TECHNOLOGY REPORT

08 | Additive manufacturing

Authors: Prof. Dr Michael F. Zäh, Head of Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich
Dr Christian Seidel, Member of the Management Board of the Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich and Head of Additive Manufacturing at Fraunhofer IGCV
Dr Dirk Sellmer, Vice President Research and Development, MAPAL Dr. Kress KG

Introduction

Introduction

In recent years, the additive manufacturing sector has experienced significant growth of an average of around 30 percent per year. This situation is essentially due to the increasing use of the technologies for so-called direct manufacturing, that is the additive manufacturing of end products [1]. While in the 1990s additive manufacturing methods were used almost exclusively to manufacture prototypes, the portion of the turnover due to direct manufacturing was already 33 percent by 2017 [2]. Along with the rapid availability of prototypes, the crucial advantages of the layer manufacturing method are

- in the attainable design freedom that makes it possible to manufacture products optimised for function,
- in the shortening of delivery chains for the supply of spare parts,
- in the possibilities for the customisation of products because the need for forming moulds is low in additive process chains, and also
- in the potential for reducing repair costs and times.

With a total market volume in 2017 of around US$ 7.3 billion [2], the additive manufacturing sector is still a niche sector. The annual growth rate for coming years determined by ten independent institutions is, however, 31 percent [3]. Here it can be seen that this niche sector will be significant in future. It can be assumed, therefore, that additive manufacturing methods will gain cross-sector relevance as production technologies in the medium term.

Today particular attention is dedicated to the additive manufacturing of metal parts. The most widespread method used in industry is laser beam melting, which is also known by trade names such as Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS) for example. There exists a series of other methods for additively manufacturing metal parts, for instance electron beam melting, metal binder jetting, the extrusion methods, laser powder deposition welding, laser wire deposition welding or wire and arc-based additive manufacturing. Today the most relevant method for tool making is laser beam melting. According to a study by Ernst & Young [5], it can be assumed that the total market for this metal processing manufacturing method will become increasingly important in the coming years.

Index

INDEX

Motivation	3
Fundamentals – basic principle of additive manufacturing	3
Tool production using additive manufacturing	6
Challenge of additive manufacturing during tool production	8
Summary	10
Bibliography	11
Imprint	11

Motivation

Motivation

Additive manufacturing methods are also used during the manufacture of precision tools. The manufacturing restrictions that cause limitations during the conventional production of tools, such as the need for machine clamping setups or the restriction to the specific geometries that are possible to manufacture, largely fall away with additive manufacturing. As such, greater design freedom is possible. The construction and design of the tools can be reconsidered and in this way lead to a new tool generation. There is potential above all in the improvement of the mechanical properties, the saving of material or mass due to lightweight design, and the possibility of optimising the cost-effectiveness and the functionality due to hybrid design.

Fundamentals – basic principle of additive manufacturing

Fundamentals – basic principle of additive manufacturing

With the aid of additive manufacturing methods, parts are built up element-by-element or layer-by-layer [1]. Therefore, in comparison to subtractive methods, there is generally a reduced need for material because the parts are generated close to the final contour. The principle of manufacturing by layers is based on the division of the part into virtual cuts that are transferred to physical layers by an additive manufacturing method and placed individually, one on top of the other, such that a three-dimensional part is produced. The geometry is printed directly from computer data or via a 3D scanner. A widespread format is STL data (Surface Tesselation Language) [6, 7]. Developments are moving, however, in the direction of other formats such as AMF (Additive Manufacturing File) or 3MF (3D Manufacturing Format) that can contain, for instance, colour or material information for the part. The principle of additive manufacturing is shown in Figure 1.

