Fraunhofer

IWS Dresden

FRAUNHOFER INSTITUTE FOR MATERIAL AND BEAM TECHNOLOGY IWS

ANNUAL REPORT 2015

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FRAUNHOFER INSTITUTE FOR MATERIAL AND BEAM TECHNOLOGY IWS

DRESDEN concept

ANNUAL REPORT 2015

DEKRA

CERTIFICATE

Fraunhofer IWS

ISO 9001:2008

DEKRA Certification GmbH hereby certifies that the company

Fraunhofer- Institut für Werkstoff- und Strahltechnik IWS

Scope of certification:

Research and development in the field of Surface Engineering / Coatings and Laser Materials Processing with the research areas PVD- and Nanotechnology, Chemical Surface and Reaction Technology, Thermal Coating and Build-up Technologies, Surface Treatment and Joining, Laser Ablation and Cutting, Microtechnology

Certified location:

D-01277 Dresden, Winterbergstraße 28

has established and maintains a quality management system according to the above mentioned standard. The conformity was adduced with audit report no. A15101061.

This certificate is valid from 2016-02-01 to 2018-09-14

Certificate registration no.: 91297819/7

Lothar Weihofen
DEKRA Certification GmbH Stuttgart, 2016-02-01

IAF DAkkS

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FOREWORD

2015 was an extraordinary year for the IWS. Once again the number of customers grew significantly; their trust in our performance is shown through the 25 percent increase in industrial revenues.

The great challenge over the next few years will be the storage of energy and in particular the storage of electric energy. A topic in which the IWS, together with its project partners in Dresden, reached a breakthrough. At the Dresden Conference "Future Energy", the institute presented sodium-sulfur batteries that operate at room temperature. Among other advantages, the technology features extremely low-cost electrode materials, a nearly unlimited supply of raw materials and problem-free recycling.

Fraunhofer IWS colleagues were awarded the Joseph-von-Fraunhofer-Prize 2015 in the field of energy efficiency. The prize was received for the development and commercialization of extremely low-friction and wear resistant diamond-like carbon coatings.

Printing is a novel and rapidly growing manufacturing technology which is completely compatible with the demands of Industry 4.0. A CAD designed part can be downloaded from the Internet and sent to a printing machine to obtain the completely fabricated product. Within the DRESDEN-concept collaboration framework the IWS and the TU Dresden combined their print technology efforts in one building.

Thanks to the government of Saxony (SMWK, SMWA), the IWS invested more than 12 million Euros in 2015. This enables the institute to use the latest technologies for the performance of R&D projects.

"If there is any secret of success, it lies in the ability to get the other person's point of view."

Henry Ford

Since the beginning of 2015, IWS has been operating two centers in the USA, the Center for Coatings and Diamond Technologies (CCD) and the Center for Laser Applications (CLA). In 2015 both centers performed a very successful technology audit.

At its CCD center the IWS is very successful with the fabrication of diamond materials using plasma processes. A challenge for the coming 2 years is to develop diamond-based power electronics.

World political challenges and a large influx of refugees require new and location-specific integration concepts. The IWS initiated a pilot project in Saxony to support the integration of recognized refugees into the workforce by means of different measures. The concept addresses fundamentally three lines of support: 1. Fit for university studies, 2. Fit for vocational training or similar and 3. Fit for the labor market. A mentoring system will support the new colleagues to integrate successfully within and outside of the institute.

Overall 2015 was an extraordinarily successful year for IWS, and we are very optimistic for 2016.

I hope that you will be inspired with new impulses and ideas when reading our annual report and that IWS can help you to implement them.

Prof. Dr. E. Beyer

CONTENTS

THE FRAUNHOFER IWS

BUSINESS UNITS

CENTERS, NETWORKS, AWARDS

FROM THE BOARD OF TRUSTEES

The Board of Trustees consults and supports the institute's management and the bodies of the Fraunhofer-Gesellschaft. The 25th Board of Trustees meeting occurred on March 20th, 2015 at the Fraunhofer IWS in Dresden. The Board of Trustees during the reporting period consisted of the following members:

How strong is Germany's economy at the end of 2015? Last year's fourth quarter delivered the very positive surprise of an overall good economic development. The beginning of 2015 was also very good while the second quarter followed with light concerns. However, in the end the third and fourth quarters did not disappoint.

In Saxony during the first quarter of 2015 we were also very successful. However, the consequences of the Ukraine-Russia crisis had a significant influence with respect to declining business with Russia, especially true in the machine and plant building industries.

The financial support of science and applied research and development thus remains an important instrument to develop the German economy. A study of the German Academic International Network (GAIN) concluded "Germany is an increasingly attractive region of science". This is great news. The chances to perform top research in Germany have enormously increased. This is one of the reasons for the increased number of German scientists returning from foreign countries. This study awakens new potential.

Industrial demand for application-oriented research grows steadily. The Fraunhofer institutes contribute substantially to this success-based growth. Dresden too contributes decisively with its strongly performing institutes and their cooperative alliances. The status of Dresden as a region of science is promoted by the collaboration and cooperation with the Technische Universität Dresden, the Max-Planck institutes, the Leibniz institutes and the Helmholtz center.

The Fraunhofer-Institut für Werkstoff und Strahltechnik Dresden (IWS) delivered throughout 2015 convincing results and met the demands for a sustainable scientific performance at high levels. The IWS works very closely to applications which also is reflected in its balance sheets. The scientific and economic results follow the high demands for innovation, excellence and economic efficiency. With this clear orientation, the IWS is well aligned and prepared for the future.

The members of the Board of Trustees follow with great attention the continual positive developments and support measures for further strategic orientation. The Board of Trustees would like to thank our customers for their trust in our colleagues, the institute's management and all our partners for their collaboration, support and the achieved results. We wish you a healthy and successful future.

Yours truly,

Dr. Frank Junker

INSTITUTE PROFILE

CORE COMPETENCES

The transfer of current research results into industrial practice is an essential driving force for research efforts at the institute. To adequately meet this "mission" we have developed and continually expanded core competences in the following areas:

LASER MATERIALS PROCESSING

- cutting and high speed cutting of metals, polymers and fiber-polymer composites
- cutting and enhancing soft-magnetic materials
- welding of hard-to-weld materials and mixed material joints
- laser buildup welding and additive manufacturing
- 2-photon polymerization
- laser surface hardening, remelting, alloying and short term heat treatments of highly stressed parts
- micro materials processing (cutting, drilling, structuring)
- ablation, cleaning and structuring, also of art and cultural goods
- process-specific laser hybrid technologies, such as laser induction welding, laser buildup welding, laser roll plating as well as plasma, TIG or MIG assisted laser beam welding

SURFACE FUNCTIONALIZATION AND COATING

- plasma, arc and flame spray processes with powders and suspensions
- high rate and precision coating processes based on physical vapor deposition
- Laser-Arc process as hybrid technology
- plasma and chemical etching, ablation, cleaning
- chemical vapor deposition and coating
- dispenser printing of functional materials
- paste deposition (also in roll-to-roll process)
- spray deposition of ultrathin coatings
- nano and micro structuring with laser and plasma

SPECIAL JOINING TECHNOLOGIES

- electromagnetic pulse welding
- 3D friction-stir welding
- adhesive bonding especially with laser and plasma pre-treatment
- thermal direct joining of thermoset composite materials

SYSTEMS TECHNOLOGY

- implementation of process know-how in development, design and fabrication of components, equipment and systems including associated software
- systems solutions and control technology for cutting, welding, ablation, deposition, surface refinement and functionalization with laser, e. g.
  · processing optics, sensorics, beam scanning and monitoring systems including control software for high speed and precision processing
  · beam shaping and process control and calibration systems for surface refinement, heat treatment, coating and additive manufacturing
  · optical systems for laser interference patterning and 2-photon polymerization
- process specific monitoring and control
- coating heads for the continuous free-directional powder or wire delivery as well as process monitoring and CAM control software
- process-oriented prototype development of components and coating systems for PVD precision and high rate deposition as well as chemical and thermal surface refinement processes

"Quality is never an accident. It is always the result of intelligent effort."

John Ruskin

- measurement systems for coating characterization, non-destructive component evaluation with laser acoustic and spectroscopic methods as well as terahertz analytics
- systems for permeation measurements and the spectroscopical monitoring of gas mixtures
- application specific design, simulation and prototype fabrication of fluidic microsystems
- technology platform for integrated pumps and valves as well as optical and electrical functional elements in microsystems
- construction and assembly technologies for the development of microsystems

PROCESS SIMULATION

- development of simulation modules for
  · thermal surface treatments and laser hardening
  · buildup welding and additive manufacturing
  · cutting and welding
  · vacuum arc deposition
- calculation of optical properties of nano coatings systems with in-house simulation tools
- use of commercial simulation modules for
  · laser beam welding and cutting
  · optimization of gas and plasma flows during coating processes and laser materials processing

MATERIALS SCIENCE / NANOTECHNOLOGY

- obtaining material data for material selection, component design and quality assurance
- metallographic, electron microscopic and micro-analytical characterization of the structure of metals, ceramics and coating composites
- determination of mechanical parameters of materials and material composites (static, cyclic)
- obtaining correlations to evaluate the fatigue strength up to $N \leq 10^9$ via time shortened fatigue testing at high frequencies
- failure analysis and evaluation of damage case
- high resolution imaging and analytical characterization and property evaluation of laser-processed and coated materials and parts
- opto-spectroscopic characterization of surfaces and coatings (nm to mm range)
- characterization of magnetic and mechanical-tribological properties
- coating thickness and Young's-modulus measurements from nm to mm coatings with laser acoustics
- ellipsometry, X-ray reflectometry and X-ray diffractometry
- imaging surface analysis with hyper-spectral imaging
- electrochemistry and electrode chemistry
- fabrication, functionalization, processing and characterizing of nanoparticles and nanotubes

HIGHLIGHTS OF THE YEAR 2015

RESEARCH TO IMPROVE ENERGY EFFICIENCY

Friction and wear reducing coatings have been a research focus of the business unit "PVD- and Nanotechnology" at the Fraunhofer IWS for many years. More recently Fraunhofer engineers have collaborated with several industry partners to ready the process for industrial deployment and commercialization. The next development goal is to reduce the energy consumption of dry and minimally lubricated systems by using low friction coatings. The BMWi will fund this project over the next three years with 7.2 million euros, which includes the Fraunhofer IWS as well as eight industry partners and two additional research institutions. The core objective of the project is to optimize tribological systems in transmissions, bearings and chains so that these will not require external lubricants (oil, grease, etc.) in the future. Such systems would feature improved energy efficiency along with reduced CO_2 emissions.

RESET – THE CENTER FOR RESOURCES CONSERVING ENERGY TECHNOLOGIES IS NOW FULLY OPERATIONAL

In 2015 the Fraunhofer institutes IWS and FEP finished the installation and startup of substantial equipment resources in a new building of the 4th expansion phase on the Fraunhofer campus. In an IWS section of the building with about 500 m^2 the installed equipment includes machines for additive manufacturing with continuous powder and wire feeds. A similarly sized IWS laboratory bundles technologies for constructive and structural lightweight technologies to combine and expand competences in polymer-metal joints and fiber reinforced composites. Additional equipment for pre- and post-treatments as well as analytical systems add to the spectrum. On July 3rd 2015, the new laboratories were presented to the public. More than 1000 guests visited with great interest.

STRATEGY PROJECT "AGENT-3D" IS ACCELERATING

The Fraunhofer IWS Dresden leads a consortium of more than 90 partners with the goal to establish additive-generative manufacturing as a key technology in Germany. In collaboration with other Fraunhofer institutes, the Fraunhofer IWS completed an initial strategy project in 2015. Now the first group of technology projects are being launched. Thanks to funding from the federal and the State of Saxony governments in form of the EFFI II investment project, the IWS was able to substantially expand its equipment resources for additive manufacturing. IWS researchers now have the option to use powder bed based additive manufacturing processes to fabricate complicated components with special functionalities. The latest results and knowledge will be presented at the second International Symposium "Additive Manufacturing" ISAM in Dresden.

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MILESTONES IN BATTERY RESEARCH

For about 5 years Fraunhofer IWS researchers have been working on the development of suitable electrode materials and manufacturing processes to produce high energy density battery cells based on lithium-sulfur technology in a cost effective manner. At the "Future Energy" conference in November 2015 researchers presented for the first time lithium-sulfur pouch cells with specific energy densities exceeding 300 Wh kg^{-1}, which is an approximately 25 percent increase over classic lithium-ion technologies. With regard to an increasing demand for low-cost stationary energy storage, IWS researchers are also working on room temperature sodium-sulfur battery cells. Anode and cathode electrolytes were adapted so that such battery cells can now be operated at room temperature instead of 300 °C. These cells have discharge capacities of up to 980 mAh per gram of active cathode material. The charging efficiency exceeds 95 percent and the cells can be reversibly discharged and recharged more than 1000 times. An EU project (ALISE) started in June 2015 so that IWS can continue with these developments. A BMBF project (DryLIZ) was finished in 2015. Here the researchers showed ways to lower fabrication costs and to reduce processing times for cutting electrodes.

DURABLE ORGANIC PHOTOVOLTAIC CELLS

In January 2015 the Fraunhofer IWS in collaboration with Heliatek GmbH launched the 3.9 million Euro EU project ALABO. The goal is to develop technologies for cost efficient manufacturing of large area, light weight and flexible photovoltaic foils. These foils are also expected to offer a significantly improved longevity. For the first time the team of researchers will apply laser structuring processes for PV cells. Jointly with its European and German partners, the Fraunhofer IWS will perform research tasks on laser processing, optical process monitoring as well as the rapid evaluation of the barrier performance. The project will use IWS developed laser systems for high speed structuring. These systems achieve effective structuring speeds of 0.9 m^2 min^{-1} on polymer surfaces. In 2015 this was a world record. Likewise, the IWS developed measurement system HiBarSens® also offers world record capabilities to measure the permeability of foils. The system detects the smallest water vapor permeability rates of 1 x 10^{-6} g m^{-2} d^{-1}.

INDUSTRIAL IMPLEMENTATION

COATING MACHINE FOR HYDRAULIC CYLINDERS

Bosch Rexroth in Boxtel, Netherlands, is a leading manufacturer of very large hydraulic cylinders. They used an existing coating machine for plasma welding, adapted it for laser coating processes and doubled the work space. The reconfigured machine started operation at the end of 2015. The system has a 20 kW high power diode laser as an energy source. A special laser module is designed so that the process is reliable but can later be upgraded to include inductive preheating. The machine is equipped with the latest generation of wide jet powder nozzles "COAX11" and also includes several process monitoring, control and observation systems. The Fraunhofer IWS is responsible for process and machine functionality and safety.

PRODUCTION PROCESS INTEGRATION OF LASER WELDING PROCESSES FOR ALUMINUM

The Finow Automotive Company in Eberswalde manufactures cooling water tubes for car engines using an IWS-developed welding process. IWS engineers retrofitted an existing laser welding machine with a fiber laser and a highly dynamic beam scanner to meet the requirements of the manufacturing process. This was possible with a newly IWS-developed laser module. The overall safety concept of the machine was also completely revamped.

DOMAIN REFINEMENT OF ELECTRIC SHEETS WITH LASER REMOTE TECHNOLOGY

Previously, the Fraunhofer IWS, the Rofin Sinar Laser GmbH and the Maschinenfabrik Arnold had jointly developed systems to refine domains in electric sheets using laser remote technology. In 2015 another system was installed for an industrial customer in Asia. The installed plant laser continually treats a moving band of material with an annual capacity of 50,000 tons. It has 4 fiber lasers and a single beam scanning system (Fig. 1).

LASER-INTEGRATED MACHINING CENTER

Under contract of the WFL Millturn Technologies GmbH in Linz IWS engineers integrated laser hardening and buildup welding processes in a drilling-turning-milling machining center. The Millturn center can now completely machine workpieces and perform steps such as the deposition of wear resistant coatings or the hardening of teeth in one and the same setup. Fraunhofer IWS engineers developed the application-specific laser processing head as well as the associated processing steps. The engineers also supported the end-user during the installation of the system and provide processes and laser technical components (Fig. 2).

ADDITIONAL REMOTE-CUTTING TECHNOLOGY TRANSFER TO THE AIRBAG INDUSTRY

The Fraunhofer IWS and the company Held Systems had developed a compact system to cut airbag fabric material with a flexible laser beam process. In 2015 two additional machines were installed for industrial customers. The 15^{th} and 16^{th} system were installed in China and Mexico to cut single and multilayer fabrics with high productivity due to the remote-cutting technology.

MACHINE RETROFIT FOR THE OIL INDUSTRY

IWS engineers retrofitted a laser hardening and coating machine at the company Precision Machinery in Dubai to improve process safety, efficiency and ergonomic operation. Three special laser modules were developed and equipped with the camera-based temperature acquisition system "E-MAqS". The customer requirements included remote observation and process monitoring capabilities. In the future the company can monitor the machine from other production locations.

