# Quality assurance concept for additive manufacturing enables series production in defined quality

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

## Summary

The use of additive manufacturing processes, either alone or in combination with traditional manufacturing methods, offers many new potentials. Due to the direct layer-by-layer construction of components from 3D CAD data, additive processes can realize virtually any structure and often save material and costs compared to conventional production.

To ensure component quality, quality management standards based on DIN EN ISO 9001:2015 are considered, which are of particular relevance to manufacturing companies. In addition to the quality management standards considered, reproducibility and the verifiability of high product safety are important aspects addressed in this article. Accordingly, a quality assurance concept is developed using various standards, which is particularly applicable 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, product launch time can be significantly reduced by directly constructing components from 3D CAD data. Furthermore, direct construction from design data offers the possibility of rapid prototype generation. The manufacturing of the developed products is subject to few restrictions, allowing the production of customized and complex components at no additional cost. Furthermore, the recycling of process waste results in the high cost-effectiveness that is a hallmark of additive manufacturing.

As a result, for example, process waste in selective laser beam melting is reduced by 90%, since unmelted powder from the interstices between components can be reused in production after undergoing a sieving process [1, 2].
Considering these special features, additive manufacturing is said to have disruptive potential, as its special manufacturing process does not build on existing conventional production methods, but rather occupies a completely new field of goods production [1].
To optimally utilize the potential of this technology in the future, many aspects still need to be investigated in more detail. In addition to the continuous expansion of the range of materials, this includes a standardized quality assurance concept that enables reproducible quality of the manufactured components, thus expanding the range of applications for 3D-printed goods.

## Development of a quality assurance concept for additive manufacturing

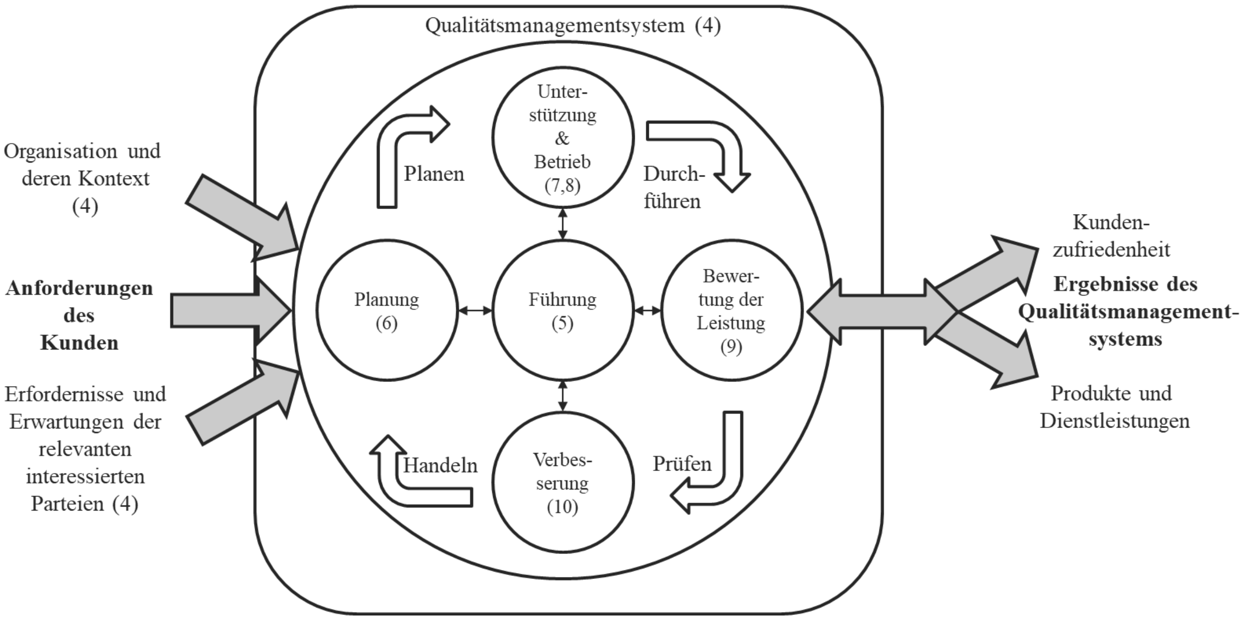
The creation and maintenance of products and services that meet a defined quality standard are subject to various quality assurance concepts. The ultimate application of the produced goods is a key factor in determining the scope of the quality management system to be applied.