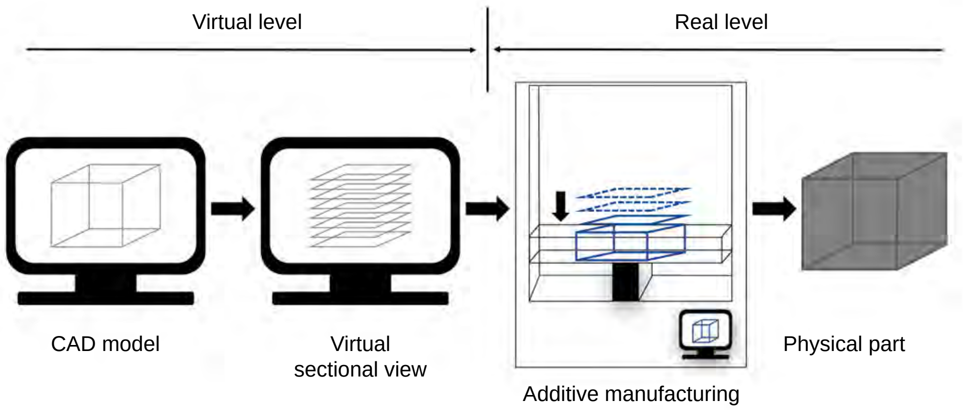

Fig. 1: Principle of additive manufacturing according to Gebhardt [7].

The range of different manufacturing methods can cause confusion. Many manufacturers have established specific process and material designations to differentiate themselves and to create different terminology and therefore supposedly unique selling points. Nevertheless, the additive manufacturing processes are in principle based on the same process. A part is created element-by-element or layer-by-layer from digital data. The material families used are also the same. For this reason, the different additive methods are classified into seven process classes according to ISO/ASTM 52900 (Figure 2) [8].

Fundamentals – basic principle of additive manufacturing

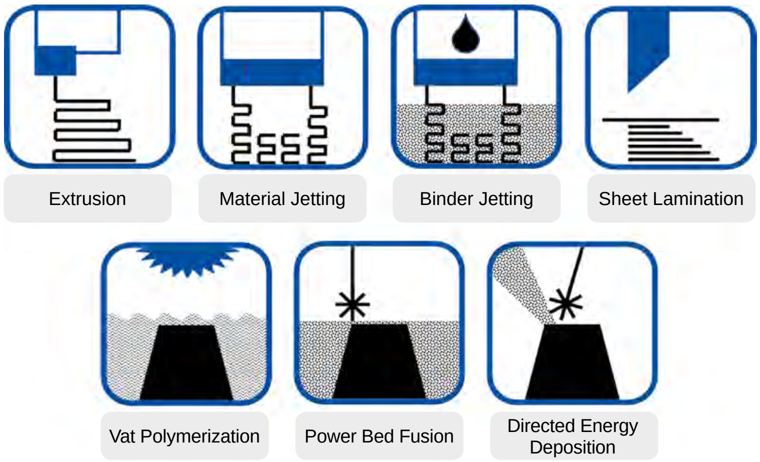

Fig. 2: The different additive methods are divided into seven process classes according to ISO/ASTM 52900 [Fraunhofer IGCV [9]].

Additive manufacturing can be used for very different purposes. The application areas are divided into rapid prototyping, direct manufacturing and rapid tooling. Prototyping relates primarily to the development of models and prototypes. Here additively manufactured parts are produced which have restricted functionality. However, specific features on the parts are sufficiently well-formed. The finished end product is produced during direct manufacturing. The manufacture of tools, that is rapid tooling, is the usage of the additive method for building end products that are used as tools, moulds or forms [6].

Laser beam melting (LBM) is often used in the area of tool making, as well as during the manufacture of end products. LBM is a powder bed-based process during which the powder is melted selectively using a laser beam to produce dense parts. The part is built from bottom to top. The manufacturing principle is shown in Figure 3.

