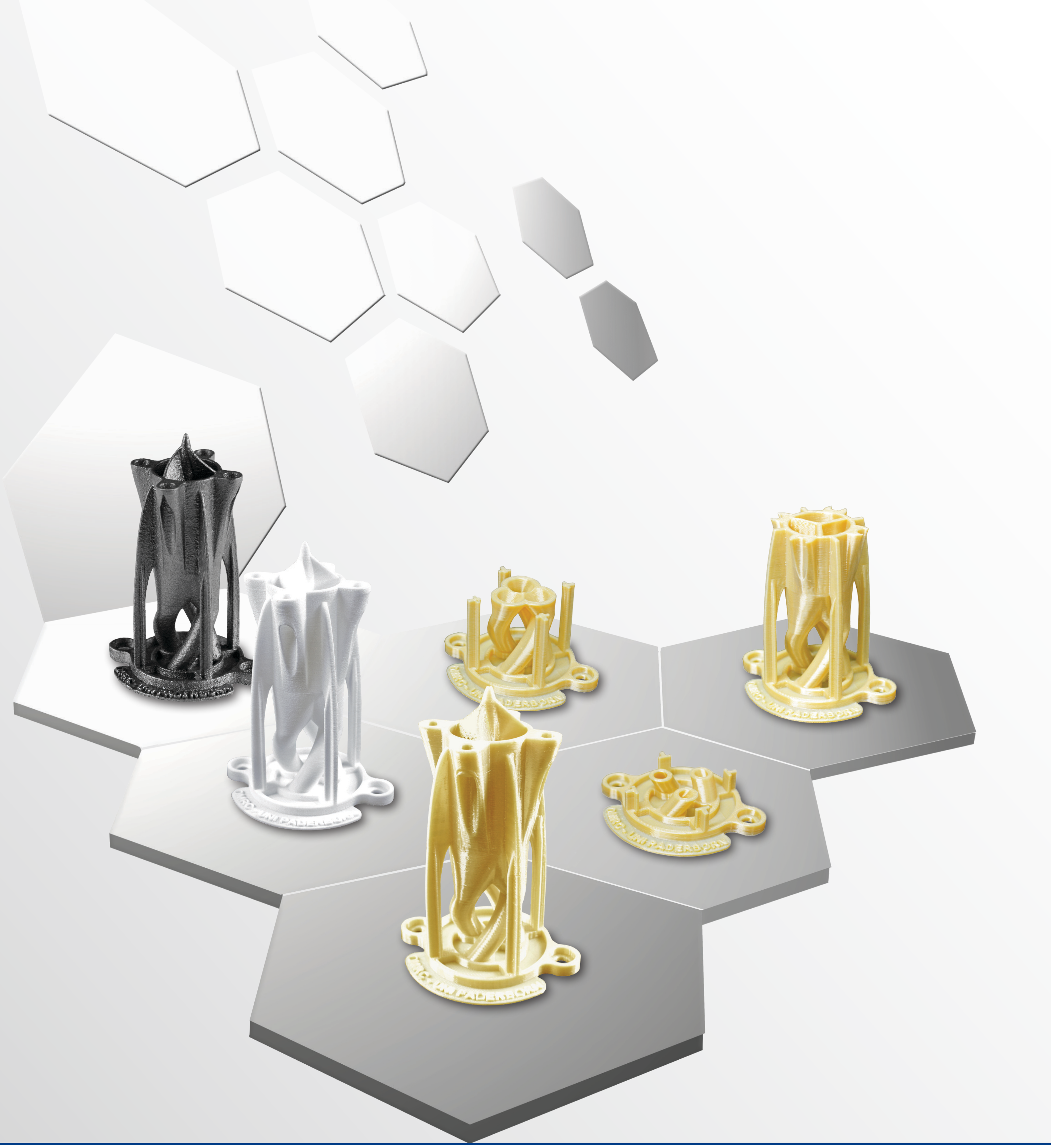
Direct Manufacturing Research Center

Annual Report 2012



DMRC
DIRECT MANUFACTURING RESEARCH CENTER

Imprint

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Direct Manufacturing Research Center

Annual Report 2012

We gratefully thank our Partners:

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1 Preface

Prof. Dr.-Ing. Hans-Joachim Schmid

Dear Reader!

We are very glad to present you this first Annual Report of the Direct Manufacturing Research Center. With this report we want to provide you with a comprehensive overview of the DMRC, the current projects and the scientific output in 2012.

The DMRC is a joint effort of academia and industry to advance the existing additive manufacturing technologies into dependable and production rugged standard manufacturing technologies. Although there is still a considerable distance to go we see significant advancements during the last years. Therefore, we feel to be very much privileged working in a fascinating and very dynamic field of research. The DMRC wants to contribute to this field by doing research which is readily transferred into industrial practice. Furthermore, the DMRC wants to promote knowledge about opportunities – as well as limitations – of additive manufacturing among both students (as the designers and decision makers of the future) and engineers working in the industry.

One distinctive feature of the DMRC is its interdisciplinary structure: According to the complexity and diversity of the processes in additive manufacturing we have different professors involved in each project in order to bring in the best expertise for each specific project. Furthermore, steering of the projects is accomplished in close cooperation of a professor from University and one or more industry representatives. Thus, we aim to provide best conditions for successful research joining the expertise from academia and industry.

Since the opening of the DMRC in 2009 the center has continuously grown in terms of industry members, staff and projects. At the moment we have 8 professors and 15 scientific staff members working on 12 projects. Additionally many students (undergraduate and graduate) are working on specific topics within the different projects. The projects can be grouped in two different types: First, technology specific projects are dealing with subjects in Laser Sintering, Laser Melting and Fused Deposition Modeling, respectively. Second, generic projects are dealing with cross-cutting topics, like e.g. AM design rules, quality, costs, market studies etc.

In the past year we were quite successful with a number of projects maturing and leading to very interesting results. The scientists at DMRC have published a number of papers with a number of manuscripts still in the pipeline to be published soon. Furthermore a considerable number of conference presentations were made. In addition, we are very proud that we received a very prestigious award 'Ort des Fortschritts' (Location of Progress) from the State Government North Rhine-Westphalia.

All the positive feedback and visible success stimulates the whole team to put all effort for a continuing and growing success of the DMRC. We are looking very forward to the next year and would be very glad if we could cooperate with you!

Kind regards

Prof. Dr.-Ing. Hans-Joachim Schmid

Dr.-Ing. Eric Klemp

Within the last years Additive Manufacturing is becoming more and more of an important technology and so the founding of the DMRC in 2008 was the right decision of the partners Boeing, Evonik, EOS and SLM Solutions. Meanwhile the consortium has nine partners, as Siemens, Stratasys, Stükerjürgen Aerospace Composites, Blue Production and Eisenhuth have joined till now. With these 9 partners the total chain of product development is represented in the DMRC, starting from R&D at the University of Paderborn and ending at the industrial use of this new technology. The mission of DMRC is still valid, which says: “The DMRC is a proactive collaboration of key technology stakeholders who have a common interest in advancing Additive Manufacturing (AM) technology into dependable, production rugged Direct Manufacturing technology (DM).”

With this fruitful constellation between industrial partners and the University of Paderborn, the interdisciplinary research is performed by meanwhile eight different institutes. The aim is to bring AM to a reliable, repeatable and production capable Direct Manufacturing technology. To achieve this aim, till now 15 finished and running projects are performed under the roof of DMRC.

Seeing the DMRC from the financial side, till 2016 up to 11 Mio € could be spent in projects. Till now approx. 55 % have been committed, so with the existing consortium nearly 5 Mio € are left to be invested into projects inside DMRC. This opens the possibility to perform new projects to satisfy DMRC partner’s needs and to achieve international reputation in different fields of research. This remarkable amount of funding should be attractive for new partners from new industries - besides those already represented in DMRC - to become member of this community.

Besides the funding of State North Rhine Westfalia, additional activities have been started in 2012 to achieve a sustainable growth. This year a few project proposals have been submitted to European Commission, ESA, DFG and as well to other national funding organizations. One of the topics for 2013 is already set, as the DMRC is proud to participate in the IT’s OWL- project (Intelligente Technische Systeme in OWL). Here DMRC will be partner in a project contributing product protection activities.

The DMRC represents itself as well via many other activities e.g. as leading the aircraft session at RapidTech and participation in Euromold together with our partners. Furthermore the DMRC appears in the Wohlers report 2012, does participate in the development of standards like ASTM and DIN / ISO / VDI. In particular the formulation of design rules does match the needs and shows an international acceptance of DMRCs research activities. Due to addressing research in many different areas, researchers from DMRC have given national and international presentations in Europe and US.

The DMRC is a centre, where collaborative research takes place under one roof. Basis of all activities are motivated and dedicated researchers who really enjoy their work and who live the spirit of Additive Manufacturing – and exactly this team itself is the DMRC. I am really proud to be part of this team.

In summary, the future for DMRC looks bright.

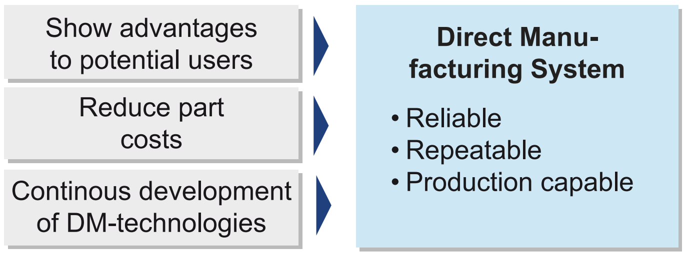
Kind regards

Dr.-Ing. Eric Klemp

2 Direct Manufacturing Research Center

Aims of the DMRC

The aim of the DMRC is a reliable, repeatable and production capable Direct Manufacturing System. To achieve this, potential users need to be informed about the advantages of the technologies, part costs have to be reduced and the development of Direct Manufacturing technologies needs to be continued.

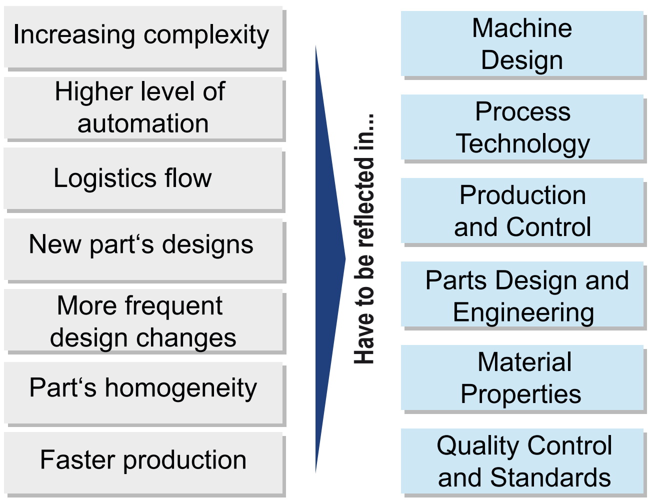


Objects of the DMRC

The leverage is to use collective resources and expertise of the leading industrial companies and the University of Paderborn. In detail this means to perform application oriented and fundamental research projects along the complete value chain. Therefor the DMRC is present as a center of best practice for tools and techniques and expert in defining process, product and quality standards. It will establish a platform for benchmarking of tools and techniques and so should incubate and spin out DM-technologies. On the education level, the DMRC will educate engineers with DM-relevant skills at the University. This aims at creating a world class community.

