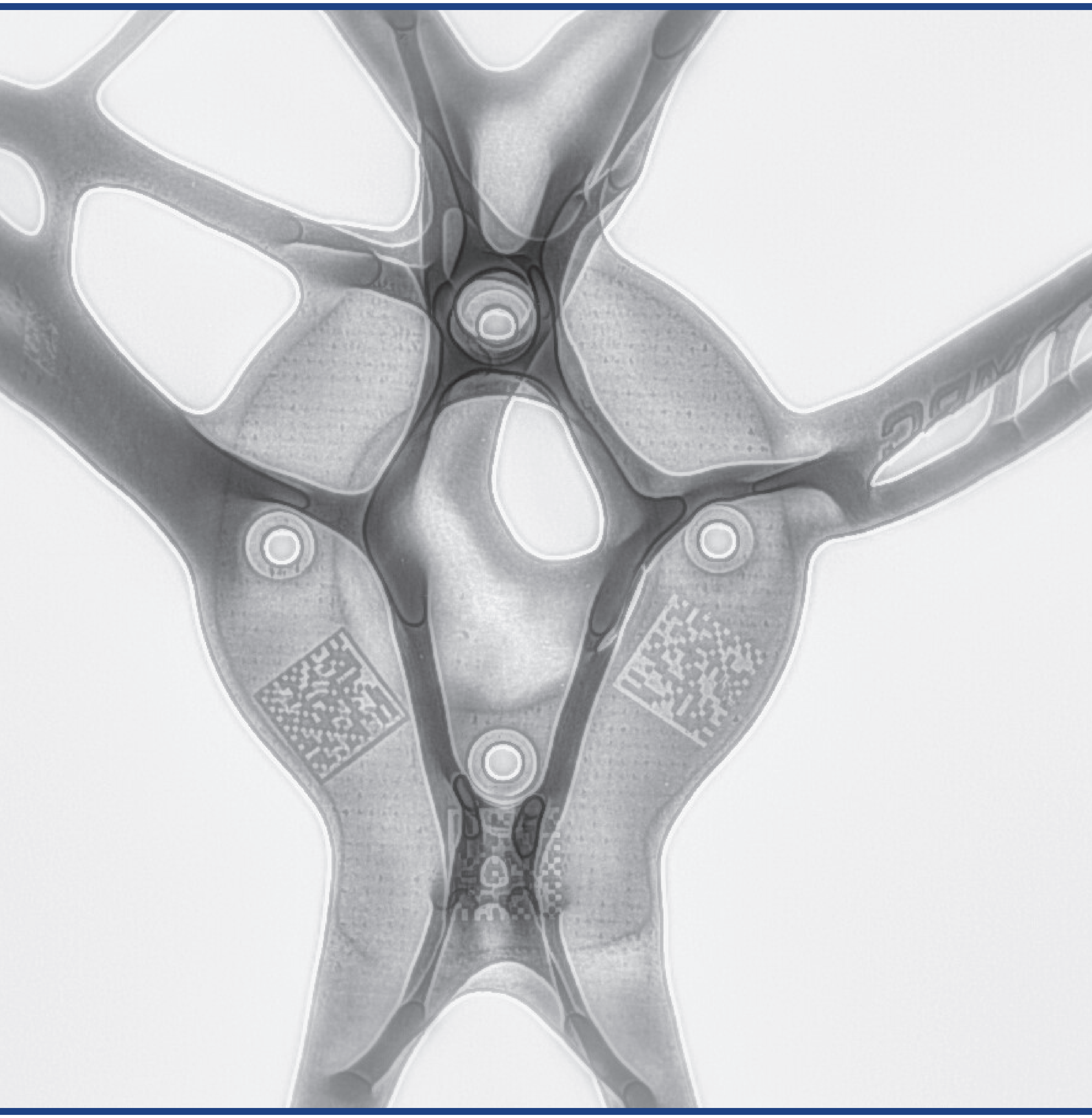
DMRC

DIRECT MANUFACTURING RESEARCH CENTER

Annual Report 2016



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Imprint

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By Order of

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Preface

Dear members and friends of the Direct Manufacturing Research Center,

As you all know, additive manufacturing is a fascinating technology with many different facets and unique characteristics. These offer numerous technical and economic advantages, as well as various possibilities and benefits. However, it must also be acknowledged that additive manufacturing is a technology that is influenced by very short innovation cycles; the current state of the art evolves exceptionally quickly. In addition, due to an increasing industrialization of the technology, new applications and application fields emerge steadily; additive manufacturing is far beyond being a technology only for aircraft and space applications. Hence, in order to not only keep track with the current state of the art of additive manufacturing but to help influence its future growth, a steady and high demand for fundamental and applied research is necessary, just as the development of innovations and the knowledge transfer in terms of industrial and academic teaching is also necessary.

Working in such a dynamic research field and facing the current challenges made 2016 a very interesting and also very intensive year. Within this fifth edition of the DMRC annual report, we would like to share some important news, impressions and achievements with you. A short summary of highlights found in this edition include:

- We are proud to welcome five more industrial companies as new firm members of the DMRC in 2016: Centroplast, Heraeus, JP Industrieanlagen, Torwegge and Voestalpine.

- Performing excellent research, innovation and teaching requires an excellent laboratory that provides numerous possibilities. We are happy to announce that the DMRC now owns a sixth additive manufacturing machine: the Arburg Freeformer. In addition, the measurement equipment and possibilities have been extended in different fields; for example, a new DSC Analysis (Netzsch DSC 214 Polyma) was put into operation.

- In terms of research, numerous publically and DMRC funded projects were performed. Thereby, new research fields – like the usage of additive manufacturing in the field of drive technologies – have been approached. The projects chapter will provide a comprehensive overview of the handled projects and research fields.

- The DMRC also invented and supported several innovations, which allowed our members and partners to build up unique selling points and to earn money. Many of these innovations are confidential, but a few selected innovations are detailed in the innovations chapter.

- In 2016, over 130 students took part in the academic lecture ‘Additive Manufacturing’ and learned fundamental knowledge about additive manufacturing. This is approximately one third of all mechanical engineering students of one year. Additionally, different industrial seminars and workshops were performed during the year.

- In the laboratory and the management two changes took place; Stephan Tölle succeeded Michael Brand as a new laboratory engineer and Dr. Guido Adam succeeded Dr. Eric Klemp as the new Commercial Director.

We wish you much joy reading this report and sincerely thank you for your continued support.

Prof. Dr.-Ing. Hans-Joachim Schmid

Scientific Director

Dr.-Ing. Guido Adam

Commercial Director

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DIRECT MANUFACTURING RESEARCH CENTER

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DMRC – Motivation and Aim

Additive Manufacturing processes create parts in layers and without using formative tools. Thereby, they transfer three-dimensional manufacturing challenges into two-dimensional ones. In addition, for many additive manufacturing processes, the material properties of the additively manufactured part arise during the manufacturing process as a function of the raw material and the used manufacturing parameters. From these manufacturing characteristics results that additive manufacturing offers lots of freedoms, like

- Design freedom: Shapes can be designed and manufactured that cannot be handled with established technologies.
- Material freedom: Material properties, which arise as a function of the raw material and the process parameters, can be influenced.
- Economic freedom: Additive manufacturing decouples the part manufacturing costs from the part quantity and the part complexity

Because these freedoms often exceed the freedoms provided by established manufacturing technologies, additive manufacturing can create various and great benefits to its users. Contrary to this, it is recognized that the technology is mainly used at technology leading companies and research institutes. Small and midsized companies do hardly participate from the benefits. Two limitation factors seem to reason this imbalance:

1. Advantages are often unknown: Possible users do not know where additive manufacturing can gain benefits especially for them.

2. Risks are often unknown: New users cannot seriously identify and rate possible (financial and technical) risks that come along with the technology

Motivated by this significant imbalance between the provided possibilities and the weak usage of the technology the DMRC has the aim to

Develop additive manufacturing towards an industrial established production process by means of internationally outstanding contributions in terms of research, innovation and teaching.

Figure1: Motivation and aim of the DMRC

DMRC – Structure of the DMRC

The aim of the DMRC implies that the additive manufacturing technology shall be handled comprehensively. This goes along with the fact that several very different disciplines need to be covered: material science, particle technology, process understanding, mechanics, applications, design, software support, business and so on. In addition, the research and development focus will change over time from one discipline to another.

Both, the various different disciplined be handled as well as the changing research and development focus, clearly define two mayor goals that the structure of the DMRC needs to meet:

1. The DMRC structure must be interdisciplinary
2. The DMRC structure must be flexible

In order to fulfill these requirements, the DMRC is structured in different layers:

- DMRC Basic Layer: This layer contains the management of the DMRC, the industrial and the scientific board as well as the laboratory. The DMRC Basic Layer has the task to steer the DMRC and to create an appropriate surrounding to perform research and innovation.
- DMRC Project Layer: Within this layer, projects are performed. Therefore, each project consist of the project leaders, who are send by both the industry and scientific board, the research assistants and, if required, additional equipment. Project tasks and budgets are defined in the DMRC Basic Layer. Based on the described tasks, the individually required personals are then invited to join the DMRC Project Layer to perform the projects. Once a project is fully finished, further research needs influence, if the expert remains in the DMRC Project Layer and continues the work or if other experts from other disciplines join.
- Paderborn University: The surrounding and the third layer for the DMRC forms the Paderborn University with its five faculties. Located in this surrounding, the DMRC can invite experts from Arts and Humanities, Business Administration and Economics, Natural Science, Mechanical Engineering, Computer Science, Electrical Engineering and Mathematics to join the DMRC and work on projects.

Based on this layered structure, the DMRC guarantees to be highly interdisciplinary and flexible.

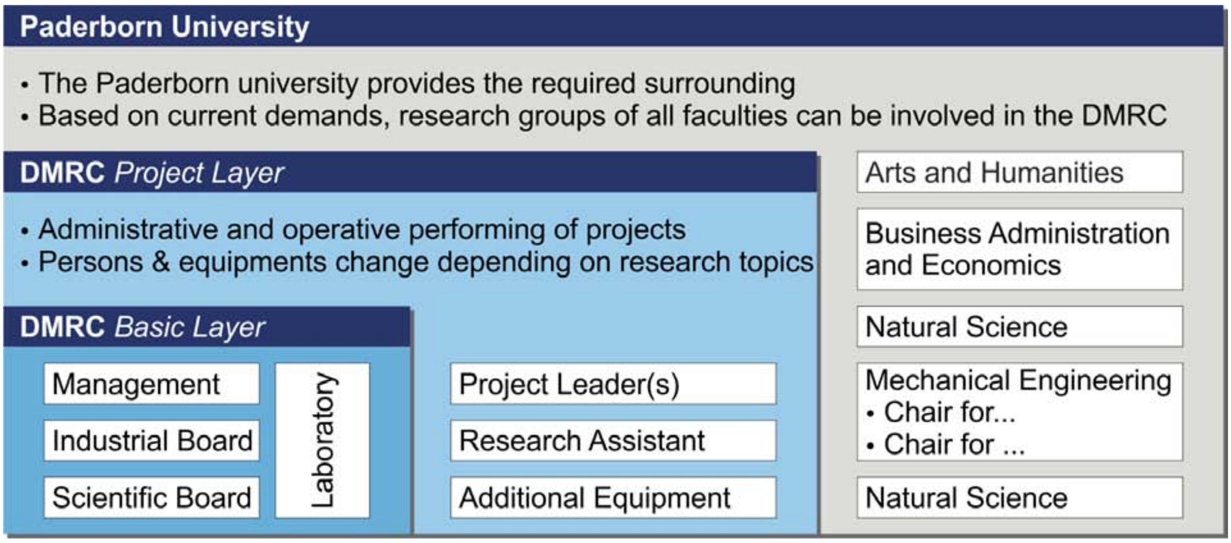


Figure2: DMRC Structure

DMRC – Chairs and Institutes

Additive Manufacturing is a highly complex technology with many different aspects and items that need to be considered, researched or innovated on the way to an industrial established technology. Therefore, it is essential to work together on these aspects and items with experts from different disciplines.

In 2016, the DMRC worked together with twelve professors from nine chairs from the faculties for Natural Science and Mechanical Engineering. The following table and the pages 75-84 introduce the professors and chairs.

Prof. Dr.-Ing.
Jürgen Gausemeier

Strategic Planning and Systems Engineering

Prof. Dr.-Ing. habil.
Gunter Kullmer

Chair of Applied Mechanics

Prof. Dr.-Ing.
Hans-Joachim Schmid

Particle Technology Group

Univ.-Prof. Dr.-Ing
Iris Gräßler

Product Creation

Prof. Dr.-Ing.
Elmar Moritzer

Polymer Technology

Prof. Dr.-Ing.
Volker Schöppner

Polymer Technology

Prof. Dr.-Ing.
Gudio Grundmeier

Technical and Macro Molecular Chemestry

Prof. Dr.-Ing. habil.
Hans Albert Richard

Chair of Applied Mechanics

Prof. Dr. rer. nat.
Thomas Tröster

Automotive Lightweight Construction

Univ.-Prof. Dr.-Ing.
Rainer Koch

Computer Application in Design and Planning

Prof. Dr.-Ing. habil.
Mirko Schaper

Chair of Material Science

Prof. Dr.-Ing.
Detmar Zimmer

Chair of Design and Drive Technology

Figure 3: Professors of the DMRC

DMRC – Partners

Being part of a network often provides benefits and possibilities that cannot be obtained individually. Therefore – besides fundamental and applied research – the DMRC provides an excellent network. At its core, this network is formed by a research community that is comprised of 24 industrial partners in 2016 from all disciplines along the value chain of Additive Manufacturing. This network allows our industry partners to benefit from both the commonly researched knowledge and the collaboration within the DMRC stakeholder network. Performing pre-competitive research, being preferred partner in publicly funded projects or exchanging knowledge about cutting-edge research findings and innovations are just a few points our partners benefit from.

Figure 4: Partners of the DMRC in 2016

DMRC – Laboratory

Performing cutting-edge research and innovation does not only require a band of excellent researchers, it also presupposes an appropriate laboratory, which is equipped with a variety of the latest manufacturing technologies and modern measurement devices. In order to fulfill this task, the DMRC provides in total six industrial relevant manufacturing machines from four different technology and material types. This capacity is enriched by a large number of mechanical, optical, geometrical and physical measurement equipment.

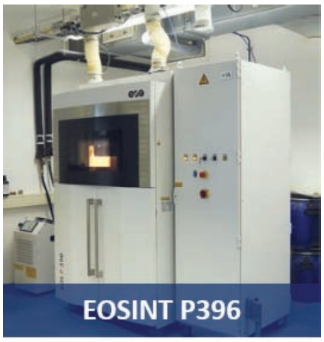
This equipment will continuously be updated and increased. Just to name a few, just recently, the DMRC owned a new coordinate measurement machine, which is mainly used to investigate geometrical properties of additively manufactured parts. Also in 2016, the DMRC set a brand new Arburg Freeformer machine into operation in order to provide latest research results with this machine to the DMRC members.

And, in case the DMRC equipment is still not sufficient for a specific task or request, the DMRC can also use all equipment, which is available at the chairs that work together in the DMRC. This chair-equipment comprises a very wide field of different testing machines, microscopes, test rigs and even computer tomography. Summarizing this, the total accessible equipment opens up the opportunity for the DMRC partners to get access to a very wide spectrum of different additive manufacturing machines and testing equipment.

To get an overview about the manufacturing machines and the testing equipment, which is installed in the DMRC, please check the tables listed on the next pages

Figure 5: Operating the Arburg Freeformer: Christina Kummert, Andre Hirsch, Stephan Tölle

Laser Sintering



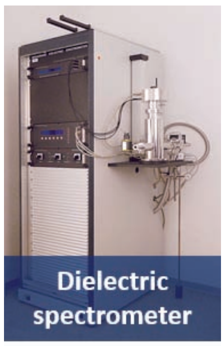
Fused Layer Modeling

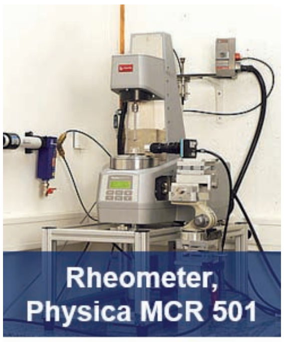
Laser Melting

DMRC – Laboratory

Optical Analysis

Physical and chemical Analysis




Rheometer, Physica MCR 501


Extrusion plastometer Mflow


Sputter Coater SC7620

Mechanical Analysis


Instron 5569


Zwick HC 10


Zwick HB 250


Test rig for bending vibrations

Geometrical Analysis


Nikon Altera 8.7.6


Hommel Etamic T8000

2 Research

Additive Manufactured Function Integrated Damping Structures

Mechanical vibrations occur in almost all industrial applications. They are usually undesired and make damping necessary. The additive manufacturing processes offer a huge amount of design freedom given by the layer wise manufacturing. Further, they possess unique process specific properties. Utilizing this, it is possible to design and manufacture parts that already imply an integrated damping function. The process characteristics can be used to directly manufacture particle damper inside the parts with additive manufacturing by integrating special shaped cavities that are filled with the powder material during manufacturing.

1. Objectives

The goal of the Additive Manufactured Function Integrated Damping Structures (AMFIDS) project is to research how additive manufacturing processes can be used to integrate damping functions into existing structures of technical systems. In addition, it has to be analyzed how the damping effect can be specifically adjusted to different occurring vibrations, in order to achieve an optimal damping value. Based on the empirically developed results a simulation model will be conceived, that can simulate the damping function for different vibrations and for different part structures. The conceived simulation model should support the design of parts with integrated damping functions for different occurring vibrations.

2. Procedure

In order to fulfil the objectives of the AMFIDS project, the required test technology has been developed and manufactured first. The test technology is able to create free and forced vibration under bending or torsional load. Furthermore test specimens with different integrated damping functions have been developed. Subsequently to the development of the test technology and the test specimens, experimental tests were conducted. For this purpose, the test specimens have been manufactured using laser beam melting (LBM), laser sintering (LS) and fused deposition modeling (FDM) processes. The goal is to determine optimal variations for the influencing factors, so that vibrations can be specifically minimized, changed or eliminated. By comparing the results to the results of a reference test specimen, which does not have an integrated damping effect, the degree of minimization, change or elimination of the vibration will be determined. Based on the experimental examinations' results a simulation model will be conceived. Finally, the results will be validated using a technical sample part. For this purpose, a damping function is integrated into a vibrating part and simulated. By means of an application test, it will be shown that the damping effect was specifically included.

3. Latest results

In the experimental investigations, free bending tests have been focused first. Therefore, test specimen with different cavity the test specimen was excited by a defined distance. After releasing the exciting force, the test specimen is able to vibrate freely. The damping behavior is evaluated by calculating the logarithmic decrement, which characterizes the decay of one displacement amplitude to the following one. Due to the non-linear behavior of particle dampers the decrement is calculated for each cycle and related to the corresponding time mean value. This proceeding allows to evaluate the logarithmic decrement as a function of time. In the charts the logarithmic decrement is plotted as a function of the maximum amplitude with a mirrored x-axis to show the time trend. By comparing the logarithmic decrement of the different test specimen the damping behavior is characterized. It is not possible to calculate the damping factor because of the non-linear behavior. By varying the different geometrical attributes of the dampers cavity, the damping effect can be significantly changed. The attribute "cavity volume" for the laser melting process as an example will show this:

Therefore, test specimen with cavities of different cross sectional area in direction of vibration are manufactured with respect to established design rules (see DMDR-projects). The material used is the stainless steel 316L. Within the tests the specimen are excited by 5mm from the neutral position. The calculated logarithmic decrements are shown in figure 6.

The highest damping appears for the biggest cavity (45 cm³). The smaller cavities show less damping. The starting point of the curves displaying the initial damping of the first amplitude also emphasizes this behavior. With similar start excitation of 5 mm the highest cavity volume shows the smallest start amplitude of 1.7 mm. For the other test specimen the initial damping is lower. The higher damping is a result of the higher amount of particles inside the cavity for higher cavity volumes leading to more impacts and by that to a higher energy dissipation. The laser sintering process does not enable such a high damping because of the reduced flowability of the particles due to higher thermal damage of the powder in the manufacturing process.

Since the FDM process does not use powder as raw material, the integration of particle dampers is not possible. Never the less, this manufacturing technology offers other approaches for the direct integration of damping structures. Using only the design freedom dynamic vibration absorbers known for skyscrapers to build earthquake-proof buildings can be manufactured. Experimental tests have shown the feasibility of this approach to reduce undesired vibrations using the FDM process. Since the material damping of additive manufactured structures is yet not known, the dynamic vibration absorber cannot be design properly.

4. Outlook

In further investigations, other vibration forms and loads will be tested. Further, the concept for a simulation model will be developed. Finally, design guidelines are derived from the experimental data to achieve a proper design for vibration damping.

Project Manager	*Prof. Dr. -Ing. Detmar Zimmer*
Scientific Associate/s	*Thomas Künneke, M.Sc.*

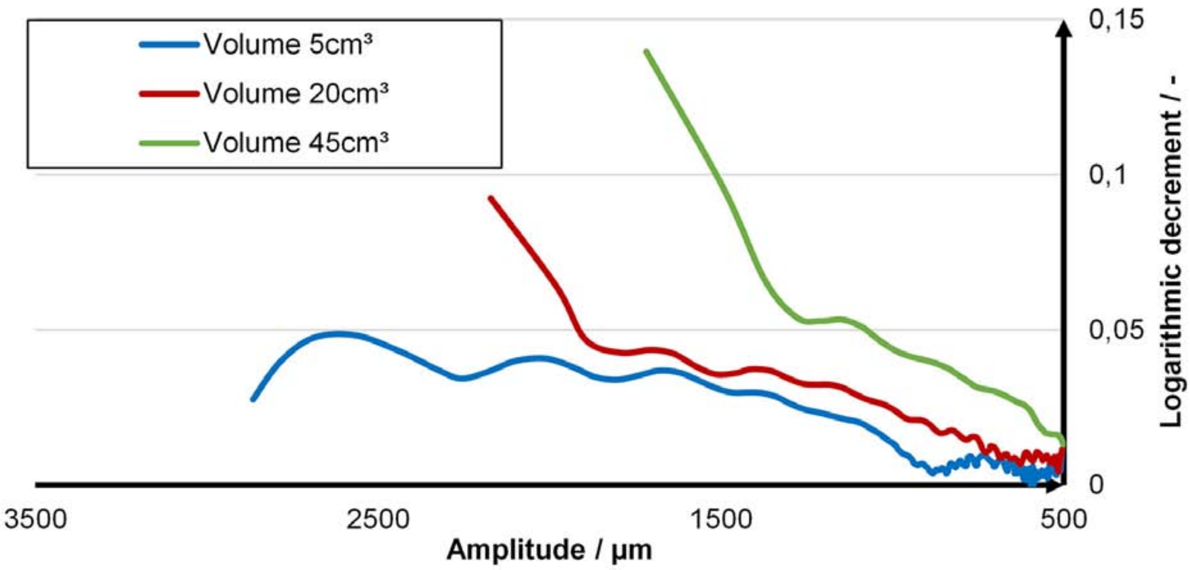


Figure 6: Damping behavior of different cavity volumes (LBM)

Additive manufactured lightweight structures for civil aircraft components

The Selective Laser Melting (SLM) process provides huge advantages for aircraft components like valve blocks and structural parts. In this project funded by the BMWi – "Federal Ministry for Economic Affairs and Energy", the benefits of substituting conventionally manufactured parts by additively manufactured parts will be examined and quantified. The scopes are, reducing costs, weight and time in comparison to the traditional design and the conventional manufacturing method.

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

1. Objectives

The aim is to develop a decision support scheme for future applications during the product engineering process and to elaborate the fundamentals for a Additive Manufacturing material database based on lightweight and composite structures, besides solid material properties. Moreover, investigations working on improving the process through topology optimization, which includes increasing the building speed of the SLM process and to develop fast and stable process routes that can be used for serial production, will be acquired. The intention is to reduce the processing time in every stage of the process chain, particularly in the Additive Manufacturing process.

2. Procedure

The project is divided into two work packages, the first work package works on identifying several promising aircraft components and to adapt a trade-off methodology to rank these parts. According to this tradeoff methodology, a decision scheme for future decisions will be developed with a complete description of process chain mapping possibilities and influencing factors for the process. The second work package works on the development of lightweight structures and composite structures and their mechanical properties for several target functions. Moreover, the mechanical properties of solid material built with various adjusted parameter sets will be determined. The gained knowledge of the previous working steps will be merged in topology-optimized components to demonstrate the possibilities of Additive Manufacturing and the results of the project.