2

3

4

LASER PROCESSING CENTER TO MANUFACTURE AND REPAIR LARGE TOOLS

The Fraunhofer IWS collaborated with the Maschinenfabrik Arnold, Ravensburg, on the installation of a 3D laser processing center for the repair, modification and surface treatment of large tools for car body manufacturing. The system was delivered to Shanghai Volkswagen. IWS engineers developed and delivered system components and processes and supported the startup of the machine in manufacturing. VW is now relying on the dynamic beam shaping unit "LASSY" for laser hardening processes also in China. A special challenge was the need for the defect-free laser buildup welding on cast iron (GGG70) material. A customer-specific system and process solution was developed to solve this problem.

MANUFACTURING OF DIAMOND TOOLS FOR WIRE SAWS

The Bekaert Company in Belgium has developed an innovative laser coating process to manufacture diamond tools for wire saws. An essential component to ensure process safety is the Fraunhofer IWS-developed temperature measurement system "E-MAqS" in combination with the process controller "LompocPro". In 2015 IWS delivered the technology for two manufacturing systems to Bekaert.

PROCESS AND SYSTEMS TECHNOLOGY FOR THE COAXIAL LASER-WIRE BUILDUP WELDING OF COMPLEX PARTS

Laser-wire buildup welding is a classic materials processing technology with strong and increasing demand from industry. One of the reasons for the increasing demand is an IWS-developed solution which packages process and laser head technology for the directionally independent buildup welding using a coaxial wire feed. Several systems were installed in 2015 at users in the turbo machinery and tool and die making industries (Fig. 3).

PLASMA SOURCE FOR THE MODIFICATION OF LARGE AREA SURFACES IN THE AEROSPACE INDUSTRY

The Fraunhofer IWS research group "Plasma Technologies and Nanomaterials" develops atmospheric pressure plasma surface functionalization technologies for titanium alloys and fiber-polymer composites. One of their products is the LARGE (Long Arc Generator) plasma source, which was developed within collaborative projects funded by the European Union and is now ready for the market. Since April 2015 a 150 mm LARGE plasma source has been in use at the Airbus company to deposit adhesion promoters on titanium and to plasma activate CFRP materials. Both material classes are important in aerospace technology and can now be plasma-processed to pre-prepare them for subsequent adhesive bonding (Fig. 4).

LOW FRICTION AND WEAR RESISTANT CARBON COATINGS

The IWS-developed Laser-Arc process efficiently and economically deposits superhard ta-C carbon coatings (Diamor®). These coatings have superior properties in terms of wear resistance and friction reduction and thus are of great interest to industry. In 2015 the IWS and the partner company Vakuumtechnik Dresden built five Laser-Arc modules and delivered them to industrial customers.

SPUTTER TECHNOLOGY TO DEPOSIT NANOMETER MULTILAYER COATINGS

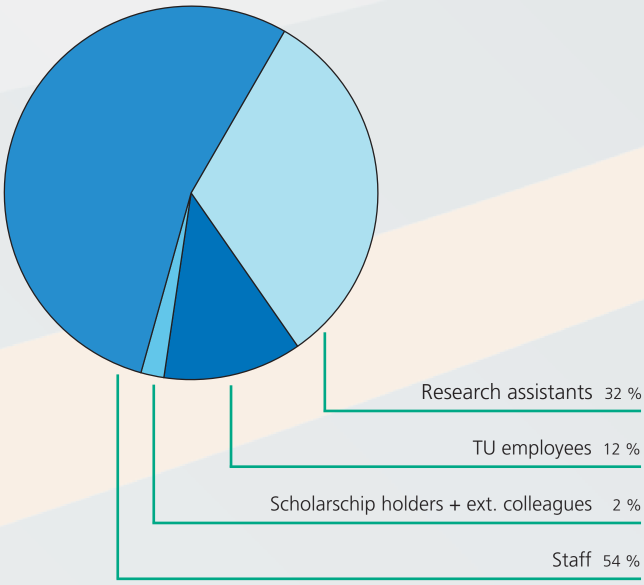
In 2015 IWS and the partner company scia Systems GmbH built a large area sputter coating machine and delivered it to an industrial customer. The system produces high precision nanometer multilayer coatings with great efficiency over large areas. These coatings are used as optical elements in X-ray applications.

INSTITUTE DATA

IWS AND GERMAN BRANCHES

EMPLOYEES

	Number
Staff	**214**
- Scientists / Engineers (TU, FH)	151
- Skilled workers with technical or mercantile education	55
- Trainees	8
TU Dresden Employees (working at the IWS)	**49**
Scholarship holders and external colleagues	**8**
Research assistants	**126**
TOTAL	**397**



"Knowledge is like a tree: The bigger it is and the more branches it has, the closer its contact to the unknown.«

Blaise Pascal

IWS PUBLICATIONS

	Number
Dissertations	**6**
Diploma theses	**14**
Master's theses	**6**
Journal papers	**136**
TOTAL	**162**

PATENTS (first filing) **27**

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HEAD OF ADMINISTRATION

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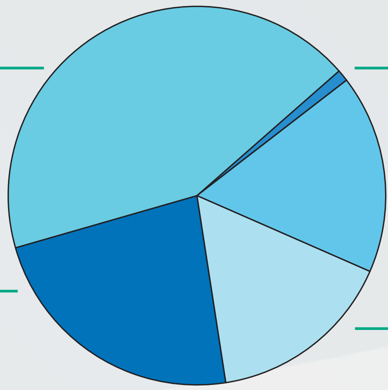
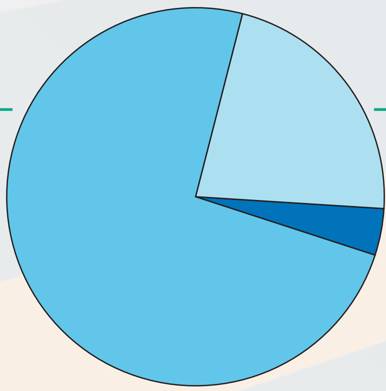
Revenues IWS and German branches 2015 (Mio. €)	Operation	Investments	Total
Project revenues from industry	13.1	0.1	13.2
Project revenues from federal, state and European sources	8.2	0.1	8.3
Base funding and Fraunhofer internal programs	5.5	3.3	8.8
Special investments from federal, state and European sources		7.1	7.1
	26.8	**10.6**	**37.4**

Fraunhofer Industry ρ_{Ind} = 48.8 %

ORIGIN OF PUBLIC REVENUES, STATE AND EUROPEAN SOURCES



GEOGRAPHICAL ORIGIN OF INDUSTRIAL REVENUES



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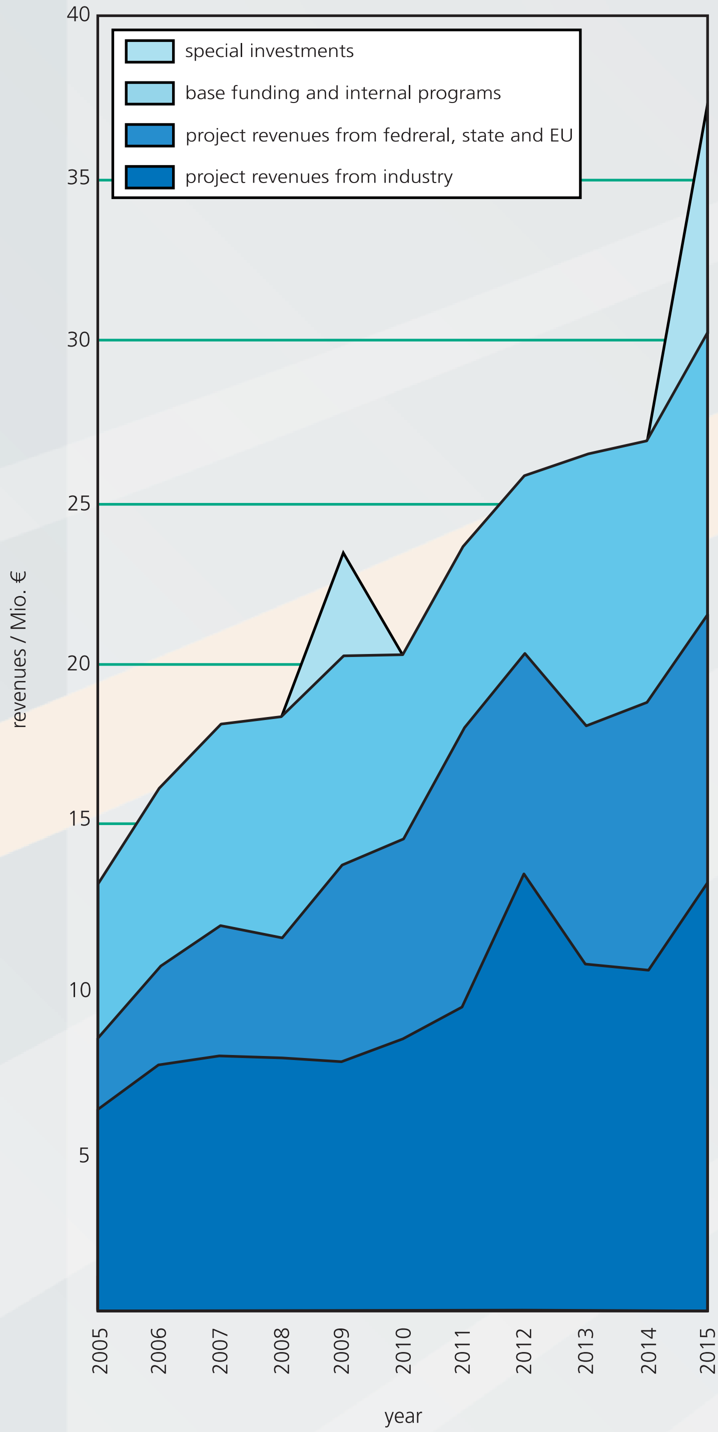
Expenditures 2015 (Mio. €)	
Personnel costs	13.4
Material costs	13.4
Investments	3.5
Special investments from federal, state and European sources	7.1
	37.4

Laboratory space	6800 m²
Office space	3200 m²



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"The secret of being able to is wanting.«

Guiseppe Mazzini

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DI C. Zellbeck ext.: 3332

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Dr. R. Jäckel ext.: 3444

Center Additive Manufacturing
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Dr. F. Brückner ext.: 3452

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ext.: 3573

Materials and Failure Analysis
Dr. J. Kaspar
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Materials and Component Reliability
Prof. Dr. M. Zimmermann
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PVD- AND NANOTECHNOLOGY

Editor: Prof. Leson, PVD coatings are being applied in large measure in cutting, forming and plastics technology. Are there new developments in this area that further expand the application possibilities of hard coatings?

Prof. Leson: Indeed, wear reducing PVD coatings are widely accepted for tooling applications. Here thicknesses of 3-5 µm are sufficient. For highly stressed surfaces however, such as those that occur in massive forming, this is not sufficient and significantly thicker layers are required. We have developed thick hard coatings for these extreme requirements. These have nanoscale designs up to the range of 100 µm and can be produced reliably and economically. The excellent properties of these layers, such as their high hardness and abrasion resistance at high surface contact loads, attract wide interest from tool manufacturers and their users, which we want to research together with our partners.

Editor: Within your business unit, the team that concerns itself with the fabrication and characteristics of carbon coatings has grown especially strong. What is causing this great demand?

Prof. Leson: We focus on hydrogen-free diamond-like carbon coatings, or so-called ta-C coatings. In comparison with the conventional DLC-coatings, which due to their advantages, are already being widely used in industry, our coatings are significantly harder and exhibit substantially improved frictional properties. Since friction and wear occur virtually everywhere, the interest in our ta-C coatings, which can be characterized as second generation DLC-coatings, is enormous. Together with the automobile industry and its suppliers, we are working intensively on the implementation of our ta-C coatings. The goals are to increase energy efficiency and to reduce CO_2 emissions.

"Knowing is not enough; we must apply. Willing is not enough; we must do."

Johann Wolfgang von Goethe

BUSINESS UNIT MANAGER

PROF. ANDREAS LESON

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But our ta-C coatings also enable a drastic improvement in the lifetime of tools used in the machining of abrasive materials such as CFRP and GRP, and so are of large interest. With our Laser-Arc technology, we have a unique industry-suited deployment-ready process that makes the economical fabrication of these coatings possible and has already been transferred to industry many times over. We are particularly pleased by the fact that this development, in which many colleagues were involved, was honored with the prestigious Joseph von Fraunhofer Prize last year.

Editor: Another unique selling point of your business unit relates to high-precision nanometer-multilayers. Besides the use in EUV lithography, are there other applications?

Prof. Leson: We use our know-how and our experiences with the deposition of nanometer-multilayers in addition to the uses in EUV lithography primarily for the development of the sophisticated X-ray optics. Thus, for example, together with scientists of the Münster University, we have developed and built a complex X-ray optical system for experiments with femtosecond resolution, designed to be deployed in the European X-Ray Free-Electron Laser (XFEL), which is currently under construction. Moreover, the investigation and development of multilayer Laue lenses, which are deployed in highest-resolution X-ray analytics, is central.

COMPETENCES AND CONTACTS

Dr. Otmar Zimmer, group manager PVD coatings
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» Physical vapor deposition (PVD) processes deposit high quality tribological and functional coatings. Coating thicknesses range from few nanometers to several hundreds of micrometers. Available technologies range from high-rate evaporation to highly activated plasma processes. A focus is, among other things, the deposition of very thick PVD coatings for various applications. «

Dr. Stefan Braun, division manager nano coatings
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» Since several years, industry has been using precision coatings of nanometer thickness. Current research and development foci are single- and multilayer coatings for optical and joining applications. The optics field includes reflective coatings for EUV and X-ray mirrors as well as multilayer Laue lenses to focus X-rays. Reactive multilayer coatings are researched for joining applications. They provide temporal and spatial control of the heat source based on self-sustaining exothermic chemical reactions. «

Dipl.-Phys. Peter Gawlitza, group manager EUV and X-ray optics
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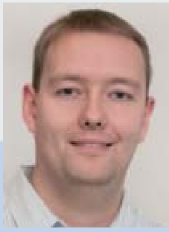
» For the deposition of nanometer single- and multilayers for EUV and X-ray optics, we utilize the methods of magnetron and ion beam sputter deposition as well as pulse laser deposition. The coating systems meet the highest standards with regard to coating thickness accuracy, roughness, chemical purity, lateral homogeneity and reproducibility. Furthermore we focus our research on ion beam processes for contouring and polishing X-ray optical substrates. «



Dipl.-Ing. Georg Dietrich, group manager energy storage coatings
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» Through the use of reactive-multilayer-systems (RMS), metals, ceramics, semiconductors and polymers can be joined effectively. A RMS is inserted between both of the components being joined, and activated. The activation causes a brief chemical reaction generating the heat precisely in the narrow region required for joining the components. «

Dr. Volker Weihnacht, division manager carbon coatings
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»The superhard ta-C carbon coatings (Diamor®) developed in the group are outstandingly suited as friction-reducing protective coatings for lubricated and non-lubricated application conditions. They can be deposited on all kinds of tools and components with very good adhesion over a wide coating thickness range. The coating is applied with the Laser-Arc technology, particularly developed for ta-C coatings. Besides the technology, for the industrial implementation of Diamor® coatings, IWS together with partner companies also supplies the necessary coating sources.«

Dipl.-Ing. Gregor Englberger, group manager coating processes
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»The group's competence is the deposition of superhard carbon coatings. A very good understanding of the process enables the adaption of ta-C coatings to various customer requirements. The IWS-developed Laser-Arc technology is an effective plasma source to deposit carbon coatings free of hydrogen, which has been optimized for industrial use.«

Dipl.-Ing. Stefan Makowski, group manager coating properties
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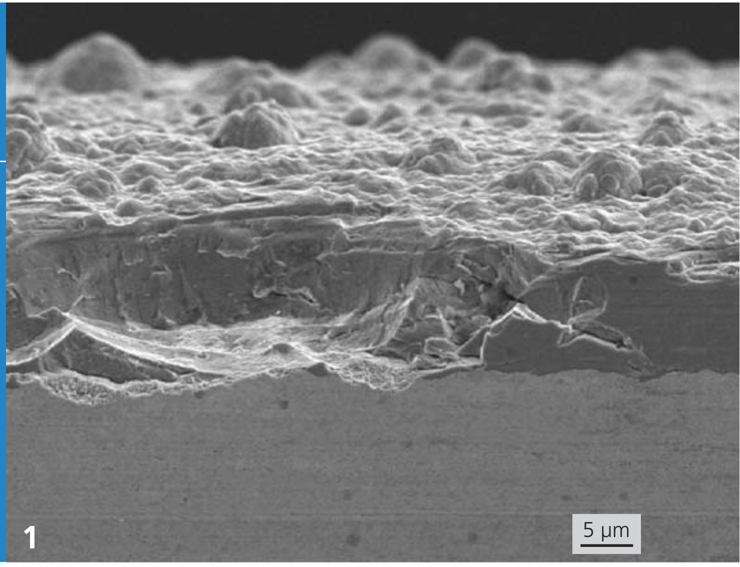
»That coating properties are relevant to applications is ensured by testing their mechanical and structural parameters. In addition to broadly used methods such as nanoindentation and tribological testing, we are also focusing on techniques such as laser acoustics (LAwave®) and adhesion testing.«

2015 PROJECT EXAMPLES



1

HIGHLY RESILIENT HARD COATINGS WITH HIGH SURFACE QUALITY

THE TASK

Thin wear-protection coatings for tools and components based on hard metal nitrides (e. g. TiN, AlTiN, CrN) are often used in industry. Typical techniques for the fabrication of such coatings up to approx. 10 µm thickness are PVD and CVD processes.