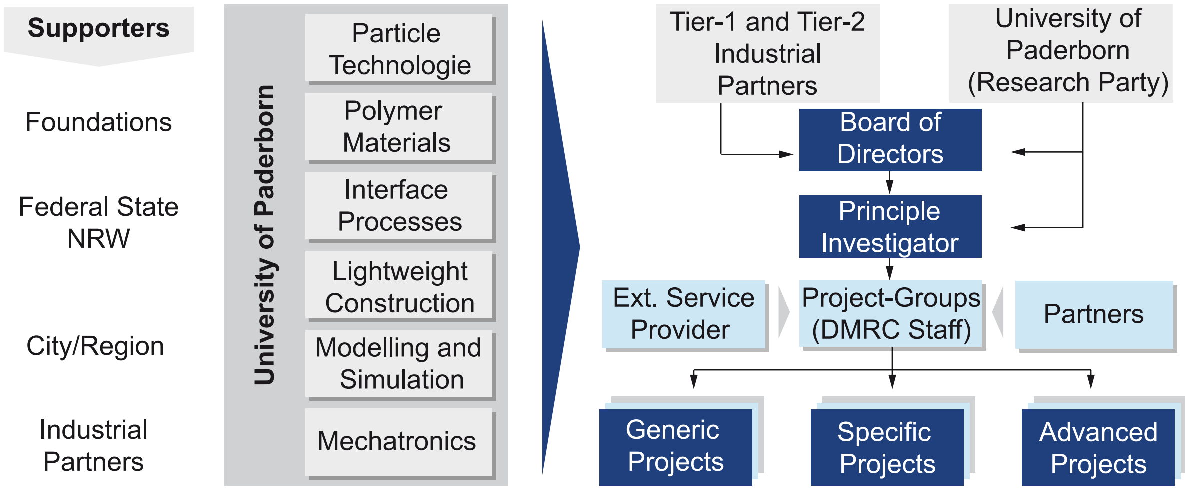
Main Challenges to be approached

The attainment of the aims of the DMRC raises many challenges which have to be reflected within all aspects of the product development process.



Structure of the DMRC

Within the DMRC there will be different kind of projects. The main focus is on generic projects, dealing with basic research tasks together with the partners of the DMRC. These projects are mainly dealing with the relevant technologies e.g. FDM, LS and SLM. Besides this, specific projects deal with particular technical tasks. The third group are advanced projects which fulfill overarching tasks as foresight studies, development of a strategy and design rules.



Joining the DMRC

Becoming a partner in the consortium means to benefit from cooperation with the main experts in the field of AM and to cooperate interdisciplinary. All partners have access to all results and Intellectual Property Rights regarding the key technology created by DMRC interdisciplinary research. Due to the funding model, it is possible to create highest gain from the research budget by pooling together with other companies and benefiting from each other. Furthermore within the consortium solutions for specific problems are developed. And nevertheless, a partnership in the DMRC means to co-steer the direction of DM in terms of research strategy.

3 Current Research Projects

The DMRC aims to improve AM technologies as one of the most promising industries. In order to achieve a continuous improvement of this technology different kinds of projects are performed at the DMRC. On the one side, the projects are technology driven on the other side, there are "overall" projects dealing with general topics.

The technology driven projects are dealing with Lasersintering (LS), Lasermelting (SLM) and Fused Deposition Modeling (FDM). Within the LS projects specific knowledge is generated in order to determine and optimize properties of materials, surfaces and especially parts, tis includes of course as well investigations about aging of materials. Together this will aim particular to qualify parts for "ready to use" applications. Within the SLM projects, different kinds of materials are in the focus. The research focus is optimizing the process and it's parameters to achieve best results in (mechanical) properties, which does implement as well to gain detailed knowledge of the fatigue strength stress behaviour, optimization of lattice structures, investigations about heat treatment and finally the product optimization itself. The FDM projects are as well an important part of DMRC research. Here improving material properties - for short and long-term use as aging - are addressed as well in order to improve the quality of processes, materials and parts.

The advanced projects deal with overarching tasks. The project "costing analysis" investigates in detail costs and their drivers over the product lifecycle, starting in the design phase and ending with the supply of spare parts. Within the QM project the understanding of influences of reproducibility, reliability and the prognosis of material and part properties is watched in order to get a full understanding of the complete process chain. Goal of the "Obama" - project is to lining out the opportunities and barriers of DM-technologies in the aerospace industry and adapted other industries. As one result three studies will be publishes. Additionally the project "research strategies for additive manufacturing" will deliver detailed information of the research been carried out at different research institutes in order to support strategies for the AM industry and for potential users. Last but not least the project "Direct Manufacturing Design Rules" has the object to develop design guidelines for all at DMRC available AM processes. The results are expected to support users and designers as well as to facilitate national and international standardisation process.

With this bunch of interesting projects it can be expected to create know-how and to receive answers for questions about optimisation of the AM process, machinery, materials and properties. So finally you will see lightweight, multifunctional AM optimised parts with predictable cost and properties as well as best practise examples for different technologies.

The following pages will let you get an overview of projects and the collaboration inside the university and interdisciplinary between the partners.

Stefan Rüsenberg

Material Characterization and Properties regarding a Boeing Design, optimized for Laser Sintering

The aim of the project is a complete investigation of the laser sintering process along the LS Process Quality Chain regarding a real design for the aerospace industry. Influencing parameters are defined reasonable to increase the reproducibility. The investigations of material and quality characteristics are the main focus of this project. One main topic is the development of a characterization method to uniquely define the powder quality of the raw material. The investigation of material properties will be performed regarding the quality of the raw material as well as other influencing factors. Furthermore the construction and design of the given requirements regarding lightweight construction, cost reduction and others round off the project specifications.

Powder Material Characterization

Investigation of a method to characterize the powder material for Laser Sintering

This chapter includes the investigation of diverse methods to characterize the powder quality. As known, the material for laser sinter processes is composed of virgin and used powder, whereas the used powder is a material, which has passed the LS process several times. Because of the temperature influence during the process the material is thermally loaded. State of the art for the raw powder quality is a given powder ratio, but the material age is not defined.

Part of the project is the definition of important methods to get information about the influence on the powder age. Reasonable methods are experimental setups to investigate rheological and thermal properties as well as particle properties. Different amounts of powder with different powder ratios, adjusted using the Melt Volume Rate (MVR), are produced. One main point of the project is the development of an industry-oriented method, so the MVR method is the easiest way to get information about the viscosity of polymer materials, wherefore it is an important parameter for the characterization of powder. Other processes are investigated as well. At first the solution viscosity and a SEC (Size Exclusion Chromatography) are performed to get information about the molecular weight and the molecular weight distribution. The flow curve is detected using a rotational and a cappillary rheometer. Information about the flowability as well as the particle size distribution and the particle morphology are important factors and are detected as well.

Material Properties

Material characterization of different important parameter along the Laser Sintering Process Quality Chain

After getting the information about possible methods for the polymer characterization, the next step includes the determination of important material properties. Next to the standard properties like mechanics, other tests are conducted, such as three point bending and compression tests to enlarge the process understanding. Other experimental setups are performed as well to examine thermal, electrical and physical properties. All tests are accomplished varying layer thickness, temperature and material quality. For the post process an automatical blasting system with a defined distance, blasting pressure and blasting time is used.

It is important to build up a reference job whereby it is possible to compare the influenced parameters. The job height, the exposure strategy as well as the exposure time are three main parameters, but there are lots of other factors which have to be defined at the beginning of the test program. Further on powder boxes are placed at defined locations to compare the material ageing, using the methods developed in the first part of the project, from job to job as well as the packing density regarding the different adjustments. Aspects like hatch conformity or shrinkage are also considered. This part has two focuses: On the one hand a reference job is constructed to detect all influencing parameters, on the other hand the determination of material properties and the influences of the testing methods are investigated as well. The results shall be transferred to chosen machine types as well as a flame retardant material.

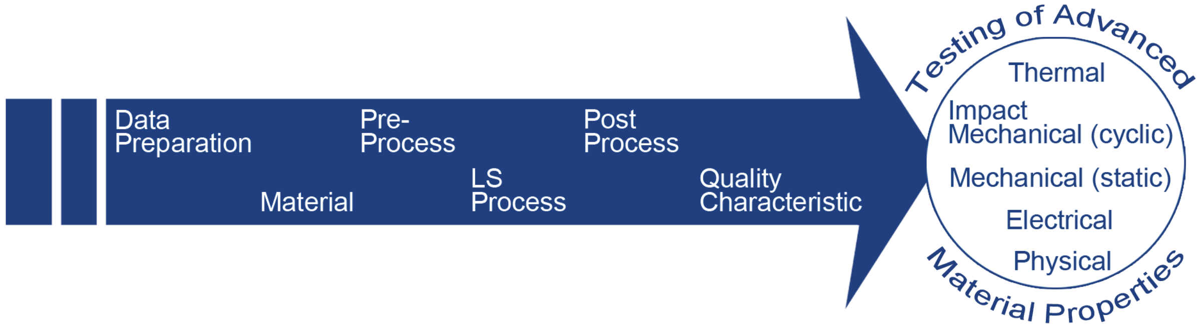


Figure 1: Investigation of material properties along the Laser Sintering Process Quality Chain

Case Study Boeing Design

Design for The Boeing Company optimized for additive and conservative manufacturing technologies

The last topic of this project is the development of a case study. It is about a real design challenge given by The Boeing Company. By means of a requirements list and a given product environment, a real part is developed for laser sintering. First designs are produced within a student seminar. The following step is an optimization for Laser Sintering and Fused Deposition Modeling, two of the main important AM technologies existing at the DMRC. For a benchmark with conventional manufacturing technologies a product with equal characteristics is designed for injection molding. The different designs are compared regarding costs, weight, functionality and other important parameters. All of these steps are processed interdisciplinary together with other DMRC staffs, who are responsible for the diverse topics.

A Finite Element Analysis is performed using the material properties described above. The laser sintered product is designed using the flame retardant material. A load test as well as a test of functionality will be performed as well.

Markus Thöne

Product Optimization for SLM-Process

The Aim of the project "Product Optimization for SLM Process" is to optimize the material performance (laser-parameter, heat treatment etc.) for Nickel-Based superalloy build with SLM. This means this project deals with material qualification, process qualification, product qualification and quality management. A nickel based alloy should be optimized for production lines.

Material qualification: **The material qualification consists of regular checks of particle dispersions and particle micrographics.**

Process qualification: **The process qualification includes the analysis of optimal process parameters and a heat treatment process.**

Product qualification: **Quasi static and fatigue behavior also under high temperature atmosphere**

Quality management: **Within the quality management the powder quality, the mechanical quality and the geometrical quality of test parts (products) will be tested.**

Material Qualification

Regular control of raw material

The Material Qualification should be the first regular process in an additive manufacturing product line. The material quality decides about a stable manufacturing process and the topics are the powder particle size and form and furthermore the chemical composition of the powder and the built parts.

