

Quality assurance concept for additive manufacturing

enables series production with defined quality

(A technical article from 2019, authors: A. Dsuban, J. Lohn)



Abstract

Whether used on their own or in combination with conventional manufacturing processes, additive manufacturing processes offer a wealth of new potential. Because components are built up directly, layer by layer, from 3D CAD data, additive processes can produce almost any structure and frequently save material and costs compared with conventional production.

To ensure component quality, quality management standards based on DIN EN ISO 9001:2015 are considered, which are of particular relevance for manufacturing companies. In addition to the quality management standards examined, reproducibility and the verifiability of a high level of product safety are an important aspect addressed in this article. To this end, a quality assurance concept is developed with the aid of various standards documents, which is applicable in particular to powder bed-based manufacturing processes.

Introduction

Additive manufacturing processes offer many advantages over conventional subtractive (turning, drilling, milling) and formative manufacturing processes (forging, casting, bending). For example, time to market can be reduced significantly by building components directly

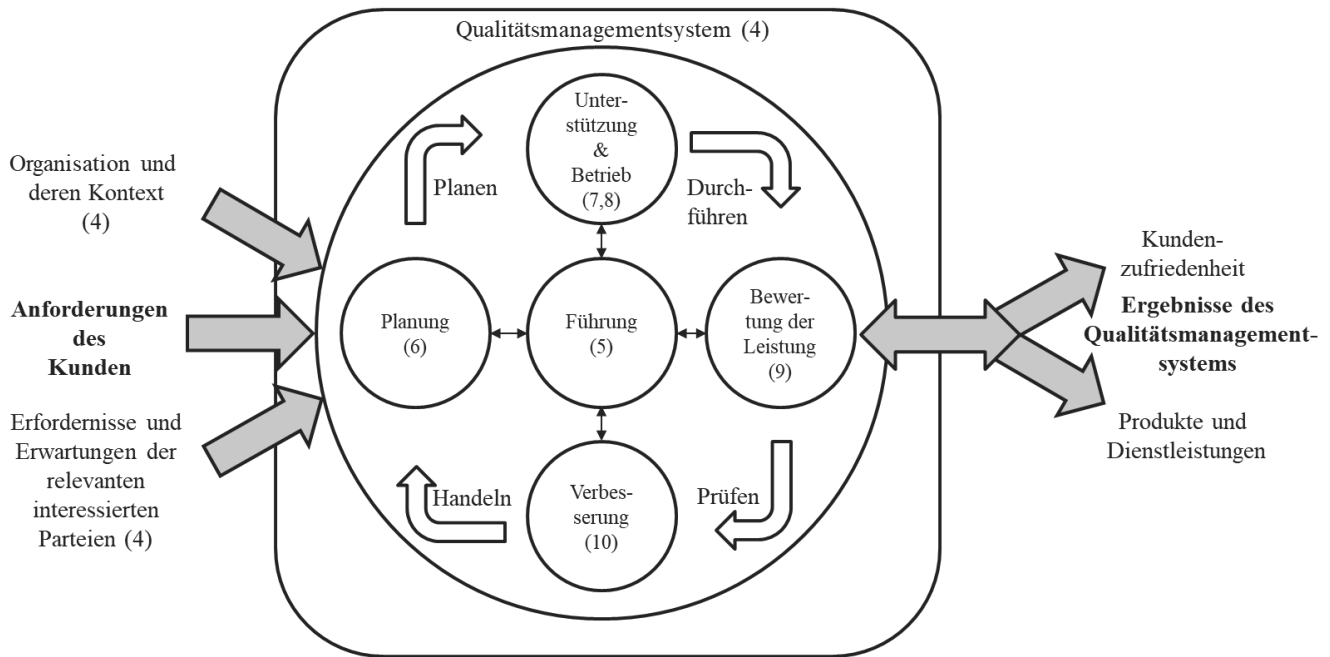
from 3D CAD data. In addition, building parts directly from the design data enables rapid prototyping.

The manufacture of the developed products is subject to only a few restrictions, so that individual and complex components can be produced at no additional cost. Furthermore, recycling process waste results in a high level of cost efficiency, which is characteristic of additive manufacturing.

For example, process waste in selective laser beam melting is reduced by 90%, since unmelted powder from the spaces between the components can be reused for production after passing through a sieving process [1, 2].

In view of these special features, additive manufacturing is said to have disruptive potential, since its special manufacturing process does not build on existing conventional production processes but instead occupies an entirely new field of goods production [1].

In order to make optimal use of the potential of this technology in the future, many aspects still need to be investigated in more detail. Besides the continuous expansion of the range of materials, this includes a standardized quality assurance concept that enables reproducible quality of the manufactured components,



▼ Figure 1: Process model with individual clauses of the standard [4]

thereby expanding the range of applications for 3D-printed goods.

Development of a quality assurance concept for additive manufacturing

The creation and maintenance of products and services that meet a defined level of quality are subject to various quality assurance concepts. The ultimate field of application of the goods produced is a decisive factor for the scope of the quality management to be applied.