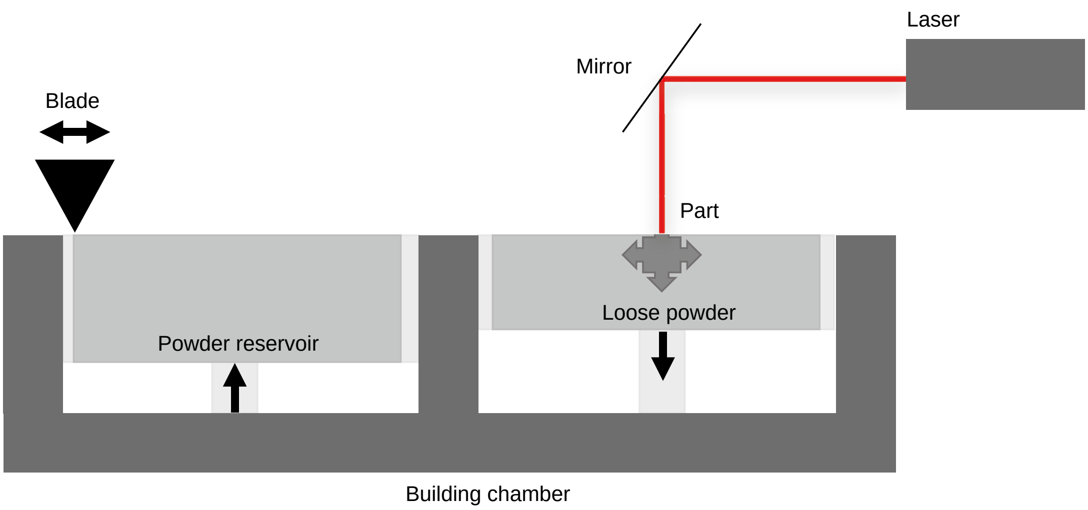

Fig. 3: Principle of the LBM process according to [26].

Different exposure strategies are available for the laser. Typically the strategies shown in Figure 4 are used. With the standard strategy (a), the layer is moved across using simple vectors, starting in a corner of the part. With the stripe strategy (b), the surface to be exposed is divided into individual stripes. The third strategy, also shown in Figure 5, is called chessboard exposure (c). Here the individual layers are divided into squares that are melted in a layer based on a statistical distribution.

Fundamentals – basic principle of additive manufacturing

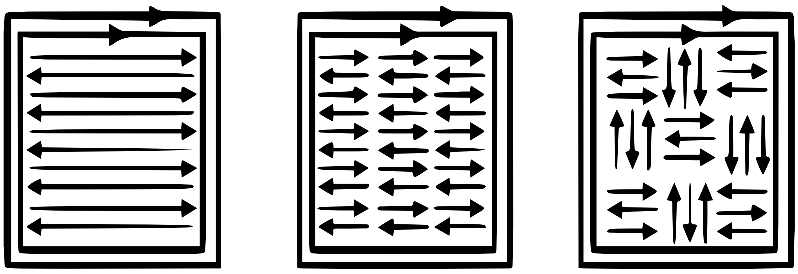

Fig. 4: Typical exposure strategies [10].

The exposure type used has a significant effect on the structure of the part. Stripe and chessboard exposure have the advantage that, as a rule, less intrinsic stress is applied to the part compared to standard exposure. The distribution of the heat in the part also prevents the excessive concentration of the introduction of the heat into one area of the part. The exposure time remains constant, even with different part geometry [11].

