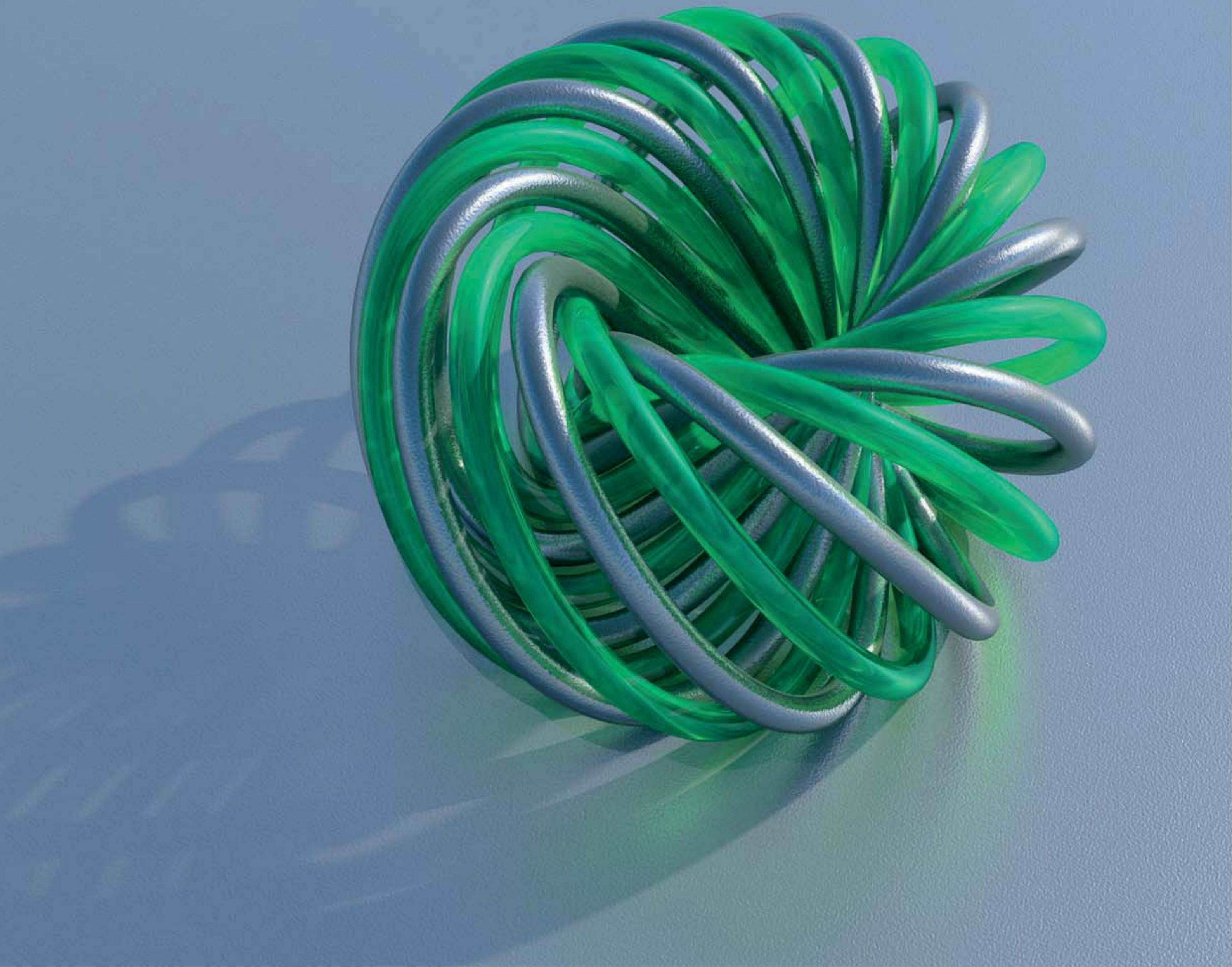
Fraunhofer
IWS

FRAUNHOFER INSTITUTE FOR MATERIAL AND BEAM TECHNOLOGY IWS

ANNUAL REPORT 2018



FRAUNHOFER IWS

Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS Dresden stands for innovations in laser and surface technology. As an institute of the Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V., IWS offers one-stop solutions ranging from the development of new processes to implementation into production up to application-oriented support. The fields of systems technology and process simulation complement the core competencies. The business fields of Fraunhofer IWS include PVD and nanotechnology, chemical surface and reaction technology, thermal surface technology, additive manufacturing and printing, joining, laser ablation and cutting as well as microtechnology. The competence field of material characterization and testing supports the research activities. At Westsächsische Hochschule Zwickau, IWS runs the Fraunhofer Application Center for Optical Metrology and Surface Technologies AZOM. The Fraunhofer project group at the Dortmunder OberflächenCentrum DOC® is also integrated into the Dresden Institute. The main cooperation partners in the U.S. include the Center for Coatings and Diamond Technologies (CCD) at Michigan State University in East Lansing and the Center for Laser Applications (CLA) in Plymouth, Michigan.


CERTIFICATE
DEKRA
Fraunhofer IWS
ISO 9001:2015
Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS

Certified according to ISO 9001:2015

Quality is the cornerstone of our success. We have made it our task to refine our own potential, as well as to establish and keep our partners' and customers' satisfaction at the highest level. For this reason, the Fraunhofer IWS Dresden introduced a quality management system in 1997, and this system has been continuously refined and regularly externally certified according to the ISO standard 9001 ever since. This audit is regarded as the basis for working sustainably by means of documented procedures on the domestic and international markets. In this way, we create the preconditions that allow our organization to achieve its objectives both efficiently and effectively – and to be a reliable partner always.

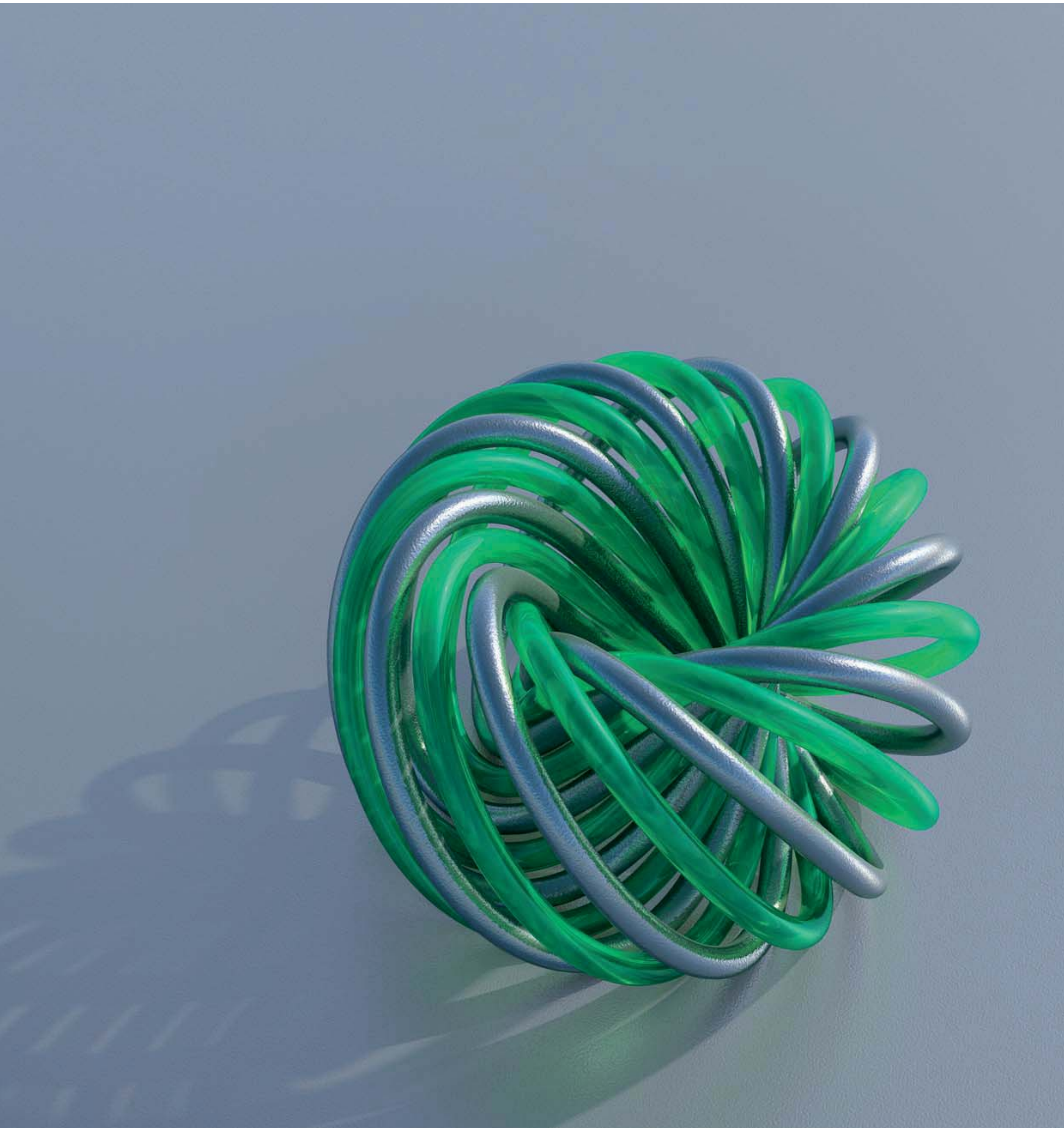
DRESDEN-concept: exellence in science and culture

Fraunhofer IWS Dresden is a proactive member in the DRESDEN-concept alliance. The cooperation comprises 26 partners from the fields of science and culture and aims to reveal and foster synergies in research, education, infrastructure, administration and transfer. For this purpose, the members coordinate their scientific strategies and identify the fields in which Dresden is an international leader. The partners cooperate to attract leading scientists worldwide to Dresden and to keep them here.

ANNUAL REPORT 2018

FRAUNHOFER INSTITUTE FOR MATERIAL AND BEAM TECHNOLOGY IWS

CONTENTS



FRAUNHOFER IWS

8 Core competencies
10 IWS at a glance
16 Industrial implementations
20 Awards and honors
22 From the Board of Trustees
24 Organization and contacts

ABOUT THE BUSINESS UNITS

28 PVD- and Nanotechnology
36 Chemical Surface and Reaction Technology
44 Thermal Surface Technology
52 Additive Manufacturing and Printing
60 Joining
68 Laser Ablation and Cutting
76 Microtechnology
82 Materials Characterization and Testing

CENTERS AND NETWORKS

90 Cooperation partners
92 Centers
95 Branches
96 Networks
98 Fraunhofer Group for Light & Surfaces
100 How to reach us
101 Editorial notes

FOREWORD

Executive Director **Prof. Dr.-Ing. Christoph Leyens**

Ladies and Gentlemen,

Looking back on the last year, I think of the image of a steering wheel. The emotional farewell speech to Prof. Ralf-Eckhard Beyer, the former institute's director, was characterized by a maritime theme and marked a milestone that was crucial not only for me. During the honorary colloquium in late September, we looked back together with many colleagues on his more than two decades of successful leadership as director of our institute and director of the Institut für Fertigungstechnik (Institute of Manufacturing Science and Engineering) at the TU Dresden. Our thanks go to him for his accomplishments. Prof. Beyer literally handed over the reins to me. It is a great honor and motivation for me to continue the IWS success story. In the future, we will base our projects and services on our core expertise in laser application, surface technology and materials science. As passionate lateral thinkers, we are keen to put new ideas into practice. We work toward the greatest benefit for users and partners.

Let me highlight three fields that we were able to inspire and promote last year. The first is thin-film technology with the so-called ta-C coatings. With low friction and high wear resistance, they are becoming increasingly popular in industry. Currently, more and more automotive users in particular are adopting the systems in the industrial process developed by our partner, Federal-Mogul Powertrain. However, this technology can also play a part in many other application scenarios in which friction and wear are critical, such as tool- and die-making.

The second field in which I see a strong potential for growth is the "organ on a chip", which was developed by the IWS team and awarded with the EARTO Innovation Award 2018 (see page 20), immediately benefits human beings. In the future, patients will profit from individualized medication tailored to their individual physiological conditions. A blood test could provide more precise information about whether or not a drug would be beneficial. This would also decrease animal testing. Even though we have already achieved a lot, we are only at the beginning of a development the extent of which we cannot predict today.

Thirdly, Additive Manufacturing continues to be important for Fraunhofer IWS. In 2018, no other business unit at the institute grew as fast. I am particularly pleased that the industry is increasingly discovering the topic as essential for itself. Of course, we are the right partner to support you in research and development. Take as proof, for example, the Joseph von Fraunhofer Prize 2018 (see page 20), which we received together with our partner Rolls-Royce for our contribution to realizing the world's most efficient large aircraft engine.

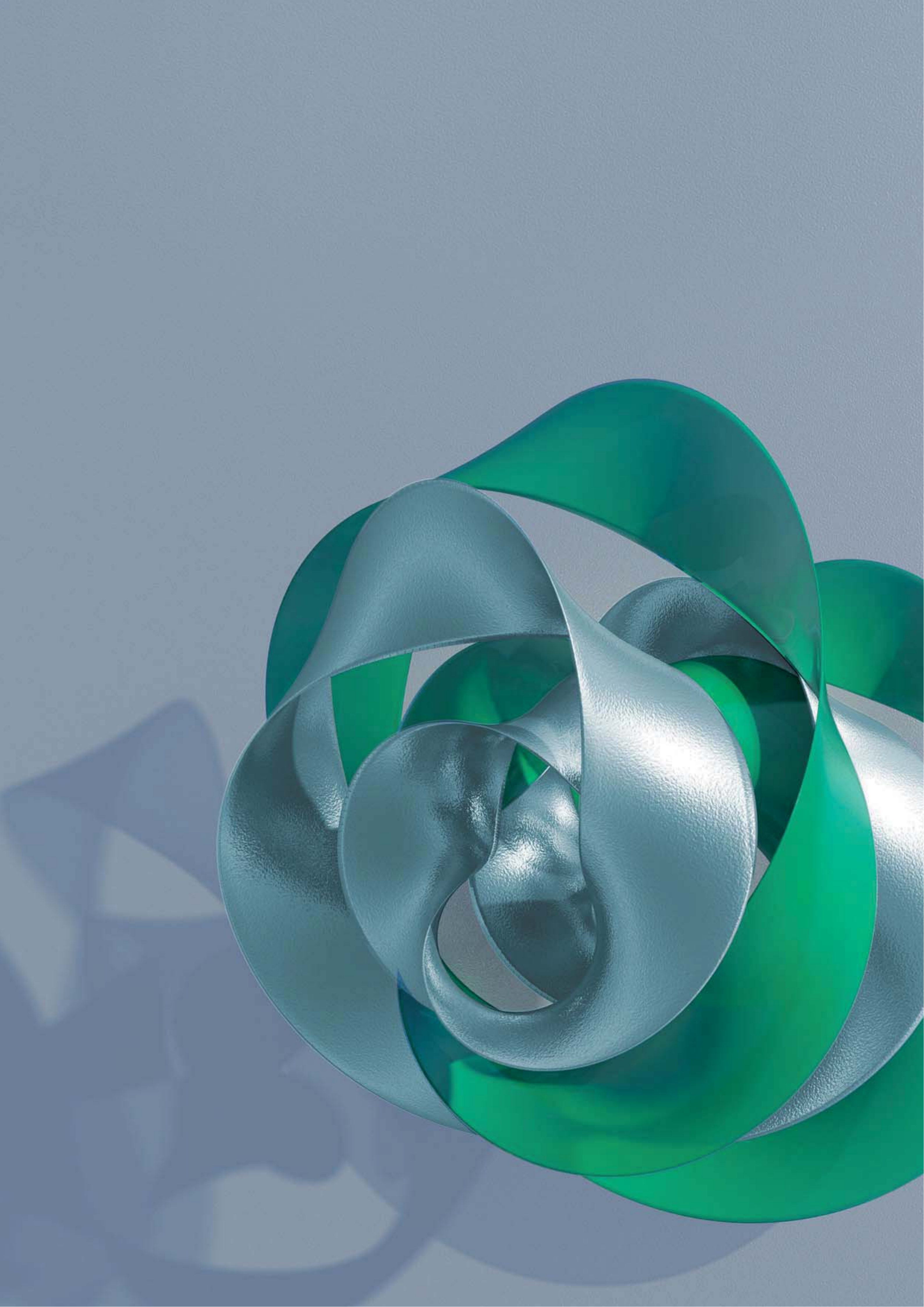
Among other subjects, we will analyze how to digitize integrated process chains (key word: "digital twin") in the coming years. While today we know a lot about producing a component retrospectively on the basis of digitally collected process data, in the future it should be possible, similar to the reverse engineering approach, to make predictions about its optimal production. In order to meet specific requirements, a specific geometry must be created from a certain material with a precise fitting structure by way of a process that will need to be defined. Determining this configuration, that’s what we are working towards. Connecting the entire process chain will mark what we consider a true quantum leap.

In the "EvoloPro" Fraunhofer main project, we are accelerating the "Biological Manufacturing System" design. To engineer a new production system generation, we want to work with other Fraunhofer institutes to utilize mechanisms that adapt to new requirements and environmental conditions in the same way as biological organisms do. Fraunhofer IWS focusses on digital integrated process chains and contributes its comprehensive expertise in both the materials and processes. The same background and approach are used in the "FutureAM" focus project. We responsibly participate in this project in the area of "Materials". AM techniques have already been explored, and they significantly redefine the limits of classic manufacturing in terms of design. A major question is now: Do the additively manufactured structures fulfil all the mechanical requirements we expect of them?

This annual report documents what other irons we currently have in the fire at Fraunhofer IWS, which technologies we transferred to industry last year, and provides many other insights into our work. I cordially invite you to make up your own mind and to contact our experts.

Yours truly,

Prof. Dr.-Ing. Christoph Leyens



FRAUNHOFER IWS

CORE COMPETENCIES

IWS AT A GLANCE

HIGHLIGHTS

FROM THE BOARD OF TRUSTEES

ORGANIZATION AND CONTACT PERSONS

CORE COMPETENCIES

The transfer of the most recent research results to industry is the primary motivation for our activities, the reason why we have continuously extended our core competencies in the areas below:

SURFACE TECHNOLOGY

A central task is to improve surface functionality. For this purpose, the IWS offers a wide range of functionalization and coating techniques. This allows us to produce coatings and layers whose thickness ranges from only a few nanometers to some millimeters, made of various materials and combinations. In many cases, researchers have to refine the system hardware, such as the plasma sources, for optimal component treatment or coating.

MATERIALS SCIENCE

Our core expertise includes surface- and interface-treated, as well as coated, welded, cut, and micro- or nano-structured materials and parts characterization. We consider this the foundation for process development and quality assurance tailored to the part and the material. This expertise is also the basis for design that meets material and manufacturing as well as load- and stress-related requirements.

LASER MATERIALS PROCESSING

Our laser materials processing competency involves managing integrated value-added chains – from analyzing the component loads and stresses, material use tailored to individual stress requirements and component-related process development up to implementing advanced techniques. IWS research focuses on material and component characteristics, which in turn determine the process and system parameters that establish the basis for equipment design. Process monitoring and control complete the portfolio.

SYSTEMS ENGINEERING

Sensors for process monitoring and networking process data contribute to securing and documenting process quality. The modification of systems engineering is often inevitable. Thanks to many transfers to industry, IWS has acquired comprehensive systems engineering expertise and has applied its procedural know-how to the development, manufacturing and design of components, equipment and systems suitable for industry and integration, as well as the necessary software.

SYSTEM AND PROCESS SIMULATION

Our simulation expertise includes not only developing simulation modules for thermal surface technology, additive manufacturing, cutting, welding and vacuum arc coating, but also calculating the nanolayer systems' optical properties. Commercial simulation modules are used to optimize gas and plasma flows during coating procedures and laser materials processing.

DIGITIZATION

Combining materials science with process and production engineering know-how is a key part of solving complex issues in all Fraunhofer IWS research areas. Digitization along the entire process chain is currently our core challenge. We primarily use the platform approach when upgrading system hardware to fully digitized systems. To achieve this, the IWS utilizes its multiple expertise in laser application, surface technology, and materials science.

IWS AT A GLANCE

IWS Main Building

IWS Adjoining Building

IWS Adjoining Building

AZOM

DOC®

Employees

IWS

	Number
Scientists / engineers (TU, FH)	158
Skilled workers with technical or trade-related training	62
Trainees	14
Research assistants	164
Scholarship holders and external colleagues	6
Guest scientists from TU Dresden	44
Total	**448**

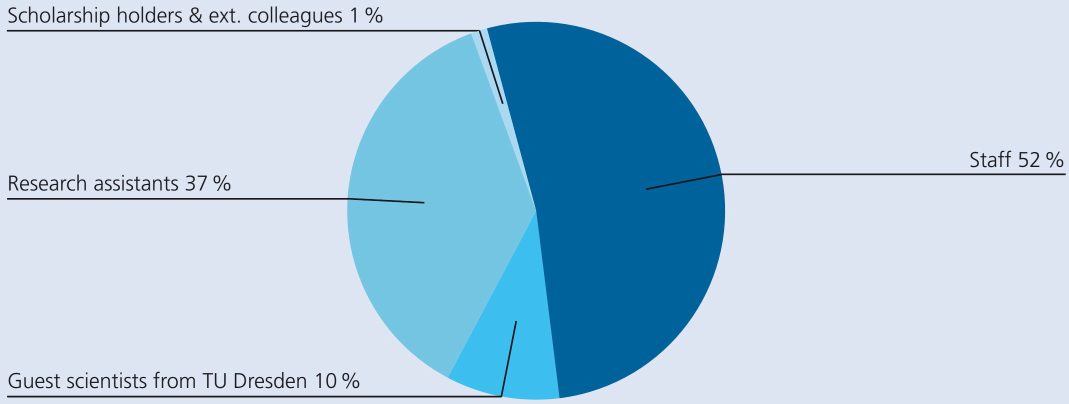
Publications

Type of publication

	Number
Dissertations	13
Diploma theses	47
Master's theses	14
Journal papers	125
Patents (first filing)	15
	214

A list of all scientific contributions by the Fraunhofer IWS published in 2018 is available via the bibliographic database "Fraunhofer-Publica":

http://publica.fraunhofer.de/institute/iws/2018



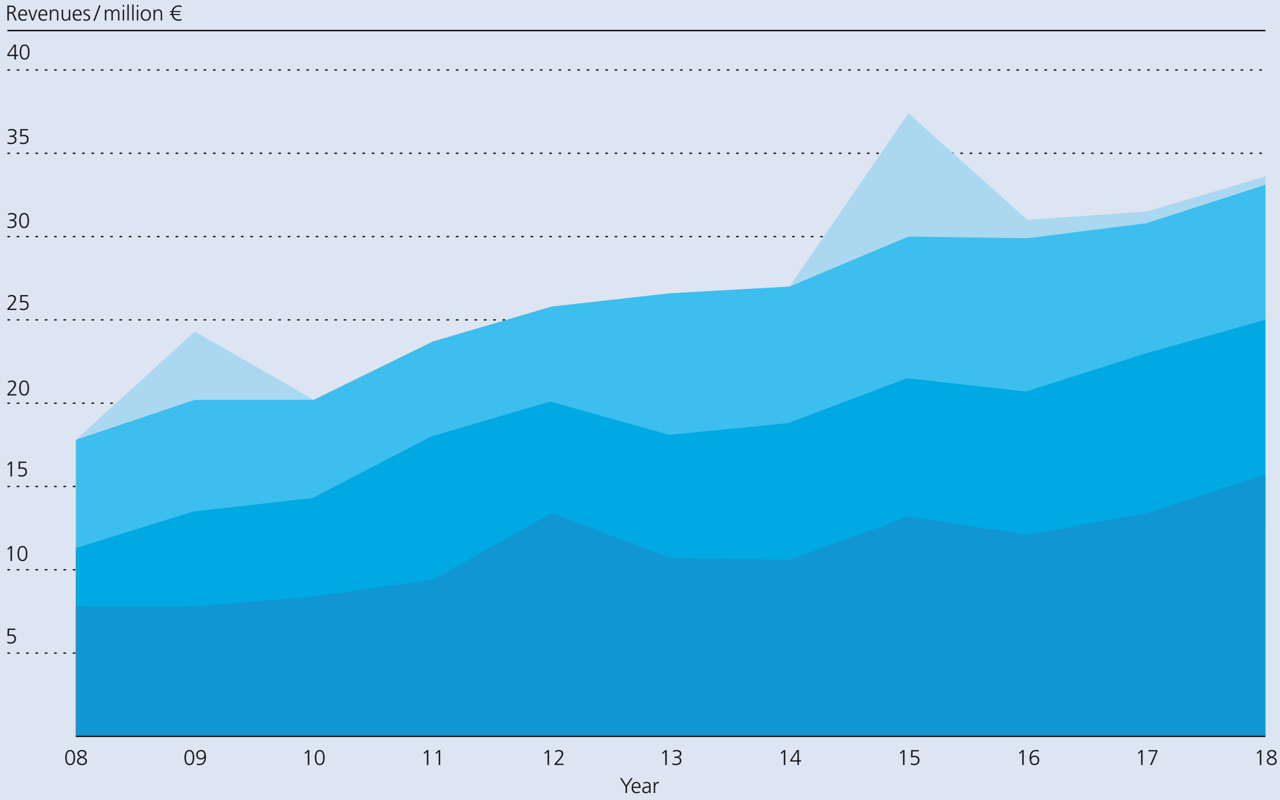
as of January 2019

Revenues

Fraunhofer IWS and German branches 2018 (million €)

	Operation	Investments	Total
Project revenues from industry	15.4	0.3	15.7
Project revenues from federal, state and European sources	9.1	0.2	9.3
Base funding and Fraunhofer internal programs	6.6	1.5	8.1
Special investments from federal, state and European sources	0.1	0.4	0.5
	31.2	**2.4**	**33.6**

Fraunhofer Industry ρ_{Ind} = 50.2%

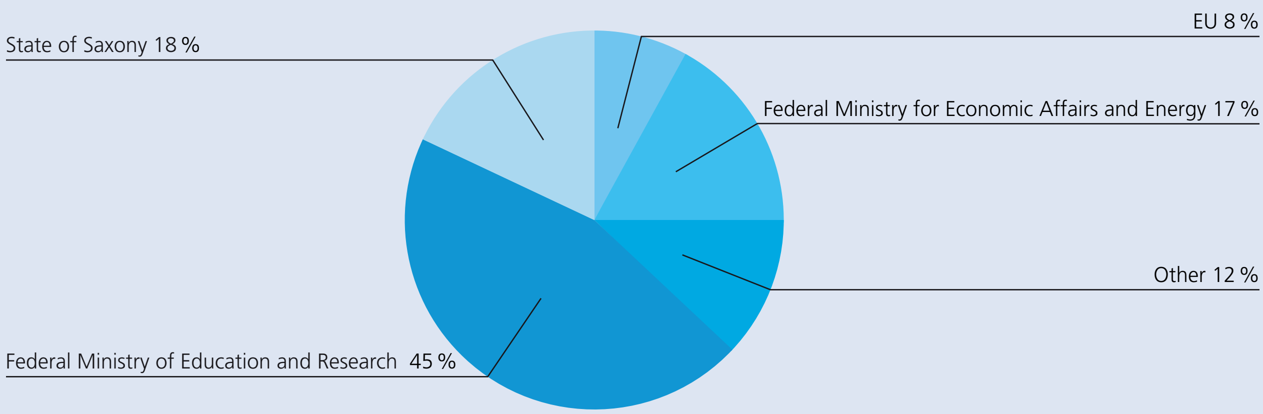


as of January 2019

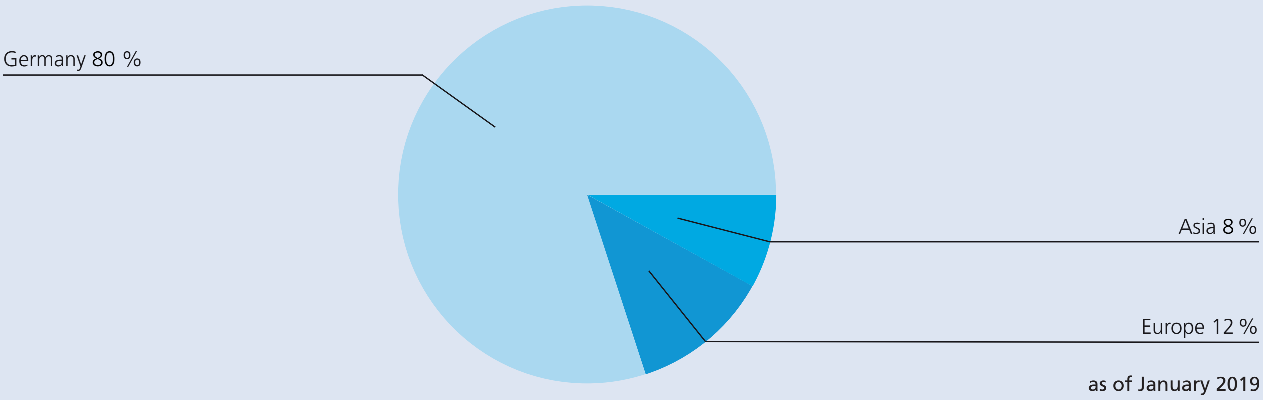
Expenses Fraunhofer IWS and German branches 2018 (million €)

Personnel costs	16.3
Material costs	14.9
Investments	2.0
Special investments from federal, state and European sources	0.4
	33.6

Public revenues by source



Industrial revenues by geographical source



as of January 2019

HIGHLIGHTS

As an institute of the Fraunhofer-Gesellschaft, we are committed to outstanding application-oriented research. We at Fraunhofer IWS use our passion to develop innovative solutions for the industry of today and tomorrow. In the "Highlights" section, we present selected results that have succeeded in industrial applications. Only genuine innovations which have been successfully applied and which penetrate the market merit the "Highlight" title. We also proudly look back on the highlights of our scientific development by noting the awards we received last year.