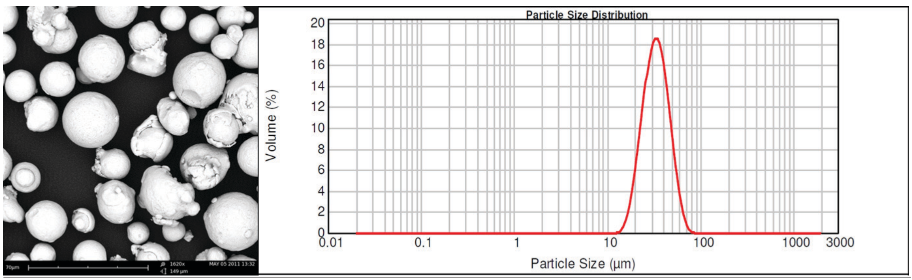


Figure 1: Particle form and size of powder material

Process Qualification

Optimization of process for product manufacturing

Another important point for additive manufacturing of products is the process qualification. Residual stress and pores have a significant influence on the mechanical behavior and also on the form tolerances of selective laser melting parts. By an optimization of exposure parameters and an appropriate subsequent heat treatment an optimized process is achieved.

Product Qualification

Mechanical behavior

To qualify a product it is significant to test the mechanical behavior according to the requirements of the product. This project deals with a high temperature Nickel-Based superalloy. Beside the static tensile tests at room temperature, high cycle fatigue tests at a high temperature atmosphere up to 900°C are essential for the product qualification.

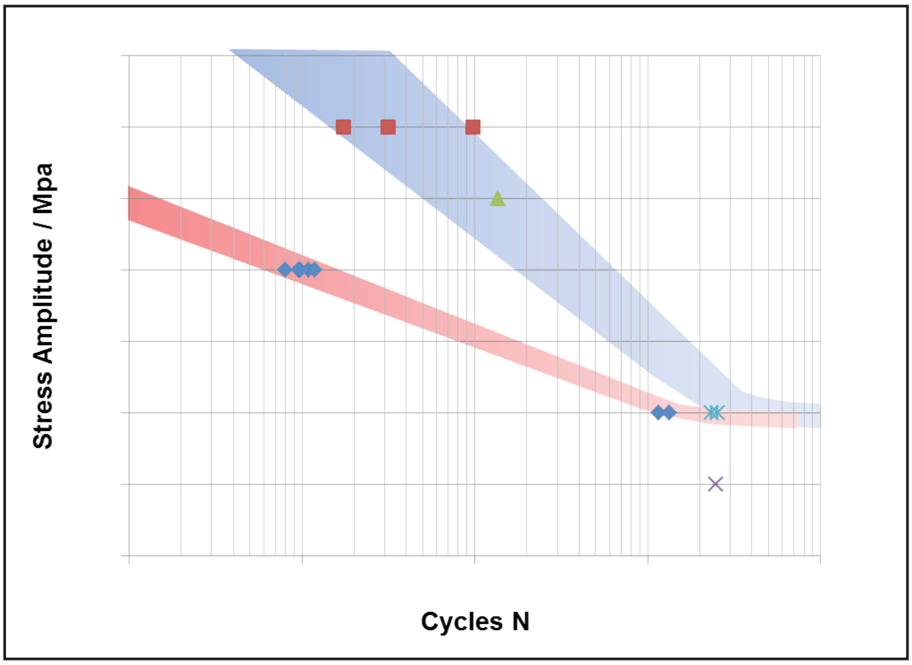


Figure 2: HCF-tests of a Nickel-based superalloy at different temperatures

Quality Management

Regular control of the part quality

The final link in the process chain is the quality management as a method for controlling the repeatability of manufacturing high quality products during the product life cycle. Quality control cards help to record the quality values of a product periodically.

Guido Adam

Direct Manufacturing Design Rules

As additive manufacturing processes create parts layer wise without using formative tools, they have a great potential to provide new design freedoms to their users. To publish these freedoms and to support a suitable design for manufacturing, design rules for additive manufacturing are required. But profound knowledge about such rules is not completely given at time. Thus the Direct Manufacturing Design Rules (DMDR) project has the objective to develop design rules for additive manufacturing. The basis for their development is given by Standard Elements.

Definition of Standard Elements

Parts consist of combined Standard Elements

Design rules shall be application-independent and easily transferable on individual part designs. Thus they will not be developed for parts but for Standard Elements which often reoccur by designing technical parts. These elements were defined initially. Their spectrum contains elementary geometries like cylinders or plates as well as transitions between these elements and structures combined of these elements. In addition to this, each Standard Element owns different attributes. For instance the thickness, length, width, orientation, position and direction are attributes of a plate. By designing technical parts Standard Elements have to be combined. Thereby their attribute values need to be varied so that the part's function is fulfilled.

Development of Design Rules

Assuming that each part is designed of combined Standard Elements, its quality depends on the qualities of the involved elements. Using design measures, these element qualities can be influenced directly by varying the element's attribute values. So design rules need to recommend ranges for suitable attribute value variations.

To figure out those ranges, Standard Elements have been manufactured with the laser sintering, laser melting and fused deposition modeling processes. Quality aspects like dimensional deviations, surface defects or the manufacturability itself were analyzed and compared with the used attribute value. Based on the results, design rules were derived which support a robust design for manufacturing.

Design Rule Catalogue

The design rules will be summarized in a design rule catalogue. Its development is currently in progress. Also, additional information about additive manufacturing principles, terminology and backgrounds of the design rules will be added. An extract of the catalogue is shown in Figure 1.

More than 60 rules are contained at time

Outlook

During the next steps the design rule catalogue will be finished. Based on the catalogue a seminar “Design for additive manufacturing” will be set up. Participants will learn how additive manufacturing influences the part design. Therefore design rules, examples for their use as well as hints for given design freedoms and limitations will provided.

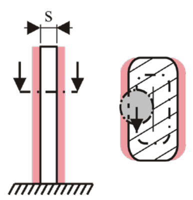
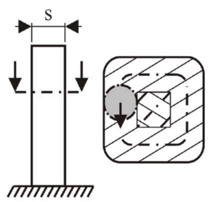
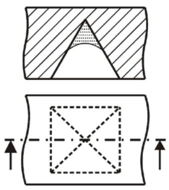
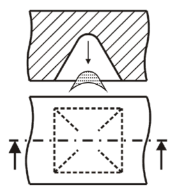
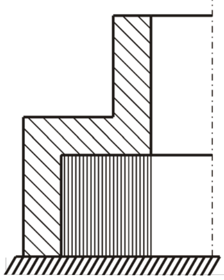
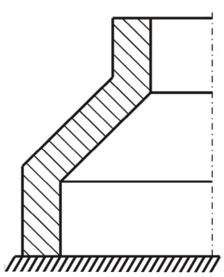
Element			Information	Examples		Techn.		
Group	Type	Attribute	Description	Not suitable for manufacturing	Suitable for manufacturing	LS	LM	FDM
Basic Elements	Plates	Thickness	Plates should be so thick that each layer can be structured of a contour with inscribed raster to minimize dimensional deviations and to avoid defects. LS: S > 1,0 mm LM: S > 0,6 mm FDM: S > 1,5 mm			X	X	X
Element transitions	Firmly bonded	Inner coners	Interior corners should be rounded to remove disperse support material more easily.			X	X	
Aggregated structures	Overhangs	Length	The length of an overhang should be small enough to avoid solid support material. Otherwise overhangs should be designed with element orientations that don`t require solid support material.				X	X

Figure 1: Extract of the design rule catalogue

Agnes Bagsik

Improvement of the FDM Process Quality

The aim of this project "Improvement of the FDM Process Quality" is to improve the layer-to-layer bonding by focusing on the fill geometry. Furthermore, some process parameters will be adjusted to optimize the part geometry of different sized parts.

Introduction

For the manufacturing of end-use parts, with required mechanical technological properties, safe processes and suitable materials are necessary. As a new material for the FDM technology the material PEI with the trade name Ultem*9085 was introduced at the beginning of the year 2009. This material is particularly interesting for the aircraft industry because of its good mechanical, thermal and electrical properties and its comparatively low density. The mechanical properties such as tensile strength for different setup parameters have so far been sufficiently tested regarding their short- and long-term mechanical strength.

The aim of this project is now to improve the layer-to-layer bonding by focusing on the fill geometry. Furthermore, some process parameters will be adjusted to optimize the part geometry of different sized parts.

Increase Z-axis Mechanical Properties of FDM Parts

Analysis of the influencing factors on the Z-axis properties

The anisotropic nature of FDM parts means that part design is often limited by the mechanical properties of the weakest axis. Many factors contribute to the layer-to-layer adhesion of FDM parts, which is the weakest axis

Therefore, understanding of these factors and determining the layer characteristics that will maximize the mechanical properties in this axis are critical to improving the part performance.

The test coupon geometry was analyzed and defined at the beginning of this work package. Coupon geometry was selected to provide robust analysis that should be able to provide confidence in the data found in the experiment.

Then a design of experiments was conducted to determine the driving factors of the mechanical properties in the Z-axis of FDM parts. One of the factors that were analyzed is the fill pattern of the coupon. The impact of seams on the Z-axis mechanical properties is also studied such as the number of seams in one layer and the seam fill density. Furthermore physical factors were analyzed such as the oven soak time as well as the location and number of specimens in the build envelope.

Fill pattern	Standard fill pattern Parallel offset part rasters Linked contours and rasters
Toolpath parameters	Raster angle Delta angle Filament width Air gap between the filaments
Seam impact	Number of seams in one layer Location of seams Seam fill density
Physical factors	Oven soak time Location in the build envelope Number of specimen in the build envelope

Figure 1: Possible influencing factors on the Z-axis mechanical properties

Optimization of the Component Geometry

Analysis of the shrinkage factor setting on the part geometry

Thermoplastic materials have the property to expand with rising temperature, meaning the specific volume increases constantly with rising temperature. Hence, thermoplastic parts shrink after the shaping manufacturing process and cooling.

This shrinkage has to be compensated for during the manufacturing process in order to achieve a high dimensional accuracy of the parts. Furthermore varying FDM part geometries produce different shrinkage conditions within the same part. Thus, the shrinkage factor has to be adjusted according to the component size and width and the used filling pattern of the part layers. Furthermore the number of parts in the build influences the different shrinkage conditions of the parts.

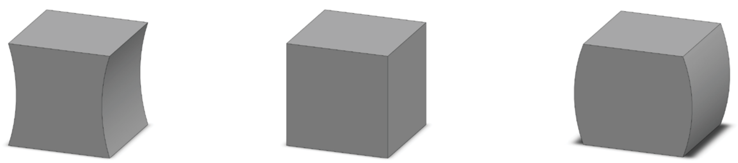


Figure 2: Possible cube geometries

In this workpackage the impact of the setting on the component geometry against the component size and width and the used filling pattern and the number of parts in the build is analyzed in order to achieve a high dimensional accuracy of the parts.

Costing Analysis for Additive Manufacturing during Product Lifecycle

Ulrich Jahnke

Christian Lindemann

The goal of this research-project is to understand and rate the cost drivers that act as the largest contributors to unit costs and to provide a focus for future cost reduction activities for the AM technology over the whole life-cycle. The results will help to identify success factors for cost reduction in the field of Additive Manufacturing. An exemplary metal part will be used to collect data and to raise the understanding of AM cost drivers. This will help to increase the fields of application for additive manufactured parts focusing on Metal Additive Manufacturing (MAM). A better understanding of the cost structure will help to compare the AM costs with costs of the traditional manufacturing technologies and make it easier to justify the use of the AM technology.