The fabrication of thicker coatings (>> 10 µm) faces a problem due to the increasing coating roughness. During Arc-PVD processes, for example, microscopically small particles act as an origin point of growing defect structures eventually leading to surface roughness. Furthermore, in nearly all thin-film processes, spontaneous disturbances emerge in the growing crystal structure, which lead to extended defect structures with increasing deposition time (see Fig. 1). The coating can then no longer fulfill its wear-minimizing function.

Fraunhofer IWS Dresden has therefore set itself the task of developing a coating technology that:
- allows the lowest possible surface roughness for layer thicknesses >>10 µm,
- ensures high efficiency in the coating process to produce thicker layers in a more reasonable timeframe.

OUR SOLUTION

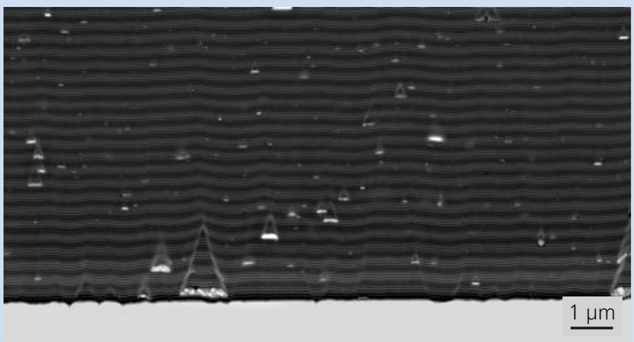
An important condition for the production of thick layers with sufficiently smooth surfaces is the suppression of the growth of defect structures. There are various approaches to achieve this, which are used singularly or in combination.

One possibility is the deposition of many layers with single-layer thicknesses in the nanometer range. With the appropriate combination of materials, the growth of defect structures on the interfaces of the single layers is interrupted. Existing defects thus become embedded in the desired layer structure and do not disrupt their function (see Fig. 2).

Another approach to defect suppression is the use of highly ionized plasmas. During the coating process the high-energy plasma particles remove unwanted roughness peaks. With the arc process, for example, the plasma excitation can be increased through appropriate parameter selection.

Optical emissions spectra were recorded during the vacuum arc process. In the standard process for depositing an AlCrN coating, singly and doubly charged Al and Cr ions are detectable. In the more highly charged process, the quantity of ions rose significantly and a trend of multiply charged ions is noticeable.

Cross section of a multilayer hard coating with neutralized defect structures



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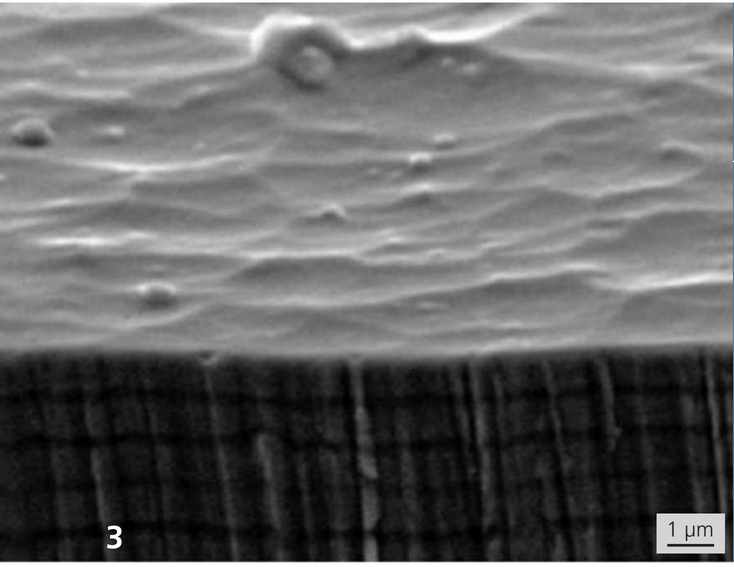
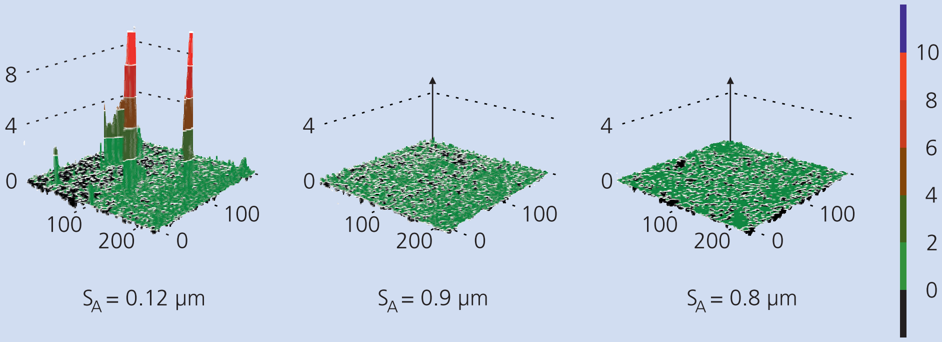


3

RESULTS

Figure 2 shows the cross section of a multilayer hard coating that was produced with increased plasma excitation. The inhomogeneities in the layer volumes, which are attributable to the deposit of microscopically small particles during the coating process, are clearly visible. These will be covered and flattened in the course of the layer growth until eventually a once again flat surface is formed.

Comparison of topographies: Standard process (a), standard process with mechanical smoothing (b), and process with increased plasma excitation and in-situ smoothing (c) in µm



4a **4b** **4c**

SEM pictures (Fig. 3) and topographical analyses (Fig. 4) of coated surfaces show that with the combination of multilayers and high ionization, smooth coating surfaces are producible. With standard processes one would have to polish the coating after the deposition process to achieve similar results.

Forging tools with smooth hard coating

5

For the coating of tools for prototype and forming processes, for example those which are shown in Figure 5, this technological approach constitutes a meaningful perspective. In extreme conditions, the coatings must meet highest demands in terms of surface quality. This is usually only achieved by coating processes in combination with sophisticated post-processing. The method presented can contribute to a substantial minimization of effort in the coating of such tools.

1 Defect-rich coating, produced with the arc process

3 Defect-poor multilayer coating, produced with highly ionized plasma

CONTACT

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1

ta-C COATED MACHINING TOOLS FOR CFC AND GFC COMPOSITE MATERIALS

THE TASK

Through the rapid technological development and the influence of international competition, an increasingly more cost-effective production with increasingly more demanding materials can be observed in the field of machining. In particular, in the area of lightweight construction materials and plastics, increasingly difficult to machine materials such as glass and carbon fiber composites (GFC and CFC) are being developed. The machining of laminates, consisting, for example, of GFC, CFC and cardboard or metal poses a special challenge in that the tool is subjected to quickly alternating processing conditions.

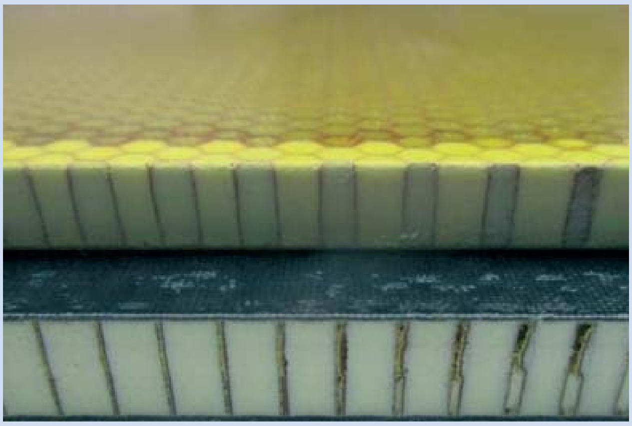
In order to cope with these demands, machining tools must always be improved. The key for that is in an appropriate surface functionalization of the tools, through a PVD coating for example. Among PVD layers, the classic TiN and the newer TiAlN and TiCN coatings are commonly used.

Applications with highly abrasive cutting edge wear are increasingly relying on crystalline or nanocrystalline CVD diamond coatings. Next to the comparatively high costs compared to PVD coatings, the high coating temperatures in the CVD process and the often observed leaching of cobalt from the hard metal substrate presents disadvantages for this coating.

OUR SOLUTION

A more affordable alternative to diamond coatings are superhard tetrahedral amorphous carbon coatings (ta-C). Their production succeeds with the Laser-Arc process at temperatures under 150 °C and is therefore suited to more applications than just coating hard metal tools. With hardnesses of up to 70 GPa, ta-C coatings nearly reach the hardness of nanocrystalline diamond coatings. This results in an unusually high resistance to abrasive wear, above all in the machining of challenging composite materials. At the same time, the carbon surface reduces adhesion of material and causes very low friction between the tool edge and the cutting chips. The combination of hardness and low friction provides ta-C coatings with a special advantage for the processing of composite materials.

Milled sandwich plate with honeycomb core comprising a honeycomb core with GFC or CFC skins



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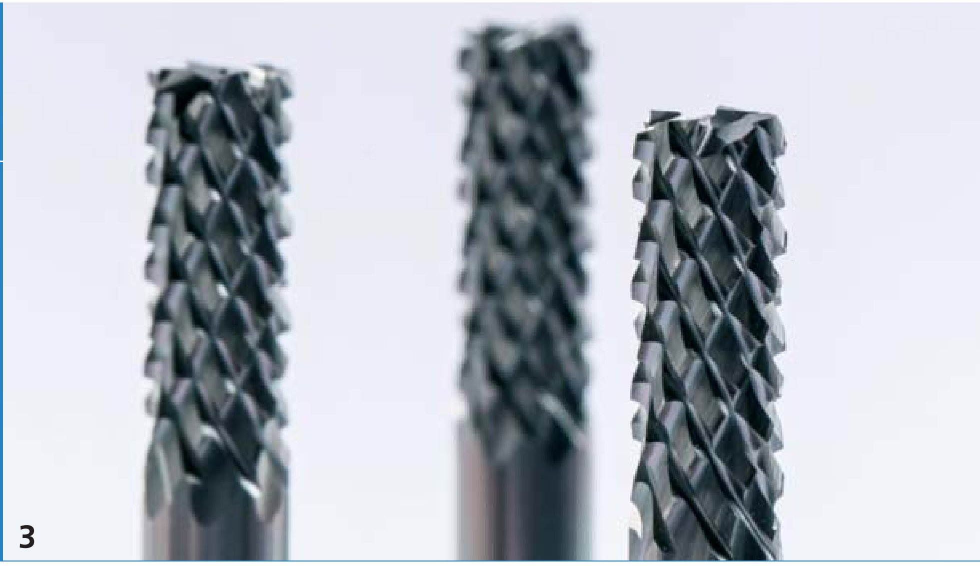

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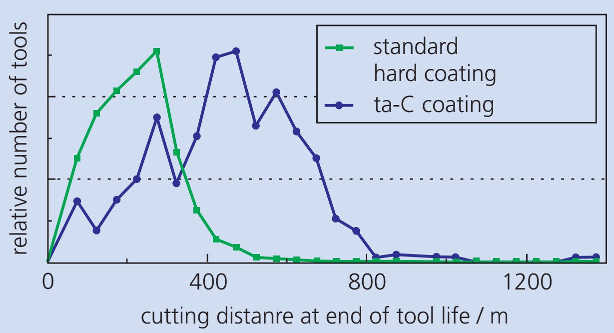
RESULTS

For machining tests in real manufacturing environments of clients, 340 hard metal multi-tooth milling tools with a diameter of 6 mm and an approximately 1.2 µm thick ta-C coating were provided (Fig. 3). The coating was deposited with the Fraunhofer IWS-developed filtered Laser-Arc technology. A 0.1 µm thick chromium film served as an adhesion promoting layer. The hardness of the ta-C coating amounted to approximately 67 GPa. The sandwich plates to be worked on consisted of a honeycomb core with GFC or CFC skins (see Fig. 2). The results of the large-scale trial are summarized in Figure 4, which plots the achieved cutting distance at the end of the tool life.

Results of the large-scale machining trial with standard hard coating and ta-C coating in comparison



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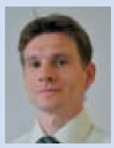
The very heterogeneous machining tasks (different sheet types, different milling jobs and menus, …) led to very different tool lifetimes. Clear effects of the influence of the tool coating appear therefore only after a large number of trials. While 2430 tools with hard coatings were tested, the diagram in Figure 4 reflects data for just 340 ta-C coated tools, which is why the ta-C results are somewhat scattered. Despite that, a prolonging of the average tool lifetime is clearly noticeable. The average cutting distance increases from 177 m (standard) to 412 m with ta-C coated tools. This is equivalent to an improvement of 132 percent.

Encouraged by these positive results, a further large-scale test of a complete monthly production volume exclusively with ta-C coated tools was subsequently carried out. In this test with approximately 1000 tools, the tool lifetime was increased by a factor of 2.4. The production was subsequently converted to using ta-C coated tools.

1 PVD system with Laser-Arc module for ta-C coating of tools

3 Hard metal multi-tooth milling tools, coated with ta-C

CONTACT



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1

2

FRICTION REDUCTION IN SINGLE-CYLINDER ENGINES THROUGH DIAMOR® COATING

THE TASK

In combustion engine-powered vehicles, approximately 50 percent of the frictional loss is accumulated in the powertrain. Friction-reducing wear-resistant coatings provide an excellent potential to substantially increase the efficiency and service life of these systems and reduce pollutant emissions.

For the development and evaluation of modern wear-protection layers, scientists in the laboratory usually use tribological test apparatuses to determine quantitative information about the coefficient of friction and wear rates. At the other end of the technology chain, engineers develop engines whose characteristics such as performance and torque are determined as a function of engine speed with dynamometers. And finally, rates of acceleration, fuel consumption and other data are determined with the assembled vehicle under actual driving conditions.

To correlate the laboratory-measured coating properties with the actual field application advantages of the use of coatings is a major challenge. In order to bridge that gap, the task was to demonstrate the advantage of Diamor® coatings in actual internal combustion engines.

OUR SOLUTION

At the Fraunhofer Center for Coatings and Diamond Technologies (CCD) (see also p. 128), the advantage of using Diamor® coatings for commercially-available single-cylinder engines was tested in collaboration with an industry partner. The engine tests were carried out at the Center for Automotive Research (CAR) of the Ohio State University in Columbus, Ohio. In the first experiment, a previously used, approximately 10 HP go-cart engine was measured on the test stand with a classic engine test (power and torque measured against the RPM). The engine was then disassembled and some critical friction components were cleaned and coated with Diamor® (Fig. 1). In this coated state, the engine test was repeated. In an additional experiment a 7 HP single cylinder motor (Kohler Command Pro CH270) was tested.

Typical applications for this engine are garden machinery, emergency generators, and pumping systems. First, a factory-fresh engine was filled with conventional Pennzoil 10W-30 oil and run in 3 times for 30 minutes, each time with fresh oil. After the third run-in period the oil remained clear indicating that the engine was properly conditioned. This was necessary in order to demonstrate the frictional advantage of the Diamor® coating as directly as possible.

In the subsequent experiments, a 3 HP electric motor was used to drive the Kohler engine at different RPMs. The engine valves were left open during this so that only the mechanical friction needed to be overcome. The required torque to drive the engine was measured. Uncoated and coated configurations were tested with conventional and synthetic (Mobil 1) oils.

The experiments were conducted at room temperature, operating temperature (the engine run for 35 minutes until the oil had reached standard operating temperature), and repeated in the cold (in dry ice).

3

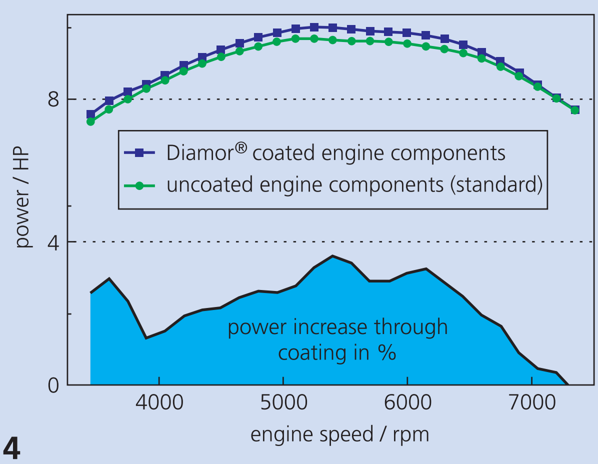
5

RESULTS

Figure 4 shows the power of the go-cart engine as a function of engine speed in the uncoated and coated conditions. The blue curve represents the power difference in percent. The data show that the Diamor® coating increased the engine power by more than 3 percent, particularly in the RPM range of peak performance. For racing motors, this power increase is significant.