3. Latest results

Since the project started in January 2016, the fundamentals for the different working steps are worked out. First ideas for the material database were discussed and the adaption of the trade-off methodology is ongoing. Furthermore, the initial steps for the determination of mechanical properties of the structures to be examined were done. A first knowledge base of the behavior of lattice, composite and support structures, and the influence of the part position on the building plate has been established.

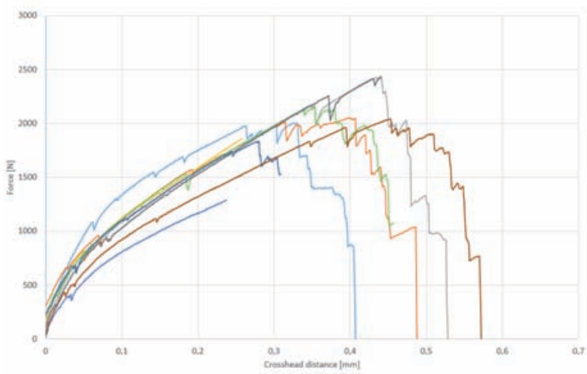


Figure 7: Force-distance diagram of support-structure (block) tensile specimen

In addition to that powder ageing effects in different build jobs with the same powder were analyzed and first investigations on increasing the building speed through parameter optimization has been done.

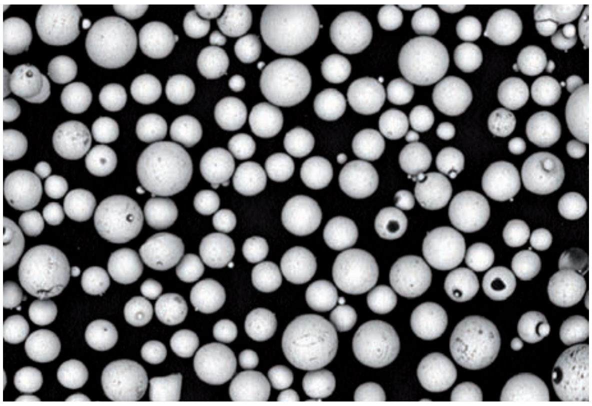


Figure 8: Influence of the number of build jobs on the powder morphology of TiAl6V4 – Morphology after 3 jobs

4. Outlook

The next working steps are further investigations on the topics mentioned above. The whole project is an iterative process and the gained knowledge during the project will be used for first topology optimized parts which will be finished in early 2017. Moreover, additional and extensive investigations on increasing the building speed while at least holding the properties and on combining different materials in composite structures will be examined.

Project Manager: *Prof. Dr. rer. nat. Thomas Tröster*

Scientific Associate/s: *Dominik, M.Sc., Peter Koppa, M.Sc*

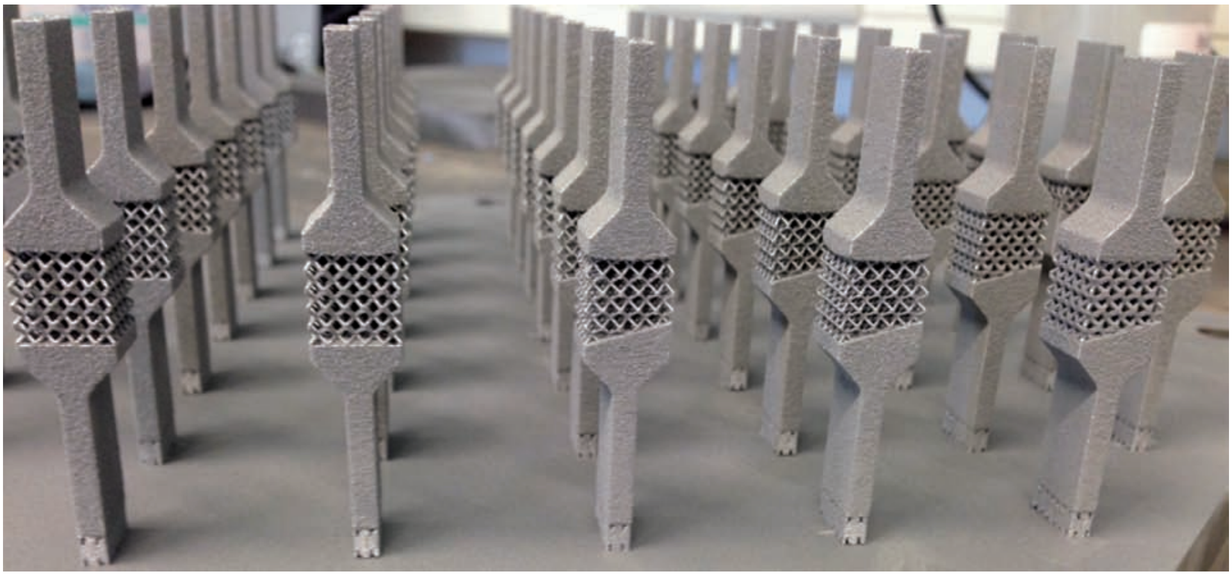


Figure 9: Building plate with different samples for the investigations on standard lightweight structures

Adhesive and Corrosion Properties of Laser Molten Fe-alloy Moulds for Polymer Processing

The insertion of cooling channels into injection molding tools leads to a faster cooling rate of the manufactured polymer parts and therefore to a decrease in the production time. These cooling channels are perfused by a cooling liquid consisting of tap water, biocides and other inhibitors and chlorides. To avoid corrosion as far as possible, different laser melting alloys were tested for their mechanical, corrosive and adhesive properties. The tensile strength of all alloys fulfills the minimum requirements for the use in injection moulds. As recommendation the results showed that either all parts that are electrolytically and electrically connected has to be constructed of Corrax (which shows the best corrosion performance due to the high Cr-content) or if this is not possible Orvar (conventionally molded as building platform) should be combined with H13 (laser sintered as injection molding tool) as otherwise galvanic corrosion would lead to a preferential corrosion of metal parts with reduced Cr-content.

1. Objectives

The insertion of cooling channels into injection molding tools leads to a faster cooling rate of the manufactured polymer parts and therefore to a decrease in the production time. These cooling channels are perfused by a cooling liquid consisting of tap water, biocides and other inhibitors and chlorides. During the cooling process the temperature varies in a wide range, affecting the solubility of oxygen. For high temperatures (here typically about 90 °C) close to the center of the injection molding tool the oxygen solubility is low but for low temperatures (here typically between 25 °C and 40 °C) the oxygen solubility is high. In combination with the aggressive components of the cooling liquid the corrosive attack to the injection molding tool leads to a malfunction. This effect is supported by enlarged surfaces and imaginable skip zones caused by incompletely molten alloy particles in the cooling channels from the selective laser sintering process, which is the only manufacturing method to form such injection molding tool with cooling channels.

To avoid the corrosion as far as possible, different laser melting alloys were tested for their mechanical, corrosive and adhesive properties: standard MS1 alloy (X3NiCoMoTi 18-9-5, high Ni-concentrations), alloy H13 and conventionally moulded Orvar (ca. 5%Cr + Mo, medium Cr-concentrations), and alloy Corrax (X3CrNiMoAl 12-9, high Ni- and Cr-concentrations).

2. Procedure

Polished and unpolished samples were tested by means of FE-SEM, EBSD, Raman spectroscopy, XPS and EDX to characterize the surface changes; XRD and TEM to characterize the crystallinity of the bulk material; tensile tests to characterize the mechanical properties and electrochemical investigations to characterize the corrosion properties.

3 Latest results

The mechanical and microstructural properties of the Corrax and MS1 alloy exhibit an isotropic and homogenous behavior for the as built condition. But a heattreatment (aging) is needed for both materials to increase the tensile strength and hardness. Directly, after SLM processing of H13, retained austenite was found within the microstructure. During the tensile test a part of the retained austenite was transformed in the ferrite matrix which indicates a TRIP effect. The mechanical properties are strongly anisotropic according to the tensile tests as well as after a heat-treatment. The ultimate tensile strength of H13 after and before a heat-treatment fulfills the minimum requirements for the use in injection moulds.

The Corrax alloy showed the highest chromium concentrations on both surfaces (polished and unpolished). Possible Cr-oxide layers after contact to the electrolyte on the polished sample led to the conclusion that a passive Cr-layer in analogy to the well-known healing effect of Cr was formed. The Corrax alloy showed the highest impedance values (~10^5 Ohm x·cm^2) on both surfaces (polished and unpolished) in comparison to the other samples (Orvar, H13, MS1).

The impedance values for polished H13 samples (laser sintered) were close to the values of Corrax. On the unpolished H13 samples the impedance values were at about ~10^4 Ohm x·cm^2. The Orvar alloy (conventionally molded) showed smaller impedance values of about ~3·10^3-5·10^3 Ohm· x cm^2. It can be assumed that a passive layer on H13 (laser sintered), caused by chromate, was build.

For the MS1 alloy the impedance values were similar to those of the Orvar alloy. The corrosion potential E_Corr was slightly more anodic than for H13/Orvar with similar corrosion current densities i_Corr.

With regard to contact corrosion between the material of the building platform and the molding tool, only materials with the same composition should be combined when they are in electric and electrolytic connection.

As recommendation the results showed that either all parts that are electrolytically and electrically connected has to be constructed of Corrax (which shows the best corrosion performance due to the high Cr-content) or if this is not possible Orvar (conventionally molded as building platform) should be combined with H13 (laser sintered as injection molding tool) as otherwise galvanic corrosion would lead to a preferential corrosion of metal parts with reduced Cr-content.

Project Manager	*Prof. Dr. -Ing. Guido Grundmeier*
Scientific Associate/s	*Dr. Markus Wiesener*

Dimensional Tolerances for Additive Manufacturing (DT-AM)

Technical parts are designed computer-aided at its theoretical ideal shape. However, manufacturing always leads to geometrical deviations. The functionality of technical parts in terms of its assembling ability is significantly influenced by the interaction of various geometrical deviations. For this reason, it is essential that the geometric shapes meet their requirements. Thus, limits need to be given for the geometrical deviations that is typically done by tolerances. For additive manufacturing, it is currently unknown how large such tolerances have to be. Thus, no reliable and comprehensive information about tolerances for additive manufacturing are defined in standards.

1. Objectives

The project “Dimensional Tolerances for Additive Manufacturing” has two different objectives.

1 Objective: Dimensional tolerances are systematically determined that can be stated if additive manufacturing is used under normal workshop conditions. Normal workshop conditions describe the application of often used and established standard parameters, materials and machine settings.

2 Objective: Relevant process parameters and manufacturing influences are investigated in order to define measures that minimize dimensional deviations.

2. Procedure

WP1 & 2: Within the first step of the project, two methods are developed. The first method describes a proceeding for the examination of dimensional deviations that can be used to derive realistic tolerance values. The second method describes a proceeding for the reduction of dimensional deviations by the identification and optimization of process parameters and manufacturing influences. **WP3 & 4:** Within the second step, experimental tests are performed to investigate occurring dimensional deviations. Parallel, optimized settings for process parameters and manufacturing influences are identified in order to reduce dimensional deviations. **WP5 & 6:** Within the third step, dimensional tolerances will be derived from the measured dimensional deviations. Furthermore, measures will be derived in terms of guidelines that can be used to reduce dimensional deviations. **WP7:** In the end, the results will be analyzed and interpreted.

3. Latest results

Based on the developed method, the experimental tests were extended for the processes laser melting, laser sintering and Fused Deposition Modeling. Besides the external dimension also internal dimension were investigated in the last year. The nominal dimension of the test specimen was manufactured up to the maximum of each machine envelope. Additionally, the nominal dimensions were aligned along the x, y and z axes (Figure 10). After the manufacturing, the test specimen were measured with a defined measurement method to identify the occurring dimensional deviations.

Figure 11 shows the detected dimensional deviations for external dimensions that were manufactured with Fused Deposition Modeling. Within the diagram, the minima, maxima and mean values for the dimensional deviations (vertical axis) for each

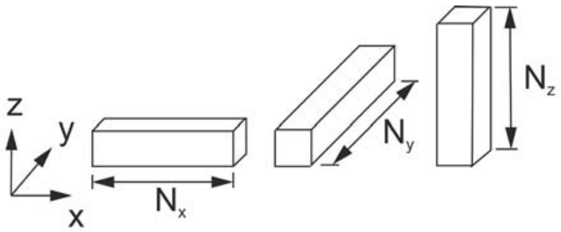


Figure 10: Test specimen for external dimensions aligned along the x, y and z axes

alignment (x, y, and z) are represented depending on the nominal dimensions (horizontal axis). The diagram emphasizes that the alignment and nominal dimension show a major impact on the dimensional deviations. For the x alignment, a positive increase of the mean values appears dependent on the nominal dimension, while for the y alignment the averaged deviations negatively increase.

The mean value of deviations range between +0.03 mm and +0.50 mm in the x alignment and between +0.06 mm and -0.30 mm in the y alignment. In the z alignment, alternating mean values are indicated between +0.12 mm and +0.47 mm. The alternating distance between averaged values compared to the x and y alignment is caused by the approximation of nominal dimensions through layers along the z-axis. Nominal dimensions, which are an integer multiple of layers, show a better dimensional accuracy in the building direction. In order to establish tolerances for additive manufacturing processes, the occurring deviations were classified in the ISO tolerance system according to DIN EN ISO 286-1. The derived tolerances between the minimum and maximum of deviations for Fused Deposition Modeling achieve IT classes between IT09 and IT14 for the external dimension. Further investigations showed that the different deviations in x, y, and z alignment were mainly caused by material shrinkage and other process parameters.

For the minimization of dimensional deviations, process parameters and manufacturing influences were investigated experimentally. The experimental studies of process factors demonstrated that dimensional deviations could be reduced significant by an optimal selection of parameter settings.

4. Outlook

The project is finished in the end of 2016 and was focused on dimensional tolerances. The next experimental test will deal with the examination of form and location tolerances. Therefore, an extension of the methodical approach is necessary in order to cover all geometrical deviations. Based on defined influential factors on the geometrical accuracy, new test specimens combined with suitable measurement methods will be developed.

Project Manager	*Prof. Dr. -Ing. Detmar Zimmer, Prof. Dr.-Ing. Hans-Joachim Schmid,*
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Scientific Associate/s	*Tobias Lieneke, M.Sc., Stefan Josupeit, M.Sc.*
	Frederick Knoop, M.Sc., Peter Koppa, M.Sc.

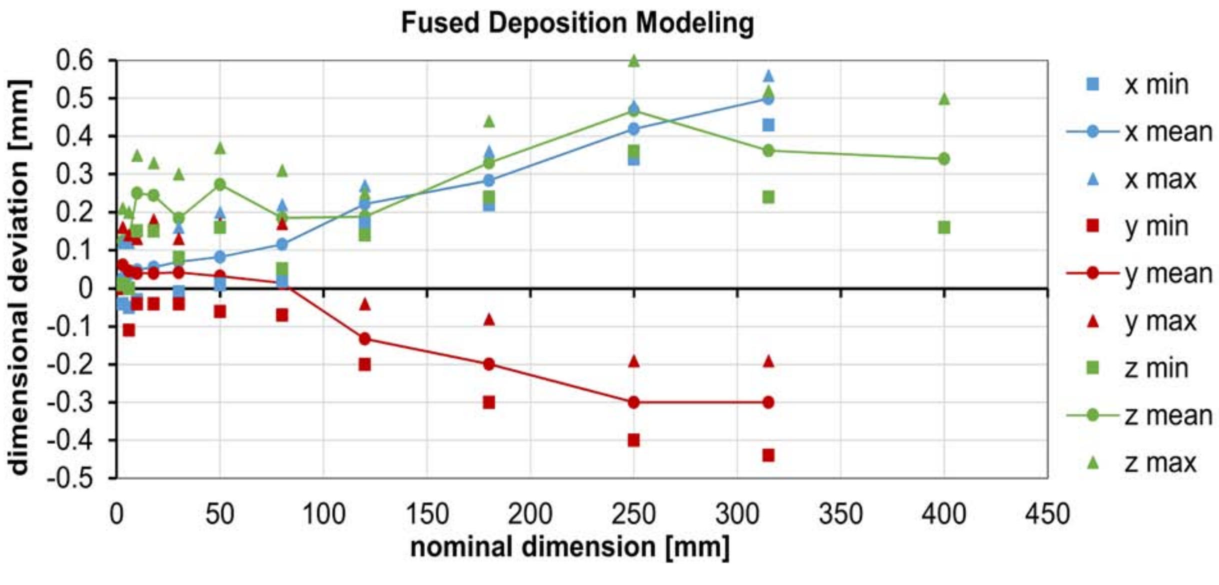


Figure 11: Maxima, minima and mean values of the occuring dimensional deviations for different nominal dimensions and alignments (x,y,z)

Direct Manufacturing Design Rules

Additive manufacturing creates parts in layers and without formative tools. Thereby, new freedoms and restrictions arise. To publish these, comprehensive design rules are required. Such design rules were developed in the Direct Manufacturing Design Rules (DMDR) project. Because the validity of these design rules was limited to only a few considered boundary conditions, the Direct Manufacturing Design Rules 2.0 project has the aim to extend the range of validity. Therefore, the tests of the DMDR project were repeated with various machines, materials and parameters. As result, a design rule catalogue for various boundary conditions is given.

1. Objectives

Within a first project, named Direct Manufacturing Design Rules (DMDR), design rules have been developed that point out possibilities and restrictions for additive manufacturing. These design rules were developed based on standard elements. These 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 Laser Sintering, Laser Melting and Fused Deposition Modeling. For each technology, one common combination of material and parameter setting was considered. This proceeding fostered the design rule development but limited the range of validity for the developed design rules.

In general, design rules for additive manufacturing technologies, which shall be used for training and teaching, need to be applicable for different boundary conditions. Thus, the research project Direct Manufacturing Design Rules 2.0 (DMDR 2.0) has the objective to extend the range of validity for the developed design rules. It shall be proven if the developed design rules apply for different boundary conditions, too. Therefore, different materials, manufacturing machines and parameter settings shall be considered.

2. Procedure

In order to extend the range of validity for the prior developed design rules, the tests of from the DMDR project will be repeated with other boundary conditions. These comprise different boundary conditions in Laser Sintering, Laser Melting and Fused Deposition Modeling.

Within the tests, standard elements have been built with different attribute value variations and different manufacturing boundary conditions. For instance a wall was built with a thickness of t = 0.2, 0.4, 0.6 … 5.0 mm. Next, the thickness of the manufactured wall was measured and the thickness-deviation calculated. By displaying the measurement curves in one diagram, commonalities, differences and general trends can be investigated (Figure 12).

3. Latest results

Within the year 2016 investigations for Fused Deposition Modeling were mainly in focus. Therefore, geometrical test specimens – standard elements – were manufactured with different combinations of the materials Ultem, PC and ABS with the machines Fortus 400mc and Fortus 900mc and parameter settings for tip sizes T10, T12 and T16. Afterwards, the measurement results were

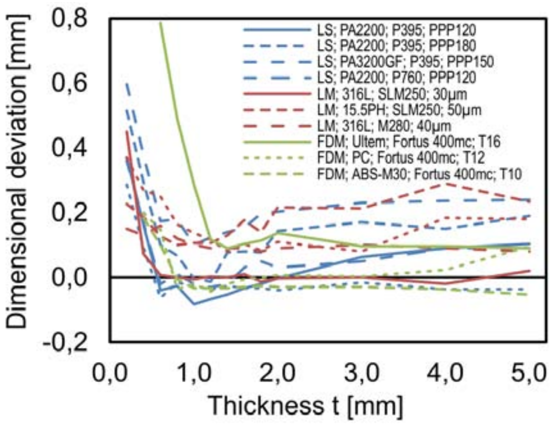


Figure 12: Dimensional deviations for walls manufactured with different thicknesses and boundary conditions

compared to results from Laser Sintering and Laser Melting (Figure 12).

Based on the comparison of the measurement results, crossprocess analysis of the results were possible. Thereby, in nearly all cases, the developed findings proved that the textual descriptions of the design rules are applicable for different boundary conditions while the numerical values change in dependence of the boundary condition. This is exactly the same finding like for Laser Sintering and Laser Melting (Figure 13).

Summarizing, the Direct Manufacturing Design Rules 2.0 project now provides a design rule catalogue for Laser Sintering, Laser Melting and Fused Deposition Modeling, which contains design infomation for various manufacturing boundary conditions.

4. Outlook

Within the next step, a general proceeding for the design rule development will be deduced. This will give guidance on how to develop individual design rules.

Also the results and findings will be implemented in seminars, publications and lectures in order to spread the developed knowledge.

Project Manager *Prof. Dr-Ing.Detmar Zimmer*

Scientific Associate/s *Dr.-Ing. Guido Adam, Stefan Lammers, M.Sc.*

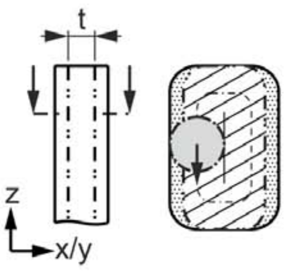
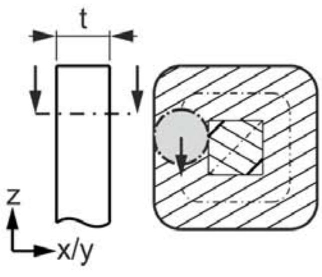
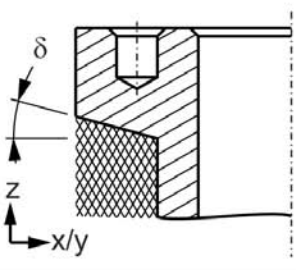
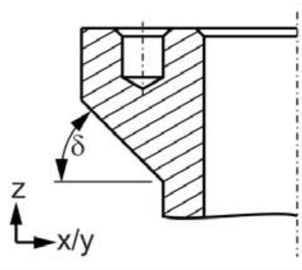
Description		Not suitable for manufacturing	Suitable for manufacturing
Thicknesses of non-curved elements should be thick enough to structure each layer with contour and raster lines			
LS (Pa2200, PPP120)	t > 1.0 mm		
LS (...)	t > ...		
LM (316L, 30 µm)	t > 0.6 mm		
LM (...)	t > ...		
FDM (Ultem, T16)	t > 1.5 mm		
FDM (...)	t > ...		
Angle of a downward facing surfaces should be large enough to avoid solid support structures			
LM (316L, 30 µm)	d > 45°		
LM (...)	d > ...		
FDM (Ultem, T16)	d > 35°		
FDM (...)	d > ...		

Figure 13: Design rule examples for the thickness of walls and the angle on a downward facing surface

DynAMiCS: Support for the implementation of Additive Manufacturing

The implementation of Additive Manufacturing (AM) in infrastructure and processes poses major challenges for companies. In the "DynAMiCS" project, methods and tools were developed to support companies in economic use of the technology. Starting from the identification of relevant product segments, suitable products and services are identified and new or extended business models are evolved. The developed methods and tools for the identification of AM potentials were validated in cooperation with DMRC partner companies such as Stükerjürgen Aerospace Composites GmbH & Co. KG, Krause DiMaTec and Parker-Hannifin.

1. Objectives

Methods and tools for implementing AM must comply to a wide range of requirements in order to meet the characteristics of manufacturing technology. Even though companies generally recognize the main benefits of AM, they are often unable to derive and quantify the specific benefits of the technology for their business. Previous studies on the utility potential of AM are rather unstructured or heuristic in many companies. In addition, the identification of potentials is primarily concerned with a few technology experts. In the research project "DynAMiCS" methods and tools for future industrial users of AM processes were developed.

2. Results

In the first phase of the project, a framework for companies with little knowledge of AM was developed. Their goal is to obtain a first impression of which benefits AM could provide for their business. To identify potentials, applications fields (in terms of market segment and product category combinations) were determined and assessed with regard to their respective AM potential. As a consequence, the DMRC is going to be equipped with a tool to answer the question "Which potentials could AM yield for me"

In the second phase of the project, a framework for product discovery was be developed. Once a company decides to apply AM (for either production or service provision), it will be confronted with the challenge "Which products and services could I offer by using AM". The main task is not to find creative product ideas, but rather to select the right ones. The DMRC can draw on the technical know-how of its engineering staff. On the other hand, product ideas have to be auspicious with regard to a company's business of the future. The project will yield a framework to generate and select promising, feasible product ideas.

