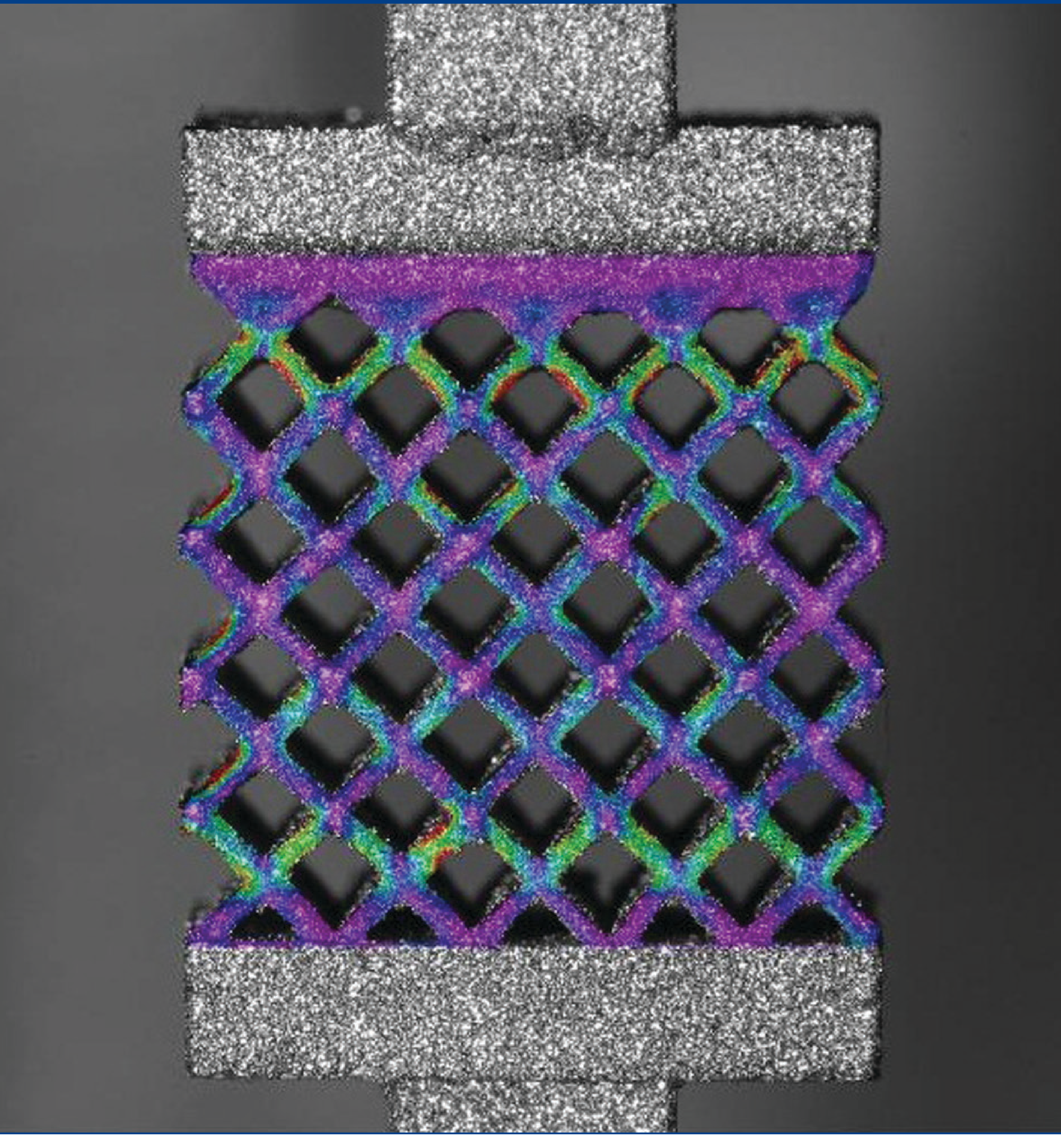
Direct Manufacturing Research Center

Annual Report 2013



DMRC
DIRECT MANUFACTURING RESEARCH CENTER

Imprint

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We gratefully thank our Partners:

The Lego Group

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1 Preface

Prof. Dr.-Ing. Hans-Joachim Schmid

Dear Reader!

We are very glad to present you this Annual Report of the Direct Manufacturing Research Center at the University of Paderborn. With this report we want to provide you with a comprehensive overview of the DMRC, the current projects and the scientific output in 2012/2013.

The DMRC is a joint effort of academia and industry with the main goal to advance the existing additive manufacturing technologies into dependable and production rugged standard manufacturing technologies. Although there is currently a huge hype about ‚3D printing' there is still a considerable distance to go until we will reach this goal. However, 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 stakeholders. 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 20 scientific staff members working on approximately 15 projects, with a considerable number of new projects and new staff starting soon. 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. This all has leaded to an ever growing visibility of the DMRC in the additive manufacturing community.

All the positive feedback and visible success stimulates the whole team to put even more 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

Additive Manufacturing became more and more visible in 2013. Due to the increasing number of articles, magazines and TV shows, people become aware about the technology.

There have been many activities which increased the visibility of am and 3D printing. For example at the Rapid Tech 2013 a new format called FabCon took place in parallel to the RapidTech. Here different kinds of “home-use-machines” for personal application have been shown. As well many print-shops in many cities in Germany have been opened, in Paderborn the Heinz Nixdorf Museum Forum presented the 3D printers and their parts in their foyer – and many more activities took place in and outside of Germany. Even if 3D printing produces optical „nice“ parts for „home-use-applications“, these parts are far away from real industrial reliable applications with known and predictable properties. In many cases the parts are not comparable to those being produced in professional systems

The approach of DMRC is to work in proactive collaboration together with the key technology stakeholders in advancing Additive Manufacturing technology into dependable, production rugged Direct Manufacturing technology. This means, our projects aim to gain knowledge in order to get reliable, repeatability parts with known properties, starting right from the beginning of design. This approach seems to be the right successful way, as there is a lot of interest from our partners as well as from third parties. In 2013 we got the Lego Group as a new member in the DMRC consortium, so last year we have been ten industrial partners. For 2014 there are already contracts in preparation, so it is more than likely, the DMRC will grow right from the beginning of 2014.

The DMRC becomes more and more visible by many activities, so e. g. being involved in the aircraft session at RapidTech, at the Euromold and Hanover-fair. As well DMRC is again visible in the Wohlers report, does participate in the development of standards like ASTM and DIN / ISO / VDI. Here especially the formulation of design rules becomes more and more relevant and visible. Due to addressing research in many different areas, national and international presentations have been held in Europe and US, so DMRC gets a reputation in the main markets in the world.

Seeing the DMRC for the financial side, the total sum of money to be spend in projects of11 Mio € till 2016 has just reached approx. 60 %. So till 2016 – with the existing consortium –more than 4.5 Mio € are left to be spend into projects inside DMRC. New projects with new subjects in different kind of applications are already in the continuous discussion with our partners. The remaining amount of budget still opens the possibility to perform new projects as well as to attract new partners from new industries and so to contribute and achieve reputation in different fields of research.

Besides the funding of State North Rhine Westphalia, meanwhile different projects have been successfully applied for and so different institutes from University of Paderborn are involved in AM. There is e.g. an EU RP7 funded project named RepAIR, a BMBF project within the it’s owl-approach named 3P (Product prevention against product piracy), an ESA funded project about structures in space applications and a material driven DFG-project supports research about AM in DMRC.

From the view of research, the DMRC itself collaborates meanwhile with 8 institutes of University of Paderborn which provide knowledge and support to the DMRC. This means a centre with a large variety of competencies, equipment and knowledge together with dedicated researchers is growing more and more. All together, the DMRC is a very successful team with the aim to become one of the leading institutes in additive manufacturing.

All companies and research parties are gratefully invited to join DMRC for collaboration.

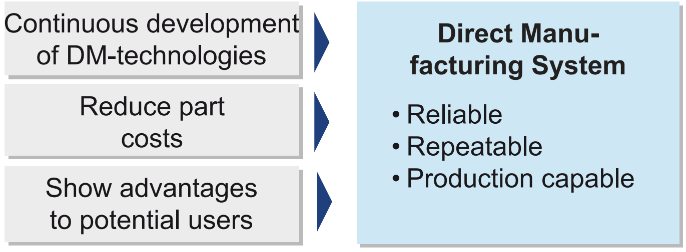
Kind regards

Dr.-Ing. Eric Klemp

2 Direct Manufacturing Research Center

Aims of the DMRC

The aim of the DMRC is to perform research in order to get reliable, repeatable and production capable Direct Manufacturing Systems. To achieve this, a continuous development of processes has to be performed. Potential users need to be informed about the advantages of the technologies in order to let them get a brought knowledge - as well part costs will be taken into account.

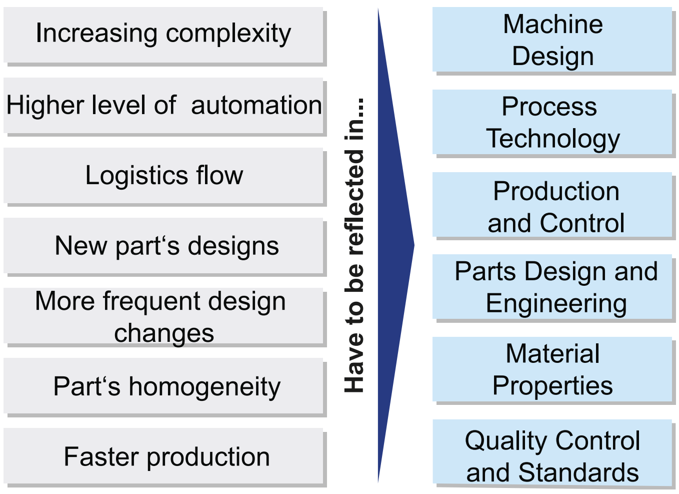


Objects of the DMRC

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. Therefore 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.

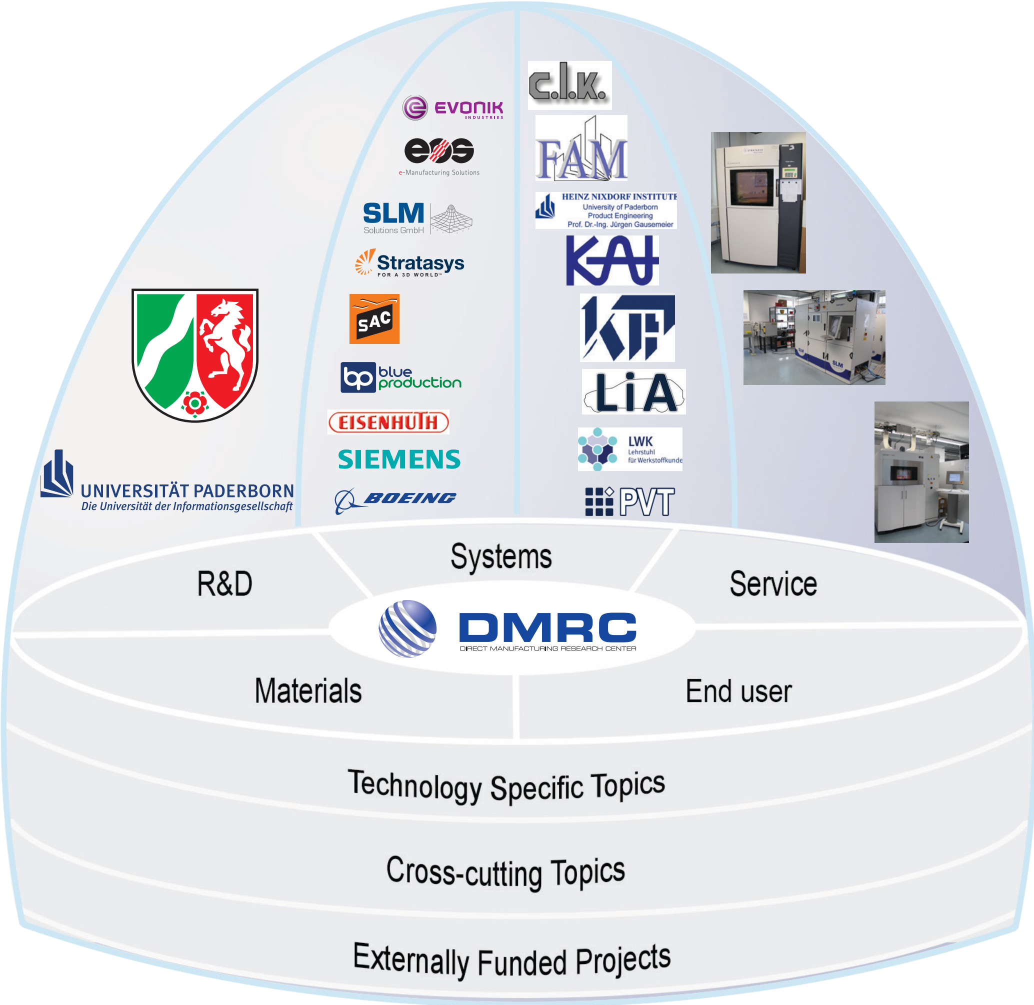
Main Challenges to be approached

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

The DMRC is a part of University of Paderborn and co-funded by State Government of Northrhine Westphalia. The current partner structure of 10 active companies performs along the production value chain. R&D is being done by University and its participating institutes. Materials are represented by Evonik. System suppliers as EOS, SLM and Stratasys are part of the consortium as well as the service and part suppliers Stükerjürgen, Blue Production and Eisenhuth. Lego, Siemens and Boeing are end users within the consortium. The integration of DMRC in the University allows to perform projects in all research areas being need. There are 8 different institutes being involved for all kind of requests, demands and topics: This means there are technology specific projects for Lasersintering, Lasermelting and Fused Deposition Modeling and cross-cutting topics like design-rules, cost, quality, foresight and strategy. All projects are performed under the roof of DMRC and University, so skills and knowledge of polymers, plastics, metals, design and processes are part of the consortium. Besides the DMRC-consortium funded projects, external projects are carried out.



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, solutions for specific problems are developed within the consortium. And nevertheless, a partnership in the DMRC means to co-steer the direction of DM in terms of research strategy.

3 Current DMRC Projects

In DMRC many research topics have to be focussed on, in order to let Additive Manufacturing become a reliable, repeatable and a successful technology. User have to get trust in this technology in order to generate business out of this in most promising industries for AM. It can be seen, there are many different technologies available for the production of parts, inside the DMRC we have installed Lasersintering, Fused Deposition Modeling and Lasermelting.

