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IAPT

FRAUNHOFER RESEARCH INSTITUTION FOR ADDITIVE MANUFACTURING TECHNOLOGIES IAPT

ANNUAL REPORT 2020

"We develop autonomous AI-based manufacturing processes with automated documentation."

Dear Readers,

2020 was a year marked by the COVID-19 pandemic, and Fraunhofer IAPT reacted immediately to this threat, forming a crisis committee, providing all employees with a laptop for home office working, and rigorously implementing the AHA rules – maintaining safe distances, observing hygiene (washing hands), and wearing masks. This has, to date, enabled us to weather the crisis quite well. Thanks to its flexibility, additive manufacturing offers enormous benefits in countering the constraints that have suddenly arisen due to the pandemic. For example, Fraunhofer IAPT printed face shields for medical facilities and schools, participated in projects involving the manufacture of 3D-printed injection molding tools for respiratory masks and face shield retainers, and cooperated actively in the development of a noninvasive ventilator.

The lockdown and ensuing uncertainty in industry resulted in a few planned and approved projects being postponed or canceled. Compensation for project losses was provided through internal coronavirus programs at Fraunhofer. Funding we obtained from the Fraunhofer-Gesellschaft therefore rose considerably in 2020.

The first quarter of the year saw Prof. Emmelmann leave Fraunhofer IAPT to embrace new challenges. Invitations for his successor have been initiated, and we hope to welcome a new colleague by the end of 2021 to lead Fraunhofer IAPT.

Fraunhofer IAPT conducted a technology audit in 2020 that was very well received in industry and resulted in a series of valuable proposals for the strategic orientation of Fraunhofer IAPT. Our overall strategy focuses on digitization, with software tools for a design, process, and quality manager currently under development.

2020 also saw us achieve impressive results through our research work. For example, Fraunhofer IAPT developed a 3D-printed wheel carrier with integrated brake caliper for the Fiat Chrysler Group. Together with a prestigious sports car manufacturer, the car door mounting was optimized through application of the AM concept, achieving a considerable reduction in manufacturing costs.

The pandemic will continue to be felt in 2021, but Fraunhofer IAPT is in a good position to retain its personnel and know-how and continues to press ahead with a few major developments, patents, and new projects that provide a basis for continuation of the planned growth trajectory in 2022.

Prof. Ralf-Eckhard Beyer | Director

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BRIEF PORTRAIT

OUR TECHNOLOGIES

Fraunhofer IAPT Technology Portfolio

Fraunhofer IAPT can avail itself of a wide variety of technologies and systems for additive production and laser technology. We provide the appropriate manufacturing technology for processing both metals and plastics, depending on requirements. From powder bed processes for delicate medical implants, filament printing, and arc welding for large structures to laser hybrid joining of components manufactured conventionally and additively, we can select the appropriate process in every case. In doing so, we provide our customers with the best cross-technology and nonproprietary solutions for their application.

Powder bed processes for metals

Fraunhofer IAPT has been working for years in the area of additive manufacturing based on metal powders in the LBM process. The system portfolio ranges from purely research facilities and medium-format machines to multi-laser systems for maximum productivity. The goal is to develop intelligent process strategies and controls, improve process speed and stability, and document each working step in a transparent manner.

Metal binder jetting achieves a high degree of component precision and process reliability and makes cost-effective manufacture of large quantities of components possible. Similarly to laser beam melting, a powder bed is created layer by layer, but instead of melting with a laser beam, the component is generated through jetting of organic ink using a print head. The printed green compacts are then subjected to debinding and finally sintered to create the metallic component. Fraunhofer IAPT develops appropriate parameters along the entire process chain for the manufacture of components for selected alloys.

Nozzle/wire processes

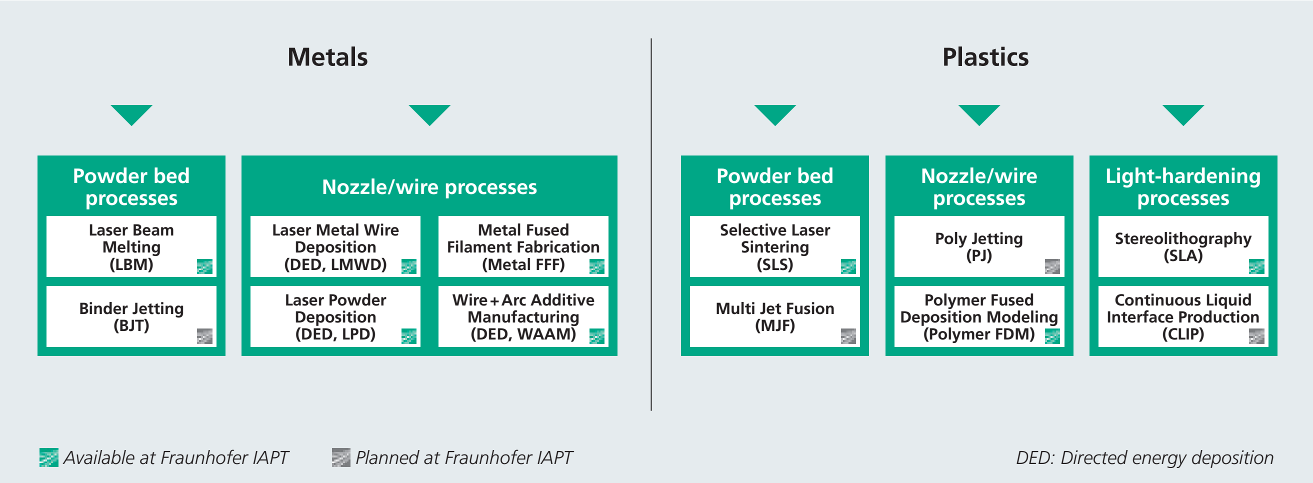
Fraunhofer IAPT exploits both laser and electric arc welding processes for nozzle- or wire-based metallic additive manufacturing. Both variants are, if robot-guided, subject to practically no build space restrictions. They are particularly suitable for cost-effective spare parts production and repairs. Post-processing involving machining is generally necessary. One new process that has become established at Fraunhofer IAPT is metal fused filament fabrication (metal FFF). It is particularly suitable for rapid, cost-effective production of prototype components made of metallic materials and, consequently, of particular interest for machine and plant engineering. A polymer filament with embedded metal powder acts as a starting material. This can be printed on an inexpensive standard 3D printer. The parts generated are then heat-treated, during which the polymer is extracted from the component and the dense metallic component created.

Laser beam processes

Fraunhofer IAPT has been involved for many years now with laser beam fusion, cutting, and deposition. Integrated solutions and adapted processing systems with sensors for automated process control and quality assurance are obtainable. One special option that is available is a 30 m long portal system.

Polymer and nonmetal processes

The development of bionic component structures and integration of new functions in polymer components are particular focal points at Fraunhofer IAPT. Particularly worthy of note is the integrated implementation of electrically conductive traces in three-dimensionally shaped electronic components. In addition, tests are being conducted on new polymer materials and materials based on PP that can be cost-effectively processed. Furthermore, plant systems are being developed, in the field of selective laser sintering in particular, that enable quicker and more efficient process control and targeted process monitoring. With a focus on industrial applications, Fraunhofer IAPT is also involved in material and process development for polymer-based fused deposition modeling (FDM).



Finishing

Surface qualities achieved directly through additive manufacturing processes usually require subsequent heat treatment and post-processing involving smoothing. Various finishing processes are available at Fraunhofer IAPT, depending on the requirements components need to meet. Post-processing of the component may involve abrasive blasting or milling, grinding, vibratory grinding, or electro-polishing. Finishing is optimized at Fraunhofer IAPT to suit the component involved.

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OUR CORE COMPETENCES

AM Design

In the AM Design department, we focus on the completely new design options additive manufacturing technologies offer. The manufacture of a component can prove particularly resource- and cost-efficient if the design is adapted to the later manufacturing process as early as the component design phase. One of our strengths is the fact that we combine bionics and computer-aided optimization with experience in additive manufacturing technologies gained over many years.

The design also significantly influences the quality of a component. Monitoring of all relevant manufacturing steps is extremely important if efficient assurance of quality is to be achieved. In order to document the process flow as completely as possible, we work on sensor- and software solutions that record all relevant component-specific parameters and continuously optimize the process on the basis of collected data.

AM Processes

Additive manufacturing processes enable a completely new rethinking of parts and technical components with regard to their structure and function. The AM Processes department focuses on the development of uninterrupted process chains from material selection and manufacturing processes to post-processing, the goal being to produce additively manufactured metal or polymer components efficiently and establish the processes on an industrial level. Fraunhofer IAPT can rely on cutting-edge laser beam melting, laser sintering, fused deposition modeling, and metal binder jetting facilities in this respect. To further advance technologies with a view to enhancing productivity and reproducibility, we develop appropriate system components for applications such as laser beam shaping and temperature control in the process, but also for reliable powder handling and finishing.

AM Systems

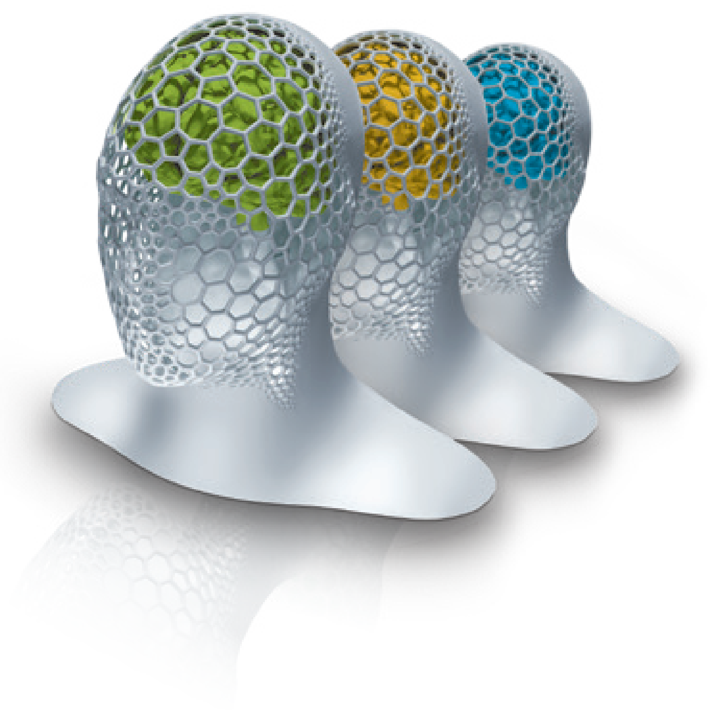
The AM Systems department has set itself the goal of increasing the precision and automation of additive manufacturing by developing sensor and system solutions for this purpose. The department focuses on the development of highly productive direct energy deposition (DED) processes and their peripheral system technology for additive manufacturing. One milestone in this respect is the location-independent and autonomous production unit in the form of the Additive Mobile Factory developed by the team. Machine-learning algorithms, internally developed software tools, and augmented reality are also employed here to further enhance the degree of automation of additive manufacturing and enable the achievement of consistent component quality at reduced costs.

Medical Center

When it comes to the development of an optimum solution from a medical point of view, the Medical Center provides the link between physicians and AM engineering experts. The economic viability of these developments is always assessed in this respect. The focus here is on two significant business areas. Ex vivo applications encompass all medical devices that are used outside the human organism (e.g. exoskeleton). The second business area involves in vivo applications, which encompass devices used within the human organism (e.g. implants). Our research approaches range from ergonomically driven products and implants to process optimization of specific medical ordering processes.

Center for Lasers and Large Structures

Fraunhofer IAPT operates its own competence center for laser processing and the creation of large structures. The specialized know-how involved encompasses laser-based joining technologies for, in particular, joining additively and conventionally manufactured components to hybrid structures. The Fraunhofer IAPT Center can contribute a fiber laser with a laser output of up to 30 kilowatts and a portal system for processing components with a length of up to 30 meters for these tasks. As the successor to LZN, Fraunhofer IAPT has gained years of experience in laser and laser hybrid welding from major publicly funded shipbuilding projects and, also, the development of highly productive joining processes for the automotive industry and both crane and rail vehicle manufacturing. Large structures are not only welded at Fraunhofer IAPT, but increasingly built through additive manufacturing. Robot-guided 3D printing of concrete has been a subject of research at the Fraunhofer IAPT Center for the last two years, enabling the achievement of a high degree of automation in the construction industry and the realization of additional functions (e.g. adiabatic cooling of technical buildings).



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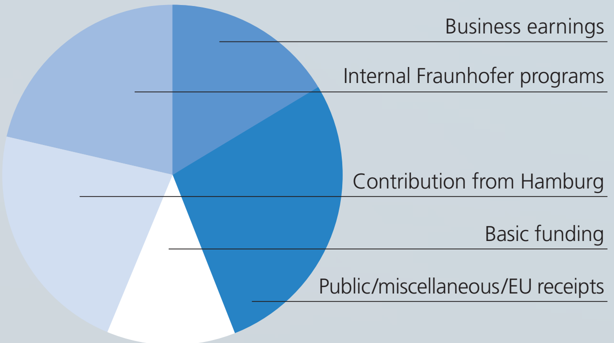
OUR TEAM

THE INSTITUTE IN FIGURES

Revenues

Fraunhofer IAPT

	in mil. €
Business earnings	2.2
Public/miscellaneous/EU receipts	3.4
Basic funding	1.4
Contribution from Hamburg	2.8
Internal Fraunhofer programs	2.6
Total	**12.4**



Expenditure

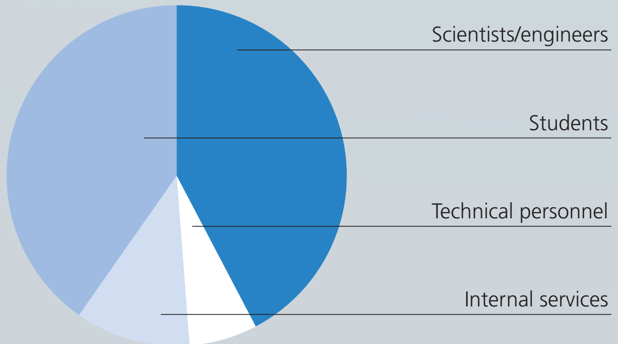
Fraunhofer IAPT

	in mil. €
Personnel costs	6.1
Non-personnel costs	3.1
Investment costs	3.2
Total	**12.4**

Employees

Fraunhofer IAPT

	Number
Scientists/engineers	59
Technical personnel	8
Internal services	14
Students	51
Total	**132**



THE BOARD OF TRUSTEES AND GROUP FOR PRODUCTION ENGINEERING

The Board of Trustees acts in an advisory capacity to the management committee of the institute and other Fraunhofer-Gesellschaft bodies and promotes links to interested groups involved in research work. The Board of Trustees included the following members in the reporting period:

Fraunhofer IAPT is a member of the Fraunhofer Group for Production, a cooperative amalgamation of 11 Fraunhofer institutes and entities. The goal is to jointly pursue production-related research and development. Utilizing the latest findings in production, engineering, and computer science, the Group offers a range of services that cover the complete product life cycle and entire value chain. Cooperation between research and industry here is interdisciplinary and takes place within a close network. Bundling of the diverse expertise and experience of individual members by the Group means the customer can be offered comprehensive solutions to problems. In this way, companies are readied for the “manufacturing of the future”. Fraunhofer IAPT is an important element in this, making its expertise in the area of industrial and autonomous solutions in additive manufacturing technologies available to the Group.

BRIEF PORTRAIT

ALLIANCE EVENT

JANUARY 22 TO 24, 2020

A REALLY SPECIAL EVENT AND PRELUDE TO THE NEW ADDITIVE ALLIANCE (JANUARY 22 TO 24, 2020)

Additive 2020, the trade conference for Fraunhofer IAPT additive manufacturing, was held in Hamburg from January 22 to 24. In a cooperation with Nortec – the trade fair for manufacturers – the conference opened ceremoniously with a forum at the Hamburg trade fair venue. A variety of manufacturers of AM systems presented their latest developments to an interested industry and trade fair audience. Exhibitors included representatives from YXLON, Comprisetec, Bionic Production, Fehrmann, EOS, SLM, HP, Trumpf, GE Additive, BeAM, 3D Systems, Stratasys, Digital Metal, HAW, and Fraunhofer IAPT.

The forum was fully devoted to industrial series production through additive manufacturing technologies. Impressive presentations from machine manufacturers demonstrated how they intend to master the challenge of productivity enhancement and help shape the additive future. Issues such as digitization and certification for specific sectors in the context of Industry 4.0 were also the subject of extensive discussions. In this context, application cases involving AI in the design process and for evaluation of manufacturing data in quality assurance were presented. The forum was open to all visitors of Nortec, which attracted more than 12,000 guests over four days.

January 23, the second day of the trade conference, saw an invitation to visit the Emporio on the panorama deck high above the rooftops of Hamburg. Over 100 participants were treated to exciting insights into joint industrial developments from Fraunhofer IAPT and its project partners. In each case, a representative of industry joined a project manager from the institute to present the results. Discussions included the future of serial additive manufacturing at Maserati and Fiat Chrysler, along with a report on 3D-printed concrete components from 24'7 agrigas. Flussfisch GmbH presented its approach to the successful use of individualized dental prosthetics, including the required certification. The second day was also primarily dominated by the issues of digitization, automation, quality assurance, and certification. Siemens reported on its vision of cloud-supported digital twins aiding the entire additive process chain. PLM Powder Light Metals and Aalberts also offered fascinating insights into issues such as the development of new materials for additive manufacturing and efficient post-processing of additively manufactured components. Participants had extensive time during the conference to network and talk shop while enjoying the fantastic view over Hamburg.

The day concluded with an evening event held exclusively for members of the Additive Alliance. Dinner together in a historic warehouse in the Speicherstadt district of Hamburg brought a fitting close to the day and provided a venue for further in-depth discussions. Prior to dinner, participants were treated to an exclusive tour of Miniatur Wunderland, the world's largest model railway. The use of 3D printing was also discussed here. Following two exciting days at the conference, the Additive Alliance, the industrial network for additive manufacturing of the Fraunhofer-Gesellschaft, was fully focused on new studies.

Participants from member companies met on the last day of the event in the former main customs office in the Speicherstadt warehouse district. A new concept that sees members of the Additive Alliance actively contributing to shaping Fraunhofer IAPT research content started this year. Experts from specialist departments presented exciting study topics for selection in three different committees. These pitches were discussed by participants to identify one trending topic in each department. Respective research questions were developed in the following half year by Fraunhofer IAPT experts, to be presented at the next virtual meeting.

The following study topics were selected in this process:

- Overview of Steel-Based LPBF Materials
- Overview of LPBF In-Process Monitoring Systems
- Evaluation of Mobile Additive Manufacturing

Two start-ups, Cybus and SpiceVR, offered a glimpse beyond the horizon of the issues being discussed, illustrating applications for big data in conventional manufacturing and augmented and virtual reality application scenarios in industry. These presentations ended a fascinating week in Hamburg that was dominated by the additive future.

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FRAUNHOFER IAPT – SPECIAL TOPICS

RESILIENCE IN THE CORONAVIRUS CRISIS THROUGH ADDITIVE MANUFACTURING

➜ ***Fig. 1:*** *Mask retainers manufactured at Fraunhofer IAPT*

And suddenly, everything was different. Change and new challenges are what motivate us in research. But when an event has such an immediate impact on so many people, it not only alters one's own professional and private environment, but also compels each of us directly or indirectly to get involved, help out, and think of US instead of ME.

The extent and dynamism with which SARS-CoV-2, the coronavirus, triggered a global pandemic quickly illustrated how unprepared people were for such a situation and how rapidly shortages and constraints that nobody had contemplated could arise in locations such as hospitals, medical practices, and schools.

This was also why the Fraunhofer-Gesellschaft launched the "Fraunhofer vs. Corona" initiative in which Fraunhofer IAPT has also become passionately involved. Wherever supply chains were interrupted or the demand for particular products could no longer be met, it was the flexibility and speed of additive manufacturing that enabled Fraunhofer IAPT to make its contribution. The coronavirus pandemic clearly demonstrated that additive manufacturing makes us more resilient in a crisis. We can react flexibly to new situations and overcome shortages such as those involving protective equipment or components for ventilators with greater alacrity.