INDUSTRIAL IMPLEMENTATIONS

COAXwire: New coaxial laser wire buildup welding applications for the body shop

Since last year, Opel has been applying the "COAXwire" laser technology to produce new dies for car body parts more flexibly, reliably, and quickly than before. "Compared to powder buildup welding, our wire-based technology is environmentally friendly, cost-saving and makes the welder's job easier and safer," emphasizes Marc Kaubisch, coordinator of the Fraunhofer IWS Laser-Wire Coating Technology team. The name COAXwire is derived from the principles used: the system feeds the wire material to be built up into the manufacturing optics in a coaxial manner, that is centrically in the laser beam axis and perpendicularly to the part. Up to now, it was necessary to laterally feed the wires to the laser head; this setup consequently prevented the manufacturing of complex geometries, and welding system programming and operation became more sophisticated. It is now possible to feed the wire perpendicularly, because IWS engineers first split the laser beam in the new manufacturing heads into three partial beams and bring them together again in the manufacturing zone. The COAXwire system's advantage in comparison with powder-based buildup welding is that it is almost waste-free. Industry employs this technology to repair dies damaged during long series manufacturing chains. It is also possible to implement particular designs and fabrications. With this technology, IWS engineers can also apply extremely hard and resistive coatings onto work blanks made of less expensive tough materials, such as mild steel. In this particular case, in cooperation with the company ALOtec Dresden, they add a COAXwire module to existing hardening equipment in the Opel die shop.

Ceramic thermal shield for economic power units

The more an engine manufacturer can increase a turbine's regular operation temperature, the more efficiently the unit will usually work. Consequently, for example, planes would require less fuel to fly. A special ceramic yttrium-stabilized zirconium oxide (YSZ) coating may help in this case. The coating acts like a thermal shield. Thanks to this coating, users can increase the turbine's operation temperature without the risk of reducing the component's temperature-dependent strength. Together with the Swiss equipment manufacturer AMT, IWS engineers scaled up for industrial use a suspension gun spraying method to apply these insulation coatings onto turbine parts at low cost and with high quality. These insulation coatings may vary in size from a few tenths of a millimeter to several millimeters in thickness. "This technique is also suited to coat large-sized turbine parts," says Dr. Maria Barbosa, Thermal Spraying group manager at Fraunhofer IWS, who sees this technology as bridging the methods commonly in use. Previous thermal insulation coatings were either generated by means of expansive electron beam evaporators (EB-PVD) under vacuum or by "atmospheric plasma spraying" (APS), providing less loadable coatings at lower costs. With the IWS' approach the researchers use a powder containing very fine YSZ particles less than one micrometer in diameter. These fine ceramic powders normally agglomerate and clog the spraying system's feeder. To solve this problem, the Fraunhofer specialists scaled up a technology in which they first transform the microparticles into suspensions, and which can subsequently be reliably sprayed. Users can produce very homogeneous, robust and thermally high-quality insulation coatings without expensive vacuum processes thanks to this technology. The renowned Swiss equipment producer AMT is now acquiring this technology under license. Industrial demand for sprayed ceramic suspensions is strong and ever rising, Dr. Barbosa adds.

1

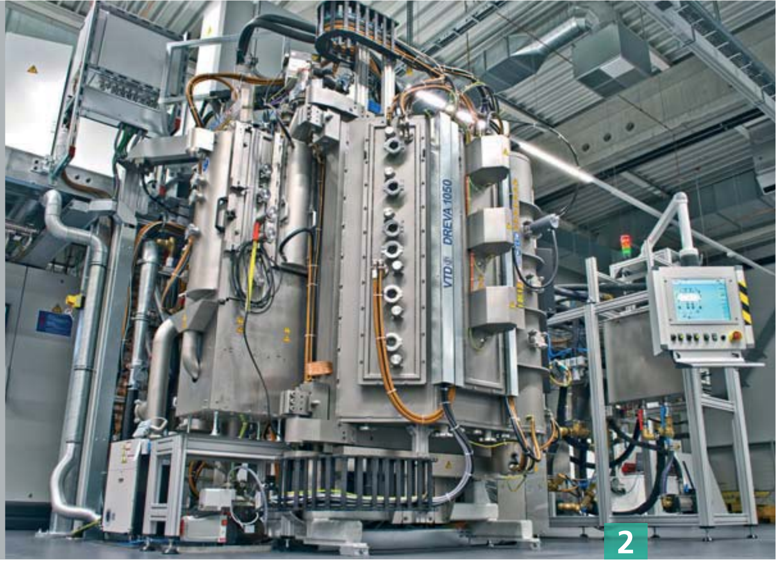
Flexible laser cutting of airbags

Flexible production and small stocks play an increasingly important role in airbag fabrication. "Lot sizes are decreasing," observes Dr. Jan Hauptmann, head of the high-speed laser processing division at the IWS. "The production processes must be adapted promptly so that steering wheel airbags can be produced in one week, knee airbags in the next and subsequently side airbags." Larger airbags are also in demand, for example for minibuses, and material mixes. Classical cutting principles are reaching their limits: Previously, many textile layers were laid on top of each other and laser-cut to shape in a single pass. The result is a large number of airbags in one pass. However, this is only efficient if the same model is used thousands of times – which is becoming increasingly rare. Therefore, the special machine manufacturer Held Systems Deutschland and the IWS have introduced a new generation of laser cutting machines into series production. In continuous operation, the textile web passes under two laser heads that cut the airbag material flexibly. These "contiLAS systems" are capable of fabricating each part anew. This is based on the superposition of continuous web feed, cutting head and laser beam movement via precisely controlled lightweight mirrors. In addition to the triggering solution developed at the IWS and the web planning algorithm, they ensure the required productivity and offer maximum flexibility. Integrated detection technologies also facilitate cutting OPW airbags to size. The "One-piece-woven" (OPW) process produces fabric strips consisting partly of interwoven layers and partly of two separate layers. The cavities into which the air shoots into the airbag in the event of an accident are already included in the flat fabric strip. "It is important that the laser does not cut into these cavities," says Dr. Hauptmann. In the meantime, Held Systems has installed more than 30 of these machines worldwide. Further industrial transfers are in preparation.

Laser structures allow electrical connectors to provide better contact

In cooperation with the "Materials Engineering Center Saarland" (MECS), Fraunhofer IWS researchers have developed a laser-based patterning process for an industrial partner in the automotive sector. Electric connectors gain improved contact performance thanks to direct laser interference patterning (DLIP). In 2018, the partners successfully launched a DLIP pilot plant at MECS. Some background: Electrical connectors can be found in almost any technical application, from automotive to medical and power engineering to home electronics. Today, the on-board power systems of advanced automobiles include a huge number of electrical connectors: An Audi A8 (model 2015), for instance, is fitted with 2,300 electric connections and 671 contact housings. Consequently, the demand for wear-resistant, easy-to-assemble electrical connectors with enhanced electric properties is rising. To improve the electrical connector's contact behavior, the IWS engineers split a pulsed laser beam into two or more partial beams. These beams are superimposed on the material surface, resulting in a large-area interference pattern which can be generated at high processing rates. In the joint project together with MECS, the IWS team designed DLIP modules for high-speed processing and integrated them into a DLIP pilot plant. With this setup, the engineers can fabricate line-like topologies at high speeds. The applied microstructures facilitated the embedding of materials for better tribological properties. The DLIP technology is particularly suitable for industrial use, since neither vacuum nor clean room conditions are required.

1 Laser airbag cutting system



2

Diamond hardness for engine piston rings

To ensure that vehicle engines last longer and consume less fuel, piston rings can be equipped with a diamond-like superhard carbon layer. The "Laser-Arc" technology developed by IWS Dresden can be employed beneficially for this coating. The industrial partners VTD Vakuumtechnik Dresden and Federal-Mogul Powertrain, who have been part of Tenneco Inc., Illinois, USA since October 2018, have further developed the process with support from Fraunhofer engineers and taken it up to serial production readiness. The coating systems designed by VTD have already been successfully transferred into production several times. The end user is Federal-Mogul Powertrain, a company marketing the piston ring coating under the name DuroGlide®. The automotive supplier operates a piston ring factory in Dresden, Germany, which supplies a large number of vehicle manufacturers. Accordingly, piston rings from Dresden with the special carbon coating are already on the road worldwide. The diamond-like carbon coating reduces friction and wear and allows the use of very thin engine oils. Cars with piston rings coated with DuroGlide® in their engines release up to 1.5 percent less carbon dioxide and consume correspondingly less fuel. In addition, thanks to their reduced wear and increased robustness, the optimized engines contribute to cutting CO_2 emissions. In the future, this technology could also be applied to other components in the powertrain of motor vehicles in order to further reduce fuel consumption.

Rapid laser film cutting

To enable companies to cut advanced multilayer films more quickly and precisely, IWS Dresden has developed an innovative laser cutting system in cooperation with the machine manufacturer LSA from Wolkenstein in Saxony's Erzgebirge region. The system consists of a mobile device carrying a laser and a scanner with tilting mirrors, as well as other devices for clamping, deflecting, and material processing. It can cut different film layers to size independently, wait for finishing steps performed by other machines in the cycle line and finally – once repositioned – shape the other film plains. Thus, for instance, layers made of transparent plastic foil, linoleum, adhesive tape or other materials can be contoured one after the other. Important to note: the laser cuts only the target layer rather than the adjacent layers. This laser technology provides several advantages over classic techniques, for example those employing steel cutting shears, as Marcel Mende from the IWS Dresden emphasizes. "First, we can achieve high processing speeds of several meters per second. In the future, we plan to run the system at eight meters per second maximum," he explains. "Secondly, there is less maintenance: here, it is no longer necessary to produce and maintain shape-specific blades. And thirdly, the targeted energy input of the laser enables flexible, precise and, above all, dimensionally stable material processing." This is particularly important since sometimes very little material remains between adjacent recesses. In this case, it is necessary to keep the material from distorting or even tearing. For this equipment, the IWS also supervised installation, commissioning, and customer support. As Mende reports, development has been largely completed: "The system is now in operation at the customer's site." The IWS team will integrate the customer experience gained in practical use into further developments.

3

4

Dry films: less energy consumption in battery production

In cooperation with the Finnish battery company BroadBit Batteries from Espoo, the IWS has developed a system that coats battery electrodes using the dry film process instead of wet slurries, as has been customary in industry so far. At the beginning of 2019, the system will go into regular operation at BroadBit. Using this approach, the Finns intend to produce innovative sodium-ion batteries. "Our technology works without drying processes and thus saves energy in battery cell production," says Dr. Benjamin Schumm, Chemical Coating Techniques group manager, describing the advantages of dry films over slurry coatings. Without the usual drying lines, which are often up to 100 meters long, the systems can also be designed more compactly. "We can also work without toxic organic solvents," Schumm notes. Although subsequent steps influence the energy balance of the entire production process, dry film technology could ultimately contribute to making large battery cell factories profitable again in Germany, a high-priced country for electricity. In order to coat the carrier films with dry electrode materials, IWS engineers mix the powder-like active material with bonding agent polymers. They subsequently pass the powder mix through a calender. The shear forces in this calender tear entire molecule chains out of the bonding agent polymers. These fibrils, in turn, bond with the electrode particles, as in a spider web. In this process, a dough-like dry film is generated on one of the calender rolls. The calender laminates this approximately 100 micrometers thick band onto an aluminum film in the next process step, thereby forming the battery electrode. "The technology is also suitable for other battery types," Benjamin Schumm emphasizes.

2 Coating system VTD – DREVA 1050 with IWS laser-arc module to produce friction-reducing carbon layers on piston rings.

3 Cutting system with positioning table and laser/scanner apparatus to process multi-layer films layer by layer.

4 Dry coating system with IWS calender unit to produce electrodes for sodium-ion batteries for the BroadBit Batteries company.

AWARDS AND HONORS

JOSEPH VON FRAUNHOFER PRIZE 2018

A research team in the Additive Manufacturing and Printing business unit managed by Prof. Frank Brückner and Mirko Riede succeeded in increasing the durability of aircraft engines under high thermal load. This effect contributes to reducing kerosene consumption and carbon dioxide emissions. In combination with other procedures, tremendous cost savings can be achieved in flight operations. The research project was established in close cooperation with the aircraft engine specialist Rolls-Royce. Since February 2018, the engines have been used in long-distance aircrafts for the Airbus A350-1000. The Trent XWB-97 is the exclusive engine for this aircraft type and currently the most efficient large engine worldwide.

EARTO INNOVATION AWARD 2018

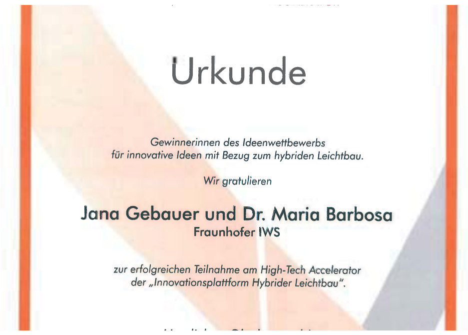
"We are very optimistic that many animal experiments may become superfluous," highlights Dr. Udo Klotzbach, Microtechnology business unit manager at Fraunhofer IWS. He and his team around Dr. Frank Sonntag, succeeded in engineering a "multi-organ chip". Their work earned them third place in the "EARTO Innovation Award 2018" in the "Impact Expected" category. The microsystem simulates animals' or human beings' blood circulation and organs. The chip is intended to support industry in developing new pharmaceuticals and cosmetics more rapidly than before. It should also act as a trendsetter in individualized medicine, enabling doctors to customize therapies for individual patients within days rather than years.

HANS-WALTER HENNICKE LECTURE COMPETITION AWARD

In memory of Prof. Hans-Walter Hennicke, the Deutsche Keramische Gesellschaft (DKG) established the Hans-Walter-Hennicke Lecture Competition Award in 1995. The society honors the three best lectures on graduation thesis content given by new ceramic engineers at the annual DKG conference. In 2018, the DKG presented one award to Juliane Moritz, a scientist from Fraunhofer IWS for her presentation on "Modifying the surface topography of zirconia ceramics for improved biocompatibility".

FRANK A. DIPIETRO AWARD

The Frank A. DiPietro Award recognizes the exchange of vision, spirit and purpose in industrial laser applications. Last year, Prof. Ralf-Eckhard Beyer received this award from the Fabricators & Manufacturers Association, International (FMA) at the Advanced Laser Applications Workshops (ALAW) in Plymouth, Michigan, USA. The steering committee selected him unanimously. Prof. Beyer has participated in ALAW conferences since their beginning and has supported European speakers in sharing insights into the latest technologies and processes. He has contributed his knowledge as a keynote speaker and regularly attended the conferences. With this award, the committee thanks him for his commitment. The award goes back to the ALAW conference founder, Frank A. DiPietro, who intended to connect laser researchers and users to share best practices, new technologies and advance manufacturing. DiPietro died in 2017. To honor his memory, the steering committee established this annual award.



Urkunde

Gewinnerinnen des Ideenwettbewerbs
für innovative Ideen mit Bezug zum hybriden Leichtbau.

Wir gratulieren

Jana Gebauer und Dr. Maria Barbosa
Fraunhofer IWS

zur erfolgreichen Teilnahme am High-Tech Accelerator
der „Innovationsplattform Hybrider Leichtbau".

COMPETITION FOR INNOVATIVE IDEAS RELATED TO HYBRID LIGHTWEIGHT DESIGN

Jana Gebauer and Dr. Maria Barbosa were honored for their successful participation in the "High-Tech Accelerator" of the "Innovation Platform for Hybrid Lightweight Design". They received the award at the conference titled "Fascination of Lightweight Design" at the Wolfsburg AG's MobileLifeCampus. The young researchers now have access to the infrastructure of the Open Hybrid LabFactory (OHLF) and are also individually supported with innovative ideas as well as industrialization, cooperation and utilization potential, in their high-tech accelerator development. ITS mobility and the OHLF, together with the AutoUni, the Allianz für die Region GmbH, the Niedersächsisches Forschungszentrum Fahrzeugtechnik (NFF) at TU Braunschweig and the Wolfsburg AG organized and hosted the lightweight design conference.

LOHRMANN MEDAL 2018

For 25 years, the Technische Universität Dresden has awarded the best faculty graduates with the Lohrmann medal. Among the 16 recipients in 2018 was IWS scientist Juliane Moritz. The prize dates to Wilhelm Gotthelf Lohrmann, the first director of the Technische Bildungsanstalt, founded in 1828, the forerunner of today's TU Dresden.

2018 was an eventful year. It is not just that the populists have come to the fore in politics in many countries. The Katowice Conference passed an agreement on implementing the Paris agreement of 2015. The German government established a program promoting solutions based on artificial intelligence – to mention only a few events. Fighting the causes of climate change and its consequences emerged as a mega trend that will be with us for a long time. There are no simple solutions available, even if some politicians want to pretend there are. The solution needed is more like a mosaic, in which a multitude of stones must be put together to create a coherent picture. Only a consistent recycling economy can maintain real sustainability.

The Fraunhofer-Gesellschaft participates in many projects in this field. One of the best-known is the Carbon2Chem project, in which valuable chemical resources are made from metallurgical gases by means of "green" hydrogen. Digital transformation penetrates all areas of life, work and research. Understanding and using data plays a decisive role in this process. The Fraunhofer-Gesellschaft is a catalyst here as well. Determining the fundamentals for an "international data space" provided a cornerstone for using data in an ethically justifiable way, in which the data creator maintains sovereignty over the use of his own data. Additive manufacturing is part of this digital change, too. Thanks to entirely new design, additive manufacturing now provides us with solutions that were inconceivable in the past. However, there is still much more research to be done in terms of manufacturing methods! The Fraunhofer Institute for Material and Beam Technology IWS is among the technology drivers here. Refining laser technology and systems is not only important for additive manufacturing and "printing" innovative components, but it also affects laser ablation and cutting, joining and thermal surface technology, as well as microtechnology.

In this context, let me particularly highlight the Joseph von Fraunhofer Prize, which IWS received for improved aircraft engine efficiency in 2018. The winners succeeded in using microstructures to increase the aircraft engine components' lifespan under high thermal load. This innovation reduces fuel consumption and CO_2 engine emissions. The decrease in turbine operation costs thus accelerated the new solution's introduction.

The scientific output and the excellent utilization of the institute's work demonstrate what we need today: not only digital skills, but also profound material and nanotechnology know-how in combination with comprehensive material and component characterization. It is precisely this ability to combine these technologies that provides an almost unbeatable factor for success. After having worked for 21 years at the Fraunhofer Institute for Material and Beam Technology and TU Dresden, Professor Ralf-Eckhard Beyer left the institute and retired in autumn 2018. His international reputation and expertise in laser technology shaped the foundation for its success and subsequent development. Since last year, he has managed the institute together with Professor Leyens, who is seamlessly continuing the institute's success story.

The Board of Trustees would like to thank the customers for their trust in our work, the IWS employees, their management, and all our partners for their collaboration, their commitment and the results achieved. We wish you a future full of success and health!

Yours truly,

Dr. Reinhold Achatz

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The Board of Trustees consults and supports the institute's management and the Fraunhofer-Gesellschaft bodies. The Board of Trustees held its 28th meeting at Fraunhofer IWS Dresden on 23 March 2018. We thank all trustees of the last reporting period:

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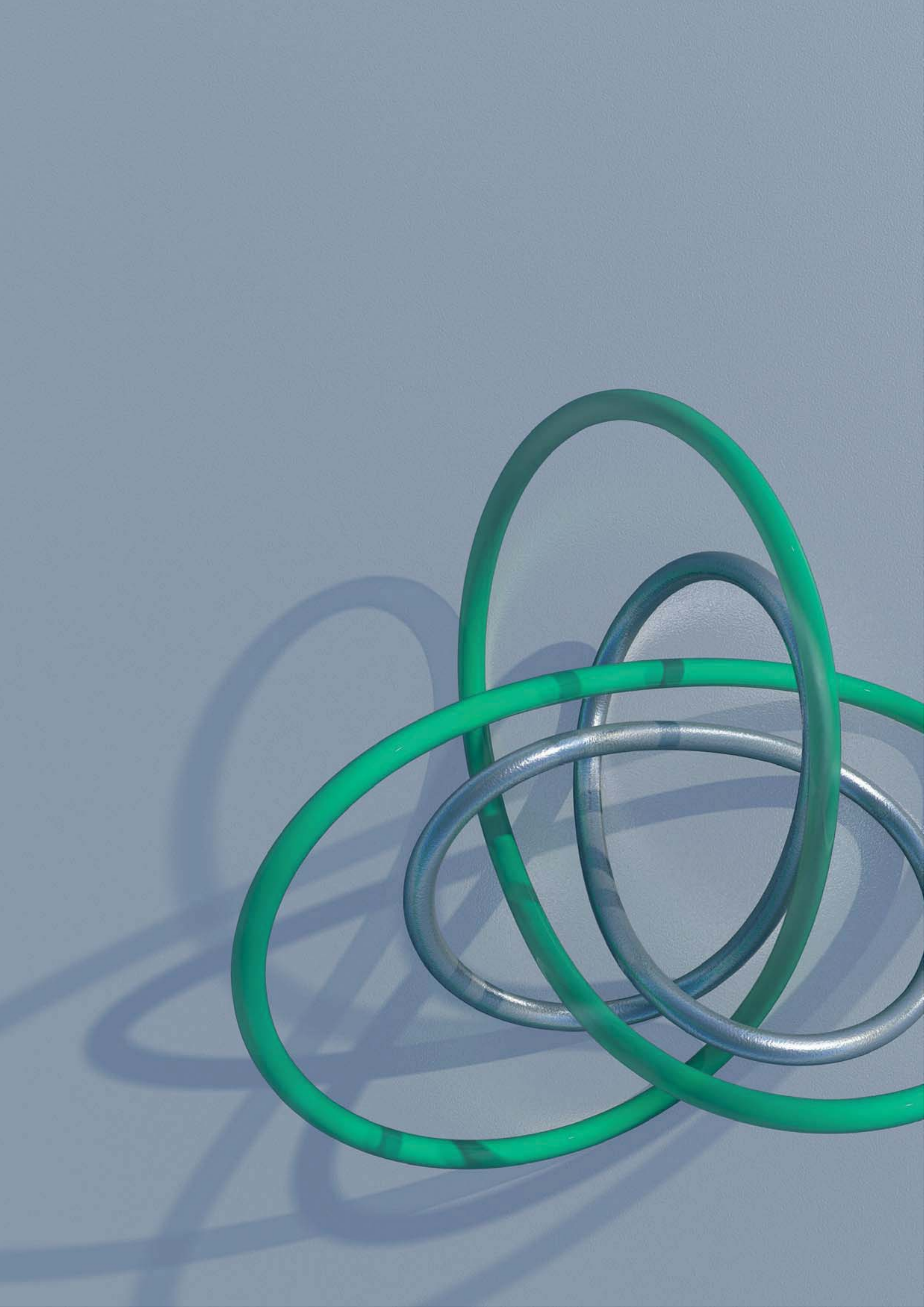

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THERMAL SURFACE TECHNOLOGY

ADDITIVE MANUFACTURING
AND PRINTING

JOINING

LASER ABLATION AND CUTTING

MICROTECHNOLOGY

MATERIALS CHARACTERIZATION
AND TESTING

PVD- AND NANOTECHNOLOGY

Business Unit Manager **Prof. Dr. Andreas Leson**

THE BUSINESS UNIT

Hard, low-friction, reflective or electrically conductive – the PVD and Nanotechnology business unit stands for unique surfaces. We research and develop techniques to produce various coatings and layer systems based on physical deposition techniques. The business unit's coating solutions have a wide variety of applications. Researchers focus on creating and utilizing super-hard carbon coatings, which are characterized by their wear resistance and low friction. Not only tribological but also functional parameters are relevant here: simulation methods and customized design imply that coating systems can be optimized for individual applications. Furthermore, the business unit specializes in fabricating extremely precise multilayers that are deposited with atomic level precision. Another major focus is the research and development of hard material coatings less or equal to 100 micrometers thick in order to enhance machine components' and tools' resistance and durability. The work also includes exploring coating procedures and engineering the suitable plants and systems.