Owing to the high potential of additive manufacturing processes for numerous industrial sectors, such as aerospace, suitable quality assurance concepts are being sought that correspond to the respective fields of application. Against this background, a number of quality assurance concepts aimed at meeting the required quality standards are presented below.

The fundamental quality management standard DIN EN ISO 9001:2015 [4] (ISO 9001) is intended to ensure that companies have a functioning management system and do their utmost to be able to offer high-quality products and services. An audit by qualified auditors takes place annually and is confirmed to the company concerned by the issuance of a certificate.

The ISO 9001 certificate helps customers identify companies that have committed to complying with the required standards and implement them.

The required standards are based on the “seven quality management principles”: customer focus, leadership, engagement of people, process approach, improvement, evidence-based decision making and relationship management [3].

ISO 9001 requires the company being audited to comply with and provide evidence of the points listed in the process model (Figure 1).

Evidence of the individual points can be provided with the aid of a manual. This so-called “quality management manual” can be structured individually or according to the clauses of the standard. In line with the structure of the standard, clause 4.1 is to describe the understanding of the organization and its context.

In the following subclause 4.2, the interested parties of the company are to be identified and their needs and expectations listed.

Clauses 4.3 and 4.4 are to address the scope of the quality management system and its processes.

In clause 5, the management level and its tasks within the framework of quality management are to be defined and characterized.

Clause 6 is intended to provide an overview of planning within the company.

In planning, it must be ensured that actions to address risks and opportunities are defined. Furthermore, qual-

ity objectives are to be specified and suitable actions derived for achieving them.

In the following clause 7, the resources that serve to support the company are to be identified and described.

Clause 8 is to illustrate the actual operation of the company. This can address company processes and define their role in the value-adding process more precisely.

In the following clause 9, a detailed analysis of quality within the company is to be carried out, taking continual improvement into account. In this context, the products and services are to be evaluated, customer satisfaction addressed and an evaluation of the quality management system (QMS) performed, among other things.

Finally, clause 10 is to set out the opportunities that contribute to improving the company [3, 4, 5].

IATF 16949 comprises the quality management standard of the automotive industry and builds on [4]. If a company is already ISO 9001 certified, an upgrade to IATF 16949 can reduce the audit duration by up to 50%.

It was published in 2016 and has since replaced ISO/TS 16949:2009, which remained valid until September 14, 2018 [6]. The new quality management standard of the automotive industry aims at a particularly pronounced continual improvement process. This is intended to help detect and avoid sources of error and to minimize variation and waste along the supply chains. Under IATF 16949, customers are placed even more in focus than under ISO 9001. Consequently, customer-specific requirements must be evaluated and taken into account in the quality management system.

In addition, enhanced traceability of the products must be guaranteed to the customer during the manufacturing process and after delivery, over a defined period. With regard to product safety, employees involved in the manufacture and testing of safety-relevant products must meet the corresponding training requirements [7].

DIN EN 9100:2016 (EN 9100) is a quality management standard that addresses the requirements for aviation, space and defense organizations. EN 9100 includes the full scope of ISO 9001 and is extended by a number of additional requirements.

These requirements are shown in italics in the text of the standard to allow better differentiation from the conventional ISO 9001 elements. Key differences arise,

among other things, from the introduction of configuration management and increased requirements with regard to product safety and the handling of counterfeit parts.

The quality management standard further requires increased documentation and evaluation of the processes running within the company.

In this context, the risk management corresponding to ISO 9001 is extended, and proactive risk-based thinking and action is practiced in all of the company's activities (including at the strategic/operational level).

Another point that requires increased attention is supplier monitoring. In this respect, at least a measurement of product or service conformity and of on-time delivery performance is required. In contrast to ISO 9001, EN 9100 also provides for a QM representative who operationally enforces compliance with the requirements of the standard [8, 9].

In view of the product safety that is frequently required, DIN 65124:2018-10 is consulted. It was designed specifically for aerospace and sets high requirements for the manufacture of metallic components by selective laser melting.

The requirements set out below serve as a supplement to and for better implementation of a QM standard.

In order to offer additively manufactured components as a supplier in the industrial sector, a company must fulfill a large number of factors.

As a basis, a suitable production facility with constant ambient conditions and permissible operational equipment must first be provided. Among other things, this requires the use of machines that are installed in accordance with the machine manufacturer's installation conditions and inspected by qualified personnel at regular maintenance intervals.

The resources required for the manufacture of laser beam melted components, such as the metal powder used, must be qualified by the material manufacturer for the additive manufacturing process and must meet the specific process requirements. Important influencing factors to be tested include, for example, the particle size distribution and the chemical composition of the powder.

The specific characteristics of the delivered powder batch are to be documented in a 3.1 inspection certificate and provided to the customer upon delivery. The customer is then obliged to ensure responsible powder handling.

Powder handling in accordance with DIN 65124 requires handling in which the powder cannot be contaminated by foreign matter (dust, desiccant, foreign powder). In addition, preventive measures with regard to oxidation and moisture absorption of the metal powder must be observed. To make powder handling as transparent as possible, batch documentation must be carried out so that the powder can be identified and traced at any time. This documentation requirement also applies to powder blends. The metal powder can be used several times to build laser beam melted components as long as the specifications of the design authority are observed [10].