Due to the high potential of additive manufacturing processes for numerous industrial sectors, such as aerospace, suitable quality assurance concepts are sought that correspond to the respective application areas. 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 designed to ensure that companies have a functioning management system and do their utmost to offer high-quality products and services. An audit by expert auditors is conducted annually, and the respective company is confirmed by the issuance of a certificate.
The ISO 9001 certificate helps customers identify companies that are committed to and implement required standards.

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

ISO 9001 requires the audited company to comply with and demonstrate the points listed in the process model (Graphic 1).




Graphic 1: Process model with individual standard chapters [4]

The individual points can be verified with the help of a manual. This so-called "quality management manual" can be subdivided individually or according to the standard chapters. Chapter 4.1 describes the understanding of the organization and its context in accordance with the subdivision of the standard.

In the following subchapter 4.2, the company's interested parties must be identified and their requirements and expectations listed.

Chapters 4.3 and 4.4 look at the scope of the quality management system and its processes.

Chapter 5 defines and characterizes the management level and its tasks within the framework of quality management.

Chapter 6 provides an overview of planning in the company.
When planning, it is important to ensure that measures for dealing with risks and opportunities are defined. Furthermore, quality objectives must be specified and suitable measures derived for their implementation.
In the following chapter 7, the resources used to support the company must be identified and described.
In chapter 8, the actual operation of the company must be clarified. To this end, company processes can be discussed and their role in the value-adding process can be defined in more detail.
In the following chapter 9, a detailed analysis of quality in the company must be carried out, taking continuous improvement into account. In this context, the products and services are to be evaluated, customer satisfaction is to be addressed and an assessment of the quality management system (QMS) is to be carried out.
Abschließend sind in Kapitel 10 die zur Verbesserung des Unternehmens beitragenden Möglichkeiten zum Ausdruck zu bringen [3, 4, 5].
Finally, Chapter 10 outlines the opportunities for 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 was valid until September 14, 2018 [6]. The automotive industry's new quality management standard is aimed at a particularly pronounced continuous improvement process. This is intended to help detect and avoid sources of error and minimize dispersion and waste along the supply chain. IATF 16949 places an even greater focus on customers than ISO 9001, meaning that customer-specific requirements must be evaluated and taken into account in the quality management system.
In addition, the customer must be guaranteed increased traceability of the products during the manufacturing process and after delivery over a defined period of time. Against the background of product safety, employees involved in the manufacture and testing of safety-relevant products must fulfill the corresponding training requirements [7].
DIN EN 9100:2016 (EN 9100) is a quality management standard aimed at the requirements of aviation, aerospace and defence organizations.

EN 9100 contains 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 in order to better differentiate them from the classic ISO 9001 components. Significant differences include the introduction of configuration management and the increased requirements with regard to product safety and the handling of counterfeit parts.
The quality management standard also requires increased documentation and evaluation of the processes taking place in the company.
In this context, risk management in accordance with ISO 9001 is extended and proactive risk-based thinking and action is practiced in all activities (including strategic/operational level) of the company.
Another point that needs to be looked at more closely is supplier monitoring. In this respect, at least one measurement of product or service conformity and adherence to delivery dates is required. In contrast to ISO 9001, EN 9100 still provides for a QM representative who enforces the fulfillment of the standard requirements [8, 9].
In view of the frequently required product safety, DIN 65124:2018-10 is used. This was designed specifically for the aerospace industry and specifies high requirements for the manufacture of metallic components using the selective laser melting process.