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LOW FRICTION AND SUPERHARD: NEW LARGE-SCALE TA-C COATING SYSTEM

Superhard amorphous carbon coatings (ta-C) combine high levels of hardness with low friction and are thus the first choice for use as wear protection coatings. Applications for these coatings include highly stressed machine and engine components as well as cutting and forming tools and dies.

Together with VTD Vakuumtechnik Dresden GmbH, the Fraunhofer IWS team developed a large-scale ta-C coating system. The DREVA 1200 system – in combination with the LAM 850 laser-arc plasma source – provides a suitable basis to further industrialize the ta-C coating technology. Combined with a plasma filter, it is possible to reliably deposit on large areas low-friction coatings that are more than 70 gigapascals hard. Thanks to the optimized coating technology, we can also generate coatings that are several micrometers thick.

Precise control and plasma distribution

Fraunhofer IWS developed the laser-arc technology to produce ta-C coatings on an industrial scale from the initial concept to series maturity. The use of a laser source for high-frequency ignition of a pulsed vacuum arc that discharges on rotating graphite cylinders allows for precise plasma distribution control over the coating height, as well as an efficient coating process that is stable over the long term. This principle can be scaled efficiently so that now plasma sources with 400-, 500- and 850-millimeter coating heights for several applications are available. Vacuum arc discharging on graphite is inevitably accompanied by the emission of clusters that are several micrometers in width. The clusters are embedded in the epitaxial layer, causing it to be rougher. The embedded defects also reduce the coating's temperature and corrosion resistance. Considering the stringent coating performance requirements, it is necessary to filter the plasma to exclude the clusters. For this purpose, a filter was added to the plasma source for modular use. The filter's working principle makes use of the plasma's electrical properties. Here, the charged particles are guided into the coating chamber. The neutral clusters, however, are not affected and are mostly caught in the filter structure.

DREVA samples large components

For the DREVA 1200 large-scale coating system, IWS engineers evaluated the results for smaller-sized laser-arc plasma sources and applied them to a module whose coating height is 850 millimeters (LAM 850). This module is equipped with a latest-generation plasma filter and the coating procedure can be fully automated. The large-scale coating system's powerful pump system enables short cycles, while the sputtering source with a coating height of 1,200 millimeters provides homogenous and smooth adhesive layers. Thanks to the coating chamber's size, large parts can be sampled to determine additional applications for ta-C coating. These applications include primarily technological fields, in which friction and wear are critical issues. The ta-C coatings have already proven effective in combustion engines. Friction-decreasing ta-C coatings are applied to piston rings in series production.

1

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Next steps

The next step is to coat complex contours subjected to severe stress (such as wheels). Other applications target cutting and forming tools and dies. Tools to cut non-ferrous metals and abrasive fiber-reinforced plastics also benefit from the very hard ta-C coatings and the materials' low tendency to stick to the carbon surface. This results in a two- to fivefold increase in tool life in comparison with conventionally coated tools, with a simultaneously higher workpiece quality. These properties are also an advantage for forming dies, increasing tool life with less maintenance and enhancing dimensional accuracy at the same time. The researchers achieved particularly outstanding results with dies used to form aluminum, since the smooth ta-C surfaces prevent metal adhesion. Another ta-C advantage is that it is biologically clean; consequently, these coatings are also attractive to the food industry and can enhance medical products from tools to implants.

1 The LAM 850 module (bottom left) cuts the macro-particles from the plasma chamber and directs them into the coating chamber (right). This principle ensures smoother surfaces.

2 Substrate holder (top view) showing the DREVA 1200's pipe segments and test specimen clamp.

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TAILORED REACTIVE JOINING OF PLASTICS

The demand for innovative lightweight design is driving the development of novel materials and material combinations. There lies great potential in the use of plastics, in particular. This also increases the challenges faced by techniques used to join together plastics or combine them with different materials.

Conventional joining processes, such as welding, usually introduce considerable heat into the component, warming up not only the joint zone. As a result, the material's microstructure changes, which in turn leads to undesirable property degradation. Other processes, such as adhesive bonding, tend to age and demand pre- and post-treatments that can result in costly and time-consuming processes. Joining with reactive multilayer systems (RMS) offers an option to overcome conventional joining technologies' limitations. RMS are customized heat sources consisting of two chemical elements positioned in alternating layers. Introducing activation energy into this system causes a self-propagating exothermal reaction front that spontaneously sets free heat. This is used to melt the surface zone of the thermoplastics. Adhesive bonding is achieved by additional joining pressure. Fraunhofer IWS scientists designed the RMS technology for strong, damage-free plastic bonding without any pre- and post-treatment. They not only selected the suitable RMS, but also modified the joining pressure, and considered the joining parts' surface characteristics. While the appropriate RMS type primarily prevents damage to the thermoplastic matrix, joining pressure and surface roughness are decisive for ensuring high strength. Joining strength values ranging from 20 to 30 megapascals were achieved for many thermoplastics. RMS joints with thermoplastics offer long-term stability if the parent material itself is durable. Thus, for instance, the thermoplastics polyphenylene sulfide, polycarbonate, and polyamide 6 demonstrated excellent stability in various ageing tests. In addition to pure plastics joints, mixed-material joints consisting of plastics and metals are also interesting. The RMS technology also proved capable of fabricating strong hybrid material joints.

This research was partly funded within the scope of the IGF projects 19069 BG and 19035 BR/1 of the Research Organization of the German Association for Welding and Related Techniques (Forschungsverband des Deutschen Verbandes für Schweißen und verwandte Verfahren e. V., DVS), by the German Federation of Industrial Research Associations (AiF) in the context of the Program for Promoting Industrial Joint Research (IGF) and by the Federal Ministry for Economic Affairs and Energy by decision of the German Bundestag.

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1

FORMABLE HARD COATINGS – PROSPECTS FOR NEW WEAR PROTECTION

Innovative concepts for hard material coatings based on nano-scale crystal structures permit new property combinations. It is now possible to ensure high levels of hardness and at the same time reduce a material's tendency to crack during forming. In this way, components can be reliably protected against wear in cases in which moderate deformation in use cannot be prevented or is even desired.

Thin hard material coatings are used to protect tools and components against wear. These are mostly metal nitrides, carbides, oxides or borides, such as titanium nitride, titanium aluminum nitride or chromium aluminum nitride. Boron nitride, as well as several carbon modifications, are other relevant coating types The coatings are characterized by high levels of hardness, Young's modulus, and melting and boiling points in comparison with the relevant metals. Increased coating hardness is commonly accompanied by pronounced brittleness with very low elongation at break. Consequently, they are limited to use in cases characterized by very low base material deformation, such as for tungsten carbide cutting tools. Adequate coating solutions have until now been unavailable for many wear protection applications. Thus, forming dies have only rarely been coated. There are few durable wear protection coatings for light metal components. The reason is the layer's brittleness. Cracks appear at even the slightest base material deformation, and the coatings fail. New layer concepts based on nanostructured hard materials are harder and more temperature-resistant than traditional coatings. This benefits, among other things, the basis for the advanced cutting tool's excellent performance. Fraunhofer IWS Dresden scientists have now succeeded in combining these coating properties with enhanced ductility. They fabricated coatings based on a design using alternating thin layers made of AlCrSiN and TiN that achieved 25 to 30 gigapascals. Simultaneously hard and comparatively ductile, they enable crack-free deformation at a maximum of two percent. This is a first. Moreover, engineers can fabricate coatings that are more than 100 micrometers thick. As a result, users have entirely new options for wear protection coating applications. Initial applications on forging dies in industry demonstrate the performance that can be achieved. The layers remained intact despite extreme surface stresses and substantial die deformation during use. Other applications, such as to protect light metal components, are also conceivable. Coatings that are some tens of micrometers thick have an advantage here.

1 *Coated forging dies to forge transmission parts: although partially deformed during use, ductile hard material coatings withstand loads and stresses under which brittle coatings would quickly break or fail.*

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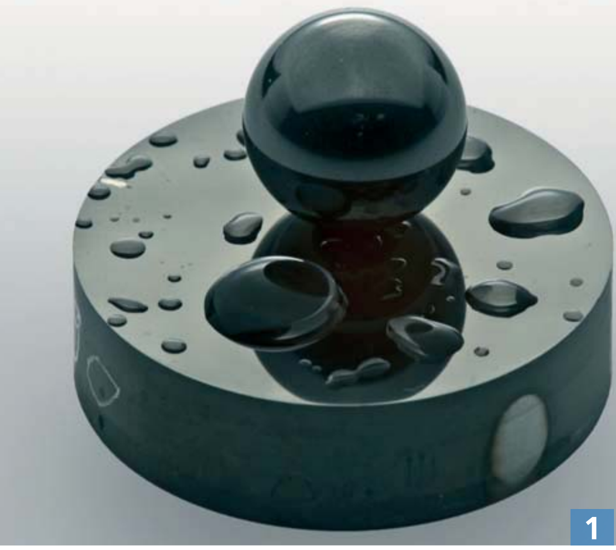


WATER AS A LUBRICANT

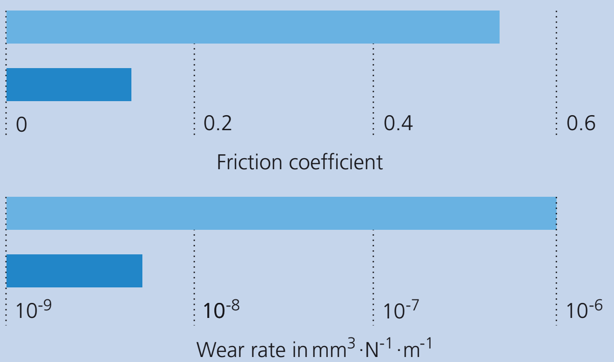
In many respects, water would be an attractive lubricant if it did not lead to undesirable cold welding in classical metal contacts due to its low load capacity. However, water and aqueous solutions are ideal lubricants for tetrahedral amorphous carbon coatings, since they passivate hard and smooth surfaces and enable sustainably optimal sliding conditions.

Availability, low cost, ideal environmental compatibility and its high cooling potential make water an attractive lubricant. However, water only forms a protecting lubricant film under certain circumstances due to low viscosity. In metal-metal contacts frequently in use, the contacting surfaces cold-weld, and, as a result, friction and wear are high and sliding contact sometimes fails. Therefore, oil-based lubricants are commonly used, requiring sealing and frequently also reservoir, filter and circulation systems. If water inevitably acts as a lubricant, for example in a water pump, complex non-metallic materials, such as sintered ceramics or diamond-coated surfaces, are needed.

A suitable lubricant for ta-C coatings

Fraunhofer IWS researchers have experienced that water is an outstandingly suitable lubricant for their in-house developed hydrogen-free tetrahedral amorphous carbon coatings (ta-C). Water passivates the smooth surface, prevents cold-welding with the counterbody and dramatically diminishes both friction and wear. The tribological properties are significantly enhanced even if only one frictional element is coated. Water as a lubricant is economically attractive if, for instance, ceramic components can be replaced by coated steel components or oil lubrication with all the infrastructure required. The ta-C layer's excellent tribological capacity, which is also true for other water-based substances, such as salt solutions, bases and acids, allows manufacturing entirely new, oil-free sliding systems for food processing, chemical and offshore industry, medical engineering and underwater applications.

Comparison of friction and wear for water-lubricated steel combinations with / without ta-C coating



Researchers performed a tribologic model test with water lubrication and one ta-C coated contact partner. Friction was reduced by at least a factor of 3 in comparison with the uncoated combination. Wear diminished by more than the 100-fold thanks to the ta-C coating.

1 Water is an eminently suitable lubricant for the hydrogen-free tetrahedral amorphous carbon coatings developed at the IWS.

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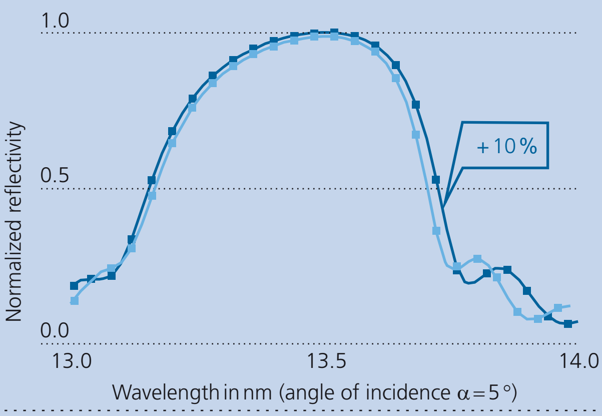
COATINGS FOR CUTTING-EDGE EUV PROJECTION OPTICS

The three-year EC project "Seven Nanometer Technology" (SeNaTe) carried out by Fraunhofer IWS and its numerous partners in the semi-conductor industry and research focused on next-generation lithography systems. The IWS contributed mirror coatings of projection optics for the 7 nanometer technology node's chip structures.

Within the scope of the SeNaTe project, IWS scientists refined coating methods for reflecting multilayer mirrors for the so-called High-Numerical-Aperture, or High-NA, projection optics. These optics systems are characterized by complex surface geometries and high apertures. This requires not only maximal reflection behavior, but also sophisticated and extremely precise layer thickness distributions, as well as minimal layer stresses at the same time. A significant step in developing the plasma-based deposition methods was to reduce the high spacial frequency roughness values (HSFR) of all interfaces incorporated in the layer stack. In this way, IWS researchers succeeded in increasing an individual mirror's maximum reflectivity by more than two percent in comparison with conventional methods at 13.5 nanometers operating wavelength. The spectrally integrated intensity of the EUV peak increased by more than 10 percent. Thanks to the large number of reflective surfaces in High-NA optical systems, these improvements significantly increased the entire system's transmission. These optical parameters are decisive for the performance and wafer throughput of state-of-the-art lithography systems. Introducing EUV lithography into industrial semiconductor fabrication at the 7 nanometers technology node and beyond is in progress – also thanks to the SeNaTe project results.

Reflection spectrum of IWS' latest EUV mirror coating



As a result of optimized coating and enhanced stack design, the EUV mirrors have both higher peak reflectivity and a spectrally wider reflection curve. The spectrally integrated intensity of the EUV peak increased by more than ten percent in comparison with the standard procedure.

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CHEMICAL SURFACE AND REACTION TECHNOLOGY

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THE BUSINESS UNIT

The business unit Chemical Surface and Reaction Technology focuses on next-generation batteries. Central research topics include electromobility and stationary energy storage. The scientists design methods for fast, efficient and reliable battery manufacturing; they focus not only on lithium-sulfur technology, but also on other innovative approaches, such as solid-state batteries. They rely on an in-depth understanding of the chemical processes inside the battery. This is the basis for IWS scientists to develop adapted system technology, monitoring and characterization methods to quickly analyze processes and coatings of varying dimensions by means of imaging techniques. For surface analysis, the team combines detailed technical expertise in system design with sophisticated materials knowledge. No matter whether coatings or functional materials are developed, the team has profound knowledge of the physical properties and application characteristics. The business unit also offers customized methods for surface evaluation, such as optical inspection by means of hyperspectral imaging.

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ENVIRONMENTALLY FRIENDLY FABRICATION OF BATTERY ELECTRODES: SOLVENT-FREE

The demand for cost-efficient fabrication techniques for battery cells has increased due to the continuing rise in the number of electric cars and portable electronic devices. Costly high-energy processes are currently still in use, particularly in battery electrode production. IWS dry coating technology provides a suitable alternative to meet this need.

How can costs of future battery cells be reduced? Scientists at Fraunhofer IWS are responding to this question by exploring two approaches: in addition to material engineering to use cost-efficient active materials, alternative manufacturing processes for battery electrodes are an essential prerequisite. The battery electrodes are currently produced in a four-step procedure. The scientists mix active materials and additives and process them into pastes using an organic solvent. Deposition on thin metal foils is followed by an extensive drying process. This step is especially costly and difficult if toxic organic solvents that cannot be emitted into the environment are in use. The solvents are cleaned in distillation processes and recovered for repeated use in the process. This development aims to replace processes based on toxic materials with more environmentally friendly and cost-efficient techniques based on water. Water-sensitive battery materials are being used, so that paste-based electrode fabrication is no longer the method of choice. Solvent-free coating techniques provide an alternative. The battery researchers at Fraunhofer IWS have been using them for material engineering on a laboratory scale for several years. In this process, they can work without any solvents at all. A bonding agent is the key to success – once mixed with the active material, it forms so-called fibrils under the impact of shearing stresses. Like the threads in a spider's web, the fibrils keep the active material particles together. Thus, the mixture can be processed into coatings on metallic current collector foils.

Successful battery cell tests in the lab

The researchers at IWS have already evaluated this electrode fabrication procedure for various battery cell technologies on a laboratory scale. They succeeded in processing both active materials for lithium-ion batteries, such as lithium-nickel-manganese-cobalt oxide (NMC), as well as next-generation battery materials, and tested them in battery cells. As a result, they could produce cathodes for so-called lithium-sulfur batteries. These cathodes can produce battery cells with a higher energy density (360 watt-hours per kilogram) than possible with current lithium-ion technology (250 watt-hours per kilogram). In cooperation with the Finnish start-up BroadBit Batteries Oy, the IWS team also developed dry film electrodes for a battery technology based on sodium ions. This technology is compelling because of its use of low-cost active materials.

Setting a new standard in research and development

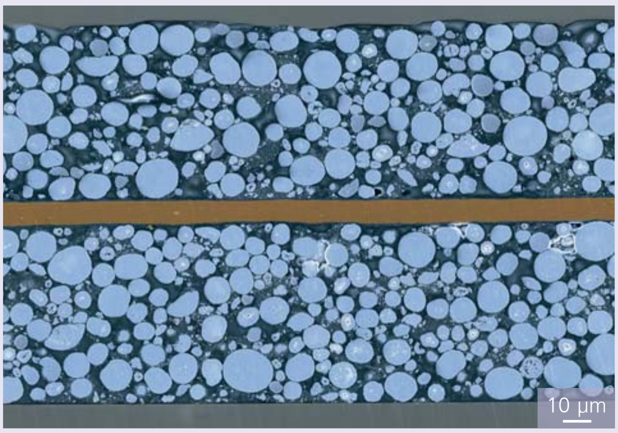
The scientists at Fraunhofer IWS aim to establish a wide-spread use of compact dry coating calenders for electrode fabrication in battery research labs. This should be an addition to the widely used doctor blade coating technology. In a multidisciplinary team, mechanical engineers and materials scientists designed a tool that enables the efficient and reproducible fabrication of dry film electrodes of up to ten centimeters

in width on a laboratory scale. The compact table-top unit is also suitable to process extremely moisture-sensitive materials like those used in solid-state batteries. For this purpose, the scientists can operate the unit in dry air or even under inert gas atmosphere in so-called glove boxes.

Prototype system development

The battery experts are not only making progress in research and development on a laboratory scale, they are also implementing processes and systems as prototypes. In an innovative powder-to-roll technique, they succeeded in implementing the dry coating process for continuous battery electrode fabrication on twenty-centimeter-wide rolls. This is a decisive step forward in securing the technique's usability in industry. Here, IWS scientists are also responsible for designing prototype systems and system technology in order to investigate this novel electrode manufacturing process in more detail. In the joint European project DryProTex, they collaborate with material and cell producers as well as plant and machine manufacturers to further enhance the technological level of the innovative dry coating procedure so that it can be reliably run in industry. In future it will be possible to fabricate battery electrodes without toxic solvents. Even the high-cost drying steps can be avoided so that innovative materials can be used. Thus, the scientists at Fraunhofer IWS are significantly contributing to reducing battery cell manufacturing costs.

Scanning electron microscopic cross-section view of an NCM electrode (lithium-nickel-cobalt-manganese oxide) made using the IWS dry coating technique.



The IWS solvent-free electrode fabrication process allows the processing of a wide range of active materials. The image shows a 10 µm thin aluminum foil (orange inked) that is NCM coated (blue inked). Thanks to the extremely low bonding agent ratio, highly compact electrodes that can be appropriately accessed by the electrolyte can be produced on ultra-thin metal foils.

1 *The prototype unit at the Fraunhofer IWS continuously fabricates electrodes without the use of solvents, making meter-long drying lines and systems for solvent recovery obsolete.*

2 *The compact dry coating calender enables solvent-free battery electrode fabrication on a laboratory scale. The IWS table-top unit is an alternative to the established hand-coating units for research and development.*

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NEW MATERIALS AND PROCESSES FOR FUTURE BATTERY SYSTEMS

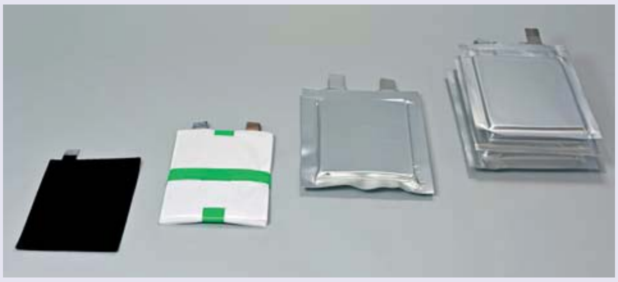
The BamoSa Wing-Center (Wing-Zentrum) has been representing excellence in battery research in Dresden since 2013. Current projects on nano- and microstructured silicon anodes reveal their potential to increase the conventional Li-ion cells' energy density by up to 40 percent. By applying a closed process chain at Fraunhofer IWS, researchers can demonstrate the innovative materials in prototype cells.

Coordinated by IWS, scientists from Dresden are developing new solutions to enhance lithium-ion battery cells' energy density in the BamoSa Wing-Center. The researchers see prospective increases in the energy content per volume from currently 600 to 700 watt-hours per liter to more than 1,000 watt-hours per liter. One of the objectives is to extend the range of electric cars with the same required space for the battery. A more than 40 percent increase in the energy density compared to current lithium-ion technology is a challenge and can only be answered by using innovative materials.

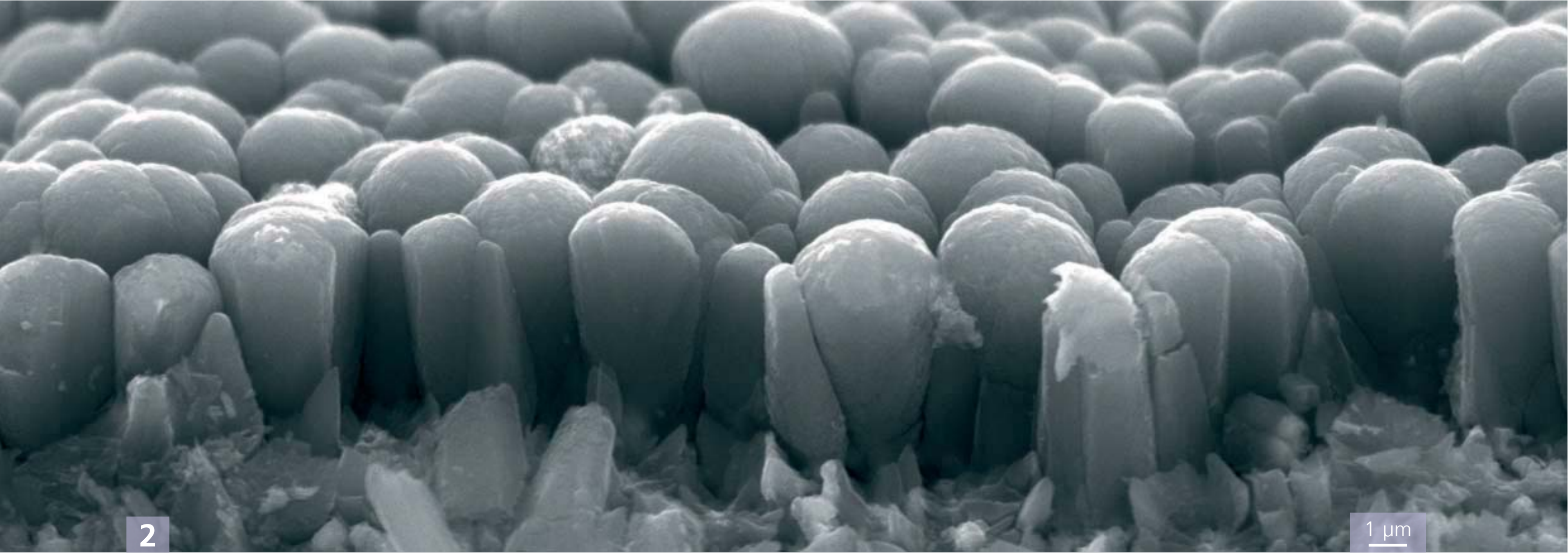
Increase in energy density due to new silicon anodes

Replacing conventional graphite anodes by silicon anodes is one of the most promising approaches to increase energy density. During charging, the lithium ions in silicon have a capacity tenfold higher than in conventional graphite anodes. This produces silicon-lithium alloys occupying almost 300 percent of the volume taken up by the base materials. The great challenge here is material design itself, which needs to compensate for this change in volume as much as possible and without significant degradation. At the same time, researchers also have to design compact electrodes to achieve maximum energy density. The BamoSa scientists compare studies of silicon nanowires, silicon-carbon-nanocomposites and microstructured silicon coatings. For this application, the scientists generate materials with a defined structure and use them as the anode in lithium-ion cells. They compare the electrochemical with the structural material parameters by means of various test methods. Nanomaterials (nanowires and composites) excellently compensate for the change in volume and can be charged and discharged up to 200 times. If the task is to store maximal energy in a minimal volume, the microstructured silicon coatings are particularly useful. Using chemical vapor deposition (CVD), these club-like structures can immediately be deposited on copper foils. Silicon layers that are approximately 10 micrometers thick can take up the same capacity currently stored by 60-micrometer-thick graphite anodes. This approach obviously provides significant increases in volumetric energy density.