For process qualification to take place along the manufacturing process, it is a prerequisite that the methods used in the manufacturing chain meet the necessary qualification requirements.

In this context, the function and requirements of the component must be defined with the customer in advance. Accordingly, laser beam melted components are to be categorized into three safety classes in accordance with DIN 65124 [10]:

- Safety class I: Failure under operating conditions results in the loss of the aircraft or spacecraft or its main components, so that persons are directly endangered.
- Safety class II: Failure under operating conditions causes malfunctions. However, the transport task is not endangered until completion.
- Safety class III: Safety and the transport function do not depend on this component.

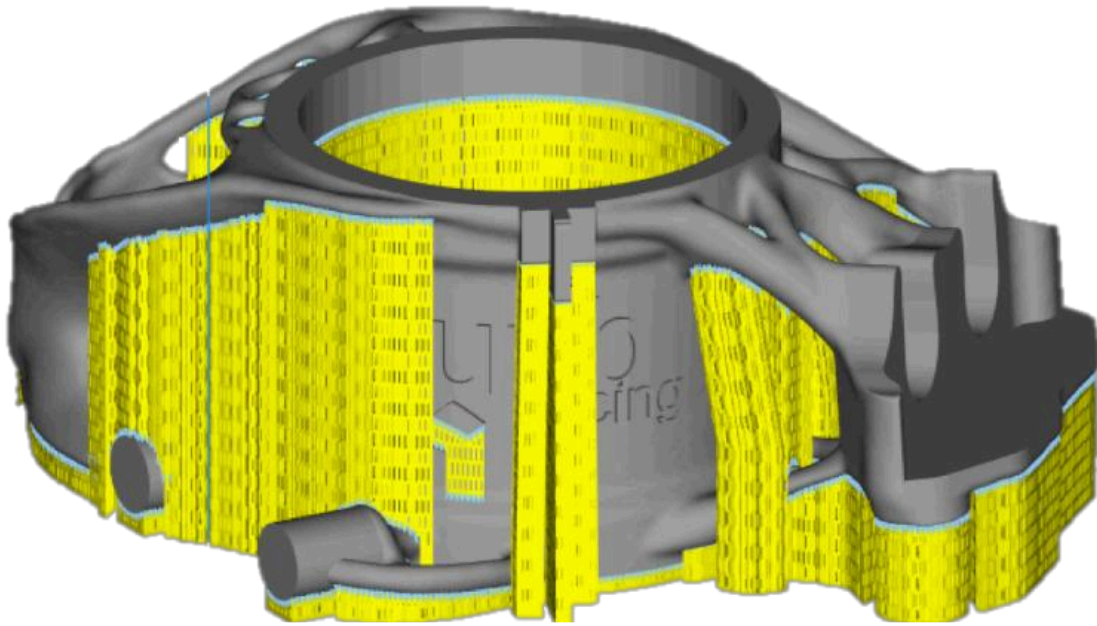
In addition to the safety categorization, the setting parameters along the value chain must be recorded. The documentation serves to improve build process monitoring and, in addition to the exposure parameters, must include the machine type including hardware/software version and serial number, the installation location, the powder batch, the recoater type, the gas specification (grade), the gas settings and the influence of all these factors on the component. Furthermore, information on the manufacturing process

used, the powder specification, the material specification of the generated component and the selected post-treatment method must be recorded. In addition, findings must be made with regard to permissible and impermissible component characteristics and component testing. To achieve build results that are as reproducible as possible, machine-specific data must be defined and documented. These provide information on the component orientation in the build chamber, the type and arrangement of the selected support structures and the number and positioning of the components. For separating the components from the substrate plate and removing the support structures, DIN 65124 provides for methods that have no negative effect on component quality. Methods such as wire EDM and sawing can therefore be used.

For the final surface treatment and to achieve the required surface roughness of the components, blasting processes (corundum, glass beads) and grinding processes, among others, can be used. Subsequent repair of components or rework of defects is only permissible if a corresponding qualification program is followed. This qualification program stipulates that repairs may only be carried out with the customer's written consent, must be performed by appropriately qualified personnel and must be documented in a detailed record that can be clearly assigned to the component. Finally, the test methods specified in the build documents must be carried out. At this point, the customer can request non-destructive and/or destructive testing of the generated components and accompanying specimens. The test methods permitted for this purpose are listed in DIN 65123. The order documents must be documented in accordance with the requirements of DIN EN 9133 and E DIN EN 9130. For adequate documentation, at least the following information must be documented: arrangement and type of support structures, arrangement of the component in the build chamber, arrangement and positioning of individual components, powder used, build platform used, shielding gas used, the information recorded in the production instructions and the production number [10].