Before a technology becomes reliable, a lot of research has to be done. Within the research in DMRC many different kinds of projects are performed. The DMRC is a research centre at the University of Paderborn, with meanwhile eight different institutes participating. The professors and researcher of these institutes work together with our industrial partners in all different kind of projects. These projects can be technology driven or deal in “overall” projects with general topics.

The technology driven projects are dealing with Lasersintering, Lasermelting and Fused Deposition Modeling. Here the institutes FAM, KTP, LiA, LWK and PVT are mostly involved. The focus of the overall-projects is larger, here the institutes CIK, KaT and HNI are performing as well high class of research. Within the next pages, detailed project descriptions together with specific information about the institutes, the available equipment and publications will follow.

The strength of DMRC is the close and interdisciplinary collaboration with the involved institutes, with all their equipment to be used in all kind of projects for the benefit of partner’s projects.

Within the LS projects specific knowledge is generated in order to determine and optimize properties of materials, surfaces and especially parts, this includes of course as well investigations about aging of materials. All together this will aim particular to qualify parts for “ready to use” applications. Within the Lasermelting projects, different kinds of materials are in the focus. The research focus is optimizing the process and its parameters to achieve best results in (mechanical) properties, which does implement as well to gain detailed knowledge of the fatigue 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. You will find details of these projects at the next pages.

The advanced projects deal with overarching tasks. The project “costing analysis” investigates in detail about 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 considered in order to get a full understanding of the complete process chain. Goal of the “Obama” - project is to line out the opportunities and barriers of DM-technologies in the aerospace industry and adapted other industries. As one result, three studies have been published and can be downloaded from the DMRC webpage. 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. Here as well first results are available at DMRC webpage for download. Last but not least the project “Direct Manufacturing Design Rules” has the objective 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. This project supports the VDI / DIN / ISO approaches, so results are available at those organisations.

With this bunch of interesting projects it can be expected to create know-how and to receive answers for questions about optimization of the AM process, machinery, materials and part properties. So finally you will see lightweight, multifunctional AM optimized 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 research between University and industrial partners.

Besides these DMRC / NRW funded projects there are a few external funded ones, which are funded by the European Commission (EU / RP 7), European Space Agency (ESA) and Bundesministerium für Bildung und Forschung (BMBF). You will get a good impression about the content taking a close look at the next pages.

3.1 Current Internal Projects

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 charac-terization 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.

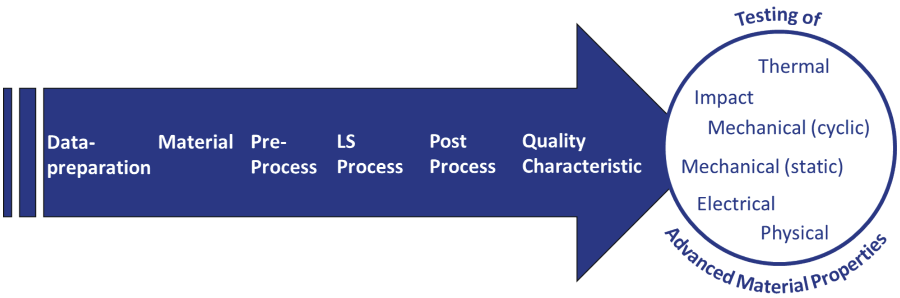


Figure 1: Investigation of material properties along the Laser Sintering Process Quality Chain

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.

Stefan Leuders

Andre Riemer

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

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.

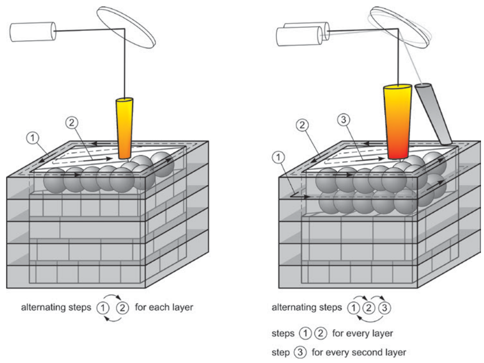


Figure 1: Schematic drawing of different exposure strategies of SLM 250^{HL} (left) and SLM 280^{HL} (right)

Microstructure-mechanical properties-relationship

The sensitivity analysis as a first major issue within this project aims at shedding light regarding the influence of exposure parameters on the mechanical properties of SLM manufactured stainless steel 316L. As an example, Figure 2 shows monotonic stress-strain curves for 316L processed on a SLM 250HL respectively SLM 280HL. It can be seen, that both processes result in fundamentally different behaviour under monotonic loadings.

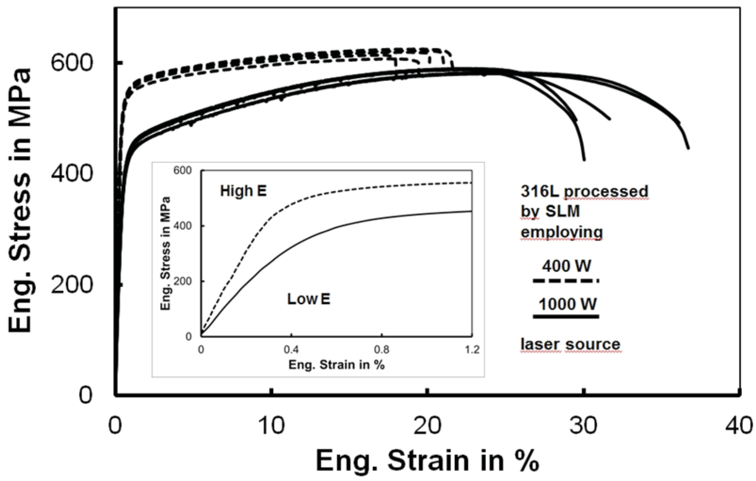


Figure 2: Monotonic stress-strain curves for the SLM processed 316L

By analysing the microstructure, the differences in strength and ductility can be explained according to the hall-petch relationship.

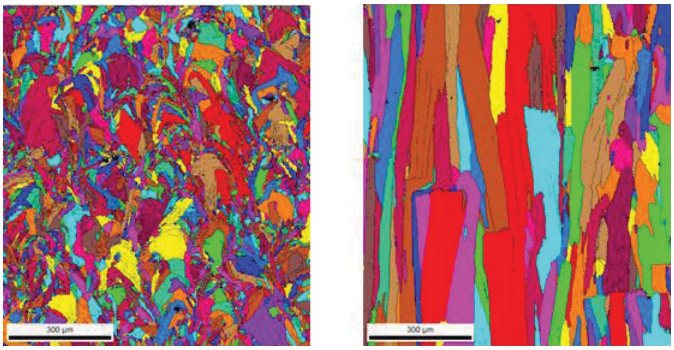


Figure 3: EBSD maps for 316L obtained through a 400 W Laser (SLM 250HL, left) and a 1000 Watt Laser SLM 280HL (right)

Design of Experiments for analyzing the effects of exposure parameters

It can be seen, that the evolution of the local microstructure is strongly depending on the exposure parameters. While the conventional 400 W laser results in a weakly textured fine grain structure, the 1000 W laser causes significantly larger grains strongly elongated in build direction. In order to obtain a deeper understanding regarding these effects of exposure parameters, design of experiments (DoE) was used to allow for a systematic approach concerning this multi-parameter problem. The optimizations were carried out towards a high density and hardness.

Investigation of build-up rate

Further work packages focus on a comparison between a SLM 250HL and a SLM 280HL with respect to build-up rate and the resulting component quality. Therefore, a reference build-job was defined in order to measure the process-cycle time of both SLM systems. Recent investigations have shown the possibility to increase the build-up rate about 77% by use of the SLM 280HL compared to the conventional SLM system. Finally, all project results regarding an optimal balance between build-up rate and component quality will be transferred 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”.

Research Strategies for Additive Manufacturing

Marina Wall

Stefan Peter

Additive Manufacturing is a disruptive technology progressively permeating diverse markets. It is capable to trigger major upheavals reshaping supply chains and business models over the next decade. Many industries are seeking for opportunities how to capitalize on the benefits AM provides; new industries progressively draw their attention to AM's potential. As well, global research initiatives funded by different governments spark new impulses in the research landscape. Established and newly founded research centers, e.g. in the UK, the US or Germany are continuously striving to close research gaps and to transfer the research results into tangible outcomes for the industry. Therefore, demand-oriented research strategies are needed.

Additive Manufacturing Research Map

AM Research Map shows research intensity within certain research fields

To deduce the need for research activity, the AM research landscape was analyzed. As a result, the AM Research Map was created (Figure 1), revealing the research intensity of the analyzed research institutes.

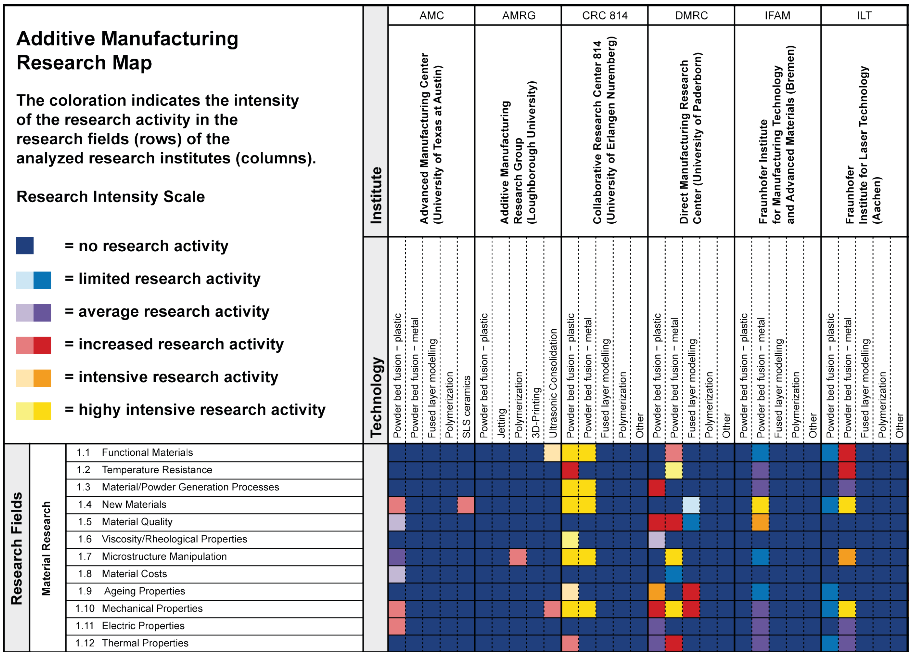


Figure 1: Excerpt from the Research Map, indicating the research intensity in different research fields (rows) for selected institutes/technologies (columns)

For instance, just a few institutes focus on cross-technological research fields, e.g. the development of design rules; the research intensity is medium; others, e.g. material research, are intensively investigated. An outstanding research intensity is prevalent in e.g. mechanical properties, new materials, material quality, microstructure manipulation. Research fields with a rather low research intensity are e.g. supply chain optimization and process automatization. Concurrently, conclusions emerge for technology-specific research intensity. The highest and lowest research activity distributed over all research fields are indicated for Powder Bed Fusion Metal and Polymerization Technologies, respectively.

Additive Manufacturing Strategy Map

To identify crucial levers for future research strategies, white spots need to be revealed. Therefore the research activity and intensity were contrasted with the future relevance of the research fields. Process automatization and design rules were determined as white spots and should be considered as levers in future strategies. Research fields such as new materials are important as well. Here however, the research intensity is already high. Based on the white spots, success factors enabling the levers were deduced. Hence, AM research could significantly benefit from e.g. a stronger interconnection of institutes within the research landscape and a closer integration of companies along the value chain.

Using white spots and success factors, consistent strategy options were developed

These aspects were taken into consideration to develop consistent strategies. The result are ten consistent strategy variants, ranging from a Fundamental Scientist to a Problem Shooter. Contrasting the developed strategies with the strategies the institutes currently pursue, a Strategy Map is resulting (Figure 2). All deduced conclusions are considered for the development of a coherent strategy for the DMRC.

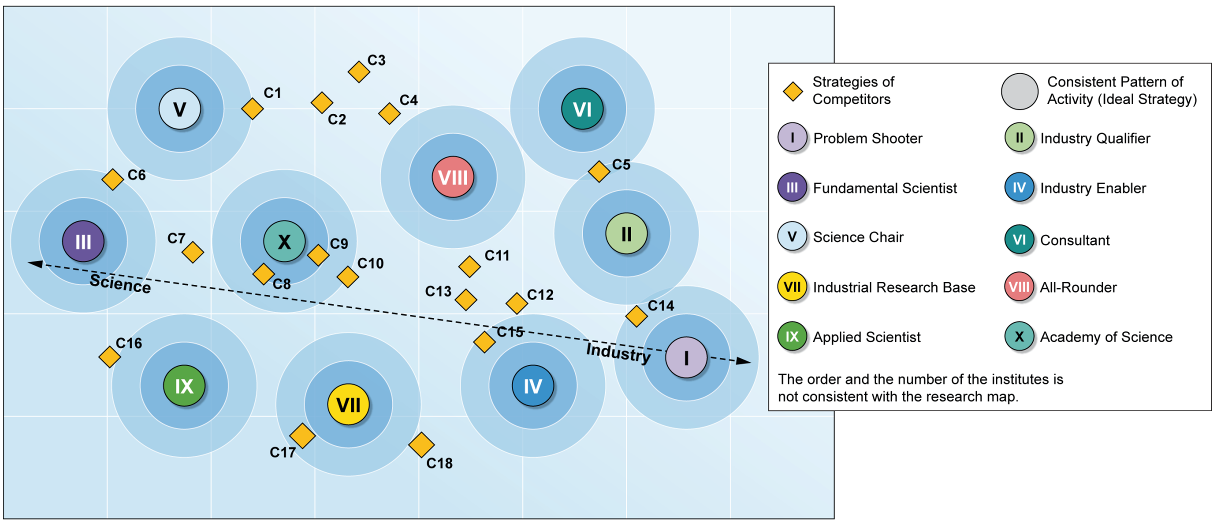


Figure 2: Strategy Map: Visualization of developed strategy variants and the current strategies in the research landscape

Michael Brand

P.V. Varghese

Drafting a Quality and Process Control System for the AM Processes in DMRC

Based on the available knowledge and results from the Year 2012 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 2013 following points were examined and developed:

- **Work instructions for all the available processes in DMRC**
- **Drafting of procedural instructions for LS, FDM. SLM**
- **Extending the DMRC QM Handbook on the basis of DIN 9001**

Work Instructions

Work Instructions are helping tools for the students and staff

The drafting / drawing up a work instruction serves as a document where specific tasks are described in detail, these specific tasks are part of a process, a product or specific for a work place. These instructions are tools for the staff so that his /her work can be done to fulfill the quality requirements, and as such part of the QM - System at the DMRC.

