FRAUNHOFER INSTITUTE FOR MACHINE TOOLS AND FORMING TECHNOLOGY

DESIGN FOR ADDITIVE MANUFACTURING

Guidelines and Case Studies for Metal Applications

prepared for INDUSTRY CANADA – MANUFACTURING & LIFE SCIENCES BRANCH (MLSB)

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Abbreviations

AM	-	Additive Manufacturing
BTF	-	Buy-to-fly
CAE	-	Computer Aided Engineering
CAD	-	Computer Aided Design
CNC	-	Computerized Numerical Control
CT	-	Computed Tomography
DD	-	Dresden
DMLS	-	Direct Metal Laser Sintering
EBM	-	Electron Beam Melting
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
HB	-	Hansa Town Bremen
HIP	-	Hot Isostatic Pressing
LBM	-	Laser Beam Melting
LPBF	-	Laser Powder Bed Fusion
MGB	-	Main Gearbox Bracket
NURBS	-	Non-Uniform Rational B-Splines
OEM	-	Original Equipment Manufacturer
SLM	-	Selective Laser Melting
SME	-	Small and Medium-sized Enterprises

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1 Scope

Additive Manufacturing (AM), often simply called 3D printing, provides nearly unrestricted freedom to design parts in order to optimize their functionality. It offers designers and manufacturers the ability to produce shapes and designs that would be impossible to produce using conventional manufacturing technologies such as moulding or machining.

Optimizing the design of parts can be achieved by reducing their weight, incorporating internal features or reducing the need for assembling separate components. AM also offers the opportunity to reduce or eliminate waste that results from manufacturing, and to reduce the need for warehousing while enhancing the value of local production.

The efficient use of AM technologies requires a rethinking in 3D design, which currently still poses a barrier particularly for small and medium-sized enterprises (SMEs) of metal industry. Advantages and opportunities as well as restrictions of additive manufacturing must be well known in order to pave the way for a successful commercialisation and to make AM a competitive manufacturing method.

This report at hand is based on seven components, which were developed and manufactured in the scope of separate projects, but have been selected, reviewed and assessed in a detailed case study particularly and retrospectively within this task.

The design of each component was tailored to the specific needs of the chosen AM technology. The development and manufacturing activities were performed by Fraunhofer Institutes, who are members of the Fraunhofer Additive Manufacturing Alliance. The alliance integrates seventeen Fraunhofer Institutes across Germany, which deal with subjects concerning additive manufacturing and represent the entire process chain including the development, application and implementation of additive production processes as well as associated materials.

The report identifies leading edge industrial applications and trends associated with the design for additive manufacturing and limitations related to current AM technologies. The evaluation of the seven case studies highlights general design principles to take best advantage of the powder bed based additive manufacturing techniques Laser Beam Melting (LBM) and Electron Beam Melting (EBM). Moreover, the design optimisation and material characterisation are analysed. Finally, there are given overall conclusions with focus on AM-specific design optimisation, main flaws and weaknesses of the considered metal AM processes as well as aspects of AM commercialisation.

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2 AM-specific Design Opportunities

Compared to conventional manufacturing methods additive manufacturing technologies provide unique opportunities and freedom in design, resulting in a high degree of product individualisation. Building parts layer by layer without using any tooling, moulds or dies enables the design and manufacturing of very complex component geometry, such as lattice structures or free formed surfaces and organic shapes. Design attributes like undercuts are no longer a limitation and with the aid of topology optimisation the component geometry can be tailored to the specific needs of application. In addition to it, features and functionalities can be incorporated into a part just during the manufacturing process in one shot and assemblies consisting of many components can be reduced to a single part. Even the assembling of different parts during primary shaping with AM technologies is possible, which has already been demonstrated for components like bearings, chains, hinges (see Fig. 2-1).

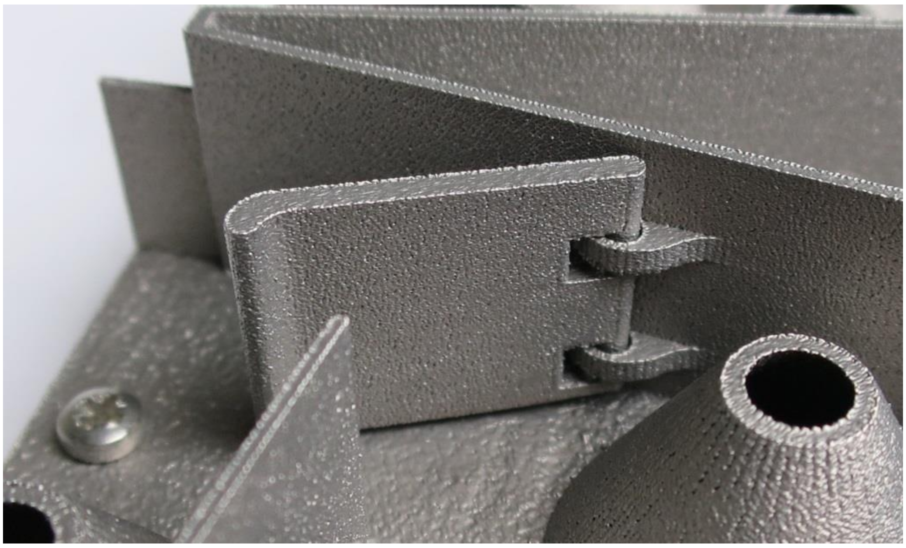


Fig. 2-1: Hinge assembly manufactured in one shot with LBM (Source: Fraunhofer IWU)

Taking the required part information directly from CAD data, AM technologies do provide a fully flexible production – the need for an adaption of forming tools does not apply and the production of components with a high diversity of variants and styles can be realized immediately one after the other [1]. This implicates significant economic potential as well – with AM technologies the unit costs can be uncoupled from production quantity, which comes into effect especially for small and medium quantities. Compared to primary shaping methods the costs for production of any forming tool do not have to be allocated to the number of items produced, since no primary shaping tool is necessary. Furthermore the part complexity may be uncoupled from unit costs as well – building a part layer by layer transfers three-dimensional production challenges into two-dimensional ones, whereas the individual shape of a single layer does not significantly influence the costs per unit. Instead of part complexity the part volume is more likely the biggest cost driver in AM.

2.1 Topology Optimisation

Dependent on specific requirements like weight reduction in combination with load distribution or functionality, the best distribution of material within a defined design space can be achieved by topology optimisation. This results in minimized material usage whilst still fulfilling the individual functional and/or loading requirements. But often the optimised topology is very complex, which leads to very high production costs or to the need for topology re-simplification in order to take account of the constraints of conventional manufacturing methods. Since AM technologies provide a very high freedom of design and therefore enable the manufacturing of very complex parts, the combination of AM methods and topology optimisation is obvious (see Fig. 2-2).

Fig. 2-2: Example for topology optimisation – skateboard axle mounting, manufactured with LBM (Source: Fraunhofer IWU)

2.2 Lattice Structures

Besides topology-optimised structures as mentioned above AM technology (especially LBM) also provides the capability to build macroscopic lattice structures. Lattice structures are a mesh consisting of interconnected bars which divide the design space into single cells, whereas for additive manufacturing the minimum size and geometry of bars and unit cells are limited by the applied AM method.

Due to the excellent ratio of weight vs. load capability such structures show high potential for light-weight design. By varying the size of the unit cells and thickness of the connecting bars graded lattice structures potentially enable the design of parts with graded stiffness and density tailored to the needs of the particular case of application. Furthermore functional aspects can also be covered, for example improved adhesive properties of a hip stem in order to fulfil special medical requirements (see Fig. 2-3).

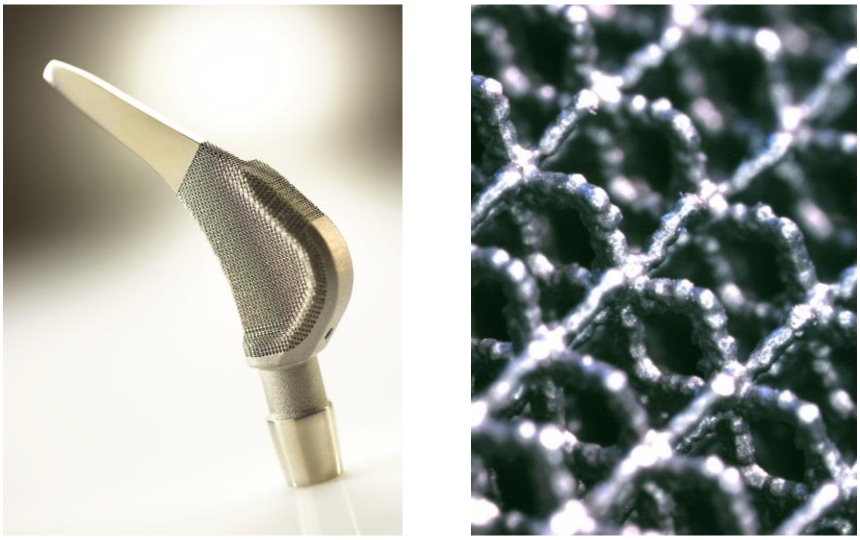


Fig. 2-3: **Titanium hip stem demonstrator with lattice structures (designed for and manufactured with LBM, Source: Fraunhofer IWU)**

Fig. 2-4: **Skateboard Truck (Titanium) , LBM design demonstrator with topology optimisation and graded lattice structures (Source: Philipp Manger)**

2.3 Integrated Functions

The particular characteristics of additive manufacturing technology offer the possibility to incorporate features and functionalities into a part just during the manufacturing process. This potential can be exploited in a variety of industrial sectors, for example in toolmaking for forming or casting, which has already been examined and demonstrated in detail by the use of LBM [2]. Tools with novel features like innovative thermal management for heating or cooling, an in-process lubrication system or sensor integration for process monitoring can significantly improve the process in terms of cycle time and scrap rate as well as the resulting part quality ([2], Fig. 2-5 and Fig. 2-6).

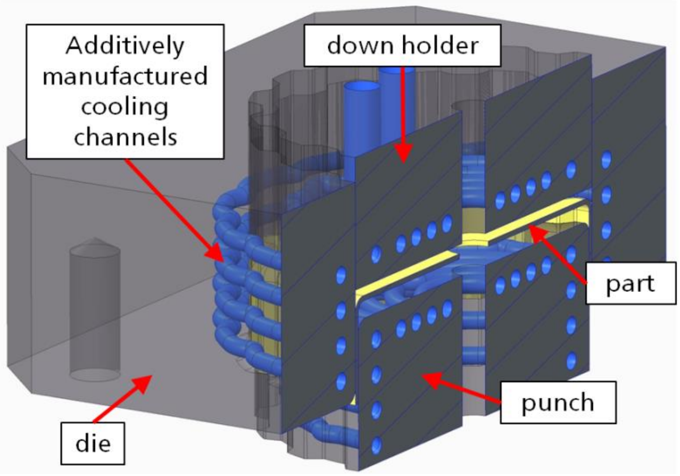


Fig. 2-5: Press hardening tool assy with conformal cooling system (Source: Fraunhofer IWU)

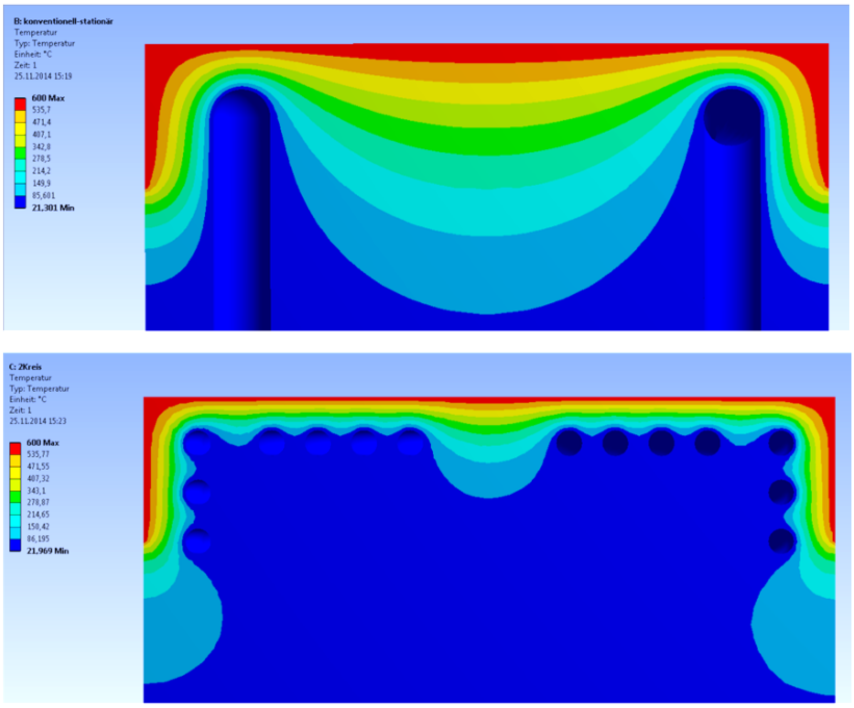


Fig. 2-6: Temperature distribution of a press hardening tool – comparison between conventional cooling (top) and contour conformal cooling system manufactured with LBM (bottom), Source: Fraunhofer IWU

3 AM Processes and Related Design Principles

One objective of this report is – based on the case study analysis – to translate AM-specific design rules and principles in a simplified format accessible to industry. Since the selected components for case study analysis were manufactured either by using the powder bed based additive manufacturing process LBM or EBM, this section gives an overview about applicable design principles only. Cases of practical application will be shown and assessed within the case study analysis itself (see chapter 6).

For other methods of metal additive manufacturing like Binder Jetting, Cladding, 3D Screen Printing etc. different or additional design principles may come into effect, which are not part of this study.

3.1 LBM vs. EBM – a brief Overview

3.1.1 Laser Beam Melting (LBM)

In Laser Beam Melting a focused laser beam locally melts the metallic material, which is provided in powder form and applied on the build platform layer by layer by the use of a scraper or roller. In industry different designations for that process have been established. While the OEMs SLM Solutions Group AG and ReaLizer GmbH both are using the term “Selective Laser Melting” (SLM), the company EOS GmbH calls this process “Direct Metal Laser Sintering” (DMLS); the company Concept Laser GmbH claims to call it “LaserCUSING” and the company TRUMPF GmbH + Co.KG calls it “Laser Metal Fusion”. Also the designation “Laser Powder Bed Fusion” (LPBF) is widely spread in industry, especially in North America.

For selective (i.e. local) melting the laser is deflected and positioned by a scan system consisting of moveable mirrors and lenses. The entire process is performed under inert atmosphere (argon or nitrogen) at room temperature or with pre-heated build platforms with temperatures up to 250°C [3] or even higher. The high temperature gradients between melting and cooling up to a maximum amount of 3.5 x 10^6 K/s [4] lead to a very fine-grained structure, but also implicate negative effects like high residual stresses and related warping. Another characteristic of this layer by layer process are anisotropic mechanical properties of the built components [5].

LBM is eminently suitable for complex internal structures and cavities, since the non-melted powder can be easily removed after the build process as long as an opening to the outer surface is provided. Such an opening can subsequently be closed by conventional welding or soldering processes.

Today, a variety of metallic materials such as tool steels, stainless steels, aluminium alloys, titanium and titanium alloys, nickel-based alloys and cobalt-chrome alloys are available in powder form and can be used for this process.

3.1.2 Electron Beam Melting (EBM)

This AM technology uses an electron beam in order to melt the metallic powder, which is also applied layer by layer by the use of a scraper. For selective (i.e. local) melting the electron beam is deflected and positioned by a system of magnet coils. The process is conducted under vacuum (~1 x 10^{-5} mbar) and temperatures between 700 and 1,000 °C. Before being melted, each powder layer is pre-heated by means of the electron beam in order to create so-called sinter bridges, which fix the powder particles and prevent them from “splashing”. Compared to loose powder the electrical and thermal conductivity of this pre-sintered “semi-rigid body” is higher, enabling the use of higher beam energy, which leads to an increased energy input [6]. At the same time, it results in total temperature gradients much lower than in Laser Beam Melting, therefore the built components also show substantially lower residual stresses and related warping. Thanks to the pre-sintered “semi-rigid body”, the use of support structures is not required for pure supporting purposes, but rather to avoid hot-spots. This is also why – in comparison to LBM – complex internal structures can be manufactured to a limited

extent only, because the non-melted powder is not trickling out based on gravity and flowability, but must be removed by mechanical brushing or blasting.
At present, materials like titanium, titanium-alloys, nickel-based alloys or cobalt-chrome alloys are qualified for this process.

3.1.3 LBM versus EBM – A Qualitative Comparison

Table 3-1 provides a qualitative comparison between Laser Beam Melting and Electron Beam Melting [5], [7], [8], [9],. For most parameters a quantitative comparison is not feasible, since their range and limits can hardly be defined with specific numbers.

	Laser Beam Melting (LBM)	**Electron Beam Melting (EBM)**
Energy Source	Laser (up to 1 kW per Laser, up to 4 Lasers per machine)	Electron Beam (up to 3.5 kW)
Range of Materials	Tool steels, Stainless steels, Aluminium alloys, Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys	Titanium and Ti-alloys, Nickel-based alloys, Cobalt-chrome alloys
Controlled Atmosphere	Nitrogen; Argon	Vacuum
Process Temperatures	No pre-heating of each layer or process chamber, build plate optionally heated up to 250 °C or even higher	Pre-heating of each layer up to 1000 °C (e.g. for TiAl)
Susceptibility to Residual Stresses	High	Low
Stress-relief heat treatment required	Yes (in most cases)	No (in most cases)
Complexity of parts	High	Medium
Size of Powder Particles (typical range)	10-45 µm	45-105 µm
Part surface roughness (as-built)	R_z = 30-140 µm	Poorer than LBM
Dimensional accuracy	0.1 mm	Poorer than LBM (~ 0.5 mm)
Typical Layer Thickness	30-50 µm	50-100 µm
Process Speed	Poorer than EBM (single laser machines)	High (very high scan rates)
Typical Applications	Components for all industrial sectors	Limited applicability due to limited complexity and accuracy of components; still low variety of materials

Table 3-1: Qualitative comparison of LBM and EBM

3.2 General Design Principles

3.2.1 Part Orientation

For the powder bed based additive manufacturing processes LBM and EBM the part orientation, position and arrangement on the build platform can have a significant influence on the process speed, process stability and various component properties, such as residual stress-induced warping (so-called "curl effect").

Due to insufficient heat dissipation the so-called curl-effect may occur in both processes, EBM and LBM. This is when high thermal gradients lead to residual stresses, whereby the component starts curling (i.e. bends up) during the process. Such critical hotspots and related distortion can be minimized by appropriate component orientation and positioning, which avoids large-area fusing within a single layer. Examples for good and poor part orientation are given with Fig. 3-1 [5].

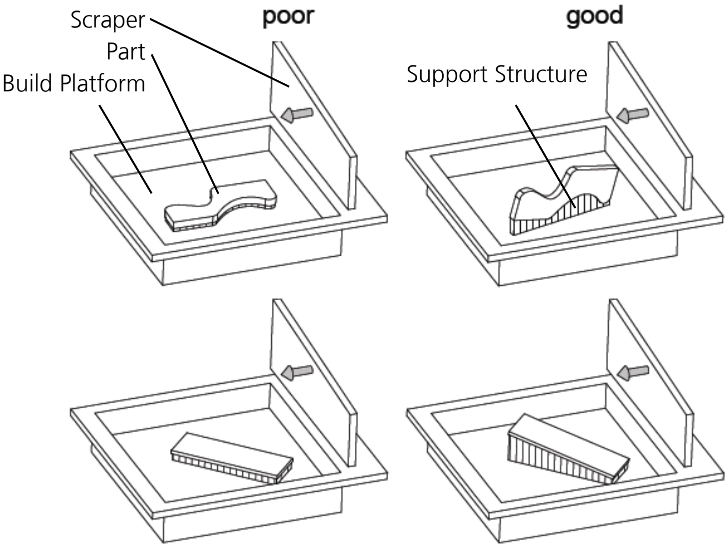


Fig. 3-1: Examples for good and poor part orientation for the avoidance of the curl-effect for LBM [5]

During the fusing process adhesion occurs between loose and melted powder on the part's surfaces. This leads to high surface roughness, which may require adequate post-processing (e.g. milling, grinding). Depending on the angle between the part surface and the build platform the surface roughness noticeably differs. Especially for LBM this effect is significant: Untreated surfaces (as-built) show a range of mean roughness values of $R_{z\,=}$ 30-140 µm [5]. Fig. 3-2 shows the qualitative correlation between part surface orientation and its related roughness [5].

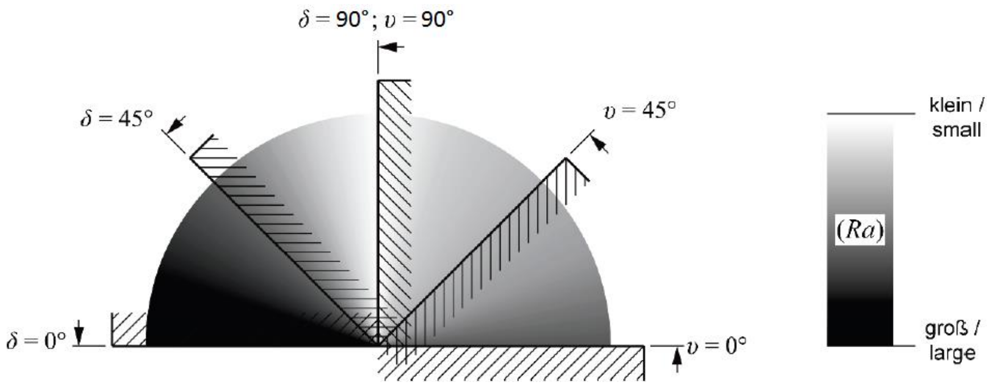


Fig. 3-2: **Relationship between up skin-angle, down skin-angle and roughness R_a for LBM [5]**

3.2.2 Anisotropic Material Properties

The layer by layer manufacturing process causes anisotropic mechanical properties, for LBM in a typical range of about 5 to 15% [10] (see Fig. 3-3). It has to be emphasised that compared to solid objects this effect is increased for delicate geometries like lattice structures [11].

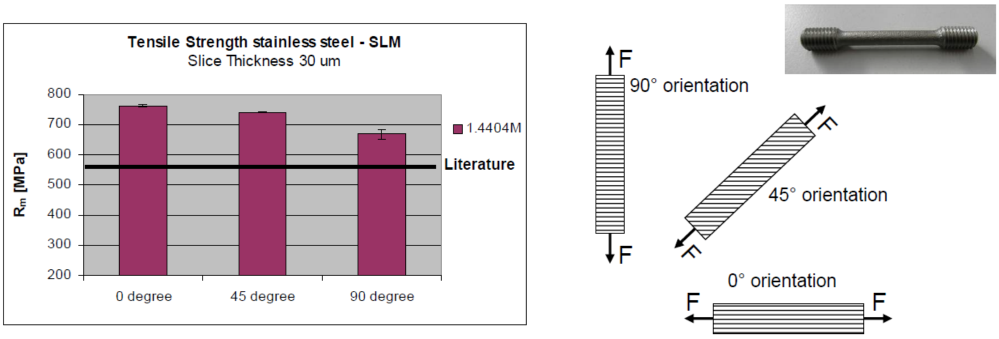


Fig. 3-3: **Exemplary illustration of anisotropic tensile strength for stainless steel 1.4404 (316L) processed by LBM [10]**

A post-process heat treatment can reduce those effects. Nevertheless the anisotropy should be considered during component orientation on the build platform. If possible the major load path within the component should be aligned parallel to the build platform (0° orientation).

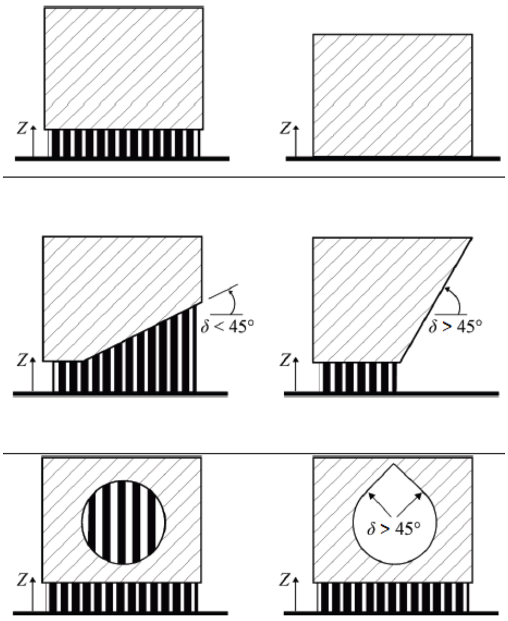
3.2.3 Support Structures

Support structures, which are not part of the manufactured component itself, may be necessary for different reasons:

- Fixation of the part on the build platform
- Support of overhanging structures (if angle of surface to build platform <45°)
- Heat dissipation and avoidance of residual stresses
- Compensation of residual stress-induced warping

Within the layer by layer build process the fusing of powder directly on a non-melted powder layer would lead to very rough and imprecise surfaces. Hence, overhangs with angles between build platform and component below a specific value (~45°, value depending on material and process) need to be supported by additional structure.

Especially for LBM this is of particular importance (see Fig. 3-4): On the one hand the weld pool has much higher density and weight than the loose powder and sinks into it, on the other hand the loose powder shows much less heat conductivity compared to solid material and therefore does not provide sufficient heat transfer. By using support structures the subsidence is avoided and the heat transfer is improved. Nevertheless residual stresses caused by inhomogeneous heat distribution cannot be fully avoided and therefore a post-process heat treatment (stress-relief annealing) is recommended in many cases. During the heat-treatment the part shall be still attached to the build platform (e.g. by means of support structure) in order to minimize warping.



Left	Right
Support structures connecting the part to the build platform	Part connected directly to the build platform
Faces with down skin-angle < 45° normally require support structures	Faces with down skin-angle > 45° do normally not require support structures (but surface quality may be adversely affected)
Hole with internal support structure	Shape of hole modified to avoid use of support structures

Fig. 3-4: Guidance on the use of support structures [5]

In EBM there is no need to support the structure against subsidence (see 3.1.2), but there is also the need to improve heat dissipation in order to minimize residual stresses. Therefore, in comparison to LBM, support structures can be designed much thinner, i.e. with less volume. In combination with the process-specific preheating of each layer the resulting residual stresses are on a very low level which usually does not require subsequent stress-relief annealing.

After the manufacturing process and optional heat treatment the support structure has to be removed mechanically from the component and affected surfaces require adequate mechanical post-processing (e.g. milling, grinding etc.).

As an example Fig. 3-5 shows a hip stem demonstrator manufactured by LBM, where support structures (blue) were required for all above mentioned reasons.

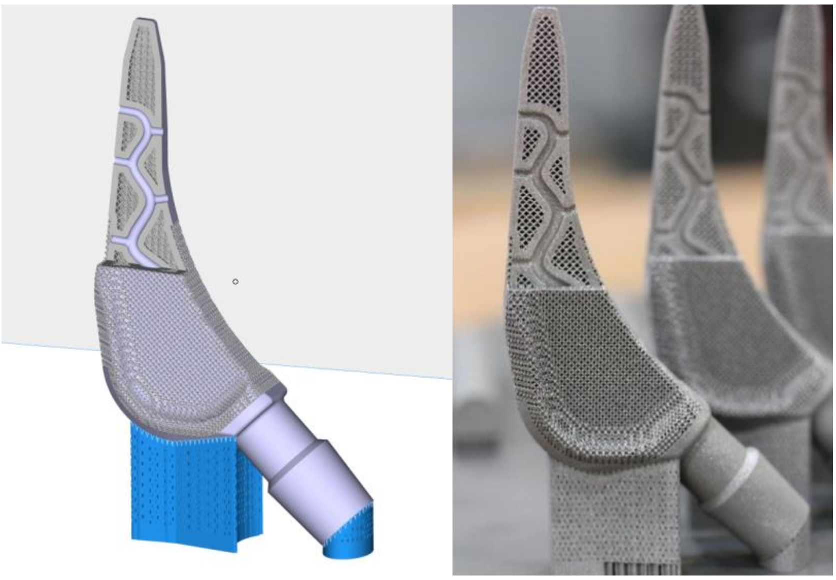


Fig. 3-5: **Titanium hip stem demonstrator with support structures – CAD (left) and real part (right) manufactured with LBM (Source: Fraunhofer IWU)**

3.2.4 Tolerances and Offset / Oversize

Additive manufacturing technologies like LBM and EBM are applicable to produce very complex shapes and geometries. Current state-of-the-art equipment and processes achieve accuracies of about ±0.1 mm for LBM and in general poorer (~0.5 mm) for EBM, which often does not fulfil the requirements with regard to geometric dimensioning and tolerances. Therefore functional surfaces and fits must be finished by suitable machining processes in order to provide sufficient accuracy.

For the design for additive manufacturing this implicates consideration of an appropriate material offset, at least for those locations on the component which have to fulfil high tolerance requirements.

3.2.5 Minimum / Maximum Allowable Size of Geometrical Features

With respect to dimensions of geometrical features it must be distinguished between positive volumes (e.g. ribs, walls, edges) and negative volumes (i.e. any kind of cavities). The minimum size of positive volumes mainly depends on the melting-process itself: LBM provides an accuracy of ± 0.1 mm, whereas the resolution of EBM is poorer (~0.5 mm), see chapter 3.1.3. On the contrary the maximum size of positive volumes is only limited by the AM machine (i.e. size of process chamber).