The requirements listed below serve to supplement and improve the implementation of a QM standard.
In order to offer additively manufactured components as a supplier in the industrial sector, a company must fulfill a number of factors.
As a basis, a suitable operating site with constant peripheral conditions and permissible operating equipment must first be provided. This requires, among other things, the use of machines that are installed in accordance with the machine manufacturer's installation conditions and inspected by expert personnel at regular maintenance intervals.
The resources required for the production of laser melting 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 checked are, for example, the particle size distribution and the chemical composition of the powder.

The specific parameters of the delivered powder batch must be documented in a 3.1 acceptance test 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 objects (dust, drying agents, foreign powder). In addition, preventive measures must be observed with regard to oxidation and moisture absorption of the metal powder. In order 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 mixtures. The metal powder can be used several times for the construction of laser melting components as long as the specifications of the development center are adhered to [10].
In order for process qualification to take place along the production process, it is assumed that the methods used in the production chain comply with the required qualification specifications.

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

| | |
|---|---|
| Safety class I: | Failure under operating conditions results in loss of the aerospace equipment or its main components, putting people at risk. |
| Safety class II: | Failure under operating conditions will cause malfunctions. However, the transport task is not endangered until completion. |
| Safety class III: | The safety and transport function does not depend on this component. |

In addition to the safety categorization, the setting parameters along the value-added process must be recorded. The documentation serves to improve the monitoring of the construction process and must include the exposure parameters, the machine type including hardware/software version and serial number, the installation location, the powder batch, the coater type, the gas specification (type), the gas settings and the influence of all the factors mentioned 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 type must be recorded.

In addition, findings must be made with regard to permissible and impermissible component characteristics and component testing. In order to achieve the most reproducible construction results possible, system-specific data must be defined and documented. These provide information about the component orientation in the installation space, the type and arrangement of the selected support structures and the number and positioning of the components. When separating the components from the substrate plate and removing the support structures, DIN 65124 specifies procedures that have no negative influence on the component quality.

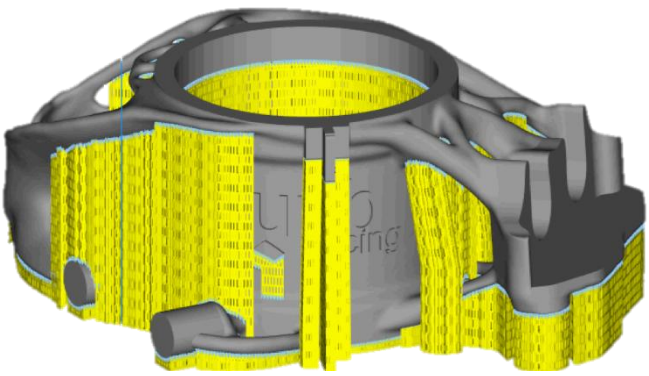
This means that processes such as wire erosion and sawing can be used.

Blasting processes (corundum, glass beads) and grinding processes can be used for the final surface treatment and to achieve the required surface roughness of the components. Subsequent repair of the components or repair of defects is only permitted if a corresponding qualification program is adhered to.