However, the more important result is that the engine with coated components required a 350 RPM lower speed to achieve the same power level as the uncoated engine. In other words, the coated engine runs slower while providing the same traction force and this consequently lowers fuel consumption, and as a result of lower friction and lower engine speeds, also wears out less. Figure 6 shows the data for the Kohler engine driven in cold temperatures. The torque required to drive the Kohler engine is plotted against the engine speed. The reduction of the required torque and thus the friction exceeds 30 percent at 3000 RPM. The greatest benefit is demonstrated at cold temperatures. Figure 7 shows the over all engine speeds averaged reduction of friction at different temperatures. As a result, in this experiment, the Diamor® coatings provide a frictional advantage of 10-30 percent, depending on temperature.

Comparison of the engine power of a go-cart motor with and without Diamor® coatings



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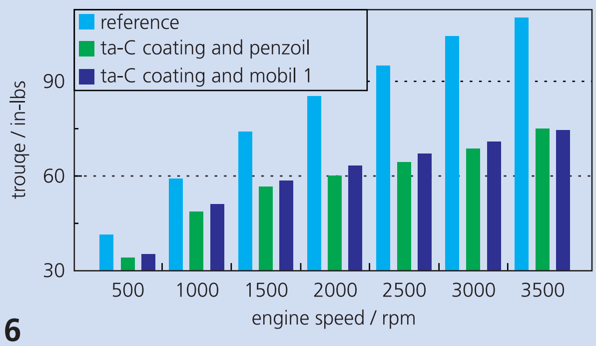
Torque in Kohler engine as a function of RPM, oil and coating at temperatures below 0°C



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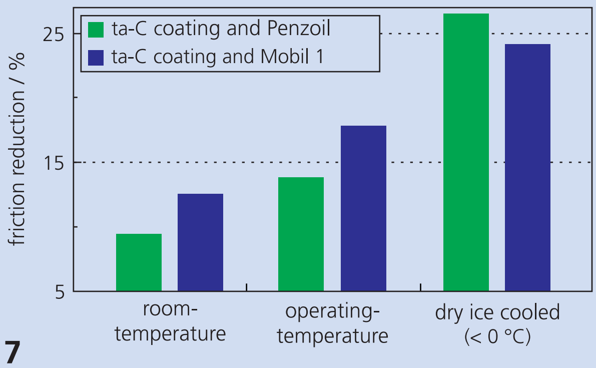
Average reduction of friction in the Kohler motor with coated components for different operating temperatures and with different oils



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1-3/5 with Diamor® coated components in the single-cylinder test engine

CONTACT

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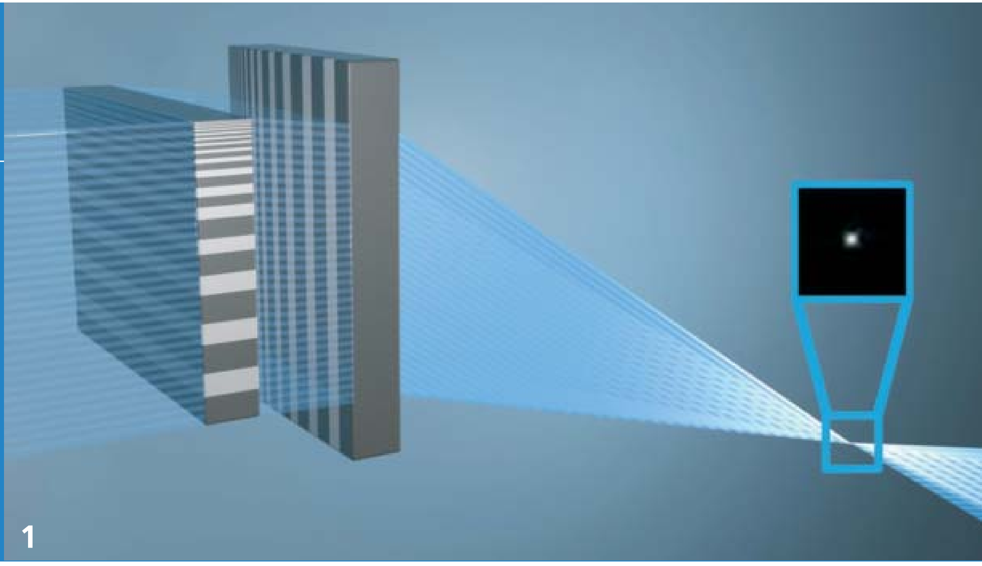
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MULTILAYER LAUE LENSES FOR HIGH-RESOLUTION MATERIAL CHARACTERIZATION

THE TASK

Material characterization with hard X-rays promises very high lateral resolutions with simultaneously high penetration capability. With regard to coherence, parallelism and intensity of X-rays, synchrotron radiation sources offer excellent conditions. The spatial resolution accessible by using these sources is primarily limited by the available optical components. By using two multilayer Laue lenses (MLL) in accordance with the schematic diagram in Figure 1, point foci in the order of 10 nm have already been realized.

The objective of ongoing research at Fraunhofer IWS is to qualify MLL for use in laboratory applications and thereby improve the lateral resolution of diffractometry, fluorescence analysis, and reflectometry of currently about 20 µm down to the submicron range. The radiation properties of synchrotron radiation sources and laboratory equipment significantly differ, which must be considered in the design of a laboratory experiment. Here, beam sizes in the range of 1 µm appear to be realistic.

OUR SOLUTION

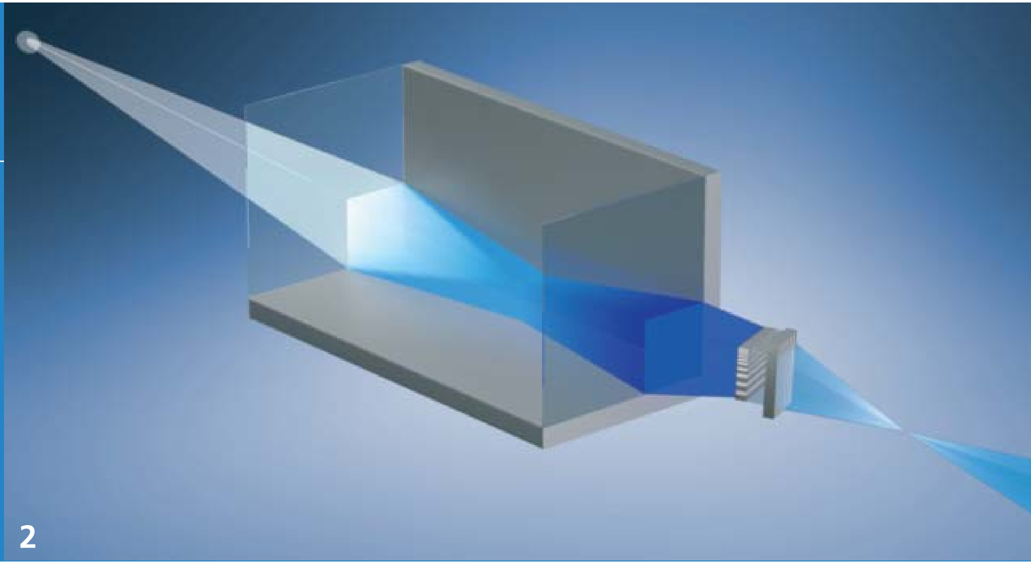
In order to maximize the portion of usable radiation, it is necessary to fabricate lenses with a large aperture. In the case of MLL this requires thick coatings. Due to residual stresses, large coating thicknesses can lead to strong bending and possibly to damage of the layer during the manufacturing process.

In order to investigate the implications connected with the transition from synchrotron to laboratory sources, a program based on the "Beam Propagation Method" was developed at the Fraunhofer IWS. The model calculations show that depending on the actual beam path and the MLL design, the significant influence factors on the anticipated focus magnification can be determined. Figure 2 schematically depicts the setup used for the model calculations. An optical mirror system ensures a pre-focusing of the radiation coming from the source onto the MLL.

At Fraunhofer IWS Dresden, strong internal stresses in MLL are reduced through a special multilayer coating design consisting of four individual layers per period. In addition to an absorber and spacer material with reversed internal stresses, a separating barrier layer is introduced at the interface (Fig. 3). With appropriate thickness ratios of the three involved materials, this material system is nearly stress-free and thereby allows the fabrication of layer systems of more than 100 µm.

RESULTS

First experiments were performed with the material system shown in Figure 3, which had a thickness of about 65 µm. For the suggested setup, calculations showed that a pre-focusing mirror with a short focal length and therefore a markedly curved wavefront is a disadvantage for the geometric separation of orders behind the MLL. The results of a configuration with a mirror with a moderate focal length of 28 cm appear useful when the MLL is placed about 3.5 cm away from the focus. With ideal beam properties for the given lens configuration, this design results in a focus size of around 40 nm. Radiation from a copper X-ray tube with a Ni absorber is dominated by $K_{\alpha 1}$ and $K_{\alpha 2}$ spectral lines. When these two lines are taken into



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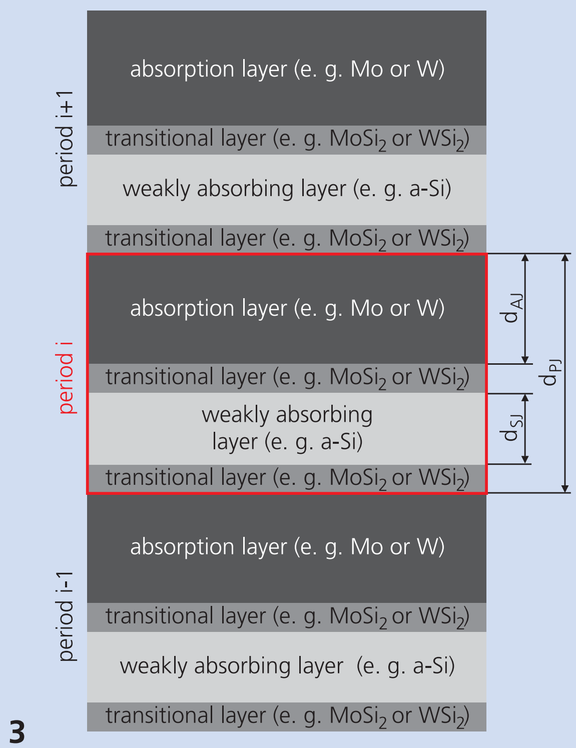
account, the calculations yield essentially two separate foci whose distance is approximately 25 µm in the propagation direction and 150 µm perpendicular to it.

In the case of coherence lengths that are smaller than the aperture of the lens, only the relevant part of the lens contributes to form the focus size, which is thereby increased; however, it does not lead to any appreciable reduction of the flux in the focus. Thus a focus size of 400 nm arises for a lens of with a size of 100 µm and a coherence length of 10 µm, according to the above mentioned example, while a coherence length of 1 µm yields a focus size of around 4 µm.

Multilayer system of four separate layers per period



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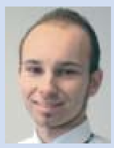
Calculations to estimate the influence of the divergence of the incoming beam show for a typical value of 0.02 ° a focus shift of up to 5 µm perpendicular to the propagation direction. This results in a corresponding enlargement of the focus of the MLL. A lower angular divergence at the entrance of the lens is achieved when a narrow-band mirror is used. This simultaneously leads to an increase of the coherence length. Further improvements can also be achieved when MLL are produced with better angular selectivity, i. e. when they are made with adjusted lamella thicknesses.

Overall, the modeling results show that through the use of MLL and optimized optics, it is possible to achieve focus sizes of 1 µm even for laboratory sources. The lateral resolution capability of diffractometry, fluorescence analysis and reflectometry can therefore be extremely improved.

1 *Crossed MLL for the pinpoint focusing*

2 *Schematic depiction of the MLL laboratory setup that was used for model calculations*

CONTACT



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1

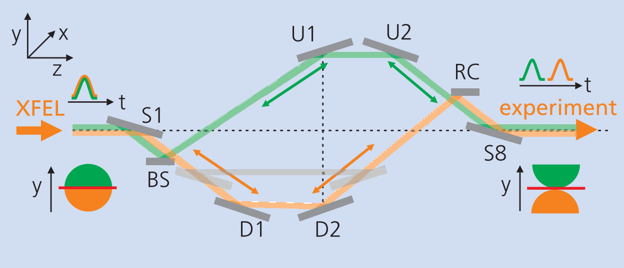
HIGH-PRECISION MULTILAYER OPTICS FOR THE X-RAY FREE-ELECTRON LASER (XFEL)

THE TASK

For experiments with femtosecond time resolution at the currently under construction European X-Ray Free-Electron Laser in Hamburg (European XFEL), mirror optics of the highest precision and thermal stability are needed. A split and delay Unit (SDU) which is used for these experiments is made up of eight flat individual mirrors, which split the extremely powerful XFEL X-ray into two beam paths of variable length and then superimposes the two partial beams for the experiment with time delay (Fig. 2).

The challenge with an X-ray SDU (Ephoton > 5 keV) is that the angles of reflection of the mirrors are very small. This requires very large SDU dimensions of up to several meters in order to achieve sufficient time delays [1]. The multilayer optics necessary for reflection angles of 1…5 ° have the peculiarity that for each photon energy, a particular angle of reflection must be precisely adjusted. Furthermore, for the energy range of interest here (5…20 keV), the best reflectivities are achieved with different materials. That means that the coatings of the individual mirrors must fit perfectly with one another to get exactly the same reflection angle or double angles for the beam splitter (BS) and the recombination mirror (RC).

Schematic illustration of the Split and Delay Unit – SDU at the European X-Ray Free-Electron Laser (European XFEL)



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In addition to the high thermal stability required by the intense XFEL radiation, precision requirements of the coating process of > 99.9 percent (that corresponds to an allowed thickness error of a single period from 2…5 pm) arise. Several material combinations must also be deposited next to each other on the mirror.

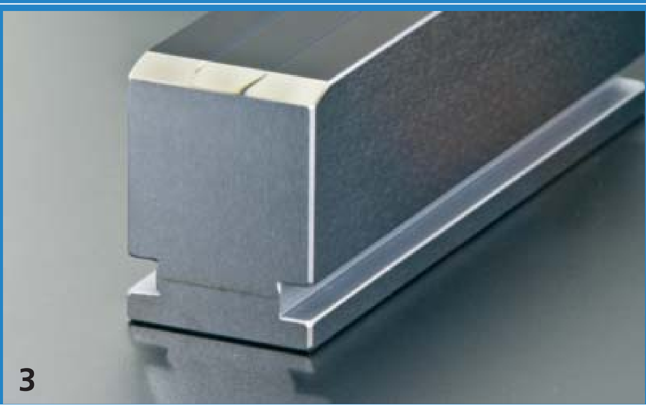
OUR SOLUTION

All of the XFEL's SDU mirrors are subdivided into three surface areas onto which the material systems Mo/B_4C, Ni/B_4C and W/B_4C are deposited with different individual layer thicknesses and numbers of periods for a particular energy range.

One of these 3 zones exhibits a peculiarity: here, so-called "two color experiments" are planned, i. e. each beam path carries different photon energies for the time delayed superposition (basic energy and the 3rd harmonic wave). The mirrors S1 and S8 therefore have special multilayer stacks, which enable the simultaneous reflection of both energies for a fixed angle of incidence [2].

[1] Roling, S. et al.: Proc. of SPIE Vol. 9210, 92100B (2014)

[2] Roling, S. et al.: Opt. Lett. 39, 2782 (2014)



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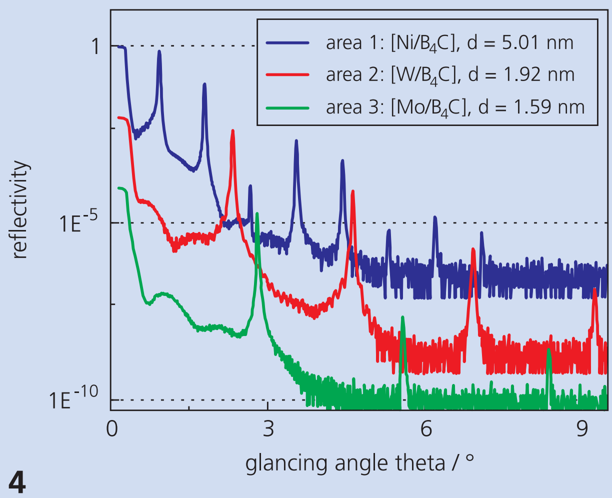
RESULTS

The SDU mirrors shown in Figure 1 have a length of 190 mm and a width of 30 mm. The beam splitter mirror depicted in the foreground is 120 mm long and possesses a partially beveled "splitter edge" (pictured at right). It is arranged directly in the middle of the XFEL beam path.

With shadowing masks, 3 multilayer stacks were applied on each of the SDU mirrors by means of ion beam or magnetron sputtering techniques. The period thicknesses of the individual stacks were in the range of 1.6 to 5.0 nm. Figure 4 shows the reflectogram of the coatings of the beam splitter mirrors. The full widths at half maximum of the reflection peaks of the first order were in the range of only 0.02…0.03 °, which simultaneously defines the homogeneity requirements of both the period thickness lengthwise and crosswise in each coating zone and also between the 8 mirrors (approximately ±0.1…0.2 percent).