As a matter of fact, there is more to AM than the plain production of parts – it changes value chains,

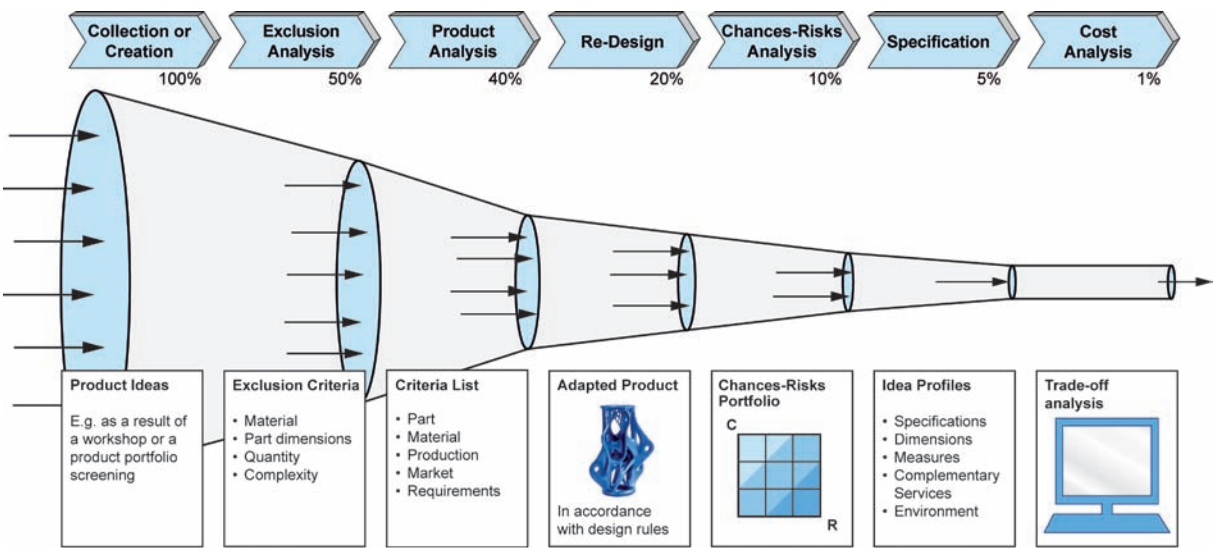


Figure 14: Idea funnel of Innovation

manufacturing complexity, competitive relationships and will drastically alter a company's competence base. Therefore, in a third step a guideline for the generation of AM-business models was developed. A business model is an abstract representation of a company's way to create value for the customer and make money. Recently, the concept of business models has gained ample attention among scholars. We extended the current understanding of business models and enabled the DMRC to develop specific AM business models.

Figure 15: DMRC BMC Workshop

Depending on the level of experience of companies with AM, different questions need to be answered to identify the specific potential of AM. For example, a company at the beginning of its investigation of the technology has to identify appropriate application fields. The key functions of AM and methods for the analysis of the business segments of a company identified in "DynAMiCS" help determine appropriate fields of application. On the basis of the selected business segments, it is necessary to identify suitable products and services with which the potential of AM can be developed. Through creative and/or deductive approach this task can be solved efficiently. In the last step to the implementation of the technology in companies, suitable business models are developed. The entirety of the phases for the identification of the potential, the selection of suitable components and the development of viable business models will enable the DMRC to support the decision in favor of the use of AM and to identify customer-specific potentials.

3. Outlook

The created results of "DynAMiCS" provide possibilities to support companies being at the beginning of AM investigations. The DMRC takes the role of a consultant possessing a collection of methods and tools to support companies for their specific AM product, services and business ideas. In bilateral projects the DMRC provides different service offers as a result of DynAMiCS.

Project Manager	*Prof. Dr-Ing. Iris Gräßler*
Scientific Associate/s	*Patrick Taplick, M.Sc., Martin Kage, M.Sc., Xiaojun Yang, M.Sc.*

Efficient manufacturing process for metal bipolar-plates using FDM-Mold

This project is funded by the DBU – "Deutsche Bundesstiftung Umwelt" and runs in cooperation with Eisenhuth and an associated automotive OEM. The research question in this project is, if the FDM process is suitable for the production of tool inserts (negative molds), which enables the production of finely textured metallic bipolar plates (BPP). Therefore different flow field designs are manufactured and tested at the DMRC. Moreover a suitable FDM-Material has to be identified which fulfills the requirements and loads for the molding process of thin metallic plates.

1. Objectives

The first part of the Project was to define and design the finely structured hydrogen channel, taking the requirements of the subsequent production steps into account. There, the limitations of the FDM-Process in this area of application and the resulting mechanical properties and geometrical characteristics has to be investigated.

2. Procedure

In the first work package, Eisenhuth designed a suitable geometry of a BPP and the negative mold was realiszied at the DMRC. In a second step the DMRC identified different thermoplastics. Subsequently extensive investigations on the optimal FDM-Parameters for building fine structures started. After the first negative mold was built, the mold was geometrically measured at the DMRC and Eisenhuth performs first molding tests. The gained results were used to optimize the shape and the production process.

3. Latest results

To optimize the channel geometries, the line waviness was mesured using the 3D Keyence macroscope. Best results were reached with Ultem, 90 degrees, horizontally with 0.53 mm canal depth in average. For the ABS material, sufficient results were reached for both orientations. In case of horizontal orientation, there may be problems due to increased attrition caused by the waves on the bars. The individual results are shown in Figure 16.

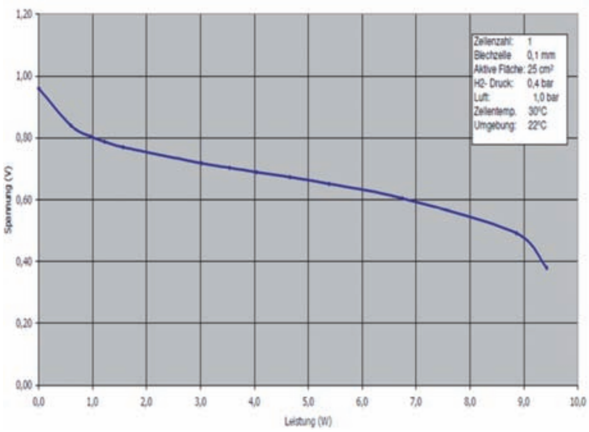


Figure 16: Results of 3D Keyence macroscope

Figure 17 shows the power-voltage-characteristics of the single fluid cell. The voltage was plotted over the power. The single cell has an output of 7W at the optimal operating point of 0.6 V. Thus, the finished plates are suitable for constructing a stack (shown in Innovations). The performance is about 470 mA/cm² with 0.6 V operating voltage. A comparable cell with a graphitic plate (current SoA) has a power of 290 mA/cm².

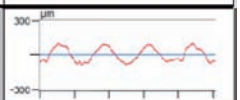
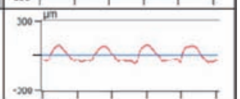
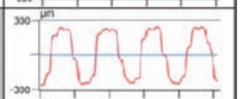
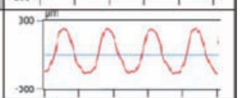
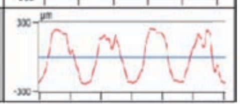
Material	Kanaltiefen in mm	Bemerkung	
Ultem 75 Grad Senkrecht	~0,18	• Ungleichmäßige Kanaltiefen • Rastlinien	
Ultem 90 Grad Senkrecht	~0,15	• Gleichmäßige Kanaltiefen • Rastlinien	
Ultem 90 Grad Waagerecht	0,53	• Sehr gleichmäßige Kanaltiefen • Leichte Zacken auf dem Steg	
ABS 90 Grad Senkrecht	0,40	• Gleichmäßige Kanaltiefen	
ABS 90 Grad Waagerecht	0,48	• Sehr gleichmäßige Kanaltiefen • Zacken auf dem Steg	

Figure 17: Power-Voltage-Character-

4. Outlook

Overall, the project has been successful. It is generally possible to produce sheet metal plates using prototype mold of a FDM-machine. The mechanical values are sufficient to produce a small series of sheet metal cells. Ultem and PC are most suitable as starting materials, because the attrition is up to 230% lower than ABS material. To obtain the homogeneous surface the process parameters and the strategy has to be adapted. The use of the technology is also conceivable in other applications, such as heat exchangers.

Project Manager	*Prof. Dr. rer. nat. Thomas Tröster, Prof. Dr.-Ing. Hans-Joachim Schmid*
Scientific Associate/s	*Dominik Ahlers, M.Sc..*

Fatigue Behavior of FDM and LS Parts

In practice, the knowledge of the fatigue properties, in addition to the static material properties, is crucial for a reliable component design. Many components are not only statically loaded, but also dynamically loaded in the area of application, such as a fastener on an airplane. Therefore, the fatigue behavior of Fused Deposition Modeling (FDM) parts manufactured with Ultem 1010 and Ultem 9085 as well as Laser Sintering (LS) parts manufactured with Polyamide (PA) 12 are analyzed in this project. Furthermore, chemical surface treatment can be used for surface smoothing of additive manufactured polymer parts. The influence of the chemical surface treatment on the mechanical properties will be analyzed in static and dynamic tests.

1. Objectives

This project will deliver valuable information regarding fatigue and creep data of different additively manufactured polymers. For FDM parts, improvement of fatigue properties by process parameter optimization will be carried out.

2. Procedure

The dynamic strength values in the form of S-N curves are initially determined for FDM components made from the materials Ultem 1010 and Ultem 9085. LS components made out of the material PA 12 (Type PA 2200). Due to a general good fatigue behavior of Polyamide, fatigue tests will concentrate on stiffness respectively possible length increase of specimens during the tests. For the LS parts an EOS P 396 and for FDM parts a Stratasys Fortus 400 mc machine is used.

Besides the detection of S-N curves the fracture of Ultem 1010 and Ultem 9085 specimens will be analyzed. Therefore, microscopy pictures will be taken. The aim of this analysis is a specific variation of process parameters with regard to improve the fatigue behavior. This improvement will be performed for both Ultem materials as well as for X, Y and Z orientation of the specimens. The classification in different built orientations in necessary, because the layer wise building process leads to anisotropic mechanical properties (cf. Figure 18). Afterwards, additional S-N curves for parts with optimized process parameters will be carried out.

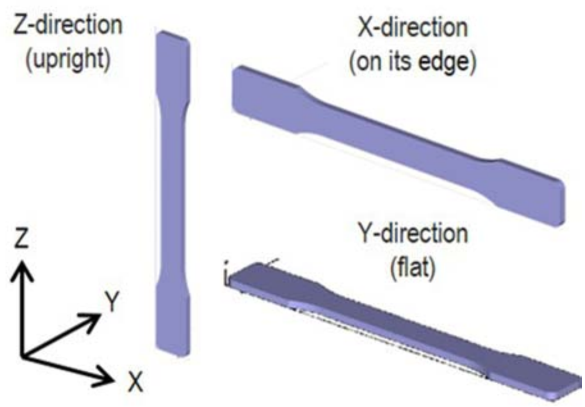


Figure 18: Build orientation tensile bars

In addition to the dynamic characteristics, the FDM materials are also analyzed on the basis of long-term creep tests, in which the failure time is determined for different load levels. The creep tests will be performed at room temperature in standard atmosphere.

The use of components as final products generally places a great demand on the appearance. For this purpose, previous projects at the DMRC have analyzed possibilities for chemical surface treatments for the materials listed above. Chemical methods have the advantage of an effective leveling of the most rough and wavy surfaces from additively manufactured products. Another focus of this project is to analyze the influence of the chemicals on the dynamic strength values and creep properties.

3. Latest results

The dynamic testing of polymers is connected to some specific features, due to the polymer-specific material behavior. For metallic materials, higher test speeds of 100 Hz, for example, are used to achieve a high number of load cycles in a short time on the test bench. Due to internal friction of the molecules, thermoplastic polymers have the ability to reach the softening temperature because of the simultaneous poor thermal conduction properties and low temperature resistance at high test frequencies. This leads to an early failure of the test specimens. Thus, dynamic testing of polymer components with significantly reduced testing frequency should be carried out, resulting in a significant increase of the test duration. The S-N curves are prepared for swelling loads with a constant minimum stress. Here it is possible to use standard tensile bars. Figure 19 shows the fatigue behavior for Ultem 9085, tested with a frequency of 5 Hz.

For Ultem 9085, chemical treatment shows no influence on mechanical properties, given that the treatment time is not too long. Due to a smoother surface, the chemical treatment may have positive influences on fatigue. First fatigue tests of Ultem 9085 specimens do not confirm this theory. Internal notches in the specimen seem to exert a significant influence on lifetime, especially with cyclic loads.

4. Outlook

Temporarily long term influence on mechanical properties are unknown for the used chemicals. Therefore, long term tests will be performed, while specimens will be treated and stored for a minimum of one year.

Project Manager *Prof. Dr-Ing. Volker Schöppner*

Scientific Associate/s *Matthias Fischer, M.Sc.*

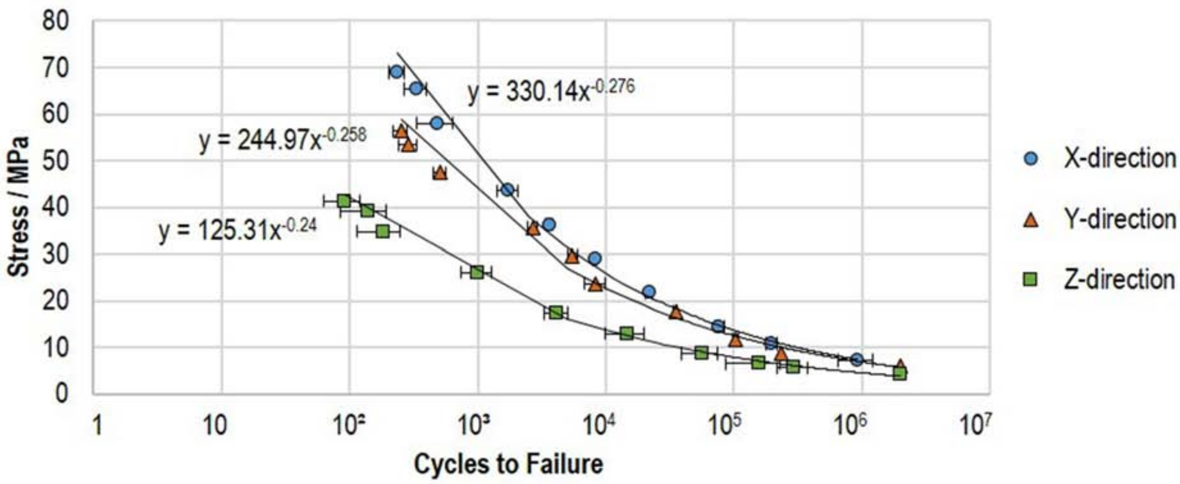


Figure 19: S-N curve for untreated Ultem 9085

Fatigue Life Manipulation

A defined arrangement of crack delay elements optimizes the life of Selective Laser Melting parts that are under fatigue loading, thus ensuring safe use in an industrial environment. For this purpose, examinations are carried out on specimens that are having different arrangements and geometries of crack delay elements and their influence on service life is tested by means of experimental and numerical methods. Fracture mechanical investigations, like influence of crack delay elements on crack initiation and crack deflection behavior are the results of this project in order to generate an optimal design for cyclically loaded components.

1. Objectives

The opportunities to optimize the fatigue behavior of additively manufactured structures are investigated in this project. Specific heat treatments, notches with different geometries on the crack path, as well as the alternating crack initiation and crack growth phases are those possible optimization measures. The service life of technical structures under fatigue loading are reduced because of various stresses, the main goal of this project is to extend the total lifetime by using sophisticated configurations of notch form, notch position and notch orientation. By varying these notch parameters, basic knowledge about crack growth behavior in SLM processed components is obtained.

Using crack growth retardation methods substantially higher fatigue life can be achieved. Here, the effect of notches on the lifetime during crack initiation and crack growth periods are taken into account. The reason for the difference in lifetime can be found in the time for crack initiation. The notches positioned on the crack path lead to a new initiation of the crack at each notch. The significantly higher number of load cycles for the reinitiation of the crack compared to the number of cycles for propagation of the crack over the distance of the notch in a specimen without notch will be used to manipulate the total lifetime.

2. Latest results

The comparison of the experimentally examined and the numerically predicted crack path for a compact tension specimen with “diamond-shaped” notches is demonstrated in Figure 20. The crack paths of both samples show a good agreement. Both, the prediction of the crack path as well as of the position of the reinitiation points are realistic. The experimental results confirm the simulation investigations and thus it is possible to predict the

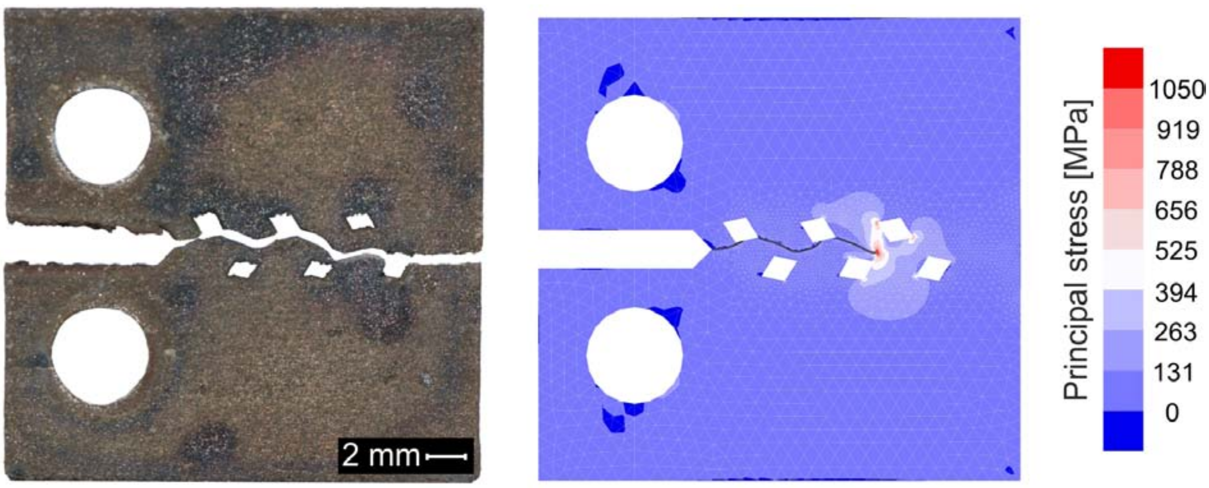


Figure 20: Comparison between experiment and simulation of the crack path of a compact tensile specimen with diamond shaped notches

crack growth behavior in additive manufactured components.

Results of investigations on notched structures show that the decrease or increase in fatigue life can be manipulated significantly by introducing notches. Taking the titanium alloy as an example, a huge lifetime extension can be achieved by using a row of notches or elongated notches. All in all the lifetime manipulation depends on notch size, notch position and on material behavior such as brittle in case of titanium alloy or ductile in case of stainless steel. By discovering optimal parameters for notch size and notch position a momentous lifetime extension can be achieved. In special cases a crack arrest is also possible. Thus, additive manufacturing offers the possibility to produce lightweight structures that have longer fatigue lifetime.

The fatigue life manipulating methods are applied to a strength and lightweight bicycle stem from the high-performance segment, Figure 21. To reduce the weight of this structure, notches are implemented. The shape of the notches is based on the earlier findings of this project. Because the stress situation is different at every point of the stem each notch shape is individually adapted to the load situation. The comparison to a commercially available stem clarifies a weight reduction of 30 % and a possible increase of the service life of this product.

3. Outlook

The future investigations in this area can be the adaptation of the main results obtained on complex, laser melted structures. The results can be targeted to redesign real parts that are under fatigue loading. These real parts should be additionally tested under actual operating loads to figure out the possible lifetime extension by using additively manufactured smart notches.

Project Manager	*Prof. Dr.-Ing. Hans Albert Richard, Prof. Dr.-Ing. Gunter Kullmer*
Scientific Associate/s	*Wadim Reschetnik, M.Sc.*

Figure 21: Three different views of additively manufactured bicycle stem with newly introduced crack delay elements

FDM-structures for the partial reinforcement of hybrid structures

The mechanical properties of thin-walled plastic components are limited. One approach of improving the stiffness and strength is to apply individual adapted FDM-structures onto the thin-walled components. To achieve an optimal reinforcing effect, the properties of the FDM-structure must be optimized first. This project will focus on the variation of the FDM process parameter, because they have the most significant impact on the mechanical properties. The results of the parameter variation shall provide findings to develop design and process guidelines for FDM-structures that are used for the partial reinforcement of hybrid structures. Besides the mechanical properties, the lightweight potential of the FDM-structure must be considered, too, because thin-walled components are often used in the field of lightweight design.

1. Objectives

This project aims to determine design and process guidelines for FDM-structures, which are aligned for specific load cases and shall be used for a partial reinforcement of lightweight parts. The reinforcement structure shall provide maximum increase of strength and stiffness with minimum increase of weight. To realize the maximum increase of the mechanical properties the inner structure is adjusted to the specific load case by using different parameters for the layer generation. In addition to this the design of the FDM-part will be varied to achieve a weight increase as minimal as possible.

2. Procedure

The strength and stiffness for various inner part structures will be determined for the different load cases by using mechanical tests (tensile, compression, flexural, impact and torsional strength). As a result, a list of load specific designs and process guidelines for the FDM-structure will be compiled. Additionally a modeling of the mechanical strength of FDM-parts will be developed. The strength is modeled as a function of the inner part structure which is directly depending on the process parameters. The modeling shall support the strength analysis of the different load cases.

At last, the design and process guidelines will be verified on a real lightweight part. This part will consist of two components, a GITBlow-part and the FDM-structure (Figure 22). To realise a joint between both parts, the FDM-structure is inserted to the injection mold first. Then the GITBlow-preform is inflated and adheres to the FDM-structure. The gain structure is only added to the thin-walled area of the GITBlow-part. For that hybrid component, different mechanical tests will be carried out.

3. Latest results

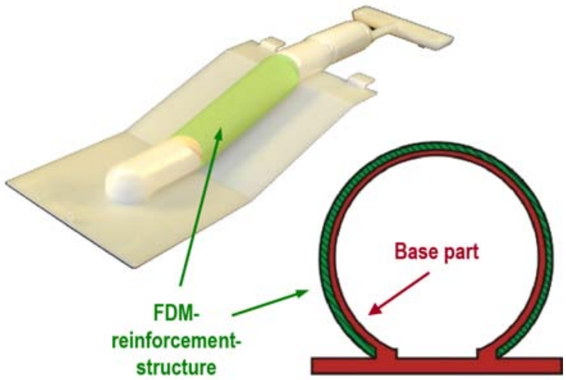


Figure 22: GITBlow part with FDM-reinforcement-structure

In preliminary investigations, an influence of the FDM-process parameters on the mechanical properties could be verified. In addition, the process parameters have an effect on the part weight and the lightweight potential of the reinforcement structure. The used material for the FDM-structure is Ultem 9085.

The vertical bar chart on the left-hand side in Figure 23 shows that the flexural strength level depends on the filling parameters. In this case the raster angle (RA), delta angle (DA) and the raster to raster air gap (AG) was varied. The low flexural strength level is caused by the positive air gap. All red bars with a 0.25 mm raster to raster air gap have a lower flexural strength level than the blue bars with an air gap of 0 mm. The highest level is achieved by a 45° raster angle and 90°

delta angle. In the second vertical bar chart in Figure 23, a comparison between the GITBlow-part without and with the FDM-reinforcement-structure is shown. The chart shows a significant increase for the reinforced hybrid component. Furthermore, there are lower mechanical properties for the reinforced component with a positive raster to raster air gap (AG).

4. Outlook

In addition to the variation of process parameters, the design of the FDM-reinforcement-structure shall be adapted. The aim is a topology-optimized construction (FEM-analysis). The process principle of the Fused Deposition Modeling is the deposition of polymer strings in layers. As a result of this process characteristic the properties of FDM-parts are heavily depending on the fill pattern and the deposition orientation. This anisotropic material behavior has to be considered in the FEM-analysis. Moreover, extended strength verifications with dynamic tests are planned and the development of specific load design and process guidelines for the FDM-reinforcement-structure shall be continued.