With respect to walls especially LBM allows production of minimal wall thicknesses within the range of the melt pool size. However, the robustness of such thin walls depends on their orientation related to the build- and coating direction, on their support, on their aspect ratio (height to thickness) and the used material. The thickness of robust walls should be a multiple of the width of the melt pool; in practice for both LBM and EBM a common value for minimum wall thickness is about 0.5 mm.

The gaps between such walls or other solid parts of a component should be always above a certain value in order to avoid fusing of the gap-forming surfaces. This minimum gap-width depends on the material and the process parameters, but should at least exceed the melt pool width.

The minimum and maximum dimensions of negative volumes do also depend on different boundary conditions, for LBM as follows: Depending on their shape, dimension and requirement for geometrical accuracy hollow structures like channels, cavities and bores can be manufactured with or without support structures. In case of internal and inaccessible cavities the use of support structure is not possible, since it cannot be removed anymore. This is why hollow structures of a component should be aligned vertical to the build platform wherever possible in order to avoid the use of support structures or any sagging effects (see Fig. 3-6).

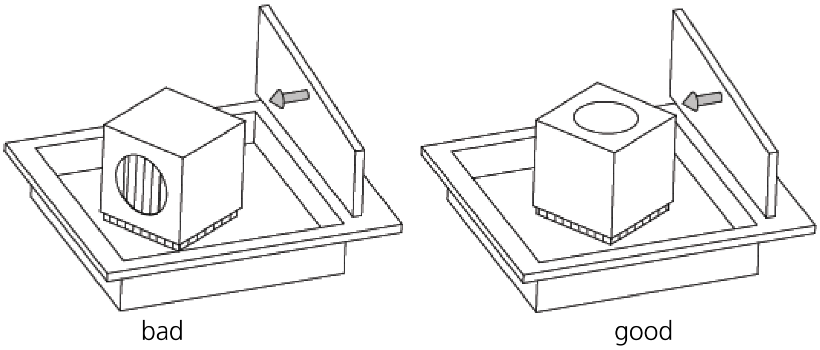


Fig. 3-6: **Example for avoidance of support structures and sagging effects [5]**

But very often such an ideal alignment is not possible, i.e. internal channels will be positioned sloped or even parallel to the build platform. In such cases a satisfying shape accuracy can be obtained by observance of a maximum diameter of d = 8 mm or/and by appropriate adaptation of the channel’s cross-section (see Fig. 3-7).

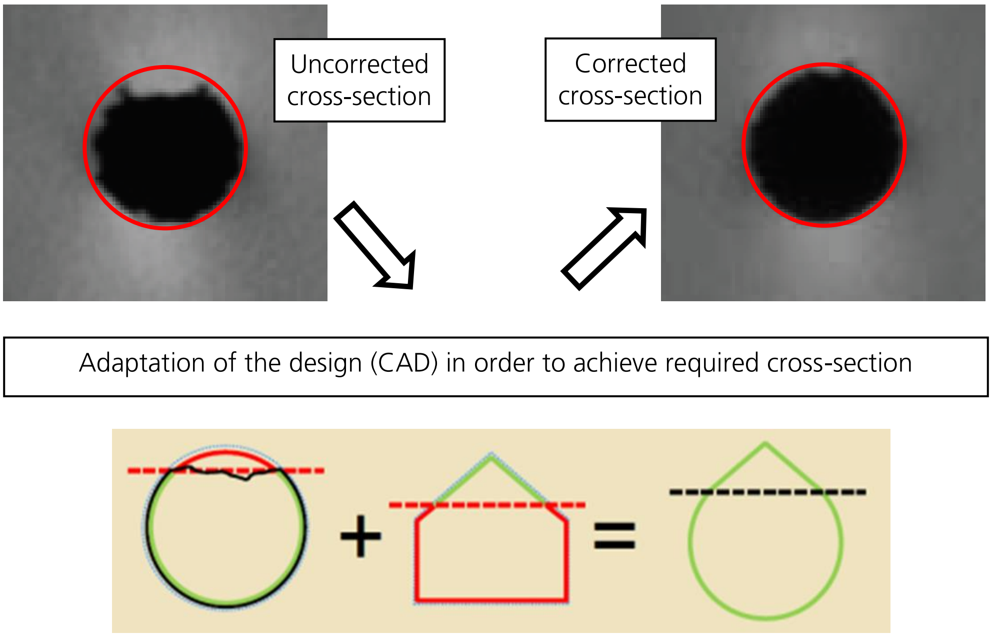


Fig. 3-7: **Avoidance of sagging effect by appropriate adaptation of cross-section [12]**

Otherwise, depending on the angle to the build platform, any down skin surfaces will sag during the manufacturing process, leading to imprecise shapes and dimensions (see Fig. 3-8).

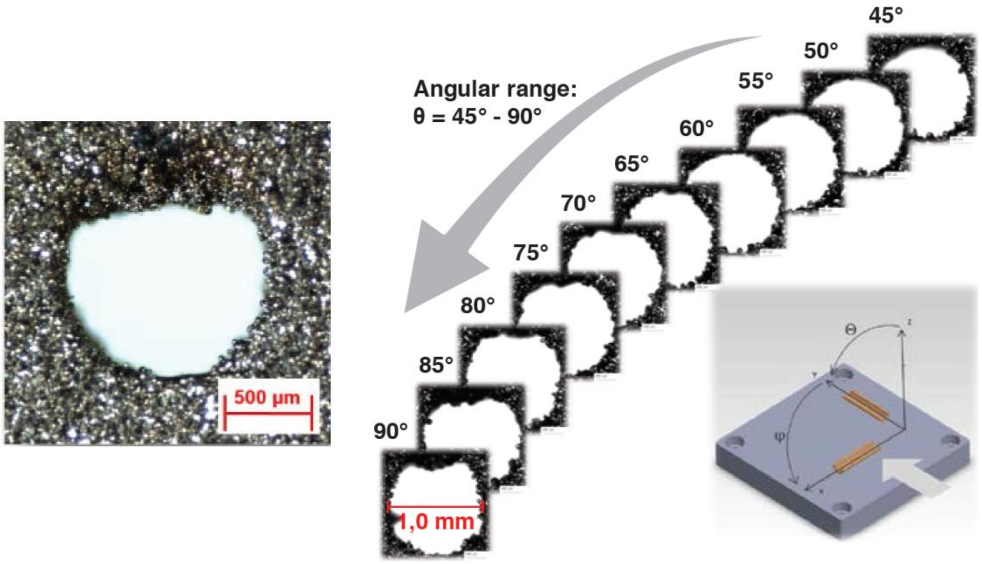


Fig. 3-8: **Geometrical deviation of a LBM channel structure (left); cross-sectional geometry as a function of the angle between channel section and build platform (right) [12]**

In addition to the effect of sagging and related insufficient dimensional accuracy another important fact must be considered during the design: the need to remove non-fused powder after the manufacturing process:

For components produced by LBM the length, complexity and shape of an internal cavity have an influence on the removability of loose powder. Internal channels oriented in parallel to the build platform or following a curved route generally should have a minimum diameter of d = 1-3 mm in order to ensure integrity and penetrability. As a best case example, simple airflow tests on a tool steel specimen manufactured with optimised LBM parameters showed a diameter limit for air penetrability of 0.4 mm for straight channels (being perpendicular to the build platform), and a limit of 0.6 mm for curved channels (see Fig. 3-9). For other media (e.g. fluids like water) these values may be insufficient.

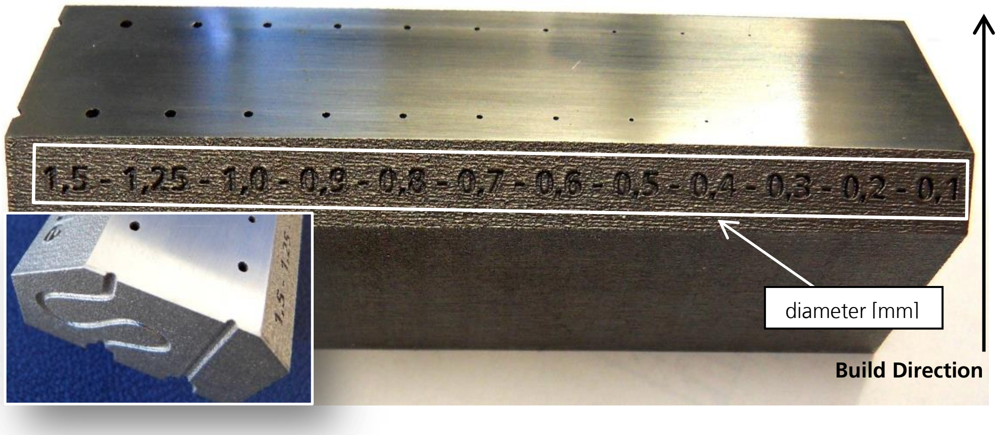


Fig. 3-9: **Tool steel specimen made by LBM, used for air penetrability tests on curved and straight channels with different diameters (Source: Fraunhofer IWU)**

Moreover, of course each cavity needs an opening to the outer surface, so that non-fused powder can be removed – it simply trickles out driven by gravity, optionally supported by shaking and blasting. The minimum permissible diameter of such an opening depends on the individual powder properties, such as particle size distribution, particle shape and resulting flowability.

In contrast in EBM the powder removal from small and complex internal cavities is very difficult, since during pre-heating also non-used powder is solidified to a "semi-rigid body" (sinter bridges between powder particles) and therefore needs removal by the help of blasting or brushing. For that reason the range of EBM applications with regard to component complexity is much lower compared to LBM.

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4 AM-relevant Standards and Guidelines

For conventional manufacturing methods a variety of standards and regulations has been developed and released in recent decades. Based on comprehensive theoretical knowledge and broad practical experience those standards are providing detailed information, serving either as guidance or as hard specification in order to define a common language in related industry.

In contrast, additive manufacturing technology is still young. Even if its history goes back to the 1980s, when the grandfather of additive manufacturing – Stereolithography (also known as Rapid Prototyping) – was invented and patented, the evolution and dissemination of today's diversity of AM methods mainly took place in the 21st century. Especially powder bed based technologies as LBM and EBM became from particular interest for industry not before related laser technology was sufficiently powerful and affordable at the same time. This prerequisite has been fulfilled for a number of years now and meanwhile not only major corporations have recognised the almost unlimited potential of additive manufacturing technology, but also SMEs are showing more and more willingness to invest in.

For the reasons mentioned above the development of standards and regulations for AM is still in an early stage. There is a significant lack of process- and material-specific standards, which are vitally needed in order to assure reproducible results and to provide a solid basis for appropriate quality control.

Table 4-1 shall give an overview about today's metal AM-relevant standards and regulations, without guarantee of being complete. Only those standards are listed, which have already been released either as an official issue or as an official draft. Worldwide there are various national and international organisations and technical committees, consisting of representatives from both industry and research, which currently work on additional guidelines being still in process and not released yet.

	Standard / Guideline	**Title**
1	ISO 17296-2:2015	Additive manufacturing -- General principles -- Part 2: Overview of process categories and feedstock
2	ISO 17296-3:2014	Additive manufacturing -- General principles -- Part 3: Main characteristics and corresponding test methods
3	ISO 17296-4:2014	Additive manufacturing -- General principles -- Part 4: Overview of data processing
4	ISO / ASTM 52900:2015	Additive manufacturing -- General principles -- Terminology
5	ISO / ASTM 52901-16	Standard Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts
6	ISO / ASTM 52910-17 (*supersedes ISO DIS 20195*)	Standard Guidelines for Design for Additive Manufacturing
7	ISO / ASTM 52921:2013	Standard terminology for additive manufacturing -- Coordinate systems and test methodologies
8	ISO / ASTM 52915:2016	Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2

	Standard / Guideline	Title
9	ASTM F2924-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
10	ASTM F2971-13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
11	ASTM F3001-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminium-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
12	ASTM F3049-14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
13	ASTM F3055-14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
14	ASTM F3056-14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
15	ASTM F3122-14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
16	ASTM F3184-16	Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion
17	VDI 3405 (supersedes 3404)	Additive manufacturing processes, rapid prototyping - Basics, definitions, processes
18	VDI 3405 Part 2	Additive manufacturing processes, rapid prototyping - Laser beam melting of metallic parts - Qualification, quality assurance and post processing
19	VDI 3405 Part 2.2 (DRAFT)	Additive manufacturing processes, Laser beam melting of metallic parts, Material data sheet nickel alloy material number 2.4668
20	VDI 3405 Part 2.1:2015-07 and related correction dated 2017-01	Additive manufacturing processes, rapid prototyping - Laser beam melting of metallic parts - Material data sheet aluminium alloy AlSi10Mg
21	VDI 3405 Part 3	Additive manufacturing processes, rapid manufacturing – Design rules for part production using laser sintering and laser beam melting
22	VDI 3405 Part 3.5 (DRAFT)	Additive Manufacturing processes, rapid manufacturing – Design rules for part production using electron beam melting

Table 4-1: Overview about AM-specific standards

5 Selection of Components for Case Study Analysis

For identification of leading edge industrial applications and trends associated with AM-specific design there have been conducted seven independent case studies based on the components listed below. Since each component was developed and manufactured in the scope of a separate project, the available level of information differs considerably from case to case. Nevertheless the case study analysis within chapter 6 provides a harmonised and homogenous structure in order to provide comparability to some extent.

	Component	**Target Industry**
1.	Bionic Wheel Carrier of Electric Vehicle	Automotive / Motorsports
2.	Main Gearbox Bracket	Aerospace
3.	Calibration Tool for Extrusion Process	Energy
4.	Heat Exchanger	Energy
5.	Miniature Heat Exchanger / Cooler	not limited to specific industry
6.	Functionally integrated Implant	Medical
7.	Functionally integrated Tooling Segment	Tooling

Comp. No.	AM technology	Replaced Manuf. Technology	Material	Equipment used
1	Laser Beam Melting (LBM)	Machining	AlSi10Mg	EOS M 400
2	Electron Beam Melting (EBM)	Milling	Ti6Al4V	Arcam A2X
3	Laser Beam Melting (LBM)	Milling and/or investment casting	Stainless Steel 1.4542 = 17-4PH	EOS M 270 Dual Mode
4	Laser Beam Melting (LBM)	Milling and/or investment casting	Nickel based alloy (~Inconel 718)	EOS M 270 Dual Mode
5	Laser Beam Melting (LBM)	Stamping, Soldering	AlSi10Mg	Concept Laser M2 Cusing
6	Laser Beam Melting (LBM)	Casting, Die Forging, Cutting	Ti-6Al-4V	Concept Laser M2 Cusing
7	Laser Beam Melting (LBM)	Milling, Drilling	1.2709 (AMS6514)	Concept Laser M2 Cusing

Table 5-1: Overview of selected components and related AM technology

All selected components were manufactured by the use of powder bed based processes, either Electron Beam Melting (EBM) or Laser Beam Melting (LBM). The design of each component was optimised according to its individual requirements and objectives while taking best advantage of the chosen AM technology.

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6 Case Study Analysis

6.1 Bionic Wheel Carrier of Electric Vehicle

Case Study Input from:	Fraunhofer EMI	Equipment used:	EOS M 400
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Machining	Parameter used:	OEM Standard + Customized
Material:	AlSi10Mg	Inert Gas used:	Argon

Table 6-1: Additive Manufacturing of bionic wheel carrier

6.1.1 Description of the Component and its Function

The case study discussed here is a bionic wheel carrier of an ultra-lightweight electric concept car named Eli16. The concept car was developed by the TUfast Eco Team, an association of students of TU Munich, and took part in the 2016 competition of the Shell Eco Marathon Europe. The goal of this competition is to consume as little energy as possible while driving a specified distance on a track in a limited amount of time. To achieve good results lightweight construction is indispensable.

The bionic wheel carrier of the front axle of Eli16 has been developed at Fraunhofer EMI. The component is designed for the production with Direct Metal Laser Sintering (DMLS = LBM) on an EOS M400 1x1000W system. The material used is AlSi10Mg. In the following, design features and special requirements for AM related to the design as well as the benefits and drawbacks compared to the replaced manufacturing technology (machining) are discussed.

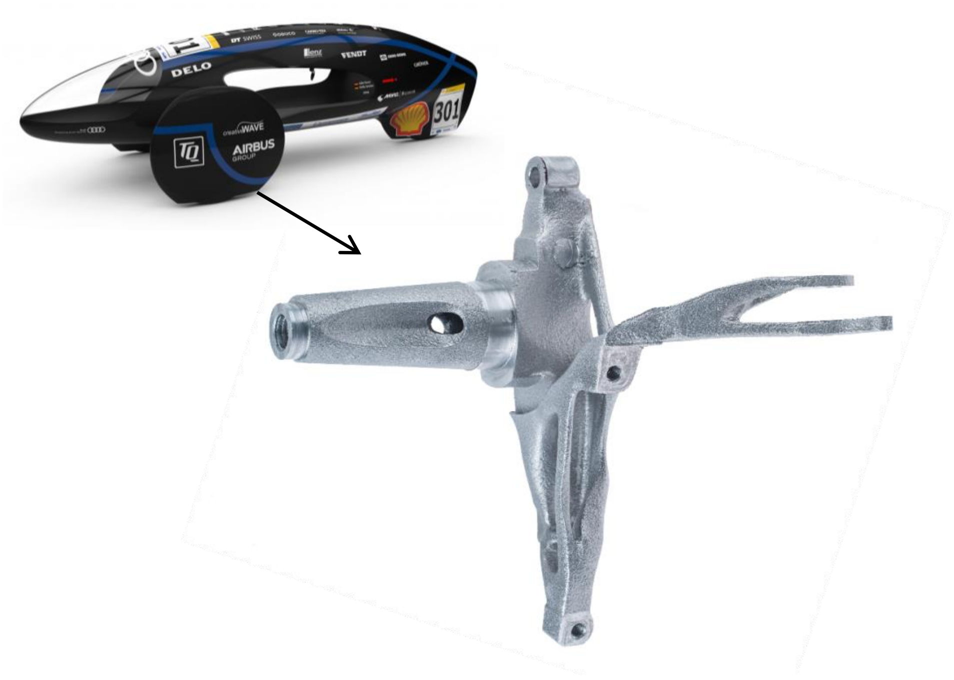

Fig. 6-1: Bionic wheel carrier manufactured by the use of LBM

6.1.2 General Design Principles

6.1.2.1 Design Features

Organic Shape:

In the product development the focus was set on the maximum performance of the component, which involves a sufficient stiffness and reliability at minimum weight achievable. To achieve this goal, numerical methods for mechanical analysis of the component were used from the beginning, namely methods of topology and shape optimisation which were applied already in the concept phase as well as continuously in the evolution of the design. On the other hand, AM production process related studies were carried out and matched in a design for additive manufacturing approach. The use of organic shapes holds high potential in enhancing the mechanical performance of technical structures. This is due to the adaption of the powerful concept of nature to only use material where it is needed for the inherent function. Where loading and stresses occur material is added and in less stressed regions material is reduced.

The construction of organic shapes can be highly complex and normally exceeds the experience and intuition of design engineers. In Fig. 6-2 a conventional geometry is illustrated in comparison to an organic shape design for the wheel carrier, which would be hard to create even for a very experienced design engineer. That is why modern numerical design tools need to be used, namely topology and shape optimisation. The adaption of this concept of nature with optimisation tools results in a potentially homogenous stress distribution throughout a structure and the most effective use of material resulting in lightweight design. Also, an enhanced mechanical performance can be reached e.g. in terms of stiffness to weight ratio.

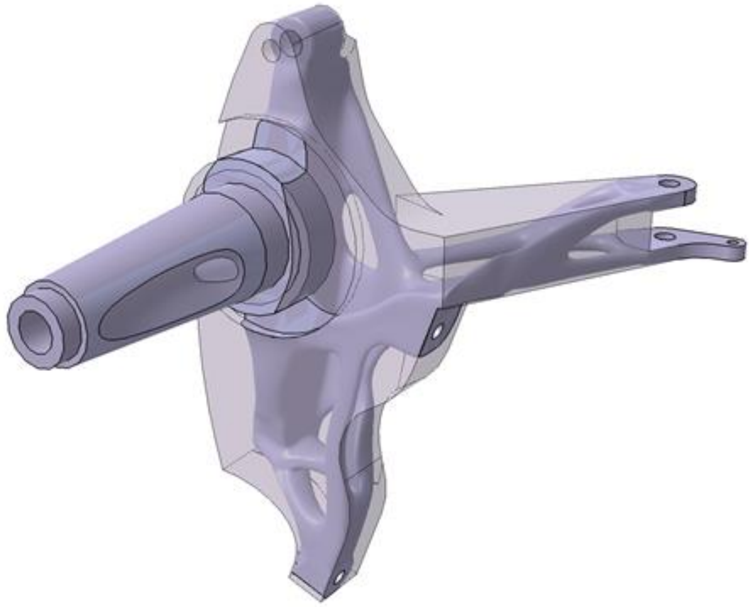

Fig. 6-2: Organic shape in comparison with conventional integrated design (transparent)

Benefits of Organic Shapes:

- Reduction of stress concentrations
- Reduction of strength requirements on material and local plasticity
- Possible enhancement of fatigue performance due to homogenous stress distribution
- Reduction of number of parts and joints due to combination of organic shapes with additive manufacturing of complex geometries
- Organic shapes seem to be favourable in terms of design for additive manufacturing because low volume structural elements do not build up high thermal stresses in the process as exemplary studies show
- Modern, fascinating and aesthetic structures

By the use of topology optimisation an effective structure is calculated, that transmits forces throughout the structure without using unnecessary diversion routes. In doing so, the material is used in the most effective way and lightweight designs can be generated that most often have an organic shape. Additionally, by avoiding force redirection, stress concentrations can be significantly reduced, which decreases strength requirements on the material and is expected to increase fatigue performance. The drawbacks of organic shapes are mostly due to the lack of knowledge in their application.

Drawbacks:

- Need for advanced CAE methods as well as experienced and well-trained application engineers
- Possible loss in robustness due to uncertainties when optimisation methods are not applied with care and reasonable engineering interpretation
- High complexity and diversity of design solutions/organic shapes – leads to drawbacks in development cost, evaluation capacity and reusability of design solutions
- Best practice guidelines for organic shapes and respective complex geometries need to be further developed

6.1.2.2 Special Requirements of AM design

Every manufacturing technology involves special requirements that should be accounted for in the product development. In the following, requirements that were assessed in the case study are presented.

There are three different design solutions shown in Fig. 6-3 that were developed in the case study of the bionic wheel carrier. The design was developed iteratively with the goal to enhance the design in matters of the mechanical performance and also with a consecutive adaption of the design to the special requirements of AM in a design for additive manufacturing approach. The mechanical performance was evaluated in a static structural analysis of the weight to stiffness ratio. Additionally, the three intermediate design solutions were manufactured with an adaption of process related parameters and strategy and respective quality evaluation.

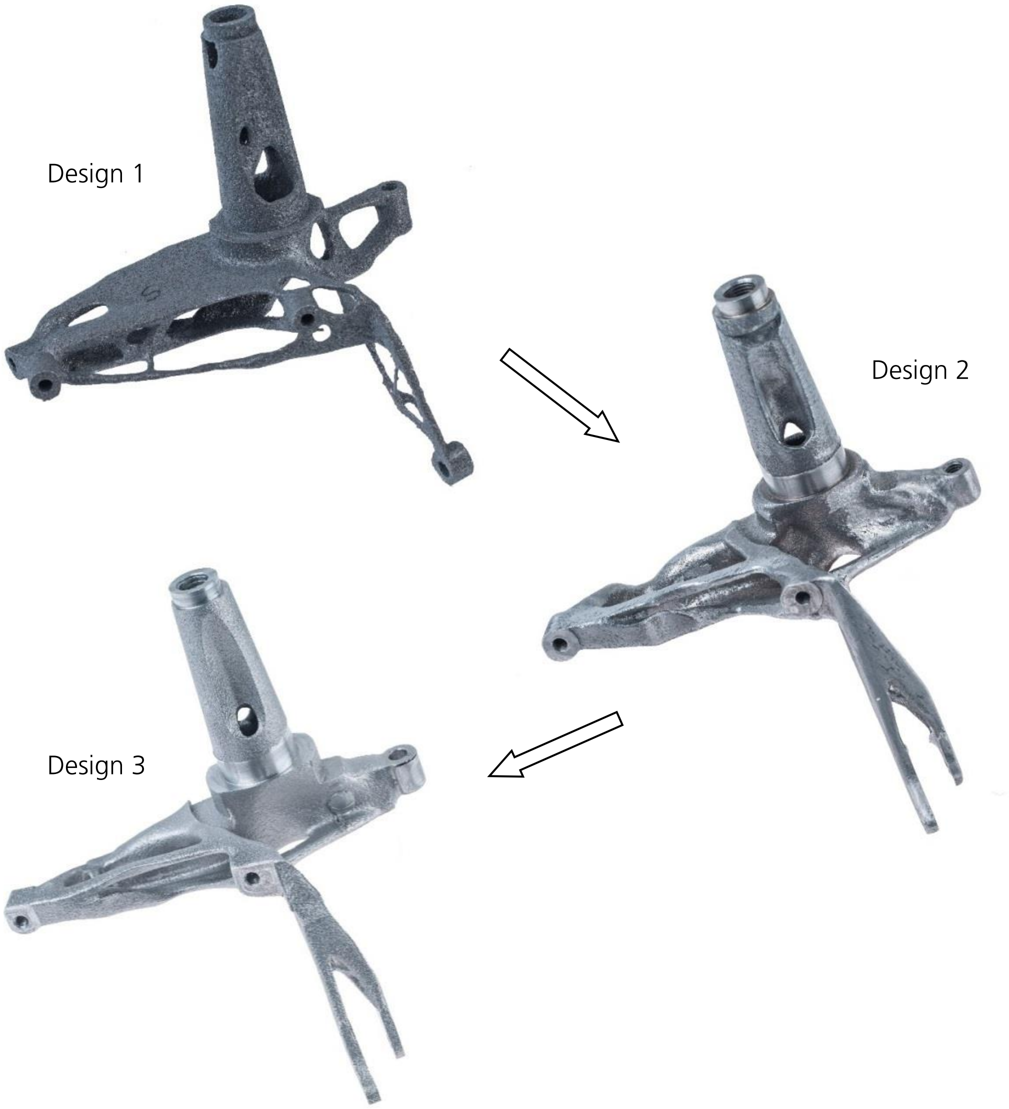

Fig. 6-3: Evolution of different design solutions

Design 1 was a very early draft design which was generated by topology optimisation and directly transferred into STL-Format and pre-processing for AM without major design adaptions. In the production, some major design flaws and requirements were identified. Some of the trusses were too thin and could not be produced accurately. Also, the production process was not very stable and robust due to distortions by thermal stresses and brittle thin trusses that collapsed in the process. Moreover, due to the direct conversion from simulation without any design interpretation there are some geometric transition areas that are not smooth and include unfavourable changes in cross sections.

Design 2 is a majored design which was constructed with an adaption of topology optimisation parameters to avoid too thin subdomains and trusses. Also, the design was smoothed with CAD and transition areas of varying cross sections were adjusted for better production quality and robustness.

Design 3 is a design interpretation of Design 2 which is based on the same topology optimisation results. Advanced NURBS-based CAD methods were utilized to construct curvature smooth surfaces and transition regions. In doing so, the design can be adjusted to be more robust to uncertainties. Also, the integration with further analysis, shape optimisation, quality assessment and CNC milling post-treatment are improved.

Geometrical Aspects:

In the development and advancement of the design of the bionic wheel carrier both the geometry was adapted to the requirements of AM as well as the geometric representation in CAD. These developments enhance the quality of both virtual process chain as well as the production.

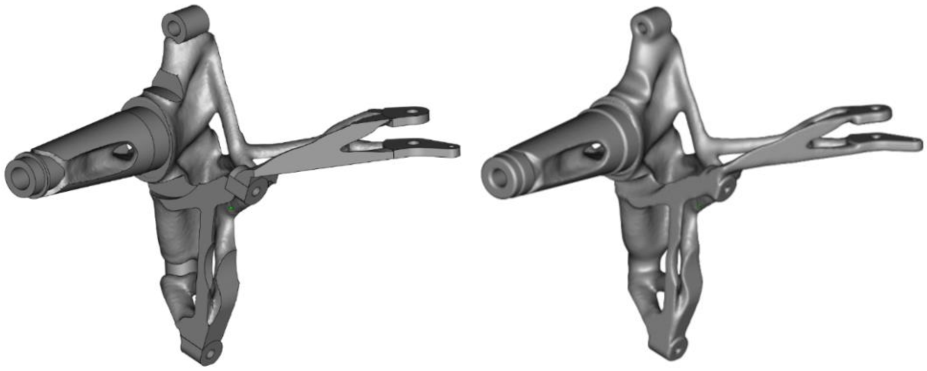

Fig. 6-4: STL-representation of Design 2 as a smoothed surface result of topology optimisation (left) and after further smoothing and CAD adjustment of transition areas of structural members (right)

In topology optimisation there is an inherent preliminary definition of functional elements, that cannot be changed and design areas that are part of the search for an effective organic shape. The transition region between those two design areas can easily be identified by sharp edges on the left of Fig. 6-4. In the second geometric representation on the right of Fig. 6-4 those design regions are smoothed and adapted to have less abrupt changes in cross sections and thus a more robust production process. In addition, accounting for geometric tolerances in the production, material is added at functional surfaces that need to be mechanically post-processed (milled).
Anyhow, both geometric representations of the bionic wheel carrier in Fig. 6-4 are constructed on STL-basis, which is in respect to data structure a point cloud without representing parametric geometries.