In Figure 5, the homogeneity profiles of the period thicknesses of the three coating zones of a SDU mirror are depicted for the transverse direction (respectively normalized to the average period thickness of the zone). It is evident that the work areas meet the requirement for an area of approximately 5…8 mm in length. In between are areas of approximately 3…4 mm width, which must remain unused. The measured deviations of the reflection peak locations of the eight SDU mirrors amount to a maximum of 0.005 ° among each other, which guarantees that they will work in the delay configuration setup according to Figure 2.

Reflectograms of the three coating zones of the beam splitter (XRR-measurements with Cu-Kα-radiation)



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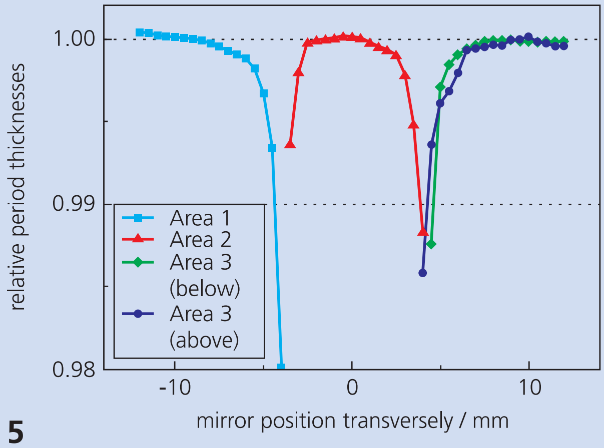
Homogeneity measurement of the period thicknesses of the three coating zones of a SDU mirror in transverse direction



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1 Eight SDU mirrors for the European XFEL

3 Detail view of the beam splitter edge of the "BS" mirror

CONTACT

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1

IMPROVEMENT OF ELECTRICAL CONDUCTIVITY OF METALLIC BIPOLAR PLATES

THE TASK

Mobility is one of the biggest challenges of our time. The future of mobility is presumably electric. Therefore, IWS has established not only a center for battery research (see page 138), but also works on the further development of fuel cell vehicles. In terms of driving range, fuel cells offer significant advantages.

In the fuel cell, hydrogen and oxygen are converted to water and the resulting electric energy is used for propulsion (see Fig. 2). The bipolar plate (BiP), a component of the fuel cell, must fulfill a series of tasks such as supplying hydrogen and oxygen, removing water and cooling. Additionally, the BiP gathers the electrons emitted on the hydrogen side and transfers them to the oxygen side after they have done work moving the vehicle. The BiP material must therefore possess excellent electrical conductivity, which also does not significantly decrease under the corrosive conditions in the fuel cell.

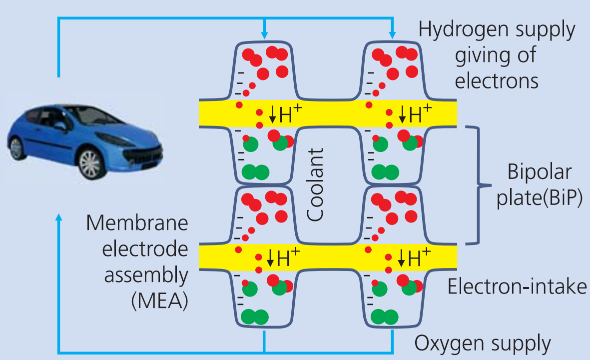
In applications in which sufficient installation space is available, graphite can be used. It is a good electric conductor as well as stable against sulfuric acid which is used as an electrolyte. If the installation space is limited, thin, deep drawn stainless steel sheets are used. These have the disadvantage that the stainless steel sheet's passivation layer, which is composed of chromium oxide, is a poor conductor. Therefore, until now, BiP from stainless steel are typically coated with gold – a solution that is still too expensive for mass markets. And so the task lies therein: to match the good resistance of gold on stainless steel through more cost-effective materials.

OUR SOLUTION

Within the scope of the miniBiP project supported by Federal Ministry of Education and Research funding code 03ET045A, two approaches were pursued: Firstly, the good bulk properties of stainless steel were combined with the good surface characteristics of graphite through a coating of the sheet surface with graphitic carbon. The starting point for this was an amorphous carbon coating developed at Fraunhofer IWS for wear protection. The deposition conditions were changed such that a majority of sp^2-hybridized, hence graphitic bonds, were formed so that the coating (GLC: Graphite-Like Carbon) showed as high a conductivity as possible.

For the other approach, a process based on the well-known plasma nitriding was developed in which the surface of the steel was enriched with nitrogen in a vacuum process through a plasma diffusion treatment. Afterwards the surface layer was enriched with carbon (sequential plasma nitrocarburizing PNC).

Diagram of a fuel cell



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RESULTS

With both processes described, initially plain sheets of stainless steel were surface modified. The processes were optimized until the resistance through the sheets corresponded to the gold-coated sheets.

The less than 100 nm thick GLC-coatings showed the best results with regard to resistance. These were deposited within a minute using pulsed vacuum arc evaporation and twofold substrate rotation. Comparative values could also be achieved with approximately 5 µm thick surface zones enriched with nitrogen and carbon, which were produced within 15 minutes through sequential plasma nitrocarburization. After that, real BiPs were treated and successfully underwent stress tests in three- to five-cell stacks.

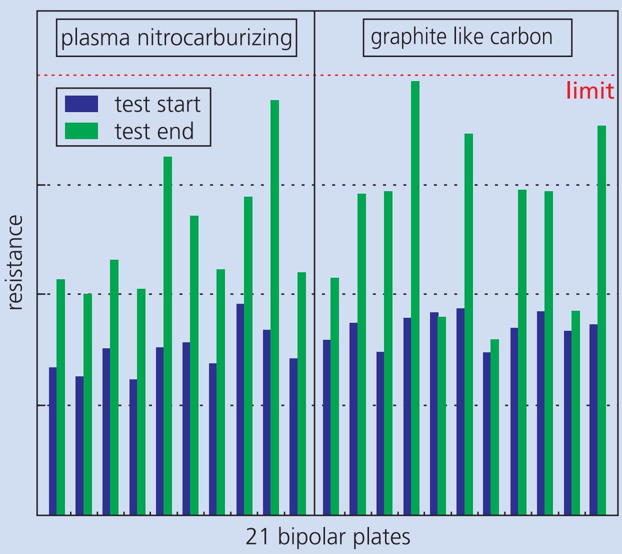
In the next step, 10 BiPs were PNC-treated under respectively identical conditions, 11 BiPs were coated with GLC, and the resistances of all BiP were measured individually (blue columns in the diagram). From these BiPs, one mosaic-stack with 20 cells was built and underwent an endurance test of 1000 hours. Afterward, the stack was dismantled and the resistances of the individual BiP were measured again (yellow columns in the diagram).

As the diagram shows, the resistances after the test are indeed higher than before (even if often only slightly), but with each individual BiP, the resistance remained below the clients limit required for these tests. With the successful completion of these tests, a demonstrator can be built with 50 cells.

The production of such fuel cells would be considerably more efficient if a plain metal strip is first coated in an inline roll-to-roll process, followed by cutting out the sheets and then forming the flow channels. Since both finishing processes are principally suitable for inline processes, further studies will include an analysis of the economics of such an inline process.

In preparation of these studies, already GLC-coated and PNC-treated plain sheets were formed into sample components (Fig. 3). After the forming, no cracks in the GLC-coatings or damage to the metal sheet with modified peripheral zones was detectable.

Resistances of PNC-treated and GLC-coated bipolar plates before and after a 1000-hour endurance test in a mosaic stack with 20 cells



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1 Fuel cell pushes mobility

3 Sample component with formed elements of a metallic bipolar plate

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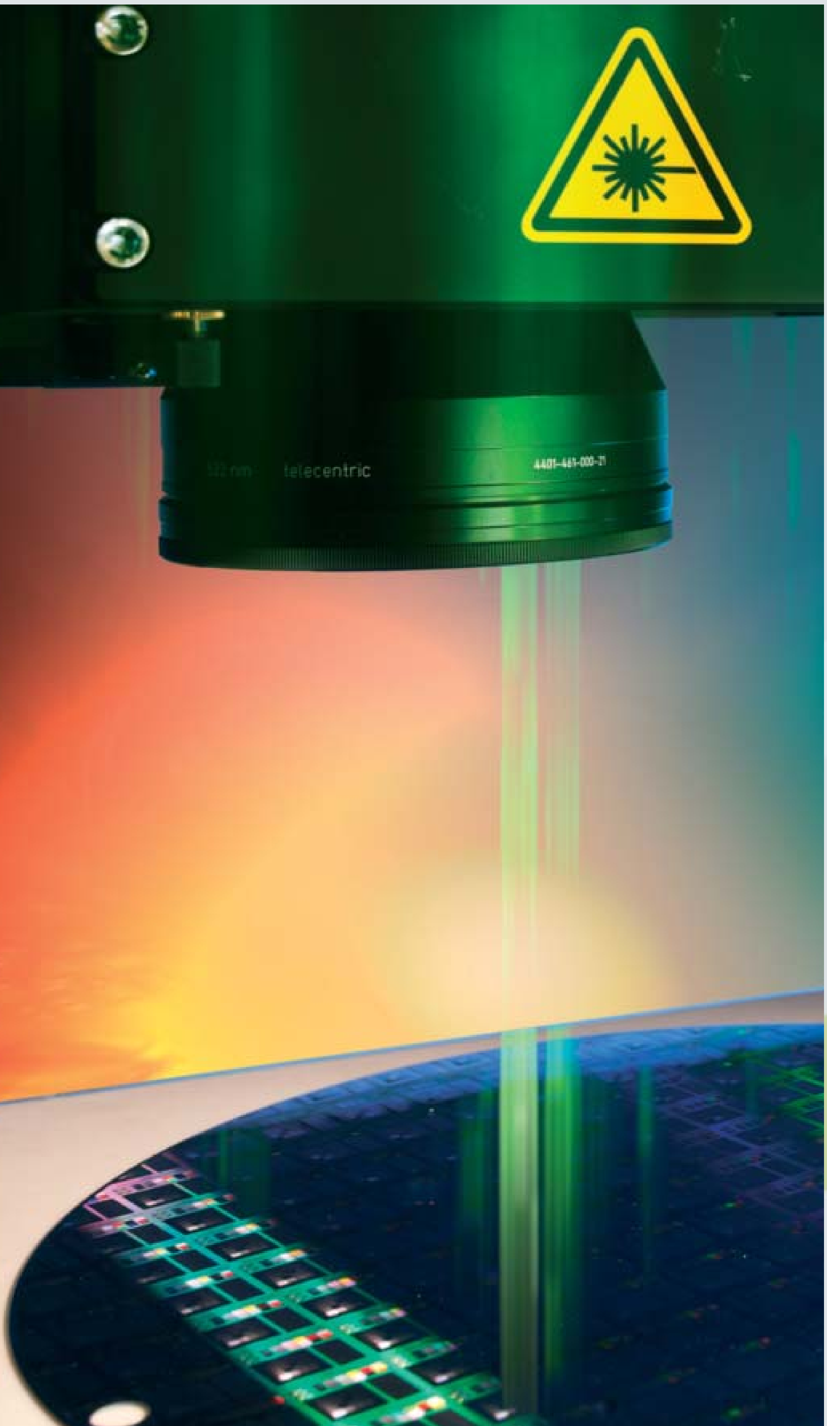
MICROTECHNOLOGY



Editor: Dr. Klotzbach, what are the trends and perspectives in microtechnology?

Dr. Klotzbach: Applied research into laser beam micro machining has great potential for a broad range of application across various sectors including mechanical engineering, vehicle manufacturing and other device building industries. Both the medical device and biotechnology industries benefit from micro technological components to enter new markets. For the coming years we have to focus on transitioning research and development results into marketable products. We see an increasing demand for innovations in micro- and microsystems technologies to support product development in mechanical engineering, bio and medical device industries, photonics and electrical engineering. Laser technology in particular offers a great potential with ultrashort pulse lasers and highly dynamic laser beam control systems for a diverse range of applications. I would like to highlight innovations in processing fiber reinforced polymers and the structuring of thin films (flexible organic photovoltaic cells and organic electronics).

Editor: European microtechnology companies are increasingly focusing on biomedical device products. The health industry sector is for many the primary target market. What potential do you see for your institute?

Dr. Klotzbach: The trend is toward ever more miniaturized systems and will continue. The technical possibilities still offer much room to be exploited to move ideas toward products. Many areas of biotechnology benefit from miniaturization. For example, solutions are offered through microfluidics, which enables the transport or dosage of liquids on the scale of picoliters. Such microfluidic reactors integrate pneumatic pumps, sensors and actors and their potential for application

"The light bulb was not invented by continously improving the candle."

unknown

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development is enormous. It includes classic lab-on-chip systems as well as cell-based and highly flexible multilayer multi-organ-chip systems. We have developed a technological platform which ranges from design and simulation to chip fabrication. For each lab-on-chip or multi-organ-chip system we offer an automated control and analysis platform. These systems are used in classical analytics, individualized medicine and the development of pharmaceuticals and cosmetic products.

Editor: Smallest microstructures, even down to the scale of submicrons, over large areas – is this not a contradiction?

Dr. Klotzbach: Five years ago I would have given you a solid "Yes" as an answer. Since then our surface functionalization team has made enormous progress in this field. Classic laser interference patterning is a process that has been known for many years. We have developed optical systems to apply this concept so that we can now process up to 0.9 m^2 of surface area per minute. For the future we aim at 3 m^2 per minute, which will take much work. In 2016 we want to focus on the further development of our optical system components such as the laser interference processing heads. The various optics need to advance from the laboratory to an industrially manufactured and marketable product.

COMPETENCES AND CONTACTS

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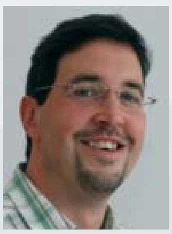
»The institute has a comprehensive modern pool of laser processing equipment and offers a wealth of know-how in laser micro processing. Applied research focuses on micro machining to miniaturize functional elements in mechanical engineering, equipment, vehicle and device manufacturing as well as bio and medical device industries. Examples include the generation of 3D structures with feature sizes in the sub-mm range. Structures are formed on the surfaces of polymers, metals, ceramics, quarzites and biocompatible materials. Laser technology is also applied to clean such surfaces. Diagnostics is equally critical to understand processes and process results. Thus the group has special foci to use high speed camera technologies for optical laser process analytics and to use terahertz radiation for non-destructive analytics of materials.«



Dr. Frank Sonntag, group manager micro- and biosystems technology
☎ *+49 351 83391-3259* / ✉ *frank.sonntag@iws.fraunhofer.de*

»Research in the field of micro- and bio systems technologies includes the design, simulation and rapid manufacturing of microfluidic structures, micro reactors and complex lab-on-chip-systems. Our scientists rely on their comprehensive know-how with regard to the implementation of integrated functional elements such as pneumatically and electrically powered micro pumps or optical and electrical sensors. These systems are completed with automation and periphery concepts (hardware and software) for laboratories in biomedical engineering. Based on design technology, additive manufacturing of 3D scaffolds and micro perfusion systems we are able to develop tailored platforms for diagnostics, non-animal testing and tissue engineering.«

Prof. Andrés-Fabián Lasagni, group manager surface functionalization
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»As a result of evolutionary processes, we find today structures on plant and animal surfaces, which provide unique properties, such as low friction or anti-bacterial effects. Following these biological structures it is nowadays possible to implement their properties in technological surfaces. New methods are able to create two and three dimensional micro and nanostructures over large macroscopic areas on surfaces of polymers, metals, ceramics and coatings. By the help of these methods, we are able to generated structured surfaces with significantly optimized properties. Thus technological modifications of chemical, optical or mechanical material properties enable the decisive advancement of products in the field of bio technology, photonics and tribology.«

2015 PROJECT EXAMPLES

2

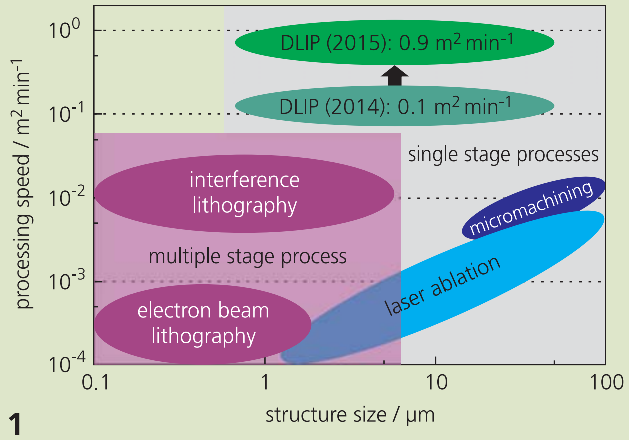
WORLD SPEED RECORD FOR DIRECT LASER MICROPATTERNING

THE TASK

Well defined micro- and submicron structures may be exploited to create innovative and application specific mechanical, biological and optical surface functions. Today such structures can be created by various technologies. Often it is critical to develop solutions that meet industrial demands in terms of efficiency and processing speeds (Fig. 1).