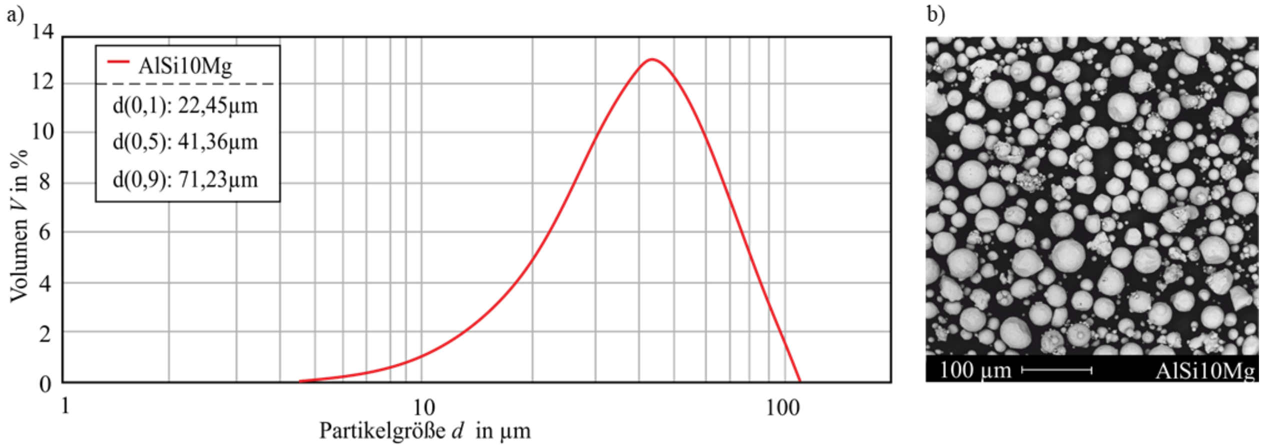
This qualification program stipulates that repairs may only be carried out with the written consent of the customer, that they must be carried out by appropriate specialist personnel and that they must be documented in a detailed report that can be clearly assigned to the component. Finally, the test procedures specified in the construction documents must be carried out. At this point, the customer can request non-destructive and/or destructive test procedures on the generated components and accompanying samples. The test methods permitted for this 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. At least the following information must be documented to ensure adequate documentation: Arrangement and type of support structures, arrangement of the component in the build space, arrangement and positioning of individual components, powder used, build platform used, shielding gas used, the information recorded in the manufacturing instructions and the manufacturing number [10].

## Validation of the procedure using a laser-melted wheel carrier

Before the actual production of the wheel carrier component using selective laser beam melting (SLM) can begin, the construction data must be prepared. During the preparation of the construction data, the 3D CAD model of the wheel carrier is provided with corresponding support structures (Graphic 2). The type of structures selected and the alignment of the wheel carrier in the build space are documented for reproducibility and the build job created is saved.



Graphic 2: Wheel carrier with support structures

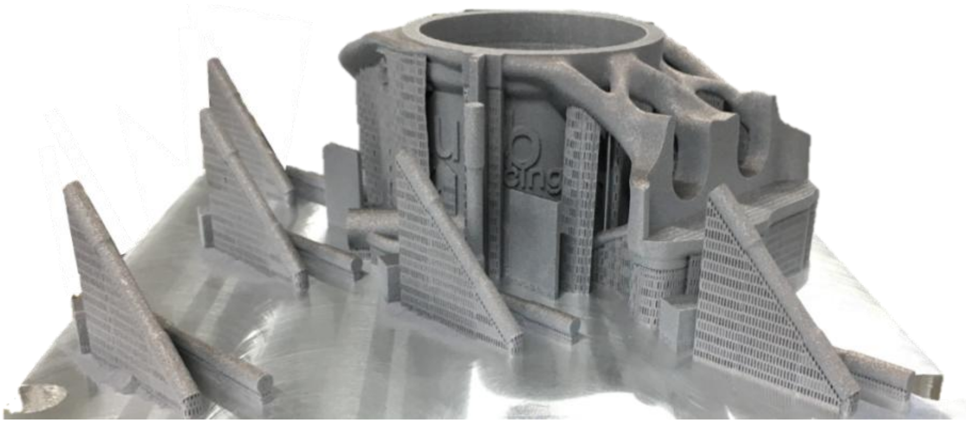



The next step is to determine the properties of the powder to be used. In this way, it can be ensured that regular quality checks are carried out on the powder and that it is suitable for processing using the SLM process. With this in mind, the average powder particle distribution is first determined for the AlSi10Mg powder used (Graphic 3a). The particle distribution shows an approximately normal distribution.

Graphic 1: Visualization of relevant powder influence quantities
a) Average powder particle distribution of the AlSi10Mg alloy
b) Scanning electron micrograph of the AlSi10Mg powder

In addition, the scanning electron micrograph in Figure 3b shows that the individual aluminum particles have a spherical structure and show few adhesions in the form of so-called satellites.
The additional moisture content of the AlSi10Mg powder measured with an infrared moisture analyzer is 0.24%.