Pouch cell formation



IWS pouch cell manufacturing: the cells are assembled by stacking individual electrode and separator layers. As a result, industry-oriented material tests can be realized for an extremely wide variety of cell systems.



Tailored evaluation of new materials in prototype cells thanks to a flexible process chain

The BamoSa project demonstrates the feasibility of these and other material concepts. Researchers at the IWS Center for Battery Research employ an established process chain for battery cell production and evaluate the new cell components in industry-oriented prototype cells. The process chain includes:

1. **Electrode fabrication**
   The scientists develop and apply not only a roll-to-roll system for paste coatings, but also new techniques, such as CVD and PVD for silicon or melt deposition techniques for lithium coatings.
2. **Laser cutting**
   The researchers apply an automated system for electrode separation by laser cutting under monitored dry air atmosphere. They can flexibly adapt the system to various materials and cell formats.
3. **Cell assembly**
   The research team combines electrodes and separators to cell stacks, contacts and fills them with electrolyte. A fully automated and scalable stacking system is available.
4. **Poling and testing**
   More than 300 testing and formation channels are available for comprehensive battery tests.

Initial prototype cells based on the new silicon anodes and conventional cathode materials have already achieved energy density values greater than 600 watt-hours per liter and thus match the performance of the best lithium-ion cells on the market. However, this motivating functional evidence is only the beginning. In subsequent steps, the researchers strive to further exploit the silicon anodes' potential for an ongoing increase in battery cells energy density. This requires specifically adapting all cell components and defining suitable operating conditions. Balancing both the anode and cathode capacity and selecting the electrolytes is very important here. Fraunhofer IWS relies on its many years of expertise in the design of lithium-sulfur cells. At present, they have already achieved an energy density (related to cell weight) 40 percent higher than the best lithium-ion cells. Thanks to its wide network of partners and customers, the renowned Center for Battery Research at IWS offers a wide R&D portfolio that includes:

- Application-oriented material evaluation in pouch cells
- Holistic prototype cell development (including lithium-ion, lithium-sulfur, sodium-sulfur and solid battery cells)
- New electrode fabrication processes, development and technology transfer into industrial application

1 Laser cut anodes for various battery cell formats. The automated process enables flexible modification for various cell formats. This makes it possible to assemble anodes in a customized way.

2 Scientists at IWS deposit silicon coatings with a defined structure using CVD and PVD techniques. They control the anode characteristics in the battery application by adjusting coating structure and thickness.

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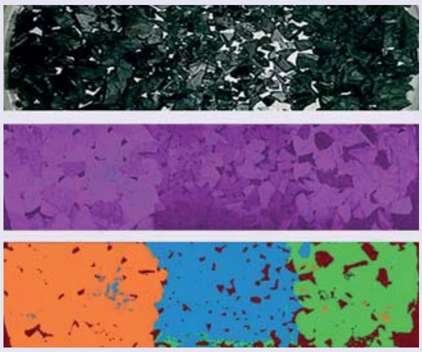
CREATING "MANY COLORS" FROM "BLACK" USING LASER LIGHT

Laser light allows for many new applications in quality and optical inspection for hyperspectral imaging. Samples that are difficult to access with classical spectral imaging can be analyzed with this new technology.

Hyperspectral imaging is a rapidly growing field in optical inspection technology, especially in continuous 100 percent testing. Users can obtain detailed information about the specimen's chemical composition and morphology due to the radiation that is reflected by the object and investigated in spectrally and laterally resolved measurement. Subsequently, quality parameters of the samples can be derived or defect areas can be easily localized by automated evaluation. Typical hyperspectral cameras operate in the visible or near-infrared wavelength spectrum with halogen lamps as illumination source. Alternatively, engineers can use hyperspectral imaging developed at Fraunhofer IWS in combination with a laser as an illumination source. This enables the development of new applications for hyperspectral imaging.

Classification of black plastic specimens



Specimen (photo, top), segment (cutout, section) of hyperspectral measurement at 650 nm (center) and classification (PA6, PA66 and TPU, bottom).

Classification of black plastics and more

Classifying black technical plastic waste is one of the possible applications. Huge amounts of black plastic waste are produced in the automotive and electronic industry. From an environmental and economic point of view, recycling options beyond thermal recycling are desirable. However, this goal involves separating and sorting the plastics, which cannot be achieved with current methods. A hyperspectral camera can detect and classify different plastics by laser excitation. This setup enables quick and efficient recycling. In addition to use in recycling, the technology offers other interesting applications in pharmaceutical industry, food inspection and material testing.

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CLEAN AIR AT WORK

Wherever materials are processed at high temperatures, there is a risk of invisible pollutant emissions into the working environment. To ensure clean air and thus maximum health protection at all times, it is necessary to reliably identify and efficiently eliminate potential risks and hazards in the air.

Nanoscaled dusts and toxic vapors appear in many industrial manufacturing processes for material welding, cutting or ablating. Dusts and vapors invisibly infiltrate the work environment and can be inhaled or penetrate the human skin. Significant health risks arise from these emissions. Depending on the process and the materials being processed, a wide range of gases, hazardous and ultrafine particles are produced. The team at Fraunhofer IWS identifies potential hazards with state-of-the-art measuring methods and devices, evaluates filter systems in order to eliminate these hazards and thus provides competent solutions for a clean workspace.

Efficient occupational health and safety through individual process assessment and safety measures

Both the choice of materials to be processed and the process conditions can substantially contribute to reducing hazardous substances. The IWS' cooperation with Elbtal Plastics highlighted this for thermal PVC film welding processes. Lower process temperature and an optimized film material reduced emissions of hazardous substances to a minimum. In the case of an unavoidable release of pollutants, for example during laser processing of certain materials, individual protective measures must be taken. Many years of expertise in evaluating commercial and advanced materials allow Fraunhofer IWS to provide the basis for the development of innovative, specific filter systems and thus, cleaning air in work environments.

Processing a PVC film

Swimming pools are lined with foil webs which are welded to ensure reliable water impermeability. Due to state-of-the-art measurement technology, Fraunhofer IWS shows that the film material from Elbtal Plastics releases only a minimal amount of pollutants during thermal processing.

1 *During welding materials, hazardous pollutants can enter the work environment. This calls for suitable protective measures.*

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THERMAL SURFACE TECHNOLOGY

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THE BUSINESS UNIT

A highly automated process from a single-source: the researchers in the Thermal Surface Technology business unit consider the entire value chain of systems engineering and process engineering with respect to coating structures and heat treatment. Energy and resource efficiency meet the process requirements both economically and ecologically. The business unit scores with its experience in research and practice in all those cases in which it comes to efficiently designing processes with a high degree of complexity, converting them into innovative processes and bringing them into line with the target product. The services offered include process and systems engineering for laser-supported coating and layer techniques, thermal spraying, and heat treatment with a special focus on highly precise surface layer hardening. With the catchphrase Industry 4.0, the researchers at Fraunhofer IWS constantly strive for higher levels of automation. The major goal is to guarantee the process reliability of an efficient, proven technology to prevent costly downtime and provide for competitive and high-quality final products.

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ONE-STEP LASER-ASSISTED THERMAL SPRAYING

Steps against anisotropy and low homogeneity are among the challenges affecting classically sprayed layers. Based on laser assistance in the coating procedure, the Fraunhofer IWS team engineered a "one-step solution" to immediately apply homogeneous high-performance metallic coatings.

Copper-based coatings are materials offering outstanding application potential, for example in electrical and automotive engineering. This is primarily due to its excellent electrical conductivity. Relevant examples are, for instance, strip conductors of all sizes made of pure copper, tungsten-copper electrodes, forming dies and molds, welding equipment made of AMPCO copper, as well as copper-tin and copper-zinc sliding bearings. Materials currently processed include environmentally critical alloys, such as beryllium-copper, which have to be replaced as soon as possible. One of the challenges encountered in thermal spraying of electrically conductive materials is the oxidation of the feedstock during the process, which increases the coatings' electric resistance. Moreover, the typically anisotropic structure results in differing electric properties along and across the coating.

Low pressure for high profitability

The new low-pressure cold spraying technique (LPCS, German abbrev.: NDKGS), in which the engineers inject powder into diverging nozzle sections at approximately six bar provides an attractive solution. LPCS systems are typically compact in design and mobile in use, and costs amount to only about ten percent of the investment required for a high-pressure cold gas spraying system. However, feasible particle velocity values impart the risk of particle-to-substrate bonding defects. To refine layer adhesion, only specially mixed powders including uncongenial ceramic particles are currently in use. However, the enclosed hard particles have a negative influence on the layer microstructure; they represent layer defects and contribute to inhomogeneities. This limits the range of applications for LPCS as a coating solution.

Laser impact on coating structure

A comparison of coatings obtained with commercial copper powder including alumina particles, fabricated without (top) and with (bottom) laser support. Positioned such that it runs ahead of the spraying particle beam, the laser spot improves bonding to the substrate.

Hybrid copper coating without alumina particles

Guided in an overlapping way and following the spray beam, the laser enables the fabrication of pure copper coatings without any pores and cracks.

Universal hardware systems with laser beam energy

One solution to overcome the anisotropic structure and the bonding defects is additional heat in the process, excactly where it is needed. Fraunhofer IWS engineered a new hybrid laser spraying head which can not only be integrated into LPCS, but also into conventional spraying systems. The laser beam offers advantages as an energy source for hybrid coupling with thermal spraying processes thanks to its targeted selection, precise controllability and low total heat input. Users can exploit the laser beam's energy intentionally for substrate pre-treatment, process support, and layer post-treatment. The key to solving the anisotropy and adhesive bond strength problem lies in the positive metallurgical effects that are used intentionally after the spray structure has been formed during the laser-induced heat treatment in the ongoing process. In commercial high-power lasers, the physically limited laser wavelength absorption commonly amounts to between 860 and 1,024 nanometers. Multiple reflections in the sprayed particles' jet and the splat-like morphology of the emerging spray layer significantly improve the values. New laser beam sources in visible green and blue wavelength ranges hold additional potential to achieve at least 40 percent radiation absorption. These types of high-power lasers are innovative beam sources whose application potential is still widely unexplored. Above all, they offer the possibility to implement the technically realized solution for the mentioned copper materials with high relevance for later industrial employing.

Improved bonding without admixed oxide

Making use of the new hybrid laser spraying head, the IWS scientists verified the achievable metallurgical effects in practice. Even using conventional spray powders containing aluminum oxide (alumina), simultaneous laser support reduced the pore and defect percentage in the solidified sprayed structure. Moreover, as a result of the laser impact an oxide admixture becomes superfluous, since dense, adhesive coatings are formed nevertheless. The binding mechanisms of the layer to the substrate even go beyond the otherwise characteristic type of purely mechanical bonding and exhibit advantageous amounts of a melt metallurgical bond. As a result, the one-step laser-supported spraying process provides very promising coating solutions offering a wide application potential for all those coating systems demanding further improved bonding and intentional coating morphology modification.

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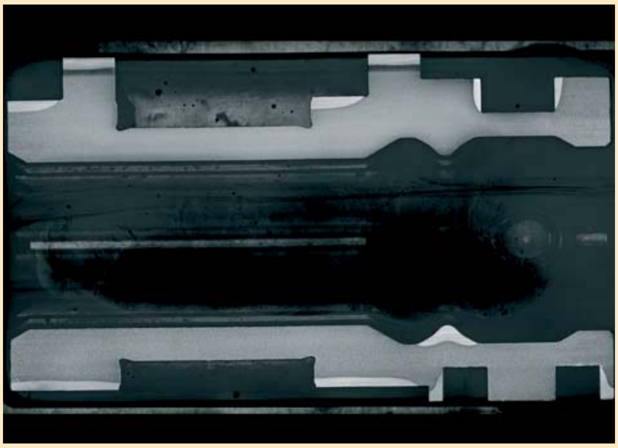
SURFACE LAYER HARDENING BY LASER SPEEDS UP ENGINE PRODUCTION

Flexible valve control in cars increases engine efficiency, up to switching off entire cylinders. This function is made possible by special-design camshafts whose cams are fixed and can be shifted in the axial direction. High-precision surface layer hardening by laser secures entirely new manufacturing concepts and improves product durablility.

Advanced camshaft systems combine the original opening and closing valve functions with additional unit efficiency optimization via control and closed-loop systems. While previously these units were conventionally produced by forging or casting, the cam parts and support shaft components are currently manufactured separately. The advanced design strategy required a complex system with free-sliding cams for finer controlling engagement rather than a fixed single cam-valve assignment, which resulted in a major change in manufacturing. Optimizing this design makes engine cycles more flexible and adapts units to driving situations as needed, for instance in order to switch off cylinders. Traditional hardening techniques aimed at providing local wear resistance and increasing durability are suitable for advanced Industry 4.0 manufacturing concepts only to a limited extent. Lasers are ideal heat treatment tools also in terms of energy consumption and for intermittent processes. To implement an efficient manufacturing flow, a multi-step hardening technology is required that performs precise hardening in a highly cyclical manner only where needed, i.e. at points where complex design makes it necessary. The structures, such as cams, shifting grooves, and detent teeth to hold the parts on the support shaft undergo laser heat treatment within the necessary geometric limits.

Laser-hardened cam part – polished and etched cross section (microsection)



Microsection of a laser-hardened cam: The IWS development aimed at hardening just the wear-relevant positions to achieve the required wear resistance and durability.

Switching off cylinders under partial load thanks to a new manufacturing strategy

The researchers at Fraunhofer IWS Dresden engineered a cam laser hardening procedure for a German car manufacturer's new engine design. This motor concept makes it possible to switch off two of four cylinders under partial load. This significantly reduces fuel consumption and carbon dioxide emissions. The developments at Fraunhofer IWS aim at precisely hardening the cam's complex geometry at the highly stressed contours. This ensures the necessary wear protection. This new combination of local laser hardening and intermediate mechanical manufacturing steps is the basis for an extremely close fit. As a result, operating loads are significantly lower. The IWS researchers developed a specific multi-step hardening procedure. The cam working surfaces are hardened in the first step. Next, the shifting grooves' surfaces and edges subjected to extensive

wear during cylinder switching are laser-hardened. Having manufactured the internally toothed geometry, the engineers harden the detent tooth only in the final heat treatment step and finish the component afterwards. The researchers at the IWS use high-power diode lasers that in general prove to be efficient laser hardening tools offering outstanding performance and beam quality at a reasonable price, along with a wide variety of available optical systems. The scientists employed the dynamic beam shaping system "LASSY" designed at Fraunhofer IWS to harden the cam contours tailored to the expected stress levels in the shortest possible cycle time.

Fully automated and reproducible laser hardening

In the processes, high-power diode lasers work simultaneously. Since hardening demands precise temperature control, the scientists combine an "E-MAqS" infrared camera with the "LompocPro" temperature control. The control system adjusts the hardening temperatures fully automatically and reliably despite the extreme changes in geometry during the process and monitors them at each position. At the same time, the control allows the individual component processes to be traced. The algorithm uses the process data generated in the system to index parts and monitor their quality. Defective components are automatically rejected from the line.

All in line

Unlike conventional batch processes, engineers now produce cams in line. In this process, they input less energy into the component than in conventional hardening techniques. The Fraunhofer IWS task was to select the materials, design technologies and manufacture the prototypes. Based on the results, the IWS team designed the series production system together with the equipment manufacturers, modifying and integrating the system components designed at Fraunhofer IWS. The scientists refined the series processes in production and assisted the launch on site. They modified the process-relevant parameters, such as the laser beam profile, hardening temperature, path speed, and laser position for the series equipment. During development, the researchers were also involved in selecting materials and assisted the car manufacturer in customizing the parts and units in terms of design and process chains for laser hardening.

1 *Researchers at the Fraunhofer IWS developed a cam laser hardening procedure for an advanced engine concept. This strategy made possible efficient part production using the new manufacturing strategy.*

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TREND-SETTING: LASER FINE WIRE CLADDING IN NEW DIMENSIONS

To utilize the wide welding wire diameter range in laser wire cladding (LWC, German abbrev.: LDA), researchers at Fraunhofer IWS redesigned and patented the laser fine wire optical system "COAXwire mini" equipped with integrated sensors. Following a coaxial, miniaturized, modular and robust design serves optimal use for cladding, repair and 3D additive manufacturing.

The industrial laser cladding user's requirements and targets have become more demanding and complex. Wires are increasingly relevant among welding fillers. With this in mind, the engineers at Fraunhofer IWS developed the laser fine wire processing optical system "COAXwire mini" – based on long-term practical experience with the established COAXwire system and methodical design. Essentially, they maintained the proven coaxial three-beam optical system so that, independently of the direction, the operator can work in almost any welding position that is technically useful. The laser optical system enables the user to process wires 0.1 to 0.6 millimeters in diameter with exchangeable driving units for typical fine wire feeders of the latest generation. The optical system's specifically developed design allows the use of fiber, disk, diode lasers and even lasers in the blue and green wavelength range. Thus, the operator now can use all available laser sources with wavelengths from 450 to 550 and 890 and 1,100 nanometers for direct metal deposition. Depending on the absorption characteristics of the metallic alloy used as the weld metal or substrate, users can optimally adjust the laser wavelength for each material. Thus, they can process a wide material range, including those used in aviation, medical technology and tool making, wavelength-selectively in an energy-efficient manner. With a fixed optical aspect ratio of 1:2, the focus diameter can be easily set by the choice of a fiber diameter according to the wire dimensions. An integrated miniature camera allows monitoring of the processes, and crossjet flows deflect unwanted spatters. The centrical wire feeding system can be finally adjusted in XYZ directions. A further feature of the COAXwire mini, besides its reduced weight and smaller installation space compared to COAXwire, is the water-cooled, environmentally friendly fume and smoke extraction module, which filters toxic metal vapors during the welding process and extracts them in any direction. The sensors integrated in to the processing optics monitor protective glasses, cooling water flows and temperatures.

1 Hollow shaft cladding (material: X45CrSi9-3), laser fine wire cladded in a corrosion-resistant way.

2 Redesigned and patented laser fine wire processing system "COAXwire mini", equipped with sensors.

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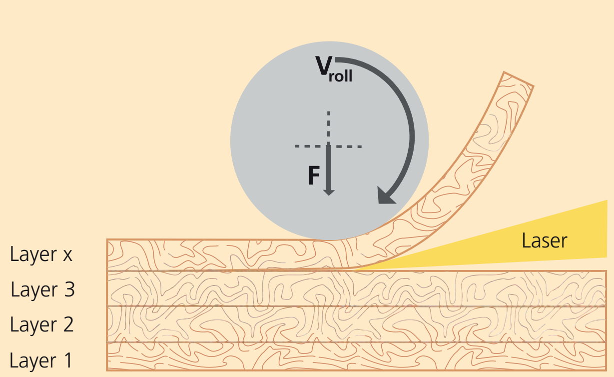
EFFECTIVE SURFACE JOINING PROCESSES FOR OPEN-POROUS METALLIC FOAMS

In chemical processing equipment, pellets consisting of open-porous metallic foams are used in huge amounts as catalysts. Due to the manufacturing process, these can only be produced as thin mats. In a further processing step, they are connected to each other over their entire surface. Researchers at Fraunhofer IWS developed a technique to join these foam mats more effectively and with less compression.

Firmly bonded, very thin-walled joints are generated with brillant laser beam sources. For industrial use, thin metallic foam mats like those fabricated by Alantum employing a patented powder-metallurgical technique, have to be joined together on their surfaces. The foam webs are a few micrometers thick. The Fraunhofer IWS team engineered a joining mechanism and applied it to join the surfaces of foams. If a gap is intentionally created during foam layer feeding, the high laser intensity is able to heat the internal surfaces quickly and fuse them partially. When compressing the foam mats, the opposite fusion drops bond. To keep heat input low, the scientists conduct the procedure continuously at a feedrate of two to three meters per minute. They control the joining zone width with a dynamic 200-millimeter deflection scanner. The metal foam hardly deforms during pressing and is consequently only minimally compressed, retaining its porosity. The compound in the joining zone does not diminish the material's porosity. Surface metallic foam welding over an opened gap is a very effective method to join several metallic foam mats. As a positive side effect, the compression losses are significantly reduced compared to conventional joining processes.

Schematic test setup to surface-join several metallic foam layers



The metallic foam layer surface joint results from combining welding by laser beam and a continuous press-on force F with rate of revolution V_{roll}. Foam porosity and thus effective functionality are preserved when using the method developed at the IWS.

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ADDITIVE MANUFACTURING AND PRINTING

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THE BUSINESS UNIT

Researchers in the Additive Manufacturing and Printing business unit apply materials layer by layer for a wide range of applications. They fabricate complex parts from basic materials, such as powder, wire, pastes and foils. They primarily work with metals and plastics, applying technologies including remelting, additive manufacturing and printing. This approach relies on profound technological and material expertise. Only by combining them can additive manufacturing be used to create sophisticated, innovative parts that are both cost-effective and reliable. The team applies various processes, such as laser cladding, using powder, electron and laser beam welding, and hybrid methods, which combine subtractive with additive techniques. In this process, Fraunhofer IWS scientists not only focus on the individual process, but also investigate and develop solutions along the process chain. Together with customers from industry, they follow the entire path of development from the initial idea to the feasibility study to system hardware engineering to full marketability.

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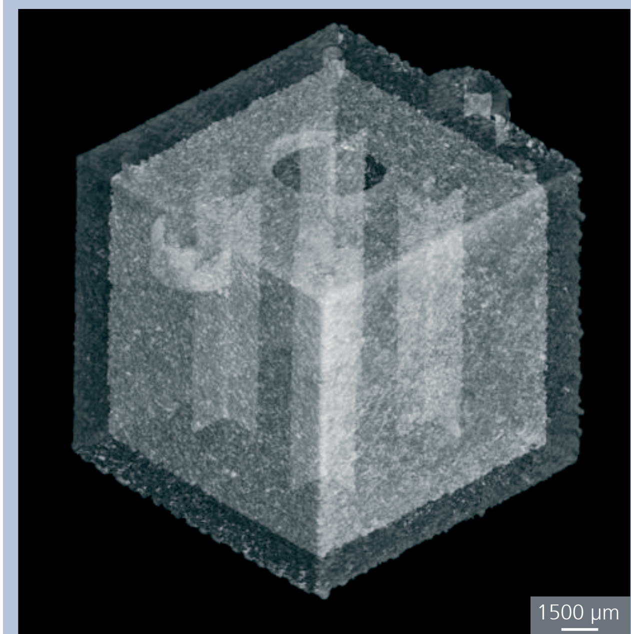
ADDITIVE MANUFACTURING MEETS SPACE

In close collaboration with the European Space Agency (ESA), IWS researchers are applying additive manufacturing techniques to develop innovative aerospace applications that were unimaginable until recently.

Additive manufacturing's cutting-edge qualities and advantages in comparison with conventional production techniques make it particularly interesting for space applications. Major advantages include the ability to integrate additional functionalities or complex structures into the component immediately in manufacturing, to significantly reduce weight thanks to highly complex geometries, and to process specific materials more easily. Researchers at Fraunhofer IWS are currently running nine projects focusing on additive manufacturing for space applications in the context of various European Space Agency (ESA) programs. Some of the applications developed in close cooperation with ESA are presented in this section.

CT image of a metallic hollow body



Example of an internally structured metallic hollow body, made by laser powder bed fusion (LPBF).

New materials for optical space components

The additive manufacturing process Laser Powder Bed Fusion (LPBF) enables the production of highly complex geometries and also offers the potential to use new materials that are difficult to process with conventional techniques. Together with Kampf Telescope Optics, the Fraunhofer IWS team manufactured highly complex mirror carriers from the crack-critical aluminum-based alloy AlSi40 (60 mass percent aluminum, 40 mass percent silicon). This alloy is not only characterized by outstanding material properties, it is also thermo-physically compatible with the nickel-phosphor (NiP) optical coating material. The engineers at Fraunhofer IWS not only produced crack-free solid specimens along a tailor-made process chain. By means of targeted process control and heat treatment, they were also able to exceed the strength of conventionally manufactured materials by more than 20 percent. Based on the material data determined, the calculation engineers at Kampf Telescope Optics optimized the topology in terms of the optomechanic properties. Targeted lattice structures enabled both enhanced optical performance and a mass reduction of more than 30 percent.

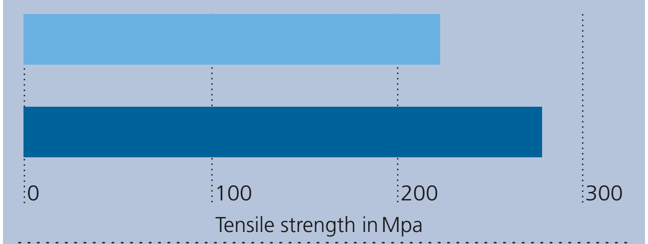
Enhanced complexity for higher efficiency

In aerospace, coils are applied for a wide range of applications. Coils are, for instance, used for satellites' position control and to actuate solenoids. Since each solenoid is customized for each application, conventional coil fabrication is time-intensive and costly. The conventional process chain also limits design and, consequently, the efficient solenoid systems' potential cannot be fully utilized. In cooperation with ZARM Technik, researchers at Fraunhofer IWS analyzed laser powder bed fusion (LPBF) technology as a manufacturing technique applied to highly complex solenoids for aerospace applications. They considered adapting the scanning strategy, designing customized support structures, and using new coating technologies in detail. As a result, the researchers succeeded in fabricating application-optimized solenoids with additive manufacturing. The "additive" solenoids are characterized by spatially resolved cross-section dimensions of up to one square millimeter, which are intended to significantly increase their efficiency. The next goal is to experimentally examine these complex coils on the test bench with regard to the achievable efficiency increase.