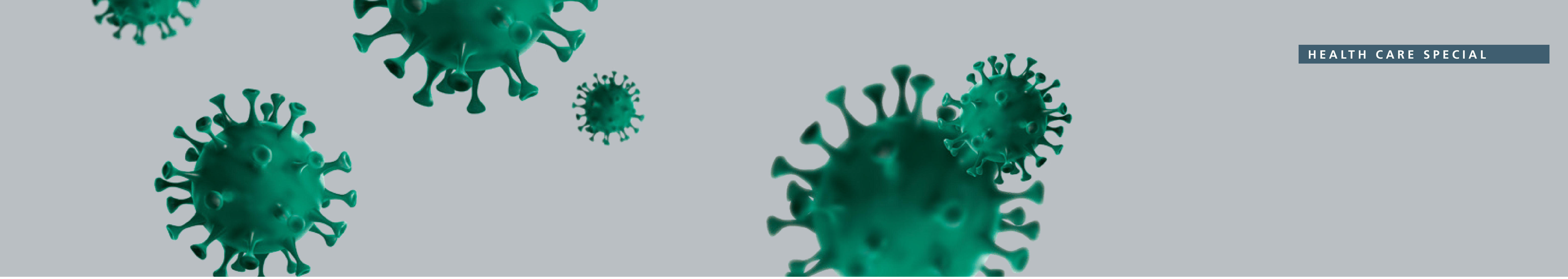
The inquiries and challenges directed to us at Fraunhofer IAPT due to coronavirus were diverse and ranged from necessary and short-term aid to strategic projects. Viewed in the long term, these also strengthened and improved preparations for facing the future. For this reason, we would like to present a brief overview of what we have already achieved – and aim to achieve in future – with our "Fraunhofer IAPT vs. Corona" projects.

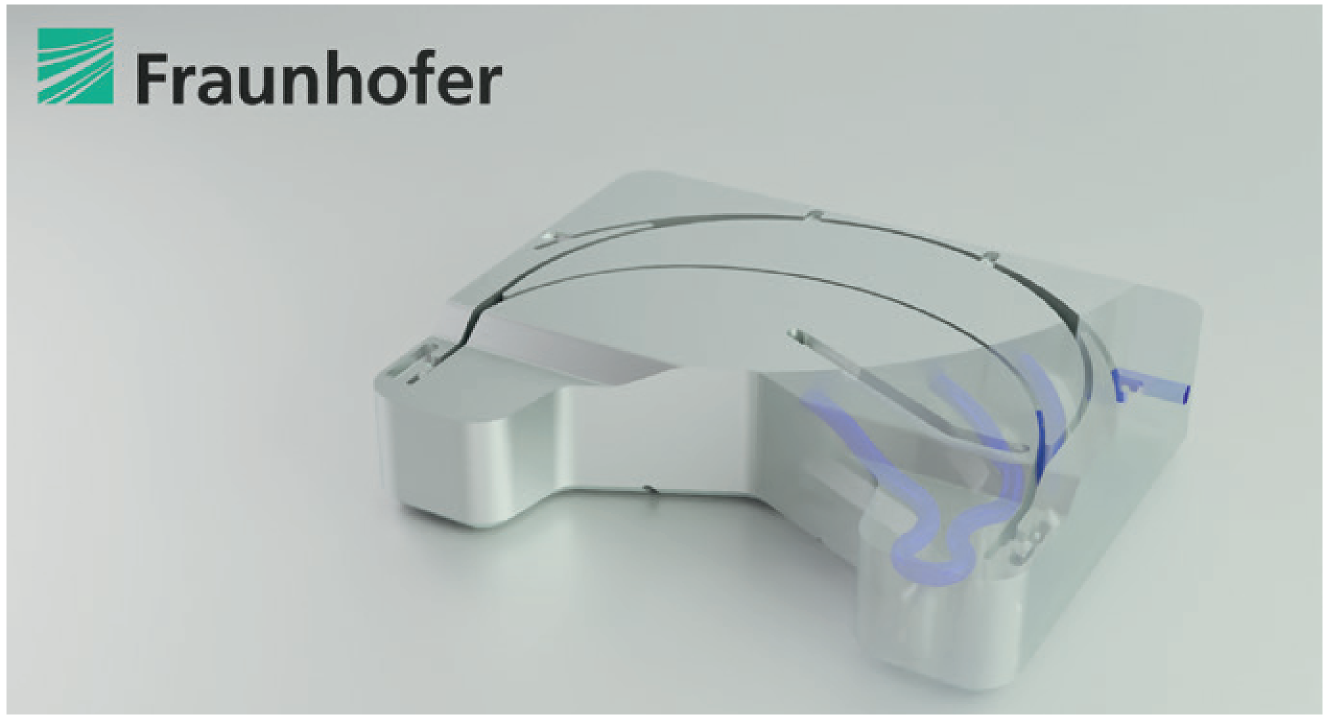
➜ ***Fig. 2:*** *Face shields with 3D-printed retainers*

Additive manufacturing of face shields

Droplet transmission in particular is regarded as the main infection mode in the COVID-19 pandemic. Face shields are a direct help when it comes to avoiding droplet transmission and, indeed, can prevent contamination with other illnesses and contribute directly to reducing the number of new infections by flattening the curve. Furthermore, wearing of face shields over medical masks is essential for anyone in direct contact with other people. These range from medical personnel in hospitals and care homes and general practitioners to staff in pharmacies, supermarkets, and drugstores. These were manufactured at Fraunhofer IAPT through selective laser sintering (SLS) and fused deposition modeling (FDM) in a short-term response to cover the demand for face shields. This enabled us to successfully aid the "Johanniter needs 5000 Face Shields" campaign instigated by the "Mobility goes Additive" initiative. Moreover, we delivered face shields to the Spanish military in an aid campaign organized by Airbus. These were then distributed to meet needs in hospitals in Madrid. Teachers at an elementary school in Hamburg were also provided with our face shields to ensure that facial expressions were not hidden by the commercially available masks that cover the nose and mouth.

➜ ***Fig. 3:*** *3D-printed parts for emergency aid campaigns from Hamburg to Madrid via Munich*





➜ ***Fig. 4:*** *Mold insert with close-to-contour cooling for manufacturing face shields*

In addition, we also printed and delivered over 1,000 head retainers for respirators for a major Hamburg hospital in cooperation with the Institute of Laser and System Technologies (iLAS) of the Hamburg University of Technology (TUHH).

3D-printed injection molding tools

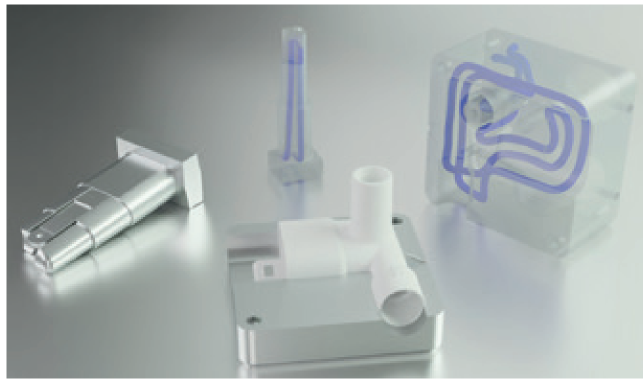
Retainers, which are primarily produced with 3D printers, are the constraining factor during manufacture of face shields. The supply of face shields to clinics, care homes, and medical staff can be assured in the long term through serial injection molding production. With this in mind, we developed a functional mold insert through the "Vechta vs. Corona" network and in cooperation with atka Kunststoffverarbeitung GmbH. This was manufactured from AlSi10Mg in the laser beam melting process. The close-to-contour layout of the cooling channels realized here in the additive mold can reduce the cycle time by approx. 20 percent when compared to a conventionally manufactured injection mold. The reduced cycle time increases the productivity of injection molding production to the same degree, enabling the long-term demand for face shields to be effectively met.

Easybreath DualAdapter and scaling through AM injection mold

Together with our technology partner CompriseTec GmbH and the Bundeswehrkrankenhaus Hamburg (Hospital of the Federal Defense Forces), we bundled expertise in the areas of injection molding, anesthesia, and additive manufacturing to develop a mask that could be used as personal protective equipment and for ventilation purposes.

A commercially available, inexpensive, mass-produced snorkel mask was converted for these purposes through a newly developed adapter. This enables the cushioning of demand peaks in crisis regions. On the anniversary of the first wave of coronavirus, we printed 300 of these Easybreath DualAdapters with SLS technology and donated them to hospitals in Madrid. The consortium then redesigned the adapter so it could be manufactured through injection molding. To this end, an appropriate injection mold was developed from scratch and printed in tool steel. Cycle times and AM production costs were reduced to a minimum through topology optimization and close-to-contour cooling. The result is an injected medical-quality Easybreath DualAdapter made of polypropylene (PP).

➜ ***Fig. 5:*** *Snorkel mask with 3D-printed adapter*

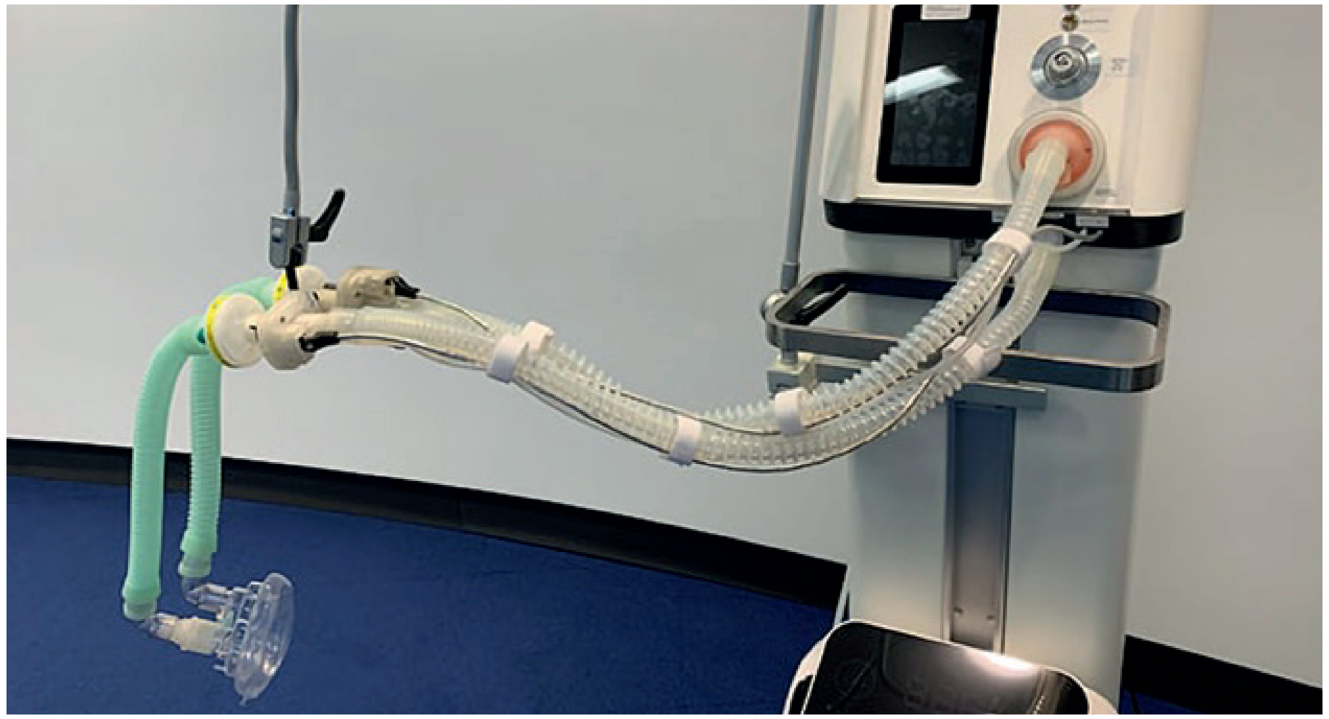


➜ ***Fig. 6:*** *Injection mold for dual adapter with close-to-contour cooling*

Give a Breath – challenge winner for noninvasive ventilators and O_2 concentrators

Cooperation with Fraunhofer ITEM and AC Aircontrols GmbH enabled us to bring together combined know-how from ventilation technology with 3D printing and, together, develop the Smart CPAP (continuous positive airway pressure). Our joint task was to develop a device that is produced through decentralized manufacturing and can be provided at any time for rapid and safe use.

Video clip of the "Give a breath" project



➜ ***Fig. 7:*** *Smart CPAP for aiding ventilation of COVID-19 patients (AC Aircontrols GmbH)*

➜ ***Fig. 8:*** *MobiMed concept*

Consequently, the Smart CPAP team developed a noninvasive ventilator that can be manufactured inexpensively and used under a wide variety of conditions. The device was designed so that all components could be purchased as standard parts or manufactured locally on a 3D printer based on data available on the Internet. The Smart CPAP can work with oxygen from different sources and also incorporates functions that save oxygen. Particular attention was paid to adapting the oxygen supply to the circumstances of COVID-19 patients during operation of the device. The device therefore provides very flexible assistance for patients during inhalation and inhibits or forestalls the need for intubation, thus ensuring that IC beds are kept free for serious cases. This is extremely important in a crisis where oxygen is a valuable commodity.

MobiMed – development of a mobile production line for medicinal products in crisis regions

The global COVID-19 pandemic has demonstrated that crisis-relevant value chains can be secured if medical products can be produced rapidly through additive manufacturing. However, the infrastructure required for this is primarily available in high-tech countries such as Germany. Countries that lack an infrastructure of this kind depend on supply chains, which sometimes cannot remedy shortages or bottlenecks quickly enough during a crisis. This applies in particular to developing countries in which the epicenters of new pandemics are to be expected. In the Fraunhofer "MobiMed" research project, Fraunhofer IAPT developed a mobile manufacturing cell in a 20-foot container format that will aid flexible production of medical accessories in crisis regions. The concept for the manufacturing module took minimum local user interaction into consideration to discourage time-consuming system and process-specific training measures. Those actions that need to be carried out (e.g. component removal from the 3D printer) are supported by AR (augmented reality), meaning the user need not have any knowledge of additive manufacturing processes or post-processing steps.

Two additive manufacturing procedures, fused filament fabrication (FFF) and stereolithography (SLA), are employed in the container solution. Their use for manufacturing medical components in the context of COVID-19 has already been sufficiently validated. Printed FFF and SLA parts are sterilized and packaged inside the container following manufacture.

A platform for managing production orders is being established to enable additive manufacturing of medical devices in the container environment that conforms to relevant standards. All production-relevant information is stored here, and a product certificate is also created.

The projects illustrated in this article were funded as part of internal programs of the Fraunhofer-Gesellschaft, funding numbers Anti-Corona 179-640001, 179-640003, 179-642000.

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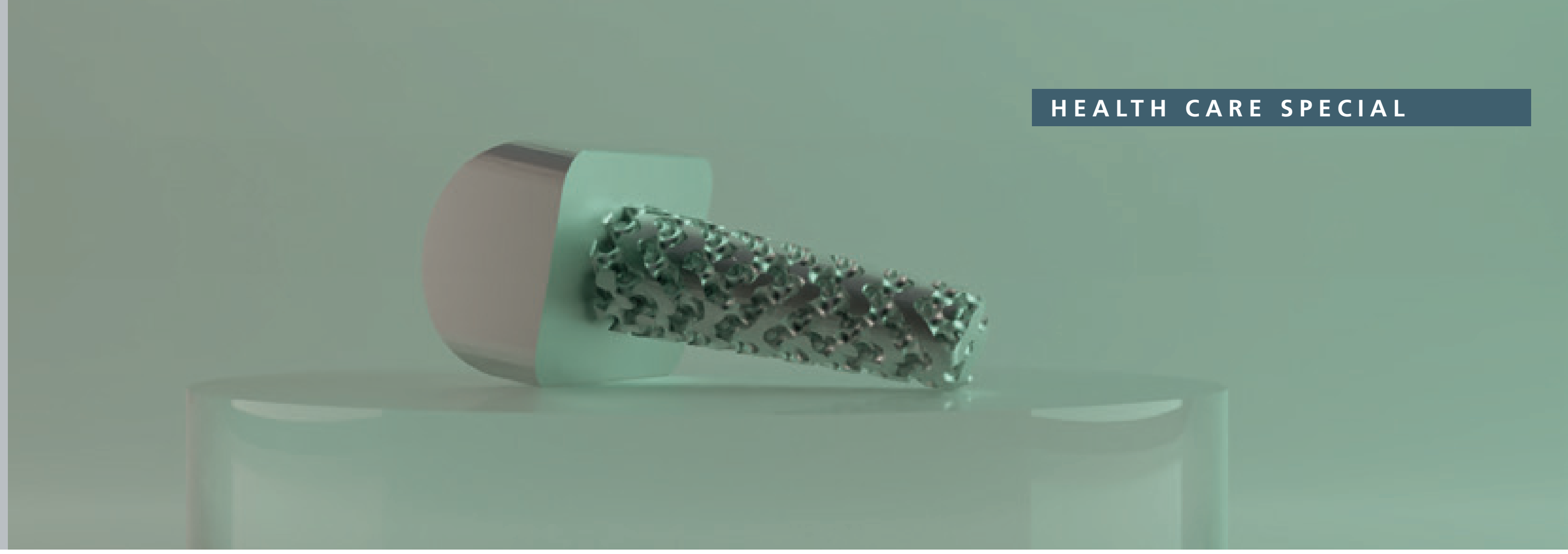
AI-BASED RECONSTRUCTION AND ADDITIVE MANUFACTURING OF IMPLANTS FOR INDIVIDUAL PATIENTS

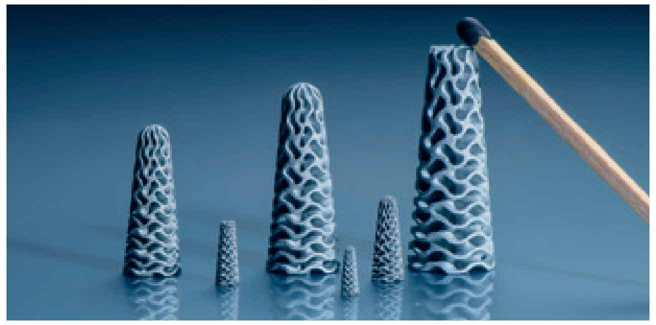


PERSONALIZED FINGER JOINT IMPLANTS FROM AM

The FingerKIt project is a collaboration between Fraunhofer IAPT, IKTS, ITEM, IWM, and MEVIS to enable a continuous automatable process chain for the first time in the manufacture of implants for individual patients, ranging from design and production to certification-compliant testing. Work within the project focuses on the growing market for finger joint implants. These comparatively small implants need to meet high requirements with regard to individual fit and biomechanical load, which is why previous forms of therapy, whether in the case of rheumatoid arthritis or trauma, have very often resulted in stiffening of the joints. The central technical goal of the consortium is to make a new form of therapy for these indications possible and achieve remobilization of finger joints through individually adapted joint implants. The development path in the FingerKIt project is illustrated in Fig. 1.

➜ ***Fig. 1:*** *Development path in the FingerKIt project*

In the Design division, Fraunhofer IAPT is currently examining the use of mesostructures to improve bone growth into the implant. A method for selecting appropriate mesostructures through the use of a database was developed in this context. First, the improvement to be achieved (e.g. osseointegration, durability) is defined. Appropriate requirements and goals are drawn from this (e.g. high specific surface, high permeability, low rigidity, high strength). In an automated process, the database software subsequently produces the appropriate mesostructure for the individual application. An initial implant design with integrated mesostructure is illustrated in Fig. 2. The shaft anchored in the implant is currently structured here. Structuring of the basal plane of the implant that also comes into contact with bone would also be conceivable.



➜ ***Fig. 2:*** *Variants of the FingerKIt implant shaft design manufactured through metal binder jetting*

AI algorithms are then used in the next step for the automatic generation of individual implant designs. Aided by deep neural networks, implant designs appropriate to the individual condition are generated automatically from the patient's X-ray images to facilitate speedy and individual care. In the Processes division, Fraunhofer IAPT is involved in material and process development for the additive manufacture of AI-generated patient-specific implants. In particular, research work focuses on implementation of the required surface properties (mesostructure, roughness, porosity) and mechanical requirements (tribology, long-term stability) in additively manufactured components. In combination with automated design, new materials ensure the optimum functionality of implants with regard to biological/biomechanical adaptation to the tissue, thus contributing to successful remobilization of joints.