Overall, the powder has good properties and enables a homogeneous powder layer to be deposited. A steel blade is used to deposit the powder layer, which distributes the powder on an aluminum substrate plate to match the processed material. To ensure that the powder is distributed as evenly as possible along the component geometry, the component is positioned at a 45° angle to the coating direction. In addition, the test specimens required to carry out quality assurance measures are also oriented on the substrate plate in accordance with VDI 3405 (Graphic 4).



Graphic 2: Validation of the quality assurance concept using a laser-melted wheel carrier from the Direct Manufacturing Research Center at Paderborn University

After completion, the excess powder is removed from the installation space using a material-specific tool set and the manufactured components are separated from the substrate plate using 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.

This visual inspection serves to ensure that possible defects in the component can be detected as early as possible before further steps are initiated as part of post-processing and quality assurance. To support this inspection process, a caliper gauge can be used to determine dimensional deviations.

Following the visual inspection, any remaining support residue is removed from the wheel carrier, functional surfaces are reground and the component is sandblasted again. Once the reworking steps have been completed, the quality assurance process continues. In this context, a dye penetration test in accordance with ISO 3452 is first carried out on the wheel carrier in order to identify cracks or increased porosity on the component surface, for example (Graphic 5).

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

Graphic 3: Dye penetration test according to ISO 3452 using the example of a wheel carrier

To better assess the surface characteristics of the wheel carrier, two rectangular specimens (l = 20 mm, h = 30 mm, b = 2 mm) are processed together with the component in the same spatial orientation and then a tactile roughness measurement is carried out in accordance with DIN EN ISO 4287 in the as-built and sandblasted condition. The values determined here show a significant reduction in surface roughness due to abrasive sandblasting. Accordingly, the arithmetic mean roughness Ra was reduced from 23.4 µm to 5.7 µm and the average roughness Rz from 141.0 µm to 35.6 µm.

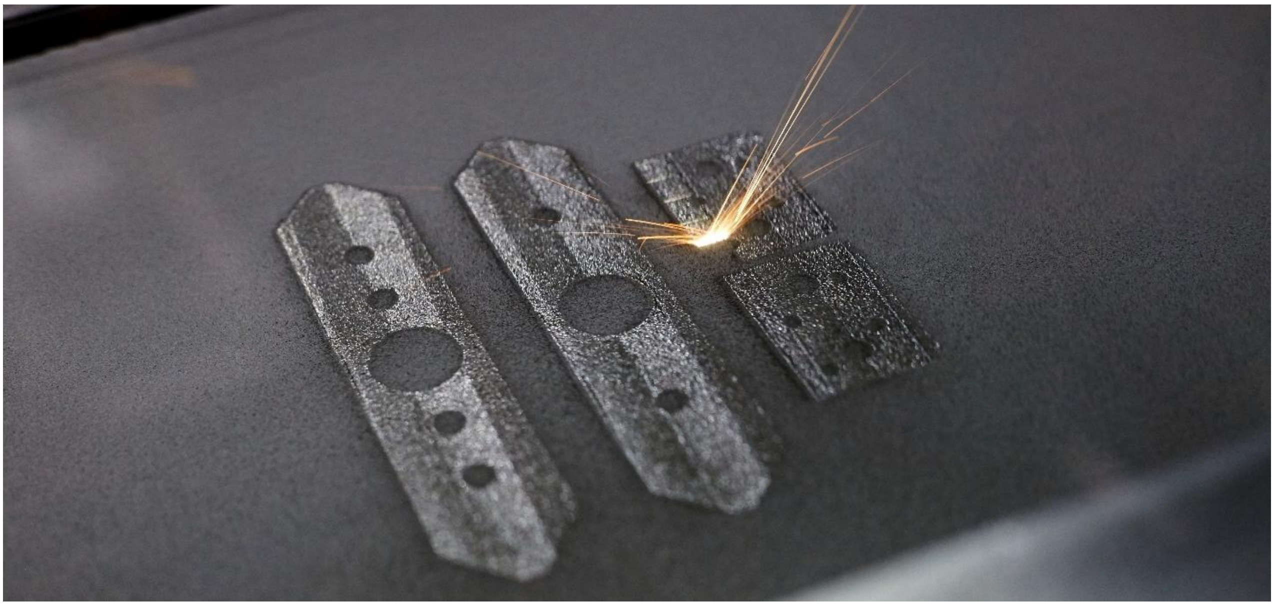
Laser beam fusion components typically have a relative density of over 99% [11]. In order to make a statement about the overall porosity of the wheel carrier, reference sample cubes with an edge length of 10 mm are processed together with the structure. The cubes are then used for density measurement in accordance with DIN EN ISO 3369.