In Fig. 6-5 a NURBS-based parametric construction is shown which represents Design 3. In using NURBS-based design tools the topology optimisation result can be adapted and fine-tuned in a higher quality then on STL-basis.

In Fig. 6-6 a comparison of a transition region of the wheel axle of both the STL-based and the NURBS-based design is shown in more detail. In the NURBS-based design all surfaces have smooth curvature and smooth transitions. This can also be realized by adapting the STL Design on an approximate basis, although the design freedom and adaptability in the NURBS-based design is superior. Also the parametric representation can be assessed easily by further virtual development software like FEM and Shape Optimisation and also by CNC tools for post-processing of parts.

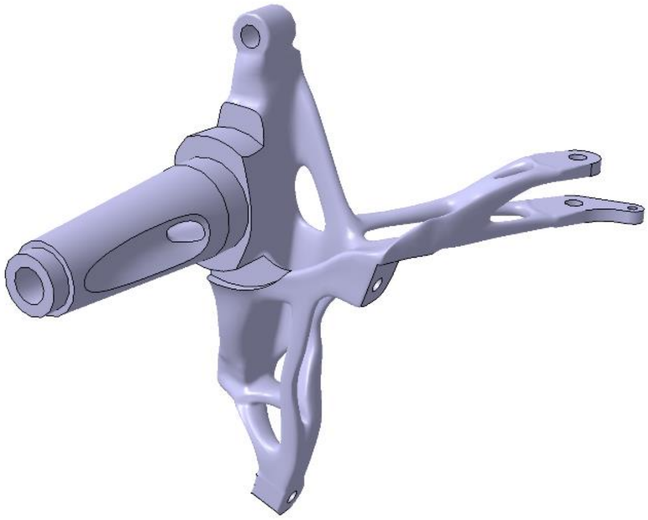

Fig. 6-5: **NURBS-based CAD Modell of Design 3 with smooth curvature surfaces and transitions**

Fig. 6-6: **Comparison of transition regions of STL-based Design 2 (left) and NURBS-based Design 3 (right)**

Most often AM parts cannot be used directly and mounted after their production. The bionic wheel carrier is a part of the assembly of wheel with bearing attachment, braking and steering system as well as the mounting to the chassis. This holds special requirements on the design of joining interfaces and functional surfaces. In Fig. 6-7 it can be seen which adaptions were made to the Design 3 of the bionic wheel carrier to foresee the milling post-treatment of functional regions: A clamping region was added, holes were closed and material was added on functional surfaces.

Need for Conventional Drawings:

For this component no drawing was required. The CNC-machines used for mechanical post-processing (milling, drilling) are able to work solely on the basis of CAD-data.

Fig. 6-7: Design 3 prior to mechanical post-treatment (milling) with foreseen design adaptations and clamping region

6.1.2.3 Replaced Manufacturing Technology

The predecessor wheel carrier of the predecessor competition car Eli15 of the 2015 season was developed as a machining design (see Fig. 6-8). Because of the manufacturing restrictions in machining the wheel carrier was developed as an assembly of four separately milled parts, all manufactured from high strength aluminium alloy Al 7075.
The focus of the development of the bionic wheel carrier of Eli16 was the reduction of weight. As the wheel carrier is mounted twice on both right and left front wheel of the concept car the benefit of weight reduction duplicates. Secondly, the reduction of assembly parts in an AM Design is beneficial as there is the need of fast adjustability of track and fall and disassembly and assembly of the carriage system during competition days. Both goals were reached with the AM design.

For the differential design of the predecessor there were several fasteners needed, which are not illustrated in Fig. 6-8. The machined design is constructed with the aluminium alloy Al 7075, which is aluminium of superior strength compared to the AM alloy AlSi10Mg. However, the stiffness of both materials by matters of Young's modulus is very similar. Consequently, the bionic wheel carrier can meet the same stiffness requirements as the machined wheel carrier because highly stressed regions can be avoided by the use of organic shapes.

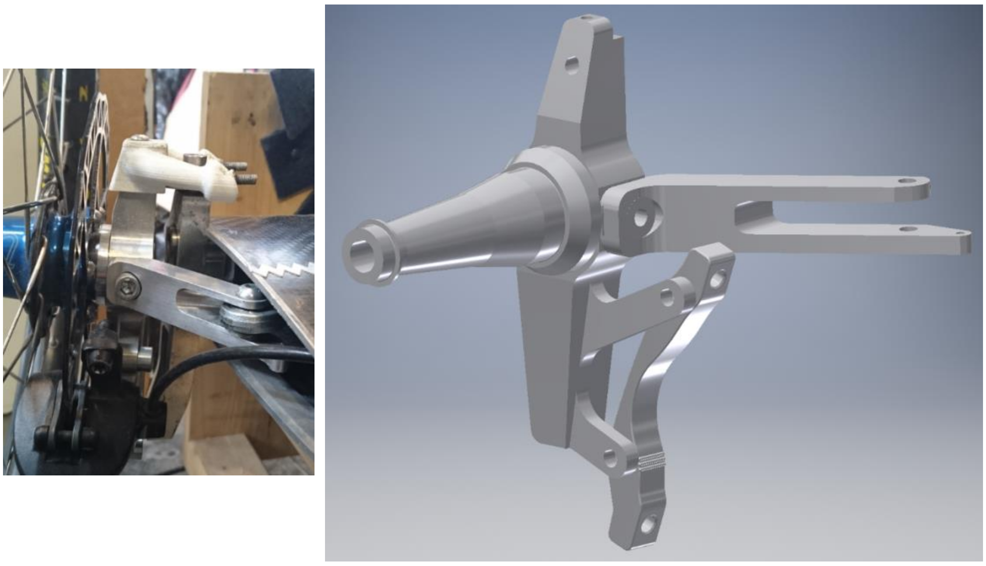

Fig. 6-8: **Predecessor (machined version) in mounted assembly of the predecessor concept car Eli15 (left) and related CAD model (right)**

In Fig. 6-9 the stress distributions of both designs are compared. The machined design contains multiple high stressed regions that result from the force redirection at sharp edges and interface regions. The differential construction as well as the restrictions in the machined design that result from design requirements in machining leads to clear disadvantages in the mechanical effectiveness of the structure.

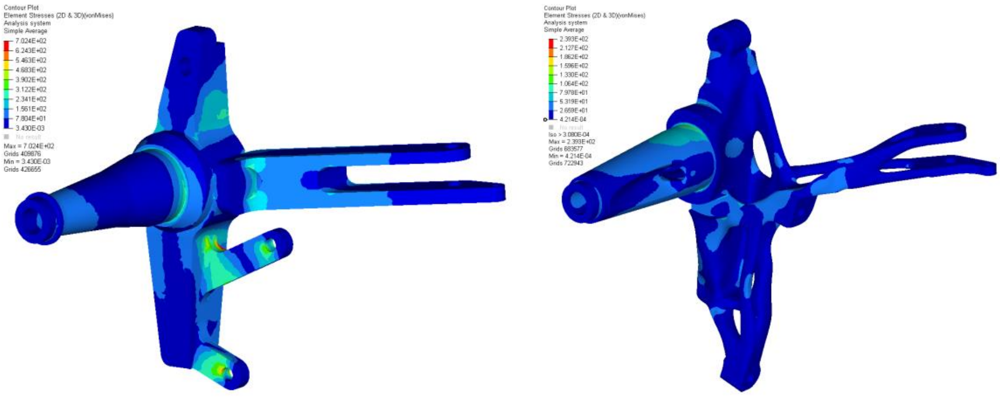

Fig. 6-9: **Von Mises stress distribution, machined version (left) vs. AM version (right)**

6.1.3 Analysis of Requirements

6.1.3.1 Identification of Inherent Trade-Offs with AM Technologies or AM-specific Design

There are inherent trade-offs in every manufacturing technology that a user needs to be aware of and that are part of the development of standards. Here the focus is set on LBM of the metal alloy AlSi10Mg. Important trade-offs with LBM are among others:

- Limitation in size of parts and structures due to available machine building volume and process related tolerances (e.g. coating system, laser caustic, thermal stresses)
- Need for support structures and suitable part orientation in order to take account of anisotropic effects as well as residual stresses that accumulate in structures during build-up
- Quality of surfaces and its correlation with support structures and geometric correlations with process parameters (e.g. low quality Down-skin surfaces)
- Limited accuracy of geometric features (e.g. edge rounding at sharp edges and corners)
- Need for powder-removal also in inaccessible areas like cavities or channels

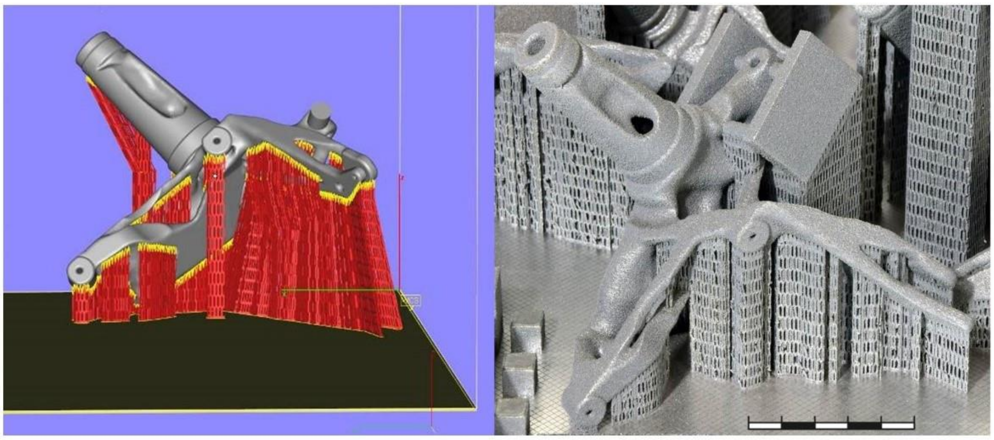

Fig. 6-10: Part’s build orientation and required support structures (left: CAD, right: real part)

6.1.3.2 AM-specific Design Limitations

In linkage to the inherent trade-offs with AM there are specific design limitations for which best practices and guidelines need to be developed. In the following sections, the focus is set on the minimum size of geometry features and tolerances related to part size and distortions, which are analysed in the case study. Both design limitations can be accounted for by adaption of the design but also by positioning the part in a suitable orientation combined with appropriate support structures.

Complex geometries like organic shapes created with the help of topology optimisation often consist of structural features with multiple angles of orientation, dimension and changes in cross section. Consequently not every surface can be orientated in a suitable way to account for limitations due to the manufacturing process. This has to be taken into account during the part design. If unfavourable angles cannot be avoided, it is important to reinforce these sectors or to apply an adequate post-treatment of down-skin surfaces. Also, if the parts accuracy is of high importance the minimum structural member size as well as changes in cross sectional areas have to be considered in order to avoid process related distortion.

Minimum / Maximum Allowable Size of Geometrical Features:

Design 1 of the bionic wheel carrier included some very thin trusses which were highly problematic in the AM process. Some of them broke already during the build-up process, very likely due to forces transmitted by the coating blade. Others broke during the separation process of the support structures.
For the enhancement of the design it was decided to only use trusses of a minimum diameter of 2 mm and also to use rips with the same minimum dimension. The definition of more guidance values for other geometric features (e.g. size of holes, width of slots, corner radius) was not necessary for the design of the bionic wheel carrier.

Tolerance Relative to Part Size / Analysis of Distortion due to Residual Stresses:

For topology-optimized parts deviations can be relatively small, since the geometry is based on firm trusses (withstanding the inner tensions which are causing deformation) and often owns a manageable change of cross sections in projection to the building area. Nevertheless a minimum diameter of trusses should be satisfied, as already shown in the previous section.

Residual stresses and therefore the part's accuracy have multiple influencing factors. It depends largely on the part-geometry, building orientation and support structures but also on process related parameters like exposure strategy and base platform heating. Depending on these conditions the deviation can be clearly visible or in contrast not perceptible prior to any measurement.
In the case study Designs 1 and 2 are analysed. The tested parts are built in AlSI10Mg on an EOS M400 system in 90 µm thick building layers (which is the vendor's standard value for this system). The base platform heating is set to 165°C, a common production value to minimise the residual stresses. The exposure is executed by standard parameters (exposure parameter of machine manufacturer). Some samples were manufactured by an alternative parameter set consisting of a higher energy input in the contour exposure; the core exposure has not been changed. An increased energy input in the contour is typically used to improve the surface quality.
The building orientation is avoiding obtuse surface angles in accordance with the manufacturing specific limitations. Horizontally placed surfaces were not avoidable and can be found in the steering linkage.
The support has been removed starting from the steering-linkage and going further over to the axle-attachment and the end of the main body, since the removal of the support structure is divining the sequence of deformation and could influence the deformation.

Rudimentary scans were executed using the hand-held laser measuring tool "Handyscan 700" of "Creaform" enabling a resolution of 50 µm with an accuracy of 30 µm. Beforehand the parts were varnished (thickness: ~50 µm) to reduce reflections of the laser scan for an improved precision.
Furthermore, CT-scans with a higher resolution were carried out on a computer tomography device ("CT-500") enabling a maximal resolution of 7 µm for small parts. Due to the size of the analysed part the resolution reached a value of approximately 30-40 µm. The data obtained by the scans has been compared with the CAD-data used for the building process.

The global analysis is shown in Fig. 6-11. The largest deformation with a deviation of 0.85 mm is found in the almost horizontally built slender steering linkage. On the upside, the steering linkage and the axel attachment show a clear deviation. The main-body in contrast shows a small divergence with a maximum deflection of 0.13 mm. Downside surfaces (right) show a deviation due to the lasers penetration depth (yellow and red areas). Apart from the downside-, axle-attachment and steering linkage section, the distortions are small. Especially the upside area has a good precision (green areas). A significant global deformation due to residual stresses is not apparent. The illustrations show that sharp edges miss precision/material according inherent tolerances with AM (blue lines/areas).
The global deviation is within the systems accuracy and resolution of 80 µm. Regions based on obtuse angles like the steering linkage allow residual stresses to cause a local deviation. Downside surfaces show a higher deflection than upside surfaces, due to the laser penetration depth. Edge rounding is apparent and within the resolution limit of 80 µm.

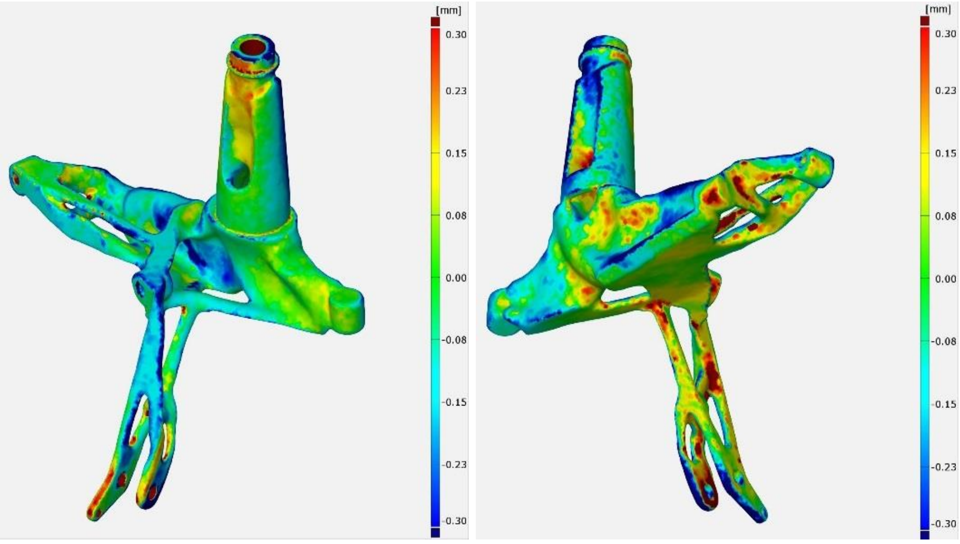

Fig. 6-11: Global deviation analysis with a displaying range from +0.3 mm/-0.3 mm . Left: Upside. Right: Downside.

The measurements mentioned above showed the need for reference planes enabling a precise alignment of the measured data with the design data (i.e. as-built vs. CAD). For that purpose the bionic wheel carrier was equipped with an external alignment body. In addition, the influence of a different contour exposure with a higher energy input was analysed. The scan is executed by a µCT-scan resulting in a finer resolution of 30-40 µm compared to the hand-held device. Since the inspection room of the µCT is limited in size, outer edges of the axle-attachment, steering linkage and lower main body are missing in the scanned data and will therefore not be analysed.
The global deviation analysis (see Fig. 6-12) is showing similar phenomena as the previous analysis. The downside reveals an intensified oversize due to the higher energy density of the contour exposure and the therefore increased penetration depth. The penetration depth is reaching a maximum of 1.26 mm and should therefore be compensated either by an exposure parameter adaption or by geometrical adaption. In addition, the upside shows certain local oversize now.

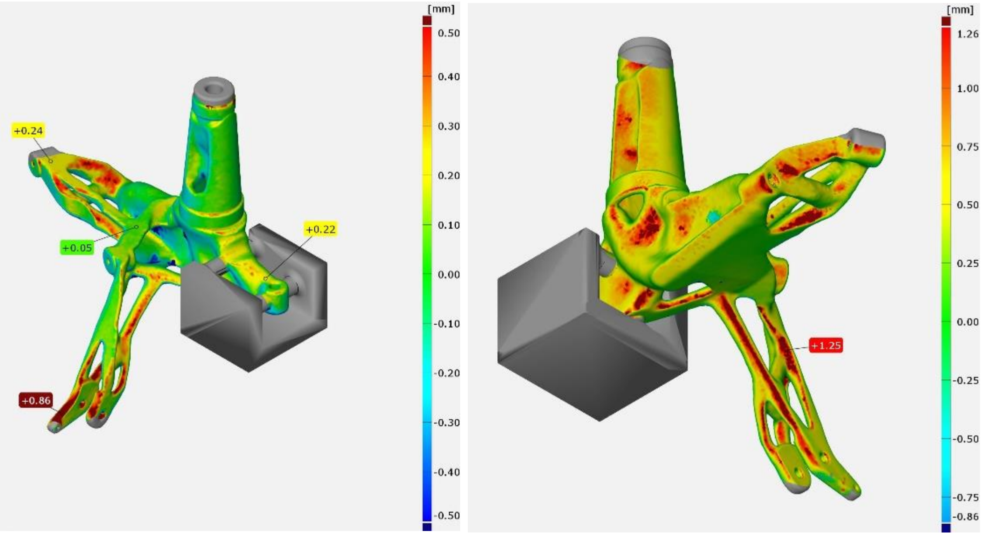

Fig. 6-12: **Global deviation analysis. Left: Upside (displaying range from +0.5 mm/-0.5 mm). Right: Downside (displaying range from +1.26 mm/-0.86 mm).**

The affected areas can be characterised by an obtuse building angle on the upside. These areas show characteristic material accumulations on the upside, which seem to be induced by the liquid metal's surface tension. A contour exposure with a higher energy input can therefore cause an unintended oversize and also results in wider edge rounding. The deformations located at the main body are comparable to the previously measured value. The edge tolerances are both undersized as well as oversized. The edge areas that show an oversize own the special characteristic, that the entrance point of the contour exposure is located on the edge. The inertia of the optical system combined with a higher energy input can lead to an augmented fuse area at the laser track's entrance.
In contrast the local deviations of the steering linkage show an increase of 0.34 mm (former deflection: 0.4 mm; new deflection: 0.74 mm), whereas the axle attachment does not contain a significant higher deviation (see Fig. 6-13).

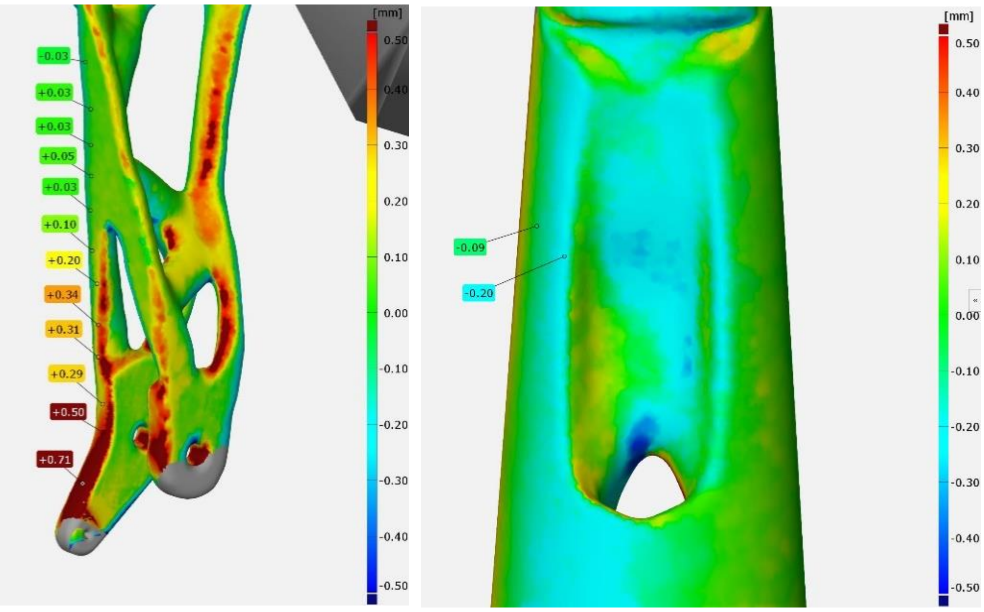

Fig. 6-13: **Deviation analysis of steering linkage and axle-attachment. Scale size: -0.5 mm/+0.5 mm. Left: Steering-linkage arm. Right: Axle-attachment.**

A rotation of the scan data around the main body's axis is leading to the same deflections observed in the former experiment regarding axle-attachment and steering linkage. Therefore, the hypothesis of a former not optimal alignment can be accepted.
The alignment strategy using an external alignment body has shown that the previous measurement is poor due to insufficient alignment. In addition, an alternative contour exposure affects the surface and edge quality due to a different solidifying range. In contrast, the influence onto the global deformation is not significant, since the core exposure has not changed. The contour exposure share is small relative to the total exposure volume and therefore the impact on global deviations is negligible.

Summary of Global Deviation Analysis:

A global deviation due to accumulated residual stresses and warpage is not apparent for the bionic wheel carrier. The main body shows slight curvature, which can be reduced by applying a stress relieving heat treatment before the support removal. Larger local displacements (max. 0.85 mm) can be found due to the unifications of different cross sections in the slender steering linkage.
Furthermore the investigation showed that the lasers penetration depth as well as the due to obtuse angles diminished surface quality in the downside areas cause a more distinct deviation than the warpage. The penetration depth is depending on the used contour exposure parameters. Instead, the change of contour exposure parameters is not showing significant effects onto the warpage behaviour.

The results proof that a suitable design, manufactured in an adequate orientation, is showing barely any geometrical deformation, making a post stress relief heat treatment non-essential. This can lead to an abbreviated manufacturing chain, which is demanding less surveillance.

For a full statement regarding the deviation-reproducibility of a component, a test series would be necessary to take disruptive influences (e.g. powder quality, individual manufacturing process) into account.

6.1.3.3 Evaluation

Cost Reduction:

No data available.

Weight Reduction:

For the evaluation of weight reduction through AM and organic shape of the bionic wheel carrier Design 3 is compared to the predecessor machined part. For the evaluation of weight savings, also the performance of the component has to be compared. The decisive value for this purpose is the weight to stiffness ratio. Some important values in this context are shown in Table 6-2.

	Machined Wheel Carrier	**Bionic Wheel Carrier (AM)**
Weight	190g (incl. 17.5g fasteners)	165.2g
Max. Stress	702 MPa	239 MPa
Max. Displacement (measured at axis dropout)	0.81mm	0.49mm

Table 6-2: Comparison of performance values for evaluation of the bionic wheel carrier

The weight of the bionic wheel carrier is reduced by ~13%. At the same time, the maximum stress and maximum displacement are significantly reduced for the most critical load case of a full braking during cornering. As the AM aluminium alloy has lower strength the strength requirements of the material are met through the reduction of stress concentrations.

Combination of Parts:

The bionic wheel carrier consists of one part that integrates four previously distinct components of the predecessor machined part. Additionally, four fasteners (screws) are omitted in the AM design. The integrated design holds benefits in terms of weight, less mounting effort and overall stiffness.

Functional Integration:

In case of the bionic wheel carrier the integration of specific functions was not intended.

Performance:

Looking in the weight savings, the improvement of performance becomes obvious: Due to the bionic design and the reduction of parts the maximum stress and displacements could be reduced, whilst decreasing the total weight of the component.

Product Life:

The analysis and improvement of the fatigue behaviour was not intended for this component. Looking at its target application there are no dedicated fatigue requirements, but nevertheless it is assumed that due to the homogenous stress distribution an increase in fatigue performance has been achieved.

Safety Margin:

No data available.

Maintainability:

Due to the combination / reduction of parts the maintainability is improved: an inspection of interfaces and fasteners of the omitted single parts for wear/tear or integrity is now obsolete.

6.1.4 Main AM Process Flaws and Weaknesses

6.1.4.1 Costs and Material Availability

The main flaws in the AM process are the costs for production and development. For the bionic wheel carrier there was no comparable design that could be refined. To reach the full potential of organic shape design with topology optimization tools most often one has to start from scratch. This is also the case when the goal of an integral design is pursued. This makes the product development very time-consuming. In addition, there are many guidelines missing for AM design or not applicable for complex organic shapes. The distortion analysis showed that there are multiple influencing factors that are also related to the geometry of the part. Therefore, for complex parts the user has to adapt process parameters to reach improved results.

The AM process stability, material processing and production quality and geometric tolerances for the bionic wheel carrier are sufficient for the application of the wheel carrier. Still, the lack in available materials and material specific parameter sets for commercial machines (like the EOS M400) ab initio lead to a disadvantage for the AM design using the inferior AlSi10Mg alloy compared to Al 7075 for the machined design. There is a lack of evaluation capacity for the AM material and material models are missing for complex truss or cellular structures. This leads to high safety margins in complex organic shapes design, especially when fatigue loaded.

Additive Manufacturing in combination with bionic shapes and integral design holds high potentials in weight savings and performance enhancement. But not all of the AM process flaws will be overcome and it will take time to develop standards and guidelines. That is why it is important to imagine AM as one of many manufacturing technologies and an AM part as one of many parts in an assembly of a technical system.

6.1.4.2 Prospect to Develop very large AM Equipment

Manufacturing larger AM equipment by LBM will provoke new challenges. Besides the need for a higher amount of metal powder that is required in the process, the weight of the built components has to be handled during the manual work. Therefore, new ways of support removal are necessary. Also, the process itself needs to advance. A bigger coating unit requires a higher degree of accuracy in order to guarantee a consistent layer quality. Therefore, especially fine structures or wall thicknesses will be more difficult to manufacture. Another minor issue is the quality of the inert gas shield (due to the powder-bed size) and therefore the degree of contaminations within the manufactured material.

Furthermore, the exposure strategy needs to evolve. Larger AM parts require a large-scale powder bed and therefore probably more laser units to cover the area. The exposure time would increase, just like the accumulated residual stress. This could limit the maximum part size, due to crack initiation during the process and increase the thermal deviation after removing the support structures. Different exposure strategies or heat treatments can be used to reduce this effect. The need for stress relieving heat treatments will rise with larger AM parts to ensure a certain geometric accuracy, but according to the examination will be depending on the design.

The case study of the bionic wheel carrier has proven the accurate production of a 120 x 135 x 105 mm³ AlSi10Mg component in a 400 x 400 x 400 mm³ building chamber.

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6.2 Main Gearbox Bracket

Case Study Input from:	Fraunhofer IFAM DD	Equipment used:	Arcam A2X
AM Technology:	Electron Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Milling	Parameter used:	OEM Standard
Material:	Ti-6Al-4V	Inert Gas used:	- (in vacuo)

Table 6-3: Additive Manufacturing of main gearbox bracket

6.2.1 Description of the Component and its Function

The main gearbox bracket (MGB) is one out of four brackets which connect a helicopter main gearbox with the airframe. The brackets transfer all translational forces caused by flight manoeuvres into the main structure. Initially the part was an assembly out of two milled parts. They were connected to each other by four bolts and a bush. The assembly was connected to the gear by a bearing and to the structure by 26 rivets. During topology optimisation all connecting points of the initial assembly to surrounding structure must remain as they are. Main goals for optimisation where combining the assembly to a single part, satisfying all static and fatigue load cases and decreasing the weight as much as possible.