Validation of the approach using a laser beam melted wheel carrier

Before the actual manufacture of the wheel carrier by selective laser beam melting (SLM) can begin, the build data must be prepared. During build data preparation, the 3D CAD model of the wheel carrier is provided with



▼ Figure 2: Wheel carrier with support structures

appropriate support structures (Figure 2). The type of structures selected and the orientation of the wheel carrier in the build chamber are documented for reproducibility, and the build job created is saved.

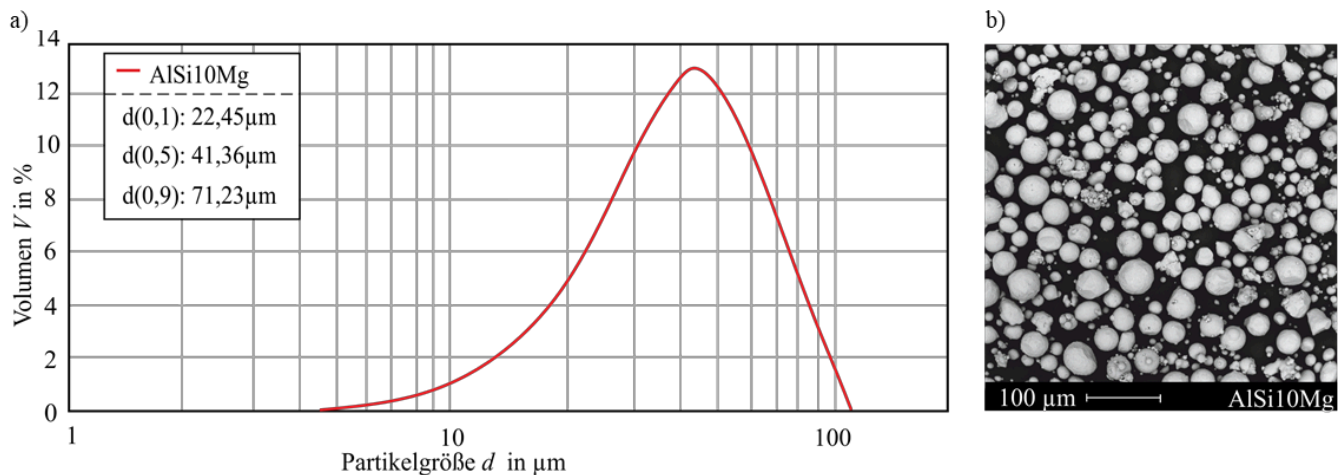
In the next step, the properties of the powder to be used must be determined. This ensures that regular quality checks of the powder take place and that it is suitable for processing by SLM. Against this background, the mean particle size distribution is first determined for the AlSi10Mg powder used (Figure 3a). The particle distribution shows an approximately normal distribution.

Furthermore, the scanning electron micrograph in Figure 3b shows that the individual aluminum particles

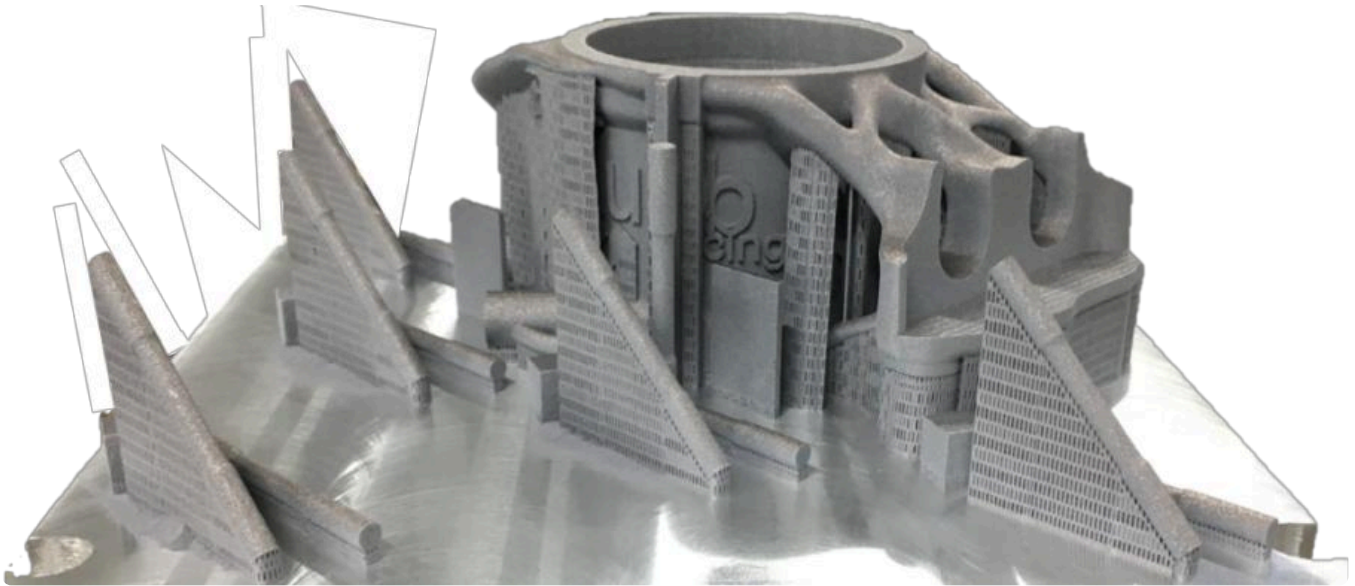
have a spherical structure and few adhesions in the form of so-called satellites.