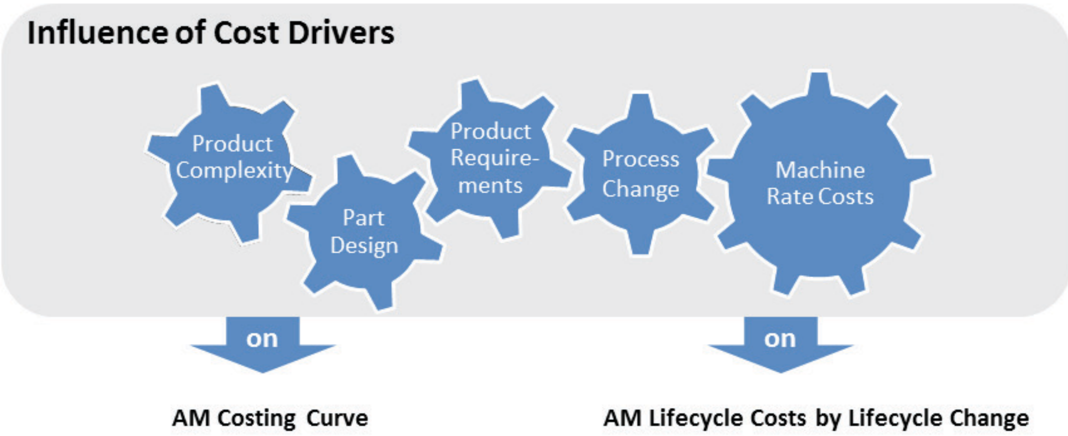


Figure 1: The CoA2mPly Project in a nutshell

Process Modeling

The modeling of costing relevant AM business processes is the basis for the work in the project. The main purpose is to gain knowledge about the costing processes relevant to the AM technology. All important costing processes for AM technologies have been identified and modeled. Interviews with the project partners and with the Direct Manufacturing Research Center (DMRC) were held to identify and to model the costing relevant processes and estimate the needed complexity of these models for the further work.

Development of a Costing Model and Part Redesign

Collection of cost related knowledge in a process model

On the basis of the gained process knowledge, a costing model for Metal Additive Manufacturing has been set up, using activity based costing elements. Therefore a first rating concerning the Selective Laser Melting (SLM) process has been made. The costing model started with a focus on the pure production process and was enhanced during project runtime. The main process steps for MAM have been identified as design, data preparation, production process, post processing, adjustment of mechanical properties.

Design of a costing model for lifecycle analysis

Potential cost reduction opportunities for the future will be identified based on different sample parts. The process gets currently enhanced by further lifecycle processes as usage and others. An exemplary metal component (see Figure 2) is being redesigned to reduce weight through efficient structure design and to compare the costing structure and part performance to traditional manufacturing. Furthermore the influence of the designer on the part costs will be investigated.

Figure 2: Sample part redesign of a wheelcarrier of the formula student series

Lifecycle Study and Generalization

Understanding and rating of cost drivers associated with AM

The product lifecycle costs of AM will be compared with conventional machining technologies. Therefore, a case study will be implemented concerning the costing processes in the intrinsic product lifecycle. Furthermore, different scenarios will show consequences of changing cost structures for AM parts during the complete lifecycle to reveal “hidden saving opportunities”. By understanding the difference between the amounts of costing analysis based on different applications, all DMRC partners may have a better understanding of cost drivers associated with Additive Manufacturing. Costing concerned success factors for the AM technology will be pointed out.

A comprehensive report will list all results in detail. A list of the largest cost drivers affecting machine rate cost and material processing will be identified as cost reduction opportunities. In detail, the final report will include an assessment of how much redesigning the part contributed to the unit cost versus machine rate decreases.

By understanding the costing differences between the different applications, all DMRC partners will have a better understanding of cost drivers associated with AM technology.

Fatigue Strength Properties of SLM Components

Stefan Leuders

André Riemer

The current study aims at shedding light on the relationships between fatigue endurance, crack growth behavior and microstructure of titanium alloy Ti-6-4 and stainless steel 316L as SLM-processed materials. The performed investigations include heat treatments, HIP, mechanical loading in the high-cycle fatigue (HCF) and crack growth regime as well as microstructural characterization by means of electron-optical microscopy and computed tomography.

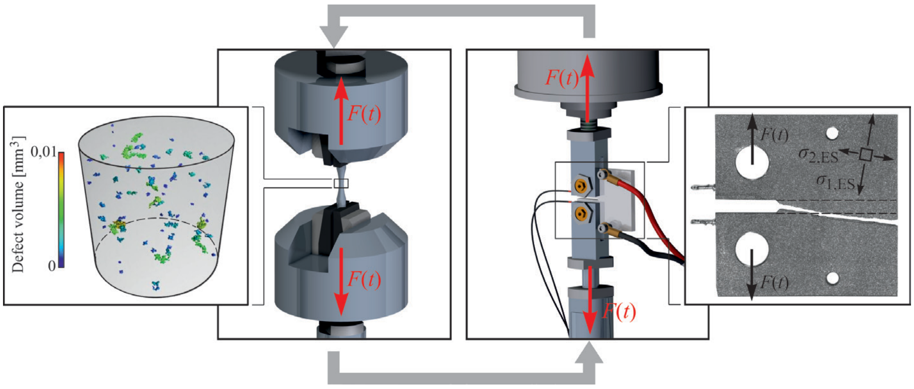


Figure 1: Interaction of fatigue, crack growth and its influencing factors

Titanium Alloy Ti-6-4

Fatigue properties

- ***Fatigue & fracture mechanical tests***
- ***influence of defects***
- ***comparison to parent materials***

Based on resulting conclusions it could be shown that crack growth in Ti-6-4 is mainly determined by internal stresses, which could be significantly reduced in order to achieve crack growth performance similar to conventionally processed Ti-6-4. Moreover, using HIP of SLM-processed parts results could be obtained in the same range of fatigue strength as the compared forged specimens. Consequently, all process related drawbacks could be diminished using proper post processing treatments.

Stainless Steel 316L

The results from tests on the stainless steel showed already in the as-built condition an acceptable material behavior. The fatigue test and fracture mechanical data received from as-built specimens showed similar performance compared to the data for treated condition. The best performance was achieved by using hot isostatic pressing.

Characterization and Comparison of Mechanical Properties of SLM Materials with Regard to Process Cycle Time Improvement

Stefan Leuders

André Riemer

Since a high productivity is a crucial criterion for the use of a specific manufacturing process, it is the aim of this project to find optimal exposure parameters of the SLM process with regard to required cycle time and component quality.

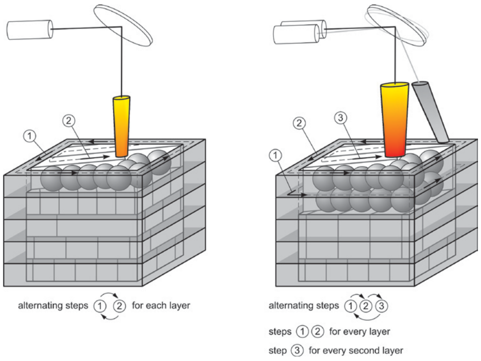


Figure 1: Schematic drawing of different exposure strategies of SLM 250^{HL} (left) and SLM 280^{HL} (right)

High-Speed-SLM

- ***Influence of exposure parameters***
- ***Analysis of process-cycle-time***
- ***Transfer analysis***

In a first step, a sensitivity analysis is performed. This analysis aims in particular at a deeper understanding of the process regarding the impact of exposure parameters on the resulting mechanical properties. Critical process parameters should be detected and their respective process window defined. A systematic approach is enabled by use of a statistical design of experiments. The current focus of the investigations is on the austenitic stainless steel 316L, processed on the SLM 280^{HL}. In the further course of the project the material AlSi7Mg as a cost-effective lightweight material should be investigated. Upcoming essential objectives of the project consist of the following points:

- Comparison between two fundamentally different SLM-systems (SLM 250^{HL} vs. SLM 280^{HL}) with respect to component properties and production rate
- Transfer analysis of obtained results to a real component in order to demonstrate the performance of the SLM process

This research project is being processed by the two departments “Automotive Lightweight Construction” and “Institute of Applied Mechanics”.

Florian Brenne

Optimization of Lattice Structures manufactured by Selective Laser Melting

The SLM technique allows the production of near net shaped metallic parts with a high degree of design flexibility at the same time. This allows for manufacturing complex parts with locally varying properties. In this project these advantages are used for manufacturing lattice structures made of Ti-6Al-4V and a Nickel-based superalloy. As the mechanical performance as well as the occurring failure mechanisms of such lattices are crucial for designing load adapted light weight parts, these topics are addressed in the scope of this project. Another issue is the microstructural condition, as both materials feature a high dependency of mechanical properties on the actual microstructure. Thus, the microstructure is examined following both, SLM and a subsequent heat treatment.

Microstructural Analysis

Microstructural characterization after SLM and heat treatment

The SLM process is characterized by high cooling rates and repeated heat dissipation during the manufacturing process. Consequently, the microstructural features are not the same as after conventional manufacturing processes, such as casting or extrusion molding. In order to understand the mechanical behavior, which is substantially influenced by the microstructure, it is imperative to gain fundamental knowledge of the microstructural processes following SLM.

Within this project the microstructure was examined using both, optical microscopy and electron backscatter diffraction. Thereby, fundamental insights into the grain size, grain morphology, grain orientation, phase composition and texture were obtained. The results were correlated to the resulting mechanical performance.

Diverse heat treatments were conducted on both materials after the manufacturing process in order to modify the material properties. The effect on the microstructure, such as stress relief and grain coarsening, were evaluated and correlated to the structural behavior.

Mechanical Testing

Tests under diverse quasi static and cyclic loading scenarios

Mechanical tests were conducted under diverse loading scenarios. First findings of the lattice performance were obtained by tests under uniaxial quasi static compressive and tensile force. As actual applications in most cases feature dynamic loads, the tests were subsequently extended to the cyclic loading regime. The mechanical behavior under a more complex loading scenario was examined via four-point-bending tests. For this purpose a shell core structure in terms of a common sandwich structure featuring bulk face sheets and a lattice core was developed. These tests gave first insights into the structures' capabilities under actual loading conditions.