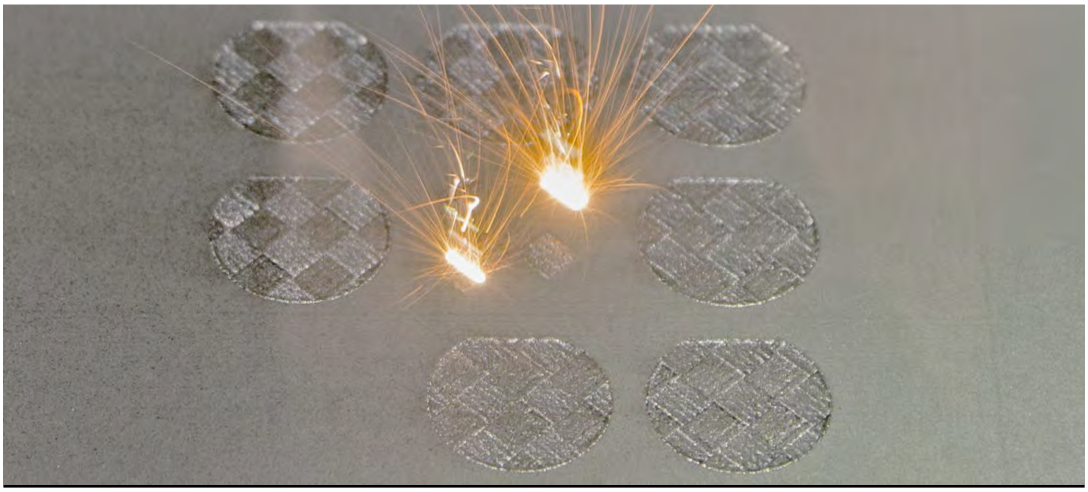

Fig. 5: Illustration of chessboard exposure during the manufacture of the indexable insert drill QTD from MAPAL. The surfaces melted are divided into squares for thermal management.

Moreover, different parameter settings are used for the external contours and the inner areas because the heat conduction conditions in these two areas of the part differ due to the greatly reduced thermal conductivity of the powder material. After a building process, a large part of the powder not melted can be re-used such that the material loss is limited.

The building chamber is limited for many additive manufacturing methods. However, today building chamber sizes of mostly up to 800 x 400 x 500 mm^3 can be realised for the LBM process [12].

Polymers dominated the market during the initial stages of additive manufacturing. Today, metals and ceramics can also be processed and are becoming more and more the industrial standard [13]. Many metals are considered feasible to process commercially using laser beam melting. It can therefore be assumed that relative densities of up to 100 percent can be achieved [8].

Commercially available alloys are limited, however the selection is expanding continuously. Metal materials and alloys used typically include, for example:

- pure titanium and Ti6Al4V,
- different steels: 316L (stainless steel), 17-4PH (stainless steel) and 18Ni300 (tool steel)
- Aluminium alloys: AlSi10Mg, AlSi7Mg, AlSi9Cu3, Scalmalloy® and AlSi12CuNiMg
- Cobalt-chromium alloys: CoCrMo and CoCr
- Nickel-based alloys: Hastelloy x, Haynes 282 Inconel 718 and Inconel 625.

Also precious metals such as gold, silver or platinum can be processed using laser beam melting [14, 15].

Tool production using additive manufacturing

Tool production using additive manufacturing

While with conventional manufacturing methods, tool production is often impaired by machine clamping setups, tools or production equipment, additive manufacturing offers many advantages and considerable freedom in this area. Parts are manufactured almost without the use of tools; as a result entirely new manufacturing possibilities arise. Complex geometries can be designed and the flexibility of the shape increases. On drills, for example, spiral cooling channel bores as well as changes between spiral and straight cooling channels can be realised. It is also possible to produce cooling channels with small tool diameters. Low-weight production is also possible due to a suitably adapted design. Other advantages are the manufacture of hybrid parts, the implementation of internal balancing as well as the more accurate distribution of the material and repairs to existing parts.

The implementation of these advantages can already be realised to a significant degree using LBM technology. As such, tools are often already additively manufactured in series production today.

The integration of functions and the optimisation of the tool are demonstrated by the example of the indexable insert drill QTD (Figure 6). Conventionally in tool bodies with constant helical pitch for indexable insert drills show a central cooling channel to the front where the coolant is distributed to the inserts via a Y-fork. The smaller tool body, the more this coolant supply system impairs the performance of the tool, because the central coolant supply weakens the core of the drill and therefore makes it unstable. Furthermore, the cooling channels have to be made increasingly smaller, which has the consequence of a reducing coolant flow rate to the front to the cutting edge. Thanks to additive manufacturing, these drills can now also be manufactured in smaller diameters than was possible up to now. The cooling channels have a spiral arrangement. In conjunction with non-circular cooling channel profiles, the coolant flow can be increased even further. On the additively manufactured drills, the tool body part manufactured using LBM is fitted to a conventionally manufactured cylindrical shank [28].