A technical challenge is to generate highly resolved structures over large areas while simultaneously achieving high processing speeds. The micro structuring technology of direct laser interference patterning (DLIP) represents a very promising solution concept that addresses the intrinsic technological conflict between achievable resolution, substrate area and processing speed. At Fraunhofer IWS it is an important commercialization goal to transfer the DLIP technology from the laboratory to industrial use. The focus is on developing high speed processing optical components and systems that can be deployed to industrial manufacturing environments.

Comparison of process velocities of different technologies



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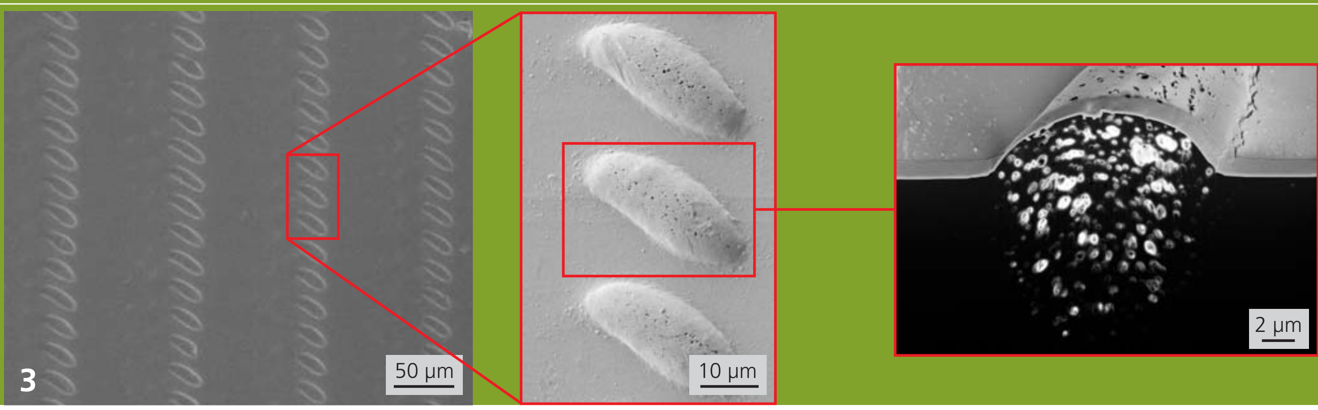
OUR SOLUTION

The direct laser interference patterning process is based on splitting a single coherent laser beam into two or more sub-beams, which are then recombined to form interference patterns on the treatment surface. Such interference patterns contain modulated regions of high laser intensities to process the substrate. The processing area corresponds to the entire overlapping region of the sub-beams. Areas up to several square centimeters can be patterned with a single laser pulse.

To make DLIP technology accessible to its customers, the Fraunhofer IWS offers a range of services including optical components for specific applications, process development and integration and complete DLIP processing systems. Various laser beam sources (IR, VIS, or UV) and part motion systems can be used depending on the application requirements.

The IWS team currently focuses on the development of compact DLIP processing heads (Fig. 2). The goal is to process various materials such as metals, ceramics or polymers in a single process step.



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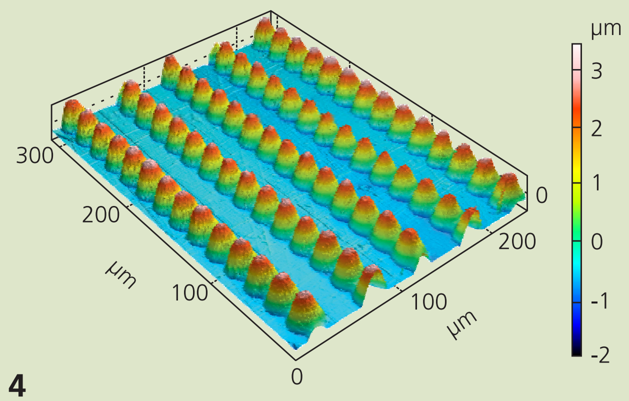
RESULTS

The Fraunhofer IWS DLIP technology is a flexible solution to pattern highly resolved sub-micron surface structures with high processing speeds approaching 1 $m^2\ min^{-1}$.

A system configuration, which was particularly optimized for high processing speeds, achieved 0.9 $m^2\ min^{-1}$ on polycarbonate and 0.35 $m^2\ min^{-1}$ on metal substrates. The patterned structures consisted of lines and dots with period lengths from 5 µm to 22 µm.

The achieved processing speeds prove the potential of the DLIP technology to efficiently manufacture highly resolved periodic surface patterns over large areas. Compared to conventional laser ablation processes it is possible to generate more structural elements per time, and thus leading to high efficiency. For example, laser ablation creates only one structure element per laser pulse whereas DLIP can produce 100 to 1,000,000 structure elements with a single laser pulse. In the future it will be possible to use higher power laser systems in combination with innovative beam shaping optics for DLIP. Processing speeds are expected to reach several $m^2\ min^{-1}$. Such processing speeds will make DLIP an attractive option for new mechanical, biological and optical applications such as in the automotive, medical devices and food industries.

Confocal microscopy image of a structured polycarbonate surface



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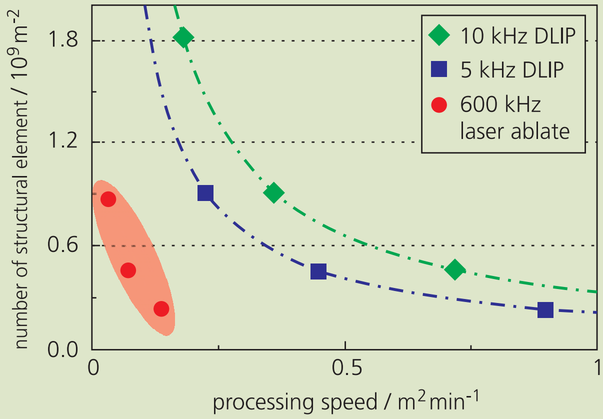
Comparison of processing speeds of DLIP with conventional laser ablation on polycarbonate substrates



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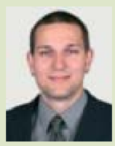
2 DLIP processing optics

3 SEM image of a structured polycarbonate surface produced with DLIP

CONTACT



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BUSINESS UNIT
MICROTECHNOLOGY


1

MONO-FRACTIONAL RECYCLING OF ALL MATERIALS IN PHOTOVOLTAIC MODULES

THE TASK

Photovoltaic modules are a key element of energy policy and reality that is driven by the desire to generate energy with environment-friendly methods, decentralized and from renewable resources. With a growing installed capacity of photovoltaic modules, the demand for recycling older modules increases as well. Recycling and reuse are not only necessary for environmental reasons, they also make economic sense. In particular, the ultrapure front glass panel is a valuable product. The modules also contain valuable materials such as copper, indium and selenium, which can be directly recycled for the European market and thus minimize risks associated with import and raw materials sourcing.

The conventional recycling method is to shred and melt down the modules. Due to cross contamination issues, this method limits the reuse to lower value products such as bottle glass. Alternative chemical or thermal processes require too much energy rendering these options undesirable. Thus a non-destructive technology is required to open the laminated glass system so that the module can be completely recycled and sorted by front and backside glass plates, metals and polymer foils.

Fraunhofer IWS engineers aim to develop a solution which separates in a damage-free manner the photovoltaic multilayer laminated composite which is also usable over larger dimensions. The goal is to 100 percent recycle the sorted components and reuse them in high value products.

OUR SOLUTION

Photovoltaic modules are laminated glass panel systems. The electricity generating metal-semiconductor layers are encapsulated between rigid backside and high-quality frontside glass panels to be stable in demanding weather conditions. The durable bond between the glass panels is ensured by laminating the entire area with polymer foil. The laminate is extremely strong and poses a great challenge for recycling.

The idea is to weaken the large sized laminate by depositing a precisely defined amount of energy in between the bonded glass panels. The aim is to use laser radiation to waken this zone so that front- and backside glass panels can be separated from each other without the need for much mechanical force. The solution is required to provide process safety and an economically feasible throughput. A laser-optical and mechanical hybrid technology was developed, which features high speed and on-the-fly processing.

RESULTS

A laser-based solution requires sufficient transmission of front- or backside glass panel (depending on processing strategy) and sufficient energy absorption in between the glass panels. Thus, laser systems were selected that radiate at near-infrared wavelengths, penetrating the glass without much losses but being almost completely absorbed in the metallic or semiconducting layer. This process offers the basic capability to deposit the energy at the right location inside the multilayer laminate.

However, the laminate needs to be uniformly weakened in the interface without locally overheating the material. The by far more challenging task is to combine the laser system technology with the processing regime. The thermally induced cracking of the flat glass panels and thus their destruction has to be avoided. For this reason, the lasers are operated in pulsed mode. Typical pulse lengths of several tens of nanoseconds were combined with fast laser velocities of up to 3 m s^{-1} to minimize the probability of local overheating of the material. During the laser pulse the metal-semiconductor layer explosively evaporates over an area that is even larger than the focal spot of the laser. Even if the laminate was not completely covered over the entire area, it was sufficiently weakened to separate the panels.

Laser parameters (e. g., focal length, pulse repetition rate) and processing parameters (e. g., line scanning with the focused laser beam, distance of the lines, type and strength of the mechanical separation force) were deliberately tuned to adapt the process to successfully separate typical solar module types.

The hybrid approach was consequently developed for on-the-fly processing. This way the photovoltaic modules can be recycled in a continuous inline process. Subsequently the metal-semiconductor layer and the polymer foils become accessible to chemical processing steps. Technologically challenging is the processing of special areas such as the edges where there is no photovoltaic active layer to absorb the laser radiation. Here too were solutions developed with adapted wavelengths and alternative mechanical process variations.

This hybrid process to separate the front- and backside glass panels is the first and economically absolutely necessary processing step to sort and recycle all the components of photovoltaic modules. Processing speeds were demonstrated to be as high as 0.75 m^2 min^{-1}, and the process is scalable.

The laser based process produces high quality recycled raw materials that can add value to other manufactured goods. Thus the process is a source of providing rare raw materials. The approach is principally usable to recycle other types of laminated systems as well.

The Free State of Saxony’s Ministry for Economy and Labor funded the effort through its central development agency SAB (FKZ 100192199/2936).

1 Mechanically shredded photovoltaic modules

2 Separating of photovoltaic module laminates by laser induced interface weakening

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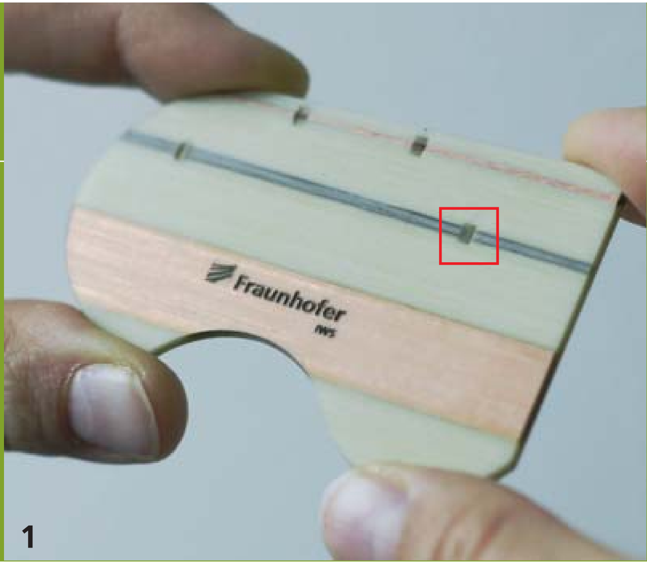


1

PROCESSING OF GLASS FIBER REINFORCED POLYMER COMPOSITES WITH PULSED LASER SYSTEMS

THE TASK

Fiber reinforced polymer composites achieve high specific strengths due to the combination of high-strength fibers with lightweight polymeric matrix materials. Due to the use of thermoplastic materials, it is also possible to apply forming processes that are established for working with polymer materials. Examples include the thermo-forming of continuous fiber reinforced organic sheets and the formation of additional structures with injection molding. A task is to ensure a strong bond of the molded structures with the load carrying fibers throughout the service life of the component.

A specific characteristic of continuous fiber reinforced composites is their layered structure. The layering offers the possibility to tune the material thickness to strength requirements and also to integrate actors and sensors in between the layers. Such inserted actors and sensors are fixed in their position during the consolidation process of the composite. Later these inserts have to be locally exposed to attach electrical contacts.

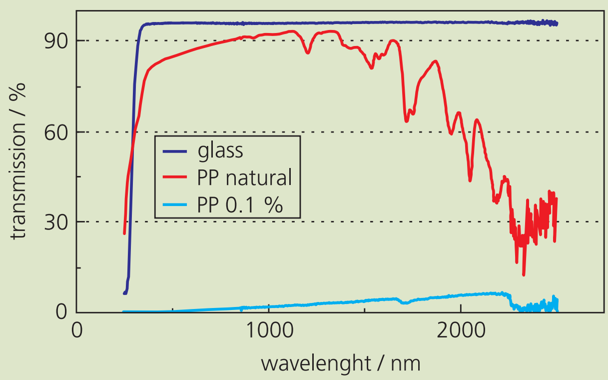
Both tasks require a tool capable of removing material at well defined locations and quantities. Fraunhofer IWS engineers tested various laser systems to qualify them for the selective and homogeneous ablation of fiber reinforced polymer composites.

OUR SOLUTION

The Fraunhofer Institute for Materials and Beam Technology has a broad spectrum of pulsed laser sources with various wavelengths and pulse durations. When selecting a laser system, the desired type of ablation has to be considered. Selective ablation means the complete removal of the polymeric matrix material while only minimally affecting the reinforcing fibers. Homogeneous ablation means the simultaneous removal of polymer matrix and reinforcing fiber.

The starting point of the investigations was the optical characterization of the composite material and its individual components. Optical spectroscopy was applied to determine the transmission spectra of the materials. In general, the polymer matrix and the reinforcing fiber have similar transmission properties. Well defined absorption properties can be tailored by incorporating additives into the matrix, which can be exploited during selective ablation of matrix and fiber materials.

Transmission spectra of reinforcing glass fiber and polymer matrix with and without additives for the wavelength range from 300 to 2500 nm



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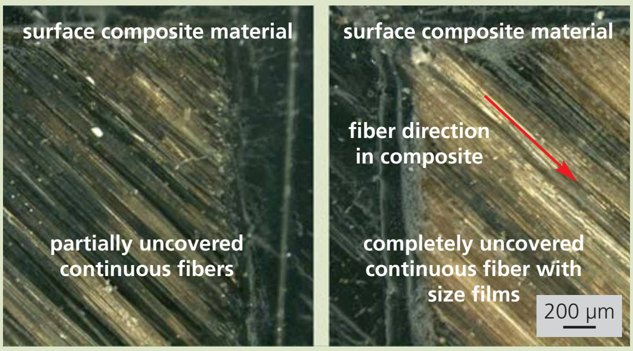
RESULTS

Matrix as well as fibers show low transmission in the UV and mid infrared spectral ranges. This means that there is only a very narrow process window for selective ablation when using lasers with wavelengths of 355 nm (frequency tripled Nd:YAG laser) and 10,600 nm (CO_2 laser). However, the entire composite can very well be homogeneously ablated. The uncolored matrix and the glass fibers have very high transmission in the visible and near infrared (Vis-NIR) spectral ranges. Thus, the selective and homogeneous ablation processes are very difficult with lasers in this wavelength range.

However, by introducing pigments to the matrix, selective ablation becomes possible with short pulse lasers in the VIS-NIR range. Research showed that under these conditions there is a broad process window to selectively remove the polymer matrix without affecting the reinforcing fibers (Fig. 4). At high powers the size film of the fibers can be completely removed. Thermal effects on the composite material depend on the laser pulse duration. The heat affected zone can be reduced to a minimum when using ultrashort pulse laser systems (USP) with pulse durations shorter than 10 ps. This approach also minimizes effects on the mechanical strength of the bordering regions. The physical effect of multiphoton absorption can be exploited to equally process uncolored and pigmented polymers with wavelengths in the VIS and NIR spectral ranges. By tuning the process parameters, USP laser systems are applicable for selective matrix removal as well has homogeneous composite ablation. Figure 1 and Figure 3 show laser generated electrical contact spots on functionalized fibers and the corresponding height profile.

Image of partially and completely uncovered continuous fibers in PP matrix after laser processing



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The here presented research was funded by AiF (FKZ: VP2097548TA3). Jointly with collaborators, the developed know-how for processing fiber composite materials is being used to develop specific applications. The selective matrix ablation process is being qualified for vehicle components to attach injection molded material to continuous fiber reinforced organic sheets.

1 USP laser processed demonstrator component made from glass fiber reinforced polypropylene with Cu inserts and functionalized fibers. The component was produced in collaboration with the IPF Dresden.