However, before buoyancy weighing can be used, the process-related support structures and surface roughness must be removed and reduced to a minimum by subsequent grinding. If this work step is neglected, the subsequent weighing in the test medium can be distorted by adhering air bubbles.

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

The density of the isopropanol corresponds to 0.786 g/cm3 at a test temperature of 21°C. The reference value for the material density of the AlSi10Mg alloy is assumed to be 2.67 g/cm3 [12].

The buoyancy weighing has shown that the determined density values show changes from the third decimal place, which indicates a reproducible component density.

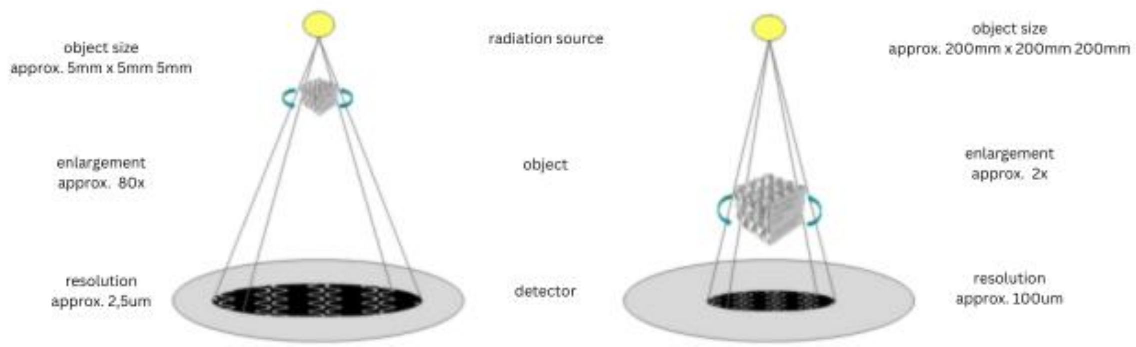


As a result, a mean value of 2.66 g/cm3 can be determined, resulting in a relative material density of 99.75% for the sample cubes. The high relative material density of the sample cubes can be considered representative of the wheel carrier, meaning that a high component quality can be assumed.

An additionally generated sample cube is used to determine the component hardness. For this purpose, a hardness measurement is carried out for the cube using the VICKERS method. The sample is first embedded in epoxy resin and then ground to create a smooth and horizontal 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 carried out, the highest and lowest measured values are deleted and the mean value is calculated from the remaining three values. The average hardness value determined is approx. 107 HV2.
In addition to the determined component density and hardness, the static strength parameters of the component are also of significant importance. To determine the strength parameters, accompanying samples 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 in accordance with the standard.