The use of standard work instructions makes sense when mistakes are repeated even by qualified and experienced staff. Work instructions also provides a good basis for job training for new staff. Figure 1 shows part of the work instructions for the Mastersizer 2000.

Process Instructions

Process Instructions help to stabilize the different processes

The drafted process instructions for LS, FDM, and SLM are aimed to control and stabilize the job building process on a lasting basis. This also facilitates the training of new staff in the technologies and processes and helps to gain a general overview of the processes. Figure 2 shows the process instructions for the FDM process.

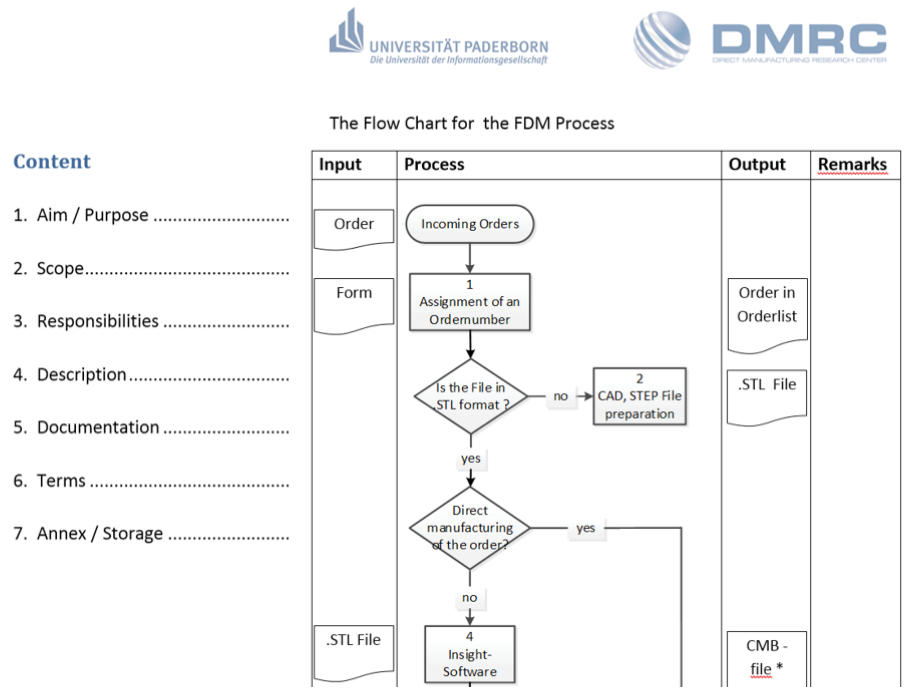


Figure 2: Example Process Instruction FDM Process

DMRC QM Manual

Quality Management System of DMRC

The aim of the QM manual is to establish a QM management system which will help develop and if possible improve the quality standards at DMRC.

All measures taken will be documented in this QM manual.

This will describe the organizational and technical measures necessary to maintain the quality standards expected of DMRC as per DIN EN ISO 9001.

The DMRC QM Manual will be constantly monitored and improved.

Matthias Fischer

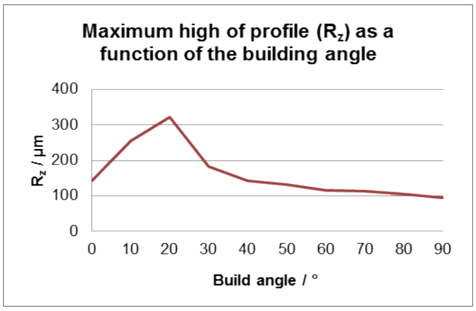
Surface Treatment Methods for FDM Parts

Fused Deposition Modeling (FDM) parts show rough and wavy surfaces with stair step effects at slopes and round part geometries. For the application of this parts, especially for end use products, the surface has to be treated primarily for decorative aspects or/and in order to achieve water tightness. The surface treatment includes a surface smoothing first and a subsequent coating or a coating that generates smooth surfaces. An important criterion for possible finishing methods is to keep the flexibility of the additive manufacturing process.

Surface quality

Characterization of the surface quality by measurement of the surface profile

The characterization of the surface quality will be done with a mechanical contact profilometer by measurement of the average height of profile, Rz. Figure 1 shows the Rz values for FDM Ultem*9085 part surfaces produced with different build angles.



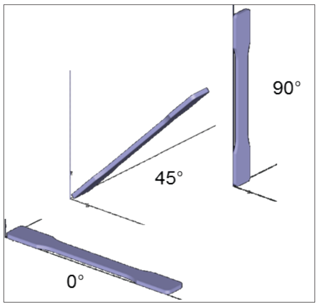


Figure 1: a) Maximum height of the profile of FDM parts; b) Tensile specimens in different building angles

The measurement of untreated FDM parts show the dependence of the surface quality over the build angle. For parts with small build angles >0° the average height of profile is much higher than for 0° or 90° build orientations. By using the Insight Software function “Visible Surface Style: Enhanced” smaller filament width and negative filament air gaps at the part surface can be generated. This results a better surface quality for 0° build angles.

Surface smoothing by mass finishing

Analysis of the finishing efficiency of the mass finishing process on parts build up with Ultem*9085

The advantage of a mass finishing process is the high flexibility and productivity. In this project the process is conducted on a disc finishing unit from the Eco 18 series, produced by OTEC Präzisionsfinish GmbH. In different experimental series the finishing efficiency of the disc finishing process was analyzed by changing the finishing time, velocity and media. For mass finishing processes many finishing media with different sizes and material grade are available. Ceramic media show promising results for a post treatment of Ultem*9085 parts. Figure 2 shows an overview of some ceramic media, which were analyzed regarding their finishing efficiency.

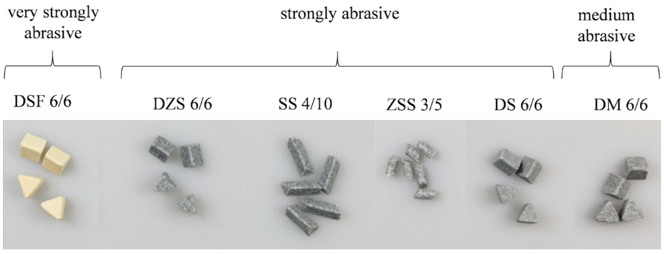


Figure 2: Ceramic finishing media

The finishing media are separated in different groups of abrasives by the producer. Besides to the standard abrasive media also polishing media are available. The influence of the disc finishing process parameters to the part surface is analyzed by using different specimen types in order to replicate different part geometries of the application. Especially the finishing of grooves and interior part surfaces show challenges. In certain cases the finishing process results an additional material erosion of corners and edges, which is shown in figure 3 by a 3D scan.

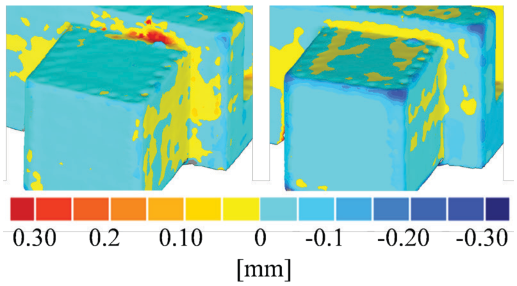


Figure 3: Material erosion at corners and edges

Coating Methods

Application of coating technologies in order to generate smooth part surfaces

The FDM process causes gaps between the oval filaments. Removing the gaps by grinding the surface by a mass finishing process takes a lot of time and results an additional material erosion of corners and edges. Therefore a combination of coating and mass finishing was analyzed regarding the optimization of the surface quality. The using of different finishing media, time and velocities for uncoated and coated parts is just as important as the choice of a suitable filler. One of the advantages of the Ultem*9085 is the certification for aerospace application. For this reason, the filler should also fulfill the requirements for an application in the aerospace industry.

Resistance Analyses

Analysis of the adhesiveness of the coating for different environmental conditions

The quality of the coating will be qualified by the adhesiveness on the Ultem*9085 part. In further investigations the resistance of the coating against environmental conditions will be carried out. Therefore, selected parts will be stored under defined conditions to determine the long-time behavior.

Guido Adam

Direct Manufacturing Design Rules

As additive manufacturing processes create parts layer by layer 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 had the objective to develop design rules for additive manufacturing. The basis for their development was 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 were not 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 were 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 were summarized in a design rule catalogue. Also, additional information about additive manufacturing principles, terminology and backgrounds of the design rules were added. An extract of the catalogue is shown in picture 1-1.

More than 60 rules are contained at time

Outlook

Based on the design rule catalogue a seminar “Design for additive manufacturing” is planned. 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.

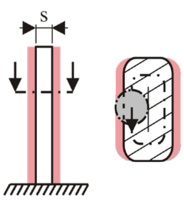
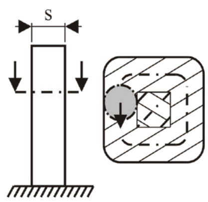
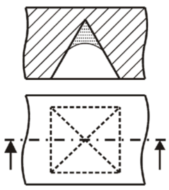
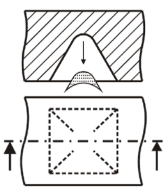
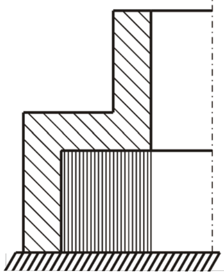
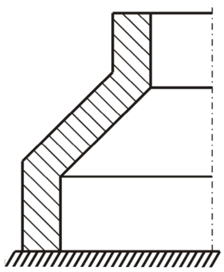
Element			Information	Examples		Techn.		
Group	Type	Attribute	Description	Not suitable for manufacturing	Suitable for manufacturing	LS	LM	FDM
Basic Elements	Plates	Thickness	Plates should be so thick that each layer can be structured of a contour with inscribed raster to minimize dimensional deviations 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

Guido Adam

Direct Manufacturing Design Rules 2.0

As additive manufacturing processes create parts layer by layer 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, comprehensive design rules for additive manufacturing are required. Within the “Direct Manufacturing Design Rules” project (DMDR) design rules for additive manufacturing processes were developed. At time, the developed design rules apply only for boundary conditions that were considered within the DMDR project. Thus, the “Direct Manufacturing Design Rules 2.0” project has the aim to extend the range of validity for the developed design rules.

Design Rules given by the DMDR project

Design rules were developed for specific boundary conditions

In order to develop design rules, standard elements were defined, first within the DMDR project. Standard elements are geometrical elements which often reoccur by designing technical products. Based on these elements a process independent method for the development of design rules was set up. Using this method, design rules were developed for the laser sintering, laser melting and fused deposition modeling processes (Figure 1). Therefore the machines Eosint P395 (laser sintering), SLM 250HL (laser melting) and Fortus 400mc (fused deposition modeling) were used. For each machine common parameter settings was considered with one material. So, for the laser sintering process the material PA2200, for the laser melting process stainless steel 316L and for the fused deposition modeling process Ultem were used.

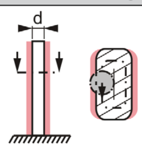
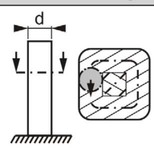
Group	Type	Attribute	Description: General / Process specific	Example: Not suitable for manufacturing	Example: Suitable for manufacturing	LS	LM	FDM
Basic Elements	Non-Curved	Thickness	Plates should be so thick that each layer can be structured of a contour with inscribed raster to minimize dimensional deviations and to avoid defects. *LS: d > 1,0 mm* *LM: d > 0,6 mm* *FDM: d > 1,5 mm*			x	x	x

Figure 1: Design Rule, developed within the DMDR project

How the material, the according parameter settings and the machine itself do influence the geometrical quality of the considered elements is unknown. Because of this, the developed design rules are only applicable for the described boundary conditions, which were considered within the DMDR project (Figure 2).

Objectives

The range of validity will be extended

In general, design rules for additive manufacturing technologies, which can be used for training and teaching, need to be applicable for different boundary conditions. Thus the research "Direct Manufacturing Design Rules 2.0" project (DMDR 2.0) has the objective to extend the range of validity for the developed design rules.

Using the method given by the DMDR project, it shall be proven if the developed design rules apply for different boundary conditions, too. Different materials, manufacturing machines and parameter settings will be considered. As a result the validity range will be extended (Figure 2) and (in case of success) the transferability of the design rules to different boundary conditions is possible.

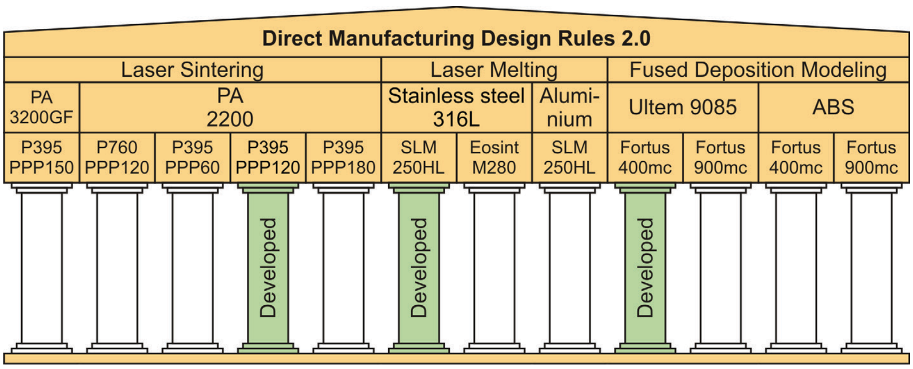


Figure 2: Range of validity for the developed design rules before (green pillars) and after (white pillars) the DMDR 2.0 project

Adaption of the design rule catalogue

A main result will be the adaption of the design rule catalogue. The catalogue was developed within the DMDR project and will be adapted with the results of the DMDR 2.0 project. Therefore the results of both the DMDR project and the DMDR 2.0 project will be analyzed and compared. It will be analyzed if the design rules given by the DMDR project fit for all considered boundary conditions. The results will be interpreted and if necessary, the design rule catalogue will be extended with additional design rules.

Stefan Josupeit

AMP² Advanced Additive Manufacturing Material and Part Properties - Reduced Refresh Rates & Cooling Process regarding Laser Sintering

This project treats important challenges regarding the Laser Sintering part quality as function of the temperature distribution and cooling rates as well as a reduced material consumption using a refresh-rate optimized nylon 12 material (PA 2221).

Investigations on PA 2221

Reduced powder consumption

With the use of PA 2221 material it is possible to use very low refresh rates of about 30% compared to 50% with the standard nylon 12 material PA 2200 investigated in former projects (see Figure 1). Maintaining similar part quality characteristics, the powder consumption and waste are thus reduced significantly. As a result, the cost efficiency of the laser sintering process can be improved.