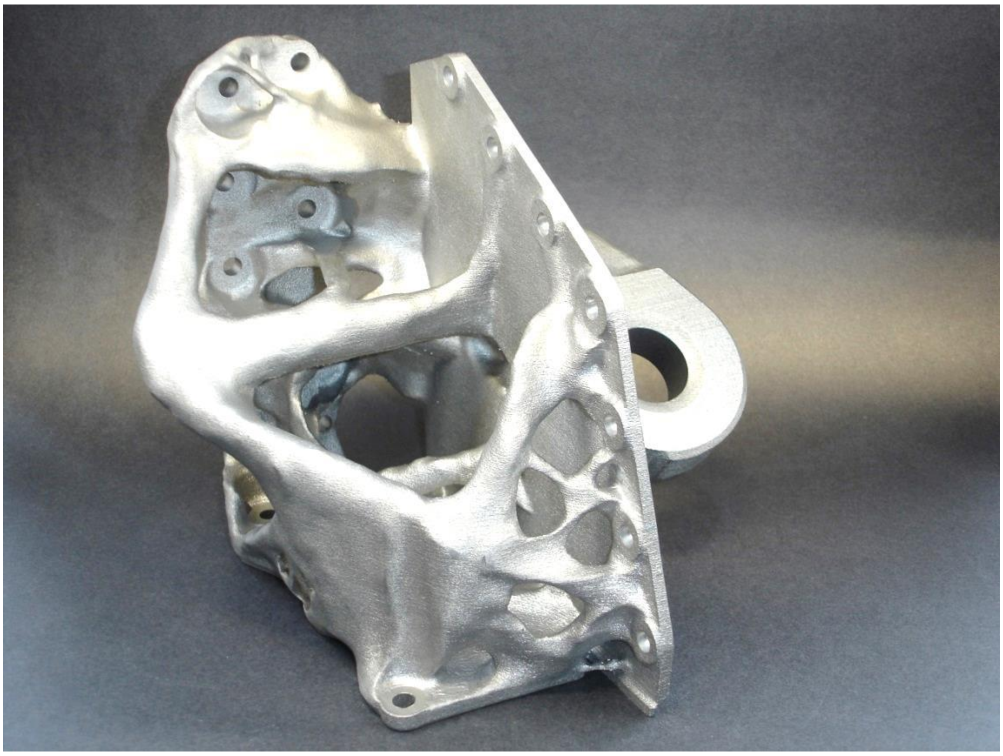


Fig. 6-14: Helicopter main gearbox bracket manufactured by the use of EBM

6.2.2 General Design Principles

6.2.2.1 Design Features

Organic Shape:

The organic shape is the result of the computer aided topology optimisation to satisfy all loads by reducing the mass as much as possible. But due to the part being safety-critical, a respective margin of safety has to be taken into account. Therefore, the maximum weight reduction possible can't be applied to the full extent.

Minimum Allowed Radius:

Due to the optimisation, the surface of the optimized structures itself has a smooth stress distribution. Some radii were only smoothed to decrease the number of rough element surfaces.

6.2.2.2 Special Requirements of AM design

Geometrical Aspects:

The mounting holes of the part were smoothened and post-processed to avoid uneven holes and positioning failures due to their tolerances. Additional material was added to the part to account for the material loss during surface smoothing. The minimum structure size was kept over 3 mm on loaded structure due to the strength drop on small structures.

Need for Conventional Drawings:

A conventional drawing is not needed for the AM itself, but it is necessary for post processing. That means that tolerances surfaces need to be tolerated on this drawing. All other surfaces are just necessary to understand the parts dimensions to avoid damaging the part during post processing.

Development of Standards:

For this part on each tolerated surface an offset of 2 mm was added. This was necessary to generate a reference surface first for post-processing all other surfaces, especially after re-positioning the part on the milling machine. That means not only the additional material for post-processing was needed, as it is defined for LBM in the German standard VDI3405-3 [5], but also additional material for first processing a reference surfaces was required.
Especially for EBM there is no specific definition (i.e. numbers) for additional material in any standards available yet.

In case of structure size and their specific strength it is pronounced, that thin structures have other metallurgical texture than usual bulk material. This should be mentioned to avoid using thin structures for strength purposes.

6.2.2.3 Differences between AM Technologies

An EBM Arcam A2X machine was used for this component. Advantages of EBM compared to LBM are, among others:

- Higher build rates (very high scan rates, multi-beam scanning mode possible)
- Higher process temperatures (pre-heating) and therefore lower temperature gradients, resulting in less residual stresses
- Less support structures needed

The EBM-typical elevated process temperature results in a significantly lower internal stress level during and after the build process. Therefore, the part needs only thin and easy-to-remove support structures. The support does not even need to be mounted directly on the build platform, but can start within the powder bed. Compared to LBM, this leads to potentially higher complexity as well as reduced production time for support structures and consequently to a reduced effort for support removal (post-processing). In addition to that, the part is less likely to deform after being removed from the build platform or after the mechanical post-processing. EBM's main drawback – a limited complexity for inner geometry features – is of limited importance for typical topology optimized geometries, like the present case study.

6.2.2.4 Replaced Manufacturing Technology

The conventional bracket was manufactured by milling and consists of two screwed single parts, one out of Steel and one out of TI6Al4V. The TI6Al4V part had a very high amount of waste material. The AM design combines these two parts and reduces the mass and the amount of waste material significantly.

6.2.3 Analysis of Requirements

6.2.3.1 Product and Product Use Considerations

At the beginning there were several parts discussed for this case study. Therefore a decision process, such as described in ISO/ASTM DIS 52910.2:2016(E) Figure 2 was performed on these parts. As a result the main gearbox bracket showed the highest potential in terms of lightweight, part integration and efficient material use. The main goal was to reduce the mass of this assembly as much as possible while satisfying all static and dynamic loads. Therefore an optimisation process was performed to find the stiffest design while withstanding all load cases.

The main gearbox bracket is one of four brackets to transfer all translational loads from the main gearbox of the helicopter to its main structure. That means the part is of safety class one. This is why it has to be designed against limit loads (the maximum loads to be expected in service) and ultimate loads (limit loads multiplied by prescribed factors of safety), which of course has to be considered also during topology optimisation by using appropriate load cases.
In addition a material offset was defined in order to keep the final dimensions above the calculated sizes after the overall surface smoothing.

6.2.3.2 Thermal Environment

The environmental temperature is about ≤ 100°C, which is uncritical for the material.

6.2.3.3 Sustainability Considerations

On the conventional assembly the buy-to-fly (BTF) ratio is about 5:1, i.e. about 80% of the material is milled away. For the EBM-built part, the BTF ratio is about 1,2:1, i.e. about 20% of the as build volume were removed during post-processing.

6.2.3.4 Cost or other Business Considerations

This part, which is still in the feasibility stage, has a considerable potential for cost and fuel savings over its lifetime, e.g. (i) the material costs may by lower due to less waste material compared to the conventional design, (ii) the part production costs may be balanced or further lowered, respectively, by the lower weight, which leads to fuel savings. With respect to part inspection / quality checks, this part is very challenging due to its complexity and the respective NDT routines have yet to be established.
With regard to exact numbers about costs and savings unfortunately no data can be provided here, since related information is confidential.

6.2.3.5 Identification of Inherent Trade-Offs with AM Technologies or AM-specific Design

The part had to be redesigned due to rough and uneven surfaces of the optimisation draft. How to redesign parts from optimisation to manufacturing was investigated more deeply with different CAD strategies to find the most efficient way. These results were published at Direct Digital Manufacturing Conference 2016 [13] and are going to be published at RapidTech 2017. Reason for this is the need of two manufacturing files, one for AM and one for mechanical post-processing (e.g. CNC machining).

6.2.3.6 AM-specific Design Limitations

Minimum / Maximum Allowable Size of Geometrical Features:

The only consideration that was made is the minimum member size of the structure, which was kept over 3 mm in order to make sure that the typical material performance can be reached by ensuring that the needed microstructure is achieved. As literature (e.g. [14]) assumes that there is a relationship between mechanical properties and structure size, a value was chosen which is sufficiently far away from the size of microstructural features, but at the same time doesn't reduce considerably the expected benefits, e.g. with respect to weight savings.

Surface Texture:

The as-built structure heavily impacts the fatigue performance of the part. Therefore an overall surface smoothing was performed after the optimisation.

Overall Surface:

The part is dimensionally acceptable except for the tolerated surfaces, which were post processed. Additionally all rivet holes were drilled during post processing to be sure that they are positioned correctly.

Tolerance relative to Part Size:

The part needs to meet ISO 2768mK (general tolerances). In addition each surface which is connected to the surrounding structure was especially tolerated. The tightest tolerances were on the rivet holes: Ø6 H8 with a positioning tolerance of 0.04 mm over a distance of about 138 mm. Furthermore, 26600mm² out of 130000 mm² needed to be mechanically post-processed which is about 20% of the overall surface area.

Acceptable Local Variation of Wall Thickness:

The wall thickness is called acceptable, if the measured value is above the designed values to avoid part failure.

6.2.3.7 Post Process Treatment Explanation

To fulfil the tolerance requirements on surfaces and rivet holes, CNC milling was performed. Furthermore, electrochemical polishing was performed on the optimized structures in order to reach the needed target values w.r.t. surface roughness. In addition a HIP treatment was done in order to tailor the microstructure and eliminate any residual porosity simultaneously.

For contractual reasons the exact values of roughness requirements are confidential, but in general the target is about Ra < 3 µm.

6.2.3.8 Evaluation

Cost Reduction:

No data available.

Weight Reduction:

60% weight reduction compared to the conventional assembly.

Combination of Parts:

The initial assembly consists of two milled parts, one bush at the connection of these both parts and at least four bolts and three screws. These 10 single parts were combined to a single one.

Functional Integration:

In case of the main gearbox bracket the integration of specific functions was not intended.

Performance:

Static and dynamic loads were satisfied. This was proven by rig tests on a number of samples, further details are confidential.

Product Life:

The part meets the lifecycle requirements.

Safety Margin:

The smallest safety margin during calculation was on low cycle fatigue at 1.12.

Maintainability:

Every rivet should be visible during inspection after a specific flight period, which is fulfilled.

6.2.4 Analysis of Material Characterisation and Differences between AM Technologies

6.2.4.1 Material Characterisation Data of Components made by AM

Yield:

Typical values according to ASTM E8 (Standard Test Methods for Tension Testing of Metallic Materials) measured on test specimen: 1000 – 1030 MPa at room temperature (sample state: as-built + heat-treated (HIP)).

Elongation:

Typical values according to ASTM E8 on test specimen: 10 – 15% at room temperature (sample state: as-built + heat-treated (HIP)).

HCF (High Cycle Fatigue):

Testing was performed at room temperature on post-processed (machined) test specimen. There is a significant influence of the heat treatment parameters on the HCF performance. The highest values obtained were in the range of 600 MPa for > 10^7 cycles.

Recommended number/type of quality standard specimen per build-job:

It is recommended to use 10 specimens per build-job for different orientations within the build space (in 0°, 45°, 90° to the beam direction).

6.2.5 Main AM Process Flaws and Weaknesses

6.2.5.1 Need to Speed Up the Process

The speed of the process is definitely a weakness compared to conventional manufacturing, especially for powder bed fusion processes. The increase of productivity, both in terms of process parameters (e.g. build rate) and no. of parts per build job is of paramount importance for the acceptance of AM for serial production. Furthermore, setting up the systems is still time-consuming and operator-dependent. Speeding up this step by e.g. standardization of the machines and possibly fewer steps might be one option. With respect to pre-processing, the need also exists. This relates to steps like the generation of supports combined with sampling and part orientation, all of which need much higher degree auf automation.

6.2.5.2 Costs

Costs for powder and the AM machines are comparatively high and need to be reduced for an improved economy of AM.

6.3 Calibration Tool for Extrusion Process

Case Study Input from:	Fraunhofer IFAM HB	Equipment used:	EOS M 270 Dual Mode
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Milling, Investment Casting	Parameter used:	OEM Standard
Material:	Stainless Steel 1.4542 = 17-4PH	Inert Gas used:	Nitrogen

Table 6-4: Additive Manufacturing of calibration tool

6.3.1 Description of the Component and its Function

This calibration tool is used within an extrusion process to calibrate the hollow geometry of extruded feedstock consisting of metal powder and additives (polymers and waxes). The results of that process are so called green blanks of pipes, which subsequently need to be sintered to fully metallic pipes.

Fig. 6-15: Calibration tool manufactured by the use of LBM

During the continuous extrusion process the feedstock is heated up and then pushed through a forming tool in order to form a hollow cylindrical shape. As the material is still hot and weak when leaving the forming tool, it has to be cooled down while maintaining its desired shape. For this purpose the calibration tool is attached directly to the forming tool, providing the cooling as well as the shape-keeping function. The cooling function is realised by a cooling fluid flowing through corresponding channels. Simultaneously a vacuum is attached to the vacuum channels, sucking the still weak material towards the cylindrical inner surface of the calibration tool. In this way the hollow geometry of the pipe is fixed and “calibrated”.

The calibration tool described here has no conventionally manufactured predecessor. Comparable conventionally manufactured tools are using compressed air for calibration, which is less effective. The tool described here was specially designed for AM to highly integrate the complex internal channels in a limited given design space. Compared to conventional calibration tools its benefit is the better thermal and calibration performance and the reduced size.

Machining of functional surfaces and geometrical features as threads was executed as post-processing steps after the printing step.

6.3.2 General Design Principles

6.3.2.1 Design Features

The internal cooling and vacuum channels have been integrated in a very compact design space; the minimum distance to each other is about 1 mm. The cooling channels are located close to the tools inner surface in order to achieve high cooling performance (see Fig. 6-16).

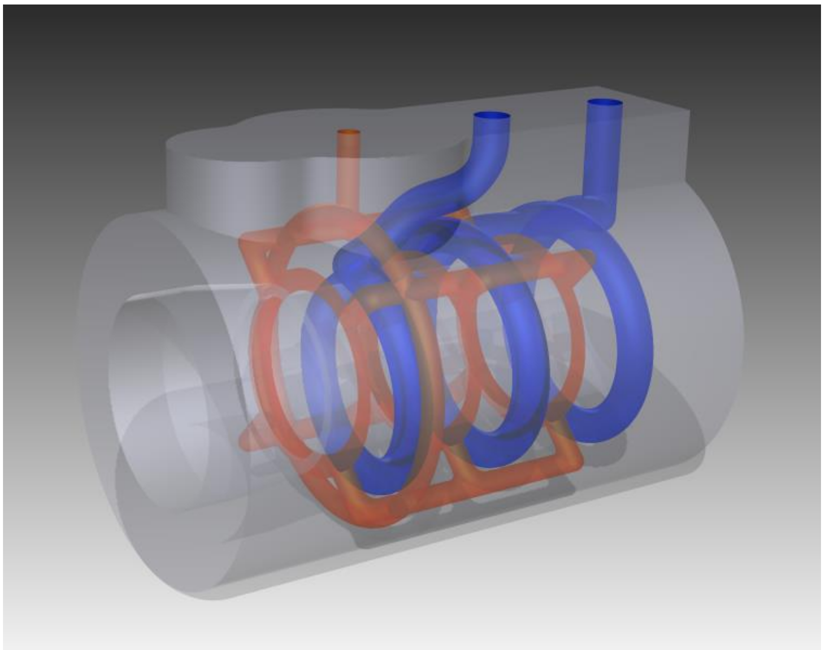


Fig. 6-16: Integrated functions – vacuum channels (red) and cooling channels (blue)

6.3.2.2 Special Requirements of AM design

Geometrical Aspects:

The calibration tool is designed with internal channels whose dimensions cannot be measured after having printed the part – except by using CT techniques. These were not used for costs reasons and because simple flow tests showed a sufficient flow behaviour and vacuum quality. We have to rely on the printing system’s capability to reproduce the designed geometry in the range of specified tolerances. Concerning the channel diameters these tolerances where in the range of ± 0.5 mm, which were met.
Another aspect is to leave the channel diameter wide enough to be able to get rid of the not bound powder particles. A sufficient width for the used 17-4 PH Stainless Steel powder is about 3 mm.

Need for Conventional Drawings:

Conventional drawings are not necessary for the printing process itself, as we work directly from the CAD data model. But to specify the part's geometry and to enable control of dimensional accuracy and surface quality, also AM needs drawings and specifications.

Especially descriptions of AM-specific surfaces are needed as for example in the case described here the surface quality of the internal channels was absolutely sufficient in their "as-built" condition, but may be insufficient in other cases of application.

Another aspect is the orientation of the part in the building chamber which may be specified in the drawing as the mechanical values differ in the different build directions. Expressions like "main part axis C in z-direction" should be added to AM-specific drawings.

Also post-processing hints should be possible like "avoid support structures here", referring to a specific surface area.

All functional surfaces should be described conventionally in the drawing, i.e. by specifying dimensions, tolerances, surface requirements (roughness) etc.

Development of Standards:

Currently there is still a lack of standards for AM and its specific different technologies. Standards will be needed for all kinds of AM related topics as:

- AM materials
- AM testing
- AM post-processing
- AM surface quality
- build direction or orientation
- allowed/not allowed support areas
- minimum diameters without support, minimum overhangs, minimum angles, minimum wall thicknesses – each related to specific AM materials and specific AM methods

6.3.2.3 Differences between AM Technologies

Here LBM was chosen because at that time it was far better concerning surface quality compared to EBM and stainless steel is a standard and well known material for LBM. Meanwhile EBM has become better concerning surface quality but is still behind LBM and still not widely used to process steel materials.

The EOS M270 Dual mode system used here was a standard system without any modifications. Dual Mode just means that it can also process light metals as aluminium or titanium.

6.3.2.4 Replaced Manufacturing Technology

The complex internal channels could have never been produced with a moulding technique. The only technique able to produce this kind of complex shaped geometries could be investment casting.

As already stated in the description, the calibration tool described here has no conventionally manufactured predecessor of the same geometry. It was specifically designed for AM to highly integrate the complex internal channels in a limited given design space. The benefit of the AM version was its better thermal and calibrating performance compared to a conventional calibration tool of higher length because it consisted of more single parts and had less performance.

Nevertheless machining is still necessary to post-process the raw part. All functional surfaces like threads or sealing faces have to be conventionally machined due to the limited surface quality AM systems are able to produce.

6.3.3 Analysis of Requirements

6.3.3.1 Product and Product Use Considerations

In this study AM was the only way to integrate the complex channels into the limited design space. The conventional tool was longer and consisted of more parts. The AM design also delivered a better thermal and vacuum performance, so slightly higher costs compared to conventional manufacturing methods were acceptable.

Stainless steel was chosen because of the chemically active ingredients of the material to be extruded. The cooling channels were designed without any sharp edges to enable smooth flow of the cooling agent to minimise fouling and abrasion inside the channels.

6.3.3.2 Thermal Environment

Guiding the channels directly below the inner surface of the tool, delivers an excellent heat transfer between cooling agent and extruded material thus resulting in sufficient cooling rates and good surface quality and geometrical accuracy of the extruded material.
There is no quantifiable comparison with a conventional calibration tool as the tool described here was used for a unique feedstock material. Its calibration performance was satisfying.

6.3.3.3 Sustainability Considerations

Again to mention: the cooling channels were designed without any sharp edges to enable smooth flow of the cooling agent to minimize fouling and abrasion inside the channels. Both lead to changes in the flow parameters and thus influence the thermal and vacuum performance as well as stability of the extrusion process.

6.3.3.4 Cost or other Business Considerations

The part is costly but not producible with other techniques. As a one-of-a-kind product the development of cheaper conventional manufacturing techniques was not sensible. The fulfilment of the desired calibration was not possible with a conventional calibration tool set-up of much larger size.

6.3.3.5 Identification of Inherent Trade-Offs with AM Technologies or AM-specific Design

With the 17-4 PH material used here, the channels have to have a certain diameter limit (maximum) to be producible by AM without internal support structures. This is about 8 mm in diameter and has to be kept in mind during design of the part.

6.3.3.6 AM-specific Design Limitations

<u>Minimum / Maximum Allowable Size of Geometrical Features:</u>

Concerning the diameter of the internal channels, there have been set tolerances in the range of ± 0.5 mm which were met. Another aspect is to leave the channel diameter wide enough to be able to get rid of the not bound powder particles. A sufficient width for the used 17-4 PH Stainless Steel powder is about 3 mm.

Surface Texture:

With the 17-4 PH material used here, the angle between building platform and bottom surfaces of the part should be more than 40° if not supported, otherwise surface roughness becomes extremely high or the so called overhangs have to be supported by lattice or strut structures which have to be removed after printing.
In this case study overhangs were avoided and channels were small enough (< 8 mm) in order to avoid support structures (see also Fig. 6-17).

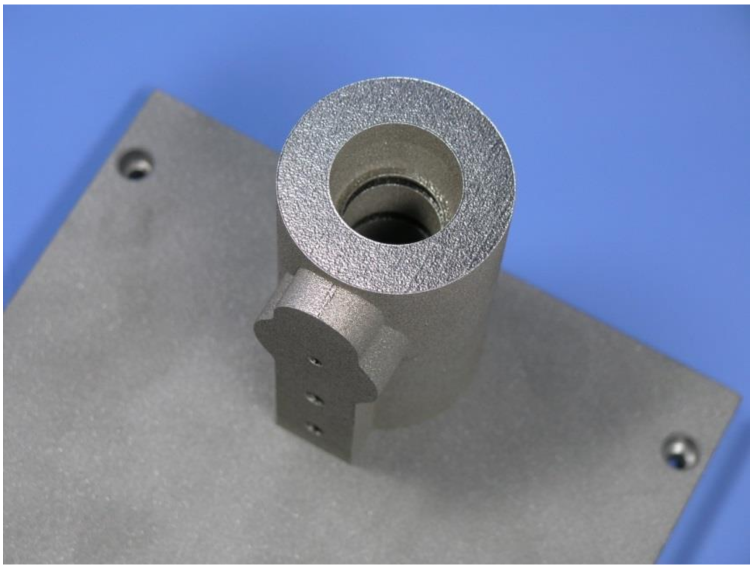


Fig. 6-17: calibration tool – raw part on build platform

Overall Surface:

The part was dimensionally acceptable directly after the AM process. Only functional surfaces had to be post-processed.

Tolerance relative to Part Size:

0.5 mm per 100 mm feature length.

Acceptable Local Variation of Wall Thickness:

About 1 %

Quality Related Information for Each Build-Job:

We would recommend 3 cylindrical specimen of 10 mm diameter, built in three directions: 0° (lying) and 45° and 90° (standing) are sufficient to judge the process quality.
Some printing service companies use only one tensile test specimen per build-job to verify the process stability and quality.
In this case study no specimens were built with the part as the process was considered of having high quality due to well established building parameters which were qualified before. Additionally the part is not life-critical.

6.3.3.7 Post Process Treatment Explanation

The part was blasted (glass beads) and was sawed off the building platform and milled at that surface. No support structures had to be removed. No heat treatment was necessary. All functional surfaces were milled (inner diameter surface) or cut (threads).
There was no additional machining. There was no additional surface treatment (peening, grinding, electro polishing etc.).

6.3.3.8 Evaluation

Cost Reduction:

The part is costly but not producible with other techniques.

Weight Reduction:

The guess here is about 50 %. The weight of the conventional solution was not measured.

Combination of Parts:

A part with the same functionality conventionally manufactured would have consisted of about 5 parts plus sealing material. Here we have all functions integrated in one part without sealing problems between single parts.

Functional Integration:

Vacuum and cooling channels are highly integrated in a limited design space. The conventional solution had approximately twice the length of the AM solution which led to sticking feedstock material in combination with insufficient geometrical accuracy.

Performance:

Placing the channels directly below the inner surface of the tool leads to sufficient heat transfer between cooling agent and extruded material, thus resulting in sufficient cooling rates and good surface quality and geometrical accuracy of the extruded material. Numbers are not available here because this was simply judged on behalf of the feedstock and material behaviour.

Product Life:

Not tested – but in the range of conventionally manufactured comparable devices. After some test runs the device showed comparable abrasion marks as conventional extrusion shaping tools of the same material.

Safety Margin:

Not calculated – but in the range of conventionally manufactured comparable devices. This assumption derives from the same wall thicknesses used in similar conventional devices.

Maintainability:

The cooling channels were designed without any sharp edges to enable smooth flow of the cooling agent to minimize fouling and abrasion inside the channels. They still have the as-built surface quality which is sufficient for the planned application to lead cooling media. As maintenance procedure there is a flushing with a special cleaning fluid.

6.3.4 Analysis of Material Characterisation and Differences between AM Technologies

6.3.4.1 Material Characterisation Data of Components made by AM

Anisotropic Material Properties:

Usually there is anisotropy between the mechanical properties of the material's mechanical performance in xy-plane direction and z-direction (build direction). The values in z-direction are sometimes 10 % below those of the xy-plane direction. This strongly depends on the printing parameters as layer thickness and energy input.

In this case study no specimens were built with the part as the process was considered of having high quality due to well established building parameters which were qualified before. Additionally the part is not life-critical.

Yield:

Not tested because not required – but is affected by anisotropic nature of the as-built material.

Elongation:

Not tested because not required – but is affected by anisotropic nature of the as-built material.

HCF (High Cycle Fatigue):

Not tested because not required – but is affected by porosity and surface quality.

LCF (Low Cycle Fatigue):

Not tested because not required – but is affected by porosity and surface quality.

6.3.4.2 Relevant Documentation

For the case study no standard was used because not required and/or not published yet.

6.3.5 Main AM Process Flaws and Weaknesses

6.3.5.1 Need to Speed Up the Process

If only looked at the printing step, this is already done by using more powerful lasers and multi laser machines with larger building chambers. Other aspects along the whole process chain are:

- Process simulation to be able to build first-time-right
- Automated data processing to control data quality of CAD models

- Automated support generation
- Automated powder handling and integrated powder recycling
- Automated and/or standardised support removal
- Automated/integrated heat treatment and/or laser polishing
- Development of continuously producing printing systems apart from the current batch printing systems … as already shown with sand-based binder jetting systems (VOXELJET VX 800)

6.3.5.2 Surface Quality

Surface quality has to be improved. Approaches with new pulse laser systems and integrated laser polishing steps are being made.

6.4 Heat Exchanger

Case Study Input from:	Fraunhofer IFAM HB	Equipment used:	EOS M 270 Dual Mode
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Milling, Investment Casting	Parameter used:	Customized
Material:	Nickel based alloy (similar to Inconel 718)	Inert Gas used:	Nitrogen

Table 6-5: Additive Manufacturing of heat exchanger

6.4.1 Description of the Component and its Function

The described counterflow heat exchanger was designed and manufactured for feasibility tests to improve the efficiency of a micro gas turbine system. Hot exhaust gas should heat up inflowing relatively cold air to improve the overall combustion efficiency of the system.

The heat exchanger described here combines 18 layers of channels for heat exchange and their collecting and connecting channels for outflowing exhaust gas coming from the turbine and inflowing cold air.

The heat exchanger described here has no conventionally manufactured predecessor of the same geometry. It was designed specifically for AM to highly integrate the complex internal channels in a limited given design space. The benefit of the AM version was its better ability to combine the channel geometry to create a maximum surface area for heat exchange and the collecting and connecting channels for outflowing exhaust gas and inflowing cold air.

Machining of functional surfaces as the connection surfaces at inlets and outlets was only done at the side towards the building platform and was executed as a post-processing step after the printing step.

Fig. 6-18: Counterflow heat exchanger manufactured by the use of LBM

6.4.2 General Design Principles

6.4.2.1 Design Features

Fig. 6-19 shows a similar conventional counterflow heat exchanger and its operating principle.

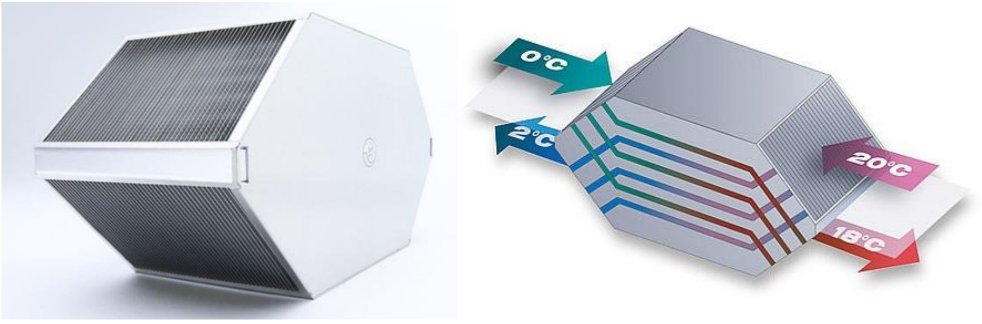


Fig. 6-19: Conventional counterflow heat exchanger and its operating principle (www.klingenburg.de)

In contrast Fig. 6-20 shows a sectional view of the additively manufactured counterflow heat exchanger. It is designed with complex internal channels and fins in combination with thin walls, which do have a very small spacing to each other. The internal channels were designed in a waved shape (radii of 3mm) in order to realise a maximum surface for an optimised heat exchange performance; and the laminar air flow causes only a small pressure drop inside the system.