Project Manager	*Prof. Dr.-Ing. Elmar Moritzer*
Scientific Associate/s	*André Hirsch, M.Sc.*

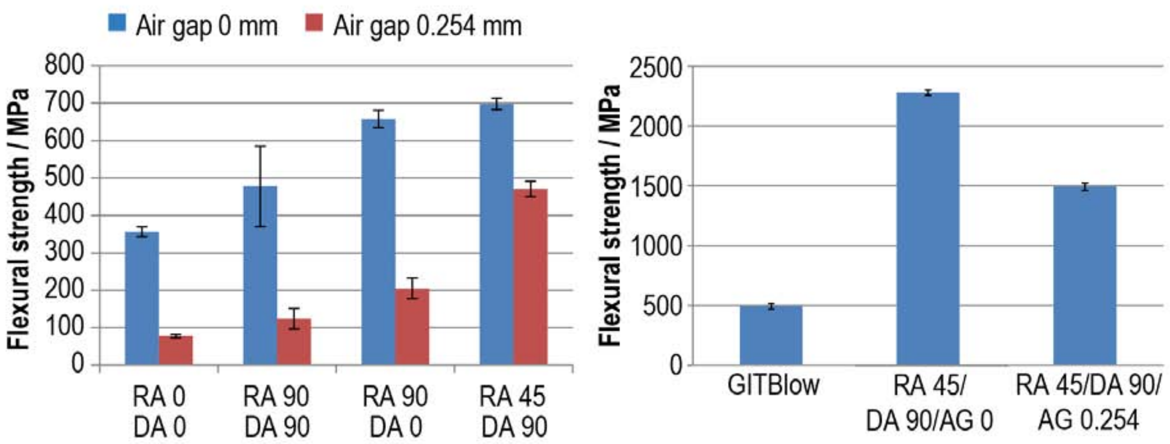


Figure 23: Flexural strength levels for different filling parameters (left) and flexural strength levels for the unreinforced GITBlow part and the reinforced GITBlow part (right)

Feasibility study 3D Printing of electric motors

The central aim of this research project is to investigate and to test the extent to which the technology of additive manufacturing is suitable for the production of rotors for encoderless regulated permanent magnetic synchronous machines (PMSM).

1. Objectives

Additive Manufacturing (AM) technologies offer three key advantages towards conventional manufacturing methods for electric motors. First advantage is, that the leakage paths of rotors can be designed so that they comply with the mechanical constraints and at the same time have a low magnetic conductivity. Therefore the design of the rotor is no longer limited to a two-dimensional sheet section. Moreover a lightweight optimization can be carried out. The second advantage is the absence of a punching tools impact which implements uncertainties of the magnetic properties at the cutting edge. Because of the absence of cutting edges AM technologies offer a significantly better prediction and reproducibility of the magnetic properties. The third advantage is the fact, that additive processes such as selective laser melting (SLM) generate components based on a powdery raw material. In principle it is possible to use additive manufactured soft magnetic composites (SMC) or other magnetic powder materials.

2. Procedure

The possibilities of a lightweight design with a low moment of inertia as well as a high tensile strength of the additive manufactured material will be pointed out. A useful material with ferromagnetic properties will be identified and the usability of SMC materials will be investigated. Specimens of the chosen material will be developed and produced with AM to investigate the resulting mechanical properties like the yield strength, the ultimate tensile strength and the hardness, as well as the electromagnetic properties like the coercitivity, the electrical conductivity and the permeability. Based on the results of preceding experimental investigations an innovative lightweight rotor design for a PMSM prototype machine will be developed, manufactured and compared to a conventional rotor design.

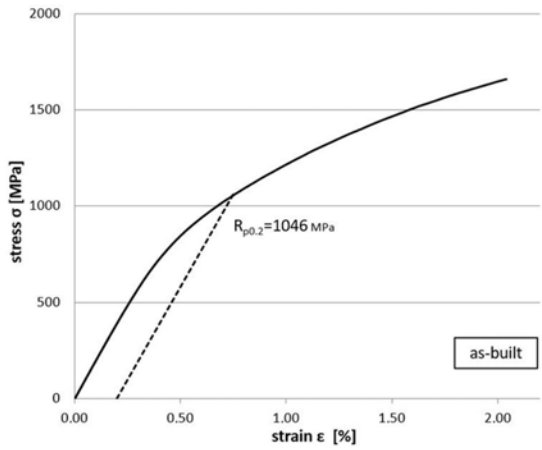


Figure 24: Results of tensile tests on H13 specimens

3. Latest results

The most suitable material for the investigations was the H13 material because of its ferromagnetic behavior and high availability. SMC material was not suitable for the SLM process because of its plastic cladding. The tensile strength and elongation at rupture of the solid material H13 (1.2344) were determined by tensile tests on R2 specimens. The geometry of the R2 specimens is based on the DIN EN IS0 6892-1 standard. The results are shown in Figure 24. The Vickers hardness varies depending on the distance of the building platform between 670 HV5 and 620 HV5. Higher layers in the building space show a higher hardness than lower layers. This results from heat dissipation through the lower layers which affects the heat treatment of the lower layers. For the investigation of the electromagnetic properties, ring cores were produced with an outer diameter of 62 mm and a cross-section of 6 x 6 mm. To identify the magnetic properties of the AM material H13, the ring cores were wound with a primary excitation winding and a secondary measurement winding to apply a magnetic field and measure the average magnetic flux density. The results showed a hard magnetic material behaviour with a poor permeability. These poor magnetic properties could be ascribed to a martensitic microstructure with parts of austenite. Heat treatment was performed to improve the magnetic properties with a ferrite-pearlite microstructure. The heat treatment resulted in a significant improvement of the permeability. The design of the PMSM was optimized in terms of a production-ready lightweight design. In order to reduce the weight while maintaining strength, cavities and lattice structures were implemented into the rotor. This lowers the moment of inertia of the rotor about 23%. In addition, gaps and holes were provided to remove the unplasticized metal powder in the area of lattice structures and cavities. The produced and mounted rotor is shown in Figure 25.

4. Outlook

The results show that the magnetic properties of H13 can be significantly improved by a heat treatment, so that its permeability nearly reaches the level of SMC materials. Finally, an improved new rotor with a lightweight design was developed and manufactured for a prototype machine. Compared to the conventional design, the mass of the rotor is reduced by 25% and the moment of inertia decreases by 23%. This leads to a shorter acceleration time by 23.2%. Additionally, sensorless control was made possible for this machine by means of rotor coils. Future materials for AM with better magnetic properties will unlock the full potential of the additional degrees of freedom in the rotor design. The results clearly demonstrate the great potential of additive manufacturing in electrical engineering applications. For future studies, more investigations of the electromagnetic behavior of additively manufactured materials are needed. Besides, realizable function integration like cooling effects or lightweight designs are required to establish additive manufacturing as a standard process in industrial process chains.

Project Manager	*Prof. Dr.-Ing. Detmar Zimmer*
Scientific Associate/s	*Stefan Lammers, M.Sc.*

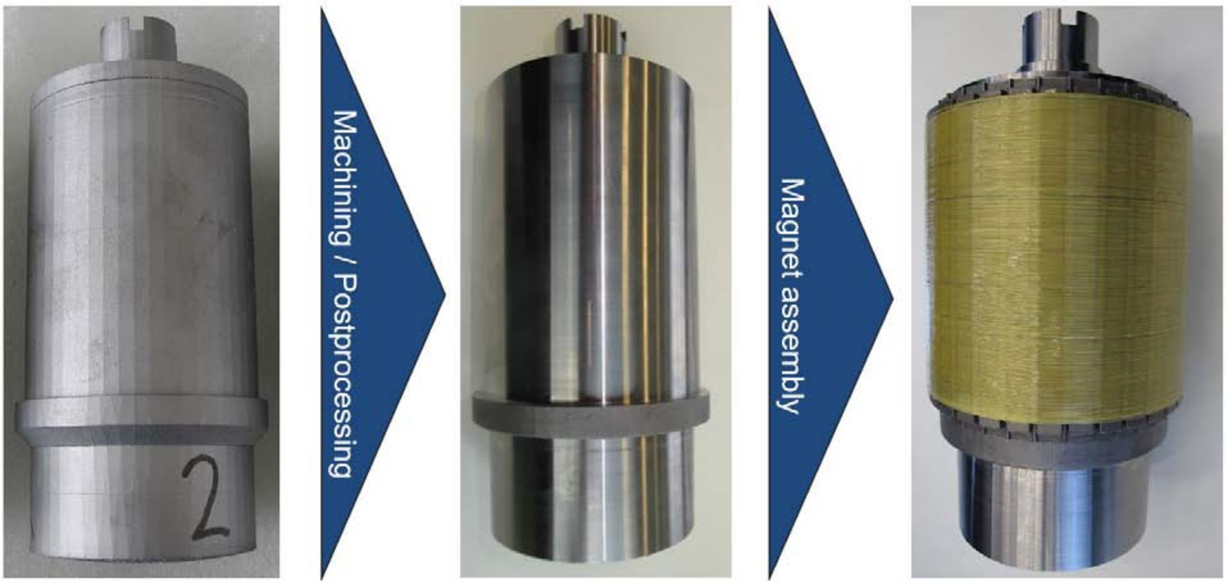


Figure 25: Additive manufactured rotor and after treatment

High Temperature Fatigue Behavior of Nickel based Superalloys Manufactured by SLM

Recently, the generic term Additive Manufacturing (AM) includes various manufacturing processes in which the components are built up layer by layer. Near-net-shape components can be produced directly based on 3D-CAD data without any other tooling. So called powder-bed laser fabrication processes, like selective laser melting (SLM®), belong to the group of metal additive manufacturing processes.

1. Objectives

Due to the layerwise production procedure, complex shaped metallic parts, whose production would be impossible or ambitious using conventional methods, can be manufactured. Moreover, a great variety of materials, such as Inconel 718 (IN 718) alloy, can be processed by SLM, respectively. IN 718 is a precipitation hardenable nickel-based alloy, which is commonly used in numerous high temperature applications such as aircraft and gas turbines due to its good creep resistance and corrosion properties at high temperatures. Furthermore, components made from IN 718 are used under different conditions in terms of loading and temperature during applications, where especially fatigue and oxidation are often responsible for damage initiation. However, some drawbacks like pores cannot be totally avoided even with optimized process parameters. In order to increase the relative density, hot isostatic pressing (HIP) is highly interesting.

2. Procedure

In view of these aspects, the influences of HIP processing and precipitation hardening on the low-cycle fatigue behavior of additively processed IN 718 alloy at 650 °C are investigated. Designation: H (HIPed), S+A (Solution annealed + aged), H+A (HIPed + aged).

3. Results

LCF tests with different specimen conditions at 650 °C

Figure 26 illustrates the corresponding hysteresis loops for the total strain amplitude $\Delta\varepsilon/2 = \pm 0.5$ % in four different conditions. The hysteresis loop of the S+A condition is in good agreement with the observed highest fatigue cycles at $\Delta\varepsilon/2 = \pm 0.5$ %. The S+A specimens exhibit the lowest plastic strain range, i.e. minimum hysteresis width. Furthermore, a comparison between as-built and H conditions shows that HIP process decreases stress values at a strain amplitude of $\Delta\varepsilon/2 = \pm 0.5$ % due to the fundamentally different microstructure. For as-built and H conditions, the material exhibits a pronounced stage of cyclic saturation until final failure.

Crack surface analysis upon LCF

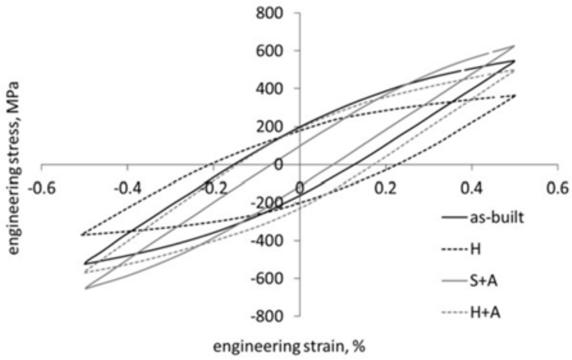


Figure 26: Half-life hysteresis loops for SLM processed IN 718. Tests were carried out at 650 °C with a total strain amplitude of $\Delta\varepsilon/2 = \pm 0.5\%$

SEM images of the partial crack surfaces after fatigue testing for the as-built and H specimens are presented in Figure 27. Upon stable crack propagation from the initiation sites, the final failure in the H condition can be regarded as ductile (Fig. 27b), as multiple dimples are observed. In contrast to this, the fracture surface of the as-built condition (Fig. 27a) shows a cleavage-like appearance including some microcracks.

4. Summary

In our previous study, it was found that recrystallization occurs during HIP processing of laser melted IN 718 and strongly affected the mechanical properties under quasi-static and cyclic loading. γ´´ precipitates evolving during aging improve LCF properties at strain amplitude $\Delta\varepsilon/2 = \pm 0.5\%$ in the solution annealed and subsequently aged condition. Other conditions show inferior properties under cyclic loading at 650 °C. Upon HIP, the samples show the lowest stress values as compared to other sample conditions, and thus, HIP leads to ductile fracture behavior under cyclic loading. Moreover, microstructural changes during LCF loading at 650 °C, i.e. shearing of precipitates and occurrence of the slip bands, are responsible for transient behavior and damage initiation.

Project Manager	*Prof. Dr.-Ing. Mirko Schaper*
Scientific Associate/s	*Mehmet Esat Aydinöz, M.Sc.*

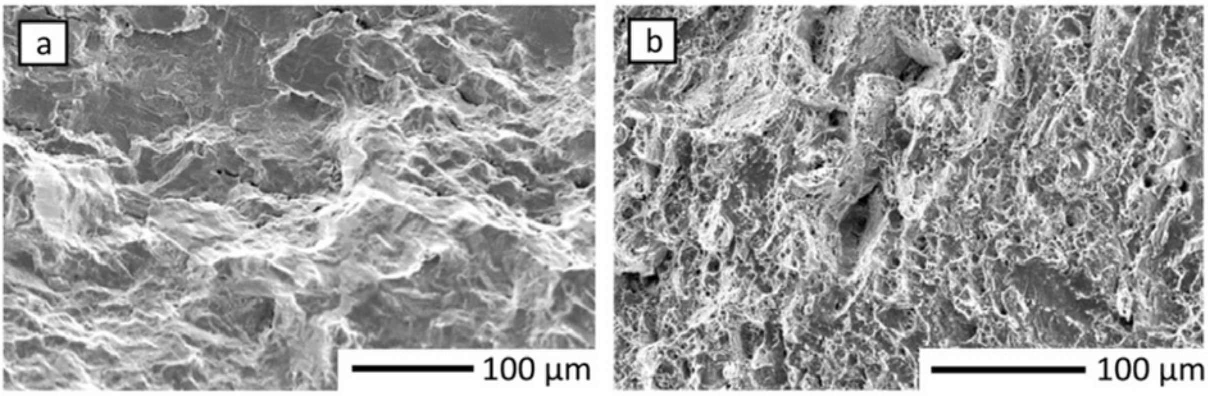


Figure 27: SEM images of the fracture surfaces after LCF testing ($\Delta\varepsilon/2$ = ± 0.35 %) at 650 °C in the as-built (a) and H (b) condition. The images were taken from the fracture surface showing instable crack growth

iBUS - an integrated business model for customer driven custom product supply chains

The overall objective for iBUS is to develop and demonstrate by 2018 an innovative internet based business model for the sustainable supply of traditional toy and furniture products that is demand driven, manufactured locally and sustainably, meeting all product safety guidelines, within the EU. The iBUS model focuses on the capture, creation and delivery of value for all stakeholders – consumers, suppliers, manufacturers, distributors and retailers.

Figure 28: iBUS project

1. Objectives

Traditionally, the process of making has been linearly with a number of distinguishable steps. Internal R&D personnel designed new products, purchasing personnel managed suppliers, products were made by manufacturing (often standard products in large volume), marketing and sold products.

IBUS model changes this paradigm. Its overall objective is to develop and demonstrate an innovative integrated business model for the sustainable supply and manufacture of safe traditional toys and nursery furniture. The model is demand driven, whereby products are customised and designed online by consumers or home-based designers, manufactured locally and sustainably to order, and meet product safety guidelines.

2. Procedure

For supporting the customers embedded services in iBUS will be developed in the main by SME Technology providers. These services include augmented reality design assistants, design verification tools for compliance with EU product safety guidelines, analysis of environmental footprint and prototyping with additive layer / 3D printing. Subsequently, parametric engineering design principles will take the design from concept to demand. This demand will then be synchronised and optimised across the supply chain, supported by the embedded supply chain optimisation tools, to produce sustainable demand driven production and supply plans.

Manufacturers will then produce the furniture and toys in small scale series production driven by the actual customer demand. Suppliers will have visibility of, and make decisions based on, end-customer demand. Likewise customers will have visibility of their orders through all stages of production and delivery. The infrastructure will be cloud based using internet and social media technologies, allowing interaction and collaboration, but also accessible to homebased or small business users, promoting social inclusion.

iBus has a budget of 7.440.362€ whereas 6.065.305€ are funded by the European H2020 programme.

Main participation of DMRC is in the WP3 "Customised Product Design Virtual Environment". A software system shall be developed enabling the customer to design or adapt the product by himself. Self-designed products have to be manufacturable and to follow the European safety guidelines. Therefore an automated safety check has to be performed by the system to ensure these requirements leading to a safe production and use. The manufacturing is supposed to be done locally and demand driven at home or at small fab shops near to the customer, mainly by additive manufacturing.

3. Latest results

This first year of the IBUS project the key progress on the development of the iBUS business model was done. The development of the model addresses a challenge faced by European industry and the consortium had spent necessary time to capture the requirements of all the stakeholders who will be impacted by the model. Concepts such as customisation possibilities, the difficulties in the operating environment that industry faces, safety requirements for any toys produced through the model, etc all have had to be understood clearly and amalgamated into the model.

The model has at its core the aim of providing equitable value sharing amongst all stakeholders. This is a core aim that is believed as necessary in order for the iBUS model to truly boost competitiveness of European organisations in this highly competitive sector. The iBUS consortium calls on organisations involved within the European toy industry supply chain to subscribe to the iBUS Special Interest Group in order to be aware of the model as it develops and to participate in its development.

4. Outlook

In the next period the collected requirements, ideas, mock-ups and approaches for safety evaluation will find their way into a web based software solution. This will show the functionality of the overall system including the upload of products, minor customization and ordering. Furthermore the iBUS demand network and iBUS supply network as a Market Opportunity Module will prove the correct demand-driven supply of customised products.

Project Manager	*Prof. Dr.-Ing. Rainer Koch*
Scientific Associate/s	*Dipl.-Ing. Ulrich Jahnke, Thomas Reiher, M.Sc., Anne Kruse, M.Sc.*

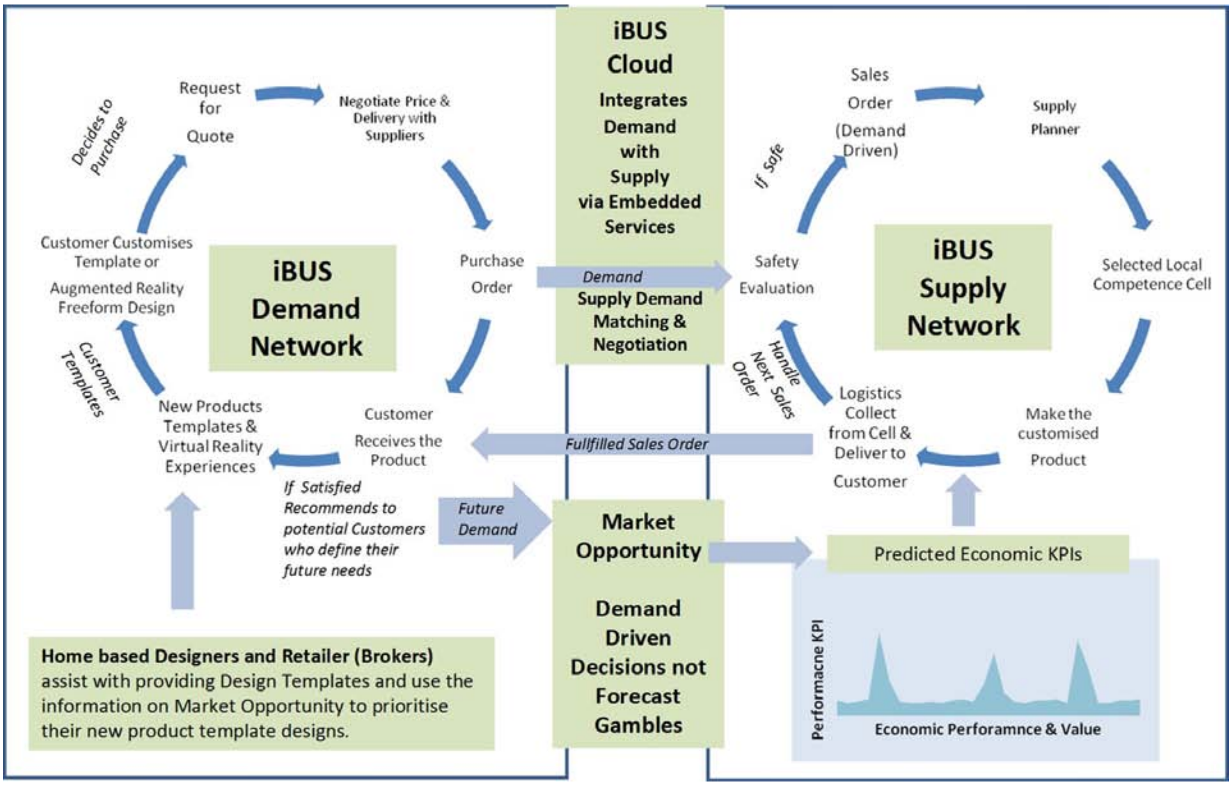


Figure 29: Non-linear supply chain model for demand-driven safe and affordable customised products

Innovative SLM Materials

Previous DMRC projects in the field of the Selective Laser Melting (SLM) process promise a lot of new properties made from conventional materials. Single-material components manufactured by this production technique have been developed by different DMRC research groups. For example, tailored mechanical properties of components as well as high strength lattice structures. Thus, the outstanding potential of this innovative Additive Manufacturing technology was demonstrated for different metals and applications. Nevertheless, all these investigations have been carried out on more or less conventional materials, such as titanium alloy TiAl6V4 or stainless steel 316L.

1. Objectives

This circumstance leaves one huge potential of the SLM process unconsidered: An in situ combination and processing of different materials in order to obtain novel materials characteristics. The innovative idea is in contrast to other conventional production-routes and offers a new degree of freedom. During the latest investigations, two different types of new materials proved to be: The easiest way to create new materials is to mix different materials to one metal matrix composite (MMC). The second way is to combine them by variating it as the dimension varies to a functionally graded material (FGM). In order to enable a systematic procedure for this project, it has been subdivided into the following work packages.

- WP01: Material-screening and definition of desired properties
- WP02: Development of exposure parameters
- WP03: Comprehensive characterization of the mechanical properties
- WP04: Concept development “locally adapted material combinations”
- WP05: Transfer analysis

Figure 30: Bronze-316L Multimaterial

The establishment of innovative materials via the combination of different materials is the main goal of this project. The two different methods, on the one hand the MMC and on the other hand the functionally graded materials, require different processing routes. The main challenge for the MMC is to find a new way to process this combination by introducing them to new exposure parameters. In order to provide new parameters it is crucial to evaluate an efficient method for detecting the optimal exposure values. The main issue on the functional graded materials is to find a way to process it in a SLM 280 machine without having to stop the process in order to change the powder or to continuously change the parameters. Finally, the exposure results of the MMC materials will be used to optimize the interface between two functionally graded materials for the purpose of improving the transition area.

2. Procedure

The first MMC material consisting of boron carbide and AlSi7Mg was designed to evaluate the exposure parameters. After some improvement loops, it shows an advantage to the mechanical properties. Due to this successful processing, the currently examined materials are 316L, H13 and bronze. The figure to the left shows a FGM made of bronze and 316L. To achieve that type of alternating structure at once, a new recoater had to be designed and produced. In combination with different slicing strategies, it is possible to change the material and the exposure parameters for every layer. According to the first microstructural and mechanical investigations, it is possible to attain good performance of the transitional area.