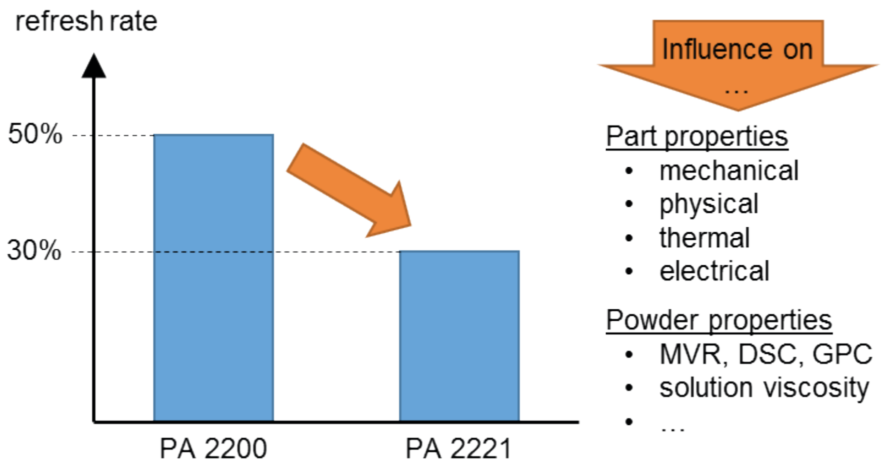


Figure 1: Tested parameters as function of the powder age and refresh rate

Specification of powder age

The influence of the thermal loading on the powder age is analyzed with various methods. For example, measurements of the solution viscosity and DSC are performed in addition to the commonly used melt volume rate (MVR). Experiments are conducted along a test series with a rising number of build cycles using the refresh rate as well as the MVR value to adjust a used/virgin powder mixture ratio.

Determination of material data

With a representative batch of refreshed PA 2221 powder, experiments are performed to determine temperature-dependent material data, e.g. the mechanical, physical, thermal, electrical or impact part properties.

Cooling behavior of the part cake

Background

In previous investigations it has been shown that the location of a part within the part cake strongly influences its quality characteristics. Especially the cooling rate varies from the edges of the building frame to the inner area, which leads to inconstant part and used powder properties depending on the position within the building frame. Many studies have already been performed to examine and correlate the temperature distribution on the first layer (see Figure 2) with different part properties. Nevertheless, the temperature distribution of the inner part cake during the whole building process (warm-up, build and cooling down phase) is not known yet.

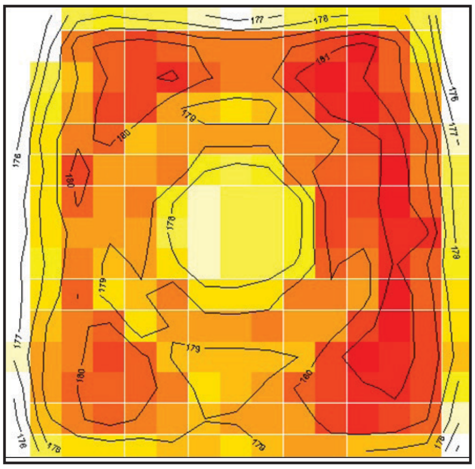


Figure 2: Temperature distribution on the first powder layer

Temperature measurement within the part cake

A measurement device to analyze the temperature distribution within the part cake is installed into the building frame. The cooling rates are determined as function of the part position and designated process parameters. For example, the influence of the energy input, the packing and bulk density, job height, environmental temperature or the layer thickness is analyzed. Different cooling rates are also correlated with specific part and powder properties, e.g. the crystallinity and MVR of the powder or the density, warpage and mechanical properties of the parts.

Cooling Simulation

In addition, the results of the temperature measurements are used to simulate the cooling phase using the Finite Element Method (FEM). In this way, different cooling down strategies can be tried out without the need of further experiments. Also, the calculation will give the possibility to shorten the build time and to improve the reproducibility of the laser sintering process.

Outlook

In general, a better understanding of the cooling process will be the main goal of this work. An optimization of the cooling process, which is vital for better and more constant part qualities, may be developed in a follow-up project.

Agnes Bagsik

Analysis of the FDM Part Quality manufactured with ABS with the Focus on the Toy Industry

The aim of this project is to establish a database that is necessary for the direct manufacturing of parts via the Fused Deposition Modeling in the toy industry with the material ABS. For this not only the strength properties and the influencing parameters on the strengths have to be worked out, but also the knowledge about possible surface finishing methods in order to achieve a part with the requirements needed. Another very important topic is the dimensional accuracy of the parts, because in some applications a very high fitting accuracy is necessary.

This research project is divided into three work packages. First the mechanical strengths are analyzed, than the surface characteristics in combination with the dimensional accuracy of FDM components manufactured with the material ABS are investigated experimentally.

Mechanical Strength Properties

Process parameter dependent strength properties

First the mechanical strength properties of ABS parts will be analyzed according to the ISO standards for plastic materials. The tests to be conducted are shown in the following figure. Therefore test specimens will be built up with different slice heights due to variation of the tip size. Furthermore the build orientation will be varied. First parts will be built up with the preset toolpath parameters and then these parameters will be changed in order to analyze the effect of the inner part structures of the fabricated parts on the resulting strength properties. Additionally some tests will be made according to the standards known from the toy industry in order to work out possible application fields.

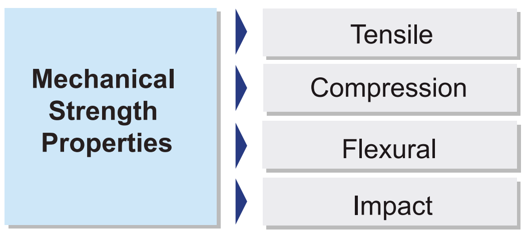


Figure 1: Mechanical properties

Surface treatment methods

Analysis of the surface characteristics

In this work package the analysis of possible smoothing methods for the ABS parts will be made. Due to the given requirements only surface smoothing methods will be conducted in order to smooth the typical wavy surface of FDM parts. For this some promising surface treatment methods will be analyzed more in detail. Furthermore an analysis of the influence of the process parameters (medium, geometry of the medium, time, velocity, etc.) on the surface characteristics will be done.

Figure 2: Good fitting accuracy

Dimensional accuracy

Optimization of the fitting accuracy

Furthermore the analysis of the dimensional accuracy of ABS parts will be done with regard to the surface smoothing method. For this also the process parameters (tip size, orientation and toolpath) will be varied. The aim is to define a general guide line how to achieve a required fitting accuracy in relation of the manufacturing process and the used surface smoothing method.

Patrick Delfs

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

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. Especially the orientation of a surface in respect to the layer orientation has a huge influence on the surface quality, too.

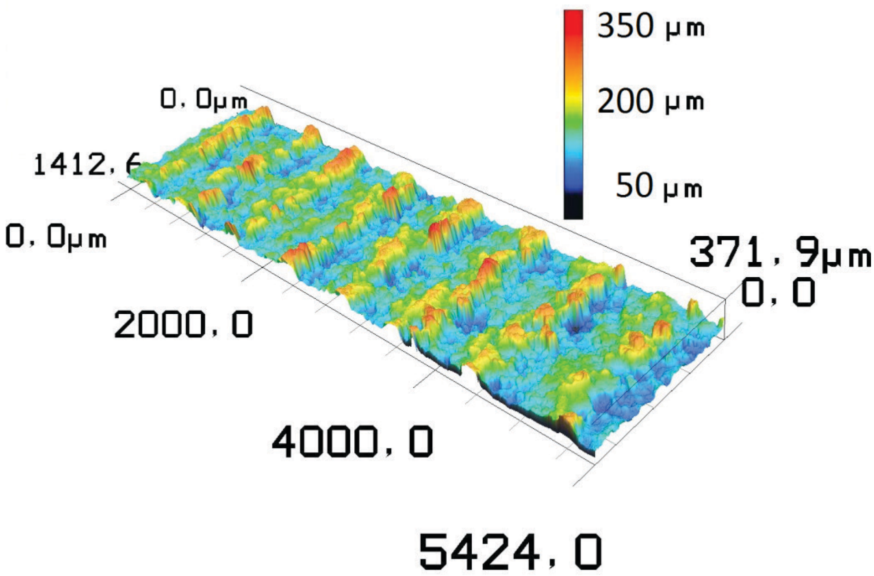


Figure 1: Surface topography of a tilted surface. The single layers and fused particles are obvious.

Surface Finish according to Process Parameter

Investigation of diverse surface finish and coating methods according to chosen process parameters

The post process is an important factor using the laser sintering process. 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 distances as well as the blasting pressure are the most important parameters. Further on the blasting material shall be investigated as well. Next to the abrasive blasting method other promising methods like grinding and chemical etching will be used. The challenges here are also to find the right materials and parameters. Another 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. 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. The evaluation of these methods is done using the characterization method determined in the chapter „Surface Quality Characterization Method".

Longtime-Testing of Laser Sintered Parts

Investigation of influences by ageing on surface quality and mechanical properties

The last part of the project deals with the ageing of post processed and untreated parts. Therefore the test specimens will exposed to light, humidity and temperature for different durations until the longest of one year. On one side the ageing will be simulated with a defined exposure of above mentioned impacts and then compared to ageing by real weather of Paderborn. Measurements will be done to evaluate the influences on surface quality and as well mechanical properties.

Christian Lindemann

Ulrich Jahnke

Project CoA²mPLy: Costing Analysis for Additive Manufacturing (AM) during Product Lifecycle

The goal of this research-project was 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 lifecycle. The results will help to identify success factors for cost reduction in the field of Additive Manufacturing. An exemplary metal part was 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.

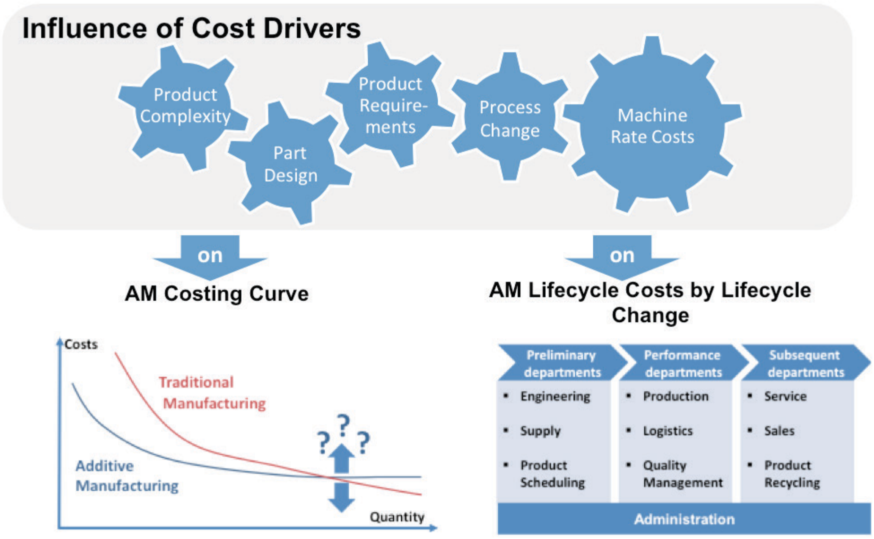


Figure 1: The CoA2mPly Project in a nutshell

Cost Related Process Modeling

Collection of cost related knowledge in a process model

The modeling of costing relevant AM business processes was the basis for the work in the project. The main purpose was to gain knowledge about the costing processes relevant to the AM technology. All important processes and related cost drivers 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

On the basis of the gained process knowledge, a costing model for Metal Additive Manufacturing (MAM) has been set up, using activity based costing elements. Therefore a rating concerning the Selective Laser Melting (SLM) process for metals has been made. The costing model started with a focus on the pure production process and was enhanced during project runtime to encompass more steps in a products lifecycle.

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 have been identified based on different sample parts. The process was continously enhanced by further lifecycle processes as usage and others. An exemplary metal component (see figure 2) has been 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 has been investigated.

Figure 2: Sample part redesign of an upright of the formula student series

Lifecycle study and generalization

Understanding and rating of cost drivers associated with AM

The product lifecycle costs of AM have been compared with conventional machining technologies. Therefore a case study has been implemented concerning the costing processes in the intrinsical product lifecycle. Furthermore different scenarios 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. So the range of potential part candidates has been enhanced. Costing concerned success factors for the AM technology has been pointed out.

The results of CoA^{2}mPLy serve as input for the follow-up project CoA^{2}mPLy 2.0

The results of the analyses done in this project show a lack of information quality for a reliable calculation and comparison of different AM processes and machines. Therefore these results will be the basis for further research activities. Gathering these needed information and the adaption of the costing model for MAM to the AM processes dealing with polymers will be focused in the follow-up project “CoA^{2}mPLy 2.0”.

Project CoA²mPLy 2.0: Costing Analysis for Additive Manufacturing (AM) during Product Lifecycle 2.0

Christian Lindemann

Ulrich Jahnke

In the project CoA²MPLy the cost structure of Additive Manufacturing (AM) has been analyzed and a costing framework considering the whole lifecycle costs is one result of CoA²MPLy. This allows a comparison between AM and traditional manufacturing concerning costs in each process in a parts lifecycle. During the research activities some problems regarding cost relevant parameters have been identified. Based on these outcomes and gathered knowledge there are three main objectives to address in the follow-up project CoA²MPLy 2.0:

(1) Enhancement of costing framework developed in CoA²MPLy

(2) Achievement of comparability between machines and technologies regarding costing aspects and particularly building rates - proposal for standardization

(3) Development of an expandable IT-System with a costing calculation module, an AM Database and a presentation of advantages of AM

Enhancement of the SLM costing framework

The SLM costing framework will be adapted to meet the specific characteristics of FDM and LS

The costing framework developed in CoA²MPLy focuses Selective Laser Melting (SLM) with its specific characteristics in terms of necessary pre- and post-processing, the manufacturing process itself and the achievable benefits during product lifecycle compared to traditional manufacturing. Objective (1) comprises an adaption of the costing model to the Laser Sinter- ing (LS) process and to the Fused Deposition Modeling (FDM) as well to provide cost calculations for the three most used additive manufacturing processes (compare figure). This work will enhance the existing framework for costing analysis to be utilized by OEMs, additive manufacturing part suppliers and additive manufacturing part users. Furthermore the applicability for different branches and impacts on supply chain will be considered.