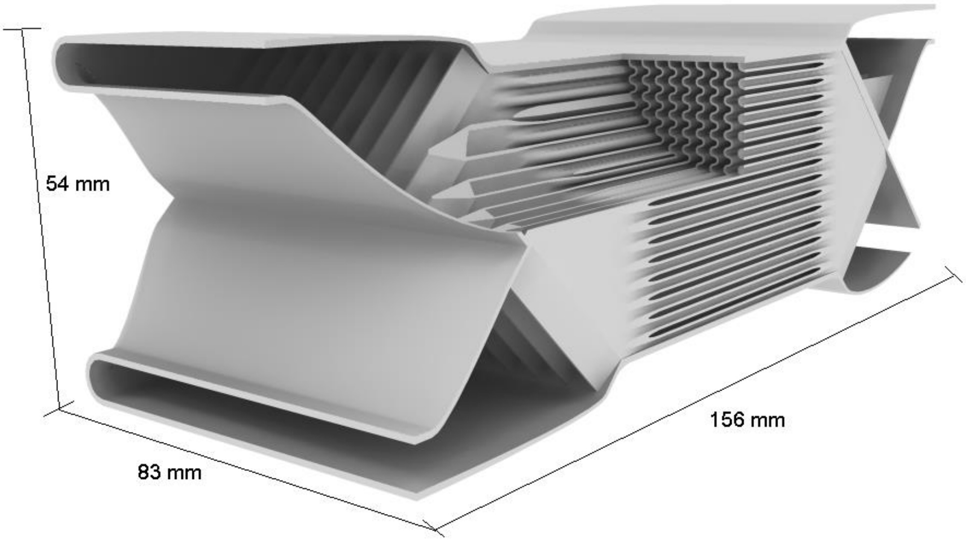


Fig. 6-20: Sectional view showing the complex internal structure

6.4.2.2 Special Requirements of AM design

Geometrical Aspects:

The dimensions of the internal channels and fins cannot be measured after having printed the part – except by using CT techniques. But these were not used for costs reasons and because simple flow tests showed a sufficient flow. We have to rely on the printing system's capability to reproduce the designed geometry in the range of the specified tolerances. Concerning the inlet and outlet positions these tolerances where in the range of ± 1.0 mm, which were met.

Another aspect here is to design the structure in a way to avoid distortion during build-up and post-processing. The Nickel-based material tends to develop high residual stresses during build-up and therefore needs a self-supporting structure and an adequate binding to the building platform – see Fig. 6-21.

We did not have to increase the wall-thickness in order to avoid too high residual stresses and distortion. Internal support was taken by the channels walls which at the same time assure sufficient heat dissipation.

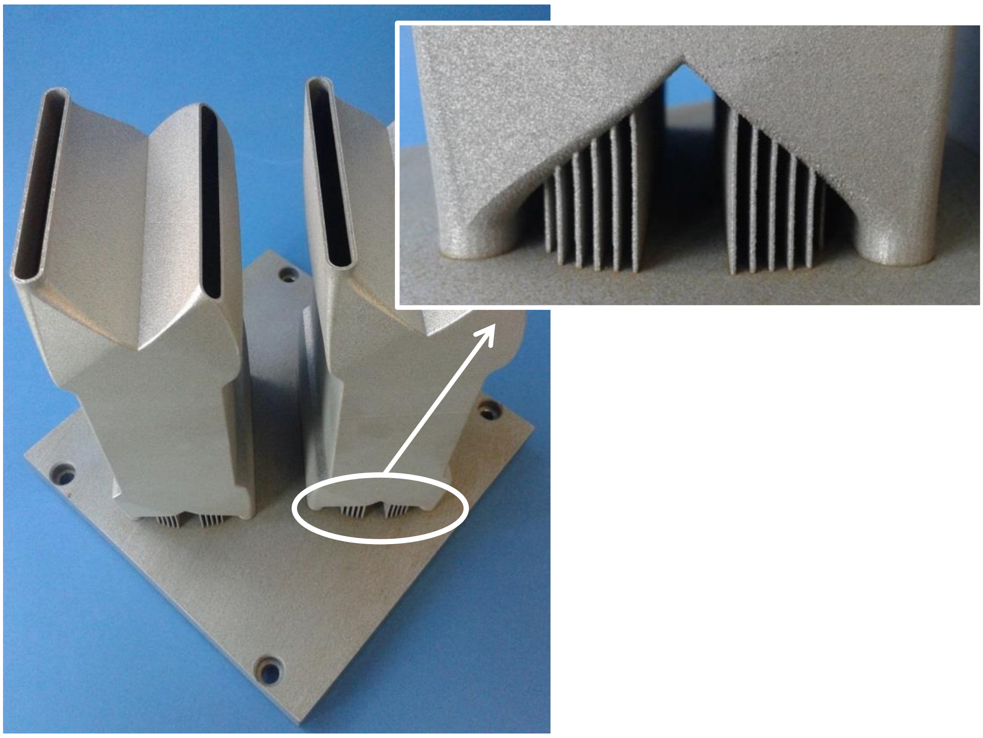


Fig. 6-21: Detail of support structure

Need for Conventional Drawings:

A conventional drawing is not necessary for the printing process itself, as we work directly from the CAD data model. But to specify the part's geometry and to enable control of dimensional accuracy and surface quality, also AM needs drawings and specifications. Especially descriptions of AM-specific surfaces are needed, as for example in the case described here the surface quality of the internal channels was absolutely sufficient in their "as-built" condition, but may be insufficient in other cases of application.

Another aspect is the orientation of the part in the building chamber which may be specified in the drawing, as the mechanical values differ in the different build directions. Expressions like "main part axis C in z-direction" should be added to AM-specific drawings. Also post-processing hints should be possible like "avoid support structures here", referring to a specific surface area. All functional surfaces should be described conventionally in the drawing, i.e. by specifying dimensions, tolerances, surface requirements (roughness) etc.

Development of Standards:

Currently there is still a lack of standards for AM and its specific different technologies. Standards will be needed for all kinds of AM related topics as:

- AM materials
- AM testing
- AM post-processing
- AM surface quality
- build direction or orientation
- allowed/not allowed support areas
- minimum diameters without support, minimum overhangs, minimum angles, minimum wall thicknesses – each related to specific AM materials and specific AM methods

6.4.2.3 Differences between AM Technologies

Here LBM was chosen because at that time EBM was not yet tested to process Nickel-based alloys. Generally speaking LBM is far better concerning surface quality compared to EBM and Nickel-based alloys are standard and well known material for LBM. Meanwhile EBM has become better concerning surface quality but is still behind LBM and still not widely used to process Nickel-based alloys.
The EOS M270 Dual mode system used here was a standard system without any modifications. Dual Mode just means that it can also process light metals as aluminium or titanium.

6.4.2.4 Replaced Manufacturing Technology

These complex internal channels and fins could have never been produced with a moulding technique. The only technique able to produce this kind of complex shaped geometries could either be investment casting or complex sheet metal design where the single sheets are soldered together. A part with the same functionality conventionally manufactured would have consisted of at least three parts as upper and lower housing as well as a stack of sheets representing the channel geometry. The sheet stack itself would have consisted of two sheets per layer – in this case this would result in 2 x18 = 36 sheets.
Nevertheless machining is still necessary to post-process the raw part. All functional surfaces like sealing faces have to be conventionally machined due to the limited surface quality AM systems are able to produce.

6.4.3 Analysis of Requirements

6.4.3.1 Product and Product Use Considerations

In this case AM was the only way to integrate the complex channels and fins to create as much surface area as possible into the design space. The AM delivered a better thermal and pressure drop performance, so slightly higher costs compared to conventional manufacturing methods were acceptable.

Nickel-based alloy was chosen because of the expected high temperatures and the chemically active gas to be led through the systems. The flow channels were designed without any sharp edges to enable smooth flow of the gas and to minimise fouling and abrasion inside the channels.

6.4.3.2 Cost or other Business Considerations

The part is costly but not producible with other techniques. As a one-of-a-kind product the development of cheaper conventional manufacturing techniques was not sensible. The fulfilment of the desired efficiency improvement during this feasibility study would not have been possible at short notice with a conventional heat exchanger. The measured efficiency of the heat exchanger was 93% which is excellent for these kinds of systems.

6.4.3.3 Identification of Inherent Trade-Offs with AM Technologies or AM-specific Design

With the Nickel-based alloy used here, the walls and support structures must have a certain dimension – here 1.0 mm – and distance – here a maximum of 3.0 mm – to each other so that no or only minimal distortion can occur due to residual stresses.

6.4.3.4 AM-specific Design Limitations

Minimum / Maximum Allowable Size of Geometrical Features:

The minimum wall thickness was 0.5 mm, driven by process and material.

Surface Texture:

With the Nickel-based alloy material used here, the angle between building platform and bottom surfaces of the part should be more than 45° if not supported, otherwise surface roughness becomes extremely high or the so called overhangs have to be supported by lattice or strut structures which have to be removed after printing.

An additional aspect in this case study is the residual stresses during the build-up which here were taken by the additional supporting fins shown in Figure 5. This support structure was not built in order to achieve better surface quality, but to provide sufficient heat dissipation, avoiding residual stress-induced distortion.

Overall Surface:

The part was dimensionally acceptable directly after the AM process concerning 3D tolerances.

Tolerance relative to Part Size:

0.5 mm per 100 mm feature length.

Acceptable Local Variation of Wall Thickness:

About 1 %

Quality Related Information for Each Build-Job:

Usually 3 cylindrical specimen of 10 mm diameter, built in three directions (0° (lying), 45° and 90° (standing)), are sufficient to judge the process quality. Some printing service companies use only one tensile test specimen per build-job to verify the process stability.
In this case study no specimens were built with the part as the process was considered of having high quality due to well established building parameters which were qualified before. Additionally the part is not life-critical.

6.4.3.5 Post Process Treatment Explanation

The part was blasted (glass beads). Before sawing the part off the building platform a heat treatment to reduce residual stresses was made. It was milled at the sawed off surface. The support structures had to be removed. There was no additional machining. There was no additional surface treatment (peening, grinding, electro polishing etc.).

6.4.3.6 Evaluation

Cost Reduction:

The part is costly but not producible with other techniques. As a one-of-a-kind product the development of cheaper conventional manufacturing techniques was not sensible. The fulfilment of the desired efficiency improvement during this feasibility study would not have been possible at short notice with a conventional heat exchanger.

Weight Reduction:

The guess here is about 30 %. The weight of a conventional solution was not measured.

Combination of Parts:

A conventionally manufactured part with the same functionality would have consisted of at least three parts: upper and lower housing as well as a stack of sheets representing the channel geometry. The sheet stack itself will have consisted of two sheets per layer – in this case resulting in 2 x18 = 36 sheets. Here we have all functions integrated in one part.

Functional Integration:

Guiding channels and heat exchanging surface areas are highly integrated in a limited design space, which is 156 x 83 x 54 mm (width x depth x height).

Performance:

Guiding the gas through this thin walled system delivers an excellent heat transfer between cooling gas and gas to be heated thus resulting in sufficient cooling/heating rates and performance of the heat exchanger. There was no data available for comparable conventional heat exchangers.

Product Life:

Not tested – but assumingly below the range of conventionally manufactured comparable devices as the surface roughness here was higher than those of conventional sheet metal material.

Safety Margin:

Not calculated – but in the range of conventionally manufactured comparable devices as sufficient wall thicknesses were used and the material properties were tested as described in section 6.4.3.4.

Maintainability:

The channels were designed without any sharp edges to enable smooth flow of the gas to minimize pressure drop inside the channels. They still have the as-built surface quality of about Ra = 40 µm which is sufficient for the planned application to guide gas.

6.4.4 Analysis of Material Characterisation and Differences between AM Technologies

6.4.4.1 Material Characterisation Data of Components made by AM

Anisotropic Material Properties:

Usually there is anisotropy between the mechanical properties of the material's mechanical performance in xy-plane direction and z-direction (build direction). The values in z-direction are sometimes 10 % below those of the xy-plane direction. This strongly depends on the printing parameters as layer thickness and energy input.

Yield:

Not tested because not required – but is affected by anisotropic nature of the as-built material.

Elongation:

Not tested because not required – but is affected by anisotropic nature of the as-built material – see 6.4.4.1.

HCF (High Cycle Fatigue):

Not tested – but is affected by porosity and surface quality

LCF (Low Cycle Fatigue):

Not tested – but is affected by porosity and surface quality

6.4.4.2 Relevant Documentation

For the case study no standard was used because not required and/or not published yet.

6.4.5 Main AM Process Flaws and Weaknesses

6.4.5.1 Need to Speed Up the Process

If only looked at the printing step, this is already done by using more powerful lasers and multi laser machines with larger building chambers. Other aspects along the whole process chain are:

- Process simulation to be able to build first-time-right
- Automated data processing to control data quality of CAD models
- Automated support generation
- Automated powder handling and integrated powder recycling
- Automated and/or standardised support removal
- Automated/integrated heat treatment and/or laser polishing
- Development of continuously producing printing systems apart from the current batch printing systems … as already shown with sand-based binder jetting systems (VOXELJET VX 800)

6.4.5.2 Surface Quality

Surface quality has to be improved. Approaches with new pulse laser systems and integrated laser polishing steps are being made.

6.5 Miniature Heat Exchanger / Cooler

Case Study Input from:	Fraunhofer IWU	Equipment used:	Concept Laser M2 Cusing
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Condition
Replaced Manufacturing Technology:	Stamping, Soldering	Parameter used:	Customized
Material:	AlSi10Mg	Inert Gas used:	Nitrogen

Table 6-6: Additive Manufacturing of miniature heat exchanger / cooler

6.5.1 Description of the Component and its Function

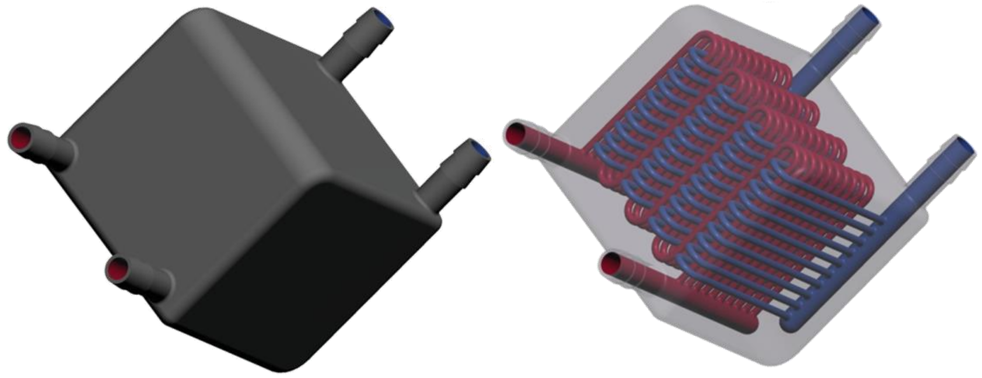


Fig. 6-22: Miniature heat exchanger (CAD model)

The counter flow water/water miniature heat exchanger was designed and manufactured for feasibility tests to demonstrate achievable efficiency compared to conventional plate heat exchangers. Aim was to use the LBM inherent freedom of design to create maximum heat exchange at minimal dimensions.

The inlets with a diameter of 6 mm fan out into 10 channels of 2 mm in diameter and a length of 400 mm. Each channel is meandering with 7 directional changes allowing a compact design while maximising the surface area for heat exchange (see Table 6-7).

<table>
<tr><td>Dimensions</td><td colspan="2">60 x 60 x 60 mm³</td></tr>
<tr><td>Weight</td><td colspan="2">0.5 kg</td></tr>
<tr><td rowspan="2">Performance</td><td colspan="2">2 kW</td></tr>
<tr><td>hot circuit
T_{in} = 50 °C
T_{out} = 37 °C
2.1 l/min</td><td>cold circuit
T_{in} = 26 °C
T_{out} = 40 °C
2.2 l/min</td></tr>
<tr><td>Pressure loss</td><td colspan="2">0.22 bar at 2.1 l/min</td></tr>
<tr><td>Heat exchange surface area</td><td colspan="2">505 cm²</td></tr>
</table>

Table 6-7: Technical specifications of the miniature heat exchanger

The channels are set only 1.5 mm apart and therefore the final component was analysed using CT scan (see Fig. 6-23) to ensure there is no leakage between the two circuits. To evaluate the theoretical data a test station was constructed where the heat exchanger could be analysed using thermal sensors and thermal imaging (see Fig. 6-24).

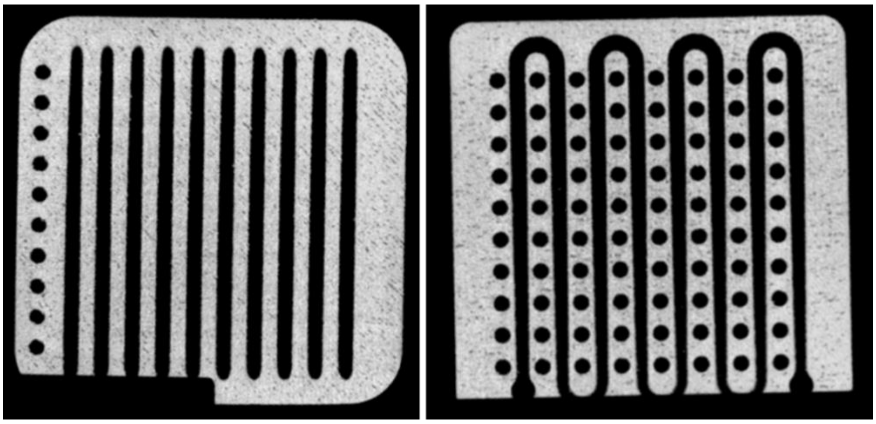


Fig. 6-23: Sectional view of the internal structure (CT-Scan)

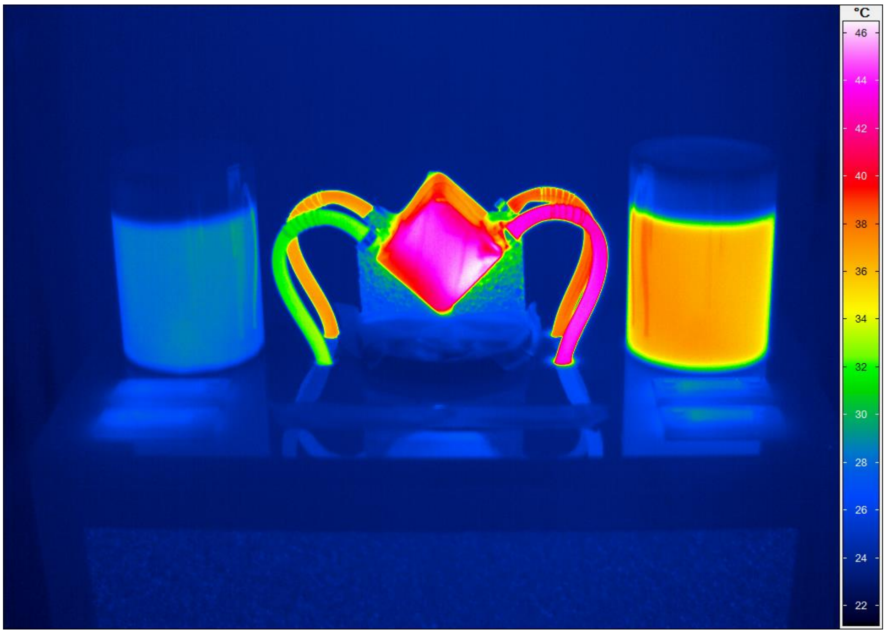


Fig. 6-24: Thermal image of the heat exchanger in the test station, cold water (left) and hot water (right)

6.5.2 General Design Principles

6.5.2.1 Design Features

Maximum Surface:

In order to maximize the heat exchange area, the hot and cold water circuits meander with 7 directional changes at an angle of 90 ° to one another. The channels of the two circuits are set only 1.5 mm apart. The inlet with a diameter of 6 mm fans out into 10 channels of 2 mm in diameter and a length of 400 mm. The complex internal structure allows a compact design while maximizing heat transfer. The disadvantage of the design is an increase in pressure loss compared to conventional plate heat exchanger with an equal performance.

6.5.2.2 Special Requirements of AM design

Geometrical Aspects:

The cubical design of the component allows an orientation in the LBM machine needing only little support structure. Most of the outer surfaces are aligned at an angle of 45 ° or more to the build platform and therefore don’t need support structure at all. Inlet and outlet are pointing in an upward direction at an angle of 45 ° as well, only needing support at the stepping of the hose connector (see Fig. 6-25). With diameters of only 6 and 2 mm the channels can be manufactured without any support.

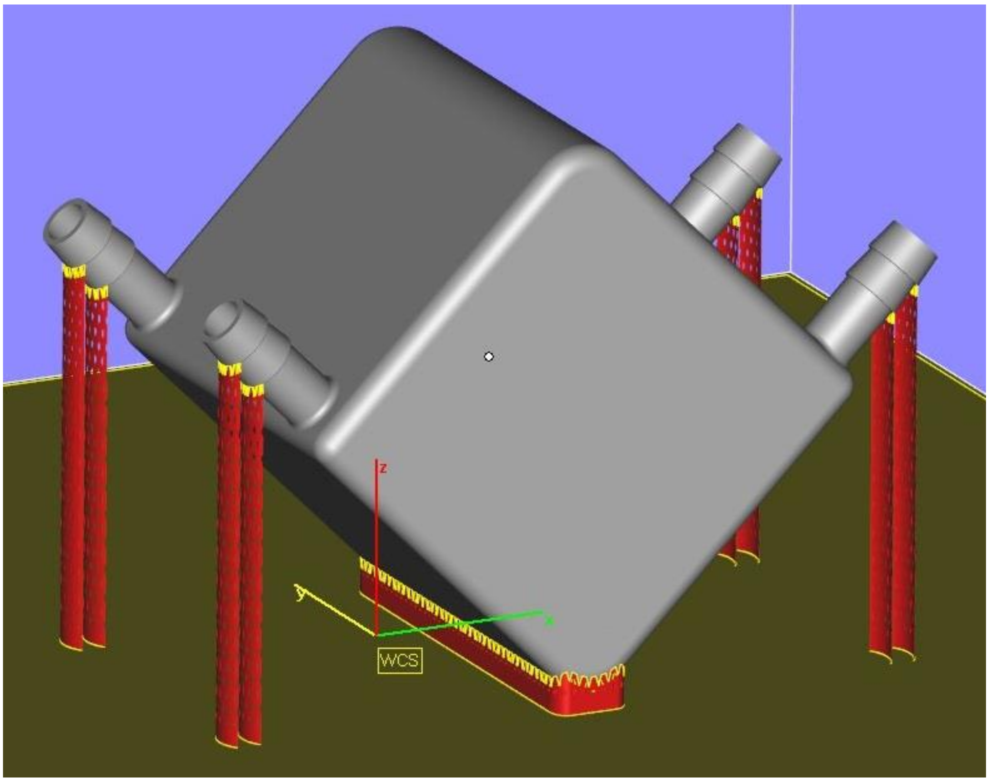


Fig. 6-25: Heat exchanger with support structure (Software: Materialise Magics®)

Need for Conventional Drawings:

In this case no additional drawing was needed. The manufacturing was purely based on a digital process chain.

6.5.2.3 Differences between AM Technologies

For the study at hand Laser Beam Melting (LBM) was used to manufacture the heat exchanger. With the Laser Beam Melting standard casting alloys like AlSi10Mg or AlSi12 can be processed and completely melted (rather than only superficially fused) to an almost 100 percent dense microstructure. Thus it has become possible to additively manufacture complex components for real applications rather than just prototypes or functional demonstrators.

In contrast processing aluminium alloys by Electron Beam Melting can currently only be considered as state of research. The vaporization of alloying elements is still critical and thus the above mentioned alloy composition is not within the DIN or ASTM standards [15]. Furthermore complex internal structures can be manufactured by EBM only to a limited extent (due to the sintering necks generated in the powder surrounding the part) LBM is the technology of choice when it comes to additive manufacturing of aluminium components.

6.5.2.4 Replaced Manufacturing Technology

These complex internal channels could not have been created by conventional manufacturing methods, such as moulding techniques. Even investment or precision casting is not an option due to the small size and complexity of the inner channels.

A conventional heat exchanger competing with the additive manufactured at hand would be a plate heat exchanger. Most common manufacturing technology is soldering. The individual plates are formed by embossing or stamping and later soldered together. Sometimes bolts are used for additional fixation. The channels would be formed by the gaps in between the sheet metal layers. Therefore the technologies replaced by additive manufacturing would be stamping and/or joining operations as well as soldering or welding.

6.5.3 Analysis of Requirements

6.5.3.1 Product and Product Use Considerations

In this study AM was the only way to integrate the complex channels while keeping the dimension really compact. Compared to a plate heat exchanger with the same performance* the AM design was much more compact and therefore lightweight (see Table 6-8). Additional advantages are:

- shape can be specifically adapted to customer requirements and available installation space
- one piece component
    - very sturdy
    - no risk of leakage occurrence during life time
    - high pressure resistance

* The performance values for the AM heat exchanger have been derived experimentally and were subsequently taken as benchmark in order to identify a conventionally manufactured heat exchanger of the same performance.

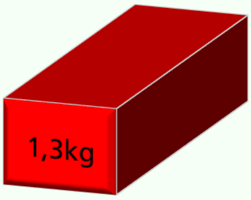
Technical data in comparison to a conventional plate heat exchanger		
	additively manufactured	**conventional**
Performance	**2 kW** at **2,1** l/min warm circuit: T_1 = **50** °C T_2 = **37** °C cold circuit: T_1 = **26** °C T_2 = **40** °C *(determined experimentally)* *(calculated)*	
Dimensions	 **60** x **60** x **60** mm *(measurements)*	 **191** x **73** x **52** mm *(numbers from the catalog)*
Transfer surface area	**0,05** m^2	**0,129** m^2

Table 6-8: Technical data in comparison to a conventional heat exchanger

6.5.3.2 Cost or other Business Considerations

While a conventional heat exchanger is a mass production part, the AM counterpart was uniquely designed and manufactured only once. Thus the AM part is 3.5 times more expensive (about 1.200 € compared to 350 €) but for the purpose of the study manufacturing cost were not considered. Objective was to show the advantages and added value that can be achieved by AM for the production of heat exchangers.

6.5.3.3 Identification of Inherent Trade-Offs with AM Technologies or AM-specific Design

Since the component was specifically designed for AM from the beginning, a redesign was not necessary. The orientation in the LBM machine was already considered during the design. The cubical outer shell allowed minimising the support structure needed. Dimensions of the inner channels were small enough to be manufactured without any support structure.

6.5.3.4 AM-specific Design Limitations

Minimum / Maximum Allowable Size of Geometrical Features:

The minimum wall thickness in between the channels of only 1.5 mm was based on experience from previous projects. It’s a compromise between good heat exchange (performance) and pressure resistance for a wide range of possible applications.
The minimum manufacturable wall thickness in LBM is mainly determined by following parameters:

- Laser spot size
- Laser power
- Scan speed respectively duration time on spot
- Material properties (Laser absorption and thermal conductivity, etc.)
- Geometrical design of the component the laser is melting (e. g. overhanging areas, solid areas, cellular structures with surrounding metal powder).

With regard to the channel dimensions diameters of only 6 and 2 mm enable the manufacturing without using any support structures.

Overall Surface:

Surface quality for this component was only critical at the hose nozzles. At these sections a good finish (polishing) is essential for tightness. The flat outer surface was grinded (sandpaper) and blasted (corundum) purely for aesthetic reasons. The rough surface of the inner channels helps to create a turbulent flow and thus increase heat exchange.

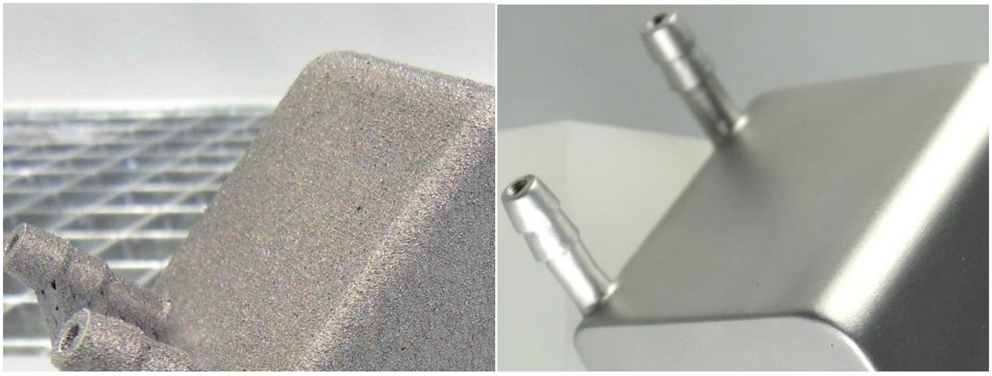


Fig. 6-26: Surface quality of the component after LBM (left) and after finishing (right)

6.5.3.5 Post Process Treatment Explanation

After the AM process the component was manually cut off from the support structure. The outer surface was smoothed using sandpaper with varying graining and as final step blasted using white corundum. The inner channels were left untouched. No additional heat treatment was performed.

6.5.3.6 Evaluation

Cost Reduction:

The AM heat exchanger is about 3.5 times the costs of a conventional plate heat exchanger with the same performance. For the purpose of the study manufacturing cost were not considered, because the objective was to show the advantages and added value that can be achieved by AM for the production of heat exchangers.

Weight Reduction:

Compared to its conventional counterpart the AM heat exchanger weighs less than half of it (about 500 g vs. 1.300 g), thanks to the smaller dimensions and volume (204 cm³ vs. 725 cm³).

Combination of Parts:

Considering that plate heat exchangers are mostly assemblies of welded or soldered layers of formed sheet metal, the AM heat exchanger (as one solid component) combines not only many parts but also substitutes a number of joining processes.