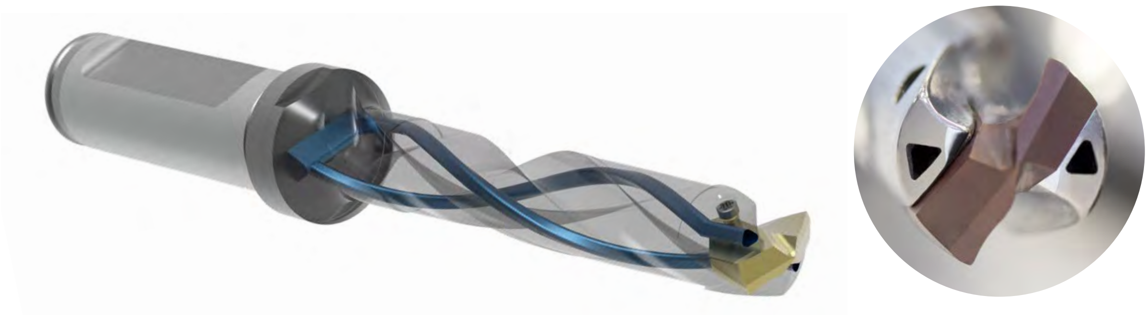

Fig. 6: Indexable insert drill QTD from MAPAL with non-circular cooling channel profile to increase the coolant flow and spiral cooling channels.

The factor of weight reduction is also already established in series production usage. If, for example, an external reamer is too heavy, this situation can affect its functionality. Too much tool mass results in inertia and therefore a limitation in the cutting speeds. For this reason, a material saving contributes to increasing the productivity of the tool because the tool can be moved significantly faster and with higher accuracy. Improved productivity can therefore be achieved, particularly during the machining of shafts with small diameters. Due to the ribbed structure shown in Figure 7, the mass of the external reamer can be reduced by more than half compared to reamers manufactured conventionally [16].

Fig. 7: Mass reduction on a MAPAL external reamer from 390 g to 172 g due to a specially developed ribbed structure inside the tool.

Tool production using additive manufacturing

Additive manufacturing can also increase the functionality and expand the applications for hydraulic clamping technology. Chucks represent the connection between machine and tool. Here many different requirements must be met. Finding the optimal combination of accuracy, process reliability and flexibility, as well as cost-effectiveness is not trivial. There exist various approaches to these different problems. Hydraulic chucks have an advantage especially in relation to the accuracy. However, the brazed joint that has been necessary up to now in the conventional production of this chuck as the connection between tool body and expanding sleeve represents a limiting factor for the thermal stability and the torque transmission. The operating temperature for the hydraulic chuck is maximum 50 °C due to the brazed joint. If higher temperatures occur, the pressure in the chuck increases. The coefficient of expansion of the oil in the interior is 50-times higher than the coefficient of expansion of steel. As a consequence, an overpressure occurs in the interior; this overpressure destroys the brazed joint.

By means of the production of an additively manufactured hydraulic chuck shown in Figure 8, the HighTorque Chuck (HTC) with narrow contour, the range of applications expands and the process reliability improves. Due to the additive manufacturing, the brazed joint is not required. The expanding sleeve can be „pressed in" directly. As a result, the maximum operating temperature increases.

Fig. 8: HTC chuck from MAPAL with optimised function.

Due to additive manufacturing, the long, narrow contour of the HTC can be realised with a back taper of three degrees. This contour was restricted to shrink chucks up to now. In this way the application area for hydraulic chucks has expanded, for example in the area of contour-critical machining tasks and machining with difficult access.

The contour also offers the advantage that custom tools with long projection length are no longer required in many cases. In the shorter standard design, the tools are cheaper and high cutting values can be used due to the short shank length. The tendency to vibration is also reduced, which results in an improved surface finish. In addition, the tool life is increased.

It is therefore already possible today to use additive manufacturing in series production and to manufacture optimised tools with a new design or integrated functions.