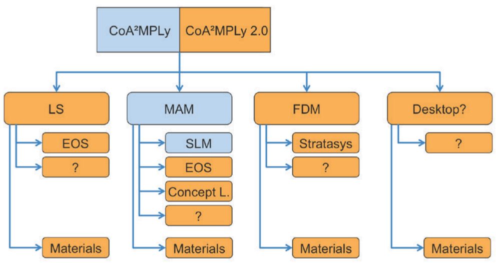


Figure 1: enhancement of previous results

Comparability between AM machines and technologies

Achievement of tranparency for customers due to comparability of building rates

Objective (2) addresses the comparability between different types of machines and technologies. At the moment the machine manufacturers measure the building rate in different ways and specify these rates even in different units for instance cm/h or mm³/h. To achieve comparability and transparency for potential customers that are facing a make or buy decision a proposal for standardization of measurement and specification of building rates will be elaborated starting with the determination of material properties that have to be one of the reference parameters. Furthermore the effieciency of th use of ressources like energy and gas will be concidered.

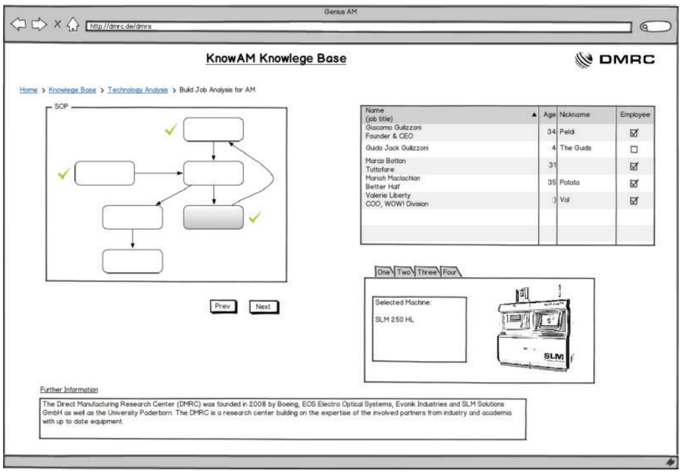


Figure 2: Mock up of the IT System

Development of an IT System for costing calculation

Breaking the limitations of spreadsheet analysis by the development of an expandable IT System

During CoA²AMPLy the costing framework mentioned before is implemented as a Microsoft Excel tool. The capabilities of this software are limited particularly in terms of usability and complexity. Thus objective (3) is meant as development and implementation of an expandable IT-System concept. Simplifying and improving the use of the costing framework will be the starting module. Due to web access to the IT-System no software will be needed for calculation. The enhancements stated in objective (1) will be considered so that users and potential customers will be able to compare costs in additive and traditional manufacturing. By reason of an interface to import STL/AMF files a more detailed calculation of expected costs will be possible. Thus utilization of building chamber of the specific machine as well as the part orientation and the concrete part geometry can be considered in the calculation. Another module of the IT-System will be used to monitor build jobs and to gather process knowledge regarding cost data, material properties and quality aspects. The concept has to be developed with respect to prospective maintenance effort that has to be low.

The overall results of the projects will help to define rules for the cost efficient utilization of additive manufacturing and therefore help to foster the growth of the technology. Furthermore the outcomes will enable the possible end users to compare different technologies in regard of building speed and efficiency.

Fatigue Life Manipulation

Andre Riemer

Technical components are subjected to various stresses during operation. They are responsible for the limited service life of the components. Fatigue cracks are often observed far below strength limitations. The life time in components under fatigue loading is divided into crack initiation and fatigue crack propagation. Using crack growth retardation methods substantially higher fatigue life can be achieved. Figure 1 shows the effect of notches on the life time during crack growth period. The reason for the difference in life time can be found in the crack growth behavior during initiation. The holes positioned in the crack path lead to a new crack initiation at each notch. The significantly higher number of load cycles within the crack initiation period (compared to the number of cycles during crack propagation), this effect will be used to manipulate the total life time.

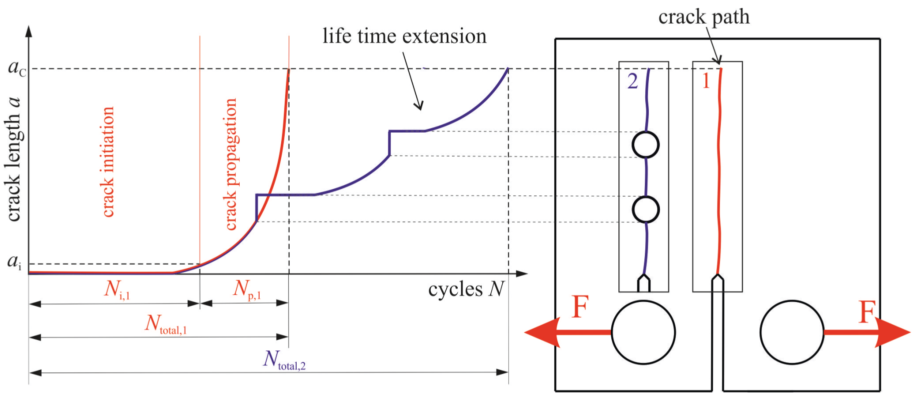


Figure 1: Schematic illustration of life time manipulation caused by notches

Objectives

Extension of fatigue crack growth period by various notch geometries

The main goal of this project is to extend the total life time of components. Using intrinsic advantages of additive manufacturing processes notched parts will be produced in order to manipulate the fatigue life, Figure 2. It is expected that due to changes in stress distribution caused by the notch the crack growth behavior will be influenced. By variations of the various notch forms, notch sizes and notch orientations basic knowledge about crack behavior in SLM processed components will be obtained.

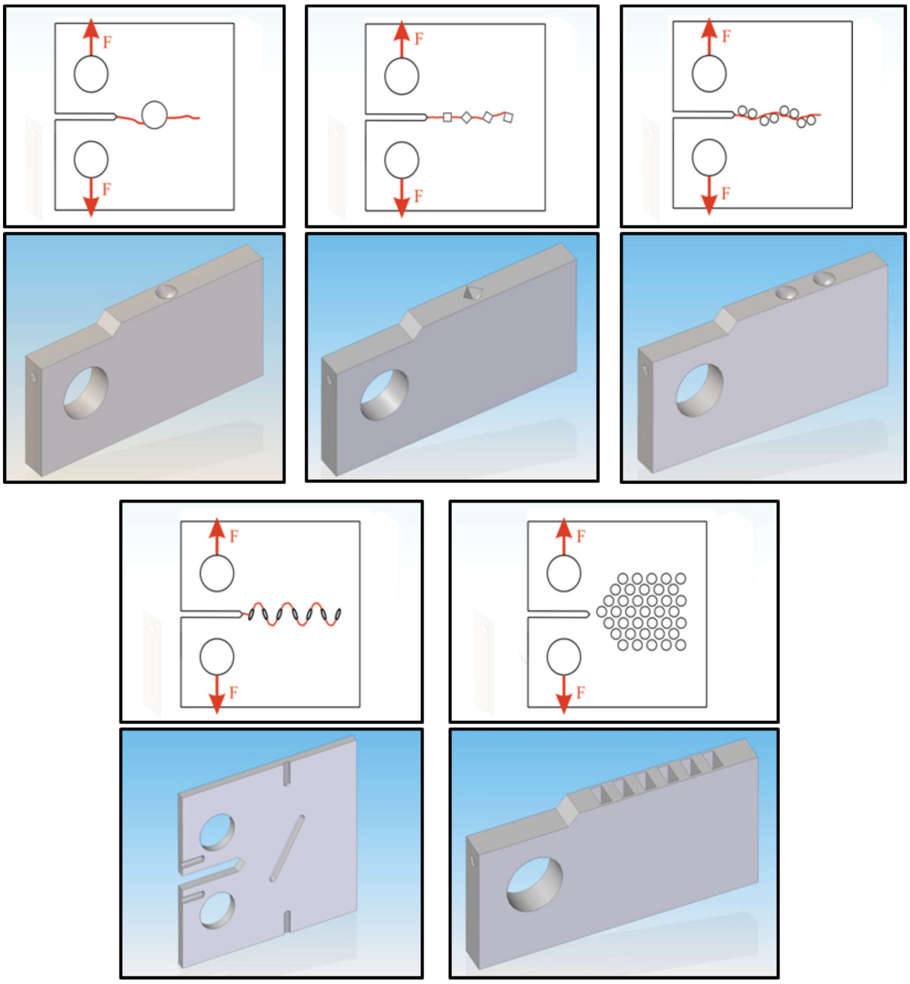


Figure 2: Schematic illustrations of notch form, notch position and notch orientation for life time manipulation

Approach

Testing program for basic investigation of life time manipulation

In the first step, preliminary tests on modified CT-specimens containing one hole will be performed, Figure 2. Furthermore, the number of holes will be elevated to a row of holes. The position of them is in the middle of the specimen. In the next step, samples with different notch positions will be produced in order to investigate life time manipulation due to crack deflection. After that, elongated holes with different orientations will be tested in order to investigate life time manipulation due to different crack deflection situations. In the last step, the number of rows will be heightened to an array of holes. The findings of this test series will be used to describe the crack growth performance in high-grade notched structures.

Florian Brenne

Light-weight Construction: Robust Simulation of complex loaded cellular Structures

In order to reduce the energy consumption of moving parts as well as the total amount of the material used, diverse light-weight strategies are currently in the focus of industry and research. One promising light-weight strategy is the application of additively manufactured cellular structures, which due to their low relative density are characterized by high relative strength. These structures can be adapted to the load by local modification of the strut diameter or strut orientation (Figure 1). Consequently, a more efficient design can be achieved allowing for reducing the structural weight as well as the overall material use. For industrial application a robust and reliable simulation is imperative, as the structural performance in dependence of both the cellular design and the microstructure has to be predictable under complex loading scenarios prevailing in many actual applications. Thus, the establishment of a robust FEA model for complex loaded cellular light-weight structures will be aim of this project.

Preliminary Analysis

Deformation behavior determined by digital image correlation (DIC) and finite elements analysis (FEA)

In a preceding project, the occurring deformation mechanisms of metallic specimens under uniaxial and bending load were investigated. A straightforward simulation of a simple cell geometry under uniaxial load showed a good accordance between the observed and simulated local deformations (Figure 2). Still a simulation under bending load proves difficult and the microstructural condition could not yet be taken into account.

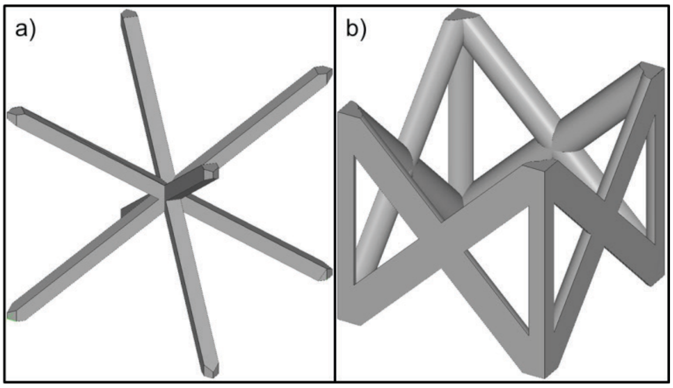


Figure 1: Design of a body- centered base cell a) and face- centered base cell with additional struts in loading direction b)

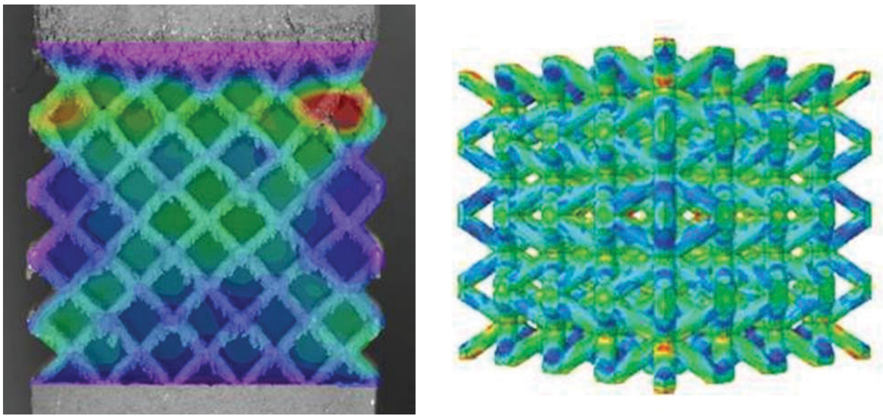


Figure 2: Local strains under compressive force as determined by DIC (left) and FEM (right).

Approach

Mechanical testing and verification of obtained FEA models for metallic and plastic materials

The key activities in order to obtain a robust FEA model include:

- Design of different base cell types to be investigated
- Microstructural modification by (local) heat treatments
- Mechanical testing and local strains analyses
- Development of different FEA models for simulation
- Verification

Stefan Leuders

Andre Riemer

Innovative SLM Materials

Through previous DMRC projects in the field of selective laser melting, very promising properties of components manufactured by this process were shown. As an example, tailored mechanical properties of components as well as high strength lattice structures could be mentioned. Thus, the high potential of the SLM process was demonstrated for different applications and deep process knowledge was built up during these projects. Nevertheless, all these investigations have been carried out on more or less conventional materials, such as titanium alloy TiAl6V4 or stainless steel 316L. This leaves a huge potential of the SLM process unconsidered: An in situ combination and processing of different materials (which possibly cannot be processed together by conventional methods) in order to obtain characteristics that are often in contrast to each other. Very promising would be e.g. a particle reinforcement of a light metal, such as a combination of AlSi7Mg and Al2O3. These ceramic particles could significantly increase the stiffness and wear resistance while the density of this combination would be only minimally affected. Hence this material would be very interesting for various applications in aerospace or tribological systems.

In order to enable a systematic procedure for the proposed project, a subdivision into the following work packages should be made:

Work package 01: Specification & Screening

Within the first work package a material-screening should be performed in order to define possible combinations of two or more materials to be investigated for the SLM process. In order to allow a non-biased screening, this work package is based on previous definition of desired properties, which should be achieved by the new materials.

Work package 02: Parameter development

Since a transferability or adaption of existing exposure parameters cannot be assumed, these parameters must be developed fundamentally new for the composite material. The development of exposure parameters will be performed in two steps: First, a stable relationship between laser power and scanning speed should be achieved by producing and investigation of single tracks. Based on these results, small cubes should be manufactured in order to consider hatch distance, layer thickness etc.

Work package 03: Mechanical properties

Since a detailed knowledge about the performance is a fundamental requirement for the use of a specific material, a comprehensive characterization of the mechanical properties should be carried out within work package 3. These studies include both quasi-static as well as cyclic tests, while the emphasis is determined in consideration of the requirements from work package 1.

Work package 04: Concept development “locally adapted material combinations”

The work package 4 aims at developing a rough concept that enables for local adaptation of mixing ratios. The concept is to identify ways and means to obtain graded properties through adapted mixing ratios, combined with appropriate exposure parameters as well. The local variation of mixing ratios should be made possible for both alongside the z-direction as well as within the x-y plane. Furthermore, through sensitivity analysis should be assessed to what extent different mixing ratios will require adjusted exposure parameters.