The moisture content of the AlSi10Mg powder, additionally measured with an infrared moisture analyzer, is 0.24%.

Overall, the powder has good properties and allows a homogeneous powder layer to be deposited. To deposit the powder layer, a steel blade suited to the processed material is used, which spreads the powder over an aluminum substrate plate. To ensure the most uniform possible distribution of the powder along the component geometry, the component is positioned at a 45° angle to the recoating direction. In addition, the speci-



▼ Figure 3: Visualization of relevant powder parameters – a) mean particle size distribution of the AlSi10Mg alloy, b) scanning electron micrograph of the AlSi10Mg powder



▼ Figure 4: Validation of the quality assurance concept using a laser beam melted wheel carrier of the Direct Manufacturing Research Center of Paderborn University

ments required for carrying out quality assurance measures are also oriented on the substrate plate in accordance with VDI 3405 (Figure 4).

After completion, the excess powder is removed from the build chamber with a material-specific tool set, and the manufactured components are separated from the substrate plate with a band saw. The support structures are then removed and the surface treated.

In the next step, a visual inspection of the component is carried out.

The purpose of this visual check is to detect possible defects on the component as early as possible, before further post-processing and quality assurance steps are initiated. A caliper can be used to support this inspection process in order to determine dimensional deviations.

Following the visual inspection, any remaining support residues are removed from the wheel carrier, functional surfaces are reground and the component is sandblasted again. Once the post-processing steps have

been completed, the quality assurance process continues. In this context, a dye penetrant test in accordance with ISO 3452 is first carried out on the wheel carrier in order to reveal, for example, cracks or increased porosity on the component surface (Figure 5).

Once the penetrant has penetrated any existing surface defects, the excess dye is removed with a special cleaner. The developer is then applied so that the dye penetrant remaining in the discontinuities is drawn out by capillary action. This creates a two-dimensional color pattern that provides information about possible defects. As can be seen in Figure 5, the wheel carrier examined is free of near-surface defects. Only the underside of the wheel carrier shows isolated color indications, which can be attributed to increased porosity.

To better assess the surface quality of the wheel carrier, two rectangular specimens ($l = 20 \text{ mm}$, $h = 30 \text{ mm}$, $w = 2 \text{ mm}$) are processed together with the component in the same spatial orientation, followed by a tactile roughness measurement in accordance with DIN EN ISO 4287 in the as-built and sandblasted condition. The values



▼ Figure 5: Dye penetrant testing in accordance with ISO 3452 using the example of a wheel carrier

determined show a significant reduction in surface roughness as a result of abrasive sandblasting. Accordingly, the arithmetic mean roughness R_a was reduced from $23.4\text{ }\mu\text{m}$ to $5.7\text{ }\mu\text{m}$ and the mean roughness depth R_z from $141.0\text{ }\mu\text{m}$ to $35.6\text{ }\mu\text{m}$.

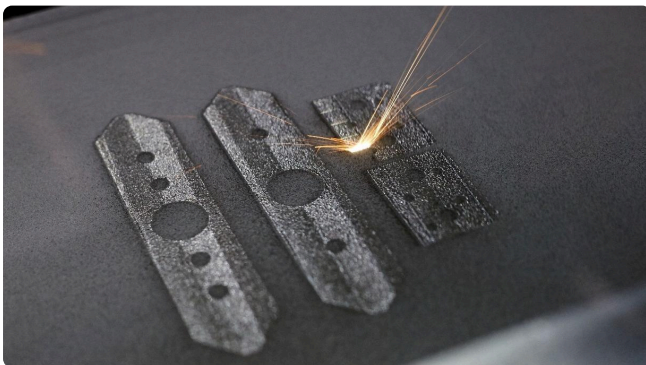
Laser beam melted components typically have a relative density of over 99% [11]. To assess the overall porosity of the wheel carrier, reference specimen cubes with an edge length of 10 mm are processed together with the structure. The cubes are then used for density measurement in accordance with DIN EN ISO 3369.

Before buoyancy weighing can be applied, however, the process-related support structures must be removed and the surface roughness reduced to a minimum by subsequent grinding. If this step is neglected, the subsequent weighing in the test medium may be falsified by adhering air bubbles.

For statistical accuracy, the density measurement is carried out on five different specimen cubes. In addition, the weight measurement both in liquid and in air is repeated three times in order to reduce possible measurement inaccuracies by calculating the arithmetic mean.

The density of the isopropanol at a test temperature of 21°C is 0.786 g/cm^3 . A value of 2.67 g/cm^3 is assumed as the reference value for the material density of the AlSi10Mg alloy [12].

Buoyancy weighing has shown that the density values determined vary only from the third decimal place onward, which indicates a reproducible component density.



