter of 0.5 mm and a height of 0.4 mm, which represents a batch volume of 0.0785 mm³.



H_{nozzle} [µm]	D_{powder} [mm]	
	core	border
100	0,8	1,3
200	0,9	2,5
300	0,9	3,0
400	1,0	3,0
500	1,2	3,3

Fig. 6: Influence of distance between nozzle and base plate

With increase of height, the difference between the core diameter and border grows disproportionately. On the one hand, this is an evidence that H_{nozzle} should be as small as possible. On the other hand, the minimal height has influence on the laminar expansion of the volume. Hence, it is necessary to reduce the batch volume itself to minimize H_{nozzle} and optimize the precision of the mechanism.

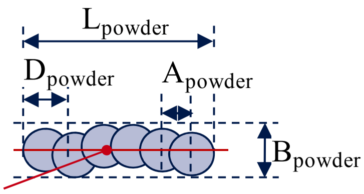


Fig. 7: Variables of printing a powder line

Combining single batch volumes to a continuous line, more parameters need to be considered. As it can be seen on the right in Fig. 5 the offset A_{powder} influences the continuity of the line. Choosing a too small gap too much powder will be positioned. Selecting the offset between two powder doses too wide, the line of powder will be irregular.
This two dimensional line can be described by two variables. First, the length of the powder line is given with the following formula (cf. Fig. 7):

$$L_{powder} = A_{powder} \cdot n + D_{powder}$$

Depending on the appointed distance A_{powder}, the diameter of the powder volume D_{powder} and the numbers of powder volumes n the length L_{powder} is defined. Second, the width of the powder line is defined with B_{powder}. This variable describes the maximal width, which is formed by D_{powder} as well as by the inaccuracy (e. g. backlash) of the powder printer. At best, B_{powder} is equal to D_{powder}. Based on these two boundary conditions the powder line can be specified. Furthermore, a process connection among selective powder recoating and melting the printed material can be defined.

The scan vectors describe the geometric paths of the laser beam during melting. Usually, the outline can be scanned with a single closed surrounding path. Melting the selectively inserted powder line requires a laminar scan strategy, because the line width B_{powder} is more expanded than the diameter of laser beam D_L. Therefore, the defined scan vectors need to be adjusted to ensure fusing of all selectively inserted powder grains. Hence, the mixing of different materials can be minimized. The adapted melting behavior can be depicted with below-mentioned formulas:

$$L_{scan} + D_L = L_{powder} + 2 \cdot O_{scanL}$$
$$B_{scan} + D_L = B_{powder} + 2 \cdot O_{scanB} = (D_L - a) \cdot n$$

The assumption of fusing all powder can be ensured by integrating an additional melting area. Therefore, O_{scan} will be defined in both directions (width, length) of the powder line. As can be seen in Fig. 8 the laminar scan strategy overlaps the powder. L_{scan} in addition with the diameter of the laser beam D_L can geometrically be described by L_{powder} and O_{scanL} for each side of the powder line. A similar coherence can be found for the characterization of the width B_{Scan}. To enable a laminar scan strategy, the paths overlap needs to be considered. Usually, a degree of overlap between 30 percent and 40 percent is chosen [14] and guarantees a plane layer composition.

When all powder grains of the first powder are fused to a solid freeform structure, the recoating and melting process of the second material can be executed by using the blade mechanism. The scan strategy for laminar inlays is identical to already carried out scientific investigations and will not be described in this paper. Further investigations can be found in [15; 14].

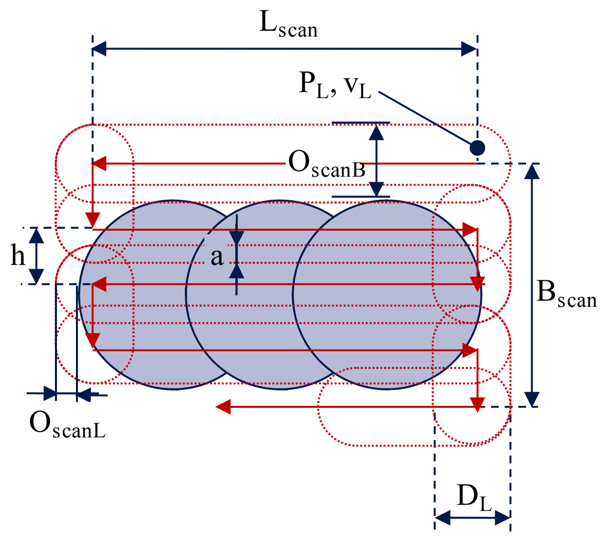


Fig. 8: Scan strategy of selectively printed powder

Process validation and example of use

The above presented multi-material process model allows new application areas. First, it is possible to build up integrated coatings, which cannot be realized by conventional manufacturing techniques. Thus, e. g. internal surfaces (cf. Fig. 9) or hard reachable surface areas can be mentioned. As shown in the adjacent Figure, internal surfaces of pipes can be coated with wear resistant materials (e. g. WC/Co) and increase durability by reducing abrasion caused by conveyed bulk solids. Moreover glass and ceramic industries are also interested in producing tools with extended durability. However, there are more applications than increasing wear resistant that can be realized.
Second, additive manufactured tool inserts could use the technological feature of form-fitting cooling channels. Hence, good advantages concerning cycle time and product quality could be achieved. However, there is still a gap between tool surface and cooling channel. By using two materials with different heat conduction coefficients, solid thermal conductors can be integrated. Consequently, further progress of reducing cycle time and improving part quality can be realized. Beside these two examples multi-material structures will have a huge relevance for future applications [5].

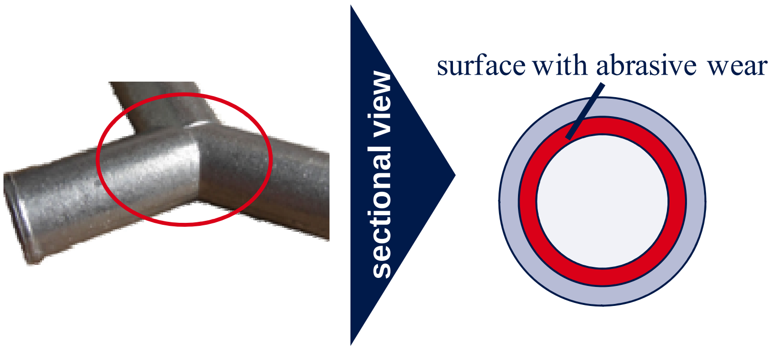


Fig. 9: Coated example of use for reducing abrasive wear

Conclusion

Additive layer manufacturing, especially selective laser melting has a high potential, mostly caused by the geometric flexibility (e. g. freedom of design). One huge restriction of SLM processes is the single material manufacturing. Enabling requested part properties requires a balanced decision between different available materials. Hence, adhesively joining of two or more kind of material offers new opportunities to achieve these part properties without any compromises. Therefore, a new recoating mechanism including the appertaining process model has been introduced, which enables multi-material structures. Above described proceedings allow to handle more than one powder flexibly and precisely. In order to raise the reproducibility, further investigations and experiments need to be executed. Multi-material manufacturing offers new applications, e. g. coating of internal surfaces or functional graded structures and afford a unique feature for additive layer manufacturing.

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