Work package 05: transfer analysis

In order to investigate a transferability of developed process parameters on other SLM systems, the new material should be also processed on an EOS system. Furthermore, a rough comparison in terms of resulting microstructure and mechanical properties between these two different SLM systems should be carried out. After development of process parameters various specimens should be built at EOS Electro Optical Systems GmbH and afterwards examined at the DMRC with respect to microstructure and mechanical properties.

This research project is being processed by the departments of “Automotive Lightweight Construction”, “Materials Science” and “Applied Mechanics”.

3.2 Current External Projects

Project RepAIR: Future RepAIR and Maintenance for Aerospace Industry

Christian Lindemann

Gereon Deppe

Jens Pottebaum

Marco Plaß

The goal of this research project with twelve partners from all over Europe and from the US is the onsite maintenance and repair of aircraft by integrated direct digital manufacturing of spare parts. Cost efficient and lightweight but robust reliable parts are obligatory for aircrafts. Additive Manufacturing allows completely new approaches: The main objective of RepAIR is to shift the 'make' or 'buy' decision towards the 'make' decision by cost reduction in the remake and rework of spare parts and therefore to improve cost efficiency for maintenance repair in aeronautics and air transport.

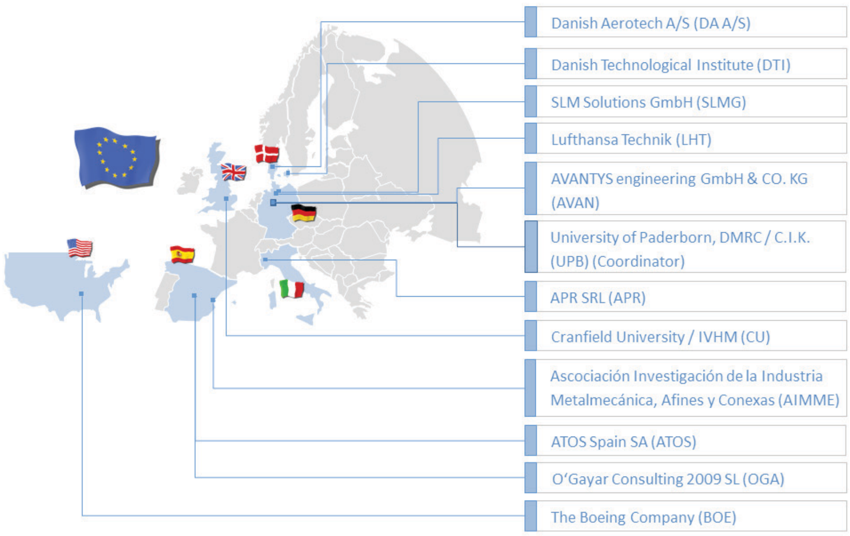


Figure 1: The Consortium of RepAIR

AM allows on-time maintenance

Flexibility of AM helps to reduce Maintenance, Repair and Overhaul costs

To foster this development the RepAIR project receives funding from the European Union Seventh Framework Programme with a total project budget of 5.971.421 EUR. The project aims to reduce the Maintenance, Repair and Overhaul (MRO) costs with the help of the Additive Manufacturing technology as its crucial advantage is the flexible availableness allowing on-time maintenance without having the need of sophisticated supply chains. The AM operations require a higher qualification and promote the preservation and expansion of highly qualified workplaces in Europe and make them more competitive.

Moreover, the storage costs will be significantly reduced and less capital is locked up. Additionally, hardly any energy-intensive produced raw material will be wasted or destroyed, but will be used optimally. New business models will become sustainable. When applied in design of new parts, the technology allows significant weight savings. These weight savings will result in less fuel consumption, therefore in a more sustainable way of flying and in a reduced carbon footprint.

New business models will become sustainable

Additive Manufacturing in the MRO

European maintenance service providers have to deal with an enormous financial pressure. Competitive carriers focus intensively on low costs of repair services and materials while retaining consistent parts and service quality. The maintenance of complex components such as engines still takes place at nearly 100% in Europe. But for European MRO providers the danger of further displacement still endures.

The maintenance of complex parts in Europe is at risk due to high wages

To face this danger one has to keep and expand the advance through mastery of knowledge and technological lead. Based on the effort of the producers to reduce quantity and variety of components, multiple functions will inevitably be merged in complex components, whose maintenance could be taken over by technological leading MRO providers. For cost optimized work, one has to decide specifically if each component has to be replaced or could be reworked or recreated. If the costs for the production and the overhaul of complex components were considerably reduced, the decision would automatically be postponed from “buy” to “make”.

Technological leading MRO providers can face the competition

A particular prospective benefit is promised by the Additive Manufacturing (AM) technology. It offers a considerably lower buy to fly ratio of material, an omission of harmful chemicals (e.g. cutting oil) and constant manufacturing efforts at an increasing complexity (single piece assembly). Further improvements of the technology concerning the processing time, accuracy and costs are foreseeable. However, a holistic integration in the MRO processes is not yet researched.

An integration of AM in the MRO processes has to be researched to leverage the technology

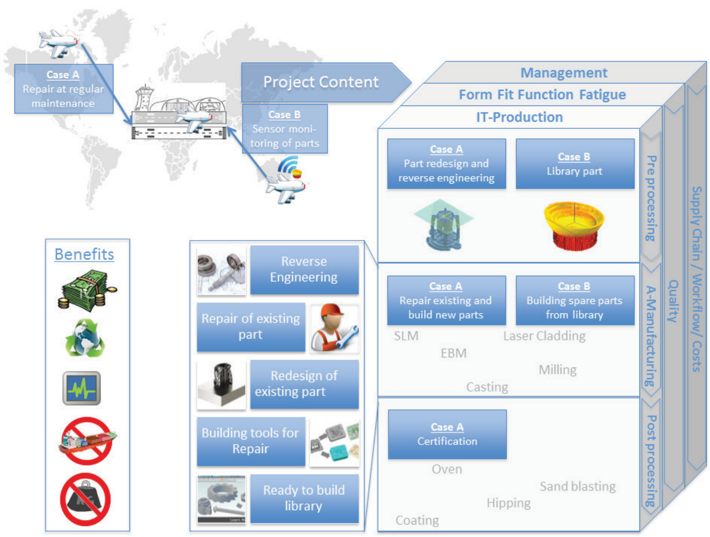


Figure 2: The RepAIR Concept

Thomas Reiher

Ulrich Jahnke

Christian Lindemann

Project NewStructure: Direct Manufacturing of structure elements for the next generation platform

The aim of the project "Direct Manufacturing of structure elements for the next generation platform" – initiated and funded by the European Space Agency (ESA) – is to examine the ability of using Additive Manufacturing for producing structural metallic parts mainly used in actual telecommunication satellites.

Participating partners

As an external project there are four companies participating. The project is funded by the ESA and led by the DMRC started in November 2013. Due to the short distances between the partners frequent meetings and thus an effective interaction can easily be realized.

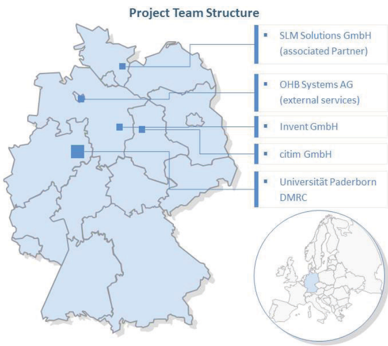


Figure 1: Geographical structure of the project team

High-experienced consortium in spacecraft and additive manufacturing

The project partner "Invent GmbH" works on structural parts for satellites made from composites or metal and brings in a lot of experience in designing and certification of these parts. Knowledge on satellite systems, potential components for the optimization and the needed requirements are provided by the system manufacturer "OHB Systems AG". The manufacturing of the sample parts will be made by "citim GmbH", an experienced manufacturer for prototypes and small series. For production of space flight-relevant metal parts machines of the "SLM Solutions GmbH" are used. SLM is the fourth partner in the project, bringing in the experience in additive manufacturing, as known from the work in the DRMC and with citim.

Project Goals

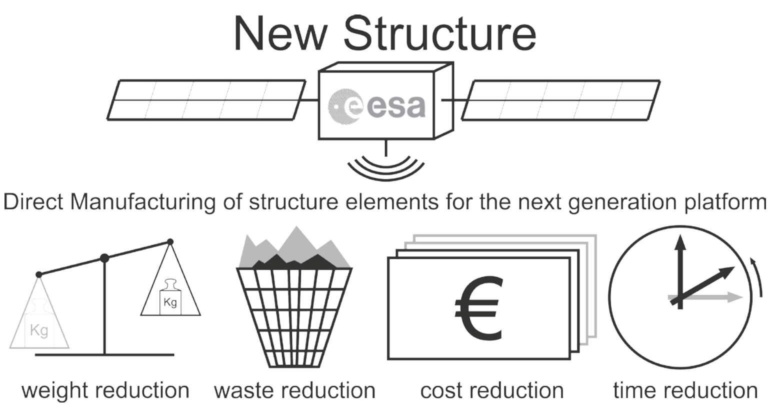


Figure 2: New Structure objectives in a nutshell

In a first step a trade-off methodology used in the project will be developed. Based on this actual structure elements will be identified and ranked according to two types:

- Case A parts: identical elements applicable to each platform
- Case B parts: more complex parts featuring a high buy-to-fly ratio

Typical relevant parts will be those with a high buy-to-fly ratio and time-consuming or complex fabrication steps. For each case one part will be examined in detail. These parts will be built in the Selective Laser Melting (SLM) process either with or without redesign especially for AM. The resulting improvements gained by changing the manufacturing process with or without a redesign on costs and weight will be figured out.

How are cost reductions possible?

Cost reduction due to reduction of weight, waste and production time

It will be analyzed which cost reductions can be achieved by Additive Manufacturing due to three different reductions.

- Reduction of weight used in the satellite
- Reduction of waste in production do to fabrication processes
- Reduction of manufacturing time

Ulrich Jahnke

it's OWL 3P: Prevention of Product Piracy

Companies mostly consider „reactive“ legal protection measures

In a fast moving age manufacturers of innovative products and products of exceptional quality are often victims of product piracy. Imitators enter the market just copying extensively developed products and reducing the deserved turnover of the original creators. To fight this current threat conscious behavior and reliable protection measures are required. But at first the companies itself have to change the way of dealing with the protection of products.

As part of the technology network "intelligent technical systems" OstWestfalenLippe (it'sOWL) funded by the Federal Ministry of Education and Research (BMBF) the project "Prevention of Product Piracy" (its-owl 3P) focuses on raising the awareness that legal measures are just one way to protect innovations and products against product piracy.

Changing the way of thinking

Nowadays a high percentage of companies try to counteract piracy just by the use of legal measures as registration of design and utility patents. These measures are important in the fight against counterfeits as well but they are more reactive than they appear. The imitations are already in the market and so the economic damage is already perceptible before companies can initiate formal complaints.

During the runtime of itsOWL 3P a methodology for the combination of different types of measures will be developed. These types will comprise various protection levels: Strategic approaches, processes and IT, legal aspects, technologies and the products itself. Innovative technologies as Additive Manufacturing (AM) and intelligent technical systems will be considered. The Direct Manufacturing Research Center (DMRC) focuses on AM technologies and will analyze the potentials of AM for innovative protection measures in terms of complex design, specific functionalities and tagging opportunities that can be realized by the use of AM.

Contribution of AM to prevention of product piracy

A comprehensive protection can be achieved by combining measures in various levels

At the projects beginning the specific characteristics and possibilities of AM has been analyzed to show the potentials to contribute to product protection. The threats of product piracy are split up in the above mentioned levels as shown in figure 1. In the focus of this model are the products itself that are surrounded by the technological level addressing the manufacturing processes. The next level deals with legal aspects in terms of registration of property rights etc. followed by the layer of Processes and IT in which for instance the ways of communication and data flow and its security are analyzed. The outer level contains strategic matters in a company and is with respect to a specific product the most abstract layer. Regarding to these different levels the specific chances and barriers of AM have been examined. The small “AM-circles” in figure 1 mark the levels to which AM can contribute due to the freedom in design, flexible production, individualization of products etc.

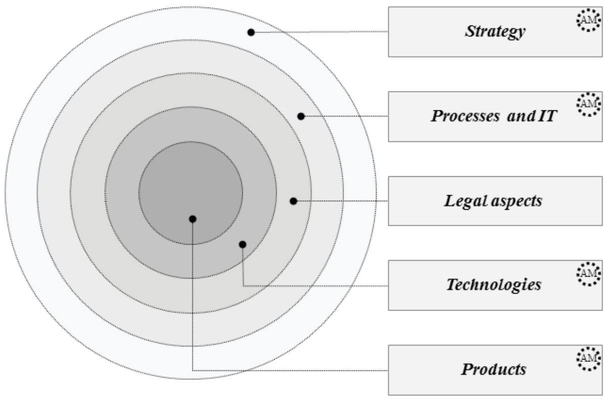


Figure 1: Levels of Protection / Potentials of AM

Consortium of it’s OWL 3P collaborates closely with companies

The DMRC cooperates with the Heinz Nixdorf Institute (HNI) of the University of Paderborn, the Fraunhofer Project Group – Mechatronic System Design (IPT-EM) and the UNITY AG as project coordinator. The companies that are part of the technology network it’sOWL will directly benefit from the projects results. For some companies the threats of product piracy will be analyzed during the project and so they will receive the knowledge of how to counteract. Simultaneously this cooperation with the companies serves to evaluate the applicability and transferability of the projects results.

High Temperature Fatigue Behavior of Nickel based Superalloys manufactured by Selective Laser Melting

Mehmet Esat Aydinöz

Employing additive manufacturing (AM) in general and selective laser melting (SLM) in particular, it is possible to produce metallic parts and components of high complexity. SLM allows designing load adapted parts with locally varying properties, either induced by geometry and/or microstructure. The aim of this project is to attain a comprehensive understanding of the process-microstructure-mechanical property relationships of Ni-based superalloys processed by SLM. This will the basis for the development of a robust processing routine for components made from Inconel 718, showing high geometric complexity and optimized microstructure for high-temperature loading. In order to reveal the potential of parts manufactured by SLM, results will be compared to similar parts obtained by traditional manufacturing techniques such as casting or forging.

Microstructural characterization after SLM

Microstructural Analyses

The microstructure of SLM material strongly influences mechanical properties such as strength, toughness, ductility, hardness etc. and consequently has to be thoroughly studied.