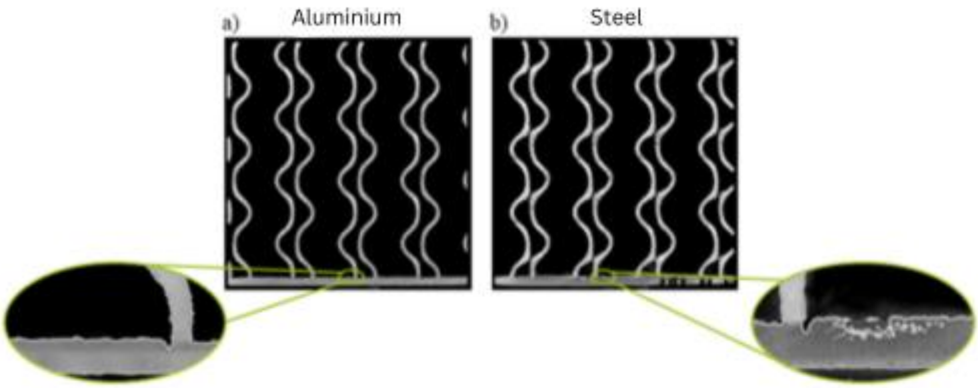
Computed tomography (CT) is another testing method used in this article. Computed tomography is used to generate three-dimensional information about a component. For this purpose, the object to be tested is positioned in a CT scanner on a turntable and a large number of X-ray projections are recorded from different angles. The projection images are then processed by a reconstruction system and a three-dimensional CT image is created. The information generated can be used to detect dimensional deviations and defects, even in complex components. Every CT scan produces so-called artifacts, which have a negative impact on the results of the scan. The occurrence of these artifacts depends on a variety of factors. The most relevant influencing factors are described in more detail below.

The object size is a decisive influencing factor when performing a CT scan. The object size and the generated resolution of the CT scan are significantly dependent on each other (Graphic 6).
The smaller the object to be scanned, the closer it can be positioned in front of the radiation source and a larger image can be projected onto the detector. The scan data is then generated from this.




Graphic 4: Object size dependence in CT scanning

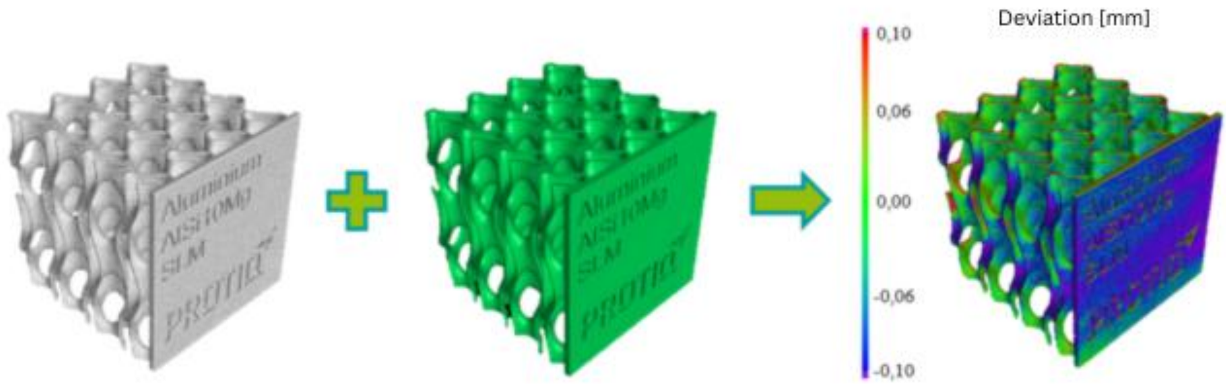
When carrying out a CT scan, the wall thickness of the object must always be taken into account. The thicker the surface to be scanned, the more the generated CAD data will deviate from the original component. It must always be taken into account that an object is rotated by 360° during scanning. For this reason, the component may have a large surface to be scanned when aligned with the beam source. With large geometries to be scanned, artifacts are more likely to occur. These artefacts lead to a distorted image of reality being generated during data reconstruction.
Another factor that influences the result and the general feasibility of the CT scan is the material of the object. As the material density increases, it becomes more difficult to determine the component surface. Due to the high material density 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 using the SLM method were imaged in the CT scanner. Figure 7 shows the extent to which surface determination becomes more difficult with increasing material density.