Frame system for printed circuit boards made by additive manufacturing with additionally integrated functions

Engineers can integrate additional functions or complex structures into components during additive manufacturing. A functional extension like this would be extremely difficult or impossible to manufacture using conventional methods. Fraunhofer IWS scientists made use of the laser powder bed fusion (LPBF) technique to fabricate clamping mechanisms for metal polymer hybrid materials following an additive manufacturing approach. They manufactured parts with internal structures and chambers by fusing a metallic powder in the powder bed layer by layer. The process did not affect the loose powder in these chambers, so that the engineers were able to remove it through an opening afterwards. Subsequently, the researchers filled the remaining cavity with internal structures with various polymer materials using a heatable nozzle. In this procedure, the internal structures caused the material to macroscopically adhere, while the inherent surface roughness resulted in effective microclamping caused by the additive manufacturing process. The result was defect-free metal-to-polymer bonding demonstrated by means of microphotographs and computer tomographic images. Applications range from biocompatible material combinations for medical applications to metal-to-polymer compounds for space applications.

Study of the tensile strength of aluminum-based alloy AlSi40 (60 mass percent aluminum, 40 mass percent silicon)



- Aluminium-based alloy AlSi40 – conventional
- Aluminium-based alloy AlSi40 – Laser Powder Bed Fusion

Inspecting tensile strength in structures fabricated by additive manufacturing: the researchers measured 280 MPa tensile strength values, in comparison with just 225 MPa for conventionally fabricated structures.

1 *Additive manufacturing enables engineering and fabrication of innovative coil geometries. One of the features: customizing the winding section with local resolution enhances thermal, mechanic and magnetic solenoid systems' properties.*

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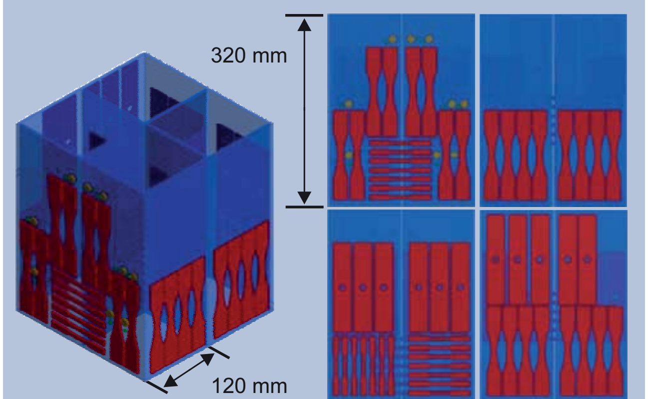
ATHENA – A BIT CLOSER TO THE STARS

The ATHENA telescope was designed to explore both temperature and energy flow in the universe. Its task is to provide answers to fundamental astrophysical questions: How did large-space structures emerge in the universe? How did black holes grow, and how did they influence the universe? Fraunhofer IWS successfully cleared a major hurdle in the ESA project.

One of the three main parts of the telescope is the optical bench, carrying 1,062 silicon pore optics. A titanium alloy is used as high-performance material. Its reliable processing requires comprehensive know-how at the interfaces of material and beam technology – the core competencies of the Fraunhofer IWS. On this basis, the European Space Agency (ESA) convinced itself of the hybrid technology developed during the Critical Design Review in May 2018, the final planning control before the implementation of the project. This milestone's greater objective was to perfectly align the interaction of the latest system hardware from additive manufacturing laser cladding, high-performance cutting, tactile and optical measurement, and intelligent process monitoring and control. Decisive success criteria include oxidation-free and near-net-shape material application and targeted adjustment of material properties. The IWS researchers are currently verifying those criteria in comprehensive tests. Characterization comprises determining the thermophysical properties, mechanical hardness tests, static and cyclic strength, and fracture behavior, as well as an in-depth materialographic analysis using high-resolution electron microscopy on, demonstrators, derived from the optical bench. Synergetic interoperation of process design and materials characterization marks the decisive step towards follow-up large-sized part fabrication.

ATHENA telescope's optical bench – hollow chamber demonstrator in detail



Built layer by layer: the hollow chamber demonstrator replicating the optical bench is made of a titanium master alloy in as-built state and carries 1,062 silicon pore optics. The image shows the test specimens derived in an application-oriented manner for tensile and fatigue tests. They also serve to determine thermal conductivity and heat absorption capacity.

1 *Customized manufacturing cell linking additive laser cladding, cryogenic high-performance cutting, tactile and optical metrology, and intelligent process monitoring and control.*

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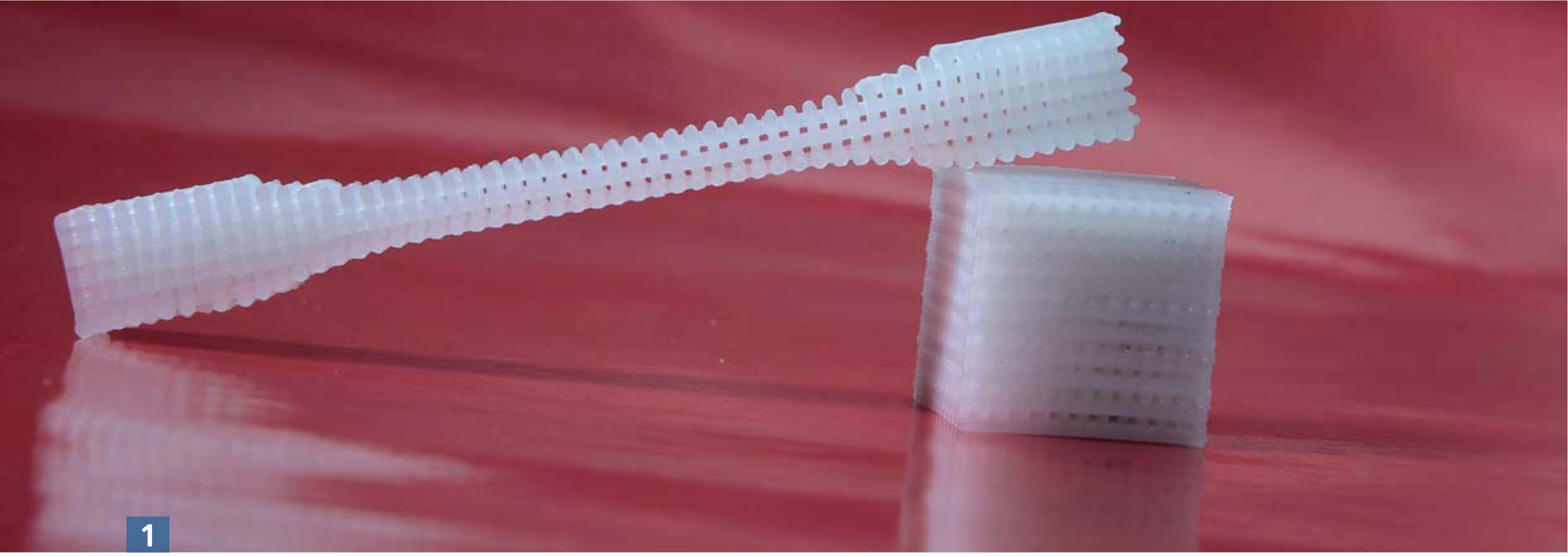
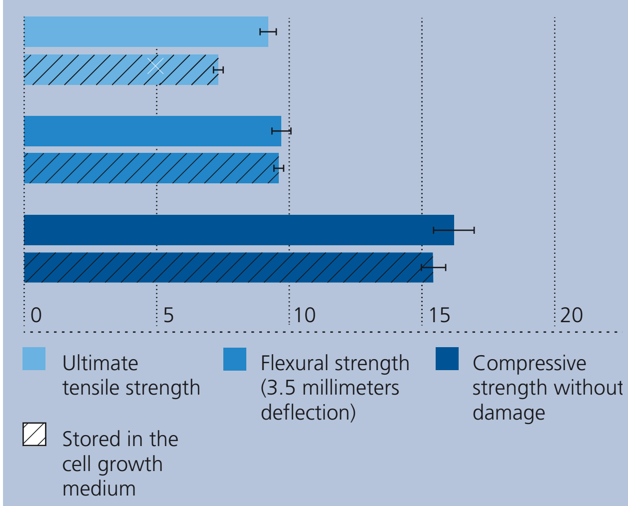


3D-PRINTED SCAFFOLD STRUCTURES AS BONE REPLACEMENT MATERIAL

Fusing polymer filaments by additive manufacturing is an elegant way to fabricate highly complex parts. This makes the additive fused filament fabrication (FFF) method a superb technique to produce individual medical products like implants. Implant scaffolds printed at Fraunhofer IWS are first intended to replace diseased or lacking tissue and serve as attachment points for regenerating tissue.

In medical applications, thermoplastic polylactide (PLA) has already shown great potential as implant material thanks to its biocompatibility and biological degradability. If used to replace human bones, the three-dimensional PLA scaffold structures made by additive FFF must match the strength values of bones. They also should not immediately lose their mechanical properties in combination with cell growth media. The engineers tested PLA scaffolds with an 0.6 by 0.6 millimeter pore area for tensile, bending and compressive strength according to the ISO 527, 14,125 and 604 standards. The porous specimens' maximal tensile strength was 9 and 7.5 megapascals, while the Young's modulus amounted to approximately 740 megapascals. All specimens passed the four-point bending test at 5.5 millimeter deflection without breaking. The compression test provided 19 megapascals without damage. Compressive strength and Young's modulus values were similar to those for human porous bone – with maximal 2 megapascals strength and 275 to 610 megapascals for the Young's modulus. After a 14-day immersion into the cell medium, no deterioration in mechanical properties was found. In vitro biocompatibility tests showed acceptance and low mortality of mouse fibroblast cells associated with cell colonization on the PLA structures. The results show that FFF procedures, together with PLA, provide an interesting perspective for bone replacement structures.

Tensile, bending and compressive strength values in megapascal



The implant scaffold printed by Fraunhofer IWS achieved mechanical values comparable to human bones in terms of compressive strength and Young's modulus.

1 *FFF-printed spongy PLA test specimens for mechanical characterization.*

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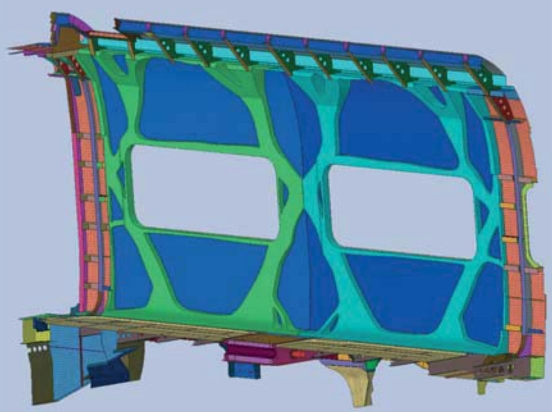
ADDITIVE MANUFACTURING OF TOPOLOGY-OPTIMIZED LARGE-SIZED COMPONENTS

Laser powder cladding enables complex lightweight structures to be produced on conventionally manufactured large components in a resource-conserving manner and with minimal manufacturing effort. This allows weight reductions of 10 to 15 percent compared to conventionally manufactured components.

At present, additive manufacturing techniques allow the fabrication of complexly shaped metal parts on an advanced scale, which are increasingly being used in high technology (aerospace). Despite many advantages, such as freedom of design, options to integrate functions and the wide range of applicable materials, technology acceptance has so far been limited in strongly cost-driven businesses such as automotive and rail vehicle industries. This is due to the relatively low build rates and corresponding high manufacturing costs and times for large components. However, today's demands for individualization, savings in operating resources and reduction of warehousing costs are forcing industries traditionally determined by applying steel, for example, in rail vehicle construction, to implement lightweight construction concepts, to combine component functionalities in larger integral components and to reduce quantities due to individualization. One example is applying topology-optimized stiffening elements to large-sized parts by means of laser powder cladding (German abbrev.: LMD) in an additive manner. Combining serial manufacturing processes with additive techniques has already dramatically increased part complexity. However, to keep this paradigm competitive in comparison to conventional production methods, it is necessary to develop LMD into a high-performance procedure. Consequently, the researchers at Fraunhofer IWS focus on reducing manufacturing times by increasing deposition rates. The immense energy and material flows inherent in the process place the highest demands on the system technology used. To ensure that it is possible to additively manufacture topology-optimized large-sized parts, above all in low quantities, in their full complexity with low resource consumption, efficiently and economically, both the process and system equipment need to be optimized continuously.

Body side panel segment, optimized in topology for additive manufacturing.



Complex lightweight structures (green and light blue) are applied to a conventionally manufactured wagon segment by laser powder cladding in a resource-conserving manner and with little production effort. This reduces weight by up to 15 percent compared to conventional processes.

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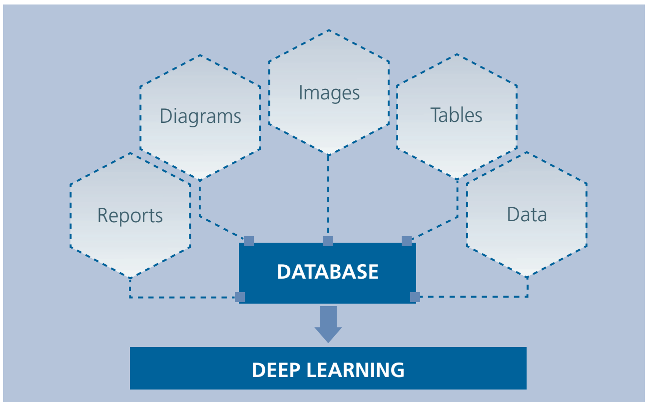
1

MATERIAL DATA MANAGEMENT AND ANALYSIS

As a precondition for future competitive production, engineers have to aggregate, structure and analyze the data generated in laser-based production processes using advanced algorithms. Therefore, Fraunhofer IWS developed a powerful database supporting deep learning paradigms in the Image Processing and Data Management working group.

The Data Management competence center focuses on the Fraunhofer IWS' cooperation with the TU Dresden and the University Hospital Dresden. Together, the partners engineer interactive database systems and deep learning methods capable of processing huge data volumes. The focus is on digital images and process parameters, as well as research and sensor data. The IWS automatically combines heterogeneous machine data and exploits them by means of deep learning. Data management and responsible handling of collected information are also very important in laser processes. Digital twins connect processes, products, equipment and employees. All these entities communicate via the internet. The term "deep learning" refers to techniques and algorithms inspired by the human brain for manifold data processing. This allows the handling of information whose volume, diversity and complexity demands new data processing and analysis techniques to disclose hidden knowledge. This knowledge, in turn, enters into processes, making deep learning a value-adding procedure itself. Researchers at Fraunhofer IWS develop and test databases such as "Prozess 4.0" in laboratory operation. The expertise of the Fraunhofer IWS Image Processing and Data Management team includes device-optimized feedback with digital twins, process tracking, deep learning, and external machine monitoring, both mobile and online. For this purpose, they use various software technologies, such as .Net, Java, Python and QT. A material and process data platform allows them to precisely track laser-based processes and build digital twins. The platform is able to create reports automatically based on process data and enables the direct application of deep learning by means of optimized database patterns.



The new data processing methodology "Prozess 4.0", developed at Fraunhofer IWS. The database allows the aggregation and structuring of heterogeneous data for optimal further processing using "deep learning".

1 Symbol image for a new data processing methodology "Prozess 4.0", created at Fraunhofer IWS.

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THE BUSINESS UNIT

The Joining business unit provides solutions in single-source responsibility. Equipped with profound technical materials knowledge, the researchers cover the complex process chain from analysis of material characteristics, via process development, to implementation in equipment. The business unit develops adapted joining technologies and is even available for support in industrial application. Laser welding enables the generation of defect-free welds from materials that are highly prone to cracking. For material-locked joining of advanced functional materials and metallic composites, the IWS team refines techniques, such as friction stir welding and electromagnetic pulse joining. Advanced labs and efficient hardware are available for the development of adhesive bonding and fiber composite technologies. In component design, the Joining business unit runs structural-mechanic Finite-Element simulations, as well as thermo-mechanically linked calculations, and verifies them in experiments. Other services include the development of customized systems hardware.

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"LASER-FUCHS" ON THE HUNT FOR HIGHLY EFFICIENT HIGH-TEMPERATURE PROCESSES

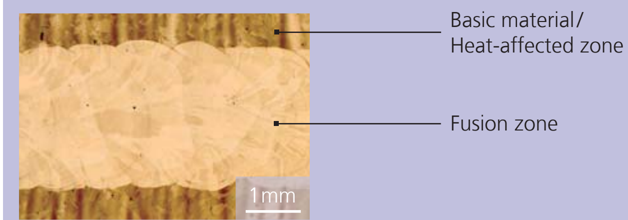
The Fraunhofer "Laser-Fuchs" (laser fox) project researches a new welding process to fabricate key components for large systems in energy technology. The development aims at enabling components inside a turbine to operate at higher working temperatures, thus substantially increasing efficiency. The team at Fraunhofer IWS contributes low-damage, highly efficient joining technology.

Developing technologies that contribute to an increase in efficiency in, for instance, turbines: the "Laser-Fuchs" project focuses on this task. If, for instance, the working temperature in combustion energy stations rises to 700 °C, efficiency will increase from 33 to 50 percent. According to estimates, the energy stations' carbon dioxide emissions would decrease by three trillion tons worldwide. In addition to positive material aspects, the developed welding method cuts production times, resulting in a leaner process chain. The Fraunhofer Institutes for Material and Beam Technology IWS, Mechanics for Materials IWM and Ceramic Technologies and Systems IKTS have set themselves the goal to develop a welding process that ensures, with respect to the properties of the seam, use of the base material's properties. The key task of Fraunhofer IWS as project leader is to engineer the laser multi-pass narrow-gap welding of the nickel alloy "617 occ (optimized chemical composition)" as a highly efficient and low-damage procedure for wall thicknesses of up to 140 millimeters. The team at Fraunhofer IWM refines the laser-welded joints under fatigue conditions at high temperature load. The tasks of Fraunhofer IKTS are quality assurance and monitoring the accompanying process design for devices and technologies.

System engineering and process design

The IWS engineers developed the laser multi-pass narrow-gap welding technology in two core areas: they built up the powerful welding system with a welding head prototype *removeld*®MES and extensively explored and engineered the process. The task was to keep the amount of energy consumed as low as possible and to simultaneously introduce the laser power to the component in a controlled way when welding the hot-crack-sensitive alloy. Highly precise scanners reflect the laser beam – supported by a sensor – with an accuracy of less than 1/10 of a millimeter into the 2-to-8-millimeter-wide joining gap, mechanically pre-processed. The team developed the process using ring segments that represent future use in thick-walled tubes for high-temperature processes. A highlight is the 500-kilogram demonstrator with a 485-millimeter outer diameter and 140-millimeter-thick walls. The scientists improved the maximum laser multi-pass narrow-gap welding deposition rate step by step to 1.5 kilograms per hour, clearly shortening the welding period. Their approach relies on the Design of Experiments method (DoE) that allows for the development of processes in a substantiated way with only a few samples, even for cost-intensive materials such as nickel.

Detail of a laser multi-pass narrow-gap weld seam



The laser multi-pass narrow-gap welding process generates a homogeneous joint promising high load capability and long component life.

2

Excellent material and fatigue behavior

The current focus is on verifying the method’s efficiency in material analysis. A fine-cell-dendritic weld metal structure with fine precipitations and homogeneously distributed carbides in the weld metal and the heat-affected zone are the first indicators of the high joint quality. Even thermal stress from the so-called stabilizing procedure that anneals at 980 °C over a period of approximately three hours causes the homogeneously distributed precipitations and carbides to coarsen only slightly; there is no risk of pronounced carbide-free zones appearing. The researchers performed demanding experiments to analyze both tensile and fatigue strength in comparison to the base material. The welded joints even outperformed the high base material strength. The samples show a slightly reduced elongation at break. The researchers at IWM inspected the mechanical behavior of specimens fabricated by the novel laser multi-pass narrow-gap welding process under loads occurring in practice in a turbine (700 °C). Based on these results, the researchers developed a life time forecasting tool that can predict both the time crack initiation and the crack propagation in welded components in high-temperature applications. The researchers demonstrated an outstanding load-bearing capacity for the joint. The specimens remain intact over a longer period, increasing the components’ life. Reduced costs can be expected in production and in future use inside the turbine as well.

Quality assurance is within reach

The researchers at Fraunhofer IKTS are developing testing methods for the laser multi-pass narrow-gap welding process that make non-destructive evaluation of the welded samples inline-capable. The "617 occ" alloy, due to the existing wall thickness and its strong damping behavior, is hard to penetrate in ultrasound testing which is common practice in energy technology. For this reason, the scientists identify hidden defects using ultrasound, analyze the specimens with acoustic sensor by sending sound waves through solids, and visualize the weld surface using Speckle photometric analysis. All three methods aim at detecting any process instabilities that may cause defects in the weld as early as possible. The researchers succeeded in generating guidelines to be used as a basis for deciding whether the process should be continued or cancelled. The user benefits from a traffic light color coding signaling the three quality states. Strict separation limits and signaling of the defect type are general requirements. The Fraunhofer researchers see their future activities in addressing these subjects to provide unambiguous quality assurance results for the laser multi-pass narrow-gap welding process.

1 *Laser multi-pass narrow-gap welded nickel ring-shaped specimen, 140 mm welding depth, for potential applications in 700 °C combustion energy stations.*

2 *remoweld®MES welding head (prototype), technically suitable to weld up to 250-mm-thick joints; integrated optical system for beam oscillation to guarantee reliable bonding of the component's side walls, as well as to melt off the welding filler metal in the laser multi-pass narrow-gap welding process.*

Funded within the framework of the internal programs of the Fraunhofer-Gesellschaft, grant number WISA 828 505.

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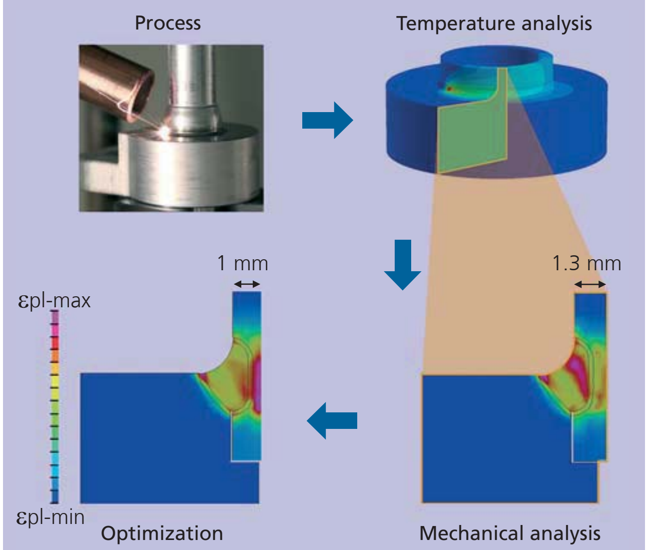
PROCESS- AND COMPONENT-ADAPTED CUSTOMIZED WELD SEAM DESIGN

The engineers at Fraunhofer IWS specialize in engineering demanding laser welding processes for applications in industry. They not only deal with process design, but also dimension the joint zone. Finite element (FE) welding simulation significantly supports both areas.

Engineering welding processes in industry is a complex task: problems in process and materials engineering, as well as design, must be solved. This is conventionally done by means of comprehensive experimental process engineering with modification in multiple iterations to generate defect-free weld joints and to withstand the operating loads in the weld. The team at Fraunhofer IWS has now gained the expertise to efficiently support welding process engineering by using specific FE process simulations. Benefits include comparatively simple process parameter screening and weld design specification without the need to perform a series of tests. The FE model represents the real component geometry and the laser beam's power distribution, and requires only a few experimental welding tests for calibration. The calculation simulates the dynamic temperature field of the laser beam and the cooling down procedure, as well as the material's phase transformations in the weld during the process. The analysis ultimately provides the values for residual welding stresses and component distortion. Moreover, the IWS scientists are able to assess the thermal load of adjacent part regions. The team preliminarily limits relevant parameters, such as laser spot geometry, energy distribution and the welding rate for subsequent process design. The scientists also optimize the component design in terms of stiffness and conduction of welding heat to avoid problems in the welding process (such as crack formation).

Distribution of plastic deformation after welding process



Comparing various wall thickness values shows how the thickness affects local plastic deformation and component distortion.

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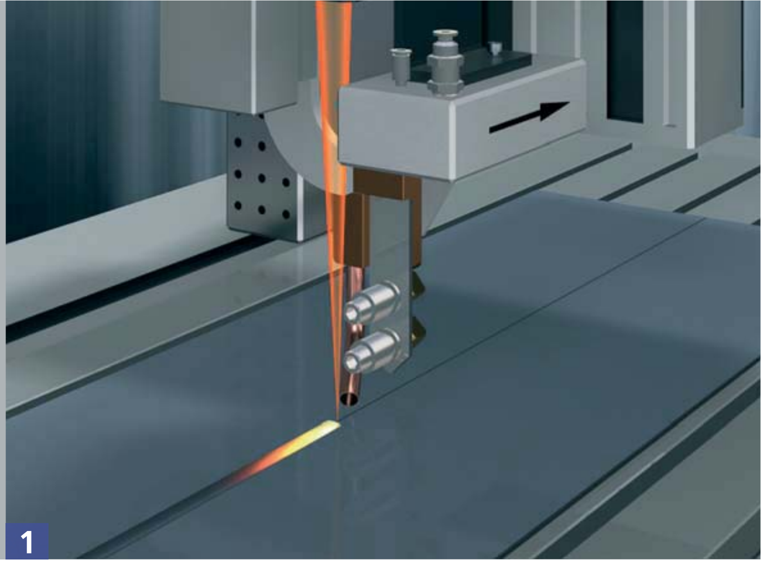
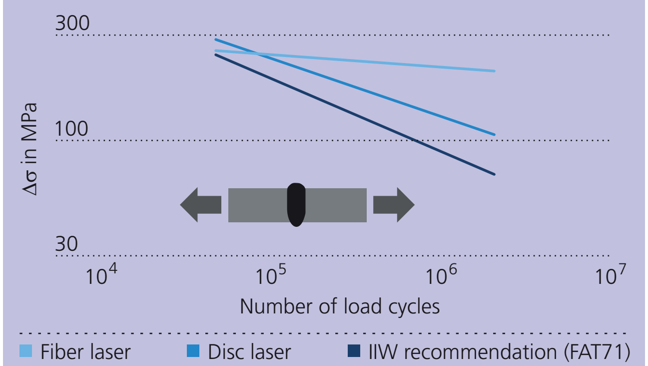


LASER BEAM WELDING: NOVEL BEAM SOURCES EXTEND APPLICATION RANGE

Research in laser sources applied to welding is rapidly progressing. Beam quality, power and flexibility are constantly improving and increasing. Many new opportunities are arising, above all for welding of high-strength structural steels in sheets up to ten millimeters thick. The engineers at Fraunhofer IWS provide process know-how and the characteristic values for weld strength.