Challenge of additive manufacturing during tool production

Challenge of additive manufacturing during tool production

The challenges of additive manufacturing relate not only to the novel design of parts, there are also limits that will need to be overcome in future. Above all the quality of the additively manufactured parts offers potential for improvement in relation to the surface finish, anisotropy effects and limitations on dimensional accuracy. Due to the principle of building by layers, steps are produced in the z direction. The flatter the construction is, the more apparent this effect becomes. The so-called step effect can be reduced if the layer thickness is reduced. However, it cannot be removed completely. As a consequence, post-treatment is necessary if a higher quality surface finish is required. This post-treatment can be either by surface smoothing or by applying a coating [6]. The particle size of the powder can also affect the characteristics of the surface finish [7]. On melting the powder, neighbouring powder may also be melted that then adheres to the surface. This effect also requires post-treatment of the part. Building element-by-element or layer-by-layer in one direction results in anisotropy effects in relation to the mechanical properties and the microstructure. As such, the strength in the z direction (building direction) is in general the lowest [17]. The greater the number of layers, the greater the potential for an erroneous application of a layer or insufficient powder application. A homogeneous structure can also only be produced to a limited extent due to the existing temperature gradients [18].

The process also has a few restrictions. The size of the part is limited by the building chamber, and the properties of the material affect the process. Several factors play a role here. In general, the metals must be suitable for welding and casting, only then can the metallic material be processed successfully using laser beam melting [14]. The powder should also be available in a spherical form and with a specific size distribution. To ensure a good bulk density of the powder, the aim is for a bimodal particle size distribution. A tight particle size distribution ensures the powder flows better [19]. The melting zone in the part during the LBM process is significantly smaller than the finished end product (typically 10^2 to 10^4 times). These locally hot areas are in direct contact with the colder original powder. This situation results in thermal gradients and therefore in intrinsic stresses and distortion, as well as an irregular microstructure [14]. These issues can be detrimental to the dimensional accuracy of parts. The temperature increase and the temperature gradients also play a role during the melting of flat surfaces. The consequence is the so-called temperature gradient mechanism. The already cooled parts of the workpiece bulge against the still hot part and the complete part distorts [11]. The building platform can be pre-heated to counteract thermal distortion. This increases the process reliability and improves the part quality and the dimensional accuracy. Also, on the usage of pre-heating, part of the supporting structures is no longer required. This reduces the process time, the post-treatment effort and the material consumption. The pre-heating temperature required depends on the material and varies between 150 and 1,800 °C. However, only systems with pre-heating temperatures of typically 500 °C are industrially available today [20].

The process also affects the accuracy that can be achieved. The powder particle size and the beam width of the laser limit the resolution of the process. The resolution, that is the dimensional and shape accuracy, that can be achieved up to now is typically greater than 50 µm [20]. The roughness of the surface is also affected by the process. Currently, a minimum roughness figure R_a of around 10 µm can be achieved with laser beam melting [20]. However, this figure is mostly insufficient for functional surfaces or areas that are subjected to dynamic loads because the surface roughness triggers the notch effect if loaded. There are also geometries that can in general not be manufactured additively, or can only be manufactured additively with a very large amount of post-treatment or effort. Threads, precision fit bores and precision fit surfaces require very high accuracy and therefore a high process resolution. To meet the requirements on such features, as a minimum post-treatment is required. For overhangs from an angle of often more than 45° between the direction of building and the building plate, supporting structures are necessary. These structures, on the one hand, support the overhanging structures and, on the other hand, ensure the attachment of the part to the building platform. In this way, unattached areas can be fastened and heat can be dissipated to prevent intrinsic stresses and thermal stresses and to prevent distortion. If repairs to parts are necessary, these can only be realised from planar surfaces.

Not only is the accuracy limited, but also the building speeds. The better the surface quality must be, the smaller the layer thickness must be selected. This aspect, in turn, reduces the building speed. The restriction to the usage of only one laser has resulted in slower building speeds. The usage of multiple laser systems can accelerate the building speed. On the other hand, the hourly rates for the machine are then often higher than for the widely used single-laser systems [25].