➜ ***Fig. 3:*** *Digital X-ray images of both hands indicate severe rheumatoid arthritis*

Three different titanium and titanium alloy powders are used to evaluate implant designs, to test the practicability of using the data generated in printed components, and to assess the suitability of the processes for manufacturing small implants in large quantities. Fraunhofer IAPT uses the cost-effective metal fused filament fabrication (metal FFF) process to examine initial design variants in titanium. The material is mixed in powdered form with a polymer-based binder in this process and formed into a filament that can then be printed, debound, and sintered using a classic filament printer. The process route for this is being developed at Fraunhofer IAPT. Depending on the process parameters involved, the materials are assessed in cooperation with our partners to determine their biocompatibility, osseointegration and mechanical properties to ensure that the fundamental requirements of implant properties are met. The printing process must offer a high degree of component precision, process reliability, and the possibility to produce implants cost-effectively in large quantities if a later transfer of the process to implant manufacturing is to be enabled. Metal binder jetting is an appropriate process. Similarly to laser beam melting, this process uses a powder bed, but instead of melting with a laser beam, the component is generated through jetting of organic ink using a print head. The printed green compacts are then subjected to debinding and finally sintered to create the metallic component. In the course of the project, Fraunhofer IAPT is developing suitable process parameters for the manufacture of implants from the selected titanium alloy. Initial investigations into stainless steel already indicated the major potential of the technology for creating high-precision small implants.

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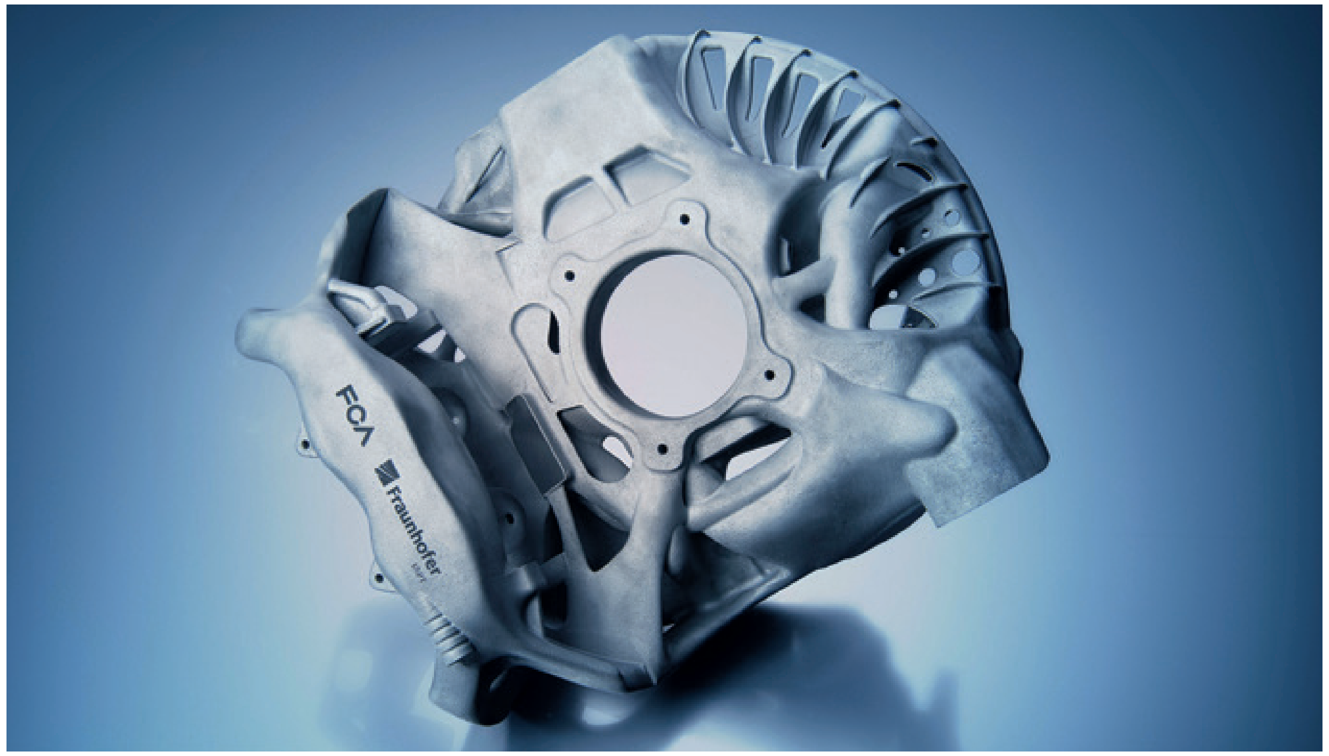
3D PRINTING: FIAT CHRYSLER COOPERATES WITH FRAUNHOFER IAPT

AND SUDDENLY THE PRINTED WHEEL CARRIER BRAKES ...



A cross-border innovation from Hamburg to Turin has attracted the attention of automotive enthusiasts. Fiat Chrysler Automobiles (FCA) and the Fraunhofer Research Institution for Additive Manufacturing Technologies IAPT have together developed a 3D-printed wheel carrier with integrated brake caliper for an FCA sports car.

The part represents the first step towards serial 3D printing of FCA vehicle components. Commenting on these ambitious goals, Carlo Carcioffi, Head of Advanced Processes and Materials Body, Interiors, Chassis, noted that "Together with our innovation partner Fraunhofer IAPT, we are reducing the costs and production effort involved in key vehicle components. The knowledge transfer will help us to improve our additive manufacturing expertise in the fields of integrated design, materials, and process technology across the Group."

All inclusive: wheel carrier with integrated brake caliper

The additive research collaboration was born of a bold question: how can a complete suspension system for a sports car be realized using 3D printing? At present, this system still consists of numerous individual components such as the wheel carrier, brake caliper, hydraulics, and heat shield. In the past, these components were manufactured individually and then assembled in several steps using screws, seals, and washers to form a complete, functioning system. All in all, a complex, time-consuming, and expensive process.

"We had, together with the FCA design team, to completely rethink the entire wheel carrier in order to achieve a one-piece bionic structure that fulfilled all the functions of the previous assembly at least equally as well, absorbed all the forces, was weight-optimized, and could be manufactured additively", recalled IAPT design engineer Yanik Senkel.

Eco-efficiency through lightweight and integral design

The result is impressive. Topology optimization has enabled the team to develop a prototype that weighs 36% less than the 12 individual parts of the conventionally manufactured component. The bionically optimized design reduces the assembly effort enormously, increases fatigue strength through a more robust structure, and should also perform better in terms of noise, vibration, and harshness (NVH). The clever integral design eliminates many typical weak points and, consequently, extends its lifetime. "The component demonstrates the potential of additive manufacturing for future cars", said Carcioffi proudly. "And, on top of that, it's a real eye-catcher", he added.

But the 3D-printed wheel carrier with integrated brake caliper, the first of its kind anywhere in the world, is only the beginning. It is the point of departure for many other projects. In numerous joint workshops, which also covered the areas of material and process development and quality assurance, several lightweight and integral construction components were completely redeveloped.

"The overall focus is on the reduction of manufacturing costs by, for example, significantly increasing production speed", explained Ruben Meuth, Head of Business Development Automotive at Fraunhofer IAPT. *"This component is an excellent example of the collaboration between industry and research. It shows how additive manufacturing can be implemented in series production of luxury and sports cars",* summed up Meuth.

But which vehicle parts does the cooperation team identify as the next 3D-printing candidates? The results should be exciting, Carcioffi insisted confidently. The FCA expert is already certain about one thing. "The project has shown that, through additive manufacturing, we can entirely rethink many areas of the automobile and lay the foundations for future innovations."

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PROFITABLE SERIAL AM FOR AUTOMOTIVE APPLICATIONS OF QUANTITIES UP TO 5,000

LIGHTER, QUICKER, AND STILL MORE COST-EFFECTIVE!

Continued success with additive manufacturing in the automotive industry

Fraunhofer IAPT demonstrates how profitable applications can be implemented today in a sports car through additive manufacturing by reducing reproducible AM production costs by 80 percent through a consistent and systematic development approach.

What has been achieved is a door mounting for this sports car that has been optimized in terms of lightweight construction, profitable applications, costs, and appearance. Specifically, 35 percent of the weight and 50 percent of costs were saved at an initial development stage when compared to the previously milled component. Moreover, bionic design makes the new door mounting a real eye-catcher and immediately appealing to every driver. The door mounting involves the installation of three individual parts.

The challenge here is not only to additively manufacture the articulated arm, the core component of the system, in low-volume production runs in future, but also to improve the visual and technical characteristics while, simultaneously, reducing costs.

Adopting an approach centered on 3D printing from the outset is unavoidable here if the cost savings potential is to be exploited to the full. The objective is to move away from a mentality that thinks in terms of milled tracks and exploit the design freedom of additive manufacturing. Simultaneously, each process step needs to be examined in terms of its cost savings and optimization potential. Only then can a profitable

➜ ***Fig. 1:*** *Installation location of component*

overall effect be achieved from a combination of different cost savings potentials. Systematic cost reductions during additive manufacturing can be clearly illustrated by examining individual steps in the process, using the example of the previously described articulated arm.

Sophisticated AM design achieves 45 percent cost savings

Intelligent orientation optimization enhances utilization

It is important to identify the most cost-effective component orientation in the 3D printing process at an early design stage if, for example, the number of support structures required is to be minimized and, simultaneously, the number of components that fit in a build space is to be maximized. Fraunhofer IAPT uses a software tool it has developed itself for orientation optimization in this context. The component orientation identified in this manner must be taken into consideration in all further manufacturing steps and leads to cost savings of 15 percent.

Consistent topology optimization drastically reduces weight

Additive manufacturing and bio-inspired design create structures that other production processes simply cannot achieve. Topology optimization ensures a favorable basic component design that only deposits material where the simulated flow of force requires it. A cavity can be achieved in the articulated arm using bionic structures inspired by natural examples such as the hollow bones of birds. Overall, this reduces weight in the case of the door joint by 35 percent. A lower material requirement and shorter printing time reduce costs by a further 20 percent.

Minimized and easily removable support structures facilitate post-processing

Every support structure that does not need to be removed saves time and, consequently, the considerable costs associated with highly manual post-processing. Reducing support structures in the design also has a positive effect on the production time and material requirement, reducing costs once again by 10 percent.

Consistent printing process optimization achieves further cost savings of 35 percent

Extensive material selection creates cost savings potential

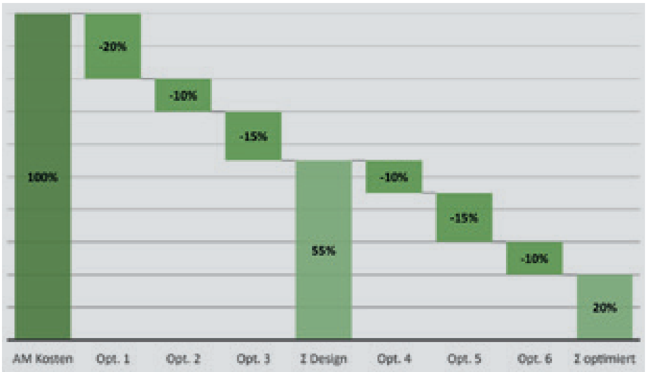
Additive manufacturing has a growing range of materials at its disposal that can be availed of for printing. The choice of material heavily influences the production time and metal powder costs. For this reason, Fraunhofer IAPT always selects the most cost-effective material for each individual case that best satisfies requirements, once again achieving cost savings of 10 percent as a result.

Speed AM: enhanced manufacturing speeds reduce production costs

Adaptation of AM process parameters opens up further options for cost reductions. A higher layer thickness during printing, optimization of process parameters, or modifying the laser beam profile considerably reduce the construction time. This leads to a slight reduction in component quality, but this continues to exceed the quality obtained in cast components, and printing costs are reduced by a further 15 percent as a result.

Clever nesting maximizes the degree of filling in the build space

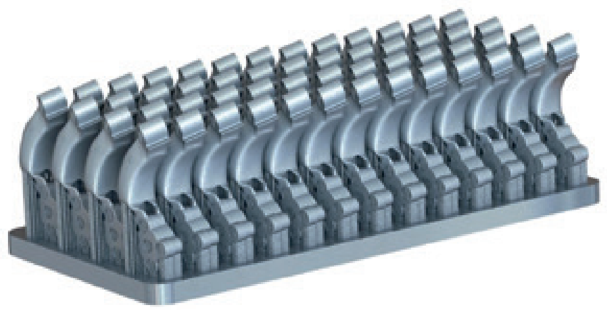
Two things are decisive during the arrangement of components in the build space. On the one hand, the number of components in a single layer must be maximized and, on the other, the practicality of printing several layers on top of and, where appropriate, stacking leads to further cost savings of 10 percent.



➜ ***Fig 2:*** *Overview of cost reduction drivers in the systematic approach*

AM costs = AM production costs without any optimizing, Opt. 1 = cost savings through orientation optimization, Opt. 2 = cost savings through topology optimization and bionic design, Opt. 3 = cost savings through minimization of support structures and post-processing, Σ design = costs following design optimizations, Opt. 4 = cost savings through intelligent material selection, Opt. 5 = cost savings through use of Speed AM parameters, Opt. 6 = cost savings through intelligent nesting and filling level maximizing, Σ optimized = minimized AM production costs following design and process optimization

In the case of the articulated arm, additive design and the rigorous pursuit of design to cost in all design and manufacturing phases enables the achievement of cost savings of 80 percent. On the one hand, this impressive result is achieved through cost reductions of 45 percent in AM design, orientation and topology optimization, and support minimization and, on the other, 35 percent through optimized material selection, speed parameters, and filling level maximization in the AM process. Component performance was simultaneously enhanced through lower weight, improved appearance, and increased durability. However, the most important point is that, by using 3D printing, manufacturing costs of the articulated arm for a racing car produced in small series were reduced by 50 percent when compared to the milling process previously employed. The AM cost reduction system illustrated can be applied to numerous automotive components and



➜ ***Fig. 3:*** *Installation location of component*

demonstrates how additive manufacturing can already be employed profitably today for large series of up to 5,000 pieces.

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HIGHLY DUCTILE AND CRASH-RESISTANT ALUMINUM ALLOY FOR THE AUTOMOTIVE INDUSTRY

Multifunctional use of new alloys

Numerous alloys and metals are employed to meet the diverse requirements of automotive applications. The "Tailored LAM aluminum materials for highly functional, varied structural components – CustoMat 3D" research project (funding reference 03XP0101H) succeeded in developing and testing an alloy that offers a high degree of rigidity, high ductility, and a large bending angle. Development of the alloy was the core aspect of the project, in which the entire process chain was covered by the consortium. With regard to development of the alloy, the Leibniz Institute for Materials Engineering IWT primarily took charge of the composition and determination of the properties, while Ecka Granules realized powder atomizing and Fraunhofer IAPT took on parameter development of the additive processes. With the support of Altair, the development of components in the design area was primarily influenced by the work of EDAG and Mercedes-Benz. Their content was forwarded to ConceptLaser and FKM who addressed questions concerning manufacturing of the components. Fraunhofer ITWM and Magma also contributed through simulations that enabled predictions in the manufacturing process. The final demonstrator components were a wheel carrier for the AMG 190 and a damper strut dome for the Mercedes-Benz E-Class from Daimler.

Alloys for additive manufacturing

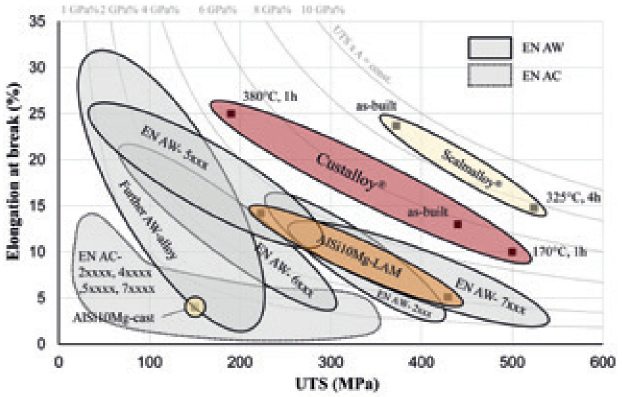
The desired alloy needs to meet mechanical requirements for the planned application and exhibit adequate corrosion resistance. One point of reference here was the 6000 series aluminum alloys with silicon and magnesium as the primary alloy elements, already used in the automotive industry. Alloy elements were adapted in numerous iterations to optimize the mechanical properties and, also, ensure good processing characteristics for additive processes. In particular, any tendency towards hot cracking and porosity formation was minimized through precise adaptations.

In addition to reliable use under the most varied mechanical loads, the production price is also a crucial factor when developing new alloys. The use of expensive or rare alloy elements (e.g. scandium) was avoided during development in order to achieve a competitive powder price.

Flexibility through heat treatment

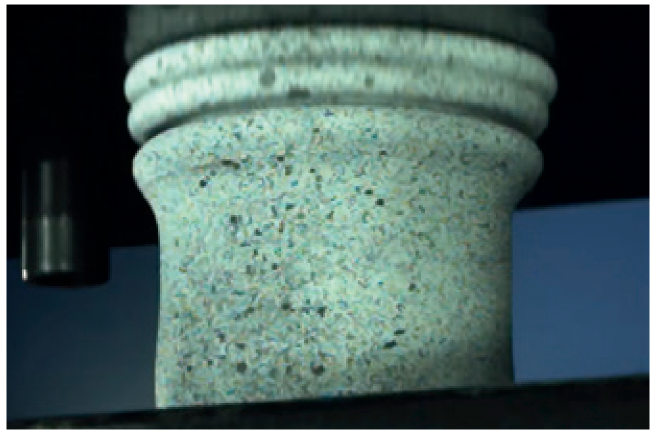
As the development of an alloy that possesses both greater strength and ductility than comparable alloys usually represents a major materials engineering challenge, as flexible an adaptation of the properties as possible was the objective with the CustAlloy alloy developed in this case.

Appropriate heat treatment enables variation of the properties of these alloys over a broad spectrum. The degree to which the alloy can be adapted is illustrated in Fig. 1. Two variants in particular were examined, namely stiffness-optimized and distortion-optimized. Mechanical tests following stiffness-optimized heat treatment indicate a tensile strength that is approx. 25 percent greater than that of AlSi10Mg alloys.



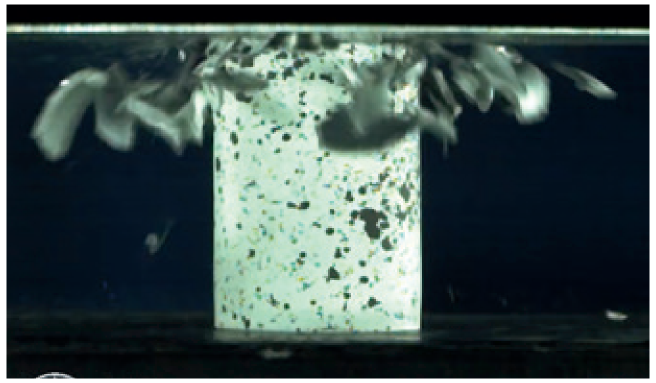
➜ ***Fig. 1:*** *Mechanical properties of the CustAlloy alloy when compared to other aluminum alloys (IWT)*

This alloy variant also impressed in the component, as all wheel carriers made of this material passed the tests conducted. Superimposed mechanical stresses were tested here that simulate several outings on a racing track. Components subject to distortion stress that could be relevant in crash situations underwent secondary heat treatment. The material exhibited a clear reduction in tensile strength in this case, but it was possible to expand it by up to 25 percent before it fractured. What is more critical in the case of this heat treatment is the increased bending angle, which is around five



➜ ***Fig. 2:*** *Advantages of heat treatment in a crash test (Mercedes-Benz)*

times greater than specimens not subjected to heat treatment. The advantages of this heat treatment are particularly clear in the crash test illustrated in Fig. 2. It is evident here that the



➜ ***Fig. 3:*** *As-built AlSi10Mg specimen in the drop tower (Mercedes-Benz)*

specimen wrinkles, and energy is optimally absorbed. By way of a direct comparison, Fig. 3 illustrates an AlSi10Mg specimen that was not subjected to heat treatment. This exhibits brittle fracture behavior that is unsuitable for crash-relevant components.

Versatile manufacturing concepts

Different processes were investigated to provide as broad an application area as possible for the CustAlloy alloys, both in terms of their properties and taking manufacturing requirements into consideration. While the initial alloy development phase was conducted in the powder-bed-based laser beam melting process, further trials that were conducted subsequently enable powder cladding. Moreover, approaches for hybrid manufacturing were examined in which casting specimens were fixed in the powder bed and augmented by additively manufactured additions. Finally, in addition to the additive manufacturing approaches, subsequent joining through laser beam welding, self-piercing half-hollow rivets, and gluing was investigated. Welded joins were also realized during manufacture of the damper strut dome in Fig. 4.