Today, new compact laser sources with sufficient beam quality and power facilitate welding tasks in conventional structural steel and plant engineering. As a prerequisite, it is necessary that typical wall thicknesses can be welded safely and weld gaps reliably bridged. In a study, the Fraunhofer IWS team verified that a 9-kW diode laser can butt weld the typical eight-millimeter-thick structural steel sheet with sufficient weld quality. Above all, the study confirmed high process reliability since welding gaps can be safely bridged up to a one millimeter gap width. This way, laser welding has shown itself applicable to new fields previously reserved mainly for conventional arc welding processes.

Results obtained in fatigue strength tests for laser butt welds made of 6-mm-thick structural steel (S355J2+N and S960QL).



Comparison of the Wöhler lines of fiber and disk laser welds with design parameters taken from the relevant technical rules and guidelines (IIW recommendations, FAT71 for single-welded butt welds without subsequent post-processing).

Verifying sufficient fatigue strength

For many applications of welded structures, the weld seam properties must be verified. Until now, however, secured fatigue strength values for laser-welded joints have not been sufficiently available. Therefore, the IWS team investigated the fatigue behavior of laser-welded structural steel joints with sheet metals up to ten millimeters thick in a joint project with TU Braunschweig. It turned out that fiber laser and disk laser welds are at least equivalent to conventionally welded arc joints in terms of fatigue strength. Thus, the researchers created the prerequisites for the use of welds fabricated by means of laser welding in fatigue-stressed structures. Laser welding of sheet samples was subjected to follow-up fatigue testing.

1 *Schematic representation: laser welding of sheet samples subjected to follow-up fatigue testing.*

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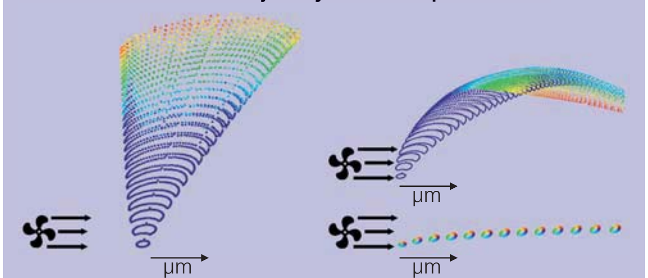
CLEAN REMOTE PROCESSES FOR RELIABLE JOINING

When using lasers to clean and ablate components, the resulting emissions must be intentionally removed from the workspace. The researchers at Fraunhofer IWS have also addressed this task for remote processes. They substantially minimized particles and smoke by means of a model environment that represents particle movement and air flows.

The local laser-assisted ablation of surface contaminations prior to adhesive bonding or thermal joining is not only intended to clean the parts. Ablation can also modify the surface topology so that adhesives or plastics bond better with the piece to be joined. The problem is that engineers must remove the particles emerging in the procedure from the processing area to avoid recontamination of the components to be joined and to protect the operator against hazardous substances. The challenge: Remote processing allows an area of up to one square meter to be machined simultaneously. The IWS team, working with researchers from TU Dresden, analyzed particle and gaseous emissions during laser processing of metal and carbon fiber-reinforced plastics. The measurements outlined clear differences both in relation to particle size distribution and the resulting gaseous species. Using the »Fluent« simulation environment, the researchers reproduced a simplified laser ablation process and visualized process-typical emission flows. They simulated empirically developed approaches that combine a transverse jet and exhaust module in the model environment and were able to optimize the configuration and flow conditions. Once the project has been completed, the laser process user will be provided with a tool that improves emission removal and thus guarantees that the processed components are sufficiently clean.

"Fluent" calculates the trajectory of various particle sizes



The emissions emerging in the laser remote process consist of various particle sizes. Therefore, the particle trajectory is determined size-selectively at given flow conditions.

1 To ensure that the injected plastic sufficiently bonds to the coated steel sheet, the laser beam locally ablates parts of the zinc coating.

Based on the decision by the German Bundestag, the Federal Ministry for Economic Affairs and Energy partially funded these activities within the scope of the "CleanRemote" (IGF:19239BR).

Funded by Federal Ministry for Economic Affairs and Energy DVS FORSCHUNG

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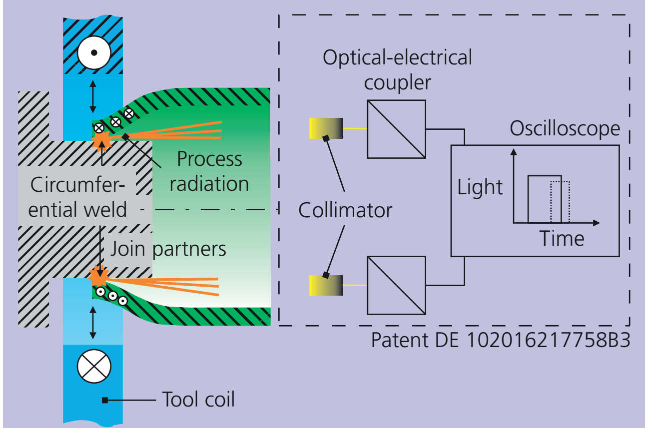
MAGNETIC PULSE WELDING BRINGS TOGETHER WHAT BELONGS TOGETHER

Future multi-material design concepts require material-locking bonding of different metals. Magnetic pulse welding is outstandingly suited for this task, and is therefore increasingly interesting for production planning engineers. Researchers at Fraunhofer IWS now provide a new method for precise welding process monitoring and parameter optimization for this cold-welding process.

Magnetic pulse welding is based on the controlled collision of two joining partners, whereby thermal energy input is clearly lower than in fusion welding. This means that researchers can achieve joint strength values at the level of the weaker base material and avoid brittle intermetallic phases. Strong magnetic fields from 20 to 30 Tesla and process times of a few microseconds complicate the recording of process-relevant physical parameters during magnetic pulse welding. Consequently, adjusting the process has been so far very difficult, and direct metrological monitoring has practically not been possible at all. Engineers at Fraunhofer IWS developed a device to record and analyze the process flashing phenomenon typical of collision welding processes (patent DE102016217758B3). They have already verified the device's potential in several projects with industrial partners. Its applications range from quickly identifying suitable process parameters to quality assurance in production. The system reliably detects defects in positioning the joining partners or unintentional contaminations of the surfaces to be joined.

Schematic representation – magnetic pulse welding and metrological photoflash measurement



In magnetic pulse welding, controlled collision causes two pieces to be joined in a cold weld. An emerging characteristic flash of light is converted into electrical signals by phototransistors and then evaluated.

1 *Flashing luminescence in magnetic pulse welding illuminates the process area.*

2 *Magnetic pulse welding is suitable both to fabricate hybrid pipe joints, in this case between steel and aluminum 80 mm in diameter, and to weld metal sheets.*

Funded by the German Research Foundation DFG (priority program 1640, registered under number BE 1875/30-3) in cooperation with the Institute of Manufacturing Science and Engineering IF (TU Dresden) and the Institute of Forming Technology and Lightweight Components IUL (TU Dortmund).

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LASER ABLATION AND CUTTING

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THE BUSINESS UNIT

Highly specialized and innovative – the Laser Ablation and Cutting business unit plays a key role in all those application fields for which the market does not offer any commercial solutions. Our scientists research and develop processes and systems technology related to lasers. Process design and analysis round off the portfolio for the efficient use of the developed solutions. Fraunhofer IWS offers a range of established laser sources with various wavelengths, power and beam quality. The researchers focus both on metallic and non-metallic materials. However, they also have comprehensive expertise in processing soft magnetic materials. Cutting speed, edge quality, contouring accuracy and cycle time optimization are crucial parameters. The team employs techniques that include laser fusion cutting, flame cutting and remote laser cutting, as well as drilling, ablation and high-speed processing with high-power lasers.

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EVALUATING THE PROCESS EFFICIENCY OF LASER MATERIALS PROCESSING TECHNIQUES

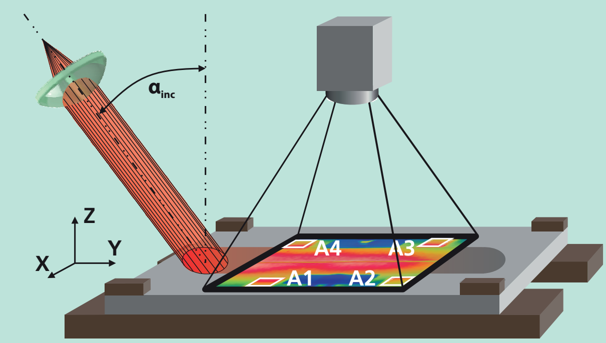
How efficient is the process? Is it possible to enhance a process' energy efficiency? How can we verify such improvements? These are just a few of the questions frequently asked in the field of laser materials processing in terms of resource-saving production. To address them, researchers have developed a method to assess thermal process efficiency.

Energy-efficient process design is one of the challenges in laser materials processing. Developments in this field aim at reducing manufacturing costs. While maintaining efficient process performance, however, it is also possible to increase the parts' manufacturing quality by reducing heat-affected zones thermally induced stresses and distortions to a minimum at the same time. Until now, there has been no precise method for evaluating thermal process efficiency under real conditions.

New measurement methodology determines process efficiencies

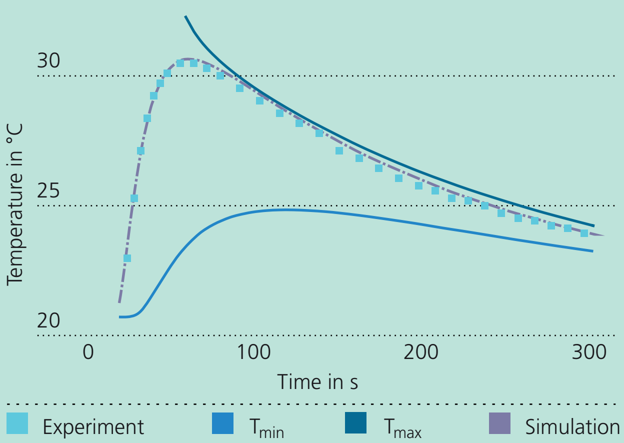
More accurate investigation techniques are required to assess processes in terms of their efficiency or enhancement potential. A manufacturing process' thermal efficiency corresponds to the ratio of effectively used energy to applied laser energy in total. The researchers can achieve high thermal efficiency values in laser materials processing when the material absorbs the highest possible proportion of irradiated laser energy. They can determine this "coupling ratio" by means of calorimetrical methods. However, conventionally applied approaches prove to be too inaccurate to analyze dynamic processes. Therefore, the researchers at Fraunhofer IWS and TU Dresden closely collaborated to engineer a new measurement methodology to determine process efficiency in laser materials processing. Their approach is based on physically defined heat propagation in solid materials. It is possible to exactly calculate the temporal and spatial temperature field in a test specimen, on the one hand. On the other hand, contactless thermographic measurements provide very exact surface temperatures. The method brings together the two signals in defined measurement areas. The signals may be equal only if the excact coupling efficiency value is used as temperature field simulation's input parameter. This value corresponds to the measurement result to evaluate process efficiency. When the scientists analyze the specimen's cooling regime over a longer time interval, they also ensure that heat transfer to the environment is considered correctly. The measuring methodology was shown to be valid for use under real process conditions. There are no special requirements for the test specimens used in the manufacturing state. Thus, the approach guarantees that the various surface states' influence

Test setup for efficiency determination



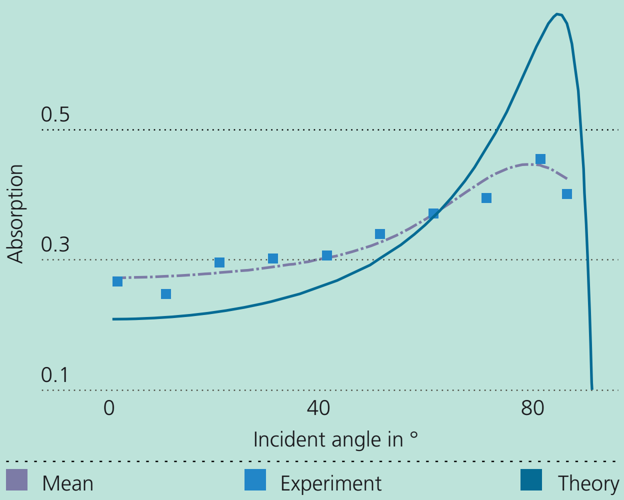
Experimental setup to determine the process efficiency of thermal processing. The surface temperatures are thermographically measured in defined and previously prepared measuring areas. In parallel, the temperature distribution in the entire sample is calculated and subsequently, the temperature profiles are adjusted to provide the required value of the coupling level.

Aligning the temperature profiles measured and calculated



The temperature curve observed in the experiment exactly coincides with simulated temperature profiles. For this approach, the researchers have to preset the actual coupling level in the temperature field simulation.

Angle-dependent coupling efficiency of stainless steel for fiber laser beams



This representation of angle-dependent absorption of stainless steel (1.4301) shows that it is necessary to determine efficiency in a process-specific manner. The real values significantly vary from those calculated in theory.

on beam absorption is also reflected in the measuring results. The scientists validated the techniques developed for various applications and provided precise results for test specimens with known coupling level.

Various applications

The measuring methodology developed at Fraunhofer IWS and TU Dresden opens up a wide range of application fields. Process efficiency values both for laser materials processing and for competitive thermal technologies can be determined. They support optimal laser beam source selection by verifying how the wavelength influences the achievable process efficiency. It is also possible to evaluate potential efficiency improvements for various process variants, such as when using dynamic modulation methods, or in a hybrid process design. Investigations can also focus on quantifying parts' thermal load, which can also be directly measured. Last but not least, the methodology enhances the precision of simulation methods' predictions by determining the coupling level for real test specimens in advance. In this way, these investigations enable more precise thermal simulation results.

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TAILORED TECHNOLOGIES FOR HIGH-RATE ABLATION

Laser beam ablation implementation in industry is becoming more and more important. To maximize ablation rates, IWS engineers combined brillant high-power lasers with high-speed beam deflection. They selected the appropriate beam source based on the material-subsurface combination. The high-laser power used is particularly challenging in terms of heat penetration when processing sensitive materials.

Laser beam ablation is increasingly being used in industry. This is due on the one hand to the high applicable laser beam intensity and on the other hand to the fact that it is easy to control. The greatest obstacle to implementation results from viewable area output. To overcome it, the IWS team uses lasers with kilowatt power values and high brillance. The researchers deal with the heat input resulting from the continuous-wave beam sources (cw) by quickly moving between the laser beam and the workpiece, which, in turn, increases the area output. The laser beam is shaped according to the application for another increase in the ablation rate: elliptic laser spots affect intensity and interaction time. Linear structures about 45 micrometers wide and 20 micrometers deep can thus be generated in metals with 2.5 kilowatts of laser power at processing speeds of up to 60 meters per second. Engineers apply them in heat-resistant structuring of magnetic sheets for transformer cores. The scientists apply much higher spot speeds in surface preparation for follow-up joining processes to achieve, for instance, rates of one square meter and more per minute in surface oxide ablation. For this task, the IWS provides a unique test stand that can run various laser beam sources with a speed of up to 300 meters per second over a width of one meter. The system's strengths lies in material ablation and large-area heat treatment. Modifiable focusing takes into account necessarily lower laser beam intensities. The researchers can design ablation technologies based on feasible wavelengths between 1 and 10.6 micrometers, as well as 515 nanometers, and approximately 5.6 and 9.3 micrometers with more than one kilowatt average power. Wavelengths in the medium infrared range are interesting, particularly when ablating organic coatings. For the first approach, IWS engineers selected the appropriate laser beam source upon determining the new layer system's absorption properties on their own. They finally decided, in consideration of process guidance and available system hardware, to use the expected application. In this process, the researchers analyzed the technological development comprehensively, selected and evaluated the suitable system hardware, and determined all associated processing parameters. Holistic solutions are thus created which meet application requirements and are ready for use in production thanks to the coordinated systems technology.

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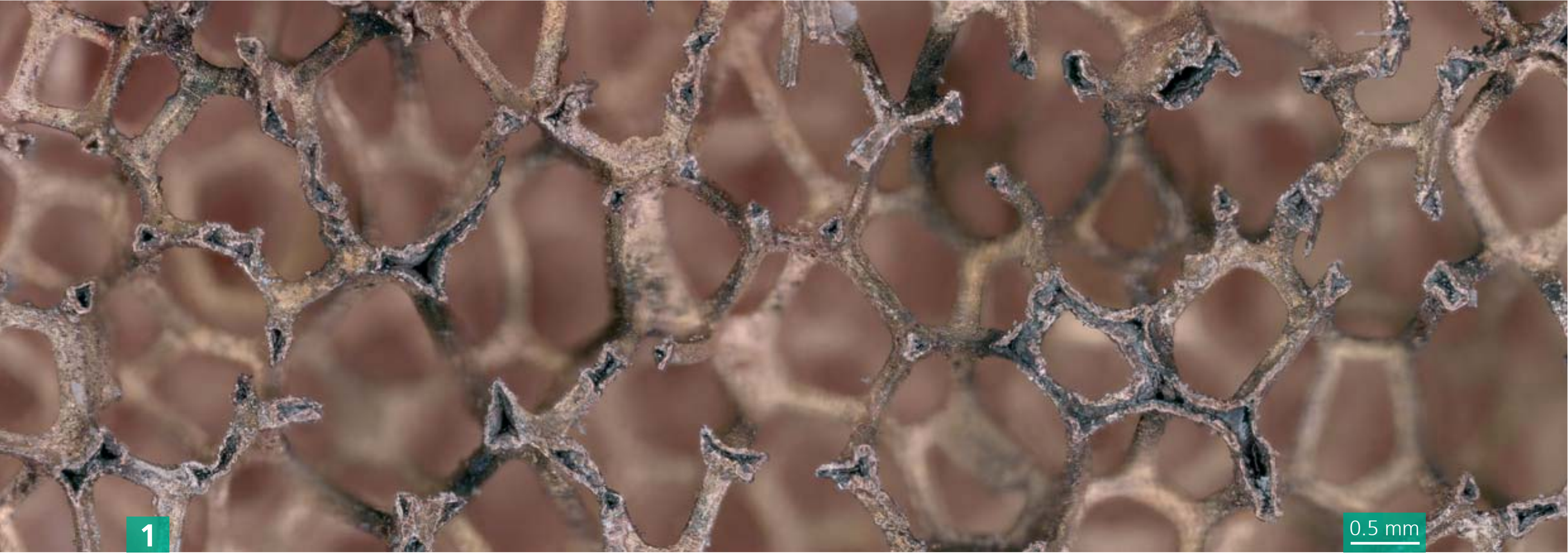

PRECISE HIGH-SPEED METALLIC FOAM LASER CUTTING

Engineers may count on open-porous metallic foams in their solutions required for managing renewable energy sources and lightweight design. In the future, users will apply open-porous foams in a wide range of applications, such as heat exchangers, battery systems or medical implants. The many applications call for an easy-to-adapt cutting technique.

In its research, the Fraunhofer IWS team focuses on cutting metallic foams to size in flexible contours. Remote laser beam cutting opens up new options to cut open-porous metallic foams highly precisely and minimal pressure to avoid unintentionally generating thermally- or mechanically-induced deformation. The cutting hardware is based on highly brillant laser sources that melt and partially evaporate the material in the interaction zone. The metal's evaporation pressure expels the molten metal. Repeating the cutting contour in successive cycles creates the cutting gap up to the full separating cut. To guarantee short process times and thus maximal profitability, the engineers deploy highly dynamic beam deflection elements. They facilitate cutting speeds of up to 300 meters per minute. A positive side effect is that they can minimize heat input into the material. It is not only possible to cut material in two dimensions, but also to create very thin metallic foams. This slitting process is necessary since primary shaping of foamed semi-finished parts requires a minimum thickness of three foam pores for process stability. Using remote laser beam cutting, users can reduce part thickness to the structural strength limit of 0.75 foam pores. Applications with this foam thickness provide technological advantages; however, they could not be implemented in the past. In comparison with conventional cutting, remote laser beam cutting provides more precise edges. The IWS team achieved ± 50 micrometers processing accuracies at consistently high cutting speeds for the foam materials investigated – copper, nickel, steel and Inconel. Another advantage is that the cutting edges remain open-porous. Consequently, remote beam laser cutting can cut open-porous metal foams very precisely and it enables a very wide range of future applications.

1 *Cutting edge of a laser remote-cut copper foam. The open-cellular structure is retained (top view).*

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HOW TO IMPLEMENT COMPLEX LASER REMOTE PROCESSES EASILY

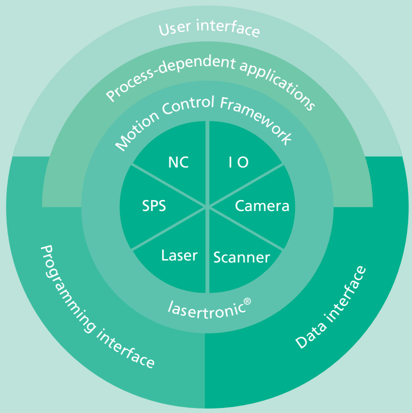
Integrating laser remote techniques into production lines presupposes efficient and flexible software solutions that can be adapted to the process' technical requirements. The team at Fraunhofer IWS engineered a motion-control framework according to this paradigm. Independent of the manufacturer, this framework offers specific sub-modules with many options for process monitoring, controlling and automation.

The more customized production is, the more flexible the manufacturing processes and the more oriented to the customers' needs individual software systems have to be. In this context, the engineers at Fraunhofer IWS designed and constantly enhanced the lasertronic®MotionControl in recent years in order to address networking between scanners and machine control. The focus is above all on interlinked and automated processes, which are applications in which the two components' interaction provides an optimized process result.

Adaptable software

Efficient but flexible software engineering to implement complex laser remote applications is based on the motion control framework. The framework not only takes into account customer-specific requirements to design the user interface, but also process technological features. The framework efficiently encapsulates complex technological relationships and makes them available to the higher-ranking application in a parameterized manner. This makes the system more user-friendly, reduces errors in process guidance and simplifies its handling. The core component in the IWS platform lasertronic®MotionControl is the universal scanner control module. Other modules are intended to link the process sensors, machine control and communication with a programmable controller. Based on their many years of expertise in process technology, the IWS researchers developed customized software solutions for various laser remote applications. Industrial applications include laser beam welding and laser cleaning, as well as ablation and cutting of both metallic and non-metallic materials.

The motion control framework



The motion control framework offers manufacturer-independent comprehensive opportunities for process monitoring, control and automation.

1 *Possible applications, derived from the motion control framework.*

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ADAPTIVE MIRRORS USED AS A HIGHLY DYNAMIC Z-AXIS FOR LASER CUTTING

In laser cutting, the area in which the laser beam and material interact is decisive. Highly dynamic beam shaping in the x and y planes overcomes their limitations and thus achieves positive results. If materials are very thick, then highly dynamic beam shaping has to be extended into the z plane.

Laser fusion cutting is a thermal conduction process requiring heat input across the entire cutting front. As theory and practice indicate, focus depth corresponds to sheet thickness as much as possible to achieve optimal process performance. However, the focus depth cannot be increased arbitrarily since it is accompanied by an increase in focal diameter, which is also a relevant process parameter. When cutting thick sheets, the cutting tool's focus depth is clearly lower than the sheet thickness to be cut. As a result, the material thickness to be cut is limited, on the one hand. On the other hand, cutting edge quality drastically deteriorates. As a default, motor-driven z-axes are laser cutting head standard elements, but are usually used for adapting the focus position to the material and the thickness for the cutting process. Their dynamic characteristics are not suitable for the desired application. For this reason, a consortium of representatives including scientists, practice engineers and managers within the project Zwanzig20 PISTOL^3 designed a z-axis achieving more than ten millimeters strokes in the kilohertz range. This setup enables the so-called laser sawing procedure. As with a jigsaw, cutting performance is thus enhanced and the effective focus depth is also significantly increased over an oscillation period. The frequency spectrum corresponds to the optimum of highly dynamic beam shaping for laser beam cutting determined by IWS researchers over several years of research work in order to positively influence heat conduction and cutting performance. Researchers at Fraunhofer IOF as project partner designed z-axis functionality, which provided long-lasting laser power stability in tests. The scientists are currently conducting a comprehensive process study to identify how cutting edge quality, cutting speed, maximal material thickness to be cut and gas consumption can be optimized. In addition to their activities in laser cutting, the scientists are also investigating laser beam welding and structuring processes in this project. In the near future, Fraunhofer will offer concepts and processes with highly dynamic three-dimensional beam shaping that enable an increase in process performance in the entire laser materials processing field.

1 The Pistol^3 project partners engineered adaptive mirrors in order to modulate the focus alignment for highly dynamic laser materials processing.

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MICROTECHNOLOGY

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THE BUSINESS UNIT

The Microtechnology business unit concentrates its research on laser micromachining to produce structures smaller than 100 µm in size. Researchers are studying and developing surfaces which functionalities resemble those of lotus leaves or sharkskin. The miniaturization trend in electronics, semiconductor manufacturing and biomedical engineering calls for ever smaller and more exact structures for a wide variety of substrates. Fraunhofer IWS supports here with laser microprocessing technology. The Microtechnology business unit's services address product-oriented users requiring solutions for highly specialized questions which can only be answered with systemic materials knowledge and corresponding laser parameters. The business unit offers technologies such as laser interference patterning, refined by Fraunhofer IWS scientists for industrial use for the first time. Microtechnology is a pioneering area in "embedded systems" and machine learning: collecting, analyzing and optimizing acoustic and visual data with regard to process speed – this is what future users will benefit from.