Functional Integration:

The component does not have any additional functions.

Performance:

The AM heat exchanger was designed and manufactured for feasibility tests to demonstrate achievable efficiency. The performance was evaluated using simulation. Results showed a heat capacity of 2 kW at 50 °C with a flow rate of 2.1 l/min. The conventional plate heat exchanger, which the AM component was compared to in terms of size and costs, was selected based on these performance values.

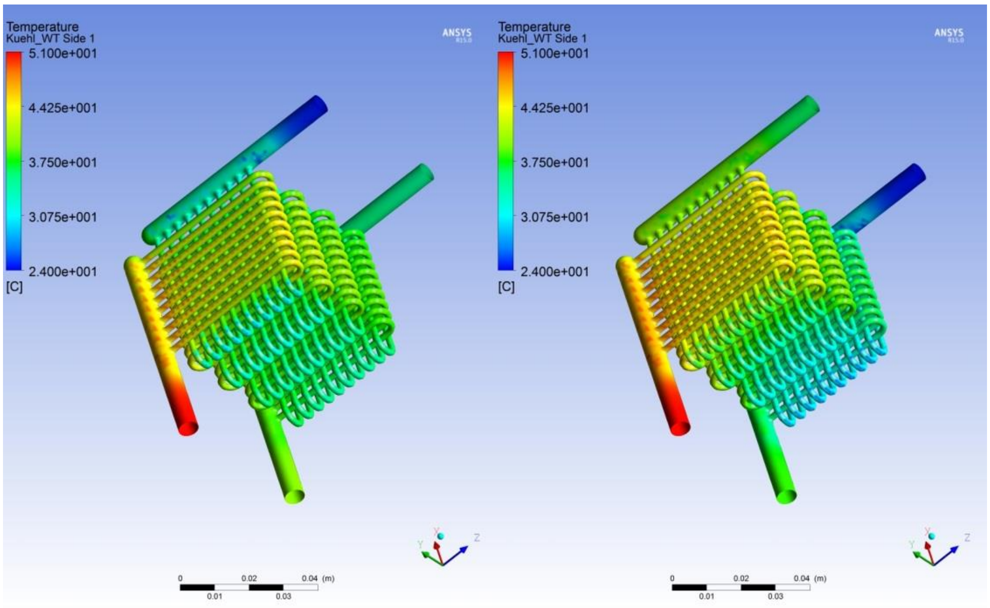


Fig. 6-27: Performance evaluation by Ansys CFX, current flow (left) and counterflow (right)

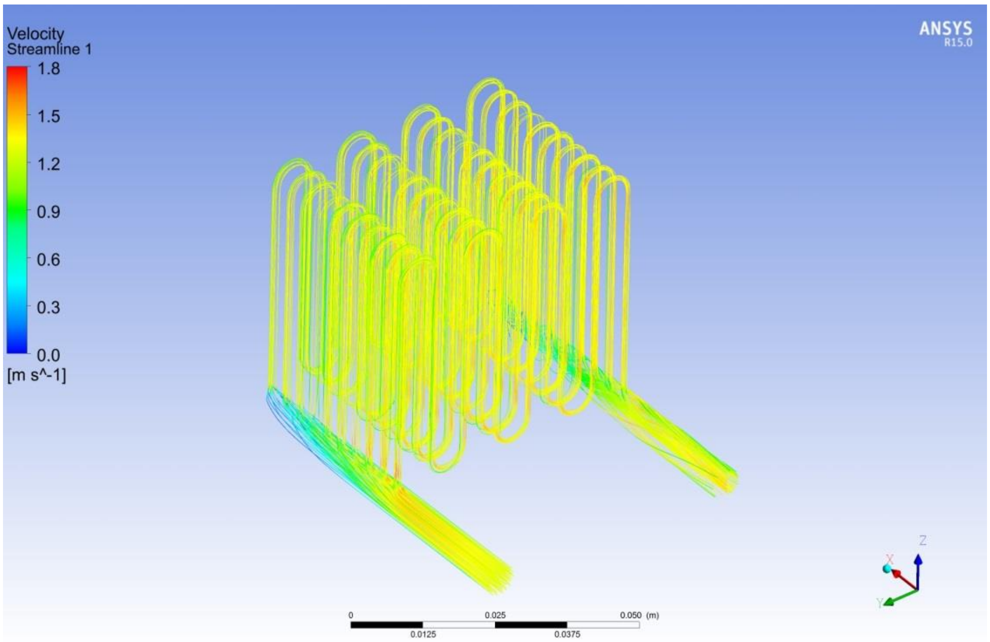


Fig. 6-28: AM heat exchanger flow analysis of one channel system, using Ansys CFX

Product Life:

Product life was not taken into account when designing the heat exchanger, it hasn't been tested either. Considering that the component is one solid object (i.e. no interfaces, no fasteners, no sealing), the life cycle should be longer in comparison to a conventional plate heat exchanger.

Safety Margin:

The minimum wall thickness in LBM is mainly determined by machine parameters and material properties. Using a conventional Concept Laser M2Cusing and a laser power of 200 W, a straight wall from AlSi10Mg build up only in Z direction, can be as thin as 0.5 mm. But previous experiments have shown, that at least 1.0 mm are required in order to create a liquid-tight wall, independent from build orientation. Considering the system pressure, the distance between the channels was set to 1.5 mm (i.e. safety margin of 50 %).

Maintainability:

Maintainability was not considered.

6.5.4 Analysis of Material Characterisation and Differences between AM Technologies

6.5.4.1 Material Characterisation Data of Components made by AM

Recommended number/type of quality standard specimen per build-job:

In case mechanical properties are crucial for the component, three specimens for tensile testing should be manufactured per job in order to rule out random deviations (if no other requirements from application or process specific standards apply).
Considering the huge number of parameters influencing the LBM process, at least one cubical test specimen for microstructure and density analyses per build-job and three specimens for tensile testing every three month would be recommended.

6.5.4.2 Relevant Documentation

- VDI 3405 Part 2 Additive manufacturing processes, rapid manufacturing – Beam melting of metallic parts – Qualification, quality assurance and post processing
- VDI 3405 Part 2.1 Additive manufacturing processes, rapid manufacturing – Laser beam melting of metallic parts; Material data sheet aluminium alloy AlSi10Mg

6.5.5 Main AM Process Flaws and Weaknesses

6.5.5.1 Need to Speed Up the Process

In order to compete with conventional manufactured heat exchangers on the open market, the costs for such an AM component need to be reduced. One solution would be to speed up the process and thus reduce the manufacturing costs.

6.5.5.2 Prospect to Develop very large AM Equipment

Very large AM equipment is not necessary for the manufacturing of miniature heat exchangers. Current build chambers of ~ 250 x 250 x 250 mm³ suffice.

6.6 Functionally Integrated Implant – MUGETO®

Case Study Input from:	Fraunhofer IWU	Equipment used:	Concept Laser M2 Cusing
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Cond.
Replaced Manufacturing Technology:	Casting, Die Forging, Cutting	Parameter used:	OEM Standard
Material:	Ti-6Al-4V	Inert Gas used:	Argon

Table 6-9: Additive Manufacturing of functionally integrated implant

6.6.1 Description of the Component and its Function

The component regarded in this case study is a prototype of hip stem endoprosthesis demonstrating the feasibility to integrate different functions (see Fig. 6-29).

Fig. 6-29: MUGETO® - hip stem endoprosthesis with functional channels and cavities, inner cellular structure and macro-porous surface areas

A hip stem replacement by an endoprosthesis can become necessary in order to achieve different potential improvements, such as:

- Pain relief
- Improved mobility
- More freedom to pursue everyday activities such as walking and climbing stairs

Fig. 6-30 shows schematically a hip stem replacement, which should illustrate the positioning within the thigh bone and the interface to the femoral head (ball) and hip:

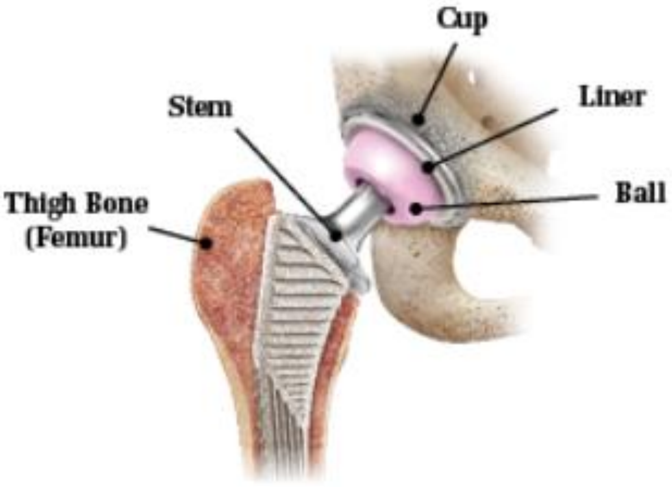


Fig. 6-30: Schematic figure of hip stem replacement (Source: www.depuysynthes.com)

6.6.2 General Design Principles

6.6.2.1 Design Features

Organic Shape:

In this case no organic shape was used. MUGETO® addresses the field of standardized implants; therefore the outer design is comparable to a standard casted or forged hip stem. In general, the addressed design features (lattice structures and channels/cavities) could also be combined with an organic shape, which for instance could be patient specific design. In Fig. 6-31 a casted organic shaped hip stem is shown.

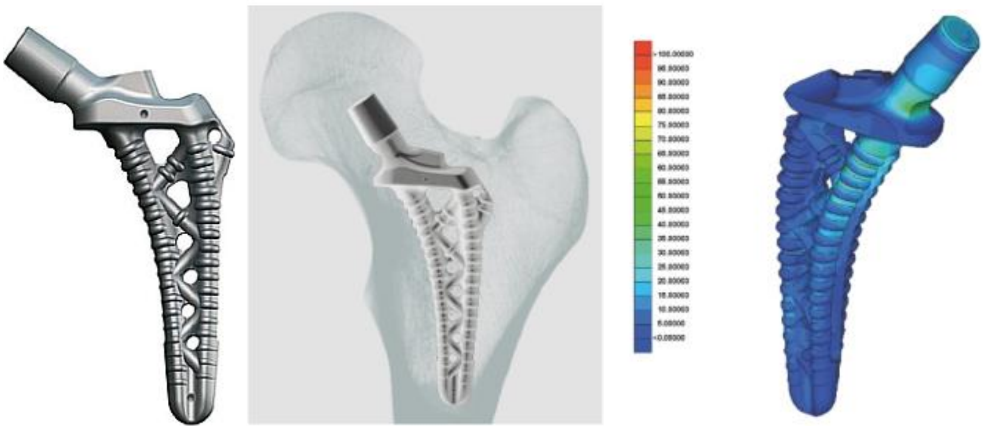


Fig. 6-31: Bionic hip stem “Physiohip” (Source: Copf-Bionic GmbH)

Internal Lattice Structure:

One of the innovative design features of MUGETO® hip stem is the inner cellular structure. Applying this kind of lattice structure to the inner volume of an endoprosthesis, the implant's stiffness and rigidity (Young's modulus) can be adapted to that of human bone. Furthermore, the implant's dead weight can be significantly reduced. Regarding the design of the cellular structure two major points should be paid attention to:

- Unit Cell

  The Unit cell should be designed in a way, that all struts have no overhanging areas towards the build platform lower than 45° (depending on the material and process parameters lower critical angles are possible).
  Furthermore, with today's FEA systems lattice structures are rather hard to calculate, especially for complex three dimensional cellular designs. Therefore substitute models on the basis of elaborate mechanical tests for each unit cell type need to be conducted. Any variation of material, strut thickness and unit cell size need to be considered.

- Powder Outlet Opening

  Using internal cellular structures inside a dense shell requires at least one powder outlet opening within the shell structure for removal of non-fused powder particles. This opening can subsequently be closed by conventional welding processes to establish a dense shell and hermetically seal the inner volume.

Macro-porous Surface Structure:

Additive Manufacturing technologies allow an implant's surface to be structured in virtually any desired design option. The surface structure can be applied either to selected surface areas or to the implant's entire surface. The structure's depth (thickness) can be chosen arbitrarily for best possible support of bone ingrowth (osseointegration). MUGETO® hip stem macro-porous surface structure is placed in the proximal region of hip stem. In this area osseointegration is essential to transmit loads between acetabular and femur bone of the hip joint.

Functional Channels and Cavities:

The geometric freedom of Beam Melting technology allows not only the manufacturing of implants with cellular structures but also the integration of complex channels and cavities for a variety of new functions in endoprostheses. To this end, an implant with inner functional channels and cavities, which can be designed to any desired requirement profile, has been developed. A hip stem has been chosen as an example for a typical implant with high potential to add functionality to it.
A variety of additional functions has been identified to add value to the implant. Main goal of all these added functions is the elongation of the implant's service life and the prolongation or even avoidance of revisal surgery. These added values are supposed to support the vision of a life-long implant and to come a significant step closer to this ultimate goal. The following sub-chapters describe these potential new functions and their benefits in detail.

Function 1 – Post-Operative Medical Treatment through Drug Depot:

Another added value of the presented endoprosthesis with functional cavities is the possibility of post-operative medical treatment of the patient. Thereby, the steady, regular release of medication from a cavity inside the implant (drug depot) through defined channels to the surrounding body's own bone and soft tissue (wound) becomes possible. A possible cavity and channel design for this purpose is shown in Fig. 6-32.

This feature allows the aimed promotion of wound healing as well as ingrowth behaviour of somatic cells into the endoprosthesis. In addition, medication for pain relief and prevention of infections (antibiotics) can be supplied through the inner channels to the implant-tissue interface.

If necessary, the channels can also be used for post-operative discharge of blood and wound ooze (drainage). With one central drain, connected to the implant's inner channel system, it becomes possible to access many different locations around the implant for drainage purposes, depending on the number of channel exits which can be numerous thanks to the design freedom of Additive Manufacturing.

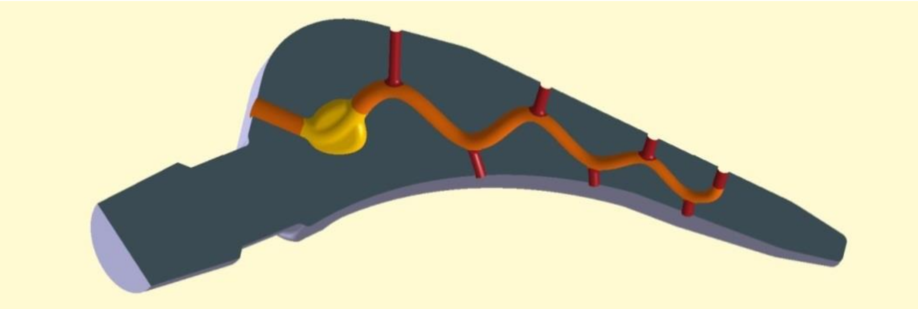


Fig. 6-32: CAD image of a hip stem with drug depot (yellow) and distribution channels (orange, red)

Function 2 – Better Fixation of Cement-free Implants

A better fixation of cement-free endoprostheses can be achieved by targeted, local insertion of bone cement or bio-resorbable filler through the inner channels to the implant-bone interface after implantation. Thereby it becomes possible to compensate fitting inaccuracies after the implant has been tapped into the bone. In addition, the surgeon receives the opportunity to backfill unexpectedly bad bone conditions, which could not be identified in pre-surgical diagnostics, during surgery with minimal amounts of a compensational substance.

Another intriguing opportunity is to do so not only during initial implantation but also rather years later to counteract loosening of an implant for preventive or correctional purposes. Rather than a heavily invasive revision operation, replacing the implant with a revision type of bigger size, this minimally invasive approach can spare valuable sound bone structure and save the patient from the inconvenience of implant replacement. A potential channel design for this added value described above can be seen in Fig. 6-33.

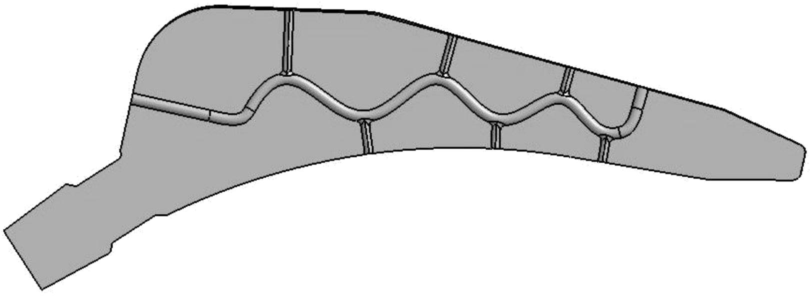


Fig. 6-33: Inner channel design of hip stem implant to distribute bone cement or bioresorbable filler to implant-bone interface

Function 3 – Endoscopic Inspection through the Implant

In another potential application the inner channels can be designed in such a way, that they can be utilized for endoscopic inspection of the contact area of implant and bone as well as surrounding body tissue. Consequently, another immediate option for post-operative, minimally invasive medical monitoring alongside imaging technologies like computer tomography is getting created, allowing earlier detection of possible complications. Fig. 6-34 shows a possible channel design for endoscopic purposes.

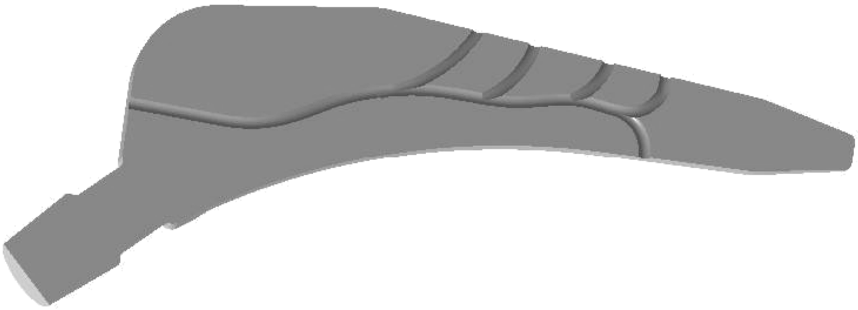


Fig. 6-34: CAD image of a potential channel design aimed for endoscopic inspection purposes in a hip stem prosthesis

Function 4 – Explantation Support

Finally, the functional channels can be utilized in case of a necessary explantation (revision operation) to distribute a medium for locally limited decomposition of implant-bone bonding to ease and speed up the surgical intervention for implant removal with minimal destruction of sound bone structure. This function can play an important role in the process of convincing surgeons to give up their hesitations to employ endoprostheses with structured surfaces due to the expected complication of a potential explantation caused by the intensive bonding and ingrowth.
Certainly, this medium has to be applied carefully and well-dosed to avoid distribution beyond the direct contact section of implant to bone.

6.6.2.2 Special Requirements of AM design

Need for Conventional Drawings:

For the overall design and dimensioning of endoprostheses like the hip stem the part's geometry can be individually adapted to the patient's anatomy. The geometrical information could be derived by appropriate medical diagnostic technique, e.g. by computer-assisted tomography (CT), and subsequently be used in / transferred to CAD-systems for the AM-specific design.
Nevertheless the use of conventional drawings is not fully obsolete. Areas with patient-independent geometry like the hip stem head (interface to the femoral head (ball)) require a well-defined geometry and surface finish, which need to be post-processed with conventional manufacturing technique (e.g. turning, milling, grinding) and therefore require specification by the means of a conventional drawing.

Development of Standards:

There is a need to standardize lattice structures as mentioned in 6.6.2.1, especially for the unit cell type and cell size with corresponding mechanical properties.

6.6.2.3 Differences between AM Technologies

Comparison of LBM and EBM technology regarding feasibility of above mentioned design features (inner cellular structures, macro-porous surface structures, functional channels and cavities):

Within the EBM process preheating of powder above 600 °C is performed using the electron beam leading to sintering bridges between the powder particles. This way the metal particles are kept at their place when the electron beam impinges upon the powder layer. So, the sintered metal particles withstand the impact force of electron beam. Preheating the metal powder in such a manner results in the disadvantage that inner cellular structures and channels/cavities are hardly / not feasible, because the unmelted powder inside the cellular structure or channel is sintered together too and can't be removed in most cases (only with mechanical shot blasting). To sum up, with EBM technology only macro-porous surface structures down to a certain pore size are feasible otherwise the unmelted powder particles can't be removed from inside the cellular structure. Nevertheless EBM technology has the major benefit compared to LBM that less stresses are applied to the material while processing under high preheating temperatures and therefore leading to less distortions and better shape accuracy after the process. In LBM high efforts in part orientation, support structure placement and post heat treatment are necessary to reduce internal strains and distortions.
In case of MUGETO® hip stem a commercial LBM machine of the type M2 Cusing by Concept Laser GmbH (Lichtenfels, Germany) was used in OEM standard delivery condition (i.e. no additional equipment or modification). Regarding CAD/CAM, the initial design was done in Catia V5 including the design of the channels and cavities. Furthermore, a segmentation of areas with dense and cellular / porous structures was done in the CAD environment. Following, using Materialise Magics with its metal structure module, the design of the cellular / porous areas was done.

6.6.2.4 Replaced Manufacturing Technology

At the current state of the art, endoprostheses are predominantly manufactured by cutting, forming or casting technologies. However, restrictions apply to these technologies, e.g. necessary accessibility for cutting tools or draft angles for moulds and dies, which restrict the geometric freedom in implant design or increase manufacturing complexity with long process chains.
Additive manufacturing is absolutely necessary to manufacture such complex structures (cellular structures and filigree internal channels and cavities). No other manufacturing technology is feasible for MUGETO® implant.
Nevertheless, post-processing by machining is still necessary to certain areas of interest:

Cone:

The cone is the interface between hip stem and spherical head (typically manufactured in ceramic material). The cone has to meet specific requirements regarding the dimensional accuracy and surface roughness. Both require post-processing by machining (e. g. cutting, turning, grinding)

Tip of the Femoral Stem (distal side):

Cementless hip stems (like MUGETO®) usually have a polished tip towards the distal side. In this area a post-processing of the AM surface is necessary, e. g. grinding and polishing.

Surface Coatings:

Usually cementless hip stems are coated in the proximal region for an improved osseointegration. Therefore often vacuum sprayed plasma coatings, e. g. porous titanium VPS coating, or hydroxyapatite coatings are applied. MUGETO® hip stem macro-porous surface structures substitutes such surface coatings (see also chapter 6.6.2.1).

6.6.3 Analysis of Requirements

6.6.3.1 Product and Product Use Considerations

Besides the main function of absorption and transmission of mechanical loads and torques, MUGETO® hip stem combines a variety of innovative features, which are hardly or not feasible in one step with any other manufacturing technology than AM. If feasible, inner channels and cavities would need extra effort within the casting design and process or would be applied by post-process machining to a forged implant (only linear deep drilled holes possible). Inner open cellular structures could be applied with investment casting. But the necessary efforts for manufacturing the lost model (wax model) are very high and again, would need AM techniques like wax 3D printing (e. g. Solidscape 3D printer). Closed cellular structures (metal foam) could be applied to a shelly designed implant body and a subsequent metal foaming process. All above mentioned process chains need additional effort compared to the one-step manufacturing AM process by LBM.

6.6.3.2 Biological / Chemical Environment:

In case of endoprostheses besides mechanical stability the biocompatibility is one of the main requirements. In case of MUGETO® a biocompatibility-approved and corrosion resistant material – Ti-6Al-4V alloy (titanium grade 23) – is used. Ti-6Al-4V is the most common used metal for cementless hip stems and has been used for medical implants for several decades.

6.6.3.3 Sustainability Considerations

Implants, so-called endoprostheses, do partially or fully replace damaged body parts, like worn joints or defective bone material, and remain permanently inside the human body. In Germany alone, more than 400,000 artificial joints are getting implanted every year. 90 percent of these implantations account for artificial hip and knee joints. The remaining cases concern the replacement of shoulder, elbow or finger joints as well as ankle and metatarsophalangeal joints (Gradinger & Gollwitzer 2006, Veit et al. 2009, N.N. 2011).

Main cause for the necessity of an artificial joint is wear of the cartilage layer between two bone ends in a joint, scrubbing against each other (arthrosis). With the artificial joint, a pain-free, every day motility and load-bearing capacity and by that the patient's quality of life are supposed to be restored (Fels 2007).

Fig. 6-35 shows that within five years only (2004 through 2008) the number of initial implantations for hip endoprostheses has increased by 14 percent.

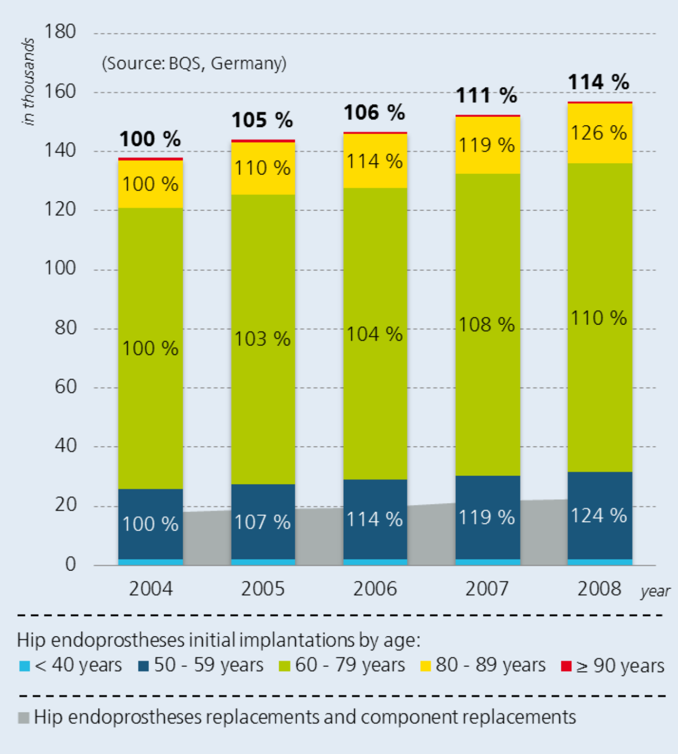


Fig. 6-35: Hip endoprostheses initial implantations (separated according to patient's age) plus hip endoprostheses replacements and component replacements in Germany between 2004 and 2008

Especially the group of 50 to 59 year olds and 80 to 89 year olds are affected by that. Explanation can be found on the one hand in the fact that today already more than fifty percent of all Germans older than fifty years are affected by arthrosis in at least one joint (N.N. 2011) and on the other hand, rising life expectancy in Germany does lead to a higher demand in endoprosthetic care for the elderly.

In addition, Fig. 6-35 shows that the number of revisal surgery with hip endoprostheses is rising. This is to be explained with the fact that endoprostheses have a limited service life only and with respective young age of initial implantation, have to be replaced during the patient's life span by a revisal implant. This results in a constantly rising demand in innovative endoprostheses with long service life and at the same time low risk in post-operative complication, e.g. wound infections (Veit et al. 2009).

Improving the primary stability (by improved bone ingrowth with macro-porous cellular structures) and the long term stability (better matching stiffness between cellular structured implant and bone) of an implant leads to reduction of health care costs and improved wellbeing of the patient.

6.6.3.4 Cost or other Business Considerations

In general, the manufacturing costs of MUGETO® hip stem are much higher compared to solid casted or forged hip stems (at least 2 to 5 times higher manufacturing costs). Both, AM and conventional processes, need a similar post-process heat treatment and machining process. Main cost savings are to be found in the functional consolidation (multiple functions combined within one hip stem) and the life-cycle cost (expected longer life-time compared to a traditional hip stem). Principal clinical investigations are not available yet.

One single benefit to highlight regarding the manufacturing costs:

Ohldin [16] has reported that porous coatings on hip implants (acetabular cups) cost between 30 and 60 € per cup. This price range is also realistic for similar coatings on hip stem endoprostheses. In case of MUGETO® hip stem the macro-porous surface structure replaces that porous coating, thus related costs can be saved.

6.6.3.5 Identification of Inherent Trade-Offs with AM Technologies or AM-specific Design

No redesign of the outer shape of the hip stem was necessary. Considering the inner cellular structures, the orientation of cellular structures need to be adjusted to the orientation of the part during the manufacturing process (build direction) to avoid overhanging areas to a certain degree in the cellular structures. Regarding the macro-porous surface structures, the cell size is so small that overhanging areas are not a limiting factor.

In general the combination of inner cellular structures, channels and cavities are weakening the mechanical strength of the hip stem. Therefore, FEA of the mechanical structure is mandatory in the design process.

6.6.3.6 AM-specific Design Limitations

Minimum / Maximum Allowable Size of Geometrical Features:

The minimum allowable size of geometry feature in LBM is mainly determined by following main parameters:

- Laser spot size
- Laser power
- Scan speed respectively duration time on spot
- Material properties (Laser absorption and heat conductivity)
- Geometrical design in the working area of the laser (e. g. overhanging areas, solid areas, cellular structures with surrounding metal powder)

In case of the LBM equipment used to manufacture MUGETO® hip stem implant, the minimum wall thickness / strut size was about 0.3 mm.

Overall Surface:

Volume and line profiles (contours) in the “as-built” condition are dimensionally acceptable.

Tolerance relative to Part Size:

Dimensional accuracy is strongly depending on the geometry of the part and the build orientation. In LBM high residual stresses are applied to the material during the build process. So, deformations are likely to occur. To counteract deformations, build parameters like scan strategy of the laser, build orientation and support structures placement are necessary aspects to be considered in the post-processing stage. In case of MUGETO® hip stem a vertical build orientation was used (cp. Fig. 2). With this orientation, the surface area of each layer is relatively small that almost no deformations occur.