As a rule, additive methods cannot compete with the manufacturing costs for conventional, established production technologies for mass production if larger numbers of parts are to be produced. To guarantee, nevertheless, a cost-effective application, it must be ensured that additive production has added value. There are many related approaches. If materials that are difficult to machine or valuable materials are processed, the cost-effectiveness increases compared to conventional machining processes [6] because the material loss can be reduced by building

Challenge of additive manufacturing during tool production

additively. Also if small series production runs or one-offs are required, additive manufacturing can have an advantage due to a reduction or the avoidance of tools or moulds that had to be specifically manufactured (see Figure 9) [13]. The higher costs for additive manufacturing, which for example are due to the increased design effort and new design guidelines as well as the post-treatment, can be compensated by the increase in functionality of the additively manufactured parts [21].

The cost-effectiveness often increases only during the utilisation phase or after the process to manufacture the parts. Cost-intensive, additively manufactured lightweight elements for aerospace can result, for example, in a significant saving in costs during aircraft operation [8].

Other aspects for increasing the cost-effectiveness can be a larger selection of materials that increase the service life of parts subjected to high loads, or the elimination of time-consuming assembly steps. In some situations, the assembly effort reduces significantly due to function integration [22].

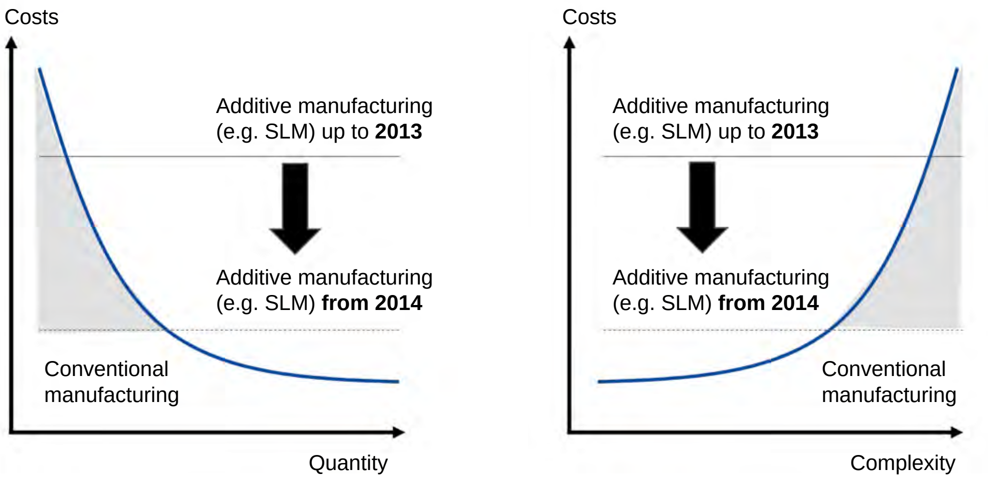

Fig. 9: Comparison of conventional production and additive manufacturing in relation to costs against quantity and geometrical complexity of the part according to Roland Berger [22] and [27].

The complete replacement of conventional manufacturing technologies by additive manufacturing is not to be expected from today's perspective. A combination of additive and conventional manufacturing can lead to the best possible achievement of cost-effectiveness and functional goals. As such, a hybrid design makes it possible to produce a part from a conventional base manufactured at low cost with the addition of an additively manufactured complex part with specific function integration.

Figure 10 shows an example of a hybrid design. The hydraulic chuck HighTorque Chuck with narrow contour is shown. The tool body is manufactured conventionally. The chuck tip and therefore the functional area is added additively using the LBM process. The portion of the additively manufactured area of the part affects the cost-effectiveness. The larger the portion, the more powder and system costs play a role. A comparison is shown in Figure 10. While for variant a the complete chuck tip is built additively, for variant b only the upper part is manufactured additively. Due to this change on the part, the building volume for the additive manufacturing is reduced and less powder is required. The system productive time is reduced from 22 hours to seven hours per run. This aspect has, in turn, positive effects on the system costs and the possible number of building jobs per day. Overall, the costs reduce to around a third for the part, the cost-effectiveness increases without restricting the functionality.