3. Latest results

The last results of the project contain the main activities which concentrate on further material combinations, which have been examined by additional optical deformation image correlation (DIC). With regard to the probable formation have been applied to the specimens of new alloy systems. Due to the development of a new generation of SLM slide-recoaters, it was necessary to design an entirely new recoater which fits into the new system. It works reliable and will be used in the future for new material combinations. The project has been completed in the year 2016.

Project Manager	*Prof. Dr. Thomas Tröster*
Scientific Associate/s	*Peter Koppa, M.Sc.*

Figure 31: Multi-Material-Recoater

It’s OWL 3P: Prevention of Product Piracy

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. As part of the technology network “Intelligent Technical Systems” OstWestfalenLippe (it’s OWL) funded by the Federal Ministry of Education and Research (BMBF) the project “It’s OWL 3P: Prevention of Product Piracy” focuses on raising the awareness that legal measures are not the only way to protect innovations and products against product piracy.

1. Objectives

The main objective of the DMRC’s part of this project is to show potentials of Additive Manufacturing to protect product from being copied. To ease the application of those potentials measures will be developed and merged in a catalog that can be used during product developed as a kind of guideline for “design for protection”. This project aims at ensuring the sustainability of investments in research and development of companies participating in the technology network.

2. Procedure

Starting with a deep analysis of the main reasons and origins of product piracy the usual procedure of copying a product will be investigated to understand a pirates’ mind. Combined with the potentials of Additive Manufacturing protective measures will be developed to increase the hurdle for pirates’ activities. To provide a benefit for potential users of those measures, real world application are taken into account. Measures will be applied to real products during projects runtime to generate best practices and success stories so that interested companies can be supported by examples. Finally all the measures, a selection methodology and experiences in terms of examples will end up in a guideline for companies.

3. Latest results

One main potential of Additive Manufacturing is that individualization of products becomes possible in a very economical way. Marking a product with a very individual number or a QR or Datamatrix code is just a kind of individualization and will not increase manufacturing costs using AM but allow traceability usable in case of liability or product optimization aims during products lifecycle etc. Traceability of products is very often mention as one requirement to achieve the main goals of Industry 4.0.

Other benefitial measures to avoid product piracy by the use of Additive Manufacturing are for example the following: Blackbox design to hide the main functionalities of a product; Functional integration to increase the complexity of a products’ structure are therefore to complicate reverse engineering; Lightweight design very often comes up with bionic structures so that also the reverse engineering is complicated as usual 3D scanning is not able to record the whole product.

Seminars at the University of Paderborn served to validate those measures in groups of representa-

Figure 32: Production integrated marking using AM

tive subjects. All of the participants had a degree in mechanical engineering or similar und has been familiar with the use of CAD software.

They tried to act like a product pirate and documented their time needed for the specific step in the Reverse Engineering process. The results are very useful to show the given protective effect when considering the “design for protection” already during product development or at least in the products’ redesign. Reverse engineering as the most important information source of product imitators has been complicated in each case.

4 Outlook

To fulfill the requirements of Industry 4.0 product markings in terms of machine-readable codes, the development of specification of codes is currently ongoing. Influencing factors like orientation and position of the parts inside the build chamber of Additive Manufacturing machines will be analyzed to come with recommendations.

During the last months of it’s OWL 3P protective measures will be validated further in real products to enhance the guideline with a best practice and success story section.

We are continuously looking for applications. You have one? Just get in contact with us!

Project Manager	*Prof. Dr.-Ing. Rainer Koch*
Scientific Associate/s	*Dipl.-Ing. Ulrich Jahnke*

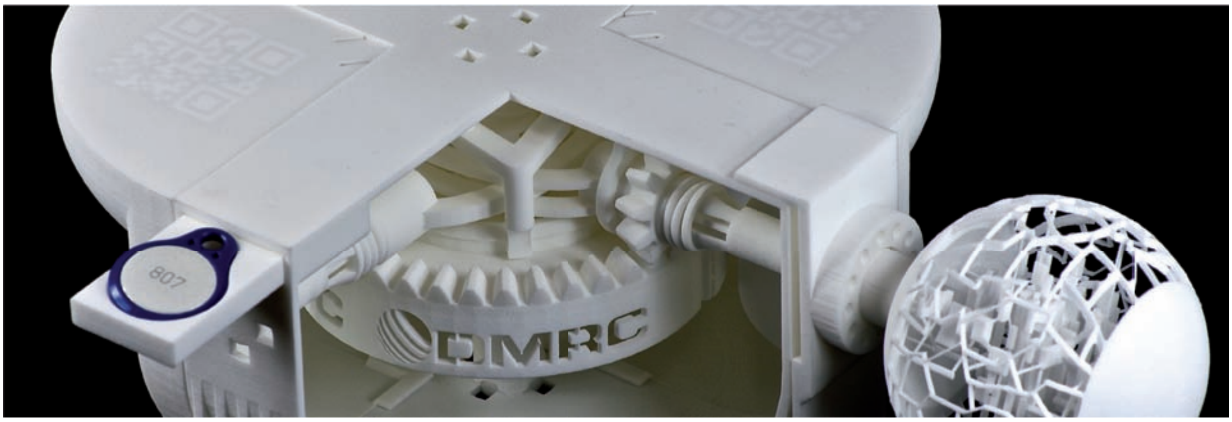


Figure 33: Demonstration of various protective measures in one fictitious product.

KnowAM

The project KnowAM deals with the processes of cost efficient design and planning regarding the use of Additive Manufacturing technologies. Costing structures of AM technologies and planning tools for early phases of the product development are part of the research. Based on best practices from product development case studies, a methodology for cost efficient design and planning is derived.

1. Objectives

The following goals are targeted in the project:

- Enhancement of costing framework developed in the Project CoA2MPLy (1)
- Achievement of comparability between machines and technologies regarding costing aspects and particularly building rates (2)
- Development of an scalable IT-System with a costing calculation module, an AM Database and a presentation of advantages of the Additive Manufacturing technology (3)
- Derive best practices for cost efficient design and planning (4)

2. Procedure

Enhancement of the SLM costing framework:

The costing framework developed in the project CoA2MPLy focuses Selective Laser Melting (SLM) with its specific characteristics. Objective (1) comprises an adaption of the costing model to the Laser Sintering (LS) process and to Fused Deposition Modeling (FDM) as well, to provide cost calculations for the three most common Additive Manufacturing processes. This work will enhance the existing framework for costing analysis to be utilized by OEMs.

AM machines and technologies:

Objective (2) addresses the comparability between different types of machines and technologies. At the moment machine manufacturers measure the building rate in different ways and even specify these rates in different units – for instance cm³/h or mm³/h. The aim is to achieve comparability and transparency for potential customers facing a make or buy decision.

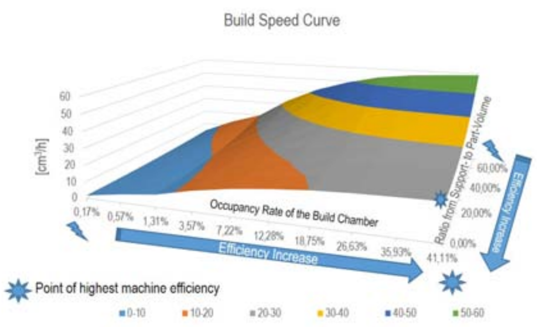


Figure 34: Build speed curve with regards to occupancy rate of the build chamber and the support ratio

Therefore, 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. Different technologies will be compared with regards to the specified methodology.

Development of an IT System for costing calculation:

This objective (3) is meant as development and implementation of a scalable IT-System concept. 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. 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 IT-Tool is now

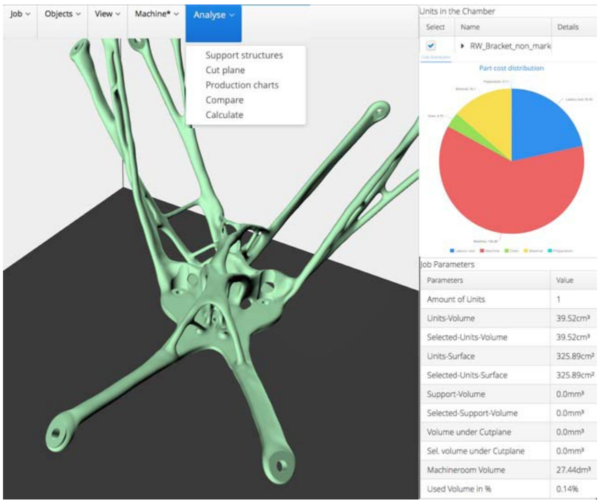


Figure 35: ReactionWheel bracket in the KnowAM-Software Tool

capable of implementing marking as proposed in the 3P-Project.

Derive best practices for cost efficient design and planning:

The overall results of the projects will help to define rules for the costefficient utilization of Additive Manufacturing and therefore help to foster the growth of the technology. Furthermore, the outcomes will enable end users to compare different technologies or design alternatives with regards to building speed and cost-efficiency. Also, best practices and a methodology for AM part candidate selection will help the designer to industrialize the AM technology.

3. Latest results

Build speed test with Laser Sintering, Fused Deposition Modeling and Selective Laser melting have been performed with multiple material and multiple layer thicknesses. The productivity of these processes can now be compared with regards to productivity and build up rates. A common terminology for build speed and productivity was implemented.

4 Outlook

As final report the project results are documented in the report "Cost efficient Design for Additive Manufacturing". The report contains rules for cost efficient design and planning, case studies, application examples and material data. Lifecycle costing guidelines and tools as well as build speed results are published din this report.

Project Manager	*Prof. Dr.-Ing. Rainer Koch*
Scientific Associate/s	*Dipl.-Wirt.-Ing. Christian Lindemann*

Light-weight construction: Robust simulation of complex loaded cellular structures

Currently, one of the main challenges in industry is the reduction of the energy consumption of moving parts as well as of the total amount of the materials used. In order to meet the demand for optimized light-weight parts, the development of load adapted structures has begun to play a key role in today's research. One approach is the employment of low density materials, such as the well-known aluminum foams. However, on small scale, these foam structures are stochastic and therefore not load optimized. At this point, additive manufacturing becomes highly beneficial as it enables for an unprecedented design freedom. By the application of additively manufactured non-stochastic cellular structures, which can be locally adapted to the prevailing stresses, an optimized relative loading capacity becomes feasible.

1. Objectives

The first focal objective of this project is the creation of a robust Finite Element Analysis (FEA) model for complex loaded cellular light-weight structures. Based on of a previously generated linear elastic simulation, the examinations will be extended to linear-plastic deformation behavior including several materials e.g., metals as 316L stainless steel (ductile) and Ti-6Al-4V alloy (brittle) and plastics as PA12. The second focal objective of the project addresses the experimental verification of the generated FEA model. Therefore, cellular structures will be additively manufactured by employing Laser Sintering (LS) as well as selective laser melting (SLM) and subsequently uniaxial and bending tests will be conducted.

2. Procedure

In the first step, two different types of base-cells for a verification of the mechanical behavior and the simulation were designed. Both geometries were then employed for compressive and four-point bending tests. In addition to the latter mechanical analysis, the local strain distribution throughout the specimen was analyzed by means of digital image correlation (DIC). This software tool enables to achieve profound insights into the local loads of single struts and thus were crucial to evaluate the accordance of simulated and actual stress distributions for both metallic and plastic additively generated specimens. During the entire duration of the project the proceedings were reported at regular intervals.

3. Latest results

Previous investigations have shown that the deformation behavior of lattice structures depend on the heat-treatment, cell-structure, microstructure and load type. For a FE-analysis, the struts' diameter is as important as the tensile strength of the material to simulate the mechanical behavior. In Fig. 36, the simulation of compressive and tensile tests is displayed and compared to the experimentally tested specimens. The main challenge was to identify the average strut-diameter of the specimens. Therefore, the compressive and tensile tests were simulated with various strut-diameters.

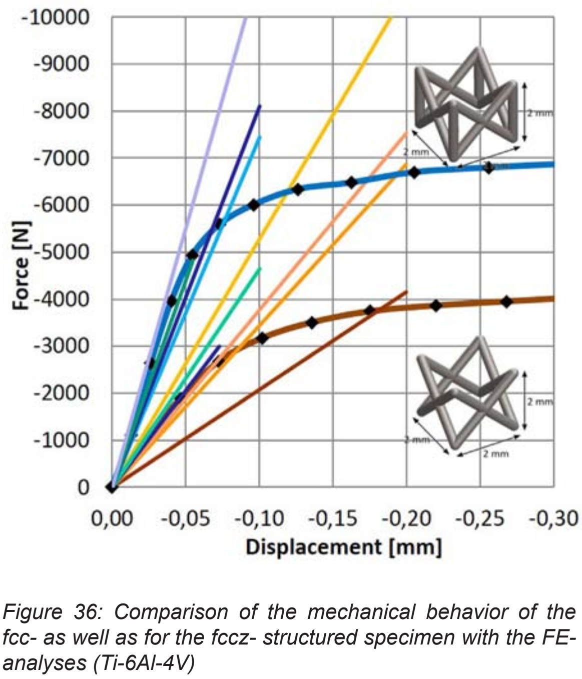


Figure 36: Comparison of the mechanical behavior of the fcc- as well as for the fccz- structured specimen with the FE-analyses (Ti-6Al-4V)

These investigations are in alignment with the SEM analyses, since a precise prediction about the diameter for the struts in different directions is not feasible. Despite the deviations in the lattice structure diameters, the data in Fig. 37 reveals that the inhomogeneous struts, however, can still be employed for the FE-Analyses.

With the information from tensile tests and simulation according to the average strut–diameter, FE-analyses were conducted and compared to the mechanically tested lattice structures during compressive (Fig. 37) and tensile tests. The comparison of both lattice structures has shown that the results of the FE-analyses are very similar to the digital image correlation in the linear-elastic range.

Project Manager	*Prof. Dr.-Ing. Mirko Schaper*
Scientific Associate/s	*Alexander Taube, M.Sc., Stefan Josupeit, M.Sc.*

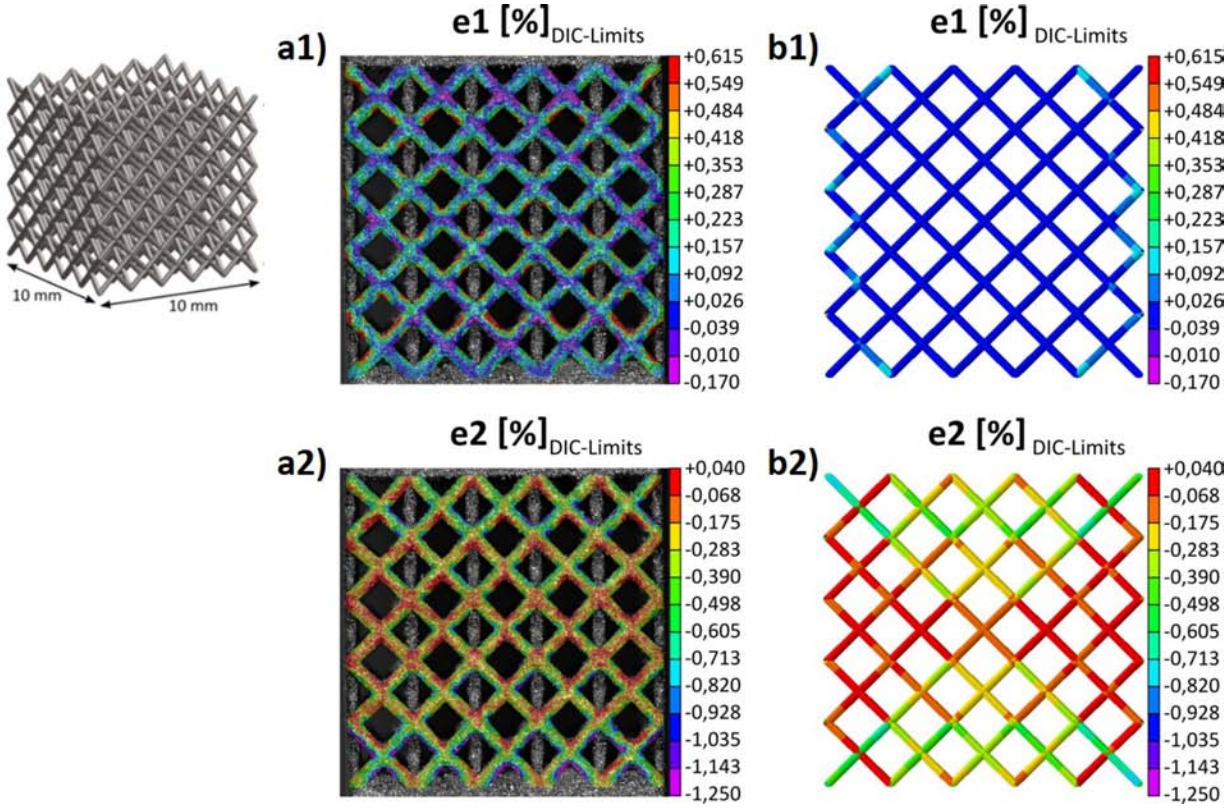


Figure 37: Local strain distribution of the fcc lattice structure under compressive load (a) maximum principal strain e1 and minimum principal strain e2 for the DIC; b) Simulation

Material development of polymers for extrusion deposition additive manufacturing processes

The aim of this project is to investigate the requirements for materials and semi-finished products which are processed in extrusion deposition 3D printing processes. By gainig a better understanding of these processes, a knowledge base should be created, to increase the variety of materials that are available. This project is conducted in cooperation with Albis Plastic and under the NRW Fortschrittskolleg "Lightweight – Efficient – Mobile" (FK LEM). As one of the six Fortschrittkollegs established in 2014, the FK LEM is sponsored by the Ministry of Innovation, Science and Research of the State of North Rhine-Westphalia.

1. Objectives

The to be examined extrusion deposition additive manufacturing processes are among the most commonly used additive manufacturing processes. For example, they are known by the terms Fused Deposition Modeling (FDM), Fused Layer Modeling (FLM) or Fused Filament Fabrication (FFF). In this methods, the semi-finished product, commonly a wire of a thermoplastic polymer, is melted and forced through a nozzle. The continuous positioning of this nozzle allows the polymer to weld together strand by strand and layer by layer to produce a component. The energy for the welding of the individual strands largely results from the thermal energy of the deposited polymer melt.

Figure 38: PA6 granulate is extruded into monofilaments

It is desirable to be able to use a similarly wide variety of materials with this method as, for example, in the profile extrusion or injection molding technology. Therefore, the processing suitability of any thermoplastic polymer should be estimated based on the material properties or characteristics in advance of the processing. This is currently not possible because, in contrast to conventional methods, only little is known about the required and desirable material properties for the processing in extrusion deposition additive manufacturing processes.

2. Procedure

In this project, the requirements for materials, semi-finished products and processes are investigated by the means of example polymer types. For this purpose, different types of polyamide 6 (PA6) will be systematically extruded into monofilaments and then a supervised processing in an extrusion deposition additive manufacturing machine will follow. By varying important material properties, such as the viscosity, the material properties should be connected to the processing properties.

To reach that aim the processability in extrusion deposition additive manufacturing processes has to be defined so that it is evaluable for different materials. Therefore custom-built specimens are created to investigate some significant characteristics like tensile strength of the welding seams or process specific warpage. Other factors like machine quality or data processing should have no or minimal influence. For that reason machine and process specific influences are considered to create custom-built specimens.

After the specimens have been verified on known materials, series of tests should be run for each characteristics. Suitable material properties are identified by rating the processability as a function of the varied material properties. Those are supervised during the whole project by methods like differential scanning calorimetry or high pressure capillary rheometry.

2. Outlook

Some characteristics like tensile strength of the welding seams or process specific warpage are currently in testing for different material types. Additional types of materials with different material properties should be tested and additional characteristics should be investigated for all tested material types. At least a polymer should be identified that shows an optimal processability. This polymer should be reinforced with fibers. Then the processing of fiber-reinforced materials should be examined. It is assumed that the procedural generation of components by juxtaposing many strands enables the influence of fiber orientation.

Project Manager	*Prof. Dr. -Ing. Volker Schöppner*
Scientific Associate/s	*Christian Schumacher, M.Sc.*

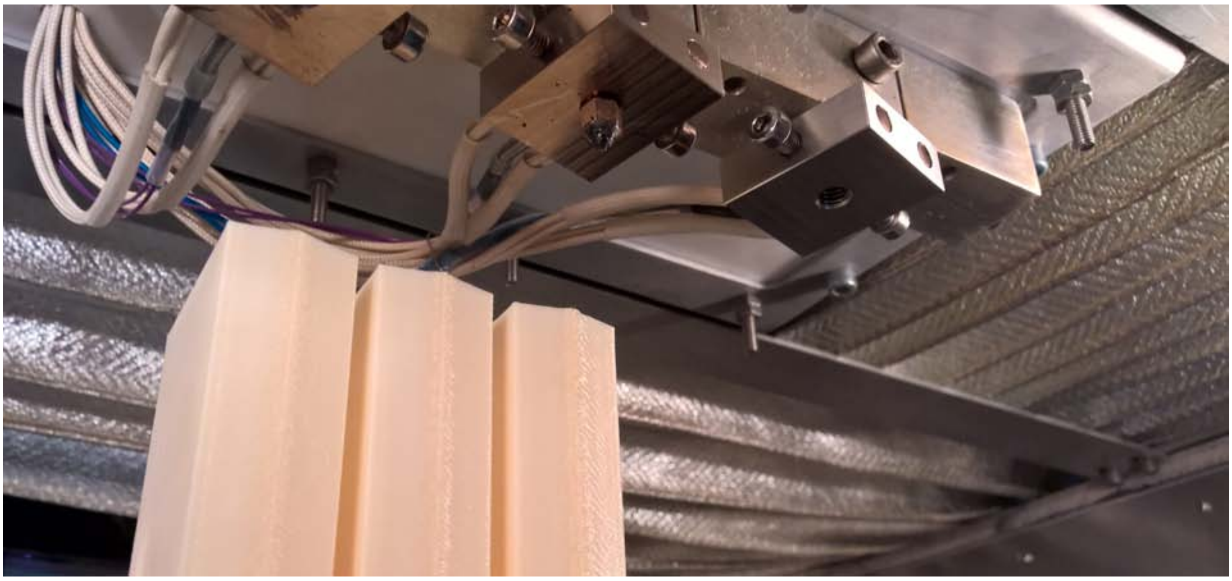


Figure 39: A custom built FDM-Machine is used during the project

RepAIR: Future RepAIR and Maintenance for Aerospace industry

The goal of this research project with twelve partners from all over Europe and from the US is the onsite maintenance and repair of aircrafts 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.

1. Objectives

The project aims to reduce the Maintenance, Repair and Overhaul (MRO) costs with the help of the Additive Manufacturing (AM) technology as its crucial advantage is the flexible availableness allowing on-time maintenance. The technology shall help to reduce the turnaround time by a higher automation level and a reduction of the inspection time by integrating continuous health management. Further optimizations are intended for a part weight reduction and less scrap and toxic chemicals in the repair process. All in all, this will strengthen the business model of European MRO service provider in the world by integrating a complete production and supply chain for complex spare part.

2. Procedure

There are dedicated work packages for each research task. First, a requirements analysis is conducted. A decision support is developed in order to automate the cost analysis. A test rig and statistical procedures are set up to implement part monitoring and usage based lifetime prediction. An automated Direct Metal Deposition machine with integrated scanning and milling tool is being developed. Further process related parameters are derived and a part redesign is conducted. This supports also the creation of a certification and QA concept as another research field in the project. This is all integrated in the RepAIR IT management platform, a new suite that combines all steps in one software and thus supports the overall objective to reduce costs and lead time.