General accuracy of the LBM process is around ± 0.1 mm. Because of layer wise build process there is a compensation of dimensional accuracy in z-direction with each manufactured layer. Regarding the dimensional accuracy in x-/y-direction the so called beam compensation of the inner filling laser paths, which is very similar to the radius compensation of a milling cutter, and the offset of the outer contour laser path towards the inside of the original part contour are the main influencing factors regarding dimensional accuracy of the manufactured LBM part. These parameters need to be adjusted to the laser power, scan speed and laser focus for each material being processed.

Acceptable Local Variation of Wall Thickness:

Local variations of wall thickness are depending on the wall thickness being produced. An increase of wall thickness results in a reduction of local variations. Looking on wall thicknesses below 1 mm, local variations are very much depending on thermal properties. For instance, wall thicknesses at intersections of walls are usually thicker because of more heat accumulation than in centre areas of walls. The same rule applies to struts of cellular structures, where you have smaller strut diameters in between intersections than in or nearby intersections.

Internal passages definition, tolerance and capabilities:

The inner lattice structure was designed with a certain aspect ratio of unit cell size to strut thickness. Together with the unit cell type, build orientation and material chosen this ratio determines the resulting mechanical properties of the cellular structure. As mentioned before, for hip stems the inner cellular structure may help to adjust the Young’s Modulus of the implant material to the one of the bone. Cortical bone (dense outside shell of the bone) is usually around 10-20 GPa, whereas solid titanium is around 100 GPa. Same tolerances as described in 2.7.3 apply. As mentioned in 1.1.2 a powder outlet opening may be necessary to remove enclosed loose powder from an inner cellular structure.

Quality Related Information for Each Build-Job:

MUGETO® hip stem is not in series production yet. But for series production a standard documentation of process parameters and resulting material properties is necessary. In case of MUGETO® hip stem different medical regulations and standards apply, which need to be taken into account depending on the type of implant/ application.

6.6.3.7 Post Process Treatment Explanation

LBM processed Ti-6Al-4V has in the as-build stage a very fine-grained microstructure with high tensile strength and comparably low elongation (below 10 %). Heat treating the LBM processed Ti-6Al-4V above beta transus temperature at temperatures around 900 °C, an increase in grain size and resulting elongation above 10 % up to 20 % is possible.

For most medical applications a post process heat treatment is necessary. Further necessary post processes are shot blasting, machining (cp. Chapter 1.4.2), surface cleaning, sterilization and packaging.

6.6.3.8 Evaluation

Cost Reduction:

In terms of sole production cost, an additive manufactured hip stem is more expensive compared to a casted or forged hip stem. But for the overall life-cycle costs, significant health care reductions are to be expected, because of better long term stability and improved wellbeing of the patient.

Weight Reduction:

Using inner cellular structures combined with the outer dense shell opens up new possibilities in structural weight reduction. For this manner finite element analysis as well as static and fatigue tests are necessary, which have not been conducted within this case study. But from the theoretical point of view, weight reductions in the range between and 10 … 40 percent compared to a monolithic titanium hip stem are feasible.

Combination of Parts:

Not applicable for this product.

Functional Integration:

Integration of different functionalities, e. g. a drug depot, a channel system for endoscopic inspection or a macro-porous surface structure for improved bone ingrowth, were realized within this one step manufactured implant.

Performance / Product Life:

For proof of long-term stability no tests are available / defined yet.

Safety Margin:

Hip endoprostheses have to withstand static and dynamic loads, what must be proven by appropriate testing. For example, the determination of endurance properties for partial and total hip joint prostheses is specified by ISO 7206 Part 4 and 6. The compliance to such standards must be kept in mind already during the design, taking into account sufficient margins of safety. But for the demonstrator at hand no loads calculation or simulation was performed, since it represents a pure feasibility study.

Maintainability:

Refer to chapter 6.6.2.1 → Post-surgical features of the internal functional channels and cavities.

6.6.4 Analysis of Material Characterisation and Differences between AM Technologies

6.6.4.1 Material Characterisation Data of Components made by AM

Anisotropic Material Properties:

Especially elongation properties are anisotropic with differences of about 10 % depending on the build orientation.

HCF (High-Cycle-Fatigue):

Not determined for MUGETO® hip stem.

LCF (Low-Cycle-Fatigue):

Not determined for MUGETO® hip stem.

Recommended number/type of quality standard specimen per build-job:

At least one test specimen (e. g. tensile specimen) per build job, if no other requirements from application or process specific standards apply.

6.6.4.2 Relevant Documentation

Medical regulations are very extensive. This is why only an excerpt of regulations within the EU regarding medical devices can be given here:

EU Medical Device Law:

- 93/42/EWG Medical devices (MDD)
- 98/79/EG In vitro diagnostic medical devices (IVDD)

National Laws and Regulations:

- In Germany: HWG (Heilmittelwerbegesetz), MPG (Medizinproduktegesetz)

Others:

- Endurance Properties, ISO 7206 – Implants for Surgery – Partial and total hip joint prostheses:
    - Part 4: Determination of endurance properties and performance of stemmed femoral components
    - Part 6: Determination of endurance properties of head and neck region of stemmed femoral components

- Conformity Assessment Procedure:
    - ISO 13485: QM system
    - ISO 14971: Risk Management
    - Clinical Evaluation
    - Documentation showing the essential requirements in the product file (technical documentation)

- Declaration of conformity (CE) by notified body

- Classification of Medical Devices (MEDDEV 2.4/1 Rev.9, Juni 2010 „Guidelines for the Classification of Medical Devices“):
    - Classification into four classes depending on the risk : I, IIa, IIb and III and subclasses Is (sterile) and Im (with measurement function)
    - based on the intended use, by manufacturer or distributor, if necessary with the involvement of a conformity assessment body

- ISO 13485:2016: Medical devices -- Quality management systems -- Requirements for regulatory purposes
- IEC 62366-1:2015: Medical devices -- Part 1: Application of usability engineering to medical devices
- ISO 14971:2007: Medical devices -- Application of risk management to medical devices fulfilling essential requirements by manufacturer
- Complete QM-System DIN EN ISO 13485
- Risk Management DIN EN ISO 14971
- Usability DIN EN 62366

Specific medical regulations for medical devices:

- ISO 13485:2016: Medical devices -- Quality management systems -- Requirements for regulatory purposes
- ISO/TC 194: Biological and clinical evaluation of medical devices

6.6.5 Main AM Process Flaws and Weaknesses

6.6.5.1 Need to Speed Up the Process

As described in chapter 2.4. and 2.5, the main goals of MUGETO® hip stem are the reduction of health care costs and improved wellbeing of the patient. At this moment no long term clinical studies on the benefits of MUGETO® hip stem do exist.
Build speed in LPBF is still the main factor for the manufacturing cost. As mentioned in chapter 2.5 manufacturing prices for an LPBF hip stem are 2 - 5 times higher than a conventional forged or casted hip stem. Clinics are cost driven by the amount of money the get for the surgery based on fixed prizes by the health care insurances (in Germany – in Canada other regulations may apply). As long as no clinical studies on the benefits of the more expensive additive manufactured implanted with new innovative features exist, no health insurance will pay for it, because no long term reduction of health care costs are proven yet.
Without neglecting the need for clinical studies, one solution would be to speed up the process and reduce the manufacturing costs.

6.6.5.2 Prospect to Develop very large AM Equipment

Not applicable for the manufacturing of hip stems. Current build chambers of ~ 250 x 250 x 250 mm³ are big enough.

6.6.5.3 In-line Process Control

For LBM several in-process monitoring systems are available on the market (e. g. Concept Laser’s QM Meltpool 3D or EOS EOSTATE MeltPool Monitoring). All these systems still need to be trained on different defects so that in the first step an automatic detection of defects and in the second step a close-loop control will be possible.
These systems will be very helpful in the future to decrease destructive and non-destructive part inspections, which are very time consuming and expensive.

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6.7 Functionally Integrated Tooling Segments

Case Study Input from:	Fraunhofer IWU	Equipment used:	Concept Laser M2 Cusing
AM Technology:	Laser Beam Melting	Equipment Configuration:	OEM Delivery Cond.
Replaced Manufacturing Technology:	Milling, Drilling	Parameter used:	OEM Standard
Material:	1.2709 (X3NiCoMoTi18-9-5)	Inert Gas used:	Nitrogen

Table 6-10: Additive Manufacturing of functionally integrated tooling segments

6.7.1 Description of the Component and its Function

Hot Sheet Metal Forming – State of the Art:

For the automotive industry the efficiency of lightweight solutions is of central importance in terms of resource conservation. The reduction of material in use is therefore probably the most important factor. Currently, the production of car body structure parts is done in highly automated stamping plants by multi-stage cold forming. But the use of high-strength steels offers enormous potential for lightweight design. To implement high-strength steel parts in car bodies, hot sheet metal forming gets applied. The sheet metal is heated above the austenitizing temperature (more than 950 °C) and rapidly cooled down during the forming process to about 200 °C, whereby a hard, martensitic microstructure is created. Thanks to this method a reduced component weight due to lesser wall thickness can be achieved.
The cycle time in hot sheet metal forming or press hardening is dominated by approx. 30 % time for cooling (holding time of closed die after forming before re-opening for part extraction) [17]. The setup of a hot forming tool is more complex than that of a conventional one. Mainly this is due to the fact that the cooling channels must be implemented into the punch and the die. The implementation of the channels is usually done by deep drilling or a segmentation of the tools. Due to complex geometry of the tools, the cooling system design is especially demanding for the tool manufacturer. The added complexity of cooling bores increases the expenses for hot forming tools. Current production effort is estimated with about one hour per meter borehole and a high consumption of resources (energy, drilling oil, compressed air, etc.).

The Project:

For the reasons mentioned above the objective of the project was the development and manufacturing of tool inserts with an optimized cooling system (see Fig. 6-36) to improve the resource efficiency in hot sheet metal forming using thermo-fluidic simulation and Laser Beam Melting. In order to achieve the best synthesis of greatest value, short production time and low costs it was decided to manufacture the tooling insert by a so-called hybrid tooling, a combination of conventional manufacturing technologies like milling, drilling with the additive Laser Beam Melting. In this case, the laser beam melted functional structure with optimized cooling channels was applied on a conventionally milled base body.
After investigating current mass production, the project partners have jointly developed a representative demonstrator (see Fig. 6-37). To enable easy transfer of the project's results into mass production, the demonstrator's geometry is very similar to a serial component. The design reflects a typical hot forming component and its difficulties and potential problems. It incorporates geometric features such as curved surfaces and cavities to demonstrate limitations of conventional, deep hole drilled cooling channels in terms of rapid and homogeneous cooling of the sheet metal component.

The tool design and the cooling system design were done based on conventional manufacturing methods such as milling and deep drilling. Parallel to this, the development of the innovative, conformal cooling system began. Various iterations of the cooling system were designed. First proof of positive effects of the optimized die temperature control was provided by numerical simulation. In the project, thermal behaviour of the tool as well as coolant flow was analysed and different cooling geometries were compared. The ideal cooling channel geometry was designed based on the simulation results, considering technical characteristics of the Laser Beam Melting technology.

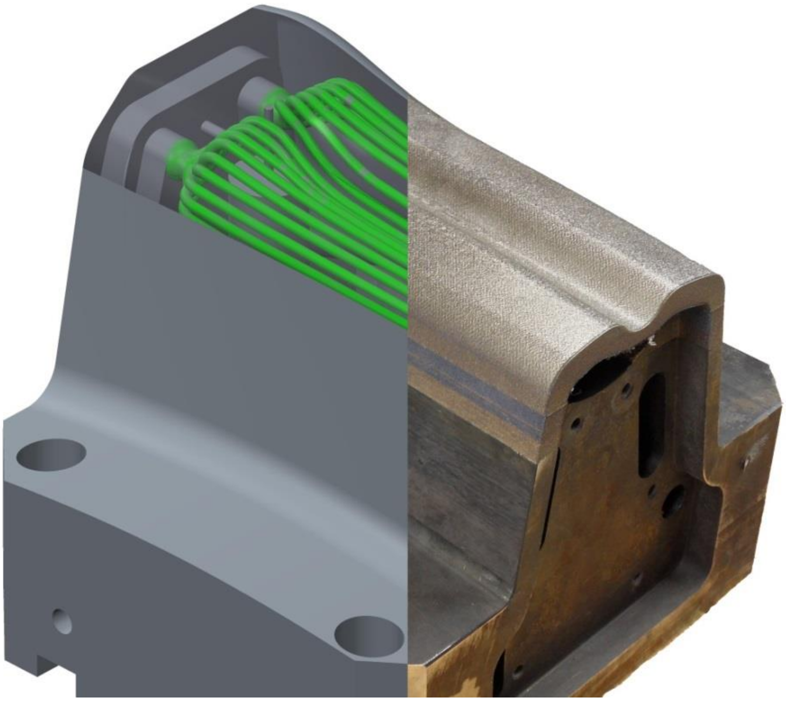


Fig. 6-36: Press hardening tool (punch) with innovative cooling system

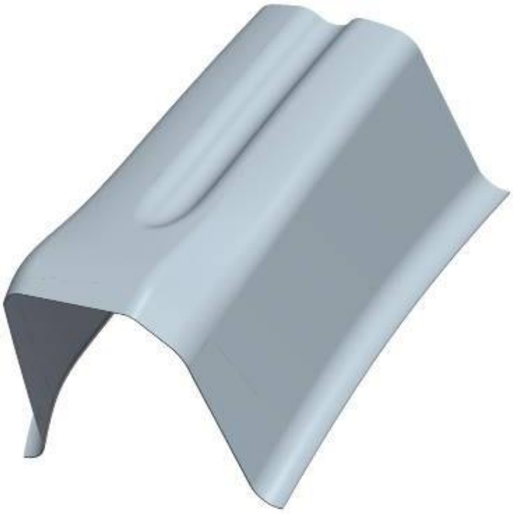


Fig. 6-37: Punch of Press Hardening Tool - Demonstrator [18]

6.7.2 General Design Principles

6.7.2.1 Design Features

The cycle time in hot sheet metal forming (press hardening) is dominated by approx. 30 % cooling time [17]. The setup of a hot forming tool is more complex than that of a conventional one. This is mainly due to the fact that the cooling system must be implemented into punch and die. The implementation of channels is usually done by drilling or a segmentation of the tools. Due to complex geometry of the tools, the cooling system design is especially demanding for the tool manufacturer. The added complexity of cooling bores increases the expenses for a hot forming tool enormously. Thus currently, a selective and conformal temperature adjustment in particular tool areas cannot be achieved or is at least restricted and/or very costly due to the limitations of the conventional manufacturing processes.

The additive approach was aiming at the next generation of metal forming tools with novel features to be developed and integrated such as contour conform cooling. The tooling application features an innovative cooling system (see Fig. 6-38) very close to the tool contour to ensure a very even temperature distribution and a very rapid cooling of the hot formed part for a significant reduction of cycle time.

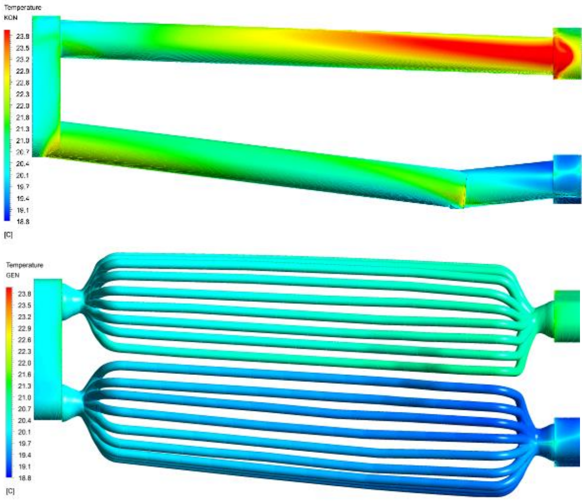


Fig. 6-38: Thermal analysis of the cooling system – conventional (top) vs. AM (bottom)

In the study, thermal behaviour of the tool as well as coolant flow was analysed and different cooling geometries were compared. The input variables such as compression force, work piece temperature, coolant temperature, flow rate, pump power and the surface roughness of cooling channels were adopted from the mass production system. The optimum cooling channel geometry was designed based on the simulation results, considering technical characteristics of the Laser Beam Melting technology (see Fig. 6-39).

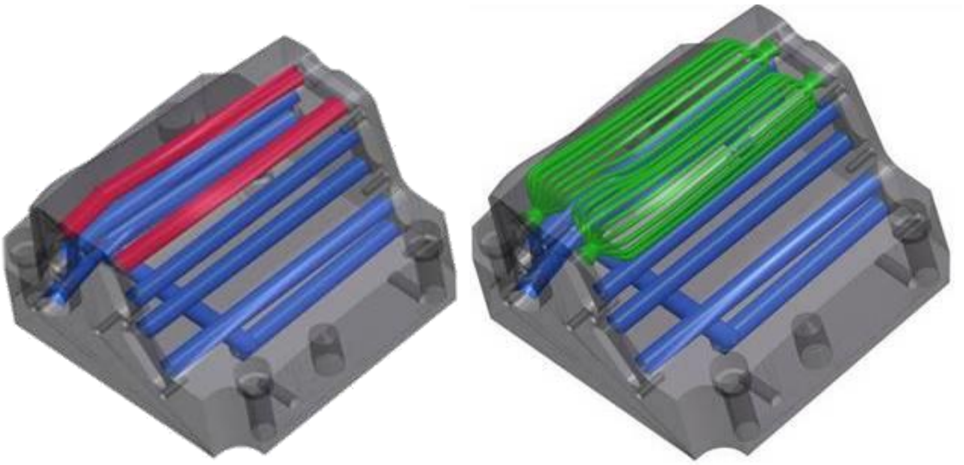


Fig. 6-39: **Comparison of conventional cooling (red, left) and AM version (green, right)**

The temperature distribution in the tool (see Fig. 6-40) showed inhomogeneous cooling due to the conventional die and limitations in its manufacturing. With AM the cooling channels can be placed very close and conformal to the surface. Due to simulation, the cooling system's efficiency could be constantly improved and resulted in a homogeneous temperature distribution within the tool and therefore in the sheet metal component. Thanks to the optimized cooling it is possible to cool down the parts more evenly and more rapidly. The simulation as well as the forming trials with the actual tool showed the holding time could to be shortened by approx. 50% from initially 10 down to 5 seconds, using the same temperature profile like in conventional cooling.

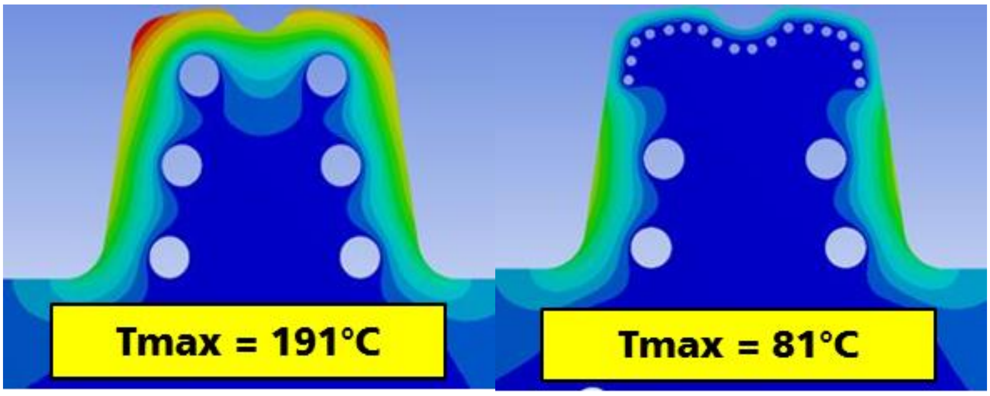


Fig. 6-40: **Comparison of temperature distribution in the punch between conventional tool (left) and additively manufactured tool (right)**

6.7.2.2 Special Requirements of AM Design

Geometrical Aspects:

The tool was manufactured using the so called hybrid tooling: an additively manufactured functional structure (cooling system) directly built up on a conventional base body (see Fig. 6-41). In order to achieve the dimensional accuracy and surface quality required for hot forming, a final machining was needed. Even though the dimensional accuracy of the laser beam melted component is within ± 0.1 mm, a material offset between 0.5 and 0.8 mm is usually set. Taking the dimensions of about 240 x 200 x 180 mm into account an offset of 2 mm was set in the case study. This was enough to compensate any inaccuracies of the manual aligning (conventional and additive part) and stress-induced deformation.

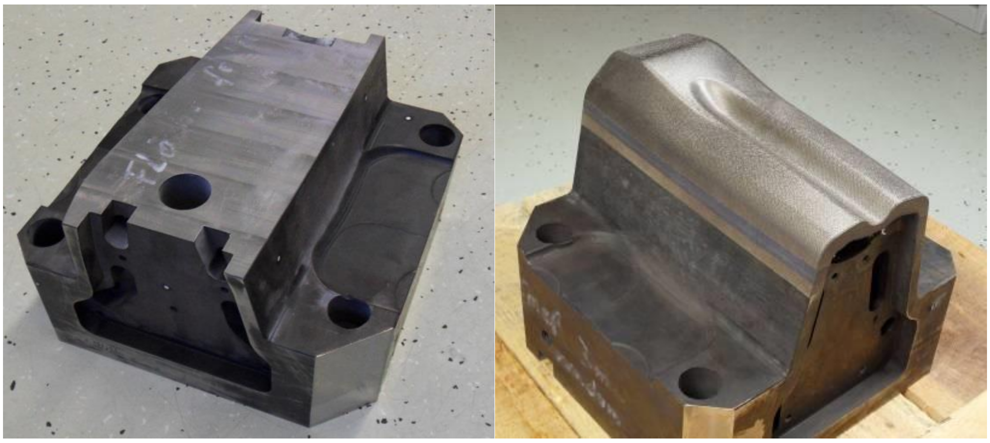


Fig. 6-41: Conventional base body of the tool punch (left) and hybrid tool punch ready for final machining (right)

Fig. 6-42: Assembly of tool punch

Need for Conventional Drawings:

In this case no additional drawing was needed. The connection surface between base body and additive applied functional structure was measured by a high resolution 3D scanner and dimensional adjustments regarding the hybrid tooling process were made only digital on the 3D CAD model, right before Laser Beam Melting. Thus the additively manufactured functional structure fits seamlessly on the base body. Even the conventional manufacturing of the base body was purely based on a CAD - CAM process chain.

6.7.2.3 Differences between AM Technologies

In the study at hand the additive Laser Beam Melting (LBM) was used to manufacture the hot sheet metal forming tool. With the Laser Beam Melting, standard tooling materials like 1.2709, Corrax® or 1.4542 can be processed and completely melted rather than only superficially fused to an almost 100 per cent dense microstructure. Thus it has become possible to manufacture full series tooling for mass production without tool life limitations compared to conventional tool making by machining or EDM. In addition the freedom of design provided by LBM allows creating innovative and very complex internal tempering systems very close to the surface for maximum tool performance.

Laser Beam Melting (LBM) as well as Electron Beam Melting (EBM) are a rather new group of technologies in additive manufacturing, developed in the mid-1990s by the no longer existing German SL system manufacturer F&S Stereolithographie-Technik GmbH in co-operation with the Fraunhofer Institute for Laser Technology ILT [19]. Both technologies would be capable of manufacturing tooling with the necessary mechanical properties but because complex internal structures can be manufactured by EBM only to a limited extent (due to the sintering necks generated in the powder surrounding the part) LBM is the technology of choice when it comes to tooling applications.

6.7.2.4 Replaced Manufacturing Technology

In this study milling and drilling processes for some sections of the tools were substituted by additive manufacturing. Using the hybrid tooling approach (milled and drilled base body + LBM functional structure) additive manufacturing was more an additional manufacturing step than a replacement for conventional machining (see Fig. 6-41). In addition final conventional machining is still needed after the LBM process.

6.7.3 Analysis of Requirements

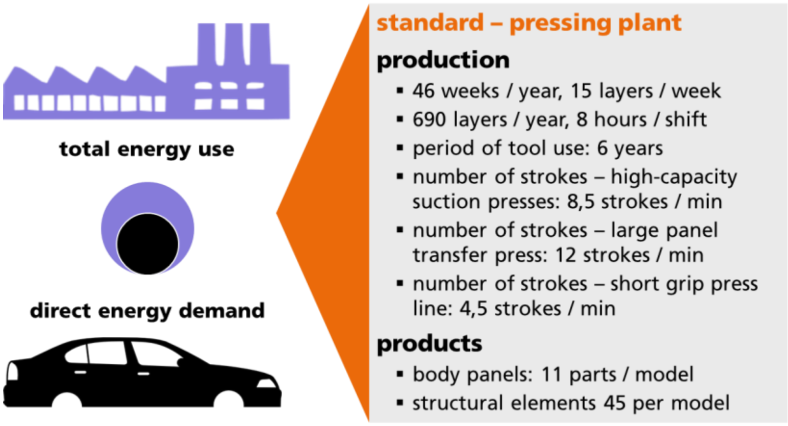
6.7.3.1 Thermal Environment

For the press hardening process sheet metal is heated above the austenitizing temperature (more than 950 °C) and rapidly cooled down during the forming process to less than 200 °C, whereby a martensitic microstructure is created.

Even though the sheet metal cools down during the transfer from the furnace to the mould the sheet metal temperature at initial contact with the tool is still around 780 - 800 °C. However, measurements showed the contact region of the tool heats up to only 300 °C for a short period of time. The innovative cooling system of the tool reduces this time even more and showed a significantly lower temperature in the tool overall.

6.7.3.2 Sustainability Considerations

Due to Laser Beam Melting, process cycle times in hot sheet metal forming can be reduced significantly and therefore it is possible to increase the resource efficiency of the entire process as well as to reduce the amount of energy used to manufacture each part. The significantly improved tool cooling results in significantly lower heating of the forming tool by approx. 100 K, the steady state (thermal equilibrium) in the tool is achieved faster and a faster cooling of the hot formed sheet metal parts could be realized. As a result the holding time (cooling time) could be reduced by 50% (from 10 s to 5 s). This corresponds to an overall cycle time reduction of 20% and thus a primary energy saving of 2.94 kWh per reference car body and in total 715 MWh per annum, representing a carbon footprint reduction of 426 tons of carbon dioxide per annum. These results refer to a theoretical reference factory as shown in Fig. 6-43.



standard – pressing plant

production

- 46 weeks / year, 15 layers / week
- 690 layers / year, 8 hours / shift
- period of tool use: 6 years
- number of strokes – high-capacity suction presses: 8,5 strokes / min
- number of strokes – large panel transfer press: 12 strokes / min
- number of strokes – short grip press line: 4,5 strokes / min

products

- body panels: 11 parts / model
- structural elements 45 per model

Fig. 6-43: Reference factory – standard pressing plant

6.7.3.3 AM-specific Design Limitations

Minimum / Maximum Allowable Size of Geometrical Features:

In order to maintain manufacturability of the tooling segments limitations of the LBM process had to be taken into account. For this application the maximum diameter of the inner cooling channels was crucial. In the project, thermal behaviour of the tool as well as coolant flow was analysed and different cooling geometries were compared. The ideal cooling channel geometry was designed based on the simulation results, considering technical characteristics of the Laser Beam Melting technology. The result was a wide mesh of small channels (Ø 4 mm) with a distance of only 6 mm to the surface. In order to maintain a uniform flow the cross section of the cooling system needs to be constant over the entire tool. Inlet and outlet were set by the conventional manufactured base body. The additively manufactured cooling system then fans out from a single 16 mm diameter inlet to a large number of smaller channels. Manufacturing this 16 mm cavity without a support structure was at the limit of LBM technology and resulted in a non-circular canal shape (see Fig. 6-44).

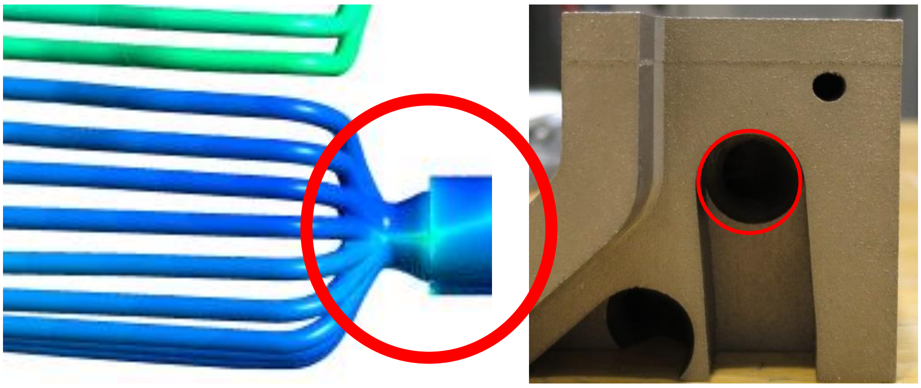


Fig. 6-44: Inlet of the additively manufactured cooling system – CAD model (left) and manufactured component (right)

6.7.3.4 Post Process Treatment Explanation

In order to achieve the required mechanical properties and to relief residual stresses the manufactured tool segments need to be heat treated. The additively processed tool steel 1.2709 differs from hot work steel usually used. Compared to conventional tool steel, the 1.2709 maraging steel is virtually carbon-free and therefore differs in terms of the hardening mechanism. The hardening in maraging steel is achieved by a metallurgical reaction. The relatively soft body centred cubic martensite, which is formed upon cooling, is hardened by the precipitation of intermetallic compounds at temperatures of about 480 °C. In the case at hand a subsequent artificial ageing was done at 510 °C for about 10 hours. Hardening measurements were carried out to determine achievement of target values. The hardness of the tool segments were in the required range between HRC 52 and 56.