Challenge of additive manufacturing during tool production

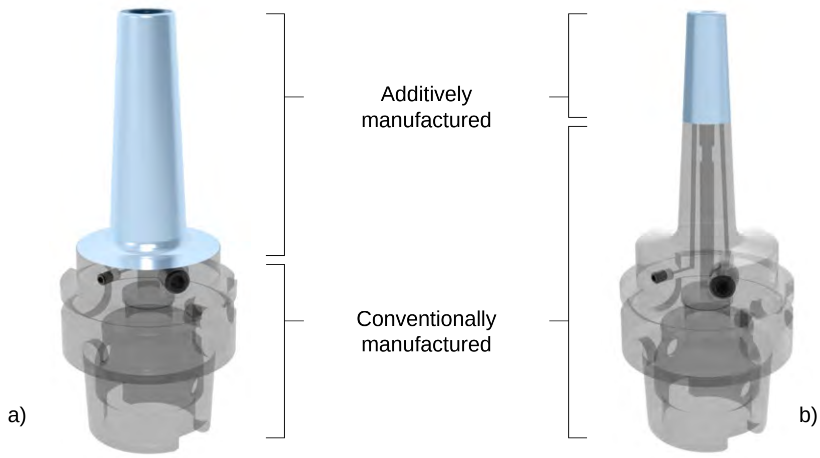

Fig. 10: Hybrid design for an HTC chuck manufactured by MAPAL. The additively manufactured section of the part has been reduced to increase the cost-effectiveness without impairing the functionality.

Summary

Summary

Additive manufacturing will gain in significance in the area of development and production. Especially in the area of tool production, additive manufacturing technology is already suitable for series production use today. Lightweight design, function integration and internal balancing can be implemented advantageously during the manufacture of tools. Steel tool bodies can be built, in the meantime, without any disadvantages in relation to strength; manufacturing conditions are also established and have been proven in series production use. In comparison with conventional manufacturing technologies, there are still limitations in relation to costs and quality, but the added value that additive manufacturing can offer has been recognised by industry and to some extent implemented as far as series production.

There continues to exist, however, the need for improvement in various areas. Flat surfaces and geometrical elements with high accuracy requirements must be post-treated conventionally. There is also no sufficiently industrial solution for the treatment of surfaces that can replace time-consuming post-treatment by machining. However, there are approaches such as laser polishing that make the post-treatment of complex parts possible. During laser polishing, a thin boundary layer on the part is melted and the surface is smoothed due to surface tension. In this way functional surfaces can be implemented without removing material [23].

In relation to the cost-effectiveness, it is necessary to improve the building speeds. This aspect also includes the development of new, faster exposure and building strategies as well as multiple laser concepts. The first manufacturers have already announced, for example, that they will place 12-laser machines on the market in the coming years [24].

To expand the application area of additive manufacturing, it is also important to reliably qualify new materials and in this way to expand the spectrum of materials. The optimisation of the existing process control also represents an important point. Knowledge obtained, for instance about machine-learning approaches, must flow automatically into the process design for new parts and contribute to the improvement of the process parameters and therefore the improvement of the part quality. In relation to the dimensional accuracy, approaches that reduce complex trial runs are also available. In this way the temperature distribution and the behaviour of the mechanical response of the part can be predicted, with limitations, using building process simulation. Using the data determined, it is to some extent possible to design parts with pre-deformation so that the parts meet the stipulated dimensional accuracy [24].

Along with the necessary further technological developments in additive manufacturing, it is down to the technology users to take better account of the existing potential during the new development of products. For this purpose, a re-think during design is necessary. The design guidelines for additive manufacturing must be internalised so the design of parts can generate added value.

In summary, it can be stated that additive manufacturing will not replace conventional technologies in the foreseeable future, but will usefully supplement them. In particular, for the manufacture of precision tools there is major potential that it has only been possible to tap partially up to now.

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Prof. Dr Michael F. Zäh
is Head of Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich

Dr Christian Seidel
is a Member of the Management Board of the Institute for Machine Tools and Industrial Management (iwb) at the Technical University of Munich and Head of Additive Manufacturing at Fraunhofer IGCV
info@iwb.mw.tum.de

Dr Dirk Sellmer
is Vice President Research and Development at MAPAL Dr. Kress KG.
dirk.sellmer@mapal.com

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Postfach 1520 | 73405 Aalen
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