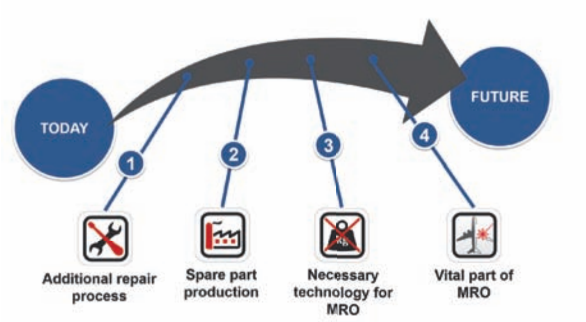


Figure 40: Future scenarios for the different integration stages of AM into aerospace

3. Latest results

In order to achieve the project's objectives a roadmap for the further progress and research needs of the considered technologies has been generated. A prototype Decision Component tool has been developed to calculate an AM part repair or production in order to determine the most cost-efficient solution. It also takes into account environmental issues to balance ecological and economical costs. A test rig was set up and a methodology has been developed to perform experiments in order to predict the remaining lifetime of a part by statistical analysis to improve the usage of parts and to map the exchange with the regular maintenance schedule of the specific aircraft. Improvements are made directly focusing on AM repair in MRO processes for high batch repair of identical parts with the design of a clamping device. The high batch repair process has been demonstrated to work properly handling the chosen sample part. An integrated 5-axis DMD/tooling machine prototype has been installed. It is capable to compare the damaged geometry with the original CAD file and to automatically calculate the milling and cladding paths to restore the part's shape. Tests for generating process parameters were started. Based upon the previously summarized regulations and requirements on the certification process, a conceptual design for a qualification process using AM has been described. A quality manual model with specific procedures for the newly developed workflow has been derived. The MRO software has been enhanced by the various RepAIR modules and now supports the integrated repair and production process in one single application.

Within the first and second RepAIR workshop, project results available up to that point have been presented and evaluated. Key performance indicators (KPI) for management platform and sub-systems have been established. For the dissemination and exploitation of the results various activities, such as participating in conferences and fairs, have been performed. Based on the dissemination strategy, several conference presentations were given and papers were published. The exploitation plan has continuously been synchronized with individual exploitation plans of each partner.

4. Outlook

The project was finished in summer 2016 but the consortium intends to use the gained knowledge in the field of Additive Manufacturing and aerospace to continue research in these fields. Results from the RepAIR project will further be disseminated and the consortium partners will proceed with their exploitation plans.

Collaboration partners of DMRC in RepAIR

APR Srl (Italy), AIMME (ES), Avantys engineering (DE), ATOS (ES), The Boeing Company (US), Cranfield University (UK), Danish Technology Institute (DK), Lufthansa Technik (DE), O'Gayar Consulting 2009 (ES) and SLM Solutions (DE)

Project Manager	*Prof. Dr-Ing. Rainer Koch*
Scientific Associate/s	*Gereon Deppe, M.Sc.*

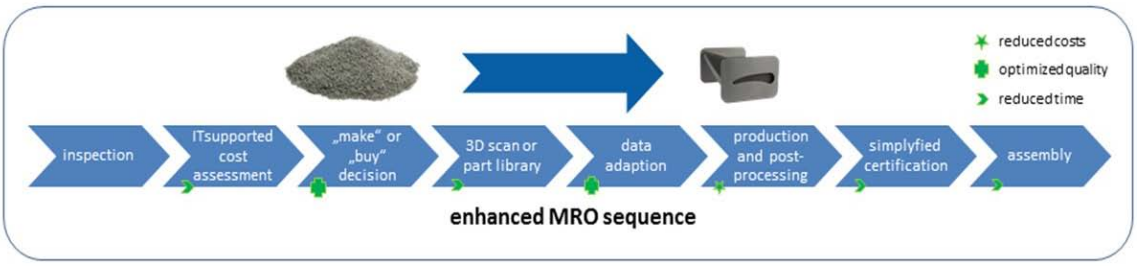


Figure 41: Enhanced MRO sequence

Surface Topography Analysis and Enhancement of Laser Sintered Parts (STEP)

Objective surface qualification values are not defined nowadays and are therefore evaluated for laser sintered part surfaces. Also, subjective haptic impressions are considered and correlated to objective values. Furthermore, the surface quality in dependence to variations of manufacturing process parameters are investigated to identify the most influencing parameters. A variety of post-processing methods are also examined according their utility for smoothing laser sintered parts. The build orientation as a main influencing factor is considered with a newly built tool to predefine the optimal orientation for good surface quality of functional areas of a part.

1. Objectives

It is known that laser sintered parts have quite rough surfaces which additionally differs on the orientation of a surface inside the manufacturing process. At the same time no useful surface quality parameters are defined for this process and how they depend on process parameters. Therefore, objective surface qualification values correlated to subjective impressions, their dependence on several process parameters and the benefit of different post-processing methods are addressed within this project.

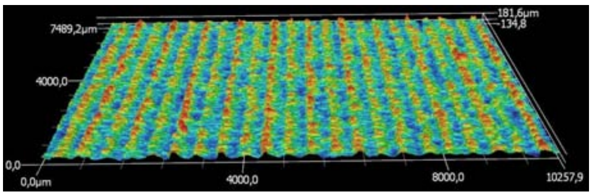


Figure 42: Exemplary 3D measurement of a 15° tilted surface. The shown field of view is used for the different analysis methods

2. Procedure

First, the identification of high potential surface characterization values and methods is done using optical 3D measurements of laser sintered parts. Both standard surface analysis values and image analysis methods known for product qualification in other areas are considered. A haptic testing setup is prepared for correlation of these values to subjective impressions of laser sintered part surfaces.

Further analyses are performed with parts build with varying manufacturing process parameters. Machine parameters (e.g. layer thickness, laser and scanning parameters, build temperature) as well as powder quality (virgin powder vs. used powder) and geometrical factors (e.g. wall thicknesses, surface orientation, spatial position, part distance, layer time) are evaluated.

Finally, different post-processing methods like mass finishing process, abrasive blasting and chemical etching are examined according their utility.

3. Latest results

A haptic test setup was prepared to get information about subjective impressions of defined sample parts. A correlation to objective surface qualification values identified at least one of them which represents the haptic impression very well.

Analyses of parts manufactured with varied process parameters showed distinct dependencies for some parameters while other showed no quantifiable influence on the surface quality. The evaluation of parts manufactured with used powder identified parameters that reduce the occurring of orange peel effect significantly.

The findings and results of the above analyses were in addition used to build up a surface topography simulation and a part orientation optimizer. The optimizer can be used to predefine the best build orientation if some functional areas of a part need to have an optimal surface quality. Simultaneously, the build height can be considered to reduce the build time and thereby the cost of that part. The validation of the tool was done experimentally with a real part from EOS, the monitor holder which is built in at their P machines.

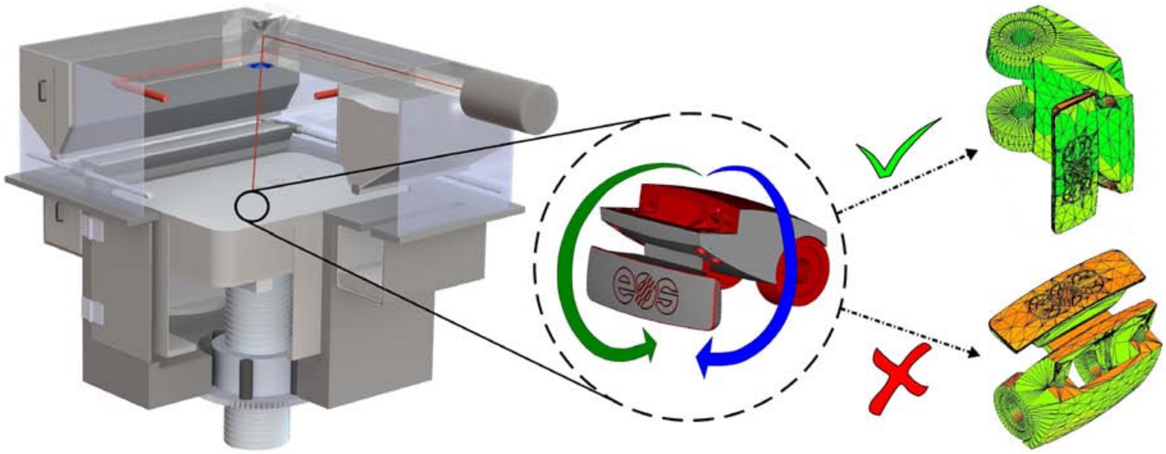


Figure 43: A part orientation optimizer calculates the optimal build orientation regarding surface quality of pre-defined functional areas and build height of a part.

4 Outlook

The project is finished this year. Also promising post-processing methods were found that need to be investigated more deeply to enable them as reproducible post-processing methods.

Project Manager	*Prof. Dr.-Ing. Hans-Joachim Schmid*
Scientific Associate/s	*Patrick Delfs, M.Sc.*

TPE-A Laser Sintering Material and Part Properties – Qualification for New Applications

Materials for laser sintering process are still rare and in focus of current research. Standard material Polyamide 12 is well known in terms of material characteristics, laser sintering process and resulting part properties. Furthermore it is applicable in a broad amount of technical cases. However Polyamide 12 is only one of numerous technical polymers and the here investigated TPE-A material supplements the material database of laser sintering. TPE-A is a thermoplastic elastomer, having elastic and simultaneously thermoplastic properties. This way it is possible to use TPE-A for the laser sintering process, realizing new applications like for bellows, seals and shoe soles. One of thermoplastic elastomer in the market is EOS's PrimePart ST, a PEBA (polyamide-based TPE), that was specifically developed for application in laser sintering. Though it is already usable on laser sintering machine, there are several aspects that have to be investigated.

1. Objectives

As the TPE material performs different from Polyamide 12 during process, powder characteristics, process parameter and part properties have to be tested. It is already known that powder characterization methods, like MVR-measurement, used for standard material PA12 to test the aging stage, aren't suitable for PrimePart ST. Therefore new procedures have to be considered, in terms of powder characterization and chemical investigations to distinguish virgin powder from thermal stressed material. Furthermore optimal process parameter, which lead to desired part characteristics are important to qualify the material for new applications of laser sintering.

2. Procedure

Since the TPE material has different polymer properties from Polyamide 12, the performance during process has to be tested. Parameters like build temperature and part thickness have to be varied. Elastic part characteristics like elongation at break analyzed by tensile test (figure 44) in correlation to build parameters of laser sintering process have to be understood, so that using PrimePart ST leads to reliable part properties. Also important for reproducible application is the aging behavior of PrimePart ST powder, due to thermal stress during laser sintering process and a targeted refreshmentrate of 50/50. This way different powder characterization methods and chemical tests are applied to investigate the difference of virgin and thermal stressed powder. Furthermore part properties like tensile behavior and discoloration of TPE parts are tested to achieve elastic laser sintering parts with applicable characteristics.

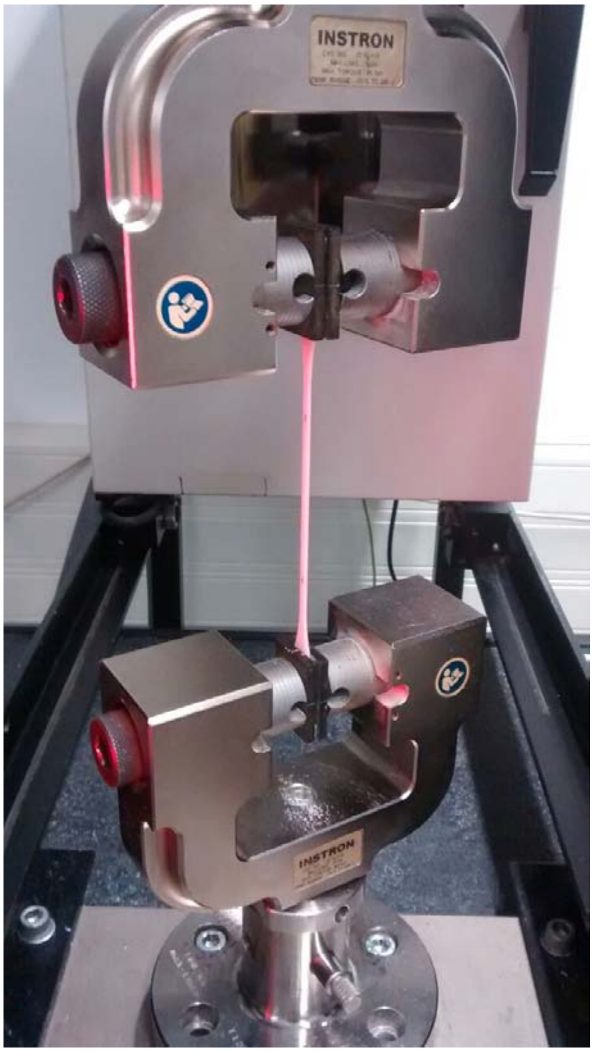


Figure 44: Tensile test of TPE specimen

3. Latest results

In former research powder was aged in an oven and in the laser sintering machine. It was find out, that after thermal stress the molecular weight of TPE powder increases slightly. Furthermore particle size distribution shifts to higher values, due to agglomeration of the particles. During compression tests, stamping dies were filled with 1.0 g of powder and were stressed with 25 kN. As you can see in figure 45, where applied load over displacement is depicted, machine aged powder (1 MA) compacts more than virgin powder (VP), as a result of mentioned agglomeration of particles. Powder that was aged two times in the machine compacts even more.

This effect can also be stated by determining bulk density. When powder is aged in the machine, bulk density is lower in comparison to virgin powder. When you test refreshed powder, namely 50 % virgin powder and 50 % aged powder, you get a medium bulk density. As a conclusion the ageing stage of the TPE material is not investigated by MVR measurement, like it is used to be done with Polyamide 12, but by determination of the bulk density.

During this year, tensile tests of specimens built at different temperatures were done. Elongation at break referred to cross section gave information about adequate build temperature at which mechanical quality is the best and dimensions are still correct.

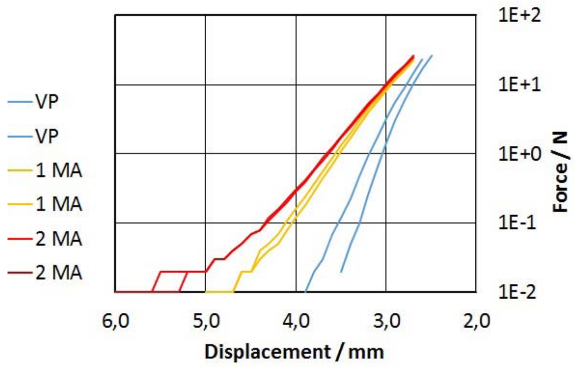


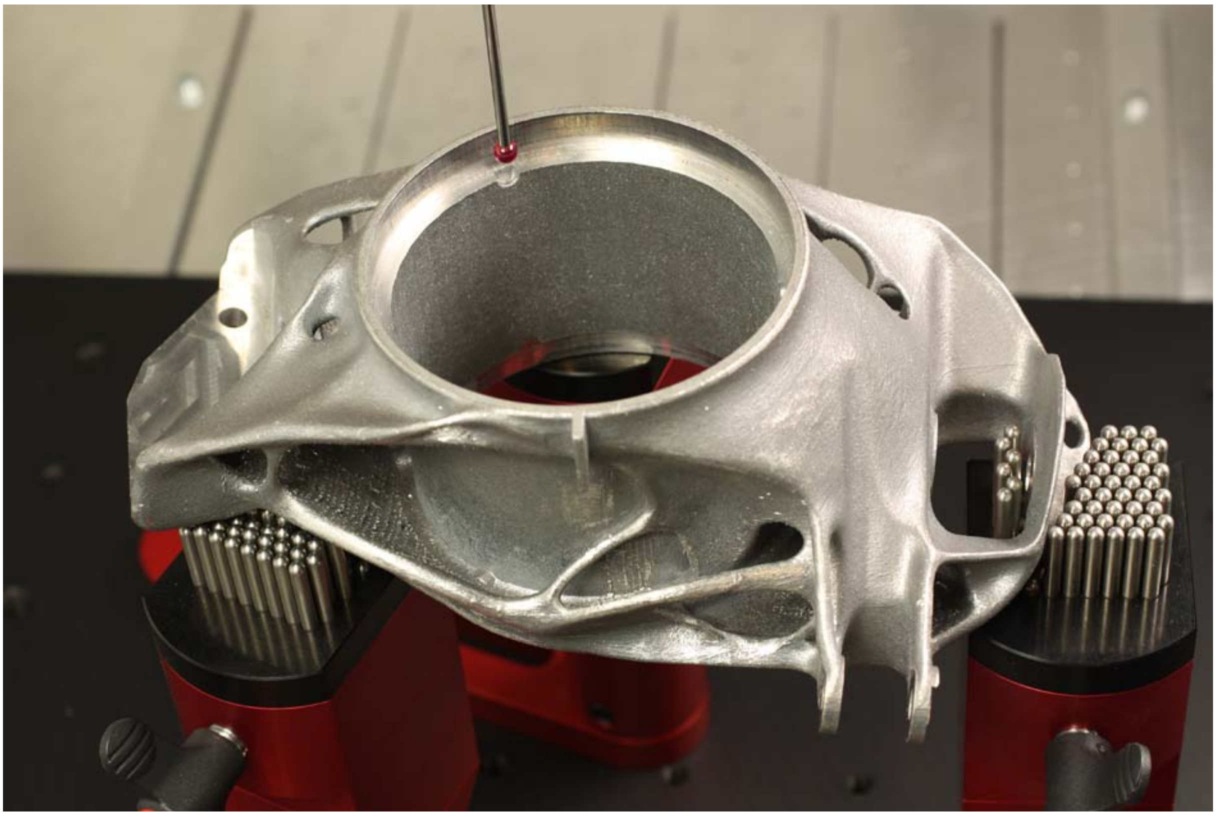
Figure 45: Powder Compression of virgin and machine aged powder

Furthermore a discoloration of parts, built with PrimePart ST, was noticed. Within one build job you can see yellow parts in varying intense. To investigate when discoloration occurs, parameters like laser energy density, wall thickness and orientation of therewith built parts are varied to build specimens for color measurement. The color measurement takes place by spectrophotometry with Minolta Spectrophotometer CM – 3600d in KTP (Kunststofftechnik Paderborn) laboratory. Yellowness is estimated according to DIN 6167 and related to before mentioned parameters. Furthermore it is tested if yellowness affects mechanical quality.

4 Outlook

Research into yellowness of TPE parts and tensile tests will be finished and a final report will be prepared.

Project Manager	*Prof. Dr.-Ing. Hans-Joachim Schmid*
Scientific Associate/s	*Dipl.-Ing. Nils Funke, Christina Kummert, M.Sc.*



3 Innovation

Aircraft bracket case study

1. Partner

The Company H&H GmbH – partner of the DMRC since 2013 – offers all the development services required to transform an idea into a series product. Thereby, H&H develops and builds prototypes and then simulates, tests and produces the idea that has taken shape in series volumes.

2. Objectives

The main purpose of this case study was to demonstrate the potential of Laser Melting for the development of brackets for the aircraft industry. Therefore, a given bracket should be redesigned, technical and economic benefits should be analyzed.

3. Procedure

For this case study a bracket was considered that mounts the luggage compartment damper to the aircraft structure and that is fabricated by milling. In order to foster a lightweight design, topology-optimization was used to define the geometry. Under consideration of design rules from the Direct Manufacturing Design Rules project, the bracket was further designed in order to stick to manufacturing constrains and to minimize post-process operations. The bracket was manufactured and tested with several different loading conditions in order to prove the computer-simulated results practically.

4. Achievements

Generally, the case study proofed that additive manufacturing can provide great advantages for the fabrication of brackets. In this particular case, the following achievements could be obtained:

- Weight reduction of -46.2% (16.13 g) compared to the milling part (29.98 g).
- Manufacturing cost increase of 39.47% (92.19 €) compared to the milling part (66.11 €)
- Lifetime cost reduction of -39.50% (511.57 €) compared to the milling part (845.57 €)

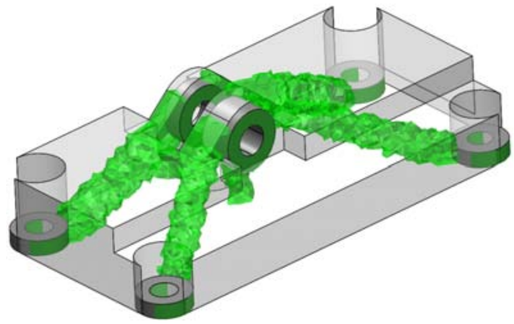


Figure 46: Topology Optimization of the bracket

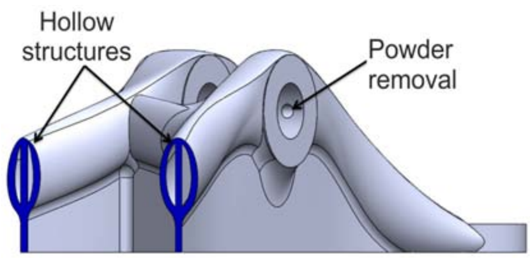


Figure 47: Bracket design with internal structures

Figure 48: Testing of the manufactured bracket

Project Manager *Prof. Dr-Ing. Dettmar Zimmer*

Scientific Associate/s *Dr.-Ing. Guido Adam, Marc Timmer, M.Sc. (H&H)*

Lightweight construction of hydraulic clamping devices processed by SLM

1. Partner

ELHA-MASCHINENBAU – a company with a long tradition – stands for technical innovation with customized machine tools providing individual manufacturing processes for advanced machining requirements. Our divisions PRODUCTION MODULES and XL MANUFACTURING SYSTEMS stand for different machine concepts and machining solutions for various industry sectors.

2. Objectives

The project is about a technical and economic study for the feasibility of a base body for a hydraulic clamping fixture by using the advantages of the SLM process. So far the fixture is made in several machining steps out of one solid piece of steel.

3. Procedure

To achieve the advantage of weight reduction and higher stiffness of the clamping system, the complete part had to be redesigned. Several iterative topology optimization steps had to be calculated considering geometry, stiffness and collision restrictions. In addition, the production costs of the fixture system made by SLM process were compared with the conventional process.

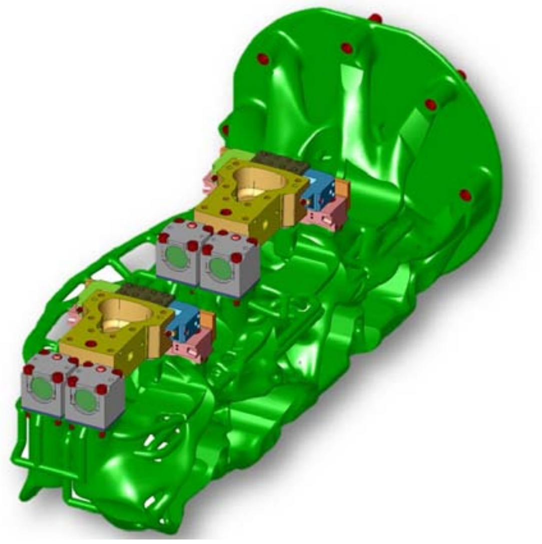


Figure 49: Topology optimized clamping device

4. Achievements

Due to the fact the clamping device lost after the optimization around 58% of weight, the dynamic and inertial forces on the milling machine decrease significantly. That has a positive effect on the weight and stiffness of the whole milling module.

- Weight reduction:- 58 %

Project Manager *Prof. Dr. Thomas Tröster, Prof. Dr. Rainer Koch*

Scientific Associate/s *Peter Koppa, M.Sc., Thomas Reiher, M.Sc.*

Direct damping of an armature plate used in a spring-loaded brake

1. Objectives

In drive systems, spring-loaded brakes are commonly used to slow down, stop and lock the drive system. They are located at the B-side of electric motors. While braking, the armature plate is pressed against the rotating friction lining by spring elements. To release the brake, an electro magnet rescinds the spring forces. The fast movement of the armature plate leads to strong impacts with the friction lining and the housing of the electric motor. This results in a vibration of the brake-system and the emission of perceivable noise.

Figure 50: Test rig used for sound pressure level tests

2. Procedure

Using the results of the AMFIDS-project, AM technologies have been used to integrate damping structures into the armature plate of a spring-loaded break. A segmented, ring shaped cavity was integrated into the armature plate consisting of eight single cavities. The powder was left inside the cavities to act as a particle damper. Further, lattice structures were integrated into the cavities to support the manufacturing process as well as to allow thinner walls. The cavity is divided into segments to achieve a better absorption of the impact forces. After manufacturing, the armature plat by laser melting process and a following turning operation experimental tests were carried out to evaluate the effect of the integrated damping structure. Therefore, the sound pressure level was measured and compared for the shift operation of the brake system.

Figure 51: Sectional view of the cavities inside the damped armature plate

3. Achievements

By integrating damping structures the mean sound pressure level could be reduced by 7.86 dB(C). This is a significant reduction in the emitted noise of the brake system and shows the tremendous potential of direct manufactured function integrated damping structures.