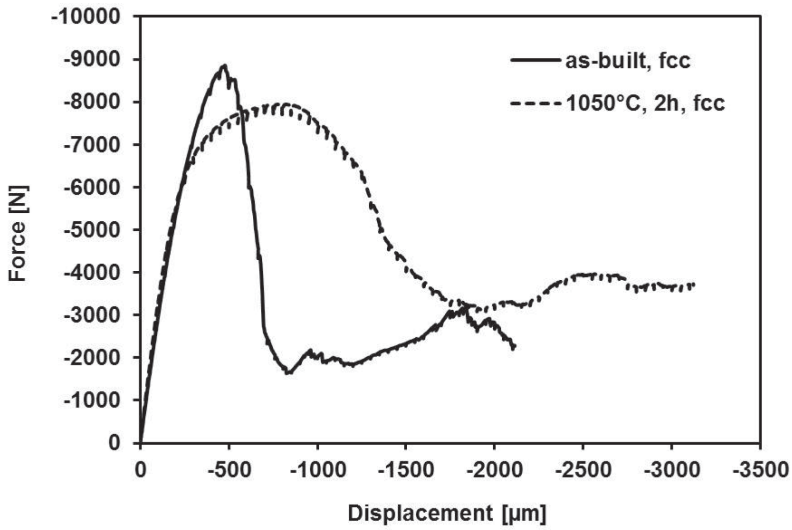


Figure 1: Deformation behavior following SLM and after heat treatment

Local Strains Analysis

Failure analysis by determination of local strain distributions

In order to find causes for structure failure and to develop approaches for optimization of the lattice geometry the deformation behavior was characterized in terms of local strains. Therefore, the tests were interrupted in regular intervals in order to take images of the sample surface, which then were compared using digital image correlation (DIC). Based on the obtained images, the strain distribution throughout the lattice was examined for local concentrations. The results allow an optimization of the geometry with regard to an improved specific loading capacity. The findings are suited for designing lattice structures of superior mechanical properties at low weight.

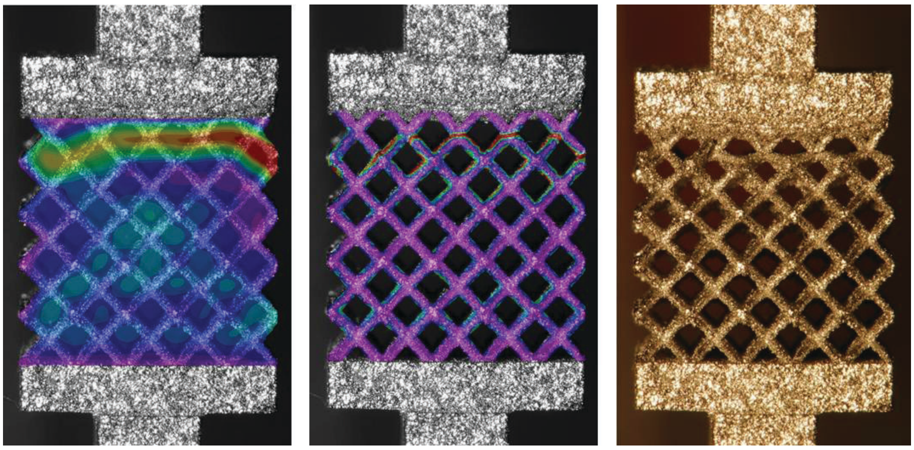


Figure 2: Local strains and sample failurestructure in terms of a common sandwich structure featuring bulk face sheets and a lattice core was developed. These tests gave first insights into the structures' capabilities under actual loading conditions.

Niklas Echterhoff

Marina Wall

Opportunities and Barriers of Direct Manufacturing Technologies within the Aerospace Industry and adapted Others

Since the last two decades, Additive Manufacturing (AM) is gaining importance. Once only used for prototyping, AM-technologies are increasingly applied for manufacturing parts which meet the mechanical requirements and can be directly used. This is Direct Manufacturing (DM). To advance AM-technologies into dependable DM-technologies, it is necessary to align the technology development with future requirements on DM. This is the starting point of the project "Opportunities and Barriers of Direct Manufacturing Technologies", conducted by the Heinz Nixdorf Institute and the Direct Manufacturing Research Center, University of Paderborn, Germany. Based on the analysis and anticipation of respectively the business of today and tomorrow, ideas for future applications of DM were developed and resulting requirements on DM are deduced. Finally, the identified requirements were validated in expert surveys to identify the most important requirements and technological advancements that are necessary for the realization of the identified (future) applications.

The Business of Additive Manufacturing

AM increasingly finds its way into production processes of various industries

Firstly, current application fields of AM are analyzed. The analysis of the "Business of Today" indicates that AM is progressively gaining importance, as it opens up new opportunities in many instances. Various industries are seeking for ways how to capitalize on the benefits AM provides, such as the freedom of design; new industries are becoming aware of these benefits. In particular the aerospace industry, which produces geometrically complex high-tech parts in small lot sizes, can benefit from AM's flexibility. Therefore, already today the aerospace industry is in the vanguard of the industrial application of AM. But AM is also widely spread within the medical sector, including dental applications, prostheses, implants etc. The technologies are also being applied within the capital goods industry, e.g. in the armament, automotive and electronics industry as well as in the tool- and mold-making industry. Even the consumer goods industry, e.g. the sports, textile, furniture, toys and the jewelry industry are becoming aware of AM's great advantages for their business. AM in means of DM is not prevalent yet, experts however underscore its huge potential [Woh11], [BLR09], [GEK+11].

The aerospace, automotive and electronics industry were identified as auspicious for the future AM business

Based on the analysis, the aerospace, automotive and electronics industry were outlined as particularly auspicious for the "Business of Tomorrow" of AM. It is drawn by scenarios developed for these three industries and the global environment. For instance, the most probable scenario combination for the aerospace industry with the highest effect on the aircraft production describes a future, where Europe sets the pace in a globalized world. The aircraft pro duction is characterized by individual customization of aircraft which fosters the application of AM-technologies. Due to the successful part implementation, additively manufactured parts start to be associated with high performance and high quality. To be successful in this future, it will be necessary to build up general ground rules for the design of secondary aircraft structures, systems etc. for AM-technologies and to flow them down to suppliers [GEK+11].

Future of aircraft production: Individual customization requires general ground rules for secondary aircraft structures

Future Applications of Direct Manufacturing

The mentioned scenarios were used as an impulse to develop ideas for future applications of DM. All in all, 120 ideas were developed and clustered to 27 innovation fields which were assessed regarding their chances and risks for the application of DM. For the aerospace industry, Morphing Structures and Multifunctional Structures have been identified as the most auspicious innovation fields:

120 application ideas in 27 innovation fields were developed

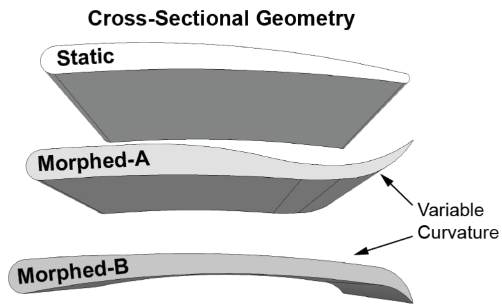
- Morphing Structures describe applications which are designed as one part that is adaptable in its shape in response to the operational environment. Instead of changing the position of a static part by using actuators, the part itself can take continuous configurations of shape to enable specific functions/properties. Figure 1-1 shows an exemplary application idea from this innovation field.
- Multifunctional Structures comprise ideas for functionally upgraded parts. Upgraded functionality can be realized by integrating acoustic and thermal insulation into aircraft parts or by embedding entire sensor/actuator systems, including electronic wiring and connectors into a part.

Morphing Wings

Description

The ability of AM to produce highly flexible and functionally integrated parts fosters the idea to create "smart" parts that quickly adapt/react in response to the operational environment – the so called Morphing Structures. For instance, by varying the cross-sectional shape, a morphing wing, providing the laminar flow of the air over the aerodynamics and control surfaces, could adapt to respective flight phases and high-speed phenomena [Wei06-ol]. Thereby, the buoyancy can be varied and viscous drag can immensely be reduced [Nat11-ol], [HKF10]. This effect can be realized more efficiently and with less turbulence by the modulation of the wing geometry. Moreover, these wings enable better aerodynamics compared to conventional wings, as affections by wind gusts can be compensated quickly by adjusting the airfoil and its stiffness [Wor11a].

Draft



Advantages/Benefits

- Fewer moving parts
- Less wiring needed
- Weight reduction
- Better aerodynamics
- Economic flying during the flight is possible (reduced fuel consumption can be exploited otherwise)

Disadvantages/Risks

- Durability of materials
- High material and repair costs
- Emergency flight properties during a system crash

Current Technical Solution

Movable control surfaces (horizontal tail and flaps) are used to change air flow/wing configuration.

Type of Ideas

☐ product update ☐ adaption ☒ innovation

Figure 1: Exemplary application idea from the innovation field Morphing Structures: Morphing Wing

The innovation fields were used to deduce requirements on DM-technologies.

To enable AM-technologies for DM in the identified future applications, it is necessary to align the technology development with current and future requirements. Therefore, the developed innovation fields are analyzed in detail to deduce requirements on DM. High process stability, certification, design rules and online-control processes are basic requirements across the most innovation fields, just to name a few [GEK+12].

Future Requirements on Direct Manufacturing

High process stability, certification, design rules and on-line quality control processes are decisive for the penetration of AM in the future

The identified requirements were validated in an expert survey in order to identify the most important requirements as well as the performance of AM-technologies concerning these requirements. As exemplarily indicated in figure 1, the overall assessment shows that today the significance of the requirements (y-Axis) largely correlates with the technology's degree of performance (x-Axis) across all considered technologies. For powder bed fusion metal technologies the following requirements are assessed to be highly significant (y-Axis) for the penetration of AM in future: high process stability, a database containing properties of AM-materials, on-line quality control processes, continuous certification, and provision of design rules.

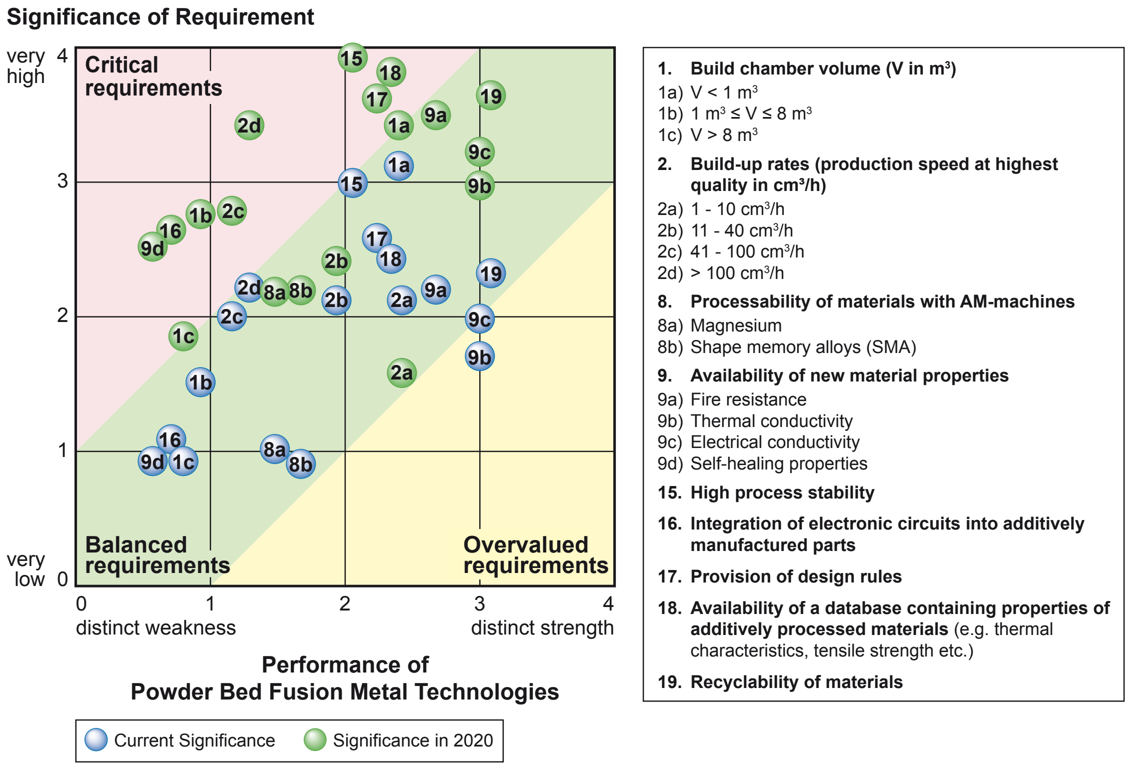


Figure 2: Extract from significance-performance portfolio for Powder Bed Fusion Metal Technologies

Fundamental, technological advancements are required to meet future requirements

As the vast majority of the requirements will gain in significance in the future, they are likely to turn into critical requirements if no technological advances will be achieved. Some requirements, such as build-up rates > 100 cm³/h, are already considered as almost critical today. Therefore for instance, research that contributes to the production speed could promote AM-technologies in future. [GEK+12].