6.7.3.5 Evaluation

Cost Reduction:

By using AM the tooling costs did increase by about 15.000 € per tool insert, mainly due to the size and volume of the additive functional structures and the resulting long manufacturing time (manufacturing performed in 2012). But thanks to the saving of cycle time when using the AM tool insert, the break-even point would be reached after about 150.000 formed parts. Using up to date LBM machines (i.e. state-of-the-art 2017), the additional AM costs could be reduced by about 30 % and therefore the break-even point could be reached already at a smaller number of parts.

Weight Reduction:

AM tool inserts and conventional ones have the same volume and mass.

Combination of Parts:

Not applicable for this project.

Functional Integration:

Considering that the conventional tool has already been cooled, there was no further function added to the AM tool inserts. The system was simply optimised using the AM inherent freedom of design.

Performance:

To confirm simulation results, extensive forming trials were done. The trials took place on a standard hot forming press, under production-like conditions and applying a variety of different parameter settings. With the help of appropriate state-of-the-art equipment like thermo-camera, temperature sensors and computer-assisted analysis, all relevant data from the trials were recorded and afterwards analysed.
In a first test series the tool was heated to an initial temperature of 200 °C and subsequently, after starting the cooling, the temperature curve during re-cooling was recorded by thermal sensors and a thermal imaging camera. In this case the additive manufactured tool with the optimized cooling system cooled down six times faster than the conventional tool with drilled cooling channels (see Fig. 6-45). In further experiments, different holding/cooling times were run with varying cooling water flow. For temperature recording once again thermocouples were used in the tool and thermography was used for the formed component. The results show, that using the optimized additive manufactured tool inserts, the holding/ cooling time can be reduced by 50 percent (from 10 to 5 s). This particular case corresponds to a total cycle time reduction of 20 %.

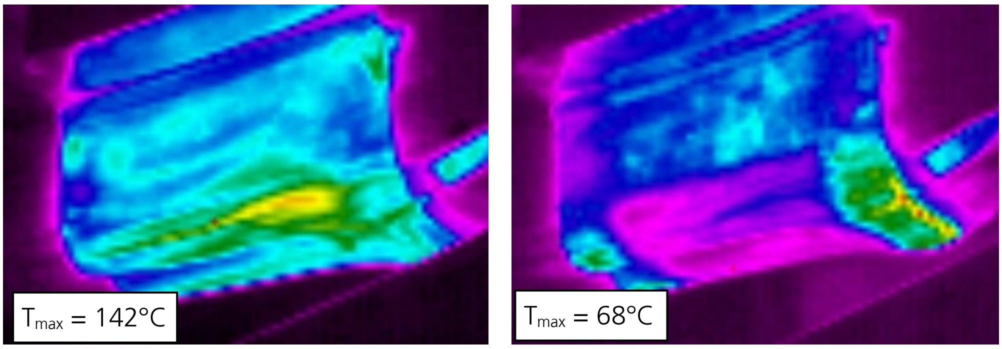


Fig. 6-45: **Thermal image of the die, 5 seconds after starting the cooling - temperature in the top section of the tool – conventional cooling system (top) versus additively manufactured cooling system (bottom)**

Product Life:

The product life couldn't be tested within the project. Only a couple of hundreds of parts were formed, where the AM tooling did not show any significant wear.

Safety Margin:

Simulation showed that the cooling channels with a diameter of 4 mm could be placed in a distance of 4 mm to the contour. But, since it was the first attempt of using an AM tooling for press hardening ever, a safety margin of 50 % was given. The final cooling system was a wide mesh of 4 mm channels with a distance of 6 mm from the contour (from the top of the channel).

Maintainability:

Maintainability was not considered while designing the tool inserts.

6.7.4 Analysis of Material Characterisation and Differences between AM Technologies

6.7.4.1 Material Characterisation Data of Components made by AM

Thermal Conductivity:

In order to assure the comparability of simulation results with reality, thermal conductivity of the specific material in use was determined experimentally (see Table 6-11). Therefore test samples from 1.2709 were additively manufactured, artificially aged at 510 °C and analysed using differential scanning calorimetry (DSC), capacitive dilatometry and laser flash analysis (LFA).

Instead of taking more theoretical data from different literature, these experimentally determined values were used as input for the simulation, improving its significance and reliability.

Temperature [°C]	Thermal conductivity [W/(m*K)]
25	**15,0**
50	**19,2**
100	**24,9**
150	**25,4**
200	**24,5**
250	**24,1**
300	**22,7**
350	**21,2**
400	**20,9**

Table 6-11: Thermal conductivity of additive processed 1.2709 at different temperatures

6.7.5 Main AM Process Flaws and Weaknesses

6.7.5.1 Need to Speed Up the Process

Considering the size and massiveness of tooling components, manufacturing time is definitely an issue and the biggest cost driver. Additive manufacturing of the functional structures for the 3 tool segments in the project took all together about 300 hours, with a 400 W laser system. That did increase the manufacturing time by almost 250 % compared to purely conventional manufacturing. In order to manufacture cost efficient there is definitely the need to speed up the process.

But not only the LBM machines need to be able to manufacture faster, the strategies of tool design need to be re-evaluated as well. In additive manufacturing reducing the amount of material corresponds almost directly to cost reduction. The additive approach needs to reduce the volume when designing tools. Components can be manufactured hollow or with lattice like structures according to the load.

6.7.5.2 Prospect to Develop very large AM Equipment

In the study only inserts or tool segments with about 200 x 200 x 170 mm³ (x,y,z) were manufactured. This can be largely attributed to the limited space available in the current machines which are able of processing tool steel. In order to have a real impact in hot sheet metal forming for the automotive industry larger tools need to be producible. Parts or tools from the size of a car body B-pillar would be the objective. Although the currently largest laser melting machine has a build envelope of 800 x 400 x 500 mm³ (x, y, z), this would still not suffice.

7 Summary and Overall Conclusions

7.1 Holistic View of Case Studies

As already mentioned in chapter 1, each component was developed and manufactured in the scope of a separate project, but was selected, reviewed and assessed in a detailed case study particularly and retrospectively within this report. This is why the available level of information differs considerably from case to case, enabling only a rough comparison. Table 7-1 provides a retrospective overview, contrasting the case studies with regard to general design objectives, specific design features, benefits and individual requirements:

	1	**2**	**3**	**4**	**5**	**6**	**7**
	Bionic Wheel Carrier	**Main Gearbox Bracket**	**Calibration Tool**	**Heat Exchanger**	**Miniature Heat Exchanger**	**Functionally Integrated Implant**	**Functionally Integrated Tooling Segment**
Design Objectives							
Integration of functions	-	-	x	-	-	x	x
Weight reduction	x	x	-	x	x	-	-
Size reduction	-	-	x	x	x	-	-
Reduction of parts	x	x	x	x	x	-	-
Related Design Features and Benefits							
Organic shape / topology optimisation	x	x	-	-	-	-	-
Lattice structures	-	-	-	-	-	x	-
Internal channels / cavities	-	-	x	x	x	x	x
Achieved weight reduction	~13%	~60%	~50%	~30%	>50%	-	-
Component- and AM-specific Requirements							
Minimum allowable size of geometrical features / driven by …	2 mm / process and mat.	3 mm / strength requirem.	3 mm / powder removal	0.5 mm / process and mat.	1.5 mm / performance	0.3 mm / process and mat.	2 mm / process and mat.
Maximum allowable size of geometrical features / driven by …	-	-	8 mm / no need for support	3 mm / applic.	8 mm / no need for support	-	8 mm / no need for support
Post-processing of functional surfaces	Milling, Drilling	Milling, Drilling	Milling, Thread cutting	-	Grinding, Polishing	Turning, Milling, Grinding, Polishing	Machining

	1	2	3	4	5	6	7
	Bionic Wheel Carrier	**Main Gearbox Bracket**	**Calibration Tool**	**Heat Exchanger**	**Miniature Heat Exchanger**	**Functionally Integrated Implant**	**Functionally Integrated Tooling Segment**
Requirements (finish) for non-functional surfaces	fatigue relevant	fatigue relevant	-	-	optical / aesthetic reasons	-	-
Post-Processing of non-functional surf.	Blasting (peanut shells)	Electro-chemical polishing	Blasting (glass beads)	Blasting (glass beads)	Grinding, Blasting (corun-dum)	Blasting (corun-dum)	Blasting (corun-dum)
Need for drawings	-	Post-Process	AM and Post-Process	AM and Post-Process	-	Post-Process	-
Post-process heat treatment	-	HIP	-	stress-relief annealing	-	stress-relief annealing	stress-relief annealing + hardening

Table 7-1: Rough Comparison of Case Studies

7.1.1 Design Objectives

Depending on its specific purpose and target industry, each evaluated component offers individual design features with the aim to benefit best from the AM technology applied. It can be seen that in general not only one single design objective was addressed, but in most cases combinations of several ones. For example, in case of component no. 4 and 5 (heat exchangers) three design targets have been addressed and achieved – besides a reduction in size and weight there was also obtained a significant reduction of parts.

7.1.2 Design Features

The AM-specific design features have been chosen according to the component's individual requirements. Topology optimisation and resulting organic shapes are reasonable for load-carrying structural components like the wheel carrier (component no. 1) or the gearbox bracket (component no. 2), whereas internal channels and cavities are applicable for different purposes – on the one hand they are essential for the integration of functions, but at the same time they are also supporting the reduction of weight, size and number of parts and consequently lead to an increase of performance. Similar advantages could also be taken by the use of lattice structures, but currently their application is still limited (see component 6 – implant).

7.1.3 Specific Requirements

The achievement of ambitious design objectives by implementation of related design features requires adequate consideration of component- and AM-specific limitations and requirements:

7.1.3.1 Minimum / Maximum Allowable Size of Geometrical Features

A theoretical description of the minimum and maximum feasible size of geometrical features is provided in chapter 3.2.5. Within the case studies the different limiting factors are shown in practice, where it becomes apparent that they are set either by the combination of AM process and material, or by the component's specific application:

- In case of the Integrated Wheel Carrier (component no. 1) the lower limit for geometrical features was driven by the LBM process and related post processing. Since very thin trusses from topology optimisation broke either during the build-up (very likely due to the coating blade) or during the separation process of the support structures, it was decided to set the minimum allowable size to a value of 2 mm. A specific upper limit (maximum value) did not exist, even though the size/volume was kept as small as possible in order to achieve significant weight savings.

- For component no. 2, the main gearbox bracket, the lower limit was defined to be 3 mm in order to guarantee the required material performance. This is based on the assumption that there is a relationship between mechanical properties and structure size. Even if the EBM process enables the production of smaller features, this value was chosen in order to fulfil the specific strength requirements; hence the limit is driven by application aspects. Also for this component no dedicated upper limit existed, nevertheless the size/volume was kept as small as possible in order to achieve the best possible weight savings.

- For the calibration tool (component no. 3) both a lower and an upper limit had to be considered. The minimum diameter of the internal channels was defined to be 3 mm in order to allow proper powder removal, in particular powder of 17-4 PH. The upper limit was set by the requirement for circular channel profiles without using support structures. This is why the diameter of internal channels was kept below 8 mm. An adaption of the channel's cross-section as shown in chapter 3.2.5, Fig. 3-7, was not performed.

- In the design of component no. 4, the heat exchanger, a minimum wall thickness of 0.5 mm was realised, driven by the LBM process and the material used. With respect to the maximum size of a feature in this case the minimum distance between walls and support structures was defined to be 3 mm in order to minimize potential residual stresses and related distortion.

- For the miniature heat exchanger/cooler, component no. 5, a compromise between performance and pressure resistance led to a minimum wall thickness of 1.5 mm. Also in this case the manufacturing of internal channels without the use of support structures was the upper limiting factor (see also component no. 3), so the maximum diameter was defined to be 6 mm in order to not exceed the recommended limit of 8 mm.

- The maximum dimensions of the functionally integrated implant (component no. 6) are limited by its target application – the overall dimensions are pre-defined by the human anatomy and based on a standard hip stem geometry. Therefore also the size of internal channels was naturally limited and could be held easily below 8 mm. As this component serves as a technical demonstrator only, specific strength and durability requirements have not been considered during the design, which would be for sure a limiting factor for the maximum dimensions of inner cavities and channels. The minimum allowable size of geometrical features was set by the LBM-process and the material used, leading to a minimum strut size of about 0.3 mm.

- Even though the dimensional accuracy of a laser beam melted component is within ± 0.1 mm, the design of component no. 7 (Functionally Integrated Tooling Segment) considered an offset of 2 mm for two reasons: The component was designed and manufactured as a hybrid of conventional and additive manufacturing, requiring a manual aligning of the base body just before starting the LBM-process. In addition the tooling segment is a very solid part (i.e. lot of material in a small design space), being susceptible to stress-induced deformation. For both challenges the offset of 2 mm provides sufficient margin for mechanical post-processing in order to fulfil the tolerance requirements.
  With respect to the maximum dimensions of geometrical features the internal cooling channels have been kept below 8 mm in order to ensure satisfying shape accuracy. Unfortunately this was not feasible for the inlet section (diameter of 16 mm) which was manufactured also without support, resulting in a non-circular shape.

7.1.3.2 Requirements for Surfaces

To date AM technology like LBM and EBM is not able to produce functional surfaces (e.g. bearing seats, interfaces, bores, threats etc.) which are ready-to-use, because the requirements with respect to precision (i.e. tolerances) and surface roughness can normally not be achieved. This is the reason why mechanical post-processing is necessary, from case to case more or less extensive. Looking on the seven components a mechanical post-processing was required in nearly every case, except for the heat exchanger (component no. 4). There the machining was only performed in order to separate the part from the build platform and to remove the support structure, all other functional surfaces (inlets and outlets) did fulfil the requirements in the as-built condition.

For non-functional surfaces there are specific requirements as well. Very often the surface roughness has to be kept below a certain limit – for example for aesthetic needs or just in order to achieve sufficient cleanability of the part. But, as shown in case study no.1 and 2, requirements for surface roughness can also be set by specific needs of application: a rough surface makes the part prone to crack initiation, decreasing its endurance performance. Especially for aerospace applications this is of major importance, that's why the main gearbox bracket (component no. 2) was treated with electrochemical polishing. Also for the bionic wheel carrier the surface roughness is fatigue relevant, but with lower requirements due to the specific target application (concept car). In that case blasting with peanut shells was deemed to be sufficient.

Notwithstanding the above, blasting by using different blasting media is in general suitable to smooth surfaces by removing powder adhesions, which is per se not an abrasive procedure but improves haptic and optical surface properties of parts built by LBM or EBM. For that reason blasting is generally performed as a minimum surface treatment, even if no specific surface requirements are defined.

7.1.3.3 Need for Drawings

In today's digital world the design and production of parts can be fully accomplished by the use of a pure digital process chain. With regard to the case studies this was feasible for three components – the bionic wheel carrier, the miniature heat exchanger and the Functionally Integrated Tooling Segment. In the other cases conventional drawings were deemed necessary at least for the post-processing, i.e. for exact definition of functional surfaces and features like bores, threads and so on. It is assumed that in those cases there was either a lack of suitable full-digital machines or a lack of an established and complete digital process chain.

However, in addition to usual information required for conventional manufacturing there is also AM-specific information, which needs to be standardized and added – regardless of whether this will be implemented in conventional drawings or purely on a digital basis. For example, as mentioned in case study no. 3 and 4, the part's orientation in the build chamber should be defined in an early design stage, since mechanical properties differ depending on the build direction (anisotropy). In addition the orientation also defines the need and the amount of support structures, having a significant influence on the build time and on the effort for mechanical post-processing.

7.1.3.4 Post-Process Heat Treatment

Inhomogeneous heat distribution and dissemination during the LBM process lead to residual stresses, which become apparent as distortions very often. The use of appropriate support structures helps to reduce this effect, but nevertheless it cannot be fully avoided. For that reason a post-process heat-treatment (stress-relief annealing) is necessary in many cases (see chapter 3.2.3), as performed for component no. 4, 6 and 7. For component no. 7, the Functionally Integrated Tooling Segment, a hardening by means of artificial ageing was performed in addition in order to fulfil the tool-specific hardness requirements.

In case of the bionic wheel carrier, the calibration tool and the miniature heat exchanger a post-process heat treatment for stress relief was not required. The case study of the bionic wheel carrier puts it in a nutshell (see chapter 6.1.3.2): a suitable design tailored to the specific needs of AM technology can minimize residual stresses and related distortion, consequently minimizing also the need for a post-process heat treatment.

Within the case study analysis the main gearbox bracket was the only component manufactured by EBM. As already explained in chapter 3.2.3 the EBM process provides a more homogeneous heat distribution, minimizing residual stresses to such a low level, that usually subsequent stress-relief annealing is not required. But due to the high requirements of aerospace applications a HIP treatment was done in order to tailor the microstructure and to eliminate any residual porosity.

7.2 Main AM Process Flaws and Weaknesses – Realistic Path toward Commercialisation of AM

Today's general assets and drawbacks of additive manufacturing technology are common knowledge, being extensively discussed across the globe in many conferences, specialists' events and in literature. This chapter of the report is not intended to give a comprehensive summary of all that knowledge, but more to point out those flaws and weaknesses of metal AM, which became apparent within the reviewed case studies and which have been identified by the components' manufacturers during development and production.

7.2.1 Design Work

7.2.1.1 CAD

Currently AM-specific advantages like the high degree of design freedom cannot be fully exploited. Limiting factors are manifold and can be found throughout the whole AM process chain. Starting with an appropriate design there is still a lack of AM-specific CAD software with a high range of functions – most of the latest CAD software is still focussed on conventional design and manufacturing methods or provides only single AM functionalities, resulting in the need to use different software packages in sequence or in iterations.

7.2.1.2 Finite Element Analysis (FEA) of Complex Lattice Structures

Another shortfall exists with regard to comprehensive and highly detailed stress analysis. As mentioned in the case study no. 6 (hip stem implant), today's state-of-the-art FEA systems are not yet suitable for analysis of complex three-dimensional cellular designs like graded lattice structures and the performance of common and affordable IT equipment is still insufficient. For reliable analysis results it is necessary to create a fine mesh of suitable elements, which represent the properties and behaviour of the material:

In case of lattice structures with strut diameters down to 0.3 mm (see chapter 6.6.3.6) the necessary mesh resolution would result in a huge number of elements, requiring high IT-performance especially for large-volume structures. With regard to this problem cloud-based analysis is an alternative, which offers processing performance on external servers and enables even ordinary equipped users to run extensive simulations / calculations. Such cloud-based solutions are already available for some applications, but not yet really widespread and popular for FEA.

Moreover, the FE simulation of the material and structural behaviour has to be reliable. Appropriate substitutional FE-models could be a solution, but their properties have to be determined on the basis of elaborate mechanical tests first, considering variations in material, topology, anisotropy, unit cell size and strut thickness. Currently there are no substitute models for different lattice unit cell types available, which should provide comparable mechanical properties for tension, compression and shear under static and dynamic loading [20]. Hence the mechanical behaviour of complex lattice structure is not sufficiently predictable yet. Analysis mistakes or inaccuracies within one strut, one unit cell or at their interfaces will be accumulated and multiplied over the complete structure, making the analysis results useless.

But, once a full FE analysis of complex lattice structures can be conducted with reasonable expenditure and reliable results, their applicability will expand significantly (see also chapter 2.2).

7.2.1.3 Topology Optimisation

Topology optimisation is a design methodology which can be used to exhaust the outstanding benefits provided by AM technology (see chapter 2.1). But, current available software solutions do neither provide an AM-convenient data format, nor do they take account of any AM-specific restrictions. The consideration of AM restrictions and appropriate design adjustment for topology optimised components is still a time-consuming and experience-based process, which needs to be more automated and supported by guidelines in order to reduce related development costs. For case study no. 1, the bionic wheel carrier, a variety of different simulations with different software packages was used in order to transform an edgy topology optimised structure into a smooth, organic shape which can be manufactured by LBM.

Moreover, the minimum feature size commonly producible with AM technology is usually not exploited, since it would require a very high number of finite elements to be defined as design variable, resulting in a topology of maximum complexity. For various reasons (e.g. IT-performance, see previous paragraph) today this is normally done for very small components only. Furthermore, the results of any topology optimisation mostly do not satisfy the process-specific needs of AM methods, as shown in the case studies of the bionic wheel carrier and the main gearbox bracket (component no. 1 and 2). Very thin trusses created by the topology optimisation of the bionic wheel carrier broke either during the AM process itself or during mechanical post processing and had to be adapted accordingly. At the main gearbox bracket the minimum strut size was kept above 3 mm in order to consider the risk of decreased strength on very small structures.

Latest software solutions like Altair Inspire or Autodesk Fusion do provide already features to define minimum dimensions of structural elements, but nevertheless the results of automated topology optimisation still need process-specific adaptation in order to enable the production by using AM technology. Consequently, not only the manufacturing stage is the limiting factor for optimal designs, but it is already the design stage. [21]

Summarising the case study analysis, it can be said that the full potential of AM cannot be exploited by slight adaptation of conventionally designed components, but requires the design work to start from scratch. In addition the high complexity and diversity of AM design (e.g. organic shapes) minimises the reusability of standard design solutions. This requires advanced CAE tools and methods as well as experienced and well-trained application engineers. Also the lack of appropriate and detailed design guidelines needs to be remedied (see chapter 4). More detailed standards and regulations in combination with reliable process simulation would support to reduce the time-consuming and costly number of iteration loops in design and production, as it was performed for the bionic wheel carrier (see chapter 6.1.2.2) and for sure for almost all other case studies, even if not explicitly mentioned.

7.2.2 Overall Costs and Process Speed

In addition to the costs for extensive design and development activities, the costs for material, for operation of the equipment as well as for the pre and post processing are still a main flaw of AM:

The prices of metal powder have not decreased noticeably during recent years. Due to the high effort for the atomisation process (i.e. powder production) and the AM-specific high requirements on powder properties, purchase prices for metal powder are currently up to ten times higher than prices of solid wrought material (e.g. Ti6Al4V). But, if more competitors will appear on the global market the powder prices should drop more and more in future.

Besides the aspect of material costs there is a strong need to accelerate and simplify the whole AM process chain in order to decrease the total costs. For manufacturing of big and high-volume parts with Laser Beam Melting, the pure operating time of the AM machine is the biggest cost driver. As an example, the additive manufacturing of the functional structures for 3 tool segments of component no. 7 took about 300 hours in total (using 1 laser with 400 W), increasing the production time by almost 250% compared to conventional manufacturing methods. Nevertheless the tooling segment demonstrator illustrated a real business case, since the contour conformal cooling can significantly reduce the cycle time (cooling time of the hot formed parts), recovering the additional manufacturing costs during the tool's entire operating life.

A continuous increase of AM machine's productivity is already addressed by the OEMs, providing enhanced manufacturing parameters, more powerful lasers and multi laser machines with larger build chambers. Nevertheless powder bed based processes like LBM or EBM do have physical limits (speed of laser scanner, coating process etc.), which will never be exceeded. Therefore the focus should be put more on the need to decrease effort (i.e. costs) for pre- and post-processing. Especially the post-processing comprising powder removal, support removal and mechanical rework needs to be more automated and speeded up in order to reduce costs significantly.

7.2.3 Limited Size of Manufactured Components

The maximum size of single components manufactured by powder bed based technology like LBM or EBM is limited by the build chamber of the machine:

At present for LBM there are machines with a build chamber up to the size of 800 x 400 x 500 mm³ (i.e. 160 litres) available on the market, e.g. the X-line 2000R from Concept Laser (www.concept-laser.de). Such machines are equipped with multiple lasers (X-line 2000R: 2 lasers) in order to increase the manufacturing speed and to assure sufficient coverage of the whole build platform whilst providing best accuracy of laser exposure.

In contrast to LBM, where about 9 different OEMs provide AM equipment on the market, for EBM there is only one single manufacturer, which is ARCAM AB (www.arcam.com). Their machine with the largest build chamber is the Arcam Q20plus, designed especially for manufacturing of aerospace components. It provides a build chamber of Ø350 x 380 mm (i.e. 37 litres).

These limitations with regard to the maximum size of AM components are one major constraint for metal AM applications. Depending on the target industry sector this may be immaterial, because a lot of very complex components like medical implants (see case study no. 6) hardly exceed these dimensions. But there are also fields of application where already now the AM equipment restricts a widespread use of AM technology – for example in the field of tool making. Contour conformal cooling by the use of additively manufactured cooling systems is a business case, but the limited size of AM-components is a real show stopper especially for the automotive industry, where larger tools are applied (see chapter 6.7.5.2, case study no. 7).

Also in the aerospace sector there is a need for bigger parts made by AM. Currently, large-scale structural elements would need to be produced in different segments, subsequently to be joined by welding, bonding etc., which means additional effort, increased weight and potential new structural weaknesses.

7.2.4 Material Development

The range of materials suitable for AM technology depends on the specific AM process. For EBM the range of qualified materials is currently very small, limited to titanium and titanium alloys, nickel-based alloys and cobalt-chrome alloys. But also for LBM the choice of material is still limited to some conventional alloys (see chapter 3.1.3, Table 3-1), most of them developed and optimised for conventional manufacturing technologies. For example, the aluminium alloys available for LBM are typical cast alloys. One exception is Scalmalloy®, which is advertised to be as ductile as titanium and as light as aluminium. This aluminium alloy was developed by Airbus and is commercialised through its subsidiary Airbus APWorks GmbH, especially designed to be processed using LBM. It shows high-strength (yield strength is approx. two times higher than for AlSi10Mg) and corrosion-resistance. Its unique properties make the alloy interesting for high-performance applications in robotics, automotive and aerospace industry. (www.apworks.de/scalmalloy)

For the bionic wheel carrier (case study no. 1) the high strength alloy Al 7075 (used for the predecessor) had to be substituted by AlSi10Mg, because Al7075 can hardly be processed by LBM. The substitution was a compromise – both materials are very similar in terms of stiffness (i.e. Young's Modulus). Finally, compared to the machined predecessor the bionic wheel carrier meets the same stiffness requirements whilst showing higher performance (reduced weight but same load capability). This could be accomplished by the use of organic shapes, decreasing local stress levels and therefore reducing the stress amplitude under similar loading conditions.

In general the development of new materials suitable for powder bed based AM has not progressed far enough yet. One limitation is the powder production. Not every kind of metallic alloy can be transformed into a powder with superior AM-specific properties, limited by the physics of the atomisation process. For example, during atomisation aluminium intends to absorb/accumulate hydrogen, which is not fully removed during the LBM process. This becomes apparent when welding two LBM-manufactured components made of aluminium (AlSi10Mg or even Scalmalloy®) – compared to a weld seam between casted aluminium components the weld seam between the LBM-components shows extreme porosity [22].

To sum up, proper material qualification for powder bed based AM should be addressed in different ways. On the one hand the AM processes need to be further developed and optimised in order to guarantee reproducible quality and to enhance productivity. On the other hand new metallic alloys should be developed, having properties especially tailored to the needs of LBM or EBM (see Scalmalloy®). A wide range of AM-specific alloys, which can fully compete with alloys for conventional manufacturing would enable new designs and higher weight savings, extending the field of application for metal AM technology. Current research activity towards development and qualification of new materials for AM focus on copper and high strength alloys (steels as well as aluminium). This does partially reflect in respective scientific publications, but is also in many cases not accessible to the public (proprietary) because of its industry-driven and/or -financed nature.

7.2.5 Quality Assurance

The development of AM-specific standards, guidelines and mandatory regulations for quality management is still in progress and in an early stage so far (see chapter 4). Depending on individual requirements and target application, an efficient quality control can be very time-consuming and cost-intensive. Especially in aerospace and medical industry it is vital to check and assure the properties of internal cavities and channels, e.g. by the use of CT scans. Therefore, on the one hand new standards and non-destructive test methods should be developed; on the other hand in-situ monitoring solutions for the different AM technologies need to be improved and extended. For LBM, several in-situ monitoring systems have become available on the market lately (e.g. Concept Laser's QM Meltpool 3D or QM Coating, or EOS' EOSTATE MeltPool Monitoring). In general all these systems still need to be trained or calibrated on different defects before providing automatic defect detection. The monitoring data can be recorded for detailed assessment after the production process, which causes not only high data quantities but also high effort. A closed-loop control and real-time trouble-shooting would resolve that problem, but the correlation between process parameters and resulting part quality (material properties etc.) needs to be further investigated and understood.

Although AM-specific quality assurance measures, guidelines and standards need to be developed, it must be pointed out that existing quality management standards and tools can be and need to be applied for AM as well, as soon as it comes down to real series production. In this regard, the challenge is rather to advance AM's reliability, reproducibility, process capability and process control to a level which is today state of the art for most conventional manufacturing processes, including machining and casting – to allow AM to meet these existing quality management regulations in the future.

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