Project Manager	*Prof. Dr-Ing. Dettmar Zimmer*
Scientific Associate/s	*Thomas Künneke, M.Sc.*

Bipolarplates using FDM-Mold

1. Partner

This Innovation was developed together with Eisenhuth GmbH & Co. KG. Eisenhuth. Eisenhuth is SME located in Germany, Osterode am Harz, and has three main competencies: Mold making, small and medium series of thermoplast, rubber, silicone and thermoset components and the production of bipolarplates from graphite compound materials. In this place the DMRC want to thank Eisenhuth for the great contribution.

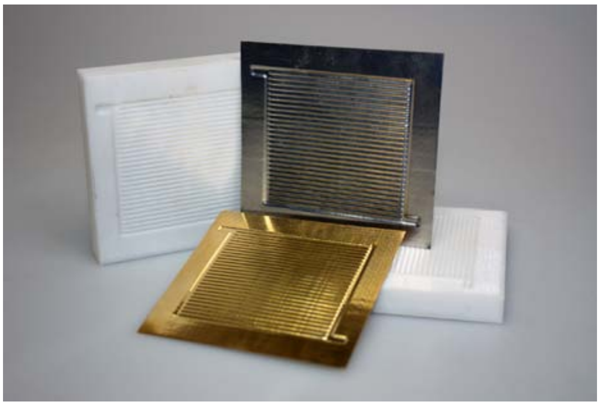


Figure 52: Pressed sheet metal

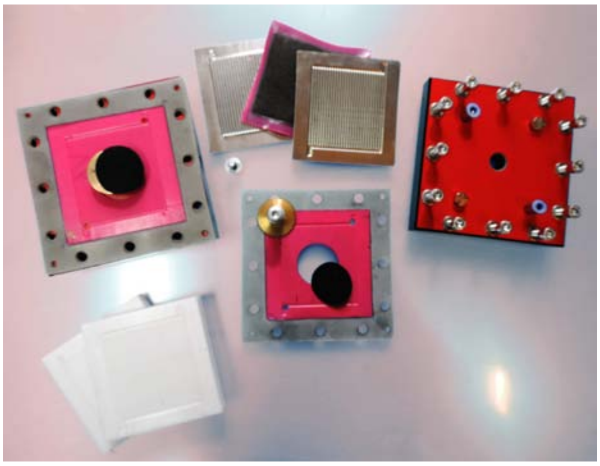


Figure 53: Experimental setup of the fuel cell

2. Objectives

The aim was to investigate, if the FDM process is suitable for the production of tool inserts (negative molds), which enables the production of finely textured metallic bipolar plates (BPP) to realize the efficient production of fuel cells.

3. Procedure

The first part of the project was to define and design the finely structured hydrogen channel, taking the requirements of the subsequent production steps into account. There, the limitations of the FDM-Process in this area of application and the resulting mechanical properties and geometrical characteristics has to be investigated.

4. Achievements

Finely textured mold with good surface quality and sufficient mechanical properties for a small series production of metallic bipolarplates. Identification of suitable materials for this application using the FDM-Process and investigations on orientation angles for optimal canal depths and shapes.

Highlights:

- Performance: up to 62% higher
- Speed: 5 times faster
- Space: up to 50% thinner

Project Manager *Prof. Dr. rer. nat. Thomas Tröster, Prof. Dr.-Ing. Hans-Joachim Schmid*

Scientific Associate/s *Dominik Ahlers, M.Sc., Matthias Fischer, M.Sc., Frederick Knoop, M.Sc.*

Lightweight Rotor Shaft for PMSM

1. Partner

The project was funded by the Forschungsvereinigung Antriebstechnik (FVA, engl.: Research Association Drive Technology). Specific the work group “Geregelte Elektroantriebe” (GEA, engl.: Controlled Electric drives) with its industrial members like Siemens, Wittenstein, Porsche, VW, Wilo. The scientific partners were the chairs IAL (University of Hanover) and the IAM (Karlsruher Institute of Technology)

2. Objectives

The aim of the project was the identification of benefits of Additive Manufacturing (AM) in electric engineering and especially the implementation of this benefits in a Permanent Magnet Synchronous Motor (PMSM)

3. Procedure

An optimal material was determined (H13) and its mechanical and electromagnetic properties were investigated and improved by a heat treatment. A suitable PMSM was selected and its rotor shaft design was optimized for AM. The rotor shaft was built out of H13 and mounted into a given stator. Finally the motor characteristics were determined.

4. Achievements

The promising results of the motor characteristic The promising results of the motor characteristic determinations showed that the weight of the rotor shaft could be reduced by 25,1%. This leads to a reduction of the moment of inertia of 23% and an reduction of the acceleration time of 23,2 %. The Investigations were performed at 71,98 Nm and 3000 rpm. Moreover the permeability of the material H13 could be improved through a heat treatment. So the permeability could be enhanced from 32 to 480 and the coercivity could be reduced from 5600 A/m to 1300 A/m. This lead to an obvious enhanced soft magnetic behavior.

Forschungsvereinigung Antriebstechnik e.V.

Figure 54: Optimized rotor shaft with lattice structures for a lightweight design.

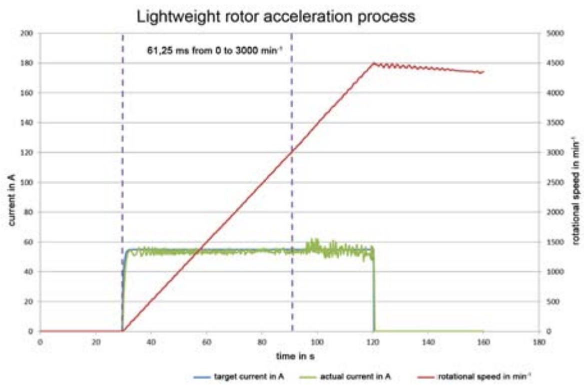


Figure 55: Results of the motor characteristics investigations.

Project Manager *Prof. Dr.-Ing. Detmar Zimmer*

Scientific Associate/s *Stefan Lammers, M.Sc.*

AM for satellites: Reaction Wheel Bracket

1. Partner

The Reaction Wheel Bracket was used as a sample part in the Project NewStructure, funded by the European Space Agency (ESA).

2. Objectives

Main aim of the study was to determine whether direct manufacturing of structure elements for satellites is feasible. High complex mission-customized parts with a high buy-to-fly ratio had to be examined to show the potential for reducing weight, waste, cost and time during production and use.

3. Procedure

After a profound analysis of many satellite parts a huge bracket was chosen. It is used four times per satellite for holding a mechanism where a mass is set into rotation to use the moment of inertia for adjusting satellites orientation in space without using propellant. As a computer-aided geometry creation topology optimization was used in a multistep optimization procedure. For the retransition of calculation results a voxel-based approach is used to cover the high complex geometries with biologic seeming shapes.

4. Achievements

During the study a new highly time efficient semi-automatic voxel-based methodology for geometry retransition of topology optimization results was found. This enables a fast and stress optimal design. Furthermore the product related key figures show the remarkable potential of additive manufacturing for huge structural parts, even with regard to costs:

- Weight reduction: -60 % (1100g -> 450g)
- Waste reduction: - 98 % (56kg -> 0.8kg)
- Cost reduction: - 53 % (8000€ -> 3800€)
- Time reduction: - 32 % (59h -> 40h)
- Max. Displacement: - 37 %
- 1st Eigen frequency: + 20 %

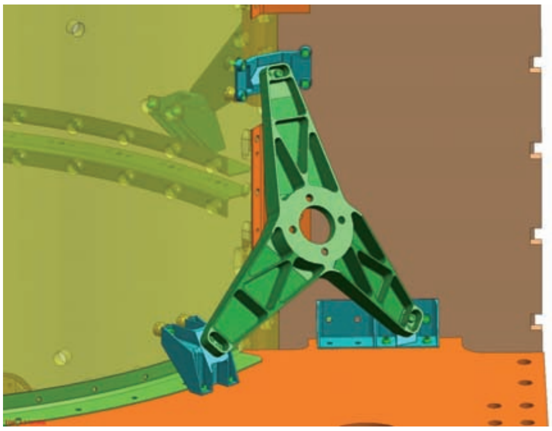
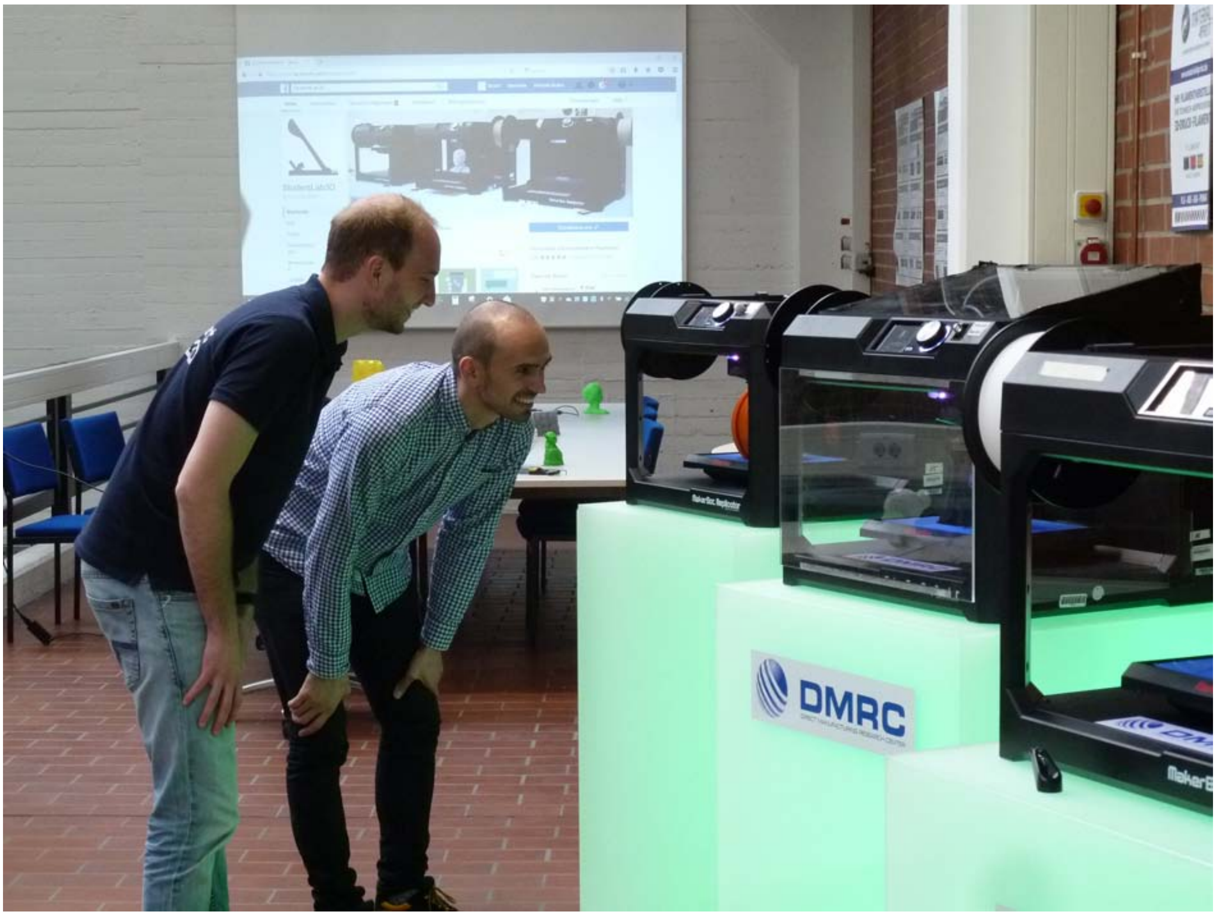


Figure 56: Traditional design of Reaction Wheel Bracket mounted in Exo Mars satellite

Figure 57: AM Designed Reaction Wheel Bracket

Project Manager	*Prof. Dr-Ing. Rainer Koch*
Scientific Associate/s	*Thomas Reiher, M.Sc.*


DMRC

4 Teaching

DMRC – AM Lesson

Education is one of the most important factors for the development of additive manufacturing towards an industrial established and production capable manufacturing technology. With this motivation, the DMRC is active in many teaching and training measures in terms of additive manufacturing. Thereby, different task groups are addressed: students, teachers/trainers as well as technology beginners and experts from the industry.

In 2016, a number of 130 students took part in the compulsory lecture “Additive Manufacturing” and learned fundamental knowledge about additive manufacturing. This knowledge of cause comprises information about all relevant additive manufacturing processes as well as information regarding a proper product development for additive manufacturing, economics, applications and so on.

Figure 58: Lessons with the topic Additive Manufacturing for students

In terms of academic teaching, the Direct Manufacturing Research Center steadily strives to implement additive manufacturing contents in the lessons at the Paderborn University. An important step has been achieved few years ago by setting up an elective module “Additive Manufacturing” within the master’s degree course in mechanical engineering. The elective module consists of the compulsory lecture “Additive Manufacturing” and of at least two other selectable courses.

In addition, for the selectable courses, students could chose two of eight selectable courses. While, the compulsory lecture “Additive Manufacturing” deals with additive manufacturing completely, each of the eight selectable courses handled additive manufacturing partially – with at least 20% of its content.

DMRC – Industrial Seminars

Besides the scholar teaching, the DMRC was active in industrial teaching as well. Several seminars have been performed together with industrial partners.

Haus der Technik: Direct Manufacturing

In cooperation with Ostwestfalen-Lippe University of Applied Sciences the DMRC performed two basic seminars on additive manufacturing. The seminars were held in Berlin and Paderborn. Within this two-days seminar participants learned fundamental information regarding additive manufacturing.

DGM-Seminar: Introduction into additive manufacturing

In cooperation with University of Kassel the DMRC performed a three-day seminar at the Paderborn University to provide basic knowledge about additive manufacturing. The seminar comprises both, theoretical knowledge together with particle exercises in order to transfer a comprehensive understanding of the technology. Both, theoretical and practical information were transferred for metal-powder, plastic-powder and plastic-filament based technologies.

Design for additive manufacturing seminars

The DMRC owns profound knowledge about design for additive manufacturing. Such knowledge is mainly desired by the industry to support the product development and product design process. In order to transfer this knowledge the DMRC performed several seminars on design for additive manufacturing with different industry partners. These seminars contained information about the advantages and disadvantages of additive manufacturing regarding product design as well as how to concept and design a part that shall be manufactured with additive manufacturing.

Potential finding and enabling seminars

Many companies currently are in the exposed position to decide whether they should use additive manufacturing in their business or not. However, the required knowledge basis to make such decision is often not fully given; potentials and risks are hardy known and difficult to detect. For such reason and in order to support companies with required information, the DMRC performed potential finding and enabling seminars together with industry partners. Together with experts from various disciplines workshops have been performed in order to identify promising parts for a beneficial additive manufacturing and the belonging business cases.

Figure 59: Workshops for the identification of AM for companies

StudentLab3D – Student Laboratory

3D printing offers big advantages such as design freedom, short production time and fast prototyping. In order to leverage the 3D printing technology apprenticeship is needed. Some of the important questions are: How to get a high quality 3D model? How to reduce support structures and is a part capable of 3D printing or not? With the StudentLab3D the Paderborn University and the DMRC offers practical teaching for all students and the staff of the Paderborn University. The aim is to enable students to work with 3D printing and related technologies. In the StudentLab3D the theoretical knowledge can be extended by practically experiences.

1. Started in 2014

The project was funded by the Paderborn University in 2014. The Direct Manufacturing Research Center won the “Award for Innovation and Quality in Teaching 2014”. With this financial support, three affordable 3D printers and a handheld 3D scanner have been purchased. In the meantime the equipment was extended by additional 3D printers, 3D scanners and software.

2. Teaching and workshops

All students and the stuff of the Paderborn University are invited to visit and use the StudentLab3D. It is a great opportunity to get to know the world of 3D printing in reality and not only in theory. While providing a 3D printing and 3D scanning service, the StudentLab3D offers three different workshops. One workshop covers the basics of the major procedures that are used in 3D printing technologies. Another workshops covers the basics of 3D scanning technologies and in the last workshop the basics of computer aided design (CAD) are taught.

Additionally, the teaching staff of all faculties of the Paderborn University is invited to implement 3D printing into their lessons and lectures. Among the integration in the engineering faculty and the master module additive manufacturing, the Stu-

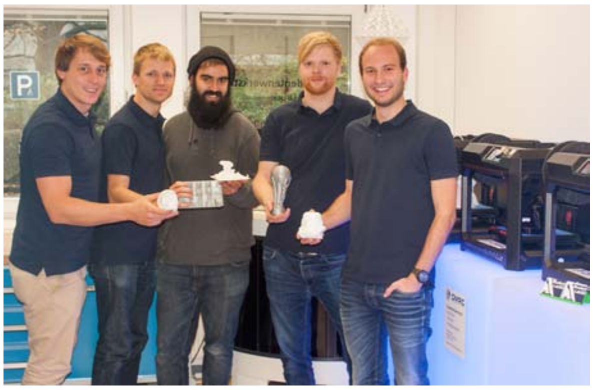


Figure 60: The team of the StudentLab3D

dentLab3D cooperates with other faculties. For example, 3D printed sculptures are designed in a cooperation with the art faculty and scaled mannequins of real-life students for tailoring purposes are manufactured in a cooperation with the textile and fashion faculty.

3. Achievements

In 2016 the printers of the StudentLab3D have produced more than 1000 individual parts for students and staff-members of various faculties of the Paderborn University. Furthermore, over 100 students obtained a certificate of completion for successfully attending all three workshops offered by the StudentLab3D.

Project Manager	*Prof. Dr.-Ing. Hans-Joachim Schmid*
Scientific Associate/s	*Johannes Lohn, M.Sc., Christian Schumacher, M.Sc.*

PADERBORN
UNIVERSITY

5 Chairs and institutes

Computer Application and Integration in Design and Planning CIK

The research group Computer Application and Integration in Design and Planning (C.I.K.) takes advantage of basic technologies and innovative IT concepts and applications together with the related methodologies. Specific research and work priorities are applications of software engineering methods from conceptual design to implementation of information systems and evaluation of research results and quality management in the product development with focus on usability of software solutions.

Bridging the gap between science and industry

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 global players. The focus on requirements and goals of human stakeholders supports the transfer of research results into practice.

The IT-based collection, processing and target oriented provision of information is studied with respect to pragmatic aspects. In this regard, business process management methods and semantic technologies have 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 knowledge management, 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.

Civil safety and Additive Manufacturing projects

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 from industry and science. 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 base for our ideas, systems and technologies in the context of planning, coordination support, training and decision support. Today fifteen research assistants and up to thirty student assistants are working for the C.I.K. bringing in knowledge from the fields of engineering, computer science, economics and mathematics.

Figure 61: Using additive manufactured QR Codes for product verification

Institute of Applied Mechanics FAM

Teaching and training

Our institute teaches the subject of applied mechanics, structure mechanics and fracture mechanics. In the application-oriented field of study of the bachelor’s program as well as of the master’s program, the Institute of Applied Mechanics offers i. a. the lectures biomechanics, structural durability, fatigue cracks, structural analysis and Finite-Element-Method (FEM).

Research

The FAM conducts application-oriented and basic 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 advances of the FEM standard software and its efficient use in various applications. In this relation the applied tools are stress and deformation analyses as well as notch stress tests and fracture mechanical tests including fatigue crack growth experiments. The propagation 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 musculoskeletal system” covers the simulation of courses of movement up to the development of intelligent healing aids. The aims are the evaluation of injury risks and the avoiding of resulting injuries. In order to provide an optimal rehabilitation process, medical devices are frequently required to be individually fitted to the patient’s physical condition. So, additive manufacturing grows to become an attractive approach in medical engineering, e. g. for orthoses, implants and prostheses. The third area of research “Optimization and new development of products in cooperation with industrial partners” deals with the solving of specific problems which occur in practice by implementing the above mentioned core competences.

Figure 62: Working at FAM

Heinz Nixdorf Institute – Chair for Product Creation HNI-PE

With systematic strategy development and goal development, the chair for Product Creation consistently focuses the research and development of manufacturing companies on the business opportunities of the future. Its main focus is on complex technical systems consisting of adaptive, configurable mechatronic systems. HNI-PE networks the diverse disciplines with appropriate development methodologies such as Systems Engineering and the V-model for mechatronic systems supported by digital and virtual tools. The emphasis lies on the effectiveness and efficiency of development and production processes.

Additive Manufacturing is an impressive example of technology push: Additive technologies drive both new product and production system designs. Firstly, new business opportunities result from innovative core products, characterized for example by outstanding material properties or 3-dimensional geometries which cannot be manufactured by conventional dissipating production technologies, such as milling or turning. Secondly, new product-services can be offered, such as provision with a component's customer's 3D-printer. Therefore, HNI-PE supports companies in identifying and measuring their specific potential of using additive manufacturing as product or production technology.

Assuming promising opportunities related to Additive Manufacturing for specific business segments at a company, we support strategic orientation, product program planning, engineering methodology, production planning and implementation of Additive Manufacturing. Engineering methodology provides tools and methods of functional realization of the product. Virtual and Augmented Reality is used as an enabler. Early consideration of production constraints, such as production site or degree of automation, is supported by integrated production management.

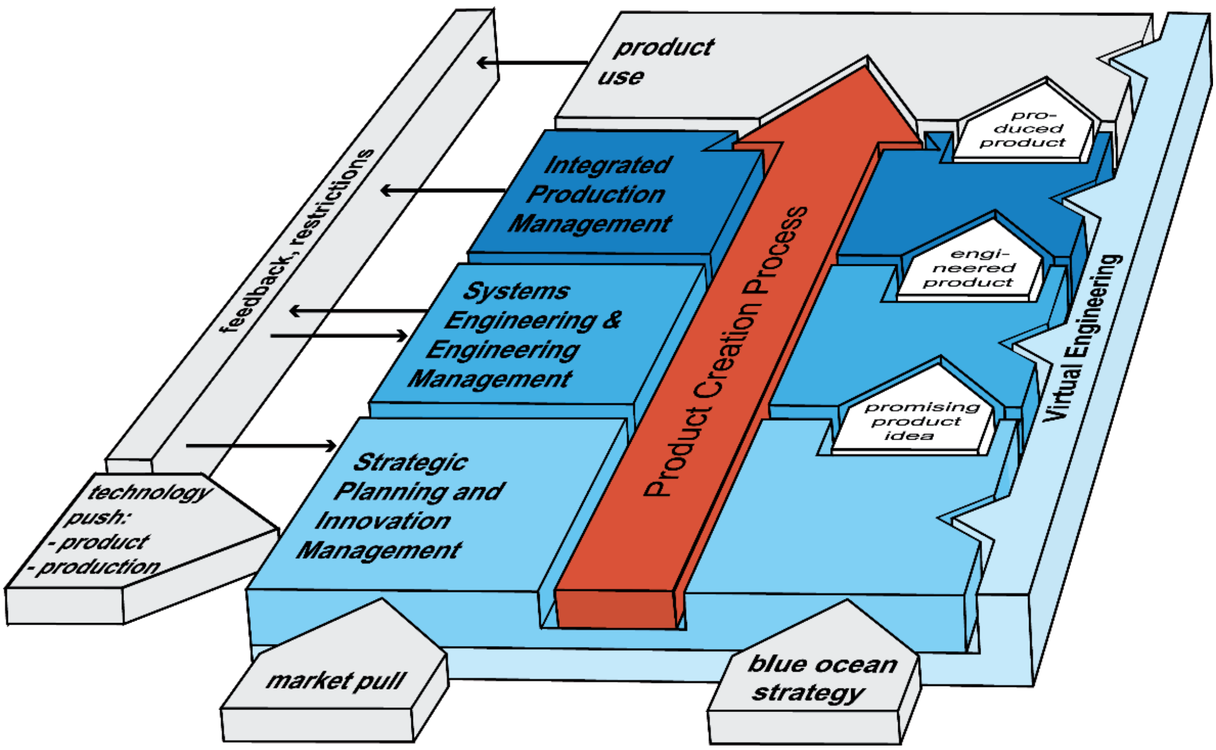


Figure 63: Action field of product creation spanning from strategic planning to lifecycle management

Chair of Design and Drive Technology KAt

The focus of the KAt lies on theoretical and experimental investigations regarding drive conceptions and on the extensions of drives' application limits. The two main research fields are electromechanical drive technology and design engineering.