Innovation Roadmapping of Required Advancements

Based on these results, a second expert survey was conducted. The main purpose of the survey was to get a sound overview of the point in time when – from AM-experts' point of view – the selected requirements will be fulfilled by selected AM-technologies. This allows the creation of innovation roadmaps, indicating when the identified requirements will be fulfilled. Figure 1-3 shows an excerpt of the innovation roadmap for powder bed fusion metal technologies. At first glance, the overall assessment shows that advancements on fulfilling the technology-specific requirements are expected to require higher effort than the fulfillment of the material-specific and general requirements. For instance, a database containing material properties and design rules are assessed to be available until 2016. In contrast, AM-machines with a larger build chamber volume and higher build-up rates are expected to become available at earliest in 2025.

Technology advancements are expected to require higher effort than general or material advancements

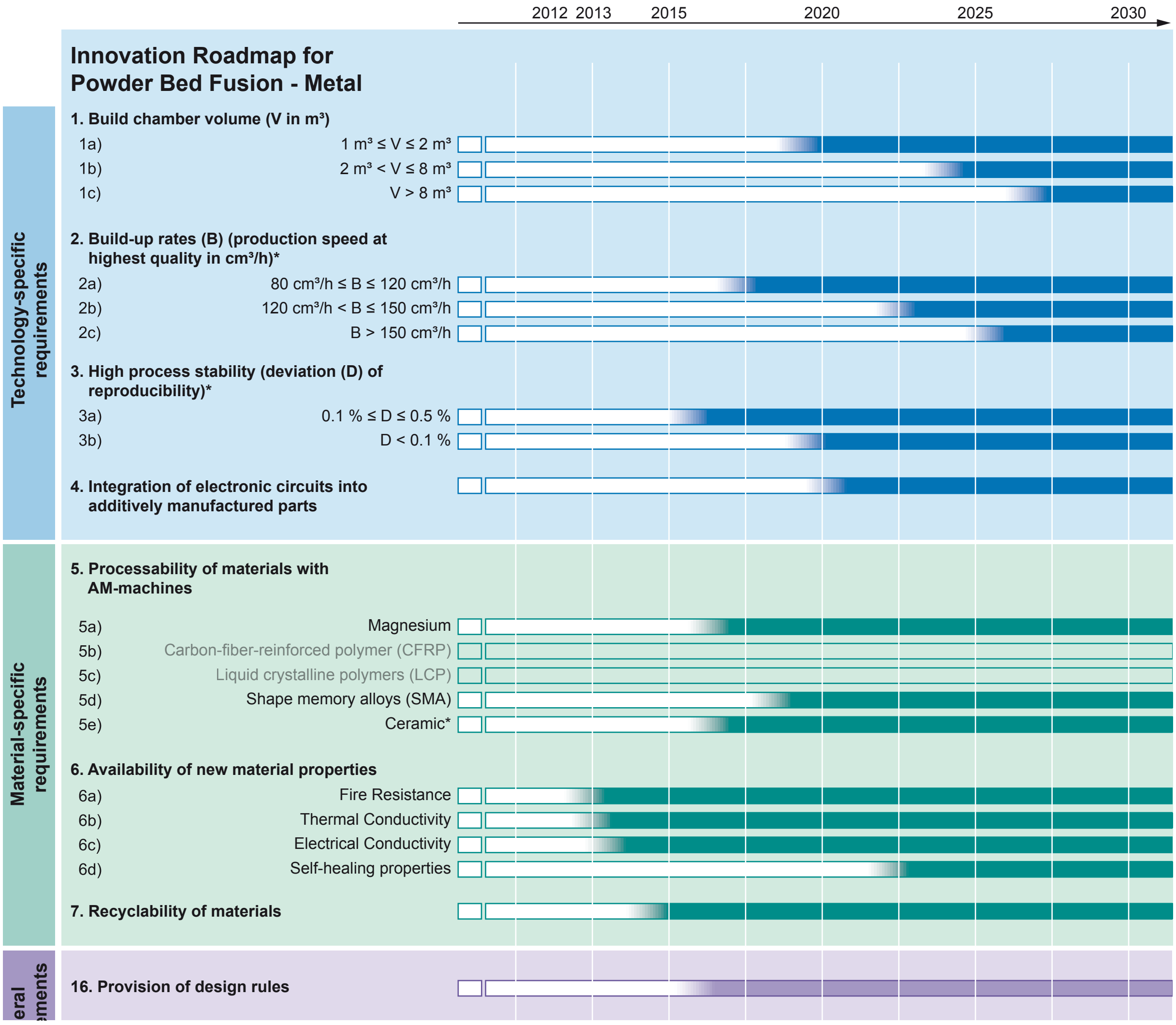


Figure 3: Extract from innovation roadmap for Powder Bed Fusion Metal Technologies

Research Strategies for Additive Manufacturing

Marina Wall

Stefan Peter

Additive Manufacturing (AM) technologies are already in the clear technological vanguard when it comes to "Freedom of Design". Seen in this light, AM has the potential to become an example for a disruptive technology that may revolutionize manufacturing and product development processes. However, there are still a large number of open research fields to be investigated. Even more, the transfer of research results into tangible outcomes for the industry is still insufficient.

The Direct Manufacturing Research Center (DMRC) is striving to bridge this gap. As a proactive collaboration of key technology suppliers and forward-thinking users, the DMRC continuously works on advancing AM-technologies to Direct Manufacturing – the application of AM in series production. To achieve this, the DMRC must concentrate its competences to consequently pursue research projects with maximum benefits for potential users of AM. This requires consistent and demand-oriented research strategies. This is the starting point of the project "Strategy" that is conducted by the Heinz Nixdorf Institute in cooperation with the DMRC. Goal of the project is a strategy that will enable the DMRC to become a leading institution in AM.

Analysis of the Research Landscape

Initially, the AM research landscape was analyzed to answer the following questions.

- How is the research landscape segmented?
- Who are the key players within each research field?
- What degree of research intensity exists within the research fields?
- Which research fields will be highly relevant in the future?
- What are the success factors for future-oriented research strategies?

AM research map shows the research intensity in the research fields: highest intensity in material research

As part of a survey, the research intensity of selected AM-institutes within defined research fields was determined. Therefore, current research projects, partners, customers, resources etc. were identified and linked to the characterized institutes. Based on these findings, an Additive Manufacturing Research Map was developed, as illustrated in figure 1. Most institutes address a large number of research fields for one special technology. A few institutes focus on cross-technology research fields, e.g. the development of design rules and standards. Material research is the field with the highest research intensity.

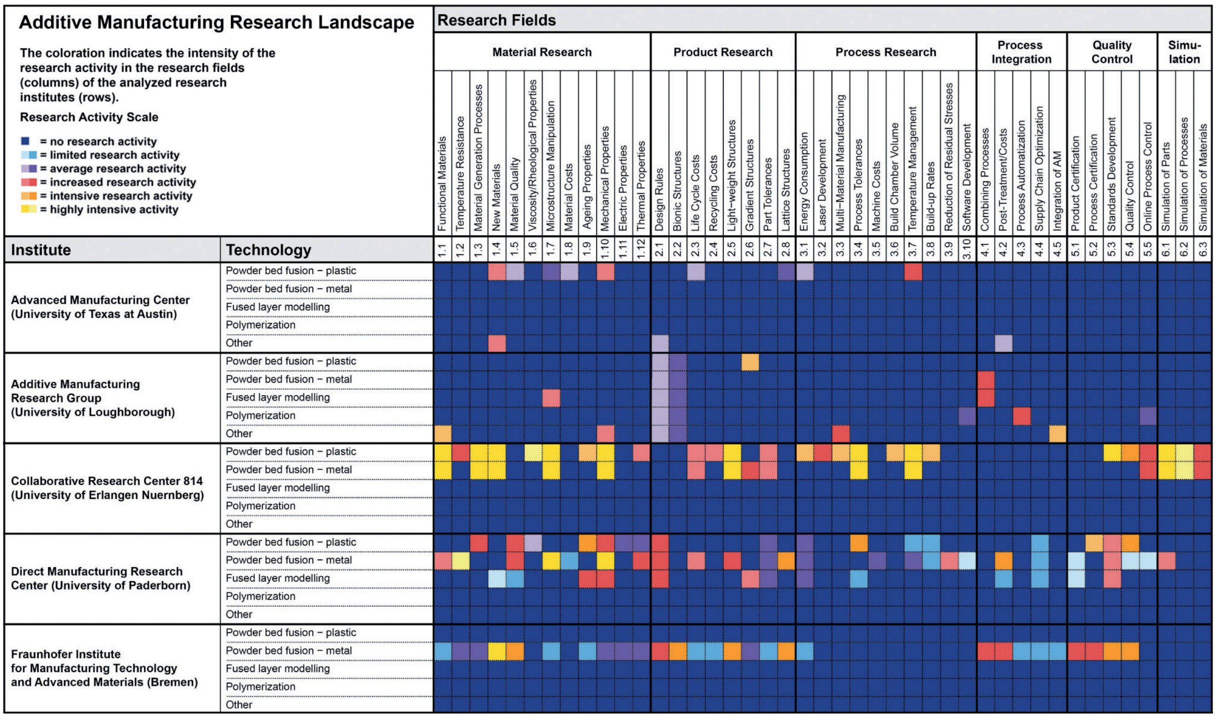


Figure 1: Excerpt from the Research map: The colored fields indicate the research intensity in different research fields (column) for selected research institute/technologies (rows).

Development of Consistent Strategy Options

Assessment of research fields regarding future relevance

By contrasting the research intensity with the future relevance of the research fields, highly relevant research fields that however are not addressed in current research projects – so called “white spots” – were identified. That counts for supply chain optimization and process automation, to name but two examples. On the basis of these findings, the success factors for research strategies such as the integration of companies along the value chain and the interconnection within the research landscape were deduced. These success factors were used as a starting point for the development of consistent strategy options using the method VITOSTRA®. VITOSTRA® is a systematic approach for the development of consistent, success promising strategy options. For instance, the DMRC can position itself as an institute providing problem-solving services or as a basic scientist providing academic education in AM.