As a result, a mean value of 2.66 g/cm^3 can therefore be determined, which results in a relative material density of 99.75% for the specimen cubes. The high relative material density of the specimen cubes can be regarded

as representative of the wheel carrier, so that a high component quality can be assumed.

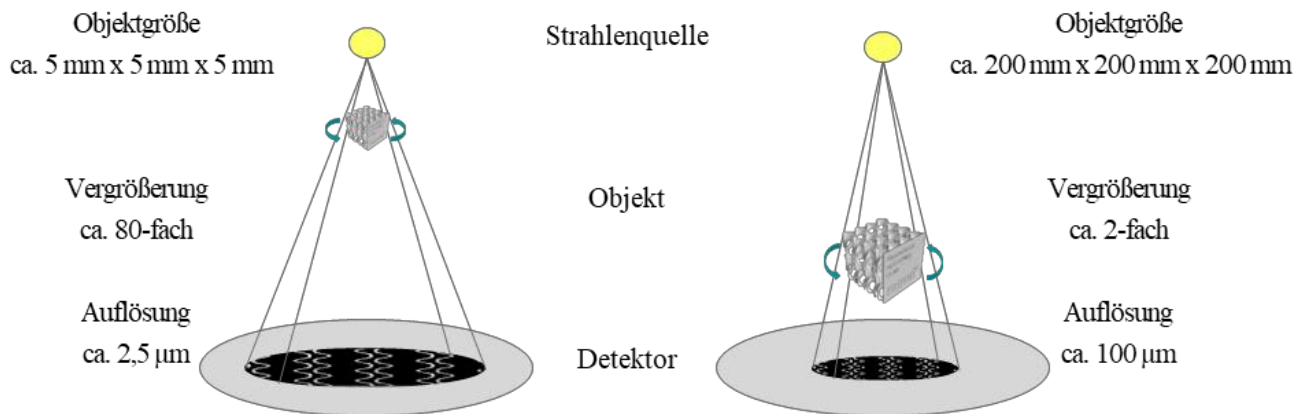
An additionally generated specimen cube is used to determine the component hardness. For this purpose, a hardness measurement is carried out on the cube using the Vickers method. The specimen is first embedded in epoxy resin and then ground to create a smooth and level test surface. The hardness measurement is then carried out on this surface with a test force of 19.61 N (HV2). For statistical accuracy, five measurements are taken, the highest and lowest values are discarded and the mean is calculated from the remaining three values. The average hardness value determined is approx. 107 HV2.

In addition to the component density and hardness determined, the static strength values of the component are also of significant importance. To determine the strength values, accompanying specimens in the form of cylindrical blanks are positioned on the substrate plate in three different orientations in accordance with VDI 3405. After the additive manufacturing process, the specimens are turned to the corresponding specimen shape in accordance with DIN 50125-B and tested according to the standard.

Another test method carried out in the course of this article is computed tomography (CT). Computed tomography generates three-dimensional information about a component. For this purpose, the object to be tested is positioned on a turntable in a CT scanner and a large number of X-ray projections are taken from different angles. The projection images are then processed by a reconstruction system and a three-dimensional CT image is created. Based on the information generated, dimensional deviations and defects can be detected, even in complex components. Every CT scan produces so-called artifacts, which have a negative effect on the result of the scan. The occurrence of these artifacts depends on a large number of factors. The most relevant influencing variables are described in more detail below.

Object size is a decisive influencing factor when performing a CT scan. Object size and the resolution generated by the CT scan are significantly interdependent (Figure 6).

The smaller the object to be scanned, the closer it can be positioned to the radiation source and the larger the



▼ Figure 6: Dependence on object size in CT scanning

image projected onto the detector. The scan data are ultimately generated from this.