➜ ***Fig. 4:*** *Damper strut dome made of CustAlloy (EDAG)*

Promising development approaches

The demand for tailored aluminum alloys in additive manufacturing is covered by the CustAlloy alloy presented here, particularly due to its unusually flexible area of application. Far from being a niche product, this alloy is suitable for numerous applications. The fact that it proved possible to verify processing of this material through different manufacturing processes underscores its universal suitability even more.

In a final examination, the alloy also impressed during testing of the components. Fraunhofer IAPT and the partners involved in the CustoMat 3D project then decided to apply for a patent for this innovative new alloy. With the support of our project partners and the German Federal Ministry of Education and Research (BMBF), Fraunhofer IAPT made possible the additive manufacturing of an innovative aluminum alloy that masters known challenges through new approaches and has the potential to contribute to other application areas in a practical manner.

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STAVARI – LASER BEAM WELDING OF NEW AM MATERIALS FOR AUTOMOTIVE MANUFACTURING

MATERIAL COST REDUCTION OF 50 PERCENT FOR AM

Powder alloys of different compositions that form the basis of every component generated in layers are used in laser additive powder-bed-based manufacturing (LAM). In addition, the powder forms the basis for mechanical properties and also influences component costs. The chemical composition of existing steel powders contains a large proportion of expensive elements in this respect, including chromium, nickel, and molybdenum. However, in many applications (e.g. in the automotive industry), these expensively purchased elements do not contribute any significant added value in terms of quality, costs, or time in the products generated. Nevertheless, a lack of alternatives means that these alloys are still used, increasing material costs significantly and restricting the introduction of additive manufacturing to series production as a consequence.

For this reason, an innovative new steel powder alloy was developed by the project consortium in the context of the StaVari project funded by the German Federal Ministry of Education and Research (BMBF). This alloy is tailored to the needs of the automotive industry. The new powder material is based on a cost-efficient medium manganese concept and reduces material costs by approx. 50 percent to €27/kg. The manganese content was set purposely to ensure that high energy absorption is possible during distortion (the transformation-induced plasticity [TRIP] effect) and, consequently, crash requirements are met in automotive manufacturing. To validate this new powder alloy for structural automotive components, the focus in the project turned to different process steps for atomizing powder, the LAM process, heat treatment, and joining characteristics. DP800 dual-phase steel, which is conventionally used in body-in-white, was selected as a reference for the strength and elongation of the new alloy. Fraunhofer IAPT developed an appropriate laser welding process for the hybrid combination of additive and rolled materials to realize large structural components. Joining is usually necessary, due to the limited component size in LAM, so investigations of welding behavior by Fraunhofer IAPT were of major importance. In the printed form, the new powder alloy exhibits comparable material and welding behavior in this respect. The hardness, strength, and weld characteristics of the welded joining specimens in different material combinations (with each other or with reference sheet material) are equal to the reference steel. The surface profile of the specimens was identified as the key to the solid laser welding results, and these can be used to achieve different positive effects with regard to welding speed, weld characteristics, and zinc outgassing.

In addition to low costs, use of the newly developed steel powder also has other decisive advantages. For example, black and white joining (i.e. joining ferritic and austenitic steels),

➜ *Fig. 1: Metallographic section of a laser welded joining specimen in the lap joint, printed LAM material above, rolled DP800 below*

➜ *Fig. 2: Demonstrator assembly from EDAG designed for an EV that encompasses the wheel housing, additively manufactured C- and B-pillar nodes, rocker panel, and adjacent body side structure.*

which is difficult in welding terms, can be avoided, different painting behavior is bypassed, and general process integration in conventional body-in-white construction is made much easier.

The StaVari research project was supported with funding from the German Federal Ministry of Education and Research (BMBF) in the "Innovation for the production, services and work of tomorrow" program under the funding reference 02P15B060 and overseen by Karlsruhe (PTKA), Dresden Office, the project manager. Fraunhofer IAPT wishes to thank its project partners EDAG Engineering, Ziehm Imaging, Salzgitter Mannesmann Forschung, Indutherm, GE Additive, Carl Cloos Schweißtechnik, Hema Electronic, TU Chemnitz, Professur SLK, and the Leibniz Institute for Materials Engineering IWT.

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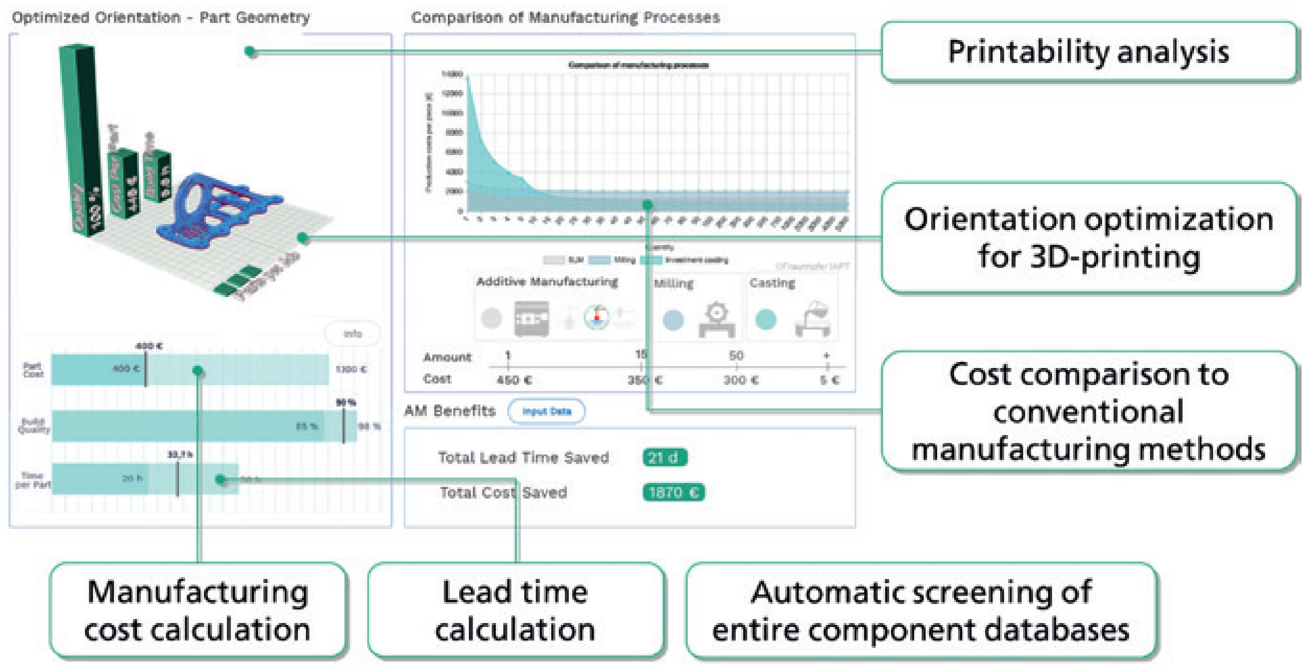
FIND THE RIGHT AM BUSINESS CASE

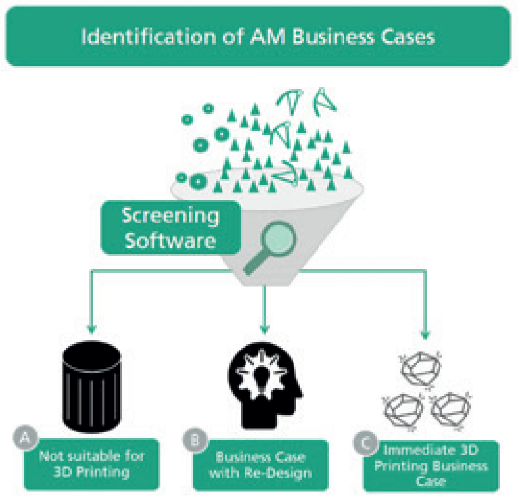


Discovering cost savings potential

3D printing harbors the potential to enhance the performance of components enormously, minimize delivery times, simplify spare parts logistics, and reduce the manufacturing costs for small series. However, companies frequently fail to identify the relevant business cases to justify the comparatively high investment costs in additive manufacturing technologies. The reasons for this range from inadequate AM know-how in the conventional manufacturing industry to the impossibility of manually investigating historic component databases in large companies.

Digital part screening

For this reason, Fraunhofer IAPT has set itself the task of digitizing the know-how required to identify business cases and minimizing the manual working effort necessary for this purpose. The application developed provides an option for examining components or entire component databases with regard to potential 3D printing application cases. The analysis is realized with regard to different manufacturing technologies, in the area of both plastics and metals. Production costs of different manufacturing processes and optimization potential (e.g. lightweight construction potential) are involved in the investigation. Only in this way can the feasibility of any application case be accurately estimated. In addition, an automatic check determines whether the restrictions of the respective additive manufacturing process (e.g. maximum overhang angle or minimum wall and gap dimensions) are taken into consideration in the component design, or whether component adaptations are necessary. Additive manufacturing of conventionally designed components is only feasible in a few special cases. In point of fact, options for a functional additive redesign of the component must be included in the feasibility study if the full potential of AM is to be exploited.



Comparison with conventional manufacturing process

Appropriate cost models (e.g. for milling and casting) must be stored to achieve comparability of production costs with conventional manufacturing processes. Additive processes frequently represent the most efficient alternatives for applications ranging from small quantities to low-volume production runs, whereas conventional manufacturing techniques such as investment casting are much more cost-effective in the case of large quantities. The software therefore enables simple identification of the break-even points of different manufacturing technologies relative to the quantity to be produced.

Flexible use in the cloud or on-premise

The software can be used in a variety of scenarios, depending on the customer's wishes. In the form of a software-as-a-service (SaaS) solution, components can be uploaded to a cloud-based application and analyzed. Alternatively, the software can be installed on customer servers for in-house use and operated from different locations. Account and role management ensure the security of data and access rights. Moreover, the software can be used as a stand-alone solution or as a plug-in for CAD software (e.g. SolidWorks).

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TAILORED PRODUCTS AT THE PUSH OF A BUTTON

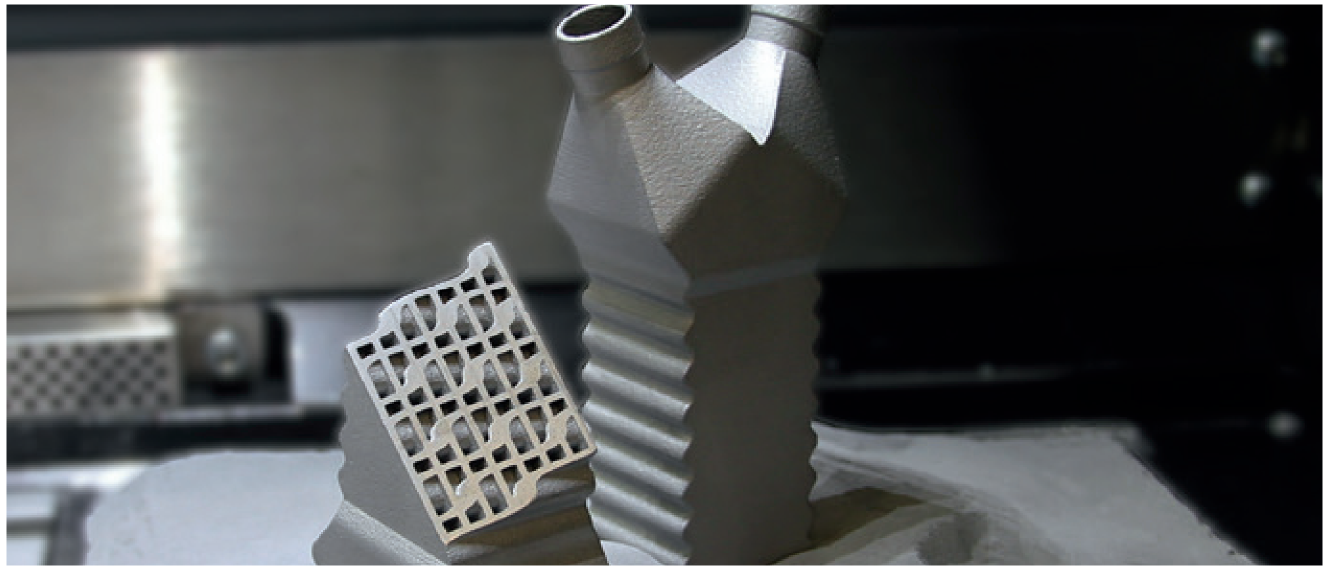
Maximum individualization and minimum storage

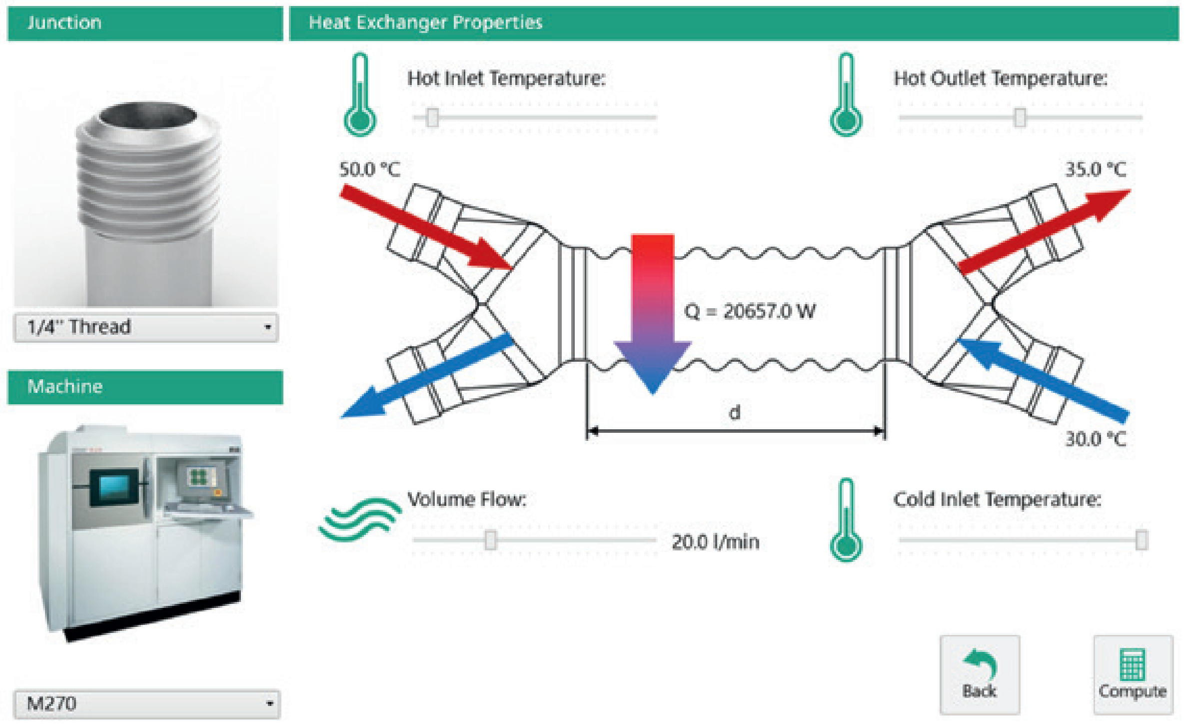
In a digitized world, customers are used to adapting products to their personal taste in just a few clicks. As far as the are concerned, these applications are in most cases backed by modular product systems or giant component catalogs, which involve a major logistical effort. Additive manufacturing, on the other hand, really offers the chance to create customized components at the push of a button.

The advantages of this technology are obvious. Components can be created when needed with minimum storage requirements, and it makes no difference in production whether 100 of the same component or 100 similar variants with minor deviations are to be manufactured. Many producers have recognized this advantage and offer configurators to allow customers to adapt the labeling, shape, size, and appearance of their products.

Automated component design

However, the greatest potential of additive manufacturing remains unexploited here: maximum functionality through practically limitless design options. Targeted design achieves advantages in weight, heat transfer, fluid dynamics, and many other areas. However, complex tasks of this nature can no longer be realized with simple configurators, but rather require complicated optimization in each individual application case through simulation by trained personnel. This leads to higher costs, particularly in the case of individualized products and small series. To solve this, Fraunhofer IAPT develops simulation apps that combine convenient operation of





configurators with digitized expertise and multiphysical simulation. This was successfully demonstrated in the case of apps such as HeatXchangeIO for individual heat exchangers. With just a few clicks, users can adapt the product to their individual requirements: temperature, flow rate, machine availability, and desired connections. The app draws upon precalculated solutions to provide ideal variants, their characteristics, and the CAD model, all in a matter of seconds. The design restrictions of the manufacturing process are considered in full in this context. Once a variant has been selected, a simulation of the heat exchanger can also be initiated to validate the prognosis and obtain exact values.

Apps of this kind can be applied to any products and, with minimal effort and limited prior knowledge, the full potential of additive manufacturing can be exploited.

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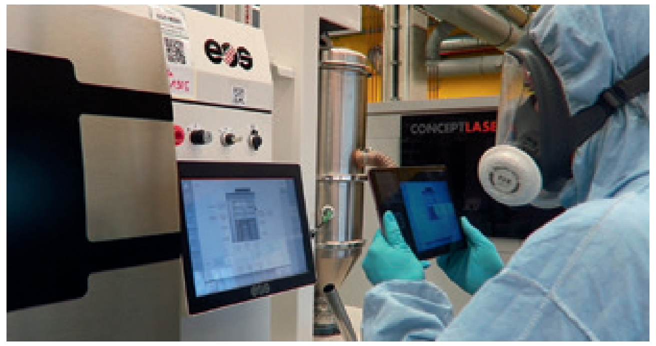
AR ASSISTANCE SYSTEMS FOR SETUP AND MAINTENANCE OPTIMIZATION IN THE AM PROCESS CHAIN

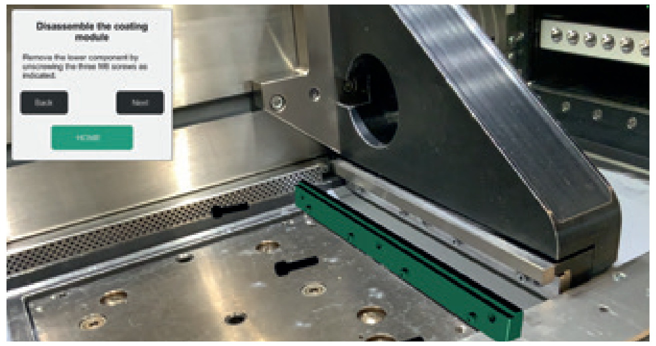
As an essential part of contemporary and future production systems, additive manufacturing is subject to continuous change. Due to basic differences when compared to conventional manufacturing processes and the variety of AM technologies, the demand for trained specialists in the sector is correspondingly high. Process chains in industrial additive manufacturing today still involve manual tasks in the process steps upstream and downstream of the build process. Human assistance is currently indispensable, particularly in the case of customized small-series production, a task for which additive manufacturing is ideal. Each step along the generic process chain requires specific know-how concerning the respective AM process, whether it be design guidelines, machine operation, or process parameters. As this specialized know-how, in addition to high investments for industrial AM systems, is required for productive use, the initial hurdle is very high, particularly for SMEs.



Digital assistance systems can be used with augmented-reality support (AR support) to respond appropriately to the interface between man and machine in digital production. AR is one of the immersive technologies, meaning processes that enable human beings to immerse themselves in a virtual environment. While the perception of the user's environment is completely replaced by a virtual world in VR (virtual reality), the real environment is enhanced through virtual information in the case of AR. Countless devices such as smartphones and tablets are available today for the use of AR, and even dedicated AR glasses can be obtained. Computer vision algorithms are used to overlay context-sensitive information in real time. These algorithms obtain information about the environment through evaluation of the camera image. Even though the potential this technology harbored for industrial use was already recognized some years ago, only recent progress in hardware and software development has enabled its efficient use in industrial operational scenarios.

For this reason, an AR-supported digital assistance system was developed at Fraunhofer IAPT to assist in complex situational process steps, speed up access to additive manufacturing for new personnel, enhance occupational safety through standardization of processes, and to avoid human error. This reduces the influence of manual tasks on the quality of components. A system of this kind was deployed for manual tasks in the laser beam melting (LBM) process chain. Further positive impacts on productivity and cost-/time-saving effects through standardization of processes were recorded.