In this project microstructure evolution is characterized using various techniques including optical microscopy, electron backscatter diffraction and X-Ray diffraction. Using these techniques in a combined fashion, deep insights into process and loading induced structures, i.e. grain sizes, grain morphology, grain orientation, phase composition and texture will be obtained.

Especially the microstructural stability under high-temperature monotonic loading as well as fatigue loading will be of high interest, as stability is crucial for the envisaged applications. Stability will be significantly influenced by precipitates formed artificially by ageing or during thermo-mechanical testing.

Tensile tests

Mechanical Testing

Mechanical experiments will be performed under different loading conditions. In a first step the characterization of the behavior under monotonic load at ambient temperature will shed light on the role of process induced microstructures, i.e. the general impact of grain shape and texture. In the following the tests will be extended to different sample and loading conditions. Clearly, an artificially aged condition needs to be characterized thoroughly, as only this condition will show good properties in the high-temperature regime. The main focus will then be in characterization of the alloy performance under cyclic loading at elevated temperature. It will be of high interest to clearly show what the reason of crack initiation is, i.e. where cracks will start, and in which ways cracks evolve during further loading.

The following figure 1 highlights the role of processing parameters, i.e. building direction, on the tensile strengths of Inconel 718 specimens tested at ambient conditions.

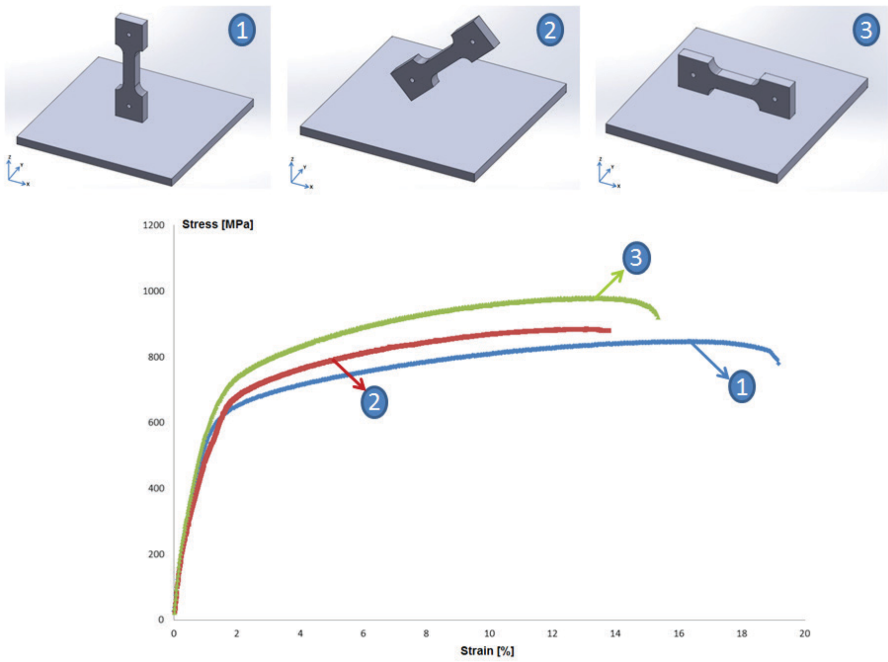


Figure 1: Stress-strain curves of Inconel 718 specimens

In further experiments high temperature fatigue properties from Inconel 718 and the influence of hot isostatic pressing on the fatigue behavior will be investigated.

4 Involved Chairs and Institutes

HEINZ NIXDORF INSTITUTE
University of Paderborn
Product Engineering
Prof. Dr.-Ing. Jürgen Gausemeier

Product Engineering

Identifying and Exploiting Success Potentials of Tomorrow

Product and production system innovations are important levers for ensuring prosperity and employment in the future. Mechanical engineering and related areas, such as the automotive industry, are playing a key role today. These sectors demonstrate the relevant success potentials of the future. It is essential to identify these potentials early on and to exploit them at the right time.

Information and communication technology does not just lead to increased productivity – but also to the creation of new products and new markets. Our general aim is to increase the innovative strength of industrial companies. Our key activities are:

- Strategic Planning and Innovation Management

The basic aim is the analysis of product requirements for future markets. Basically, it is about anticipating the development of technologies and markets, as well as creating technology, product and business strategies.

- Design Methodology for Mechatronic Systems

This level involves the interdisciplinary design and specification of mechatronic systems, methods for increasing the reliability of such systems, as well as development guidelines for products that include new technologies, such as the MID-technology (Molded Interconnect Devices).

- Production System Planning

The focus lies in the strategic conception of production systems for mechatronic products. This conception is characterized by the interplay of process planning, place of work planning, production resource planning and production logistics.

- Virtual Engineering

Technologies like Augmented Reality, Virtual Reality and Simulation increase the efficiency of Product Engineering.

The aim of our teaching is to supply our students with a comprehensive overview of modern industrial companies, in order to highlight the success potentials of the future and to illustrate ways of achieving these potentials. Our students gain the expertise that is necessary for an industrial career of the future.

Computer Application and Integration in Design and Planning

The research group Computer Application and Integration in Design and Planning (C.I.K.) takes advantage of basic technologies and innovative IT concepts and technologies together with the related methodologies. Specific research and work priorities are:

- Analysis of requirements in close cooperation with stakeholders based on the adaption and advancement of approved requirement engineering methods.
- Application of software engineering methods from conceptual design to implementation of information systems.
- Evaluation of research results and quality management in the product development with focus on usability of software solutions.

In collaborative research projects the C.I.K. bridges the gap between science, industry and user. This is emphasized by close connections with manufacturing and service companies including small and medium sized enterprises as well as large industry. The focus on problems and goals of human stakeholders supports the transfer of research results into practice.

In the context of decision support and expert systems as well as knowledge based approaches and information management various methods are applied and scientifically analysed. The IT-based collection, processing and target oriented provision of information is studied with respect to pragmatic aspects. In this regard, the use of business process management methods and semantic technologies is a major priority in current projects.

The projects of the C.I.K. cover a broad spectrum of relevant topics in the field of Design and Planning. Specific goals are given by the collection of experiences, the integration of expert knowledge into product and process models, the identification and utilization of hidden knowledge as well as IT support in complex environments.

The research group C.I.K. is one of the leading German institutes for research on civil safety and security. Within numerous projects the research group is building the bridge between civil rescue organisations, additional end user groups and other project partners. The experience in industry research has been enhanced with the beginning of scientific projects in the field of Additive Manufacturing. The C.I.K. is currently attracting international attention with the coordination of the EU funded project “RepAir” and the ESA project “New Structure”. The gained expertise is the foundation for our ideas, systems and technologies in the context of emergency planning, coordination support, training and decision support.

Today thirteen research assistants and about twenty student assistants are working for the C.I.K. bringing in knowledge from the fields of engineering, computer science, economics and mathematics.

LWK
Lehrstuhl
für Werkstoffkunde

Material Science

The main research field is the development of validated material models which allow for predicting material- and component-properties under relevant loading conditions. Therefore, the macroscopic and microscopic material behavior under superimposed mechanical, corrosive and thermic loads is determined in experiments whereat mainly metallic materials are investigated. Typically, characterization of the microstructure before and after the experiments by light, X-ray and electron-optical methods is carried out in order to determine the microstructural evolution during the experiments. In particular the research activities involve the following topics:

- Fatigue behavior of nickel based alloys at high temperatures
- Fatigue behavior of high manganese steels
- High temperature shape memory alloys
- Microstructure and mechanical behavior of structures manufactured by selective laser melting
- Phase transformation behavior in steels

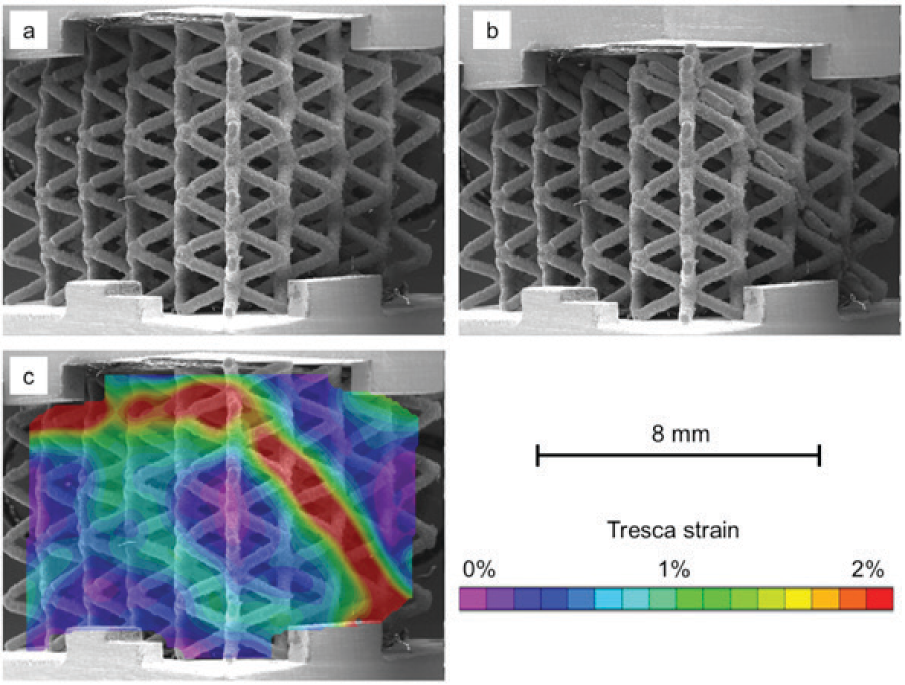


Figure 1: Compression test of a lattice structure in the initial (a) and deformed (b) condition. Furthermore, the local tresca strains (c) measured by digital image correlation are shown.

Applied Mechanics

Teaching and training

During the lectures of the institute for applied mechanics, basic knowledge and procedures to assess stress conditions and the course of movements of components as well as of machines is imparted. Model design, which identifies the process of transferring real components into abstract models for calculation purposes, plays an important role. During the undergraduate study period the courses are characterized by the imparting of basic knowledge concerning technical mechanics (static, strength theory, dynamics) while during the advanced study period basic research and practically oriented knowledge is consolidated especially with respect to strength optimized and fracture save design, methods of structure analysis, the Finite-Element Method, computer supported product optimization and biomechanics.

Research

The FAM conducts application oriented and pure research and development in the area of applied mechanics. The motivation essentially arises from the areas of structural mechanics, biomechanics and computer simulation and may be divided into three main research fields.

“Strength optimized and rupture safe design of components” deals with the dimensioning and optimization of components and structures with respect to the practically oriented development of the existing Finite-Element-Method standard software and its efficient use in various applications. In this connection the applied tools are stress and deformation analysis as well as notch stress tests and fracture mechanical tests including fatigue crack growth experiments. The extension behavior of fatigue cracks in many cases determines the life time of the components and technical structures. To predict the crack growth behavior and to prevent damage, various crack growth simulation programs were created and are in use at the institute.

The area “Biomechanical analysis of the human motor activity” covers the designing of the human bone structure with the help of computers over the simulation of courses of movement up to the optimization of implants and prosthesis and the development of intelligent healing aids. The aims are the evaluation of injury risks, the avoiding of resulting injuries and the optimized use of prostheses and implants.

The third area of research “Optimization and new development of products in cooperation with industrial partners” deals with the solving of concrete problems which occur in practice by implementing the above mentioned core competences.

Particle Technology Group

Particle technology is a specialization in Process Engineering. We investigate the properties of particulate systems; the production, conditioning and manipulation of particulate systems as well as the characterization of particulate systems. Such particulate systems may consist either of solid, liquid (i.e. droplets) or even gaseous (i.e. bubbles) particles in a matrix which might be either gaseous or liquid. These systems show a complex behavior, sometimes called the ‚fourth state of aggregation'. Particularly, if particles become smaller and smaller particle-particle interactions become dominant for the behavior of such systems. The Particle Technology Group is involved in both fundamental and applied research in the field of particle technology. We have a strong focus on understanding the behavior of particulate systems and to learn how to produce a requested particulate product property. Therefore, doing fundamental, publicly funded research is considered to be equally important as cooperations with companies on very specific projects to develop solutions in the field of particle technology. The Particle Technology Group performs research and offers expertise in the following fields:

particle synthesis

- arosol particle formation
- precipitation / crystallization in liquids

characterisation of particles and dispersed systems

- analysis of particle size distribution and particle structure
- analysis of powder properties, e.g. bulk flow properties, bulk density
- rheology of suspensions
- analysis of multi-phase flows, e.g. measuring velocity fields

handling and manipulation of particulate systems and products

- production of composite materials
- filtration and separation
- dispersion and mixing technology
- interface phenomena and nanoparticulate systems

simulation of particulate systems

- particle level (e.g. simulation of evolution of particle properties)
- unit operation level (e.g. Computational Fluid Dynamics, Population Balance Modeling)
- process level (e.g. flow-sheet simulation of complete particulate processes)

Polymer Processing

The KTP stands for thirty years of successful research and development of manufacturing processes in the field of polymers and rubbers. This results a qualified training in the theoretical and practical field of polymer engineering as well as an intensive cooperation with regional, national and international industrial companies. International congresses and conferences are regularly participated by the KTP staff. The KTP belongs to the faculty of engineering at the University of Paderborn and its two professorships ensure a broad range of knowledge transfer.

- Polymer Engineering, Prof. Dr.-Ing. Elmar Moritzer

- Polymer Processing, Prof. Dr.-Ing. Volker Schöppner

The research at the KTP is about different kinds of polymers as innovative solid material, the potential of which is by far not exhausted. Polymers become more and more significant in the field of mechanical engineering, above all in the automobile industry, and displace traditional materials in their application fields. To adapt the processing performances optimally to the technical requirements, the KTP has developed application-oriented simulation tools for all fields of polymer processing. These software tools help to find solutions of problems quickly and make it possible to achieve a high process transparency.

The research foci have a special concentration on the transformation of process models, which have been built on the basis of process analyses (experimentally or theoretically), into tools to simulate polymer processing procedures. The central aim is the simulation of the process chain from the molecule to the end product. Due to the experimental verification of the models and simulation tools as well as in return the use of simulation tools to improve the processes, an interplay between theory, experiment and modeling/simulation, in terms of a continuous improving process exists. To realize this strongly feedback-oriented proceeding, real processes in the laboratory- and production measure – the latter often in cooperation with industrial partners – are of the same importance as the theoretical and simulation-based analysis of the processes and the necessary IT- equipment and competence. Hence, the KTP emphasizes a good laboratory equipment.