3 Laser generated contact area

CONTACT

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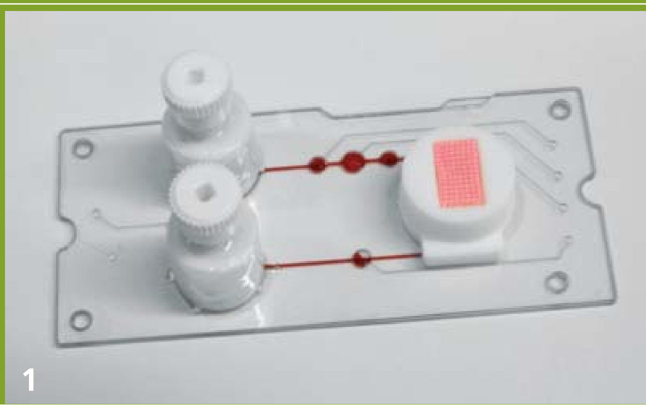


1

UNIVERSAL LAB-ON-CHIP PLATFORM FOR PRINTED, COMPLEX 3D TISSUES

THE TASK

The fabrication and cultivation of three-dimensional organ-type tissues is of great importance for the pharmaceutical and cosmetic industries. Three-dimensional tissues reproduce organ-type functions much better than the classic two-dimensional cell culture models. The practical implementation, however, proves to be an interdisciplinary challenge. Complex tissues require a continuous supply of nutrients. Thus they can only be fabricated in continuously perfused lab-on-chip (LOC) systems.

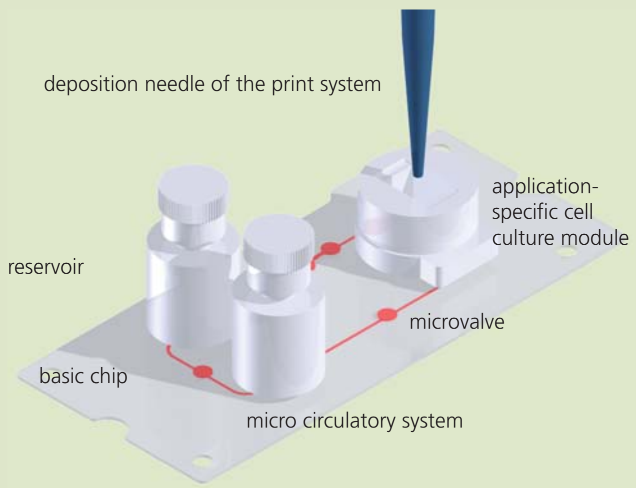
Additive manufacturing methods open fascinating possibilities for many applications including the fabrication of microsystems and the generation of complex organ-type tissues. The 3D printing of living cells (sometimes called biofabrication or 3D bioprinting) enables the fabrication of complex tissues, which consist of different cells and materials and integrate supply channels. Analogous to the human body, the tissues require permanent blood supply already during the fabrication process since the internal cells cannot be sufficiently supplied with oxygen and nutrients based on diffusion only. Nutrients need to be transported by convection to the internal cells, otherwise they die. Under sterile conditions it is possible to supply blood or a suitable solution with nutrients via the integrated supply channels.

OUR SOLUTION

Fraunhofer IWS engineers developed and established a universal and modular LOC platform that is capable of continuously supplying complex 3D printed tissues with nutrients in a sterile environment.

The platform consists of a basic chip that can be combined with application-specific cell culture modules (Fig. 1 and Fig. 2). The basic chips are made from laser microstructured polymer and elastomer foils that are assembled to form three-dimensional microfluidic systems using application specific technologies. Highly transparent polymers are used to provide optical access for non-invasive online monitoring. Integrated flexible membranes can be pneumatically deflected. This permits the integration of valves and peristaltic micropumps to transport and regulate volumetric flows.

Schematics of the LOC platform



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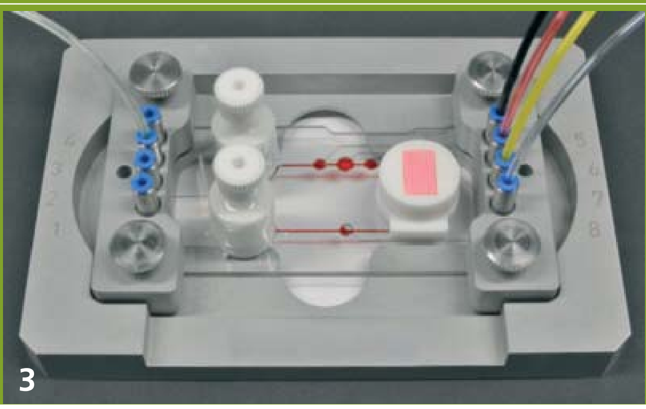

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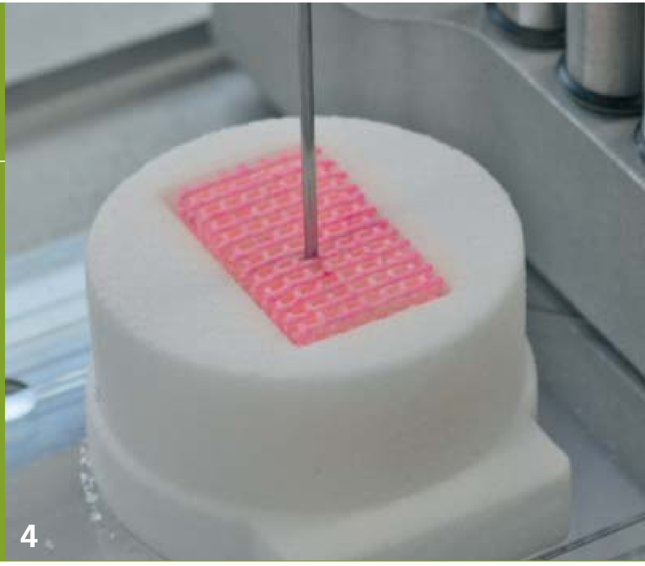

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RESULTS

3D printed complex polymeric components provide the basis for the application-specific cell culture modules. Standard interfaces to connect 3D printed fluidic components and to handle the tissues are located on top and bottom surfaces (Fig. 3).

Complex three-dimensional tissues are directly printed into the cell culture modules (Fig. 4). The printing process generates at defined locations liquid-tight connections between tissue and cell culture module. This ensures that the blood or nutrient solution flows through the tissue integrated supply channels.

The versatile possibilities of the LOC platform require a complex and freely programmable embedded system based on Linux. This system provides 24 independently switchable pneumatic exit ports and enables the control of up to eight pumps. Furthermore, the system offers numerous interfaces to peripheral devices such as actors and sensors, data storage and networks. The Linux network stack offers the possibility to remote control the system and to communicate with laboratory information management and automation systems. The user interaction is handled via an integrated 7” touchscreen or corresponding PC software.

Different fabrication systems were used to print complex three-dimensional tissues with living cells directly into the cell culture modules of the LOC platform. Liquid-tight connections between tissue and cell culture module were created during the printing process enabling the nutrient solution to flow through the tissue supply channels. The tissues were supplied continuously for 28 days. The cells inside the tissue remain vital throughout the test period since they receive sufficient oxygen and nutrients.

This universal and modular LOC platform provides a sterile environment to continuously supply 3D bioprinted tissues with nutrients and oxygen for several weeks.

1 LOC system

3 LOC system when receiving

4 Tissue printing in LOC platform

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1

BIGDATA: DATA MANAGEMENT DATA ANALYSIS IN MEDICINE AND PRODUCTION

THE TASK

Data management and the responsible handling of information are an important topic of our time not only in the fields of medicine and life sciences. The management of medical data such as the results of medical tests, takes researchers up to one quarter of their time. Furthermore, the various diagnostics and laboratory machines generate different data types, which quickly adds complexity.

Within large and complex medical datasets are important information, which cannot be extracted with common techniques and analytical processes. The term "BigData" describes data structures that are so large, diverse and complex that their analysis requires new data processing and analytical methods. Such BigData solutions are explored during laboratory operation at the Fraunhofer IWS Dresden.

In medical and treatment research medical routine data are a valuable resource to better understand treatment and risk patterns based on which one can develop individualized preventive and therapy strategies. Large amounts of data require new technical possibilities for storage, processing and analysis in order to advance medical research. BigData processes offer especially for treatment research and personalized medicine new possibilities and can deliver important and so far unknown information about the risks and development of illnesses as well as the therapeutic responses to medications.

OUR SOLUTION

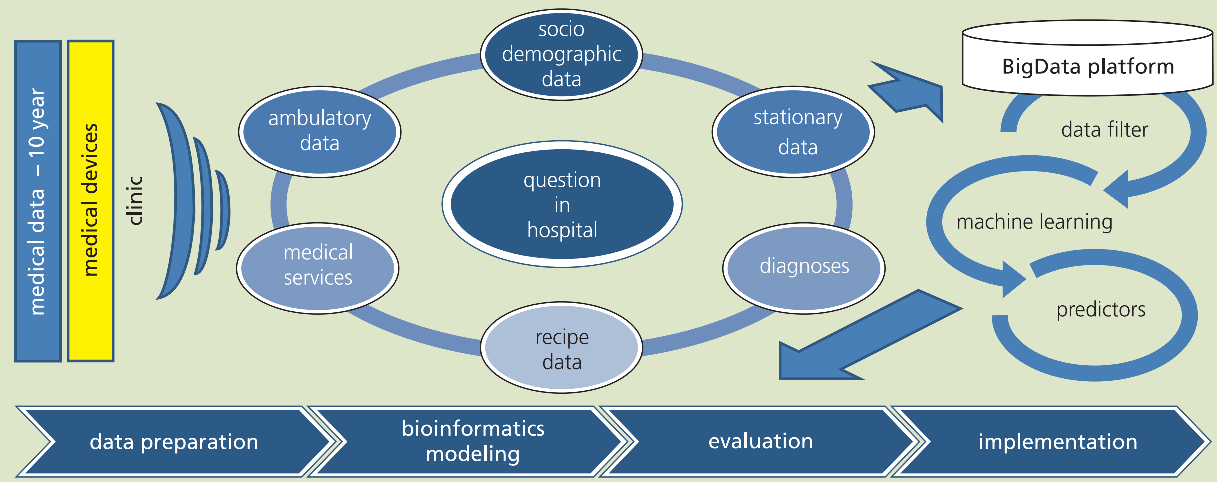
For the first time researchers at the Fraunhofer IWS Dresden are working on several publically funded projects to use BigData analysis methods in the processing and scientific analysis of routine data from hospitals and health insurers. The aim is to identify indicators in routine medical data that can predict illnesses. To do so multi parametric methods of machine based learning are used already. Now, for the first time, BigData methods of bioinformatics are applied for pattern recognition.

Cooperation partners are the university clinic Carl Gustav Carus Dresden and the Society of University Clinics in Germany e. V. The researchers explain to users the concepts of BigData, implement the methods and demonstrate practical examples.

The Fraunhofer IWS BigData group has the following competences:

- research using the BigData platform and adaption to applications,
- process optimization for database management and storage,
- visual analytics,
- multiparametric and statistical data analysis, visualization, management,
- automated real-time data processing and management,
- image processing and 3D visualization,
- development of biomedical image formats,
- software development for planning, modeling, architecture, analysis,
- development of technology and data standards for the management of digital images and meta data,
- professional software development and consulting with respect to object oriented programming languages, professional project management and modeling of IT and software infrastructure.

Model for the evaluation of medical data



2

RESULTS

The use of BigData in medical studies serves as a source to generate new hypotheses for risks and development of illnesses. It also provides new hypotheses about causes, causalities and consequences of such illnesses. Individualized measures for prevention and therapy are developed based on these hypotheses. BigData can also be used to determine predictors for the efficient and safe application of medicines and treatment paths for patients, which in the end improves the treatment.

The new approach to apply pattern recognition methods of bioinformatics research in medical routine data can be adapted to numerous other illnesses and questions in treatment research. New and so far unknown causalities between target variables and studied impact factors (exposition factors) are researched with non-parametric processes using machine learning methods. Very many different initial data are bundled in groups and compared to find similarities. This approach can also be adapted to examples in industrial manufacturing and analytics.

1 Cluster server for BigData platform

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THERMAL SURFACE TECHNOLOGY

Editor: Prof. Leyens, laser buildup welding using wires has recently found substantial interest among industrial clients. Does this technology offer an alternative to laser powder buildup welding?

Prof. Leyens: The IWS systems technology for wire based laser buildup welding is indeed of great interest. The advantage of the process is obvious: The wire material is used 100 percent when depositing the coating or building a 3D structure. That makes the process simultaneously clean and economical. The IWS also develops a process control technology, which guarantees the uniform quality of the deposit. Such an automated process is interesting for many applications. Wire based laser beam buildup welding is therefore an excellent addition to powder based processes. However, it also requires that desired materials are available in wire form, which means there is a somewhat smaller material base to select from.

Editor: What is so special about the COAXwire wire head made by IWS?

Prof. Leyens: When we developed the wire head we were guided by customer requirements for a robust and practicable tool. The wire head is coaxial meaning the laser beam is first split into three parts which then coaxially meet to melt the wire. Metals with high melting points can be melted using lasers of up to 6 kW power. The head itself has a modular design. It is compact, weighs 13 kg and thus can be used without trouble in robot platforms or CNC machines.

Editor: Thermal spray technology is also an IWS competence area. What progress has been made?

"It is not simply enough to invent something you must also realize that you have invented it."

Karl Steinbuch

BUSINESS UNIT MANAGER

PROF. CHRISTOPH LEYENS

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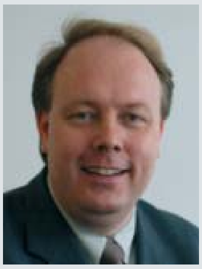
Prof. Leyens: In our special field, spraying processes with suspensions, we have used the IWS-developed systems technology to work on coating solutions for various application areas. These include the protection from wear, oxidation and corrosion but also sensor and thermoelectric applications. The knowledge about the correlation of process conditions with material properties is of high importance. This makes it possible to tailor solutions for specific applications.

Editor: Is this correlation also important for laser hardening?

Prof. Leyens: Indeed. During laser hardening the structure of the material changes through the deposited heat, usually with the goal to improve its hardness. Too much hardness, however, can have disadvantages such as, for example, the material may crack. Our experience is helpful to identify the appropriate solution for our customers. The solution depends on factors such as material, component geometry and of course on the conditions in which the part is used. We conduct intensive discussions and technical consultations with our customers to capture the requirements and to achieve the best possible outcome. Our clients very much appreciate that we offer One-Stop Solutions, which address process and system challenges and may also include material characterization and testing of the final parts.

COMPETENCES AND CONTACTS



Dr. Steffen Bonß, division manager heat treatment and plating
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» For part geometries, wear scenarios and materials where conventional hardening technologies fail, alternative surface technologies such laser beam hardening and laser beam remelting often offer new approaches to generate wear resistant surfaces. This is especially relevant for the selective hardening of parts with multidimensional curved surfaces, inner surface or hard-to-reach areas, bores or notches as well as for those parts that are prone to distortion. «

Dipl.-Ing. Jan Hannweber, group manager heat treatment systems
☎ *+49 351 83391-3360* / ✉ *jan.hannweber@iws.fraunhofer.de*

» The successful transfer of a technology toward industrial implementation is essentially depending on the technological maturity of its individual components. The group's core competence is the development of new and the improvement of existing laser materials processing systems technology with a focus on laser beam hardening. The conception and development of systems ranging from individual devices to complex machinery during the project performance, follows consequently current European guidelines. The project "Industry 4.0" provides important guidance. «

Dipl.-Phys. Marko Seifert, group manager mechanical-thermal processes
☎ *+49 351 83391-3204* / ✉ *marko.seifert@iws.fraunhofer.de*

» The group's core competence is the development of processes and customer-specific processing concepts in the field of laser-assisted mechanical-thermal materials processing. Main work areas are laser hardening of steel materials and laser induction roll plating to create complex mixed metal joints. Furthermore, we offer special technical solutions for soldering, remelting and gas alloying. Tools are multi kilowatt high power lasers up to 9 kW. A focus in all developments is the realization of precise temperature controls to provide the basis for reproducible industrial processes. «

Dr. Filofteia-Laura Toma, group manager thermal spraying
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»Atmospheric plasma spraying (APS) and high velocity oxygen fuel (HVOF and HVAF) spraying technologies are available for thermal coating process development with powders and suspensions. Metal, hard metal and ceramic coatings are deposited on components made from steel, lightweight metals or other materials. Core competences include the development of tailored coating solutions, of system components and their integration into adapted machine concepts. Supporting the technology deployment on-site at the customer installation is an important aspect of know-how transfer.«

Prof. Steffen Nowotny, division manager buildup welding
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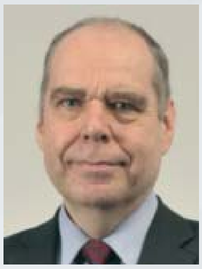

»The competence field encompasses the application of laser buildup welding technology with powders and wire for the purposes of surface coating and surface functionalization. An important focus is the development of processing heads, component technologies and CAM software. To use the technology in production we support our customers with expertise in process development, systems technology and on-site consulting. We also offer consulting, education and training programs.«

2015 PROJECT EXAMPLES

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2

INDUSTRIAL SOLUTIONS FOR LARGE AREA LASER BUILDUP WELDING

THE TASK

A special feature of laser technology is its capability to deposit materials of micro- and macroscopic dimensions with one and the same tool. No other buildup welding technology can do this in comparable form. Laser based process variations are used in industry, which deposit tracks with widths ranging from 30 µm to 30 mm. These dimensions cover the enormous range of 4 orders of magnitude, which in turn results in a wide application spectrum spanning many areas.