The digital assistance system is clearly structured. The user can select every manual process required for setup and operation of an LBM system via a simple user interface. Maintenance and setup processes include configuring the build space, cleaning of the process chamber, and replacement of the coating blade. The user is guided step by step through every process. In addition to overlaying text concerning the specific task, the process step is visually enhanced with instructions and animations through object and image recognition to ensure



unambiguous handling. A process assistant helps to select the process steps required for the manual task to be carried out. The software can be used on a tablet to facilitate collective use and, in addition to LBM, also supports other additive processes.

Its use for replacing the coating blade is illustrated by way of example. In the LBM process, a defined layer of powder is applied with a coating blade, enabling selective solidifying of component geometries with a laser, layer by layer. The coating blade must be replaced in the event of wear and depending on the material processed. Process termination is possible if it is incorrectly mounted, as consistent application of powder is not assured in this case. The process involved in installing a new coating blade on an EOS-M290 industrial system involves 14 steps. In general, all 14 process steps are described through text-based instructions to fully assist the process. The work area must be set up at the beginning by connecting the grounding cable. The connection point in the production facility is visually highlighted for the user to facilitate this, and it is only possible to continue to the next step after connection has been confirmed. The coating component is in the system build space. This is identified by a computer vision algorithm, and the screws to be loosened are depicted in animation in the correct sequence. Following successful removal and replacement of the coating blade, assistance is also provided for correct replacement of the components.

Even if automation of the entire process chain is the goal of many plans relating to line integration of additive manufacturing, process steps will continue to be realized or monitored by people in the near future. In particular, human assistance remains essential at the moment when it comes to needs-based individual production. For the medium term, AR also offers a new area of activity as an interface in the socio-cyberphysical system for human–machine interaction. Human-centricity and collaboration between people as intelligent machine users should take place, as required in the progressive Industry 5.0.

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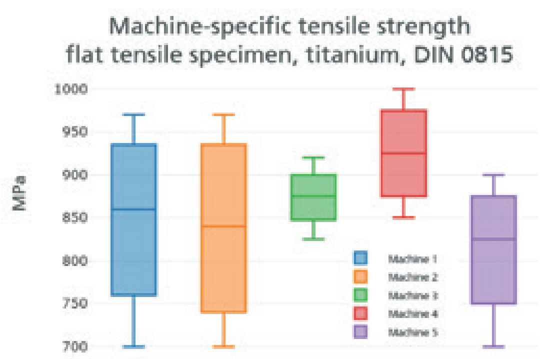
QUALITY OPTIMIZATION THROUGH BIG DATA AND CERTIFICATION

The production of safety-related components requires a high level of process control, reproducibility, and quality assurance. In particular, markets such as aviation, medical engineering, and the automotive sector demand a verifiable and reliable production process. Up until now, the complex additive manufacturing process has not yet met these requirements to an adequate degree.

High process stability due to big data

With the Additive Quality Manager® (AQM), Fraunhofer IAPT has developed its own software solution that takes the specific requirements of additive manufacturing into consideration. The objective was to enable a reliable production process and simple traceability. All relevant production and quality data is stored in AQM in a common database. With the aid of

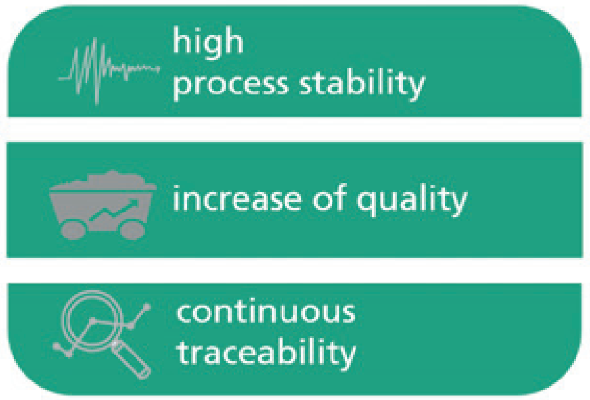


➜ ***Fig. 1:*** *The analysis module clearly indicates the variation of material properties between different plant systems*

statistical analysis and machine learning, the cause-and-effect relationships of influencing factors can be better understood with the structured data, and the quality of the products can be continually improved. The analysis module clearly indicates the variation of material properties between different plant systems.

Traceability and quality certificates

Based on the data, malfunctions that occur can be speedily identified and remedied. The comprehensive database also ensures the traceability of components, and automated quality certificates can be generated for manufactured components.



➜ ***Fig. 2:*** *Advantages of AQM in production*

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RESEARCH AND DEVELOPMENT

PROCESS MONITORING AND DATA ANALYSIS

QUALITY ASSURANCE IN AM

3D printers that manufacture products with complex geometries from metal powder are steadily gaining in importance. Sectors such as aviation, medical technology, and mechanical engineering increasingly rely on this technology. However, 3D printers have to date exhibited limited options for error detection, as they only have a few sensors for process monitoring, and the interpretation of data poses a challenge. As a consequence, it is not possible to respond to unforeseen malfunctions in the manufacturing process, and component quality cannot be reliably guaranteed. Consequently, complex and expensive quality assurance of the manufactured components is necessary (e.g. through µCT).

Error detection through multi-sensor technology

The aim of the InSensa research project (in-process sensor and adaptive control systems for additive manufacturing) was, therefore, the development and integration of sensor and control technology for powder-bed-based metal 3D printing systems to reduce the error rate. Component faults were to be identified during the production process and prevented during subsequent printing processes.

To achieve this, Fraunhofer IAPT developed a flexible solution for integration of radiation sensors, topography sensors, and cameras for the visible and invisible infrared range. The suitability of sensors with regard to the detectability of different defect types was investigated together with the project partners Materialise, Aconity, Precitec, Optris, ISRA Vision, BIMAQ, and C.F.K. The sensors record the printing process in the system in real time and create a new data basis for process monitoring.

Data analysis with AI

The numerous sensors involved and their high clock rates mean that copious volumes of data are created during manufacturing. Interpretation of this data volume is, in a "classical" sense, practically impossible to accomplish, which is why, even beyond the project itself, Fraunhofer IAPT has developed machine-learning algorithms for the detection of process deviations and component faults on the basis of layer topographies and thermal emissions. Specimens and processes for the provocation of defects enable an exact correlation between sensor signal and defects in this respect.

Real-time control for process stabilization

Furthermore, a control loop was successfully tested in the InSensa project that compensates for irregularities through real-time adaptation of the laser output, meaning faults can be prevented as they occur.

This research and development project was supported with funding from the German Federal Ministry of Education and Research (BMBF) within the "Research for the production of tomorrow" framework concept (funding reference 02P15B076) and headed by the project manager Forschungszentrum Karlsruhe (Karlsruhe Research Center), Production and Manufacturing Technologies Division (PTKA-PFT).

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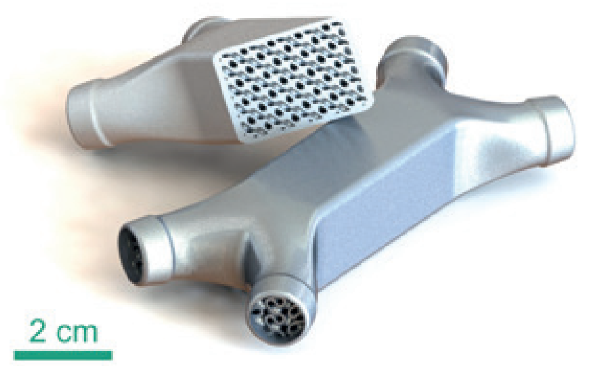
FUNCTION OPTIMIZATION THROUGH ADDITIVE MANUFACTURING

In addition to being ideal for lightweight construction, the geometric design freedom associated with additive manufacturing (AM) enables it to improve and optimize components with regard to other functions (e.g. heat transfer, flow, acoustics and vibration). In particular, this makes functionally optimized lightweight design of components possible.



➜ *Fig. 1: Oil/water heat exchanger for high-performance motors based on cellular structures (below: full version, above: half section)*

Heat optimization through AM

The design of highly efficient heat exchangers is a common application area for additive manufacturing. Research at Fraunhofer IAPT in this context has focused on an optimized design for cooling channels based on cellular structures.

An example of a heat exchanger based on cellular structures is illustrated in Fig. 1. This heat exchanger can, for example, be used with high-performance motors to cool extremely hot oil down to operating temperature again with the aid of water.

The realization of cooling channels as cellular structures represents an effective compromise between low flow resistance and effective heat transfer in a compact design. A further application area for heat exchangers based on cellular structures is in the cooling of computer chips or power electronics.

Acoustic design through AM

➜ *Fig. 2: Additively manufactured tube muffler (left: full version, right: quarter section)*

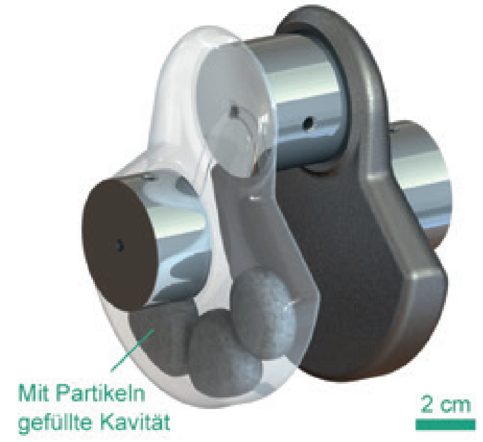
Aside from their contribution to the design of optimized cooling channels, cellular structures also facilitate acoustic or sound design. These structures are capable of influencing sound propagation of certain frequencies or even filtering out complete frequency bands.

One application example for acoustic design is the tube muffler illustrated in Fig. 2, which can be used to attenuate air-conditioning noise. In electric vehicles (EV) in particular, background noise caused by the air-conditioning system frequently comes to the fore. The muffler illustrated can significantly reduce this noise. One challenge faced during development is the limited build space available, and this is where the highly integrative approach of additive manufacturing really demonstrates its advantages. Another application area is the integration of mufflers in valve housings or other sound-radiating structures.

Integrated particle damping through AM

Many technical systems exhibit unwelcome vibration that needs to be dampened. The use of (powder-bed-based) additive manufacturing enables the depositing of powder in cavities in the high vibration amplitude ranges, achieving targeted damping of the component. Classic particle dampers typically need to be fitted manually to the exterior or integrated in the component. Integrated particle damping dispenses with this effort, and areas to which classic dampers have no access can also be dampened. Research at Fraunhofer IAPT is investigating the degree to which the principle of integrated particle damping can be exploited for a variety of technical applications.

One example of such a technical application is illustrated in the section view of the crankshaft in Fig. 3. This contains several cavities in its flywheel masses that are filled with powder, effectively damping vibration caused by combustion impulses and irregular combustion. This facilitates the use of smaller flywheel masses, permitting a more compact design of the entire engine.



➜ *Fig. 3: Additively manufactured crankshaft (section) with integrated particle dampers (the transparent illustration is the front flywheel mass)*

Funded by the Fraunhofer-Gesellschaft in the “Light Materials 4 Mobility – LM4M” project.

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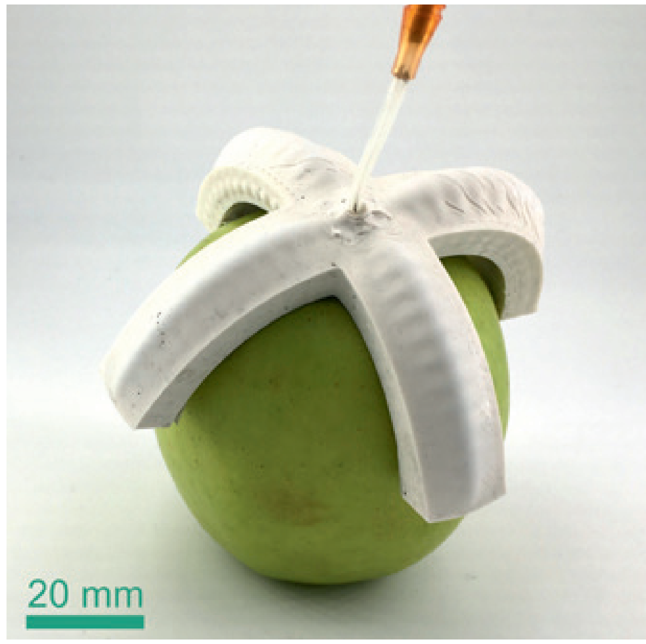
ROBOTS FROM THE SILICONE PRINTER

Soft robotics is a rapidly developing field of science and engineering that can be viewed as more an extension of than competition for classic hard robotics. Soft robots can interact safely with people and their surroundings, adapt well to different objects, and are characterized by low weight and reduced energy consumption. However, full exploitation of the potential of soft machines has until now been hindered by a lack of suitable manufacturing processes. 3D silicone printing now enables the cost-effective production of complex pneumatically powered structures, individually and without additional tools.

The design of soft robots is frequently based on natural systems without hard internal skeletons (e.g. squid, jellyfish, or worms). Their specific characteristics enable a broad spectrum of new applications. In medical applications, rehabilitation and assistance systems such as prostheses can be realized much more flexibly through soft robotics, making them more compatible with and tolerable for patients. Other application areas are in the gripping and manipulation of unfamiliar and/or fragile objects and human–machine interfaces (e.g. soft exoskeletons).

Soft robotic systems that are produced using 3D silicone printing and pneumatically powered are developed at Fraunhofer IAPT. One example of a system of this kind is the soft universal gripper illustrated in Fig. 1, which can gently hold objects of different shapes. Grippers of this kind are employed in logistics and the handling of food items. 3D printing enables the achievement of a high degree of individualization and cost-effective manufacturing of order quantities as low as one.



➜ ***Fig. 1:*** *Additively manufactured soft universal gripper holding an apple (in cooperation with Lynxter, France) (Lynxter SAS, France)*

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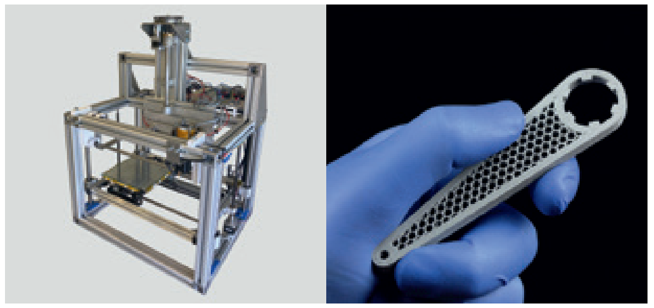
GRANULATE-BASED METAL 3D PRINTING FOR THE MIM INDUSTRY

The starting material processed in metal injection molding (MIM), the so-called feedstock, consists of plastic granules with a high metallic filler content (>50% by volume). This feedstock is formed into green parts through injection molding, following which it is successively freed of its polymer components (binder system) and, finally, sintered to create dense metallic components. As an injection mold is required for component manufacturing, MIM is primarily suitable for larger quantities.

Direct processing of these feedstock systems through 3D printing for the profitable manufacture of functional prototypes, spare parts, or small series of functional components is currently only possible through screw-type material extrusion (fused granular fabrication – FGF). The disadvantage of this process is the expensive system technology required when compared to filament-based material extrusion (fused filament fabrication – FFF). Plant costs for FGF systems are more expensive by approximately a factor of ten. In contrast, system technology for FFF, the most widespread 3D printing process, is considerably more cost-effective, but processing of MIM feedstock systems is not possible without adaption of the binder system in the feedstock. This, in turn, is necessary to produce the stringy semi-finished products required for the FFF process, the filaments. A plant system based on cost-effective FFF system technology that can, however, process granular MIM feedstock systems is the goal of the ZIM cooperation project SinTiM (funding ref.: ZF4547817DE8). ZIM is the Central Innovation Program for SMEs of the German Federal Ministry for Economic Affairs and Energy. A plant system was developed during this research project with a functional structure based on a commercially available FFF printer and, consequently, is also in a similar price range (€5,000–10,000). Furthermore, the system was designed to also process coarser pelletized commercial MIM feedstock systems without difficulty. This enables further processing of additively manufactured green parts using the same process chain as injection molded green parts, meaning major savings potentials can be exploited for applications such as the production of functional prototypes. Piston-based material extrusion (piston-based feedstock fabrication – PFF) was selected for this purpose instead of screw-type extrusion.



➜ ***Fig. 1:*** *System for piston-based feedstock extrusion and functional demonstrator (Element 22 GmbH)*

The PFF system has already been successfully validated for a titanium feedstock in cooperation with our partner, Element 22 GmbH. The resulting material properties have already achieved target market standards and are comparable with MIM, even exceeding it with regard to the achievable ductility.

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TAILORED ALUMINUM ALLOYS FOR ADDITIVE MANUFACTURING

Use of aluminum alloys – ideal for lightweight construction

A hitherto limited selection of materials and the great potential for tailored application solutions make specialized aluminum alloys one of the most significant areas of research at Fraunhofer IAPT in material and process development.

Aluminum alloys are used in all major industrial sectors, including the automotive industry and shipbuilding, construction, and machine and plant engineering. Combined with AM topology optimization options, the low density and associated high level of suitability for lightweight components make aluminum an ideal material for the majority of weight-optimized components.

However, rapid development and the growing importance of additive manufacturing in industry is, unfortunately, being inhibited by a comparatively limited material spectrum. The development of new alloys is an essential prerequisite for significant expansion of the application area for laser additive manufacturing. In addition to numerous advantages, obstacles also need to be overcome in the development of new aluminum alloys. For example, poor weldability and an instable process are frequent criticisms aimed at high-strength variants.
A variety of methods and concepts are being implemented at Fraunhofer IAPT to overcome process-related obstacles.

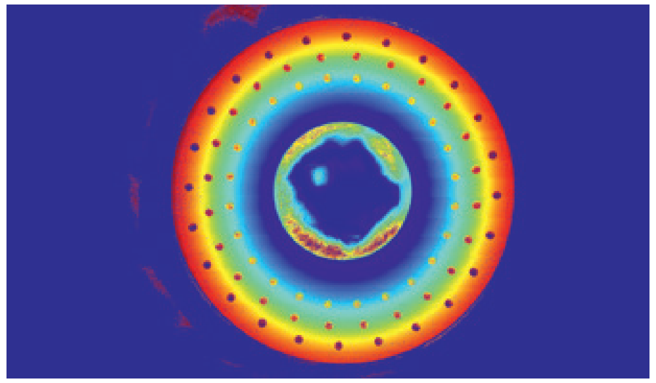
Alternative system technology for processing high-strength AlMg alloys

High-strength aluminum alloys are often reliant on rare and expensive alloy elements such as scandium. In addition to enhanced performance, this also increases the price. Conversely, aluminum-magnesium alloys exhibit very good mechanical properties while dispensing with exotic alloy components, which is why they represent an interesting alternative.

An alternative beam profile was used at Fraunhofer IAPT to enable processing of this sophisticated alloy which, when used in the additive manufacturing process, tends to be associated with hot cracking and the formation of pores. While the energy input where a conventional Gaussian beam profile is used is concentrated in the middle and exhibits a heterogeneous distribution, the focus of the energy input was homogenized where an M-profile was used.

This measure effectively reduces the combustion of certain alloy elements (magnesium in this case) and, consequently, smoldering in the process, significantly enhancing process stability. A clear increase in process speed was also achieved during these trials. As a consequence, this alloy, which is also used in sand casting and, for example, for Olympic sailing dinghies, was successfully used in the additive process.

Hybrid production – high-strength AM aluminum alloys and sensor-based hybrid production



→ ***Fig. 1:*** *Brake disc elevation profile recorded by OCT sensor*

During the LHASA project (Laser additive production of high-strength aluminum structures, funding reference: 16KN021234), PLM 905, a heat-resistant, naturally hard aluminum material that is an improvement on AA2618, and PLM 432neo, a hypereutectic piston alloy with optimized properties when compared to AA4032, were two alloys that qualified for the LB-PBF process. Both alloys exhibited a tensile strength of 450–550 Mpa in this context.

Qualification occurred on demonstrators from the automotive sector for a valve spring retainer and brake disc. The brake disc here was generated as a hybrid construction consisting of a conventional base and an upper part produced through laser additive manufacturing. This enabled the achievement of an interior aeration structure through a cost-saving process. The position of the conventionally manufactured semi-finished product must be recorded to ensure a precision fit transition. An OCT sensor was developed for this purpose, the output of which is depicted as an elevation profile in Fig. 1. The aim of using hybrid manufacturing methods is, among other things, to enhance efficiency. Conventionally manufactured semifinished products will continue to be used in this context to reduce costs and increase the process speed.