Automotive Lightweight Construction

Endowed chair by Benteler AG since 2007

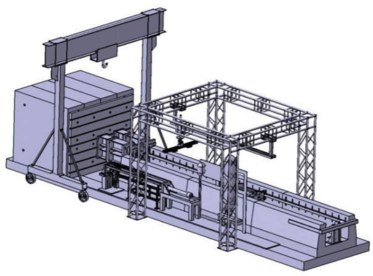
Due to exhaustible raw materials and demands on climate protection, the reduction of vehicle masses in order to reduce fuel consumption is of critical importance. Therefore, our focus lies on innovative solutions for automotive lightweight constructions, e.g. steel lightweight products like press-hardened ultra-high-strength steel components. Going towards load adapted parts, we are especially concerned with components, where the properties of different sections are adjusted to meet the specific product requirements. Thus, low or high strength, brittle or ductile areas can be created locally. A further focus lies on hybrid-components composed of material-combinations, e.g. metal - fiber-reinforced plastics, which symbiotically use the specific material advantages. The chair possesses extensive possibilities for studying material as well as component properties. This includes static, cyclic, and dynamical tests, as well as microstructural studies. Crash tests can be performed up to impact velocities of 25 m/s, at which a high speed 3D camera system is used to locally study the deformation of the components.

Major goals

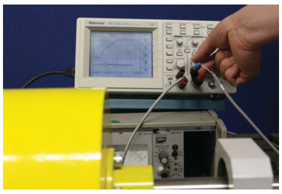
- Product and application-oriented research
- Optimized lightweight construction (Costs / Weight)
- Development of property adjusted (tailored) products
- Research on material and process fundamentals

Equipment

- crash test facility equipped with high speed camera system
- impact energy up to 31 kJ, slide mass 50 to 500 kg, velocity up to 25 m/s
- 3 axle testing
- static and cyclic forces up to 80 kN
- materials testing
- cupping tests (temperatures up to 800 °C)
- tensile and fatigue tests (max. forces up to 250 kN)
- simulation tools
- Abaqus, LS-Dyna, Hyperworks



Design and Drive Technology



The focus of our work lies on theoretical and experimental investigations regarding drive conceptions and on the extensions of drives' application limits.

Thereby, key aspects are

- the reduction of the resources needed for the operation of drive systems, and
- the modularity of drive systems in the context of an intelligent variant management.

The optimization of components, assemblies and machines by

- systematic, function-oriented and production-oriented design is another area of work of our chair. Thereby, an important aspect forms the
- tolerance management.

Regardless of the task field, we often work with industry partners on joint projects.

Primarily, we deal with it

- drive systems, such as „energy-efficient spring-applied brakes", „self-optimizing air gap adjustment", „multi-drive concepts", „modular drive systems"
- drive components, such as „power loss reduced sealing systems", „reduction of fretting corrosion" and
- design technology, such as „development of design rules for additive manufactured parts" and „tolerance management".

For our work we usually use software tools to create geometry (CAD), for modeling and calculating the motion behavior (multi-body simulation). In parallel, we develop and use test equipment to conduct experimental studies.

In teaching, we offer courses on the following topics:

- Basic bachelor studies: Technical drawing, machine elements - fundamentals, machine elements - joints, machine elements - drive components, design drafts.
- Deepening bachelor and master studies: Methodology of design, technical design, industrial drives, geometrical tolerancing.

5 Staff

Directors

Scientific Director

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6 Publications

2013

- **Onsite maintenance and repair of aircraft by integrated direct digital manufacturing of spare parts**
  C. Lindemann
  AIRTEC International Aerospace Supply Fair
  Frankfurt/ Germany, 15th November
- **Exploring The Capabilities And Costs Of Additive Manufacturing Technologies For Production**
  C. Lindemann
  3D Printing & Additive Manfuacturing Industrial Applications Global Summit 2013
  London/ GB, 19th November
- **Impact and Influence Factors of Additive Manufacturing on Product Lifecycle Costs**
  C. Lindemann, U. Jahnke, M. Moi, R. Koch
  24th Annual International Solid Freeform Fabrication Symposium
  Austin/ Texas/ USA 12th-14th August
- **An event-driven software architecture for process analysis in Additive Manufacturing**
  M. Moi, C. Lindemann, U. Jahnke, R. Koch
  24th Annual International Solid Freeform Fabrication Symposium
  Austin/ Texas/ USA, 12th-14th August
- **Potentials of Additive Manufacturing to Prevent Product Piracy**
  U. Jahnke, C. Lindemann, M. Moi, R. Koch
  24th Annual International Solid Freeform Fabrication Symposium
  Austin/ Texas/ USA 12th-14th August
- **A material-based Quality Concept for Polymer Laser Sintering**
  S. Josupeit, S. Rüsenberg, H.-J. Schmid
  24th Annual International Solid Freeform Fabrication Symposium
  Austin/ Texas/ USA, 12th-14th August
- **Some Investigations Regarding the Surface Treatment of Ultem*9085 Parts Manufactured with Fused Deposition Modeling**
  M. Fischer, V. Schöppner
  24th Annual International Solid Freeform Fabrication Symposium
  Austin/ Texas/ USA, 12th-14th August
- **Verhalten von lasergeschmolzenen Bauteilen aus der Titan-Aluminium-Legierung TiAl6V4 unter zyklischer Beanspruchung**
  A. Riemer, S. Leuders, H. A. Richard, T. Tröster
  Materials Testing; Carl Hanser Verlag
  München, August

- **Mechanical Analysis of Lightweight Constructions Manufactured with Fused Deposition Modeling**
  A. Bagsik. V. Schöppner, E. Klemp
  Proceedings of the Polymer Processing Society 29th Annual Meeting - PPS 29
  Nuremberg/ Germany, 15th-19th Juli
- **Fracture mechanical investigations on Selective Laser Melting materials**
  A. Riemer, H. A. Richard, E. Klemp
  13th International Conference on Fracture
  Beijing/ China, 16th-21th June
- **Bruchmechanische Charakterisierung zyklisch belasteter SLM-Bauteile**
  A. Riemer, H. A. Richard
  45th Tagung des DVM-Arbeitskreises Bruchvorgänge
  Berlin/ Germany, 19th-20th February
- **On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting**
  S. Leuders, M. Thöne, A. Riemer, T. Niendorf, T. Tröster, H.A. Richard, H.J. Maier
  Fatigue resistance and crack growth performance, Int. J. Fatigue 48, 2013, 300-307
- **Additively manufactured cellular structures: Impact of microstructure and local strains on the monotonic and cyclic behavior under uniaxial and bending load**
  F. Brenne, T. Niendorf, H.J. Maier
  J. Mater. Proc. Tech. 213, 2013, 1558-1564
- **Steel showing twinning-induced plasticity processed by selective laser melting - An additively manufactured high performance material**
  T. Niendorf, F. Brenne
  Materials Characterization 85, 2013, 57-63
- **Inconel 939 processed by Selective Laser Melting: Effect of microstructure and temperature on the mechanical properties under static and cyclic loading**
  P. Kanagarajah, F. Brenne, T. Niendorf, H.J. Maier
  Mater. Sci. Eng. A 588, 2013, 188-195
- **Optimization of Lattice Structures manufactured by Selective Laser Melting**
  F. Brenne, T. Niendorf, H.J. Maier: Proc. 1st Int. Conf. Int. J. Struct. Integrity
  Porto, 2012, on CD
- **Damage evolution in truss structures manufactured by selective laser melting – effect of loading conditions**
  T. Niendorf, F. Brenne, H.J. Maier: , Proc. CELLMAT2012
  Dresden, 2012, on CD
- **Additive Manufacturing als serienreifes Produktionsverfahren**
  C. Lindemann, U. Jahnke, E. Klemp, R. Koch
  Industrie Management 2/2013; Gito Verlag
  Berlin/ 25-28

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
- **On the microstructure – mechanical property – damage evolution relationships in lattice structures manufactured by selective laser melting**
  T. Niendorf, F. Brenne, H.J. Maier
  MSE 2012, 25th- 27th September, 2012, Darmstadt, Germany
- **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
- **Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing**
  C. Lindemann; U. Jahnke; M. Moi; R. Koch
  23th Annual International Solid Freeform Fabrication Symposium
  Austin/ Texas/ USA 6th-8th August 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
  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

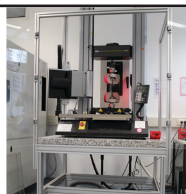
7 Equipment

DMRC

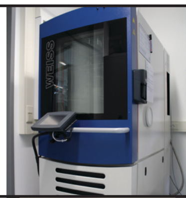
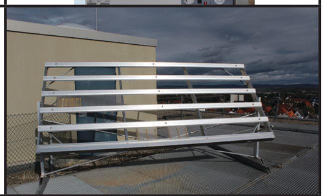
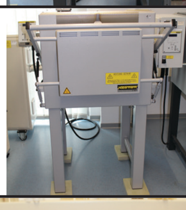
Additive Manufacturing Systems

Polymer Laser Sintering Machine, EOSINT P395, EOS GmbH	
Selective Laser Melting machine, SLM 250HL, SLM Solutions GmbH	
Fused Deposition Modeling machine, Fortus 400mc, Stratasys	

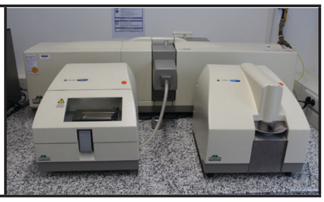
Mechanical Analysis

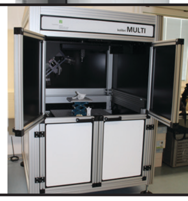
Universal testing system, Instron 5569, Instron	
Universal testing system, HB 250, Zwick GmbH	

Thermal Treatment and Analysis

Climate chamber WK3-180/70, Weiss Umwelttechnik GmbH	
Furnace, UT6, Thermo Electron LED GmbH	
Outdoor weathering frame, Q-Lab	
Annealing furnace N30/85HA(-K), Nabertherm GmbH	
Annealing furnace N41/H, Nabertherm GmbH	
Thermographic camera, P640, FLIR Systems, Inc.	

Optical Analysis

Particle size analyser, Mastersizer 2000, Malvern Instruments Ltd.	

Scanning Electron Microscope (SEM), Phenom SEM, Phenom World	
3D scanning device, kolibriMulti, FhG IOF	

Physical Analysis

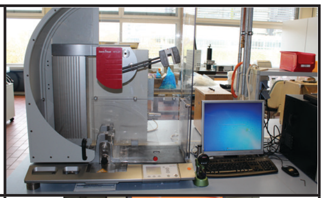
Mechanical profilometer, Hommel Etamic T8000, Jenoptik AG	
Moisture measurement device, **AQUATRAC, Brabender Messtechnik GmbH**	
Precision balance, CPA 224s, Satorius AG	
Broadbrand dielectric spectrometer, Novocontrol GmbH	
Rheometer, Physica MCR 501, Anton Paar GmbH	

Surface Treatment

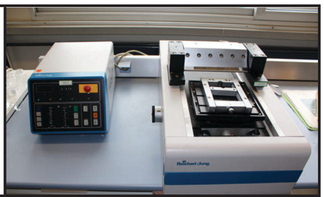
Centrifugal force device, ECO 18, OTEC Präzisionsfinish GmbH	
Sputter coater, SC7620, Quorum Technologies Ltd.	
Ultrasonic clean station, UW90, German Sonic Ultraschallanlagen GmbH	
Glass sphere blasting cabin, Normfinish Junior, Arteka	
Glass sphere & Corundum blasting cabin, SMG 25DUO, MHG Strahlanlagen GmbH	

KTP

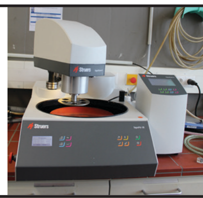
Mechanical Analysis

Pendulum impact tester, HIT5.5P, Zwick Roell	
Universal testing machine for tensile-, bending-, pressure- and peel tests with different load cells (145kN, 10 kN), Zwick 1446	

Optical Analysis

Thin Cutting device, Polycut, Reichert Jung	
Digital microscope, VHX- 600, Keyence	
Confocal laser microscope, VK - 9710, Keyence	

Physical Analysis

Grinding and polishing device, Tegral/ Force -5, Streurs	
Computer tomograph (CT), Phoenix nanotom s, GE	

Thermal Analysis

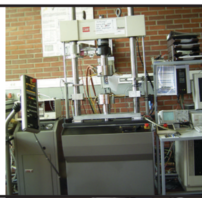
Melt Index Tester, Mflow BMF-001, Zwick/Roell	
High-pressure capillary rheometer, Rheograph 2002, Göttfert	
thermoanalytical testing devices, TGA/DSC 1 Star-System + TMA/ SDTA841, Mettler Toledo Intl. Inc.	

Joining Laboratory

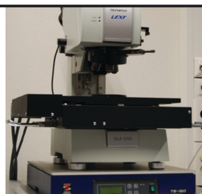
Hot plate welding machine, K2150, Bielomatik Leuze GmbH	
Ultrasonic welding machine, LV 2020-CPC, KLN Ultraschall AG	

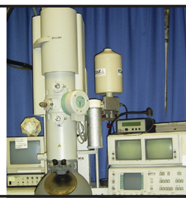
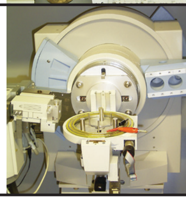
LWK

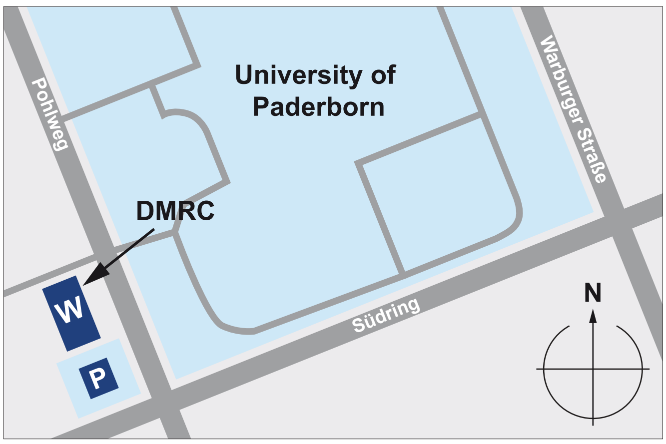
Mechanical Analysis

Servo-hydraulical testing system, MTS Systems	
Servo-hydraulical testing System, MTS 858 Table Top System, MTS Systems	
Servo-hydraulical testing system, MTS Landmark, MTS Systems	
Testing system, ElectroForce 3550, Bose	

Optical Analysis

Confocal laser scanning microscope, OLS3100, Olympus	
Scanning electron microscope, XL 40 ESM TMP, Philips	

Transmission electron microscope, CM200STEM, Philips	
X-Ray diffractometer, X‘pert Pro, Philips	



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