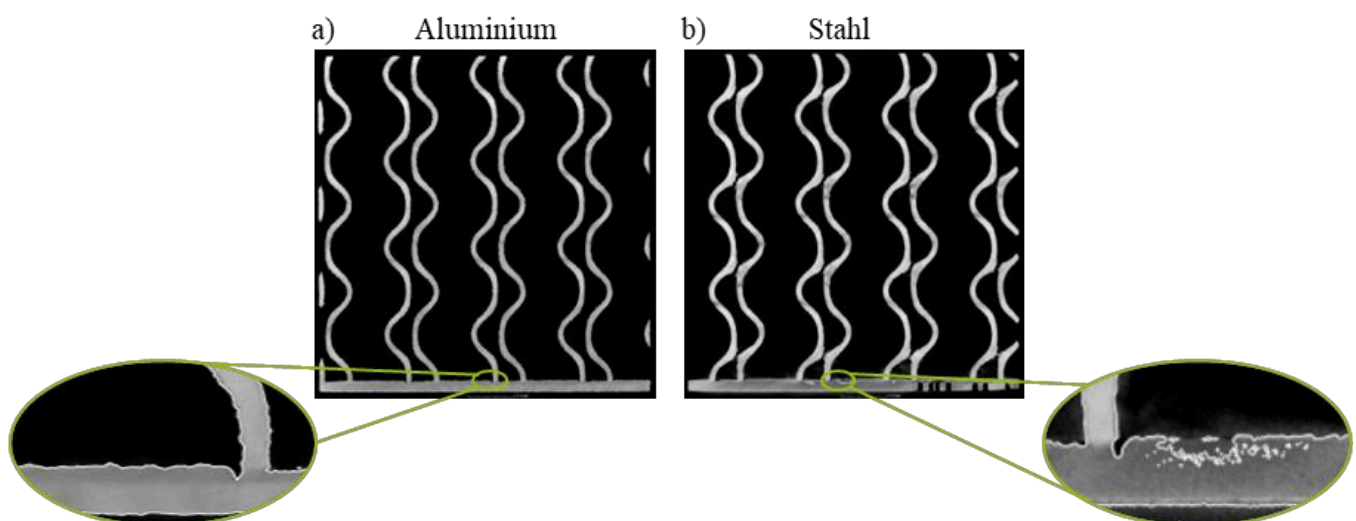
When performing a CT scan, the wall thickness of the object must always be taken into account. The more massive the area to be penetrated by the radiation, the more the generated CAD data deviate from the original component. It must always be borne in mind that an object is rotated through 360° during scanning. For this reason, depending on its orientation relative to the radiation source, the component may present a large area to be penetrated. Large geometries to be penetrated produce more artifacts. During data reconstruction, these artifacts lead to a distorted image of reality.

Another influencing factor that affects the result or the general feasibility of the CT scan is the material of the object. As material density increases, determining the component surface becomes more difficult. Owing to the high material densities of metals, the physical limits

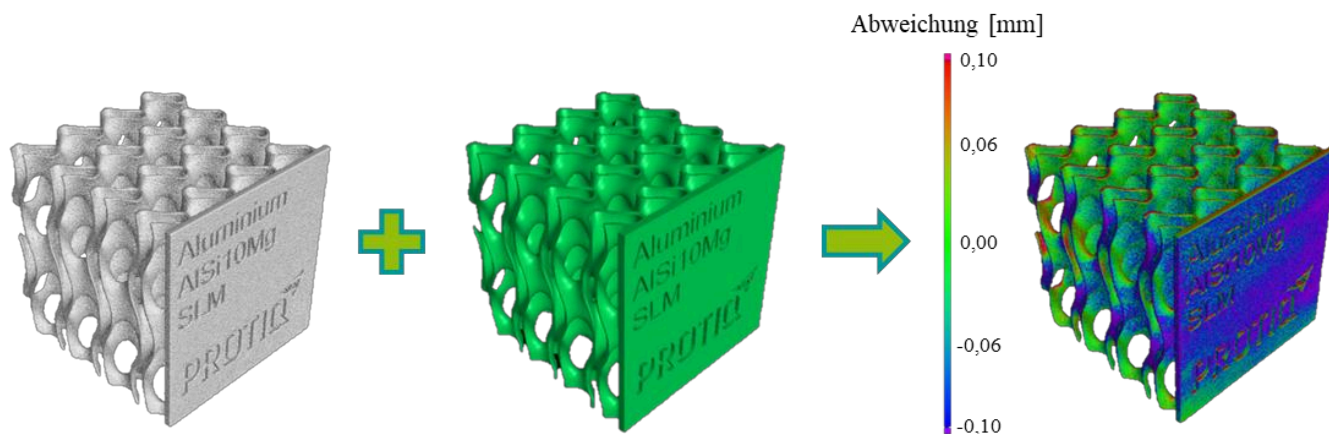
of computed tomography are quickly reached and disruptive artifacts occur more frequently. To illustrate this effect, two gyroids made of aluminum and steel processed by SLM were scanned in the CT scanner. Figure 7 shows how surface determination becomes more difficult as material density increases.

The image in Figure 7a shows a homogeneously determined surface, whereas the image in Figure 7b shows numerous artifacts. These artifacts do not reflect the real properties of the scanned component and therefore falsify the result of the CT scan. For this reason, no representative quality assurance by means of a target/actual comparison could be carried out with data falsified in this way.

To create a target/actual comparison, three-dimensional information about a component is first generated. The data obtained (actual data) are then superimposed on the CAD data provided (target data) using a specific



▼ Figure 7: Material dependence in CT scanning – a) CT image of an aluminum gyroid with few artifacts, b) CT image of a steel gyroid with numerous artifacts



▼ Figure 8: Procedure of a target/actual comparison of a laser beam melted gyroid

alignment logic, the so-called “best-fit” method (Figure 8). In the next step, existing deviations are displayed using a false-color model. The false-color model visualizes in which areas the generated CAD data of the 3D-printed component deviate from the target data provided. Computed tomography thus enables the measurement of complex or internal geometries and freeform surfaces.

The green area indicates agreement between the target and actual data. Areas in which the component is larger than the target data are shown in red, and areas in which the component is smaller than the target data are shown in blue. The following Figure 9 visualizes the false-color model of the processed wheel carrier from four different views. The predominantly green coloring shows that the component deviates only slightly from the original CAD model.