Graphic 5: Material dependence in CT scanning
a) CT image of an aluminum gyroid with few artifacts
b) CT scan of a steel gyroid with numerous artifacts

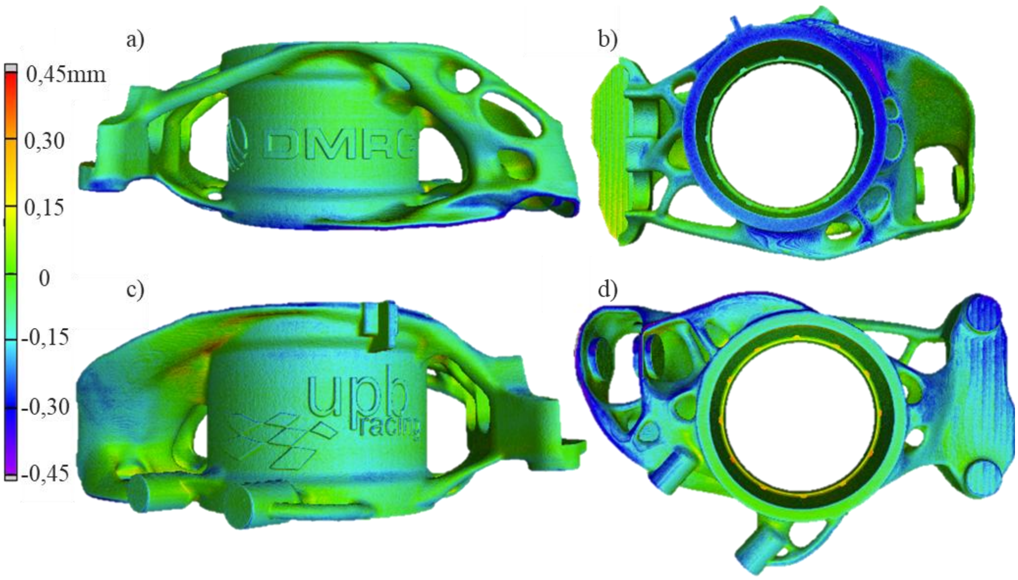
The image in Graphic 7a shows a homogeneously determined surface, whereas the image in Graphic 7b shows a large number of artifacts. These artifacts do not represent the real properties of the scanned component and therefore distort the result of the CT scan. For this reason, no representative quality assurance could be carried out with such distorted data using a target/actual comparison.

To create a target/actual comparison, three-dimensional information about a component is first generated. The data obtained (actual data) is then superimposed with the CAD data provided (target data) using a specific alignment logic, the so-called "best-fit" method (Graphic 8). In the next step, existing deviations are displayed using a false color model. The false colour model visualizes the areas in which the created CAD data of the 3D-printed component deviates from the target data provided. Computed tomography therefore makes it possible to measure complex or internal geometries and free-form surfaces.




Graphic 6: Sequence of a target/actual comparison of a laser-melted gyroid

The green area shows a match 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.
Graphic 9 below visualizes the false colour model of the processed wheel carrier from four different views. The predominantly green coloring shows that the component has only minor deviations from the original CAD model.




Graphic 7: Target/actual comparison of the aluminium wheel carrier
a) Front view
b) Top view
c) Rear view
d) View from below

The front and rear views in particular show predominantly green areas, meaning that a deviation of almost 0 mm can be assumed. Most deviations can be seen in the connection points to the lower wishbone. Here, the top view shows a deviation of mostly 0.15-0.30 mm, which increases to over 0.45 mm towards the edge. On the underside, however, the deviations are somewhat smaller at 0-0.15 mm. Only the round joint areas show a negative deviation, but this is due to mechanical removal during the finishing process. Overall, however, the deviations of the processed wheel carrier are very small and are predominantly within the specified tolerance range of 0.7% [13].

## Summary and outlook:

The use of additive manufacturing for the direct and tool-free production of end products guarantees a high level of quality. As part of these investigations, suitable test methods were selected based on applicable standards and used as examples to demonstrate their transferability to additive manufacturing. The properties of the powder raw material, the material properties of the assembled components and the geometric accuracy of the components were examined. In order to also carry out destructive tests, samples were produced and tested in a construction job in accordance with the VDI3405 standard as a representative of the component properties. [11]
The results of the tests show that a statement can be made about the component quality achieved on the basis of the characteristic values determined. Irregularities in the construction process are usually immediately revealed by the measurement results.

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

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