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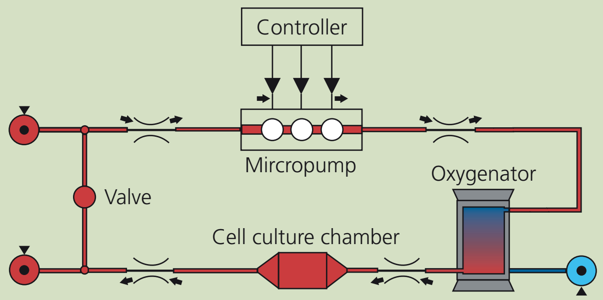
MICROSYSTEMS FOR ARTIFICIAL KIDNEY MODELS

Human organotypic kidney tissue cultures are the key to better understanding cellular processes inside the kidney and are an important tool in medical research. Microphysiological systems developed at Fraunhofer IWS shape the technical environment for tissue cultures. Kidney diseases and drugs' side effects can be researched by means of these systems.

Three-dimensional organotypic tissue cultures mimic organ and cell functions much better than classic two-dimensional cell culture models. They are the best choice for model systems for basic medical research and to investigate drug interactions. Artificial kidney systems are particularly important since they can map the natural excretory processes significant for all pharmaceuticals' effects. Two essential processes control excretion in the kidney. Filtration through a cellular barrier in the kidney glomerulus is the first step in excretion. Soluble substances pass through the filtration membrane while blood cells are retained. Special cellular transporters then return vital substances to the blood via the renal tubules in the so-called reabsorption process. If toxic substances damage these cellular transporters, the kidneys fail. The microphysiological system developed at Fraunhofer IWS allows researchers to reproduce and analyze these processes.

The microphysiological kidney systems as a network simulation



It is possible to map flow in the kidney's microphysiological model by simulating the fluidic circulation as a network. The researchers subdivide the microphysiological system into functional units, such as the integrated pump, the cell culture chamber and other elements. These are then represented by means of differential equations and connected in simulation. The result is an overall microphysiological system model to find pressure, flow rate and other physical system parameters.

What characterizes microphysiological kidney models

Artificially mapping the filtration and reabsorption process is the essential basis for mimicking the kidney's function. Cell-based barrier models on an artificial membrane simulate the filtration and reabsorption transport processes. It is also necessary to adjust the cellular barriers' physiological environmental conditions so that they are kidney-specific. This means that temperature, pressure, membrane extension and the concentration of the substances to be filtered in the microphysiological system are reproduced according to the conditions inside the kidney.

How microphysiological systems enhance the kidney model

The researchers cultivate cell-based models for the kidneys' barriers in artificial scaffolds, known as Transwell® inserts. Here, they colonize human cells layer by layer on the scaffold's porous insert membrane. After about eight days in the cell culture, the cells form a closed layer, and the kidney barrier performs its fundamental function. However, transport processes can only be analyzed by integrating the scaffold in the kidney-specific microphysiological system created by Fraunhofer IWS. The

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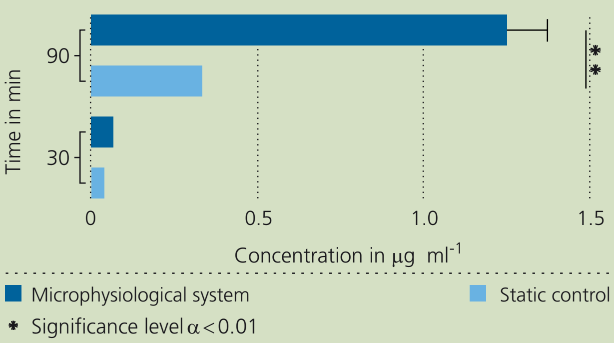
Dresden institute's researchers adjust pressure and flow conditions for the reproduced kidney section and enable the cells to perform their organ-specific function. The micropump integrated into the microphysiological system feeds the blood-like cell culture medium through the microphysiological system. Like the human heart, it is equipped with both a chamber and valves. This small "heart-on-a-chip" runs by means of an IWS-developed controller which operates chamber and valves in timed cycles. To mimic the flow in the kidney capillaries, IWS scientists set a slightly pulsatile flow at approximately 5 millibar pressure by modified pump triggering. These modifications are based on the microphysiological system's simulation via a network model. Simulation allows to calculate pressure and flow processes in advance, thus reducing the number of large cell culture experiments. Simulating the kidney capillaries when mapping the reabsorption processes in the microphysiological proximal renal tubule model is important in this context. As in the human body, cellular transporters move glucose from the tubular space back into the blood vessel. The model visualizes transport velocity by means of fluorescent-colored glucose. Their transport velocity is higher than that of the static kidney model in the microphysiological system, and reflects the human kidney's speed and results from the flow in the artificial capillary. In addition to reabsorption, researchers can also mimic other organs' abnormal phenomena, such as high blood pressure. This helps researchers to understand the interaction between the kidney's filtration processes and the cardiovascular system.

Active glucose transport through the artificial tubular kidney barrier



Researchers took comparative measurements of the fluorescent glucose analogue's concentration 2-NBDG on the tubule model's capillary side. After 90 minutes, they were able to observe a significant difference in concentration between the microphysiological system and static inspection. As in the kidney, capillary flow and the number of active glucose transporters accelerate transport.

1 The IWS microphysiological system simulates the transport process in the renal tubule.

This project was partially funded within the scope of the IGF project 19175 BR/1 of the Research Association DECHEMA e. V. of the German Federation of Industrial Research Associations AIF as part of the Program for Promoting Industrial Joint Research (IGF) by the Federal Ministry for Economic Affairs and Energy based on a decision by the German Bundestag.

Funded by

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LIGHT AS PLASTICS AND STRONG AS METAL

The quest for lighter components is part of everyday life. Cars, airplanes and sports equipment are constantly losing weight. Lightweight components often have to provide the same properties as heavier conventional materials, such as environmental and wear resistance. To achieve this balancing act, new process designs and strategies are needed, such as functionalized fiber-reinforced plastics with metallic properties.

With new materials and new developments in process design, lightweight construction lowers weight and results in reduced emissions when mass is moved. Frequently, lighter fiber-plastic composites replace heavy metal components. Nevertheless, it is impossible to completely replace metal, for example, if abrasion resistance or specific sliding characteristics are required. Fraunhofer IWS researchers have found solutions to introduce typical metallic functions into plastic-based components – locally and without joints. The surface texture of the component to-be-coated is essential for a reliable bonding of metallic sprayed coatings on plastic-based substrates. The rougher the surface, the more anchoring points are available for the metallic or ceramic particles in the coating procedure. Surface pretreatment methods established in metal processing, such as sand blasting, can only be used for fiber-reinforced plastics to a limited extent. The particles' high impact energy creates roughness, but also damages the fibers near the surface. These defects result in air locks during coating and in failure during use.

Customized solutions for a wide variety of requirements

Selective matrix removal, using a pulsed laser beam, exposes the fibers gently, creating anchoring spots for the sprayed particles. The coating material's splats enclose the load-bearing fibers. The generated form fit causes the coating to bond optimally. Fiber-plastic composite coating offers numerous opportunities for functionalization. Customized properties can be immediately integrated into the fiber-plastic composite. It is possible to implement various functions – from anti-wear for plain bearings via thermal insulation to heating functions, such as for battery housings. Laser material processing with follow-up coating is based on established and economically attractive subprocesses. Combining lasers with thermal spraying allows fabricating diverse components with various functionalities without additional tools or masking. This method enables, for instance, the intentional exposure of highly limited functional surfaces. The coating material only bonds in the pretreated zone thanks to local laser roughing. Using this approach, Fraunhofer IWS has engineered a highly flexible process capable of integrating various functions with an exact fit into each substrate.

1 *Fiber-plastic composite functionalization by coating laser-structured surfaces.*

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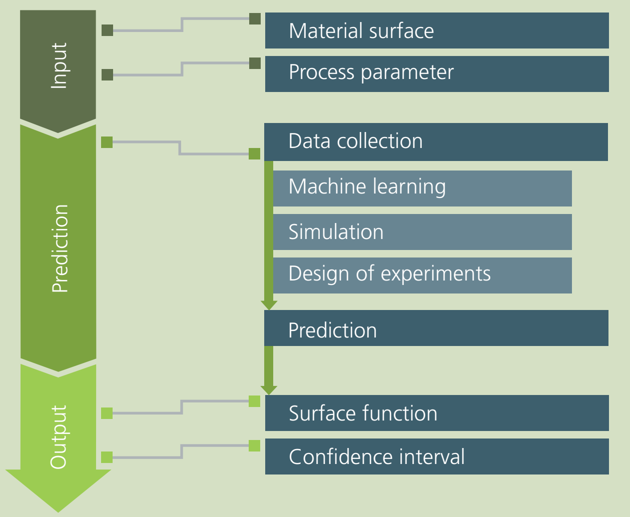
OPTIMIZED SURFACES THANKS TO MACHINE LEARNING

Nature provides a perfect model for technical surfaces: in addition to the lotus leaf for repelling water and sharkskin for reducing flow resistance, there are many examples of optimized surfaces. Fraunhofer IWS offers models based on artificial intelligence and predicting intentional surface functionalities.

At present, it is possible to intentionally influence surface properties using laser patterning so that surfaces are cleaned more easily. Thanks to hydrophobic effects, implants are better tolerated by the human body, and engines operate more efficiently. Researchers are using more and more statistical and machine learning methods to identify suitable surface structures. As a result, functions can be predicted before the patterning process itself. The IWS synergetic approach including scientific know-how, simulation and experimental data modeling allows to predict specific surface functions. The Fraunhofer IWS team uses various machine learning algorithms as well as further deep learning paradigms, particularly for unexplored materials, to identify correlations between structure and surface function. This approach facilitates ever faster rough predictions of the final surface function, so that the work required for surface structure development is significantly reduced. The IWS' task as a central consortium partner in the Horizon 2020 "SHARK" project is focused on creating prediction models for future production processes. In this way, the Dresden researchers contribute to making surface function an easily selectable parameter.

Prediction of water-repellent surfaces



It is possible to determine laser-patterned surfaces' properties by means of prediction modeling. The models, in turn, use more and more empirical and numerical methods based on machine learning. As a result, users can for example implement self-cleaning surfaces more efficiently. Having entered the parameters required, the scientists draw on machine learning, simulation models and knowledge gained from experiments for prediction.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 768701.

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MATERIALS CHARACTERIZATION AND TESTING

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THE FIELD OF EXPERTISE

Intentionally destroying in a controlled process what others have created: IWS material and component testing researchers examine the material up to the smallest detail. In this process, the scientists evaluate material and component quality and suggest ways to optimize manufacturing processes. Comprehensive material knowledge, years of experience in techniques and a wide range of available equipment and devices provide the basis for their research and engineering projects. The service portfolio includes the metallographic characterization and electron-microscopic analysis of materials and their compounds, from the macro to the nano scale. Characteristic properties are determined and strategies are derived in order to be able to design components according to material and operational demands. The scientists assess suitability, select materials, and optimize the component for the development and refinement of manufacturing technologies. In addition, they develop, evaluate and modify test methods. Failure and damage analyses are also part of the portfolio.

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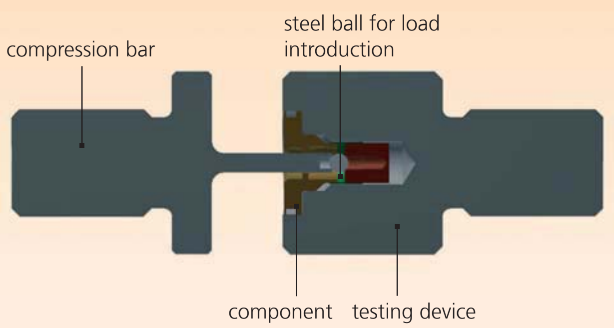
HIGH-VELOCITY FATIGUE: COMPONENT TESTING AT 1,000 HERTZ

Technical components are often subject to repeated mechanical loads. The design for these external loads is usually carried out in so-called "high cycle fatigue tests", which can be both time- and cost-intensive. Fraunhofer IWS has responded to this trend by developing a modern high-frequency testing technology which allows the fatigue strength to be determined at high speed.

Calculation or testing? This question is rarely discussed as intensively as in fatigue-resistant component design. Several high-profile dimensioning guidelines issue recommendations for estimating technical components' fatigue strength that solely rely on calculations. Due to their more universal application, these approaches are conservative to insufficient for later use in intensive lightweight design. Experimental strength tests, by contrast, remain relevant in these future cases. The objective is always minimal testing time with low testing costs while guaranteeing a reliable experimental database. In this respect, the modern high-frequency testing technology of Fraunhofer IWS offers significant advantages compared to conventional testing methods. Researchers can fatigue both material specimens and compact parts at 1,000 Hertz test frequency and, in turn, achieve enormous savings in time and costs. Using the example of a laser-welded component from a passenger car injection system, the scientists at IWS demonstrated how important experimental validation is up to Very-High-Cycle-Fatigue (VHCF) and how clearly the actual fatigue strength of a component can deviate from the calculated estimate.

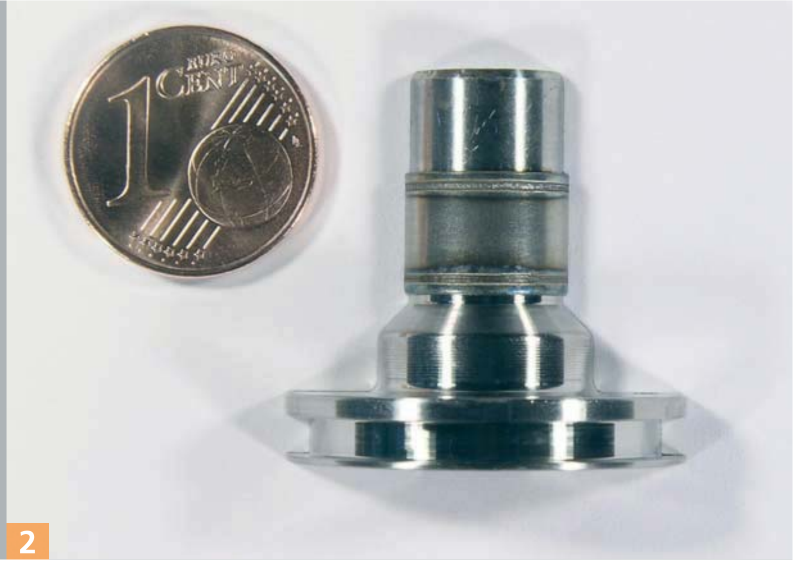
Schematic representation of the component load on the test bed



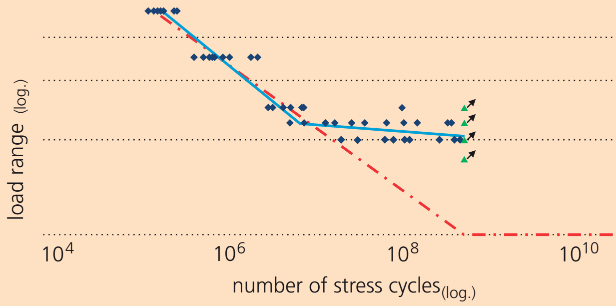
The geometric testing device design unambiguously defines both test specimen position and location, thereby systematically excluding inaccuracy during part mounting.

Component test preparation

In a joint project with the Robert Bosch GmbH, the Fraunhofer IWS team has applied the innovative 1,000 Hertz resonance test bed to experimentally validate the alternating fatigue strength of a laser-welded serial part during development. This component consists of three individual parts joined by two laser-welded seams. In its future application, the unit will be subject to frequent cyclic loads, as it is one of the key functional elements in a passenger car injection system. This use requires a "quasi infinite fatigue life" design that will allow the unit to withstand mechanical stresses over the entire operating period. Given an expected car life of approximately 15 years, the unit may be subject to many more load cycles ($N \geq 10^9$) than considered in established "classical" fatigue strength tests. Before starting the fatigue tests, scientists at Fraunhofer IWS designed a customized testing device that reproduced the actual load situation in the use case. The focus was on the simplest possible and most robust test setup design. Positioning indicators in the design define both part position and orientation in the device. Consequently, potential inaccuracy during mounting into the test bed could be systematically avoided. A centered steel ball



Component testing at 1000 Hz



- ◆ failed
- ▲ runout specimens
- ■ Woehler curve component testing
- ■ FKM Woehler curve

The Woehler diagram shows how experimental results ensure the component's fatigue strength results (blue line) in comparison with calculated assessments (red line). The calculated assessments following accepted design guidelines clearly underestimate the components' actual strength level.

introduces the force into the component. In this way, the engineers safeguard axial and constraining force-free load introduction. The steel ball can also be exchanged without any problem in the case of unacceptable wear. Afterwards, the researchers verified the newly developed test setup. For this purpose, they conducted a so-called static-dynamic adjustment, in which they determined the actual load situation on the test bed.

1,000 Hertz component fatigue: advantages and opportunities

After its successful verification, the researchers applied the testing system to component testing. The components to be tested differed in terms of their welding process, weld seam position and manufacturing technique. The high-frequency fatigue testing equipment used at Fraunhofer IWS made it possible to achieve the comprehensive parameter studies within the preset project period. Within three months, the IWS engineers tested approximately 100 components at defined load horizons of up to 10^8 cycles. With conventional testing devices, 500 days are needed to test the whole volume, much longer than allowed within the framework of the project. The amount of component failures at more than 10^7 load cycles demonstrates how essential the experimental validation at very high cycle fatigue (VHCF) is even for heterogeneous and joined components. The actual strength potential revealed by these extensive stress cycles is clearly higher than the strength level qualitatively estimated according to the established design guidelines laid down by the research board of trustees for mechanical engineering (Forschungskuratorium Maschinenbau FKM) or the International Institute of Welding. The test results unambiguously showed that it is only possible to achieve an ideal design in terms of lightweight engineering and resource-conservation if the actual component loadability is known. The innovative testing technology provides VHCF testing that also takes into account the economic aspects of the industrial environment.

1 *Close-to-application component load is possible thanks to the test setup for much faster component fatigue tests on a 1,000 Hertz resonance test bed.*

2 *As a key functional element in a passenger car injection system, the laser-welded component has to be designed to be "fatigue-resistant" against its operating loads.*

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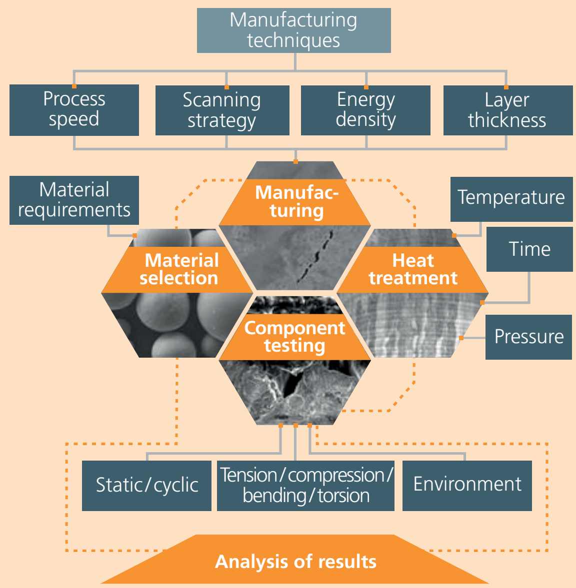
THE DIGITAL TWIN: TESTED FOR ORIGINALITY

Following the digitization trend, it is becoming more and more important to predict material characteristics with simulation-added forecast models. State-of-the-art lightweight design strategies additionally call for reliable material property prediction. The researchers at Fraunhofer IWS address this supposed conflict with new paradigms in experimental validation.

Digitization has found its way into all businesses and stages of product life cycles and has become an important driver in safeguarding the German industry's competitiveness and its value-added chain. The Fraunhofer IWS team draws on comprehensive expertise and technologies to validate the correlation between processes and material or component properties in experiments. Targeted experimental analyses make it possible to identify how various manufacturing processes affect the microstructure and overall product reliability in terms of strength, functionality, shape and optical properties. Activities to implement "Industrie 4.0" as well as digital transformation aim at planning and establishing entire process chains that meet "First-time-right" requirements. However, when describing the processes, the researchers have to pay attention to many influencing factors. This can be demonstrated, for example, for additive manufacturing. Metallographic and electron microscope methods to analyze how a manufacturing process changes the microstructure are refined by more and more automated evaluation in the sense of high-throughput experiments. The engineers apply the high-frequency fatigue testing technology to reduce the time required to validate how processes influence a component's mechanical properties. The engineers at Fraunhofer IWS are currently establishing a comprehensive database on process-structure-property correlations, opening up the way toward "Reverse Engineering".

Factors influencing additively manufactured structures' properties



The diagram highlights potential factors influencing both microstructure development and the properties of additively manufactured components that have to be considered when validating a digital twin in experiments. This requires the use of various analysis and testing methods customized with a view to shorter product development times at Fraunhofer IWS.

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NEW HIGH-PERFORMANCE METALS FOR ADDITIVE MANUFACTURING

High-entropy alloys are innovative metallic materials that provide property combinations that have never been achieved with conventional materials. Thus, for instance, they can be very strong and ductile at the same time, and have a wide application potential, in particular at high application temperatures.

Mixing at least five main elements in identical or at least similar composition provides a high-entropy alloy. This is fundamentally different to classic alloys, in which a base element, such as iron, has its properties customized through the addition of alloying elements in relatively small amounts. The high-entropy approach results in simple, usually single-phase, lattice structures of sound ductility, extraordinary strength due to solid solution hardening and temperature-stable microstructures. Researchers have generated high-entropy alloys only in minimal volumes on a laboratory scale up to now. It is very complicated to synthesize the material and the material costs are very high. These obstacles make additive manufacturing the technology of choice for high-entropy alloy synthesis. Using additive manufacturing techniques extends the range of applications and utilizes the alloy systems' potential better than conventional manufacturing routines. Producing components with integrated functions is another goal and will be a much greater innovation. To identify new material systems that are highly relevant for use, researchers at Fraunhofer IWS developed techniques and methods for a so-called high-throughput screening for synthesis and characterization purposes. The scientists can deposit numerous alloy variations simultaneously by utilizing a PVD coating process and targets of various compositions. They analyze them quickly using automated measurement procedures that access hardness and chemical composition and evaluate their suitability. The engineers succeeded in synthesizing selected material systems with laser powder and laser wire cladding in the form of multi-layer surface coatings. A worldwide innovation is the successful synthesis of refractory alloys that are preferred for high-temperature applications by means of laser wire cladding, shown for the "TiZrNbHfTa" system. The IWS researchers have for the first time also qualified the so-called fused filament fabrication technique for the 3D printing of high-entropy alloys.

1 *Grain morphology of the generated TiZrNbHfTa alloy. Successful synthesis of the refractory alloys preferred for high-temperature applications by laser wire cladding is a worldwide first.*

2 *Scientists at IWS have printed 3D high-entropy demonstrator structures consisting of the so-called Cantor alloy with a CrMnFeCoNi composition for the first time.*

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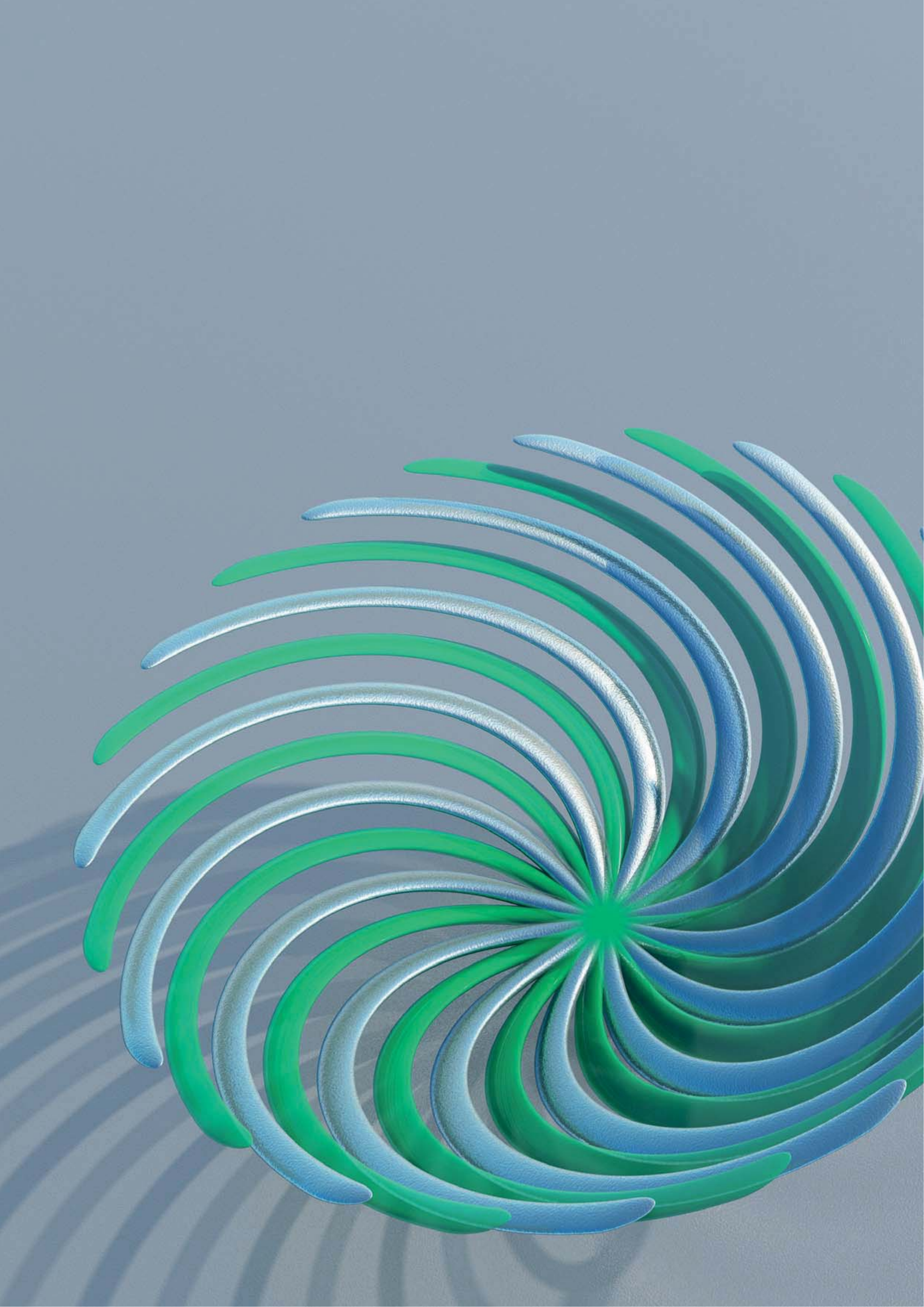

CENTERS AND NETWORKS

COOPERATION PARTNERS

CENTERS

BRANCHES

NETWORKS

FRAUNHOFER GROUP FOR LIGHT & SURFACES

HOW TO REACH US

EDITORIAL NOTES

COOPERATION PARTNERS

CENTER FOR COATINGS AND DIAMOND TECHNOLOGIES CCD

Staying competitive in today's economic situation calls for innovative products and manufacturing solutions. In particular, the Fraunhofer CCD's projects address coating and technology solutions that combine expertise in processes, materials, and systems engineering with scientific excellence, quality and project management. The services involve material coating and testing for customer applications, research and development projects for product development, consultation and engineering services and material characterizations, as well as system development, integration, installation and support. The Fraunhofer Center for Coatings and Diamond Technologies CCD is located in East Lansing, Michigan, on the campus of the Michigan State University MSU. For thirteen years, IWS scientists have been cooperating with Fraunhofer CCD and MSU in the fields of thin layer and diamond technology.