Electromechanical drive technology

Within this research field, key aspects are the reduction of resources required for the operation of drive systems and the modularity of drive systems in light of an intelligent variant management. Regardless of the task fields, the KAt often works with industry partners on joint projects.

Primarily, the KAt deals with:

- drive systems, such as „energy-efficient spring-applied brakes“, „multi-drive concepts“, „modular drive systems“
- drive components, such as „power loss reduced sealing systems“, „reduction of fretting corrosion“
- additive manufacturing of drive systems

Design Engineering

The design engineering contents of the optimization of components, assemblies and machines by systematic, function-oriented and production-oriented design. Thereby, an important aspect forms the tolerance management. Core subjects are – particularly in conjunction with additive manufacturing – design rules, function integration, additive manufactured drive components and geometrical tolerances.

Software and test equipment

The KAt usually uses different software tools to create geometry or to model and calculate the motion behavior (CAD, FEM, multi-body simulations). Parallel, the chair develops and uses test equipment to conduct experimental studies (extensive test engineering for experimental analyses).

Lessons

In teaching, the KAt offers courses on the following topics:

- Basic bachelor studies: Technical drawing, machine elements – fundamentals, – joints, – drive components.
- In-depth bachelor and master studies: Methodology of design, technical design, industrial drives and geometrical tolerances.

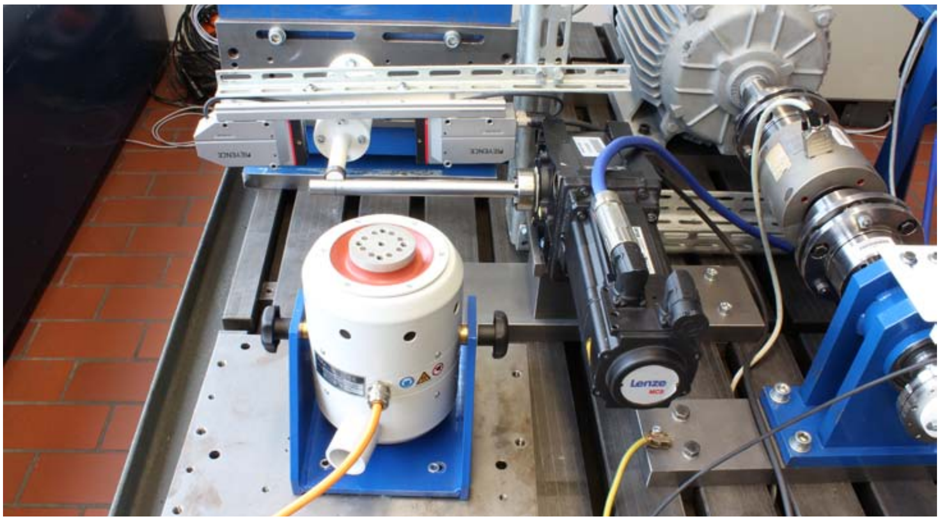


Figure 64: Developed test rigs for the investigation of additive manufactured damping structures

Kunststofftechnik Paderborn KTP

The KTP stands for thirty years of successful research and development of manufacturing processes in the field of polymers and rubbers. This results in a qualified training in the theoretical and practical field of polymer engineering as well as in an intensive cooperation with national and international industrial companies. International congresses and conferences are regularly participated by the KTP staff. The two professorships of the KTP 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, which become more and more significant in the field of mechanical engineering 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 into tools to simulate polymer processing procedures. 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, real processes in the laboratory- and production measure 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.

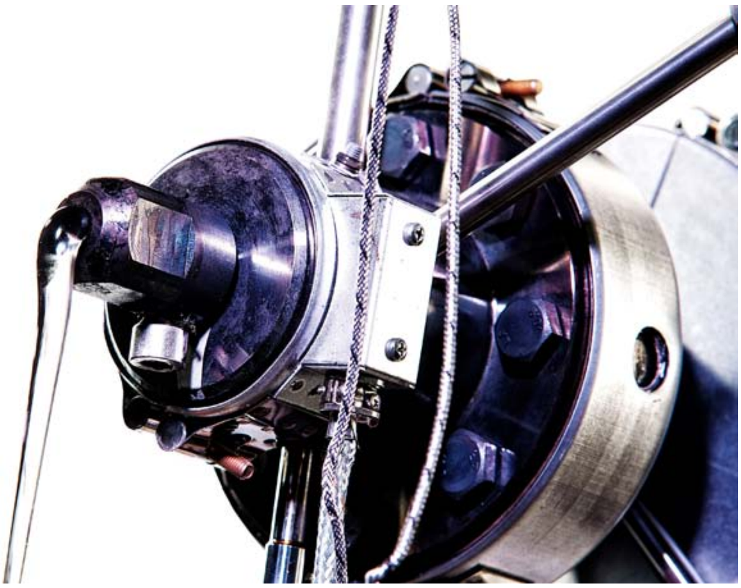


Figure 65: Single screw Extruder in the KTP laboratory

Chair of Automotive Lightweight Construction LiA

Research Activities

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, main focus of the group “Automotive Lightweight Construction” is on innovative solutions for the automotive industry and related others in terms of materials, processes and applications. As the economic efficiency is a critical issue for most industries, the cost structures of different process-routes are also taken into account in order to develop innovative components and applications, featuring high performances as well as balanced cost-to-weight ratios. For example, load-bearing components made of ultra-high-strength steel processed by the press-hardening technique could be mentioned here.

Another important research field pursued by this chair is the development of load adapted parts. Within these parts, the material properties in different sections of a component are adjusted depending on specific product-requirements, e.g. the mechanical loading. Thus, low or high strengths as well as brittle or ductile areas can be locally tailored by an appropriate selection of the applied process-route. Techniques used in this area are for example the inductive heating, whereby the evolution of the microstructure as well as physical properties can be modified within a short period of time.

Equipment

Regarding the technical equipment, the chair provides different possibilities for studying material as well as component properties. This covers a wide range of static, cyclic and dynamic tests as well as microstructural studies. In addition to 3 axle tests with static and cyclic forces up to 80 kN, cupping tests with temperatures up to 800 °C can also be performed. Crash tests can be performed with impact velocities of up to 25 m/s and impact energies up to 31 kJ, whereby this test facility can be equipped with an a high speed 3D camera system in order to analyze, for example, local strain distributions. Furthermore, the group of Automotive Lightweight Constructions has licenses of the major CAD and simulation tools, such as SolidWorks, Abaqus, LS-Dyna and Hyperworks.

Figure 66: Equipment of LiA

Chair for Materials Science LWK

Chair for Materials Science

As the majority of innovations is based on the devel-opment of new materials or on enhancements of materials already used, the field of materials science is one of the key activities of today´s research in academia and industry. Under the impact of the increasingly scarce resources the efficient use of materials is the central theme for actual developments. Different strategies can be observed in order to improve the energy consumption of moving parts as well as the overall material amount used in any kind of construction. Depending on the actual requirements in the application the research efforts aim at improving the specific strength or ductility of the materials (light-weight concept) or at integration of additional functions to the materials, as for example can be observed in case of shape-memory alloys. Other approaches comprise the combination of different materials in order to obtain completely new properties or the enhancement of the material behavior through an optimized microstructural design by advanced processing techniques.

Consequently, the major objective of research at the chair of materials science is to develop validated material models, which allow for predicting the behavior of materials and components under actual loading conditions. In the experiments the stress-strain response and damage evolution of various materials under superimposed mechanical, corrosive and thermal loading conditions is studied. Most of the materials tested are high-performance metallic engineering alloys.

The research projects cover following subject areas:

- Production of aluminum-steel clad strips by means of twin-roll casting
- High temperature fatigue behavior of nickel based superalloys
- Microstructural investigations of aluminum and copper wire bonds
- Optimization of materials processed by selective laser melting
- Heat treatment of high strength steels for the production of hybrid metal structures with tapered properties and its microstructural characterization
- Development of new materials for additive manufacturing
- Intrinsic manufacturing of hybrid structural components in a modified RTM-process
- Investigation on the influence of architecture and doping of diamond like carbon coatings - damage behavior under cyclic mechanical stress

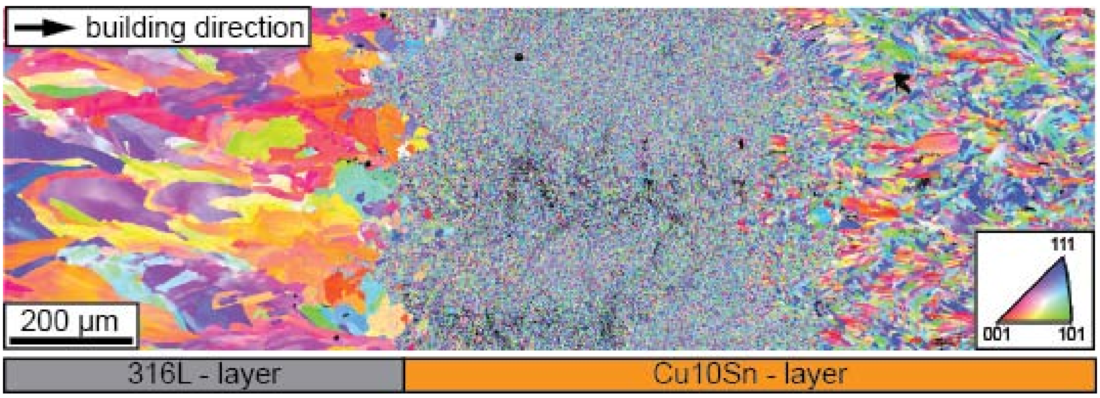


Figure 67: Color-coded orientation map of the functional graded mutli-material consisting of 316L and Cu10Sn at an interface area.

Particle Technology Group PVT

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 their characterization. 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

- Aerosol particle formation
- Precipitation / crystallization in liquids

Characterization 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 nano-particulate systems

Figure 68: Team of the Particle Technology Group

Chair of Technical and Macromolecular Chemistry TMC

The chair of Technical and Macromolecular Chemistry TMC led by Prof. Dr.-Ing. Guido Grundmeier is organized into four research areas, namely

- "Adhesion and Corrosion Science"
- "Interfacial Engineering of Advanced Materials"
- "Nanotechnology and Nanomaterials"
- "Nanobiomaterials".

Structures, forces and processes at interfaces are of utmost importance for materials development in various technological fields. Examples of modern applications of interface-dominated materials are polymer/metal composites, biomaterials, particle technology, and energy conversion.

Researchers at the TMC are developing new analytical methods and surface technologies in the fields of

- in-situ analysis of interfacial processes (e.g. adsorption, desorption, self-organization, corrosion),
- analysis of molecular interfacial forces and mechanics,
- coating and adhesive bonding of metals and polymers,
- biomaterials and biomolecular self-assembly.

The interdisciplinary work is combining spectroscopy, microscopy, and electrochemistry. Molecular defined systems are investigated by optical in-situ spectroscopy, electron spectroscopy, atomic force microscopy as well as electrochemistry regarding their structure-property-correlation. Based on this special research approach we are on the one hand able to understand macroscopic processes on a molecular level and on the other hand to create new materials and composites bottom-up.

The TMC teaches students studying chemistry, chemical engineering, and mechanical engineering in the fields of Technical Chemistry, Interface Chemistry, Interface Analysis, Electrochemistry, Biointerfaces, and Functional Materials.

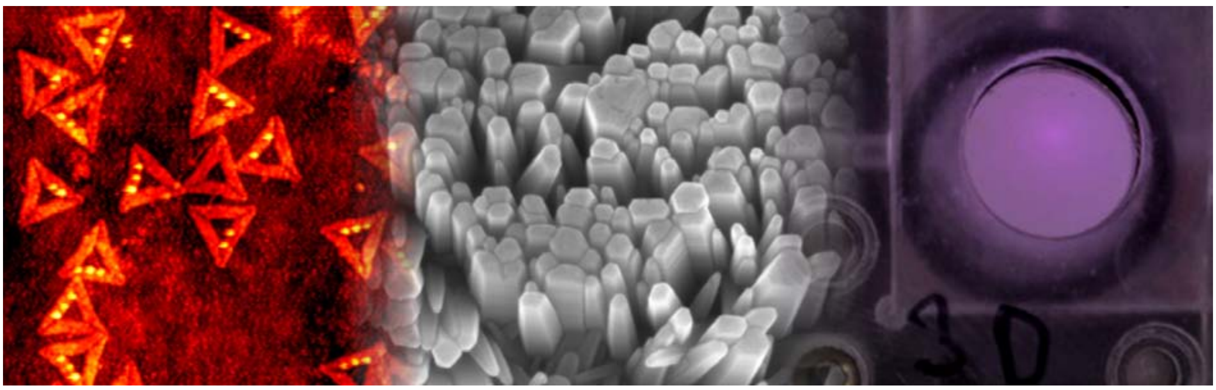
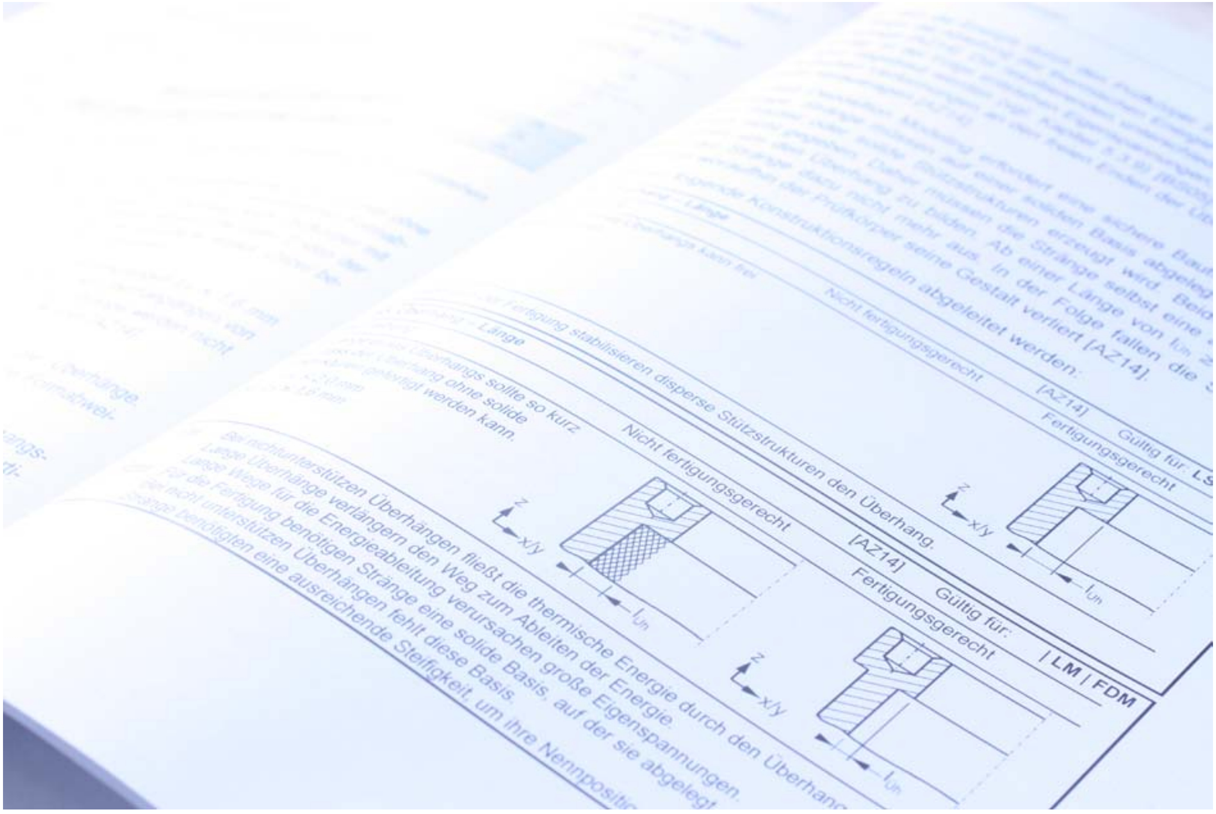


Figure 69: DNA origami nanostructures (left), ZnO nanorods (center), electrochemical cell (right)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6 Publications

Publications 2016

Scenario Based Outlook of Additive Manufacturing Applications for the Aerospace Market

Lindemann, C.; Deppe, G.; Koch, R

Digital Manufacturing – Prospects and Challenges

Weimar, 2016

Neue Prototypen-Werkzeugtechnologie für Bipolarplatten und Batterie-komponenten

T. Hickmann, D. Ahlers, N. Fulland

Der Stahlformenbauer

Velbert, 5/2016, pp.34-36

Temperature history within laser sintered part cakes and its influence on process quality

S. Josupeit, H.-J. Schmid

Rapid Prototyping Journal

22/2016, pp.788-793

Modelling of temperatures and heat flow within laser sintered part cakes

S. Josupeit, L. Ordia, H.-J. Schmid

Additive Manufacturing

12B/2016

Optimized build orientation of additive manufactured parts for improved surface quality and build time

P. Delfs, M. Töws, H.-J. Schmid

Additive Manufacturing

12B/2016

Process Gas Infiltration in Inconel 718 Samples during SLM Processing

C. Schaak, W. Tillmann, M. Schaper, M.E. Aydinöz

RTejournal - Forum für Rapid Technologie

2016

On the microstructural and mechanical properties of post-treated additively manufactured Inconel 718 superalloy under quasi-static and cyclic loading

M.E. Aydinöz, F. Brenne, M.Schaper, C. Schaak, W. Tillmann, J. Nellesen, T. Niendorf

Materials Science and Engineering A

669/2016, pp. 246-258

Fatigue crack growth behavior and mechanical properties of additively processed EN AW-7075 aluminium alloy

W. Reschetnik, J.-P. Brüggemann, M.E. Aydinöz, O. Grydin, K.-P. Hoyer, G. Kullmer, H.A. Richard

Procedia Structural Integrity

2/2016, pp. 3040-3048

Crack Propagation in Additive Manufactured Materials and Structures

A. Riemer, H.A. Richard

Procedia Structural Integrity

2/2016, pp. 1229-1236

Conference Proceedings 2016

Additive Fertigung in der Medizintechnik - Überblick und Beispiele -

B. Schramm, J.-P. Brüggemann, A. Riemer, H. A. Richard

DVM Conference - Additively manufactured components and structures, pp. 21-30

Berlin, November 2-3, 2016

IN 718 processed by selective laser melting: Effect of precipitation hardening and hot isostatic pressing on the low-cycle fatigue behavior at 650 °C

M.E. Aydinöz, C. Schaak, F. Hengsbach, K.-P. Hoyer, T. Niendorf, W. Tillmann, M. Schaper

DVM Conference - Additively manufactured components and structures, pp. 141-150

Berlin, November 2-3, 2016

Lebensdauerbeeinflussung durch additive Fertigung

W. Reschetnik, J.-P. Brüggemann, M.E. Aydinöz, G. Kullmer, H.A. Richard, M. Schaper

DVM Tagung - Additiv gefertigte Bauteile und Strukturen, pp. 131-140

Berlin, November 2-3, 2016

Optimierung von Fahrradtretkurbeln mittels additiver Fertigung

J.-P. Brüggemann, A. Riemer, W. Reschetnik, M.E. Aydinöz, G. Kullmer, H.A. Richard, M. Schaper

DVM Tagung - Additiv gefertigte Bauteile und Strukturen, pp. 101-112

Berlin, November 2-3, 2016

Quality Improvement of FDM Parts by Parameter Optimization

F. Knoop, A. Kloke, V. Schoeppner

32nd International Conference of the Polymer Processing Society

Lyon, July 25-29, 2016

Chemical Surface Treatment of Ultem 9085 Parts

M. Fischer, O. Seewald, V. Schöppner

Rapid.Tech – International Trade Show & Conference for Additive Manufacturing, pp. 121-132

Erfurt, June 14-16, 2016

Reproducibility of the Dimensional Accuracy: Investigations for Fused Deposition Modeling

F. Knoop, T. Lieneke, V. Schoeppner

ASPE 2016 Summer Topical Meeting, pp. 3-8

Raleigh, June 27-30, 2016

Dimensional tolerances for additive manufacturing: Experimental investigation of manufacturing accuracy for Selective Laser Melting

T. Lieneke, S. de Groot, G.A.O. Adam, D. Zimmer

ASPE 2016 Summer Topical Meeting, pp. 9-15

Raleigh, June 27-30, 2016

Dimensional tolerances for additive manufacturing: Experimental investigation for Fused Deposition Modeling

T. Lieneke, V. Denzer, G.A.O. Adam, D. Zimmer

CAT 2016

Gothenburg, May 18-20, 2016

Extended Analyis of the Surface Topography of Laser Sintered Polymer Parts

P. Delfs, H.-J. Schmid

Fraunhofer Direct Digital Manufacturing Conference

Berlin, March 16-17, 2016

Thermal properties of polyamide 12 powder for application in laser sintering

S. Josupeit, H.-J. Schmid

International Congress on Particle Technology (PARTEC)

Nuremberg, April 19-21, 2016

Festigkeits- und leichtbauoptimierte Konstruktion und Auslegung eines additiv gefertigten Fahrradvorbaus

J.-P. Brüggemann, W. Reschetnik, H.A. Richard, G. Kullmer, B. Schramm

Rapid.Tech – International Trade Show & Conference for Additive Manufacturing, pp. 290-300

Erfurt, June 14-16, 2016

Dimensional accuracy of polymer laser sintered parts: Influences and measures

S. Josupeit, P. Delfs, T. Lieneke, G. Adam, H.-J. Schmid

Rapid.Tech – International Trade Show & Conference for Additive Manufacturing, pp. 107-120

Erfurt, June 14-16, 2016

Manufacturability and Mechanical Characterization of Laser Sintered lattice Structures

S. Josupeit, P. Delfs, D. Menge, H.-J. Schmid

27th Annual International Solid Freeform Fabrication Symposium, pp. 2077-2086

Austin, August 8-10, 2016

Herstellbarkeit und mechanische Charakterisierung von lasergesinterten Gitterstrukturen

S. Josupeit, P. Delfs, D. Menge, H.-J. Schmid

1. DVM-Tagung “Additiv gefertigte Bauteile und Strukturen”, pp. 51-61

Berlin, November 2-3, 2016

Unterstützung des Additive Manufacturing Entscheidungsprozesses in der Luftfahrtersatzteilversorgung

G. Deppe, R. Koch

Proceedings of the RapidTech 2016

Erfurt, June 14-16, 2016

Supporting the Decision Process for applying Additive Manufacturing in the MRO Aerospace Business by MADM

G. Deppe, R. Koch

27th Annual International Solid Freeform Fabrication Symposium Proceedings

Austin, August 8-10, 2016

Combining Material Efficiency and Part Reliability by Product Optimization Applying Additive Manufacturing

T. Reiher, G. Deppe, R. Koch

International Conference Production Engineering and Management 2016, pp. 27-38

Lemgo, September 29-30, 2016

Product Optimization with and for Additive Manufacturing

T. Reiher, R. Koch

27th Annual International Solid Freeform Fabrication Symposium

Austin, August 8-10, 2016

Data Management for additive manufacturing: survey on requirements and current state

I. Gräßler, P. Taplick, J. Pottebaum, P. Scholle, T. Reiher

14th International DESIGN Conference 2016

Dubrovnik, May 16-19, 2016

Additive Manufacturing of a Lightweight Rotor for a Permanent Magnet Synchronous Machine

S. Lammers, G. Adam, H.-J. Schmid, F. Quattrone, B. Ponick, R. Mrozek, R. Oberacker

, M.J. Hoffmann

6th International Electric Drives Production Conference and Exhibition 2016 EDPC, pp. 41-45

Nuremberg, November 29-30, 2016

Books 2016

Untersuchung der Werkstoff-, Prozess- und Bauteileigenschaften beim Fused Deposition Modeling Verfahren

A. Kloke

Shaker Verlag

Paderborn, 2016

Einfluss prozess-induzierter Defekte auf die Ermüdungseigenschaften metallischer Werkstoffe verarbeitet mittels Laserstrahlschmelzen

S. Leuders

Shaker Verlag

Paderborn, 2016

Ermüdungsverhalten und mikrostrukturelle Charakterisierung der im Laserschmelzverfahren hergestellten Nickelbasis-Superlegierung Inconel

P. Kanagarajah

Shaker Verlag

Paderborn, 2016


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