Based on white spots and success factors consistent strategy options were developed

Strategy Development for the DMRC

A coherent strategy will enable the DMRC to become a leading AM-institute

The developed strategy options, the position of the DMRC and its competitors were analyzed in detail. These results will be considered for the development of a vision and a coherent strategy for the DMRC. The vision answers the question what the DMRC wants to be in five years. A strategy represents a guideline for daily operations describing how to achieve the visionary picture of the future from today’s point of view. The strategy will enable the DMRC and its partners to be one step ahead of its respective competitors.

QM- System for Additive Manufacturing Processes in DMRC

Michael Brand

P.V. Varghese

Based on the available knowledge and results from the Year 2011 new approaches were initiated to optimize the processes available at the DMRC which should lead to better quality control methods. The aim was to avoid or minimize possible sources of failure which would lead to the crashing of jobs or part failure due to process problems.

In the project ``QM System for the additive processes installed at the DMRC`` during the year 2012 following points were examined and developed:

- **Failure Mode Effect Analysis (FMEA) and Ishikawa Diagram**
- **Drafting an error documentation protocol and an operator checklist for the SLM and LS processes.**
- **Drawing up a concept for a DMRC QM manual on the basis of DIN 9001**

Failure Mode Effect Analysis (FMEA) and Ishikawa Diagram

FMEA ensures good quality

The basis for a good quality assurance depends on the elaboration of the failure mode effect analysis and the resulting Ishikawa Diagram (Figure 1). This will point out the importance of the various influencing parameters like manpower, material, machine, maintenance etc. The operator checklist and error documentation was drafted after analyzing the Ishikawa Diagram. For each process an Ishikawa diagram has been drafted.

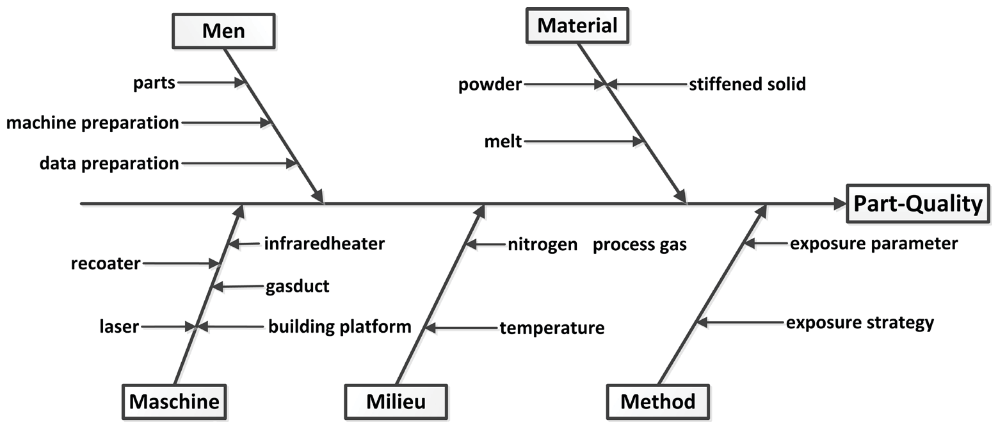


Figure 1: Example of an Ishikawa-diagram for laser sintering

Error Documentation and Operator Checklist

Important machine parameters, type of failure if any, corresponding failure correction actions will be recorded in the error documentation list with a link to the order number. This will be the documentation for the DMRC as well as the customer for future reference and product traceability in case of an unexpected product failure.

Similarly the checklist also serves as a control mechanism so that inadvertent failures can be avoided before the parts are produced.

So both the error documentation and checklist are two important modules for product quality. For each process a documentation and operator checklist will be available.

DMRC QM Manual

Building up a QM Manual

The drafting of a QM manual has started taking form, the aim of the QM manual is to establish a QM management system which will describe the organizational and technical measures necessary to maintain the quality standards expected of the DMRC as per DIN EN ISO 9001.

The DMRC QM Manual will be structured as follows:

1. General declaration regarding the DMRC QM handbook
2. Setup, structure and management of the DMRC
3. Procedure processes at the research facility
4. Quality management system
5. Responsibilities
6. Management of resources
7. Product/service/research implementation
8. Measurement analysis and improvements

Quantitative Assessment of Surface Quality obtained by Post Processing of Laser Sintered Parts

Hans-JoachimSchmid

To quantitatively assess the surface quality (i.e. surface "roughness" on a number of scales) of laser sintered parts a reliable characterization method has to be found. With this method the surface quality of laser sintered parts depending on different machine parameters has to be analyzed in order to describe the correlation between machine settings and surface quality. Further testing will cover post processing methods to improve the surface finish with reasonable effort in terms of costs and labor. Furthermore, the effects of surface quality (due to sintering parameters as well as post processing methods) on mechanical properties as well as aging by comparison of post processed and untreated parts in long-time testing will be examined. The overall aim is a surface quality analysis of laser sintered parts.

Surface Quality Characterization Method

Investigation of a Surface Quality Characterization Method applied for Laser Sintered parts

This part of the project includes the investigation of diverse existing methods to characterize the surface quality and their applicability to assess laser sintered parts. For characterization of laser sintered parts it is important to keep in mind imperfections at different levels of scale: shape deviations (i.e. mismatch of characteristic admeasurements with design), surface deviations (e.g. waviness, terrace formation) and surface roughness (ranging from sub-millimeter to micrometer scale).

Different methods are investigated in order to test their ability to assess surface imperfections at these different scales. Tactile and non-tactile measurement systems are investigated as well. As optical instruments white light-interferometry and confocal laser scanning microscopy are investigated and evaluated. Main emphasis is on suitable mathematical methods to extract valid information about surface defects on different scales from obtained data. Another challenge is to get comparable information from completely different measurement techniques. Further on a subjective assessment of the surface quality by haptic testing is aimed at. For this purpose suitable test specimens are used and assessed through blind-testing by different test persons. Finally, we aim to get a correlation of subjective and objective assessment of different surfaces.

The resulting surface quality for different machine parameters (e.g. layer thickness, laser and scanning parameters) and powder quality (virgin powder vs. used powder) is tested with the methods developed previously.

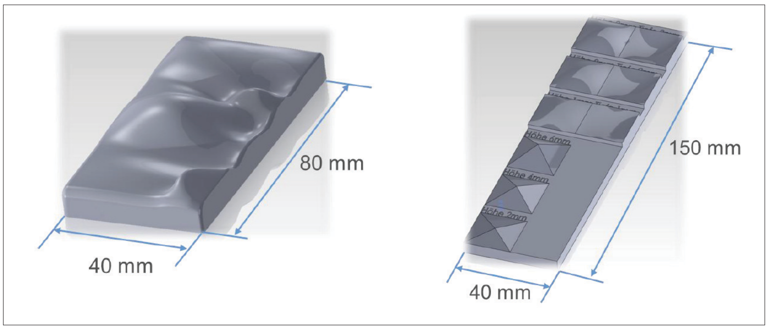


Figure 1: Test specimen geometry for optical measurement systems

Surface Finish according to Process Parameter

Investigation of diverse surface finish methods according chosen process parameter

The post process is an important factor using the laser sintering process. After the process time the building job has to cool down for 10 hours within the laser sintering machine in a nitrogen environment. After this duration a cooling down phase outside the LS machine is necessary. After the unpacking process the powder has to be removed from the parts, which is performed by using a blasting cabin. In this part of the project the post process regarding the different post process parameter shall be investigated. The blasting time, the blasting distance as well as the blasting pressure are the most important parameters. Further on the blasting material shall be investigated as well. Next to the adjustment of diverse blasting parameters, the building parameters shall be investigated as well. Energy density and orientation of test specimens have an influence on the surface quality as well. These parameters are tested using the characterization method determined in the chapter „Surface Quality Characterization Method“.

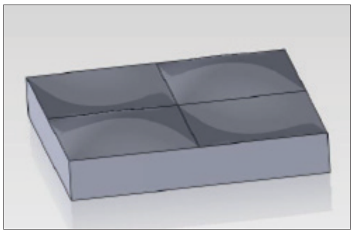


Figure 2: Test specimen geometry for haptic tests

Coating of Laser Sintered Parts

Investigation of diverse coating processes optimized for Laser Sintering

The last step of this project should be the investigation of diverse coating processes. Because of a lower surface quality, compared to injection molding, laser sintered parts are not used in visible areas of the manufacturing fields. A coating might be the solution for this challenge. Within this part of the project promising coating processes shall be listed and the most promising ones shall be investigated. Diverse parameters to test the coating quality might be temperature, humidity or ageing. Types of post processing can be lacquering (e.g. dip-coating). The main focus is on a harder and smoother surface with a minimal effort of manual labor. Therefore, reasonable target quantities have to be determined, such as lacquering properties and lacquering costs. Those should be specified as a function of defined properties, as a sensible parameter of surface roughness or a judgment of surface quality, as well as mechanical properties, etc..

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Quantification of Surface Quality obtained by Post Processing of Laser Sintered Parts

Material Characterization and Properties regarding a Boeing Design, optimized for Laser Sintering

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Opportunities and Barriers of Direct Manufacturing Technologies for the Aerospace Industry and adapted others

Development of Future Promising Research Strategies for Additive Manufacturing

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Fatigue Strength Properties of SLM-Components

Characterization and Comparison of Mechanical Properties of SLM Materials with regard to Process Cycle Time Improvement

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Quantification of Surface Quality obtained by Post Processing of Laser Sintered Parts

Material Characterization and Properties regarding a Boeing Design, optimized for Laser Sintering

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Product Optimization for SLM-Process

Characterization and Comparison of Mechanical Proper ties of SLM Materials with regard to Process

Cycle Time Improvement

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5 Publications

2012

- **On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance**

  S. Leuders, M. Thöne, A. Riemer, T. Niendorf, T. Troster, H.A. Richard, H.J. Maier

  International Journal of Fatigue

- **Im freien Fall - Bionik-Projekt „Fly Sense“**

  M. Bähr, H. Frey, E. Klemp, L. Schmidt

  rapidX - Produktentwicklung und Additive Fertigung, Ausgabe 03/12

- **Tensile and Flexural Properties of Fused Deposition Modeling Parts manufactured with Ultem9085**

  A. Bagsik, V. Schöppner, E. Klemp

  1st International Conference on Thermo-Mechanically Graded Materials

  Kassel/ Germany, 29th -30th October 2012

- **Extensive Analysis of the Mechanical Strength Properties of Fused Deposition Modeling Parts manufactured with Ultem9085**

  A. Bagsik, V. Schöppner, E. Klemp

  5th International PMI Conference

  Ghent/ Belgien, 12th-14th September 2012

- **Controlling the Quality of Laser Sintered Parts Along the Process Chain**

  S. Rüsenberg, R. Weiffen, F. Knoop, M. Gessler, H. Pfisterer, H.-J. Schmid

  23th Annual International Solid Freeform Fabrication Symposium

  Austin/ Texas/ USA, 6th -8th August 2012

- **Long-term ageing effects on FDM Parts manufactured with Ultem9085**

  A. Bagsik, V. Schöppner, E. Klemp

  23th Annual International Solid Freeform Fabrication Symposium

  Austin/ Texas/ USA, 6th-8th August 2012

- **Werkstoffe und Fügeverfahren – Neue Herausforderungen für die Betriebsfestigkeit**