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CENTER FOR LASER APPLICATIONS CLA

The Fraunhofer Center for Laser Applications CLA is the result of bundling all the laser research activities of Fraunhofer USA in a joint center. Since 1994, this center has been developing new laser applications in the United States for a wide variety of industrial users. With its expertise in laser processing of materials and its state-of-the-art laser systems, Fraunhofer CLA provides support in the process solutions development for customized use. Its activities focus on providing laser technologies and systems. The center provides a wide range of laser processes, including welding, cutting, drilling, coating, heat treatment, surface marking and patterning, as well as additive manufacturing. Another special field is systems development for process monitoring and control. The researchers at Fraunhofer CLA also develop processing heads for build-up welding and additive manufacturing. The CLA is located in Plymouth, Michigan, next to Detroit.

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FRAUNHOFER PROJECT CENTER – WROCŁAW CENTER OF EXCELLENCE FOR MANUFACTURING

Founded in partnership with the Wrocław University of Technology, the Fraunhofer Project Center for Laser-Integrated Manufacturing expands Fraunhofer IWS' cooperation network to Eastern Europe and plays a pioneering role in Polish-German cooperation. The objectives in the cooperation prioritize contract research as well as development and engineering services for Polish industrial customers. Furthermore, the cooperation partners also expand the center's training programs and contribute to transnational scientific exchange. The researchers at the Fraunhofer Project Center in Wrocław are working on new methods and technologies for optical measurements and surface inspections of components that are difficult to refine. Reverse Engineering activities are closely linked with physical objects digitization and 3D computer model creation. In addition, Wrocław's scientists research laser materials processing, rapid prototyping and tooling, exchanging approaches and findings with the researchers in the Material Testing field at Fraunhofer IWS.

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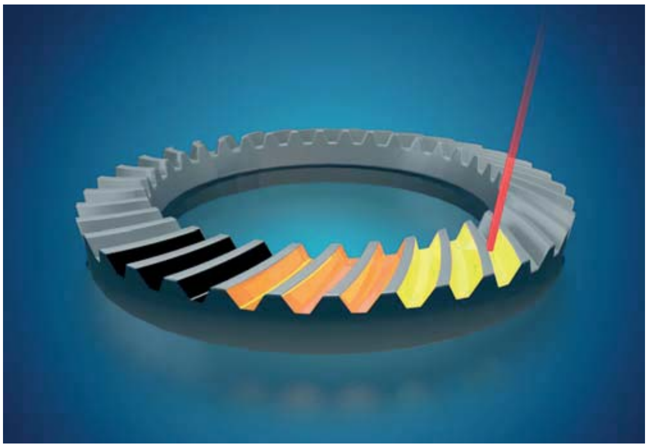
CENTERS



CENTER FOR THERMAL SURFACE TECHNOLOGY

Fraunhofer IWS has established a variety of surface coating and refinement techniques that is unique in Europe. The Center for Thermal Surface Technology deploys this profound material knowledge to develop complete solutions for complex tasks from a wide range of industries and rapidly transfers the results into practice. The Center does not only offer laboratory solutions. Users benefit in particular from Fraunhofer IWS' experience in transferring technological developments, including application-specific hardware and software components, to industrial production. Users of the thermal surface techniques portfolio come from the automotive industry and electrical power engineering, the aeronautics and space industries, medical engineering, gas and oil industries, mechanical engineering, as well as tool and die-making. Part sizes range from a few millimeters to several meters.

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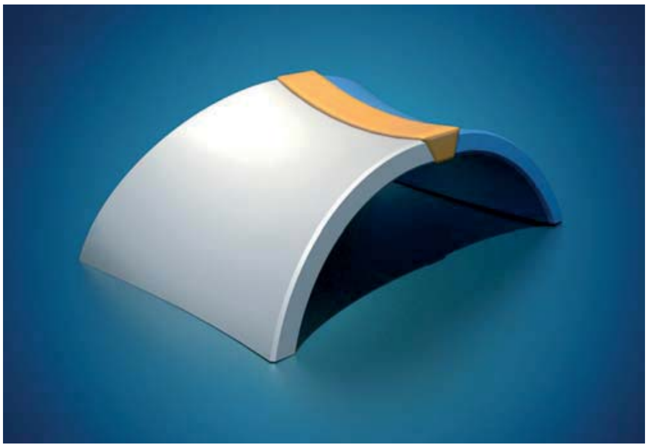

CENTER FOR TAILORED JOINING

Joining represents a key challenge in production and frequently significant costs. The Tailored Joining Center was established in cooperation with TU Dresden and other partners to achieve further improvements and inspire new ideas. The aim is to give users an overview of the possibilities and limitations of various joining processes, to enable a direct comparison, to present new developments in a compact way and to present industry-related solutions. The Center's partners are TU Dresden and the University of Applied Sciences – Hochschule für Technik und Wirtschaft HTW. TU Dresden, with the Chair of Joining Technology and Assembly, focuses on techniques and tools for thermal, mechanical and hybrid joining, as well as joining by forming; the chair also deals with integrated planning of assembly, handling and joining processes. The University of Applied Sciences HTW Dresden with its expertise in electron beam welding has been actively contributing to the Dresden research alliance since 2014. All partners pay special attention to comparing the various solutions without assessment, so that users receive direct decision support for their particular tasks.

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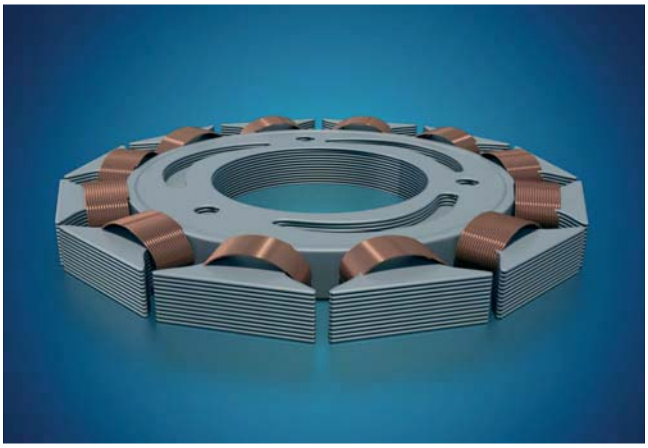
CENTER FOR ENERGY EFFICIENCY



Research and development activities at the Center for Energy Efficiency primarily focus on using energy economically and refining resource-saving technologies. The Center for Energy Efficiency concentrates researchers' strengths to establish and expand energy efficiency as an integral part of research and development projects. To create public awareness for energy efficiency outside the institute and to accelerate new developments, Fraunhofer IWS, for example, founded the Dresden Innovation Center for Energy Efficiency DIZE^{EFF} in 2009. At DIZE^{EFF} scientists at TU Dresden and the Dresden Fraunhofer Institutes collaborate in numerous projects and research in the areas of high-performance solar and fuel cells, high-temperature power engineering, lightweight design, as well as highly efficient electric motors, manufacturing and energy-saving displays.

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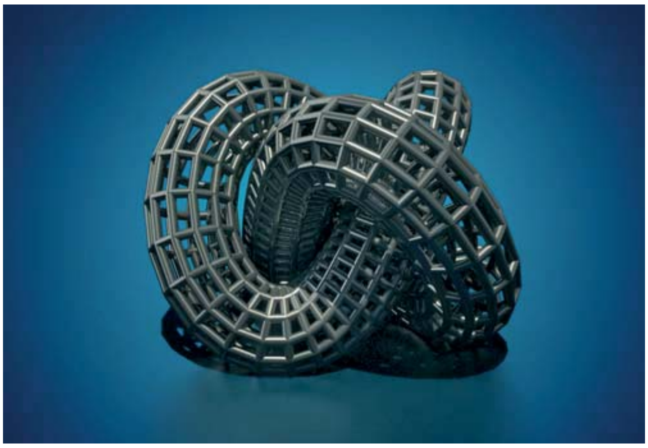
ADDITIVE MANUFACTURING CENTER DRESDEN



A paradigm shift in manufacturing technology: layer by layer part fabrication can overcome conventional manufacturing limits and enable completely new geometries. This great opportunity faces many unsolved questions. Closely linking science and industry, the Center for Additive Manufacturing investigates cross-procedural material and manufacturing solutions for challenging products. Fraunhofer IWS and TU Dresden have established the Additive Manufacturing Center Dresden AMCD as an institution with a strong international reputation. The Center is an ideal industry networking platform to cross-link basic research at the university and user-oriented studies in a fast-paced high-tech field.

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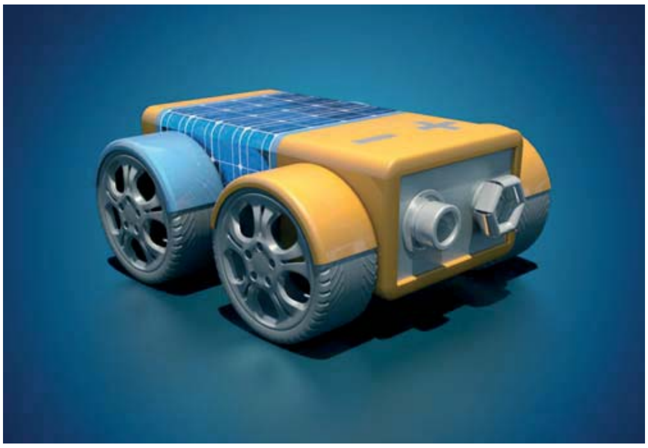

CENTER FOR BATTERY RESEARCH

The scientists at the Center for Battery Research focus on technologies for new energy storage devices. The challenge: finding solutions with higher energy density at a reasonable cost for many growth markets. Developing cost-efficient production techniques scalable for industrial use is not only crucial to bringing a new cell generation to the market, but also to reducing existing cell technologies' costs. Consequently, Fraunhofer IWS has established a process chain for battery cell production – from electrode fabrication via configuring, assembling electrode stacks, up to packed pouch cells. In addition to the classical battery electrodes' wet coating, the researchers are developing a completely solvent-free approach to process initial materials to free-standing electrode films. Configuration and assembly of the electrodes are laser cut and can thus be adapted to various cell formats.

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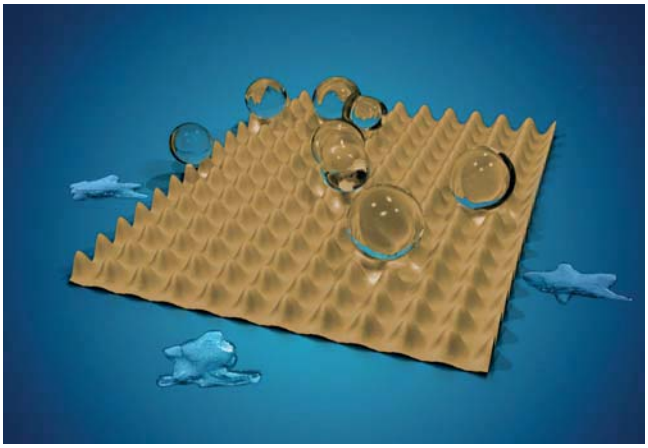

CENTER FOR ADVANCED MICRO-PHOTONICS CAMP

CAMP explores laser-based surface modification and patterning methods. Driven by current trends in laser-based microprocessing, the Center targets opportunities and challenges in the development of new system, process and measurement solutions. To transfer technologies into industrial processes, the researchers implemented every operation along the entire process chain. CAMP demonstrates cross-operational approaches from simulation via laser process and optical measurements to machine learning. In these endeavors, scientists at Fraunhofer IWS, in cooperation with TU Dresden, focus on various applications of laser microprocessing and measuring operations. The Center deploys a wide range of current technologies, with numerous applications, such as microdrilling, microcutting and patterning, as well as laser marking and laser interference patterning.

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PROJECT GROUP OF FRAUNHOFER IWS AT THE DORTMUND SURFACE CENTER DOC®

The DOC® typically provides customized coatings to be used in continuous techniques on steel strips. The development projects primarily target improving functions such as corrosion and scratch resistance, electric conductivity or cleaning properties. The group's activities concentrate on PVD surface coatings and thermal coating techniques, as well as laser surface processing. Among other objectives, the DOC® emphazises on engineering electrically conductive, formable carbon layer systems and surfaces for electric mobility for fuel cells, Diamor® coating systems for wear protection, based on the "short pulsed Arc" (spArc®) technique, the latest PVD high-performance methods, arc wire spraying under vacuum and large-area remelting with high-power lasers for strip refinement.

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APPLICATION CENTER FOR OPTICAL METROLOGY AND SURFACE TECHNOLOGIES AZOM

Situated in the Westsächsische Hochschule Zwickau's (WHZ, University of Applied Sciences) vicinity, the AZOM bridges the gap between Fraunhofer IWS in Dresden and regional industry. The researchers develop and proof-test optical measuring techniques for industry companies. The portfolio of services comprises sensors for different process parameters and variables as well as complex measuring stations and devices connected with the customers' data processing equipment. AZOM expands Fraunhofer IWS' range of applications in surface analytics. At the same time, student and graduate WHZ engineers get the chance to collaborate in industrial projects. The Fraunhofer Application Center, which is unique in this sense in the new Federal States in Germany, features laboratory rooms equipped with optical tables, system modules and numerous measuring devices, as well as systems for surface analysis.

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NETWORKS

FRAUNHOFER-GESELLSCHAFT

Research of practical utility lies at the heart of all activities pursued by the Fraunhofer-Gesellschaft. Founded in 1949, the research organization undertakes applied research that drives economic development and serves the wider benefit of society. Its services are solicited by customers and contractual partners in industry, the service sector and public administration.

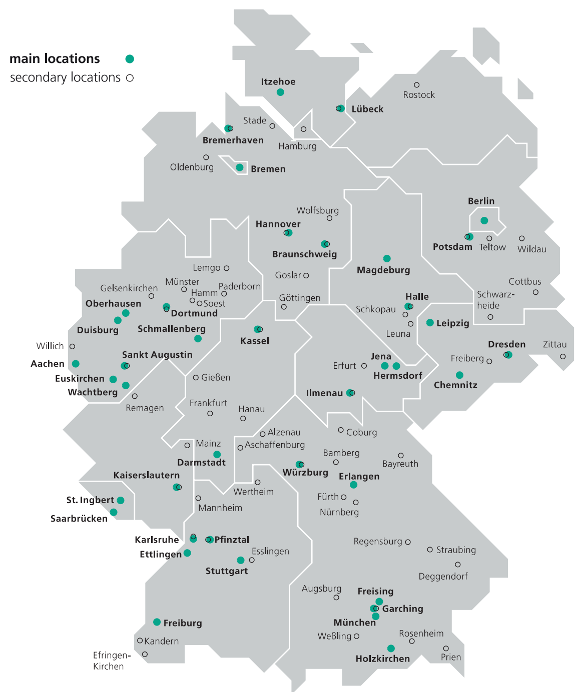
At present, the Fraunhofer-Gesellschaft maintains 72 institutes and research units. The majority of the more than 26,600 staff are qualified scientists and engineers, who work with an annual research budget of more than 2.5 billion euros. Of this sum, more than 2.1 billion euros is generated through contract research. Around 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Around 30 percent is contributed by the German federal and state governments in the form of base funding, enabling the institutes to work ahead on solutions to problems that will not become acutely relevant to industry and society until five or ten years from now.

International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

With its clearly defined mission of application-oriented research and its focus on key technologies of relevance to the future, the Fraunhofer-Gesellschaft plays a prominent role in the German and European innovation process. Applied research has a knock-on effect that extends beyond the direct benefits perceived by the customer: Through their research and development work, the Fraunhofer Institutes help to reinforce the competitive strength of the economy in their local region, and throughout Germany and Europe. They do so by promoting innovation, strengthening the technological base, improving the acceptance of new technologies, and helping to train the urgently needed future generation of scientists and engineers.

As an employer, the Fraunhofer-Gesellschaft offers its staff the opportunity to develop the professional and personal skills that will allow them to take up positions of responsibility within their institute, at universities, in industry and in society. Students who choose to work on projects at the Fraunhofer Institutes have excellent prospects of starting and developing a career in industry by virtue of the practical training and experience they have acquired.

The Fraunhofer-Gesellschaft is a recognized non-profit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.



TECHNISCHE UNIVERSITÄT DRESDEN

Excellent cooperation: Since its founding in 1997, Fraunhofer IWS has continuously expanded its collaboration with various chairs at TU Dresden. This enables the scientists to combine the university's comprehensive fundamental knowledge with application-oriented development at IWS. Professors and scientists at TU Dresden are closely involved in the institute's research projects and have access to its technical equipment and infrastructure. IWS managers and employees assist the university in qualifying students and doctoral candidates, thus recruiting the next generation of scientists.

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Chair of Materials Science

PROF. DR. STEFAN KASKEL
Faculty of Mathematics and Natural Sciences
Department of Chemistry and Food Chemistry

Chair of Inorganic Chemistry

PROF. DR. KAROL KOZAK
Faculty of Medicine
Clinic for Neurology

Chair of Data Management and Evaluation

PROF. DR. ANDRÉS-FABIÁN LASAGNI
Faculty of Mechanical Science and Engineering
Institute of Manufacturing Technology

Chair of Large Area Laser-Based Surface Structuring

PROF. DR. ANDREAS LESON
Faculty of Mechanical Science and Engineering, Institute of Manufacturing Technology

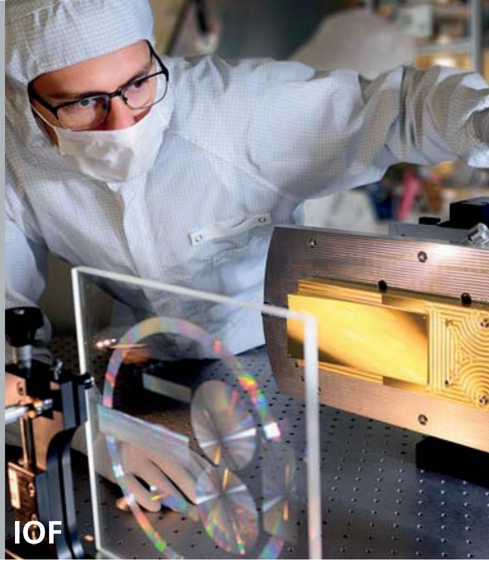
Chair of Nano- and Coating Technology

PROF. DR. MARTINA ZIMMERMANN
Faculty of Mechanical Science and Engineering
Institute of Materials Science

Chair of Mechanics of Materials and Failure Analysis

TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept



FRAUNHOFER GROUP FOR LIGHT & SURFACES

COMPETENCE BY NETWORKING

Six Fraunhofer institutes cooperate in the Fraunhofer Group for Light & Surfaces. Coordinated competences allow quick and flexible alignment of research work on the requirements of different fields of application to answer actual and future challenges, especially in the fields of energy, environment, production, information and security. This market-oriented approach ensures an even wider range of services and creates synergetic effects for the benefit of our customers.

CORE COMPETENCES OF THE GROUP

- Surface and coating functionalization
- Laser-based manufacturing processes
- Laser development and nonlinear optics
- Materials in optics and photonics
- Microassembly and system integration
- Micro and nano technology
- Carbon technology
- Measurement methods and characterization
- Ultra precision engineering
- Material technology
- Plasma and electron beam sources

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FRAUNHOFER INSTITUTE FOR ORGANIC ELECTRONIC, ELECTRON BEAM AND PLASMA TECHNOLOGY FEP, DRESDEN

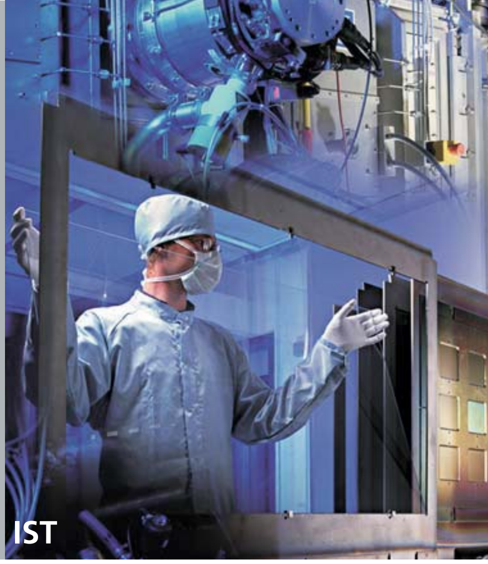
Electron beam technology, sputtering technology, plasma-activated high-rate deposition and high-rate PECVD are the core areas of expertise of Fraunhofer FEP. The business units include vacuum coating, surface modification and treatment with electrons and plasmas. Besides developing layer systems, products and technologies, another main area of work is the scale-up of technologies for coating and treatment of large areas at high productivity.

www.fep.fraunhofer.de

FRAUNHOFER INSTITUTE FOR LASER TECHNOLOGY ILT, AACHEN

Since 1985 the Fraunhofer Institute for Laser Technology ILT has developed innovative laser beam sources, laser technologies, and laser systems for its partners from the industry. Our technology areas cover the following topics: laser and optics, medical technology and biophotonics, laser measurement technology and laser materials processing. This includes laser cutting, caving, drilling, welding and soldering as well as surface treatment, micro processing and rapid manufacturing. Furthermore, Fraunhofer ILT is engaged in laser plant technology, process control, modeling as well as in the entire system technology.

www.ilt.fraunhofer.de



FRAUNHOFER INSTITUTE FOR SURFACE ENGINEERING AND THIN FILMS IST, BRAUNSCHWEIG

As an industry oriented R&D service center, Fraunhofer IST is pooling competencies in the areas film deposition, coating application, film characterization, and surface analysis. Scientists, engineers, and technicians are busily working to provide various types of surfaces with new or improved functions and, as a result, help create innovative marketable products. The institute's business segments are: mechanical and automotive engineering, aerospace, tools, energy, glass and facade, optics, information and communication, life science and ecology.

www.ist.fraunhofer.de

FRAUNHOFER INSTITUTE FOR APPLIED OPTICS AND PRECISION ENGINEERING IOF, JENA

Fraunhofer IOF develops solutions with light to cope foremost challenges for the future in the areas energy and environment, information and security, as well as health care and medical technology. The competences comprise the entire process chain starting with optics and mechanics design via the development of manufacturing processes for optical and mechanical components and processes of system integration up to the manufacturing of prototypes. Focus of research is put on multifunctional optical coatings, micro- and nano-optics, solid state light sources, optical measurement systems, and opto-mechanical precision systems.

www.iof.fraunhofer.de

FRAUNHOFER INSTITUTE FOR PHYSICAL MEASUREMENT TECHNIQUES IPM, FREIBURG

Fraunhofer IPM develops and builds optical sensor and imaging systems. These mostly laser-based systems combine optical, mechanical, electronic and software components to create perfect solutions of robust design that are individually tailored to suit the conditions at the site of deployment. In the field of thermoelectrics, the institute has extensive know-how in materials research, simulation, and systems. Fraunhofer IPM also specializes in thin-film technologies for application in the production of materials, manufacturing processes and systems.

www.ipm.fraunhofer.de

FRAUNHOFER INSTITUTE FOR MATERIAL AND BEAM TECHNOLOGY IWS, DRESDEN

Light and layer: Fraunhofer IWS works wherever lasers and surface technology meet. The Dresden institute comes into play if the task is to deposit different materials layer by layer, to join, cut, functionalize or analyze. Services range from developing new techniques via integration into manufacturing, up to user-oriented support – in single-source responsibility. Fraunhofer IWS is meeting the challenges of digitization with a focus on researching and developing solutions for "Industry 4.0".

www.iws.fraunhofer.de

HOW TO REACH US

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By car

- Take Autobahn A 4 or A 13 to motorway junction Dresden-West, follow Autobahn A 17 to exit Südvorstadt/Zentrum
- Follow road B 170 to Stadtzentrum (city center) to Pirnaischer Platz (about six kilometers)
- At Pirnaischer Platz, turn right towards "Gruna/VW-Manufaktur"
- Continue straight until the end of the "Großer Garten" (Great Garden) and then turn right onto "Karcherallee"
- At the next traffic light turn left onto Winterbergstraße and continue straight until you reach IWS.

By rail and tram

- From Dresden, take line #10 to Straßburger Platz
- Change to line #1 (Prohlis) or #2 (Kleinzschachwitz) heading out from the city; exit at "Zwinglistraße"
- From there, continue on foot (in the direction of Grunaer Weg) for 10 minutes

By air plane

- From Airport Dresden-Klotzsche, take a taxi to Winterbergstraße 28 (about 10 kilometers)
- Alternatively use public transport (shuttle train) to Dresden Central Station (Hauptbahnhof) and continue by tram

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	p. 98	Fraunhofer FEP
	p. 99	Fraunhofer ILT, IPM, IST
	p. 97	Lothar Sprenger
	p. 90	Fraunhofer USA
	p. 91	Wrocław University of Technology
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