Outlook – the future of aluminum alloys in additive manufacturing

In addition to achieving high-strength or highly ductile properties through modification of the chemical composition, an approach is currently being pursued in the context of a German Research Foundation (DFG) project that strengthens the material structure with ceramic particles within a metal matrix composite bond. With regard to additive manufacturing processes, aluminum-based materials will play an increasing role in the LB-PBF area to close the requirement gap between expensive lightweight construction alloys such as Ti64 or AlSc and a normal AlSi10Mg casting alloy even further.

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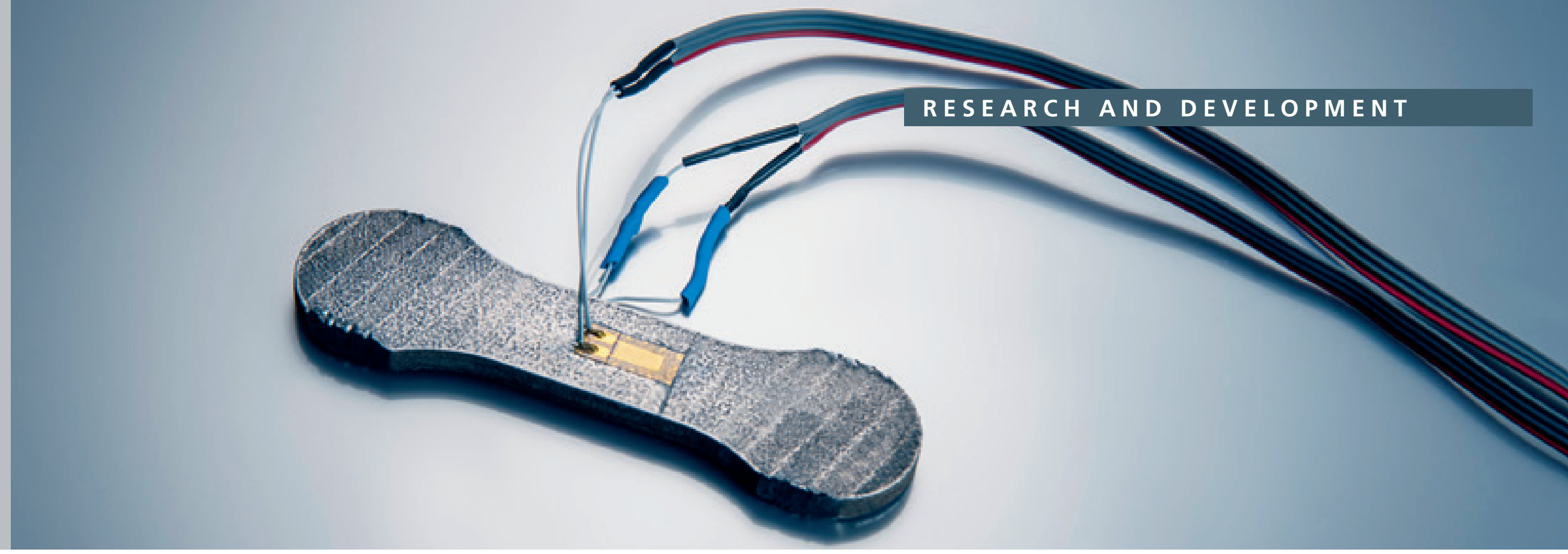
ENHANCED ADDED VALUE IN POWDER BED PROCESSES



HIGHER COMPONENT QUALITY THROUGH INTELLIGENT SCAN STRATEGIES

New materials allow the potential of additive manufacturing to be fully developed

In many cases, innovative new production processes are initially evaluated in a comparison with established materials, simply because these are well researched and, accordingly, deviations from typical behavior can be well classified. Nevertheless, alloys specially developed for a particular application or manufacturing process offer enormous potential for enhanced added value. When compared to alloys once developed for conventional processes, new alloys of this kind specifically developed for the laser beam melting process offer the advantage of an optimum combination of properties for the application case and, simultaneously, reliable and high-quality processing of the material.

This concept has successfully been implemented in the past at Fraunhofer IAPT for both the automotive industry and aerospace. Fraunhofer IAPT is currently examining a new alloy model of a Ti/Nb/Ta alloy developed by its partner TANIOBIS GmbH fur use in medical engineering. The goal of alloy development is to achieve an approximation of the elasticity of an orthopedic implant to the elasticity module of human bone, thus preventing receding of the bone around the implant through what is known as stress shielding. Simultaneously, alloy components (which, unlike cobalt and chromium, are not toxic) encourage bone cell growth on the implant.

Productivity and costs – the path to industrialization of LBM

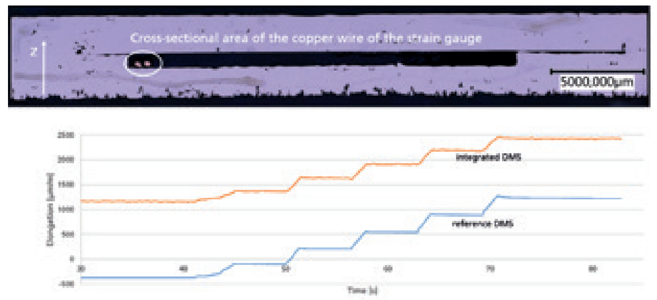
New alloys for additive manufacturing, individual value chains and innovative solutions can address the growing customer requirements, which are increasing in complexity, and generate new products, but use of these products in business is still the exception rather than the norm. One primary reason for this is the still comparatively high production costs associated with additive manufacturing. As with additive serial production, it is once again evident that, if further industrialization of additive manufacturing is to be pursued, one crucial task is to reduce production costs. The greatest instrument for lowering costs during laser beam melting is to be found during phases of exposure to the laser beam (or laser beams). Fraunhofer IAPT is currently investigating different aspects of the process in order to broaden the process limits. Fundamental physical influences of process parameters on melt pool formation are being examined in this context. These findings are used to create concepts for new process control that further optimize the productivity of the process.

Additive manufacturing as part of a value chain

However, for a long time now, the actual production process has no longer been the sole constituent in the value chain of additively manufactured components. The question of how to best integrate additive manufacturing processes in the entire value chain plays an increasingly significant role. In addition to investigating appropriate surface post-processing methods, Fraunhofer IAPT develops concepts and solutions that demonstrate how the creative freedom of additive manufacturing can be exploited to enable the realization of downstream processes in the value chain as efficiently as possible. With this in mind, Fraunhofer IAPT is working, in the context of a project from the German Federal Ministry of Education and Research (BMBF), on a hybrid implant consisting of an additively manufactured titanium component and a ceramic component joined by glass solder. The focus here is on the design of the connecting surface and its surface quality, the objective being automated application of the glass solder directly after additive manufacturing.

Intelligent LBM components as key elements of Industry 4.0

Laser beam melting provides engineers with new options for integrating additional functionalities in complex geometries. The layered build-up in the process enables modification and manipulation of almost every area of the component. This is why integration of sensors in the component during the manufacturing process is possible. This approach is of major industrial interest, as embedded sensors can be inserted directly into the areas in which a measurement value is required. Intelligent components can then monitor their own conditions and critical changes can, for example, be recorded through statistical evaluations. This enables proactive maintenance of additively manufactured components. Investigations at Fraunhofer IAPT in cooperation with MAS Tooling GmbH indicate that monitoring of component conditions of this kind can be realized according to individual requirements of industry. A tensile test specimen with an embedded strain gage and its cross-sectional area is illustrated in Fig. 1. The position of the embedded sensor is only accessible during the manufacturing process in the positive z-direction during a brief interruption. The elastic deformation recorded by the strain gage integrated in the LBM process exhibits a good correlation with the reference strain gage fitted to the exterior. The findings are transferred to a demonstrator tool in the next step. The integrated sensor will transmit measurement data in real time to a controller and provide the user with information on the operating status.



➜ ***Fig. 1:*** *Tensile specimen cross-sectional area. Below: Measured strains over the duration of the tensile test.*

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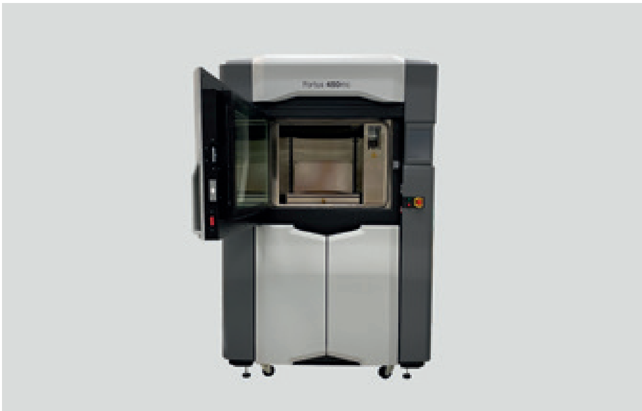
EXTRUSION-BASED POLYMER AM PROCESSES

POLYMER-BASED MATERIAL EXTRUSION

Material extrusion with stringy plastic filaments is the most widespread additive manufacturing technology on the market. Smaller and very inexpensive consumer devices are frequently included as part of this. The designation of the process they employ is predominantly described as fused filament fabrication (FFF), an unrestricted term. FFF printers are frequently used for prototype production, and the manufacture of tooling fixtures and components employed for private use. A major cost advantage of these devices is to be found in the, in part, free choice with regard to the required slicing software for component preparation and procurement of starting materials (filaments) from third-party providers. However, when it comes to the industrial production of functional components, these plant systems frequently lack the required reproducibility of component properties, particularly in the case of high-temperature plastics. Among other reasons, this can be traced back to a high level of potential user interaction, such as a change of process parameters in the slicing software. For this reason, production systems have become established in industries such as aerospace and rail vehicle manufacturing that, from the material and slicing software to the 3D printer, are fully coordinated in every respect.

In order to exploit new application areas and research continuous digital and physical process chains for industrial material extrusion, an FDM production system was successfully commissioned in the middle of the year at Fraunhofer IAPT in the form of the Fortus 450mc from Stratasys. One focus of research in this respect is the optimization of existing sub-process steps relating to the production system. In particular, physical post-processing in conjunction with digital networking within the overall process chain is the focus of research work in the area of industrial material extrusion.



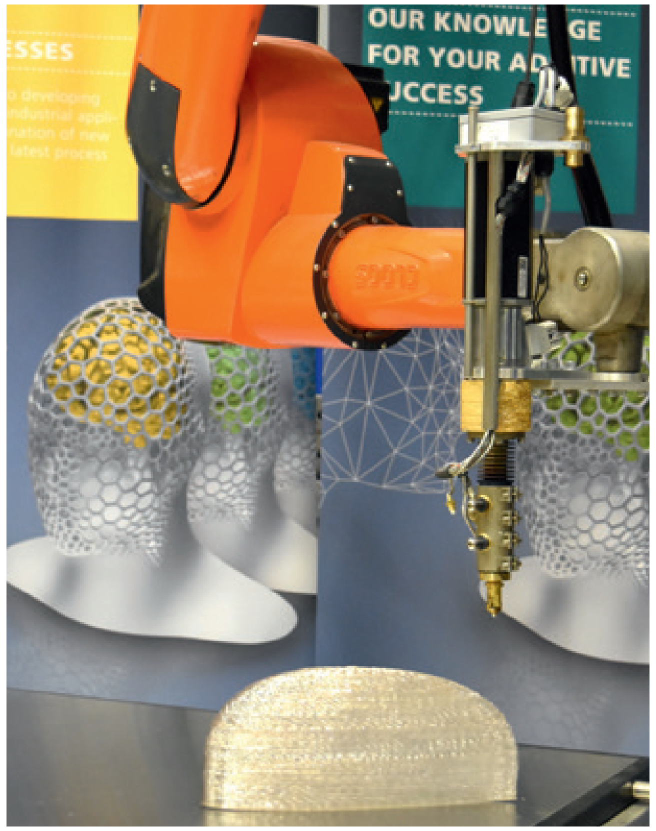
➜ ***Fig. 1:*** *FDM production system (Stratasys Fortus 450mc)*

One further research focus is the development of stable and robust processes for filament-based material extrusion in conjunction with conventional industrial robots. A system was implemented for this purpose at the beginning of the year that can realize build rates of up to 1 kg/hour through screw-type extrusion. Both costs and time are saved during the manufacture of components with a large volume through the use of robot systems and screw extruders with high feed rates. Moreover, this technology and its many levels of freedom enable the production of complex freeform surfaces.

One of the potential application areas is the maritime sector. With this in mind, Fraunhofer IAPT developed process parameters last year to create a demonstrator of a component for improving propulsion for shipping. Individualized components with complex freeform surfaces can be produced through this additive manufacturing process, enabling reduction of the propulsion requirement of a vessel and thus saving fuel.

Current challenges faced by this technology include stabilizing the extrusion process, the elimination of process errors, and securing quality in economic terms. High expenditure of time and money should be planned in the case of conventional downstream test methods for checking dimensional accuracy and fault detection. In particular, automation of quality assurance is currently not economically feasible in the case of individualized products.

Future research projects at Fraunhofer IAPT will endeavor to find a solution to these problems. Digitized online quality control is a significant component in this respect. A sensor system will be developed for this purpose with which the geometric data of the component can be recorded independent of direction during the process. These data records will be used to provide the user with information on process and component quality. Targeted readjustment can correct process errors in this manner, layer by layer. This sensor system stabilizes the process, and fewer process interruptions are to be expected.



➜ ***Fig. 2:*** *Robot-based screw-type extrusion*

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SLS QUENCH BOX

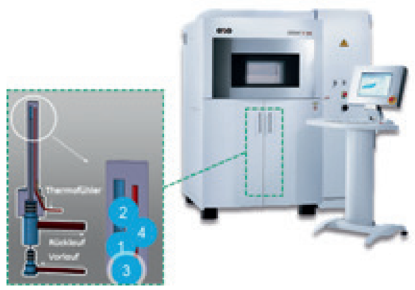
SLS QUENCH BOX – ACTIVE COOLING IN THE SLS BUILD CONTAINER

Selective laser sintering (SLS) is one of the most widespread additive manufacturing processes for producing industrially relevant prototypes and small series components. The powder-bed-based process permits the manufacture of components from thermoplastics with the highest level of design freedom. Plastic powder valued at approx. €290 million is processed annually all over the world for this purpose. On its own, the manufacturer EOS operates around 1,000 SLS systems on a global level.

One weak point of this process is aging of the powder under process conditions. This results in surplus production of used powder that is estimated to amount to a waste powder volume of 30 percent per build job. In addition, time-consuming cooling of the powder cake means that components are not available in less than three days, which, when compared to other processes, is a very long period.

In "Homogeneous cooling", a cooperative project with the Central Innovation Program for SMEs (ZIM) (funding reference: 16KN073020), active cooling of the powder cake during the SLS process using cooling lances is being investigated in collaboration with Stemke Cooling Systems GmbH. Furthermore, the SLS quench box is being created as a prototype of a typical practical build container with integrated cooling lances, and this will serve as a precursor of a product suitable for series production on the market.

The mode of operation of the cooling principle has already been successfully tested at Fraunhofer IAPT with an experimental cooling lance. It is evident that the cooling principle is effective, material properties are not adversely affected, and component distortion is only marginally impacted by the active cooling involved. If the refreshing rate of an SLS powder can be reduced from 40 to 20 percent, extensive use of the SLS quench box can, on a global level, mean material cost savings of €145 million. Moreover, reducing powder waste by two-thirds contributes significantly to the sustainability of the process and AM technology in general. Component availability was shortened from three to two days as of the beginning of production.



➜ ***Fig. 1:*** *Cooling principle: temperature-controlled cooling lances in the build container of a commercial EOS P390 rapidly cool the powder cake (EOS)*

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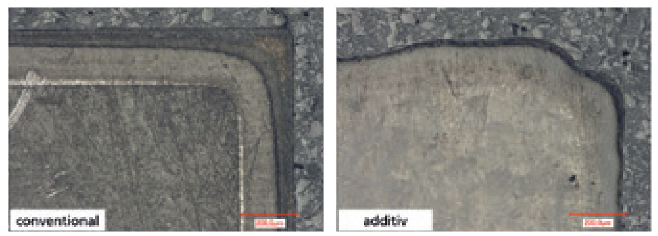
HYBRID ADDITIVE MANUFACTURING

ENHANCEMENT OF ADDITIVELY MANUFACTURED STEEL PARTS THROUGH SURFACE AND HEAT TREATMENT

Enhancement of additively manufactured steel components is realized in the AddRand project through effective surface and heat treatment. It primarily addresses manufacturers of tools, machine components, and spare parts with complex geometries in single-batch and small series and associated companies involved in heat treatment and surface hardening.

Preliminary investigations have shown that established surface hardening processes such as nitriding achieve poorer results in the case of laser beam melting (LBM) components when compared to conventional process routes (see Fig. 2). It became clear that the thickness of the surface layer in the case of additively manufactured components is considerably reduced and not as pronounced (dark coloration). The main objective in this project is to increase wear resistance and, simultaneously, reduce residual stress. The entire component manufacturing process chain is taken into consideration and adapted to increase surface hardness by >50 percent and reduce the process time for heat treatment and the nitriding processes by 20 percent. The improved properties mean that additively manufactured components can also be used for applications involving higher levels of stress. Furthermore, the cost savings potential is indicated by a significant shortening of the process route.

Process parameters were first developed in the project for the laser beam melting process. The years of know-how gained by Fraunhofer IAPT in the area of process development ensured that effective process parameters were quickly developed in the project and the project partner could be provided with test specimens for the nitriding processes. The project partner (Fraunhofer IST) has many years of expertise in the area of surface post-processing and, consequently, can rapidly adapt parameters in a targeted manner for each material. Processing and subsequent surface post-processing of the additively manufactured components are being investigated in the project using a common maraging steel (1.2709), a hot working tool steel (1.2343), and a nitriding steel (1.8550). All the steels were easy to process in the laser beam melting process, whereby the core objective was the identification of appropriate parameters with regard to high density and a simultaneously high build rate. Both of these goals were achieved, meaning Fraunhofer IAPT has enlarged its material portfolio and is now able to offer its customers processing of further alloys. The next step involves Fraunhofer IST investigating different nitriding processes based on the components generated where, in addition to achieving the mechanical targets, a consideration of economic viability is also very much in the foreground.



➜ ***Fig. 2:*** *Results of preliminary trials without specific adaptations of nitriding processes*

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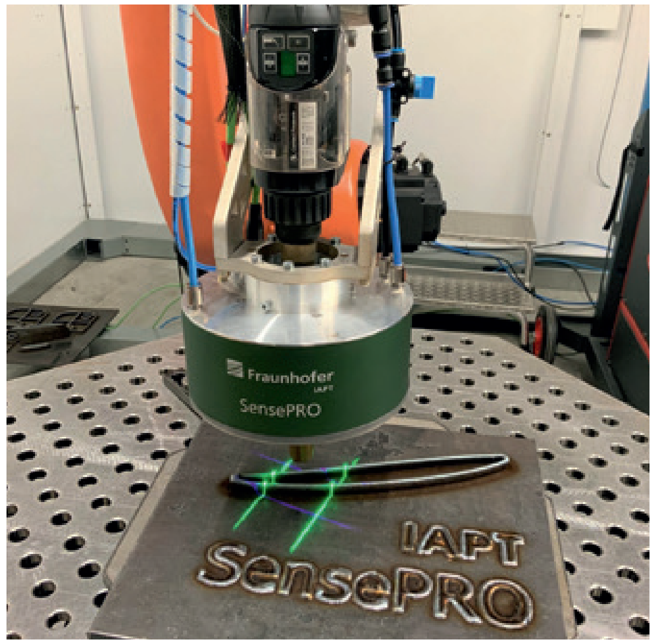
SENSEPRO – SENSORS FOR CLADDING

SENSEPRO SENSORS FOR IN-PROCESS QUALITY ASSURANCE DURING CLADDING

Due to its high build rates, cladding is considered to possess great potential for additive manufacturing. This group of directed energy deposition (DED) technologies includes laser material deposition and wire arc additive manufacturing, but their successful industrialization is currently thwarted by unstable processes and an absence of quality assurance. Recourse to classic automation technology in this respect only offers limited relief.