  A. Riemer, S. Leuders, T. Tröster, H.A. Richard

  39. Tagung DVM-AK Betriebsfestigkeit

- **Influence of heat-treatment on Selective Laser Melting products – e.g. Ti6Al4V**

  M. Thöne, S. Leuders, A. Riemer, T. Tröster, H.A. Richard

  23th Annual International Solid Freeform Fabrication Symposium

  Austin/ Texas/ USA, 6th -8th August 2012

- **Mechanical Properties as a Result of Multitude of Parameters**

  S. Rüsenberg, H.-J. Schmid

  AEPR’12, 17th European Forum on Rapid Prototyping and Manufacturing

  Paris/ France, 12th -14th June 2012

- **Die Produktion von morgen – Additive Fertigungsverfahren im industriellen Einsatz**

  E. Klemp, M. Wall

  Digital Engineering Magazin 4/12

- **Thinking ahead the Future of Additive Manufacturing – Future Applications Study**

  J. Gausemeier, N. Echterhoff, M. Kokoschka, M. Wall

  Study Part 2

- **Thinking ahead the Future of Additive Manufacturing - Scenario-based Matching of Technology Push and Market Pull**

  J. Gausemeier, N. Echterhoff, M. Kokoschka, M. Wall

  Fraunhofer Direct Digital Manufacturing Conference 2012

- **Automobilleichtbau mit innovativen Werkstoffen und Prozessen**

  T. Tröster, T. Marten, D. Thomas, H. Block, C. Lauter, M. Thöne

  Forschungs-Forum Paderborn

2011

- **Direct Manufacturing – Innovative Fertigungsverfahren für die Produkte von morgen**

  J. Gausemeier, N. Echterhoff, M. Kokoschka

  Gausemeier, J. (Hrsg.) Vorausschau und Technologieplanung, Nr. 300, 24th- 25th November 2011, Heinz Nixdorf Institut, HNI Verlagsschriftenreihe, Paderborn

- **In situ characterization of the deformation and failure behavior of non-stochastic porous structures processed by selective laser melting**

  B. Gorny, T. Niendorf, J. Lackmann, M. Thoene, T. Troester, H.J. Maier

  Materials Science and Engineering, Volume 528, No. 27, 2011

- **Schicht für Schicht**

  A. Bagsik, V. Schöppner, E. Klemp

  Kunststoffe Heft 10/2011

- **Porosity as a Key to Increase Material Properties of Laser Sintered Parts**

  S. Rüsenberg, L. Schmid, H. Hosse, H.-J. Schmid

  5th International Conference on Advanced Research in Virtual and Rapid Prototyping

  Leiria/ Portugal, 28th September -1st October 2011

- **Direct Manufacturing Design Rules Advanced Research in Virtual and Rapid**

  D. Zimmer, G. Adam

  5th International Conference on Advanced Research in Virtual and Rapid Prototyping

  Leiria/ Portugal, 28th September-1st October 2011

- **Powder Aging upon Laser Sintering-Characterization and Consequences**

  H.-J. Schmid, S.Rüsenberg, Z. Sun

  22th Annual International Solid Freeform Fabrication Symposium

  Austin/ Texas/ USA, 8th -10th August 2011

- **Mechanical and Physical Properties-A Way to assess quality of Laser Sintered Parts**

  S. Rüsenberg, L. Schmidt, H.-J. Schmid

  22th Annual International Solid Freeform Fabrication Symposium -An Additive Manufacturing Conference

  Austin/ Texas/ USA, 8th -10th August 2011

- **Mechanical and Physical Properties – A Way to assess quality of Laser Sintered Parts**

  S. Rüsenberg, L. Schmidt, H.-J. Schmid

  22th Annual International Solid Freeform Fabrication Symposium

  Austin/ Texas/ USA, 8th -10th August 2011

- **Thinking ahead the Future of Additive Manufacturing – Analysis of Promising Industries Report**

  J. Gausemeier, N. Echterhoff, M. Kokoschka, M. Wall

- **Mechanical Properties of Fused Deposition Modeling Parts Manufactured with Ultem*9085**

  A. Bagsik, V. Schöppner

  ANTEC 2011, Boston/ Massachusetts/ USA, 1st -5th May

2010

- **Klein, stark und wendig**

  E. Klemp, A. Trächter, C. Loh

  Konstruktion & Engineering, p. 10-11

- **Konstruktionsregeln für additive Fertigung in Forschung und Lehre**

  D. Zimmer, G. Adam

  Berliner Kreis News, Ausgabe 2/2010

- **FDM Part Quality Manufactured with Ultem*9085**

  A. Bagsik, V. Schöppner, E. Klemp

  14th International Scientific Conference on Polymeric Materials

  Halle/ Germany, 15th -17th 2010

6 Equipment

Additive Manufacturing Systems

- **EOS P395, EOS GmbH Electro Optical Systems**

  Materials: Polyamid 12

  Building dimensions: 340 x 340 x 620 mm

  Layer thickness: 60 - 180 µm

  Laser type: CO2 laser

  Scanning speed: 6000 mm/s (max.)

- **SLM 250HL, SML Solution GmbH**

  Materials: stainless steel 1.4404, TIAl6V4, Inconel 625

  Building dimensions: 250 x 250 x 250 mm

  Layer thickness: 20 - 100 µm

  Laser type: ytterbium laser

  Scanning speed: 20000 mm/s (max.)

- **FDM Fortus 400mc, Stratasys**

  Materials, ABS, PC, PC-ABS, PPSF, Ultem

  Building dimensions: 355 x 254 x 254 mm

  Layer thickness: 127 - 330 µm (material dependent)

  Accuracy: ±127 µm

Mechanical Analysis Methods

- **Universal testing system Instron 5569**

  Load cell: 5 kN, 50 kN

  Tensile, compression and flexural testing

  Heating/cooling chamber: -100°C…+350°C

- **Universal testing system Zwick HB 250**

  Load cell: 5 kN - 250 kN

  Static and dynamic tests

  Clip gauge: 20 mm, 50 mm

  Cylinder stroke: 400 mm

Thermal Analysis Methods

- **Climate chamber WK3-180/70, Weiss Umwelttechnik**

  Temperature control: -72°C…+180°C

  Humidity control

  Test room dimensions: 750 x 580 x 450 mm

- **Heating chambers UT 6, Heraeus Funktion Line**

  Labored air change

  Temperature control: +20°C…+250°C

  Test room dimensions: 400 x 380 x 450 mm

- **Outdoor weathering frame, Q-Lab**

  Dimensions: 3660 x 1680 x 100 mm

- **Annealing furnace N30/85HA(-K), Nabertherm**

  Test room dimensions: 290 x 420 x 260 mm

  Max. Temperature: 850°C

- **Annealing furnace N41/H, Nabertherm**

  Test room dimensions: 350x500x250 mm

  Max. Temperature: 1280°C

- **Instrument for thermal photography P 640, FLIR**

  Temperature range: -40°C…+2000°C

Optical Analysis Methods

- **Particle Size Analysis, Master Sizer 2000, Malvern**

  Measuring range: 0.02 to 2000 µm

  Accuracy and Reproducibility: ±1 % of the volume median diameter (Dv50)

  Measurement principle: Mie scattering

  Sample types: emulsions, suspensions and dry powders

- **Scanning Electron Microscope (SEM), Phenom SEM, Phenom World**

  Magnification range : 24 - 24,000x

  Images: 2048 x 2048 px (max.)

  Resolution: 30 nm (max.)

- **Optical 3D-multi-sensor-system kolibri MULTI, Frauenhofer**

  Measurement uncertainty: 0,5 to 150 µm

  Measuring volume (max.): 180 x 50 mm (diameter x height)

  Resolution: 80 or 200 µm point spacing

Physical Analysis Methods

- **Surface roughness measurement, Hommel Etamic T8000, Jenoptic**

  Measuring principle: tactile scanning

  waveline™ 20 traverse unit

  – Traverse length: 20 mm

  – Guide accuracy: 0.2 µm/20 mm

  – Internal alignment range: ± 2º

  Roughness standard RNDH2

  Pick-up set TKU 300

  – Measuring range: ±300 µm

  Roughness parameters, Core roughness parameters, Profile parameters, Waviness parameters, Motif parameters

- **Moisture measuring device, AQUATRAC E3, Brabernder**

  Measuring principle: chemical reaction with hydrolith

  Weighted sample: 0,1 - 100 g

  Measuring temperatures: +60°C…+200°C

  Measuring accuracy: ±2 % of measured value, ±1 % of measuring range

  Measuring ranges: < 0,1 %, 0,1 - 0,5 %, >0,5 %

- **Precision balance, CPA 224s, Satorius**

  Gravimetric analysis with method for density determination

  Scale-reading precision: 0,1 mg

  Max. measuring range: 220 g

Surface Treatment

- **Centrifugal force device, ECO 18, Otec**

  Dimensions: 640 x 740 x 820 mm

  Different s abrasive and polish products

- **Sputter Coater Quorum SC 7620**

  Coating thickness: 5 to 15 nm

  Dimensions: Ø 100 mm, height 100 mm

- **Cleanstation UW90, German Sonic**

  Temperature: 15°C…85°C

  Capacity: 90L

  Dimensions: 500 x 500 x 450 mm

- **Blasting, Junior®, Normfinish**

  Glass bead: Ø 100 - Ø 200 µm

  Dimensions: 1100 x 750 x 750 mm

- **Blasting, 2x SMG 25 KP, MHG**

  Glass bead: Ø 100 - Ø200 µm

  Corundum: Ø210 -Ø 297 µm

  Dimensions: 700 x 950 x 1700 mm

Other

- **Anton Paar Rheometer MCR 501,**

  Torque range: 0,1 µNm - 230 mNm

  Torque precision: 0,5 %; max. 0,2 µNm

  Revolutions per minute: 10-7 - 3000

  Frequency range: 10-5 - 100 Hz

  Normal force range: -50 - +50 N

  Normal force precision: 2,5 %; max. 0,03 N

  Temperature range: -150 - 1000°C

7 References

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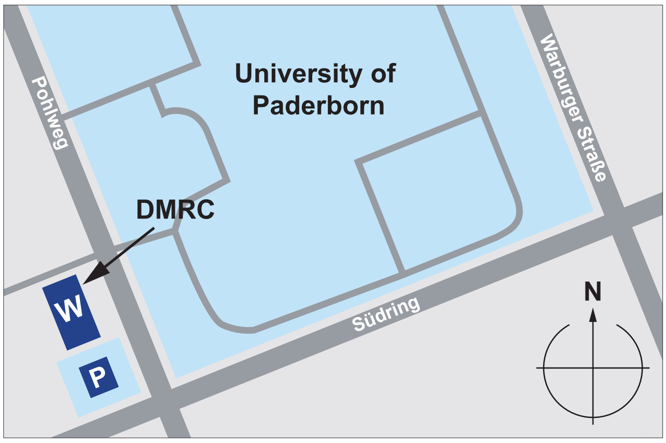

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