The front view and the rear view in particular show predominantly green areas, so that a deviation of almost 0 mm can be assumed. Most deviations occur at the connection points to the lower control arm. Here, the top view shows a deviation of mostly 0.15-0.30 mm, which increases to over 0.45 mm toward the edge. On the underside, by contrast, the deviations are somewhat smaller at 0-0.15 mm. Only the round connection areas show a negative deviation, which, however, can be attributed to mechanical material removal during post-processing. Overall, however, the deviations of the processed wheel carrier are very small and lie predominantly within the specified tolerance range of 0.7% [13].

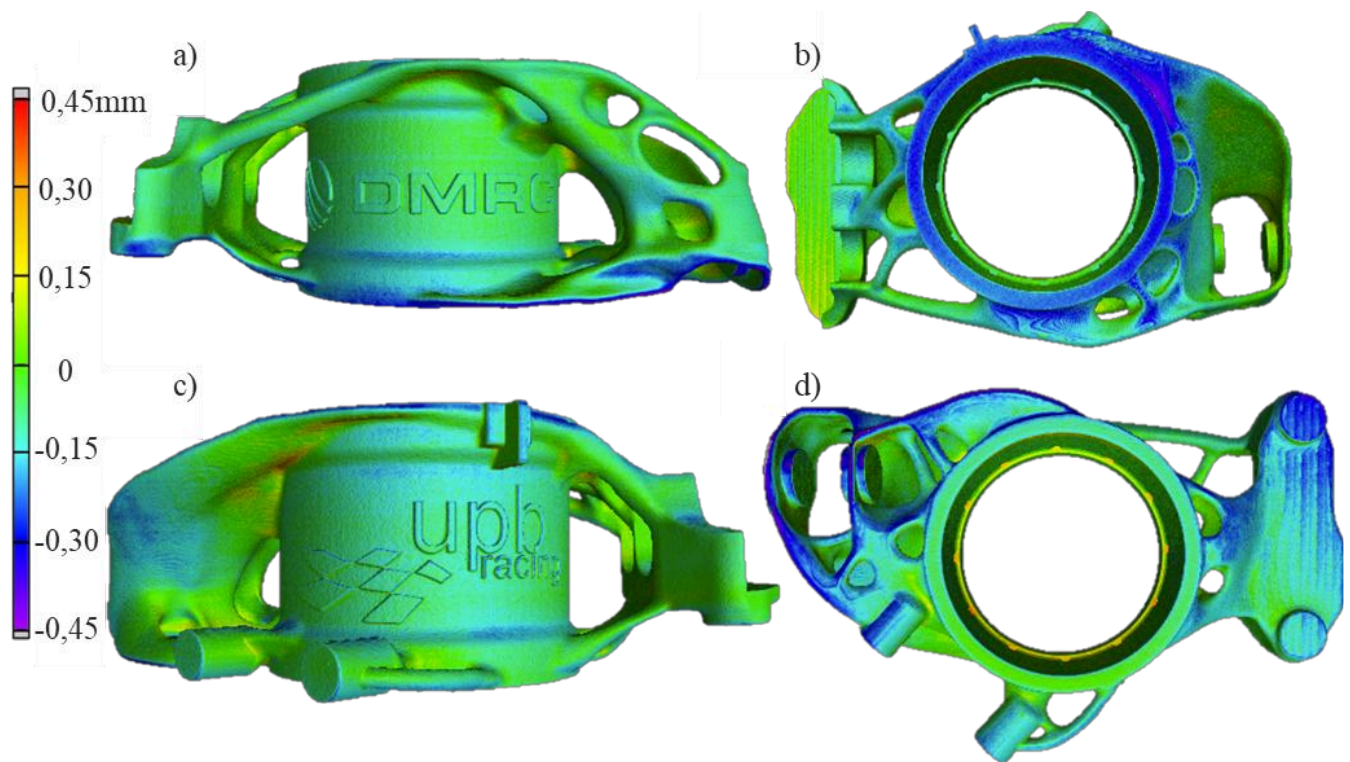
Summary and outlook:

When additive manufacturing is used for the direct, tool-free production of end products, a high level of quality must be guaranteed. In the course of these investigations, suitable test methods were selected based on applicable standards and applied by way of example to demonstrate their transferability to additive manufacturing. The properties of the powder raw material, the material properties of the built components and the geometric accuracy of the components were examined. In order to also carry out destructive tests, specimens representative of the component properties were manufactured in the same build job in accordance with VDI 3405 and tested. [11]

The results of the investigations show that, on the basis of the characteristic values determined, a statement can be made about the component quality achieved.

Irregularities in the build process are usually revealed immediately by the measurement results.

With the quality assurance concept developed, a large number of influencing variables can already be controlled and limit values defined. However, it became clear that further optimization of machine and system technology is required for reliable production with consistent quality. The integration of additional online process monitoring instruments, such as thermography, optical systems and other sensors, is desirable.



▼ Figure 9: Target/actual comparison of the aluminum wheel carrier – a) front view, b) top view, c) rear view, d) bottom view

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