➜ ***Fig. 1:*** *SensePRO on cladding optics*

For this reason, the modular direction-independent SensePRO sensor system was developed at Fraunhofer IAPT for cladding processes in the context of an EXIST research transfer project. It enables the creation of a layer-by-layer geometric digital image of the deposited structures based on the triangulation principle. With the aid of this continuous component digitization, users can, for the first time, obtain geometric insights into their components without taking a further process step. This makes it possible to detect faults relating to layer thickness or position during the process and stabilize the process through integrated DED control. When compared to conventional, direction-dependent triangulation sensors, the SensePRO system and its direction-independent 360° laser field that enables all-round sensor visibility keeps the motional flexibility of the process in view, thus avoiding costly downtimes for separate scan procedures.

Even harsh process conditions that can be encountered during cladding are unable to impair SensePRO. Thanks to its integrated additively manufactured cooling design, it also offers a calibrated accuracy level under these conditions. The sensor system also demonstrated its strengths in this respect during extensive trials under process conditions. That laid the cornerstone for productive use in a high-temperature wire arc additive manufacturing process.

The sensor can be integrated into a variety of commercial systems to suit customer specifications and employed for different welding processes.

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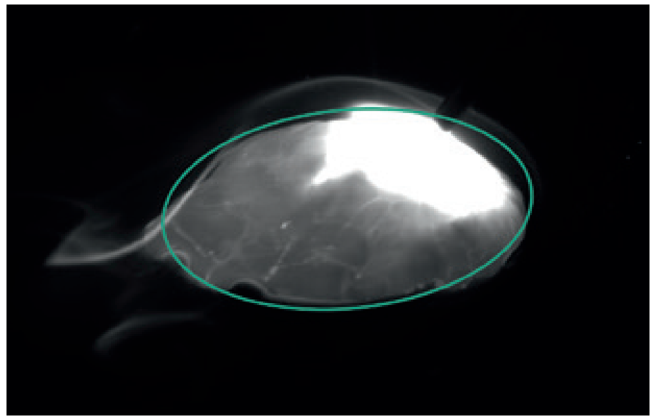
SENSELIGHT

OPTICAL IN-PROCESS SENSORS FOR WIRE ARC ADDITIVE MANUFACTURING



➜ ***Fig. 1:*** *SenseLight-based in-situ melt pool monitoring with detected ellipse contour*

2020 saw functional and optimized component contours being realized through both established additive powder bed processes and deposition processes. One of these processes, wire arc additive manufacturing (WAAM), draws on the simple principles of the arc welding process, where an electric arc generated by the power supply is used to melt a wire-shaped starting material. A metallic near net shape contour is created in the shortest possible time with this principle, layer by layer and at high deposition rates. As a result, the WAAM process is growing in relevance in a variety of industrial areas.

This development is slowed by process-related instabilities, particularly in three-dimensional use for producing components, due to complex temperature correlations and slight fluctuations in parameters that already exist (e.g. shielding gas supply or working distance of wire from the workpiece surfaces). These fluctuations come to the fore in two central features during the process, namely discontinuity of melt pool geometry and fluctuation in the melt pool temperature. There are currently no established process monitoring solutions on the market that can identify and take countermeasures against these instabilities.

Fraunhofer IAPT developed the SenseLight sensor system for this purpose. The sensor system offers direction-independent evaluation of the melt pool, a compact design, and use of inexpensive electronic components for an efficient overall system. SenseLight exploits the explicit lighting of the melt, subsequent filtering out of other process emissions, and the depiction of the melt with an area scanning camera to detect the melt pool. The additional detection capacity for relative temperature fluctuations in the melt pool based on optical signals enables all-round real-time monitoring of the stability of the WAAM process. A further special feature of SenseLight is the option for coupling in optical beam paths and, consequently, monitoring the melt pool in a laser-based process. This means it is possible to use it in a WAAM process and, also, welding and deposition processes of the same or related types.

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ADDITIVE MOBILE FACTORY

LOCATION-INDEPENDENT SPARE PARTS PRODUCTION AND REPAIR THROUGH MOBILE AM CONTAINER SOLUTION

Additive manufacturing (AM) processes play a crucial role in the reliable and speedy supply of spare parts. Spare parts can be produced directly and as required through AM without special costs for tools or storage. The concept of the Additive Mobile Factory (AMF) goes a step further and enables decentralized and resilient spare parts supply and component repair as a container-based production unit. This means that spare parts requirements can be met in remote and inaccessible locations. This approach reduces costly downtimes to a minimum, detached from long production and supply chains.

Additive production technology for building close-to-final-contour component geometries is at the core of the Additive Mobile Factory. However, to avoid only making blanks, the following processing steps that automatically bring the component to the final dimensions and enable the desired functionality are integrated. Integration of the entire physical and digital process chain in a space-saving, standardized freight container enables simple location-independent operation (plug and play). Wire-based cladding processes in particular harbor a great deal of potential when it comes to mobile additive manufacturing. Wire as a base material is available more cheaply than powder, and its handling is safe for the operator and the environment. Both complete spare parts production and mobile repair of existing components can therefore be realized. When combined with robot-based handling, a flexible, robust, and cost-effective system solution is created. By linking with the DED Process Manager software solution developed by Fraunhofer IAPT, the container can be operated without any expert knowledge, thus enabling reliable on-site use. The compact version of the AMF illustrated shows an automated hybrid process chain taking up a minimum of space in a 10-foot sea container. A robot takes care of component handling, meaning all process steps can be realized on the respective fixed processing stations. Flexible repair or production primarily of small to medium-sized steel or aluminum components is therefore possible. The peripheral and control technology required for the process is located outside the production cell in a separate supply unit and serves to demonstrate the modular concept. Depending on the application involved, standardized 10-, 20-, or 40-foot containers are individually equipped with the process chain.

The concept shown is modular in its organization, facilitating individual customer configuration. Building on the indicated results and potential of the integrated hybrid process chain, it is possible to address different application cases and challenges in a targeted manner. In close cooperation with industrial partners, AMF enables the development of new and innovative solutions for spare parts production and component repair, both on-site and on request.

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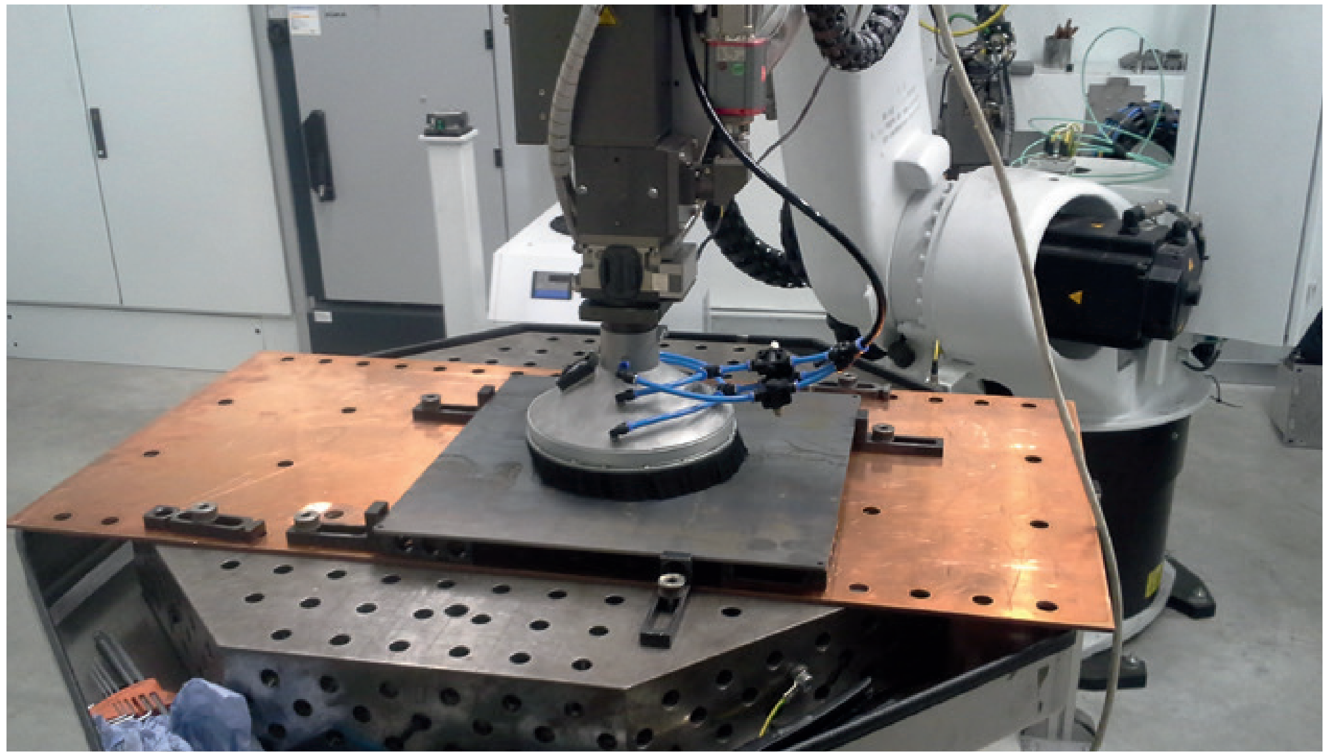
LARGE TITANIUM STRUCTURES FOR AVIATION

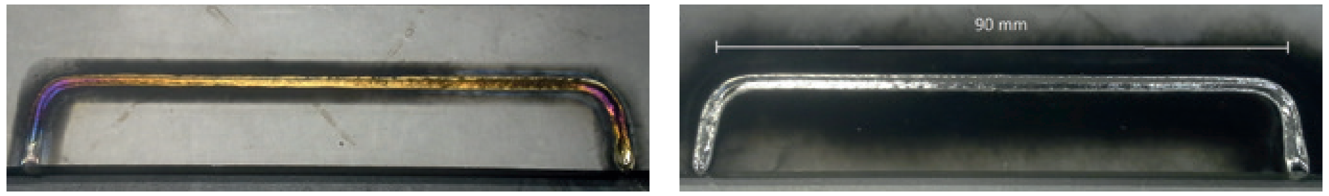
LASER BEAM FUSION OF 3D-PRINTED TITANIUM COMPONENTS – FREE OF OXIDATION AND AVIATION-COMPLIANT



➜ ***Fig. 1:*** *Shielding gas bell on standard laser welding optic*

In the REGIS project (realization of additively manufactured integral structures), processes for large-scale 3D-printed structural components made of Ti-6Al-4V for the aerospace industry are developed with the affiliated partners Airbus, Gefertec, bias, Premium Aerotec, IWT, and TUHH. The limited build space sizes of commercially available 3D printers means that large structures cannot be printed as a single component. For this reason, part geometries are produced in this project in a shielding gas chamber using the directed energy deposition (DED) process of wire arc additive manufacturing and then joined by laser beam welding to create a final large structure (approx. 2.5 × 1.5 × 0.4 meters) for use in aircraft construction. Following machining, a total of approximately 28 individual parts are joined by laser welding to create a large structure.

Regardless of the welding process involved, welding of titanium is highly demanding when it comes to the shielding gas cover of the joint zone, which is why work generally must be realized in costly shielding gas chambers. Due to the component size described, this technique is only used to a limited degree for economic reasons (e.g. shielding gas volume). For this reason, Fraunhofer IAPT developed a locally acting shielding gas bell that can be fitted to a standard welding optic. This system permits the realization of laser welding joins on titanium components in a local shielding gas atmosphere, completely free of discoloration and aviation-compliant. In contrast to already familiar and tested drag nozzles that are only designed for one welding direction, this shielding gas bell permits completely direction-independent and, consequently, more productive operation for creating welds on level components.



➜ ***Fig. 2:*** *Plan view of a weld in Ti64 with inadequate shielding gas cover (left) and with local shielding gas cover (right)*

With regard to the planned application, joins between printed Ti-6Al-4V components and, also, hybrid connections between printed and conventional materials were investigated. Micro-hardness measurements in the cross-sectional area of the welds proved that, when compared to the surrounding base material, no increase in hardness occurred in the melt zone. Furthermore, tensile tests also proved that the welded joints created with the involvement of a printed joint partner were comparable with welds on conventional material in terms of their strength and elongation at break. This provided the basis for producing a complex integral structure consisting of printed elements welded with standard semifinished products (sheets, angles, tubes), wherever technically appropriate, to create an overall structure.

Initial cost estimates for the planned demonstrator component, the interior reinforcement of the aircraft outer skin in the vicinity of the two emergency exits, give reason to anticipate a reduction in manufacturing costs of approx. 50 percent. This is achieved through resource-conserving usage of the raw material (close-to-final-contour DED printing process and, consequently, a significant reduction in the titanium machining volume) and use of standard semifinished products.

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MOBILE MOLD REPAIR THROUGH CLADDING

COMPACT LASER WIRE CLADDING SYSTEM FOR MOBILE REPAIR OF LARGE MOLDS

Casting and forming tools form the basis of highly productive metal and plastic component manufacturing at one-second intervals. Heavy usage coupled with material fatigue and incorrect use leads to defects in these tools in the long term that require complex and expensive repair. Currently, these repairs are either carried out manually through TIG arc welding or with enormous effort in separate processing stations. As complex dismantling is necessary for this purpose, and the manual welding process damages the component due to high local heat input, there is an urgent need for an efficient repair process. Fraunhofer IAPT and its partner LMB Automation GmbH have set themselves the goal of making these repairs possible directly on-site with the aid of a mobile laser wire cladding system.

The laser wire cladding process opens up the possibility of automated and reproducible repair. The material to be deposited is fed into the process in wire form and melted directly at the defect. As the process is normally realized in fixed plant installations, the tools need to be first removed, transported, and centrally repaired. The complex handling of the molds and longer downtimes mean that the savings potential of the repair process cannot currently be exploited to the full.

As an efficient and sustainable counterweight to these challenges, a flexible and mobile processing unit will be developed that permits an on-site repair process to be realized directly on the tool. In contrast to deposition welding systems available on the market, particular attention will be dedicated to the compactness and mobility of the system. Thanks to an innovative new gimbal that keeps the processing optics level, removal of the damaged tool is no longer necessary, and machine downtimes are minimized.

Control of the newly developed seven-axes machining system is based on the robot operating system (ROS). Three-dimensional monitoring of the process zone is possible, thanks to an integrated stereo camera system. The link to the 3D head-mounted display allows the user to observe the process at a safe distance while enjoying ideal ergonomics. The intuitive human-machine interface thus enables both manual and semiautomated control of the laser wire process. The system is designed for medium-term transfer to 5G remote processing. This will save travel expenses, and repairs can be offered at a more attractive rate.

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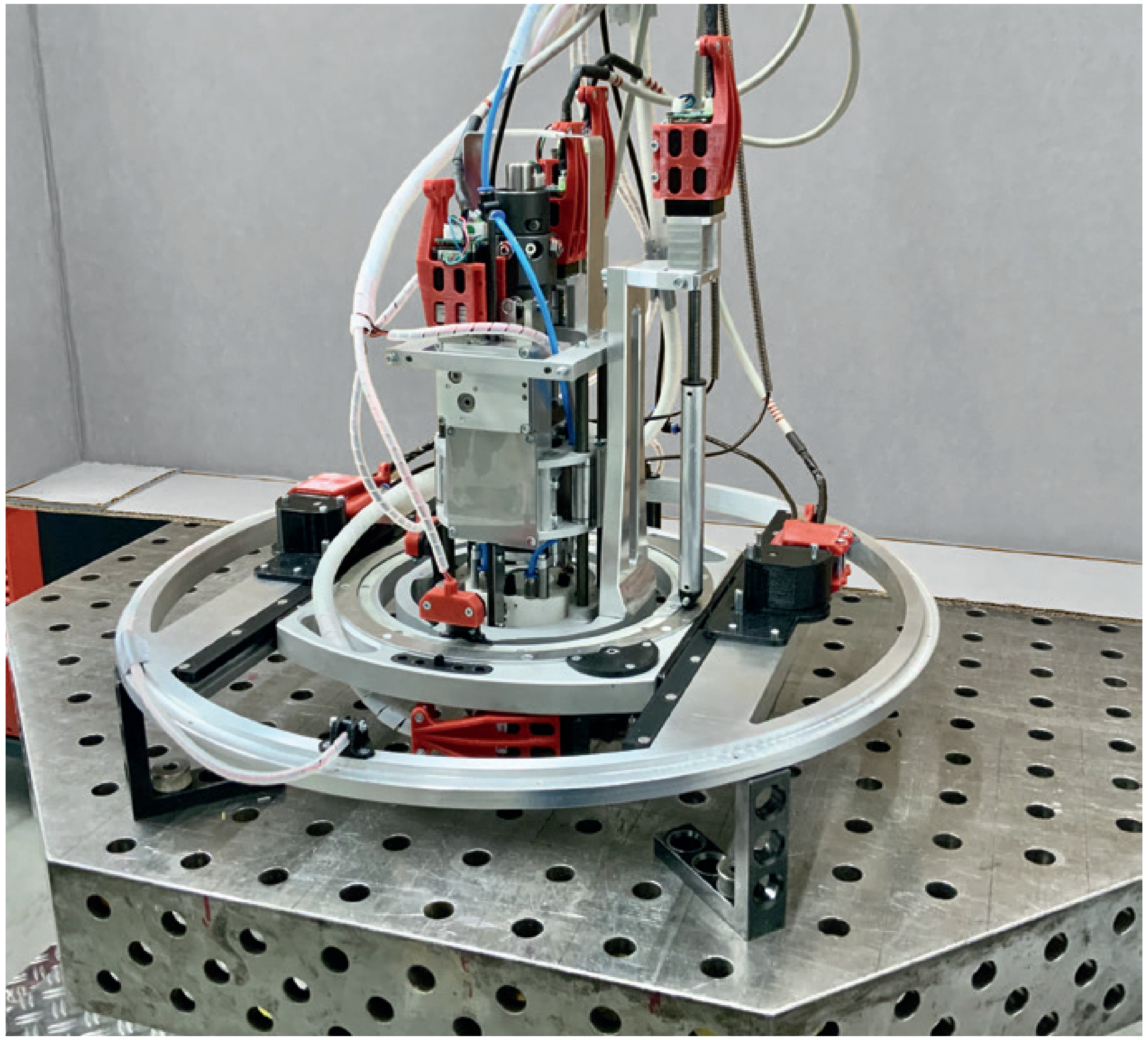


➜ ***Fig. 1:*** *Current development state of a flexible laser wire cladding system as a mobile five-axes processing unit*

PUBLICATIONS AND TEACHING

STUDIES ON REWORKING ADDITIVELY MANUFACTURED COMPONENTS

Reworking as the key to successful additive manufacturing

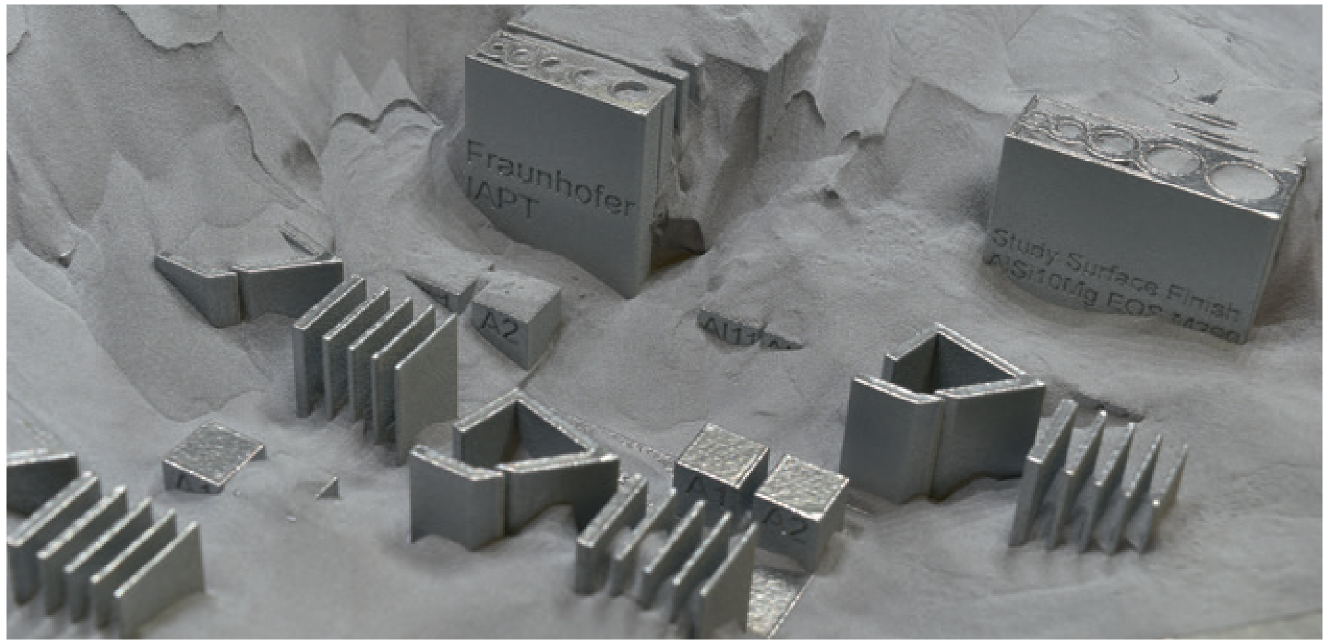
Complexity for free – an additive manufacturing promise that represents one of the greatest challenges for reworking of AM components. This applies all the more as surface treatment and, indeed, the manufacturing process itself have a significant effect on the quality of the finished part. Only those who know the advantages and disadvantages of the numerous processing methods with regard to their application to AM components can use this information in a targeted manner, taking it into consideration during component design. In addition to achievable surface qualities or efficiency, the effects on mechanical properties also play a decisive role in this context. For this reason, Fraunhofer IAPT has conducted several studies to investigate reworking of complex AM components in particular, and it provides application-oriented decision-making assistance to further promote the industrialization of additive manufacturing.

Challenges during reworking of additively manufactured components

In contrast to conventional manufacturing, undercuts or internal channel courses pose fewer problems in the additive manufacturing generation process, generally not limiting component design, or only insignificantly. However, other technical hurdles need to be overcome if these advantages are to be exploited. Component surface quality requirements are frequently high where, for example, components need to exhibit fatigue strength. The rule here is: the more complex the components, the greater the expectations of subsequent post-processing steps. Material-removing media can sometimes only partially follow the complex course of AM designs, and correct processes need to be selected for efficient and successful surface improvement. In addition to the challenges involved in the accessibility and flexibility of reworking, it should be noted that AM components frequently exhibit an extremely heterogeneous surface quality in the as-built state. Dependencies on staircase effects, local geometry-dependent heat distribution and dissipation, and the use of support structures lead to numerous different surface conditions following the printing process. Achieving optimum smoothing of the components or freeing them of support structures therefore requires an individual and component-specific reworking solution, which can consist of a combination of several processes.

The Fraunhofer IAPT solution for selecting suitable reworking processes for AM components

But what technical options does the market currently offer, and what costs are concealed behind individual processes? Fraunhofer IAPT has now answered these questions in an independent and comprehensive study of the issue of surface smoothing of AM components. The **Surface Benchmark Study** examines eight different processes of market relevance to ascertain their reworking suitability for AM-specific challenges. Part of the investigations involved chemical and electrochemical polishing, abrasive and compressed blasting, vibration finishing, and special procedures such as isotropic superfinishing, metal DryLyte, and the micro-machining process. The established Ti64, AlSi10Mg, and 1.4404 (316L) alloys were selected to enable determination of material-specific



➜ ***Fig. 1:*** *Specimens for the Surface Benchmark Study*

differences. In addition to surface roughness, the penetration depth, edge rounding, erosion rate, hardness, legibility of markings, and reworking costs were investigated in detail to obtain a meaningful comparison of the strengths and weaknesses of different post-processing methods.

Three different demonstrators were developed especially for this study. These offered numerous geometric functions, based on which reworking results were quantified. In all, more than 100 components were printed and analyzed, approximately 17,000 segment measurements taken, and over 700 measuring hours used, all of which were ultimately included in a 120-page report.

The **Surface Benchmark Study** provides a detailed picture of current reworking options in additive manufacturing and is available at Fraunhofer IAPT in both printed and digital form.

Which questions remain unanswered?

Fraunhofer IAPT has set itself the goal of providing solid answers in future to questions that are still unanswered. For example, the impact reworking processes have on mechanical properties, especially fatigue strength, which process combinations can achieve an economic advantage while ensuring consistent quality, or what an AM component design suitable for reworking might look like currently remain uncertain. To this end, work is currently underway on a further study, the **Additive Fatigue Study.** As in the previous study, reworking processes are being systematically investigated here and, especially, examined to determine their impact on fatigue strength behavior. Ti64 and Inc718 materials and eight different reworking conditions are being used in this case. A combination of processes is also part of investigations this time. In addition, Fraunhofer IAPT would like to focus in future projects on the realization of consistent process chains from the perspective of efficient and digitized reworking. From the component design and the creation and manufacture of components and support structures suitable for reworking to automated solutions over the entire process chain, all aspects will be optimized in the long term, and applications will be made ready for market and implemented in appropriate projects at Fraunhofer IAPT. If you are interested in the content presented, please contact our **Surface Finish Team** (surface.finishing@iapt.fraunhofer.de).

➜ ***Fig. 2:*** *Depending on the requirement, it is important to find the appropriate post-processing procedure for AM components and, as with the printing process itself, surface post-processing considerably influences the quality of the finished part*

➜ ***Fig. 3:*** *Additively manufactured and post-processed specimens for the Additive Fatigue Study*

➜ ***Fig. 4:*** *Additive Fatigue Study specimens after testing*

PROCESS MONITORING – THE FUTURE OF QUALITY ASSURANCE

Process monitoring is the key element for AM components, not only for process validation, but also to minimize the need for downstream quality control.

Currently, conducting of X-ray inspections for critical components is common in heavily regulated sectors such as aerospace and medicine, to ensure that the components are free of faults. However, this practice hinders broader use of AM technology, due to the costs involved and longer production cycles. In situ quality control, also known as in situ process monitoring (IPM), promises a unique solution for the quality assurance (QA) of AM components.

"Quality assurance is definitely the crucial factor when it comes to widespread use of AM components. The methods currently employed in downstream quality assurance tend to be time consuming, expensive, or both", says Peter Lindecke, Head of the Quality Assurance & Certification specialist group at Fraunhofer IAPT. "In addition to focusing on increasing trust in component quality, process monitoring ultimately aims to minimize downstream quality control methods such as μCT and 3D measurements." These so-called born-qualified components are the goal of IPM systems in the coming years.

Implementing process monitoring

In essence, there are currently two options available for using process monitoring in a production scenario: known as process-signature-based and anomaly-detection-based methods.

Component/process signature

These methods concentrate on one aspect, namely process reproducibility. Components produce emissions during manufacture that can be collected and analyzed. Each component generates unique emission values, depending on the geometry, temperature, and material properties, and these are referred to as the component signature. A deviation from these values indicates a change in component characteristics and, consequently, the possibility of an anomaly.

Statistical process control (SPC) is implemented to identify these deviations and signal them to the user. Several prints are required to determine the fundamental truth of the comparison. It is therefore ideal for series production scenarios that could be termed statistical prints. One of the disadvantages of this method is that the user cannot say what exactly the anomaly is or its extent, which is why this method concentrates on pursuing the reproducibility aspect of the process.

Detection of the anomaly

This is the next evolutionary step in the process signature method. An improved understanding of the data collected and the development of more advanced algorithms for data analysis opens the Pandora's box of direct fault detection.

"What is clear is that, in order to achieve direct anomaly detection, companies need to refine their current detection philosophy and bring it up to date", says Hussein Tarhini, Consultant for Quality Assurance.

"The focus needs to be shifted to data fusion from several sources and the implementation of AI-based algorithms for better interpretation."

The fact is that many systems are still very far from direct fault detection and, without this, the production of born-qualified components is still a goal for the near future.

What are the current process monitoring systems, and what are they capable of?

The indisputable advantages of process monitoring are accompanied by an enormous increase in industrial interest in the introduction of this technology. By way of a reaction to this, machine manufacturers are developing an IPM system and integrating it into their machines. In addition, third-party providers who specialize in monitoring systems are appearing on the market. Everyone is presenting their own success stories or those of a close partner.

"IPM manufacturers have tested their systems with a variety of methods and demonstrated the capabilities of their products in different ways", says Lindecke, "but only minor efforts have been made to have the system tested under similar conditions by an independent party. Which is why my specialist group has decided to assume the role of an independent auditor to evaluate the capabilities of such systems."

To solve this problem, Fraunhofer IAPT conducted a detailed study that concentrated on testing already existing and soon-to-be-released process monitoring systems from machine suppliers and independent providers.

The study examines IPM systems and their abilities to detect component anomalies under different conditions. "IPM systems were tested to varying degrees by their manufacturers under laboratory conditions", says Hussein Tarhini. "The problem, essentially, relates to the ability to reproduce anomalies in the form in which they would occur in industrial production scenarios."

This study, which encompassed both theoretical and practical investigations, not only depends on the knowledge of Fraunhofer IAPT regarding the AM process and formation of anomalies, but also the ability to develop reproducible analyses which, for the first time, enable the uniform and comparable performance assessment of different IPMS systems.

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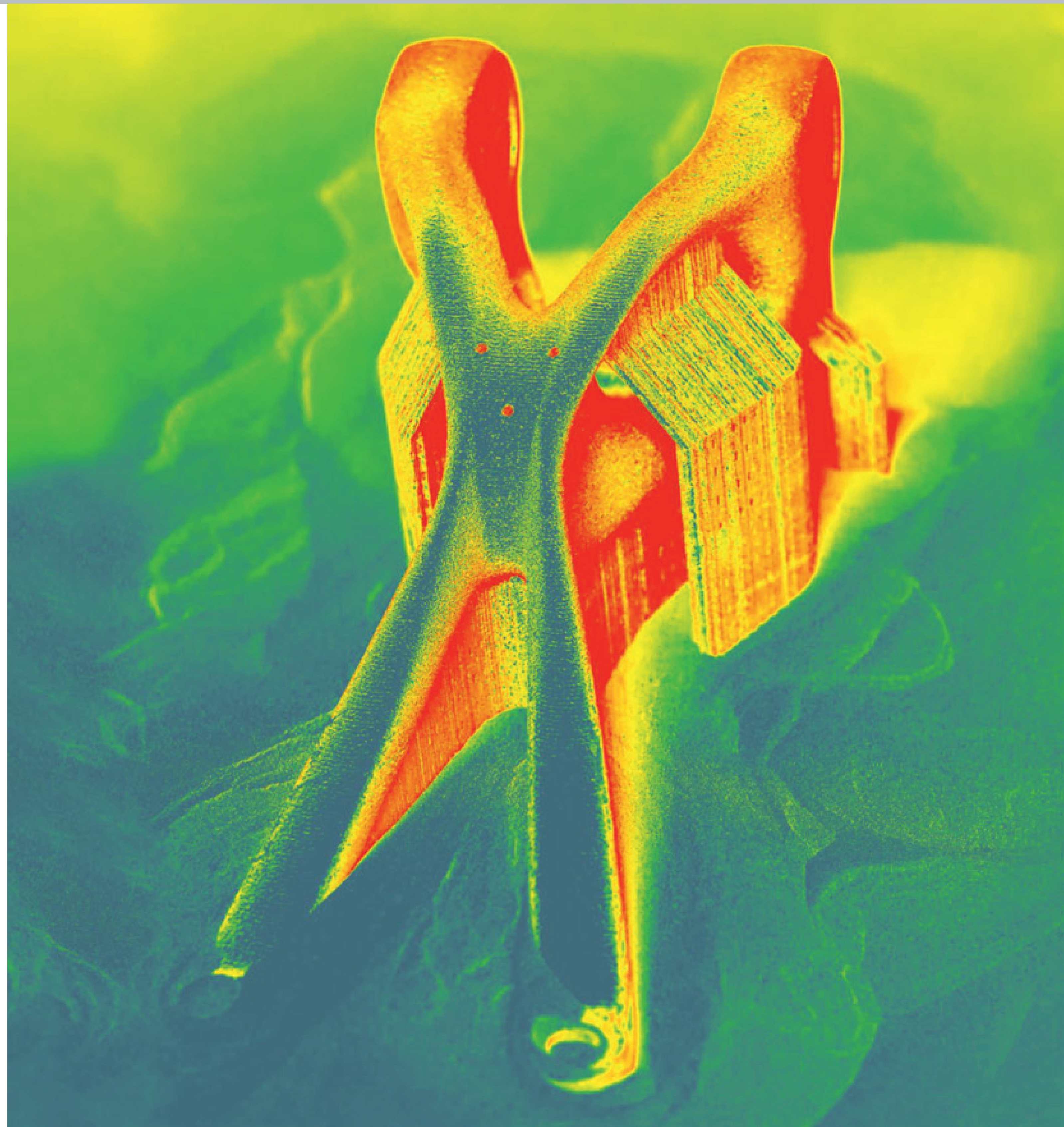

CERTIFICATE COURSES AND E-LEARNING FROM THE ACADEMY

ADDITIVE ACADEMY GOES DIGITAL

Additive Academy broadens training program with digital courses

The Additive Academy has positioned itself successfully for many years under the USP "Transfer Center for User-Oriented Assistance Systems". An unambiguous market orientation, technical expertise with practical relevance, and continuous further development of the program it offers characterize the Additive Academy.

Although the advantages of face-to-face and classroom events are undisputed, and these still remain the classic medium for training measures and workshops, e-learning will occupy an important place in future when it comes to in-service training and education measures. The targeted combination of both formats releases new potential. The Additive Academy has also intensified its digital measures since this year, both in situ and at customer facilities, and the training program is continually being expanded and supplemented.

E-learning: achieving a lot for very little

A new learning concept was required to implement the ambitious goal of an international automotive Group to train numerous employees at an international level in the basics of additive manufacturing. The development of a six-hour e-learning program saw this objective being successfully implemented with a cost-effective solution. On the one hand, e-learning allows participants to get to know the different technologies involved in additive manufacturing with metal and plastic, independent of time and location and at their own speed. On the other, in addition to the acquisition of knowledge, many employees can identify specific application cases from their working environment and engage with the appropriate choice of technology (process selection).

On the basis of examples from their own automotive Group, explanatory videos, relevant technology comparisons, exercises, and quizzes, each participant can try things out for themselves,

and a sense of the potential and limits of individual additive manufacturing technologies is rapidly gained.

Digital workshops: support with targeted knowledge

Our experience with digital workshops has been very positive when it comes to solving a specific problem – of the same automotive Group. A targeted transfer of knowledge aided the development of a basis for specifications and quality assurance standards.

Several experts from Fraunhofer IAPT met with the customer for four half-day digital workshops instead of a two-day face-to-face workshop format. What is telling is the consistently positive feedback regarding this format, which not only relates to the elimination of travel costs and time, but particularly the practical transfer of knowledge and positive integration into the daily working routine.

Digital basic training: more than an alternative during the COVID-19 crisis

Even if travel limitations due to COVID-19 have provided the impetus for a timely conversion of our familiar AM basic training sessions, the advantages rapidly became clear to our customers and the Additive Academy. Instead of the one-day training sessions held before, participants and experts from Fraunhofer IAPT met through video conference on two mornings.

And the conclusion during the COVID-19 crisis? The digital form is more than just an emergency solution. Targeted moderation aided group bonding, and the adapted organization sorted out the learning content. Learning was extremely focused, with an intensive exchange within the group, and the participants were particularly fond of the group work. Despite all of this, digital course programs are only suitable for certain content. Integration in a combined learning concept remains mandatory, and practical exercises (e.g. directly on the machine as in the Additive Academy hands-on training) cannot be digitally replicated.

Metal AM Professional – Design: certificate course compliant with ISO 17024

With immediate effect, the Additive Academy is offering a two-week course in "Metal Additive Manufacturing Professional – Design". This certification conforms to ISO 17024 and indicates that the recipient has successfully realized design tasks for metal-based additive manufacturing, ranging from potential analysis and design to manufacturing preparation, all while observing applicable design guidelines.

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TEACHING AT FRAUNHOFER IAPT

DOCTORATES AND THESES

2020 | Doctorates/Published theses | *Max Oberlander*
Process monitoring of laser remote cutting

Laser remote cutting of high-strength steels and carbon-fiber-reinforced plastics (CFRP) represents an efficient alternative to conventional methods. Characterization of process emissions allows conclusions on process progress to be drawn, enabling increased processing speed and enhancement of process efficiency.

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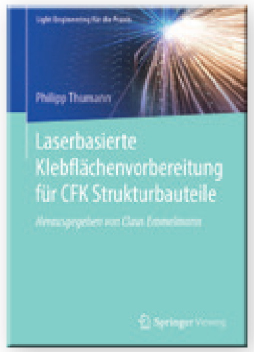

2020 | Doctorates/Published theses | *Philipp Thumann*
Laser-based adhesive surface preparation for CFRP structural components

The repair of CFRP structural components is one of the most significant challenges in the maintenance of modern commercial aircraft. This thesis illustrates a process for laser-based adhesive surface preparation for a repair realized with adhesive.

ISBN 978-3-662-62241-4 | DOI 10.1007/978-3-662-62241

FRAUNHOFER IAPT TEACHING ASSIGNMENTS

Fraunhofer IAPT has set itself the task of carrying the enthusiasm for and knowledge about additive manufacturing and welding technology into the future. Numerous teaching assignments are carried out by our technically competent scientists as lecturers from Hamburg to South-West Germany, with complete dedication and in a variety of languages. The table presents a small selection of our teaching activities, which are supplemented by both external and internal lectures, presentations, and training sessions.

Training/educational facility	Lecture title
Hamburg University of Technology	3D Printing Laboratory Six Sigma Method in Quality Management Additive Production Laser Systems and Process Technologies Additive Production Seminar Structural Optimization Manufacturing Technology II (Laser System Technology)
Schweisstechnische Lehr- und Versuchsanstalt Nord (welding technology training and research institute)	Additive Manufacturing
Hamburger Fern-Hochschule (Hamburg University of Applied Sciences)	Laser Production Technology Lab
Duale Hochschule Baden-Württemberg Mosbach	Current developments in additive manufacturing processes

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Equality and gender
In the interest of better readability, we have, in part, dispensed with simultaneous use of female and male linguistic forms. This, however, does not imply discrimination against the female gender, but, in the context of linguistic simplification, should be understood as gender-neutral.

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THE FRAUNHOFER-GESELLSCHAFT

Headquartered in Germany, the Fraunhofer-Gesellschaft is the world's leading application-oriented research organization. With its focus on developing key technologies that will shape the future and enabling the commercial exploitation of this work by business and industry, it plays a central role in the innovation process. Fraunhofer is an innovator and catalyst for groundbreaking developments and scientific excellence. Through inspirational ideas and sustainable scientific and technological solutions, the Fraunhofer-Gesellschaft promotes science and industry, helping to shape both our society and our future.

Interdisciplinary research teams at the Fraunhofer-Gesellschaft work together with partners from the private and public sectors to transform original ideas into innovative technologies, coordinate and realize key research policy projects of systematic relevance, and strengthen the German and European economy with a commitment to creating value added that is truly value oriented. International collaboration with outstanding research partners and companies from around the world brings Fraunhofer into direct exchanges and interaction with the most influential scientific and economic regions.

Established in 1949, the organization currently operates 75 institutes and research facilities in Germany. Approximately 29,000 employees, primarily qualified scientists and engineers, generate an annual research budget of 2.8 billion euros. 2.4 billion euros of this is created through contract research. Around two thirds of Fraunhofer's revenue is derived from industrial contracts and publicly funded research projects. Approximately one third comes from the German federal and state governments in the form of basic funding, enabling the institutes to develop solutions to problems today that will be crucial for business and society in the near future.

The impact of applied research is felt far beyond the direct benefits experienced by clients. Fraunhofer institutes strengthen the performance and efficiency of companies, promote the acceptance of new technologies within society, and ensure the education and training of the urgently needed future generation of scientists and engineers.

Working at the cutting edge of research, our highly motivated personnel are the key factor in our success as a scientific organization. Fraunhofer therefore offers them the opportunity to work independently and creatively while pursuing a specific goal, encouraging the development of professional and personal skills that will enable them to take up positions of responsibility in the institutes, at universities, in the economy, and within society. Students enjoy excellent career prospects and development opportunities in companies by virtue of practical training and the early contact they have with clients.

A recognized non-profit organization, the Fraunhofer-Gesellschaft takes its name from Joseph von Fraunhofer (1787–1826), the Munich physicist and extremely successful researcher, inventor, and entrepreneur.

Figures are from January 2021
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