Micro laser buildup welding often addresses challenges and requirements concerning precision and reproducibility of the deposition. The success of macro processes on the other hand is often related to the design of optical components and processing heads as well as to durability concerns of the systems technology. The use of highest laser powers and large sized melt pools radiates enormous heat toward the powered nozzles. Other challenges include melting parameters such as heating and cooling rates as well as the dynamics of laser induced melt pools with comparably low depths and wide widths.

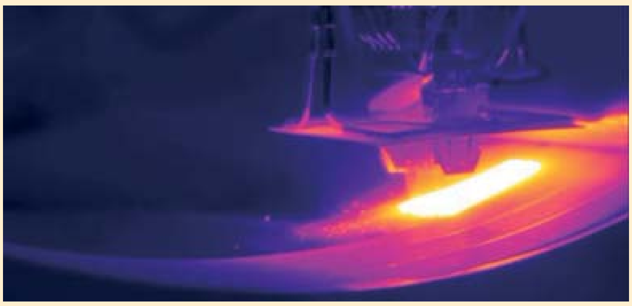
The development of modern laser processing heads presents scientific and technical challenges with respect to achieving a homogeneous, rectangular or line shaped powder jet profile and a long-term stable powder delivery under enormous heat loads. Simultaneously these processing heads have to be capable to meet the demands associated with the economical deposition over large areas.

OUR SOLUTION

Fraunhofer IWS developed a modular processing head system solution. The solution consists of a series of COAXn processing heads, which are continually improved and qualified for new applications. Recent development work has focused on the concept of the wide jet nozzle with rectangular powder jet cross section. This new and patented wide jet processing head has significant advantages compared to the current state-of-the-art: it includes a reworked powder delivery concept, which was particularly adapted to meet the requirements related to the use of highest laser powers and highest powder feed rates (Fig. 1).

The powder is delivered through special and exchangeable channel plates. These plates are adapted to the shape of the laser spot and to the required powder throughput. The standard configuration of the wide jet processing head has a focus size of 16 mm x 6 mm. In other configurations it can be adapted to laser focus widths of 45 mm. The working distance is adjusted between 20 mm and 30 mm depending on the process requirements and the component.

Thermal image during laser powder buildup welding with 15 kW laser power and wide jet nozzle



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RESULTS

Figures 4 and 5 show typical welding results on flat and cylindrical samples, which were achieved with the 45 mm wide rectangular powder jet cross section. The special design of the powder channels guarantees that the mass flow is homogeneously distributed even for such wide jet widths. A typical sample with a single 45 mm wide Ni base alloy IN82 track was cross sectioned and polished (Fig. 6). Even for such an unusually large width, the cross section shows uniform and flawless track material that is metallurgically bonded to the substrate.

When using the highest available power from the 20 kW diode laser, the maximum deposition rate for the Ni base powders is 14 kg h^{-1} at 90 percent powder utilization. The rate is not limited by the powder delivery but by the available laser power. Laser build-up welding with a wide rectangular beam is different from using a laser with a circular beam. The process works with lower laser power density and slower welding speed to maintain a calm welding process and to reduce the risk of overheating the melt pool. The slower welding speed causes reduced cooling rates, which are advantageous for processing powder materials that are prone to crack formation and for using substrate materials with temperature sensitive hardening properties.

The application spectrum benefits from the high deposition rates and efficient areal coverage of the process. Examples include large area coating of power plant and offshore components that are exposed to corrosion and wear. Figure 7 shows the coating of large container parts at an industry customer. This research and development project was the first test opportunity for the wide jet processing head with 45 mm track width.

System for large area laser buildup welding of container parts with IWS wide jet processing optics

7

1 Wide jet processing head

2 Laser powder buildup welding process with 20 kW laser power and 45 mm wide jet nozzle

4/5 Parts coated with 45 mm track width

6 Polished cross section of a single IN82 track

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1

MINIATURE LASER PROCESSING OPTICS FOR HARD METAL INTERNAL CLADDINGS

THE TASK

Wear resistant hard metal coatings are an excellent choice for cladding. A potential application is the coating of cylinders in extruder tools, which are used in the fabrication of plastic raw materials. Plastic raw materials are poured through a funnel into a heated cylinder with an internal extruder screw. Movement and pressure mix the plastics and the melt is ejected through a narrow exit port. The cylinders are up to 8 m long and experience strong wear due the external heat and high friction. The aim of an EU project (EU-DEBACOAT, FP-7, FZK: 315417) was to clad the inner diameter surfaces of the cylinder with a wear resistant hard material coating. The surface to be coated is deep inside the cylinder with small diameter and hard to reach.

The Fraunhofer IWS research task aimed at developing an inner diameter laser cladding head, which could clad especially hard materials. The following requirements had to be fulfilled:

- internal cladding of long cylinders, which could also be conical or double-performed,
- a maximum immersion depth of 1800 mm at minimum inner diameters of 58 mm,
- maximum possible laser power of 1000 W while being capable of long-term stable processing of at least one hour,
- the integration of a process camera and temperature monitoring.

OUR SOLUTION

The new "Mini-ID" optics (Fig. 1) is capable of immersion depths of up to 3000 mm at a minimum inner tube diameter of 50 mm. The optical fiber is completely integrated into the center of the head. All media delivery channels for powder, inert gas and cooling water, run along the outside of the optical fiber like a magazine. Behind the fiber connector there is a connecting element for the powder gas mixture, the inert gas, cooling water input and output flows, a thermocouple running to the farthest optical component and also an integrated endoscope camera, which is mounted very close to the melt pool. After the laser beam exits the fiber it is collimated by optical lenses and focused using long focal lengths. Then it is diverted by 90 ° and again focused to the substrate. The final optical element is integrated into a cassette so that it can be quickly exchanged.

The powder delivery feed is connected from the side and is suitable to be used for dragging as well as pushing welding directions inside the tube (Fig. 2). The melt pool is shielded with inert gas, which runs along the laser beam to the exit port. The inner diameter cladding head is completely water cooled, all the way from the connecting element to the laser beam exit port. The head offers to adjust the collimated laser beam to the exit port and to align the powder nozzle with respect to the melt pool. A ball pressure screw can be used to support the inner diameter coating head inside the tube that is cladded. The head is modular and can be expanded with 500 mm long extension modules.

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4

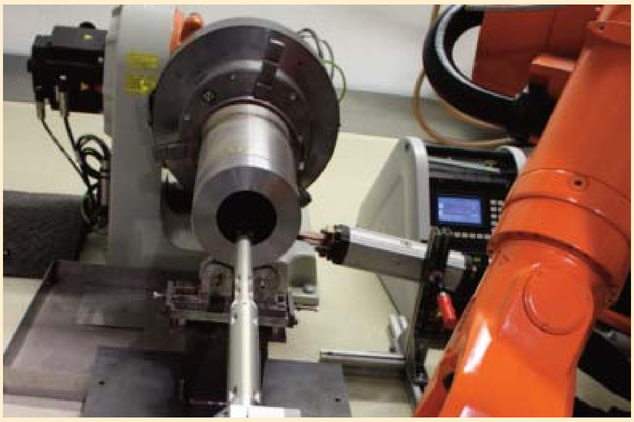
RESULTS

The inner diameter laser cladding optics Mini-ID can handle up to 1.5 kW laser power. A thermocouple for temperature measurements of the final optical component and an endoscope camera for process monitoring are integrated into the head.

Prior to performing long-term process stability tests with deep tubes, the optics had to be thoroughly tested to demonstrate its process technology and welding quality. Welding tests of 15 min were successfully performed on flat samples with Ni base alloys and a typical laser beam diameter of 1.8 mm, a working distance of 6.5 mm and 500 W laser power.

The long-term stability tests were performed through cladding real parts for the plastics manufacturing industry. The cylinders had an outer diameter of 200 mm, an inner diameter of 110 mm and a length of 500 mm. The parts were inductively pre- and post heated so that hard metal alloys could be internally coated while avoiding crack formation. Figure 4 shows the welding setup with induction support.

Welding setup for inductively assisted inner diameter cladding



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Long-term internal cladding runs were performed for up to 2 hours. The tubes were preheated to 300 °C, with a laser power of 700 W and a laser beam diameter of about 2 mm, the feed rates of the head inside the tube were 500 mm min^{-1} (Fig. 3). The Ni base alloy was coated on the inside surface of the cylinder to a thickness of 0.5 mm. At the end of the process the cylinder temperature was 370 °C. All optical components of the constantly cooled internal diameter cladding head survived the test without damage despite the heat load inside the heated tube and being surrounded with a flow of residual powder.

1 *Internal diameter cladding optics Mini-ID mounted to KUKA robot*

2 *Lateral powder gas flow at the cladding head*

4 *Long-term coating of a cylinder with laser powder cladding*

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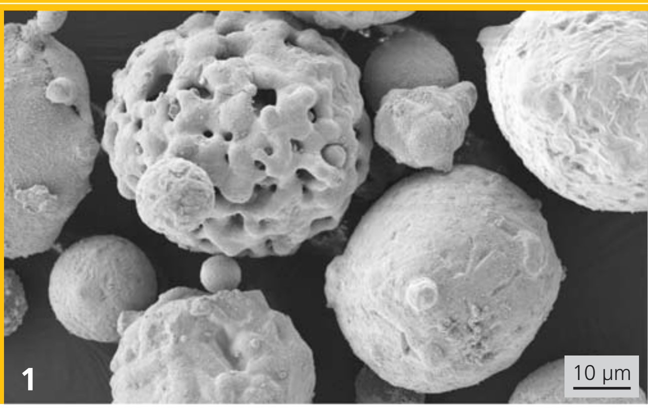
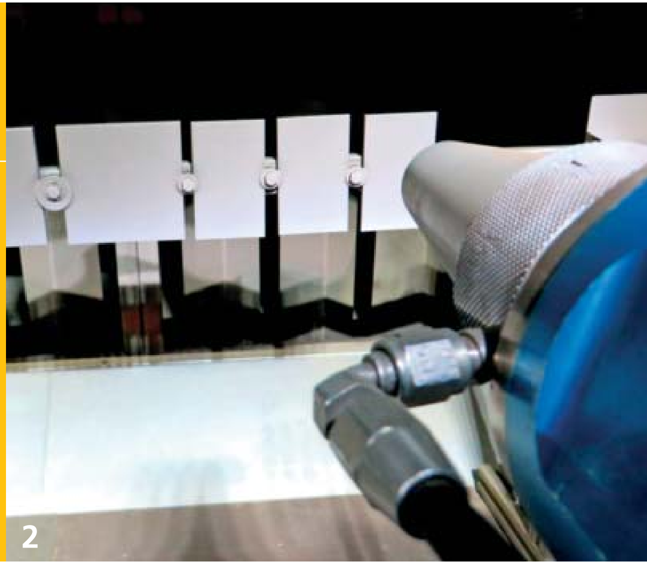




EFFICIENT HARD MEDAL DEPOSITION FOR HIGH TEMPERATURE APPLICATIONS

THE TASK

Protection against wear is one of the most important applications of thermal spray hard metal coatings. Hard metal coatings based on WC and Cr_3C_2 with various binders (Co, Ni or NiCr) are state-of-the-art. Such coatings are predominantly deposited using high velocity oxygen fuel spray processes (HVOF). An issue in industrial use is the low deposition efficiency of only 35 to 40 percent for HVOF systems using liquid fuel. HVOF guns of the third generation use gaseous fuel and can reach a deposition efficiency of about 60 percent, however at reduced powder feeding rates. One of the reasons for the low deposition efficiency is the non-uniform heating of the powder particles in the flame jet. Moreover, high deposition efficiencies do not automatically lead to high quality coatings.

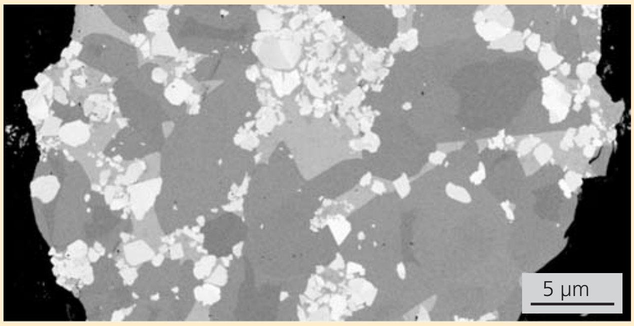
The development of new applications typically faces technical as well as economic challenges. An example is the need to improve the coating quality at high temperatures while, at the same time, to reduce the coating costs, for instance by increasing the coating efficiency. Furthermore, the correlation between powder properties, spraying process parameters and the resulting tribological properties of the coatings is only partially known.

To address these questions we systematically studied the effects of various feedstock powders on the properties of the resulting coatings and on the deposition efficiency during high velocity oxygen fuel thermal spraying. The studied feedstock powder materials were Cr_3C_2-NiCr and Cr_3C_2-WC-Ni. In addition to the economic parameters the study focused on the wear performance of the coatings at temperatures up to 800 °C.

OUR SOLUTION

After spray drying of the Cr_3C_2-NiCr powders (C1 to C5), they were consolidated by sintering or plasma densification. Due to different manufacturing processes, the powders vary in terms of morphology, porosity and carbide corn size. The Cr_3C_2-WC-Ni powders (W1 and W2) contain Cr_3C_2 carbides but also very fine WC carbides. The binder phase consists mostly of nickel (Fig. 3).

SEM image of Cr_3C_2-WC-Ni (W1) powder particle: WC (white), Cr_3C_2 (dark gray) and binder (light gray)



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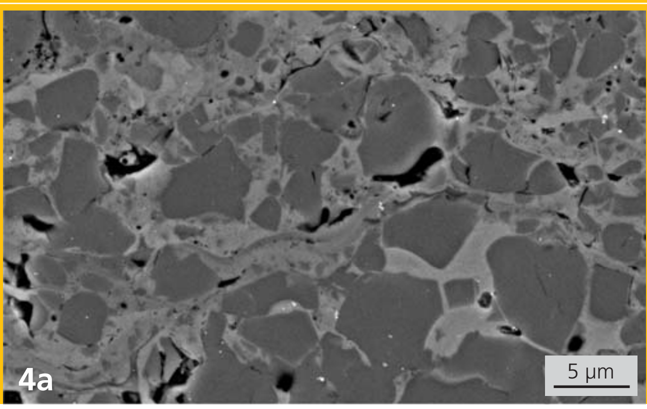
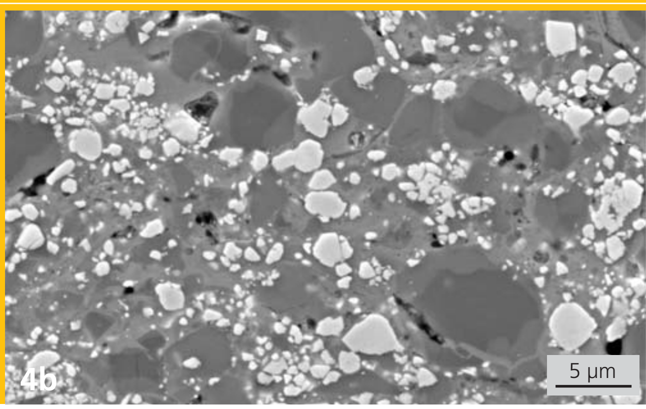
The coatings were produced using two different HVOF processes with liquid (K2) and gaseous fuel (DJ2700), as well as with an HVAF process (M3). Compared to HVOF, the use of the HVAF process is relatively rare, but it has a high potential in terms of the technical performance of the coatings as well as economic considerations. The coating were produced with parameter sets that provide dense coatings and high deposition efficiencies.





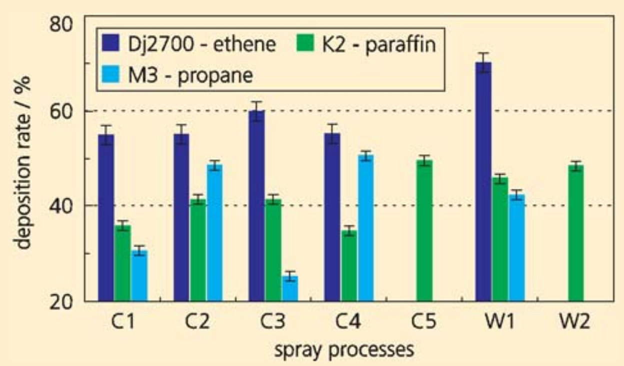
RESULTS

Those sprayed coatings which were deposited using liquid fuels (HVOF K2 and HVAF M3) were much denser than those deposited with gaseous fuel (HVOF DJ2700). The carbides remain mostly intact in the coatings (Fig. 4a and 4b), maintaining the same morphology as in the powder. In Cr_3C_2-NiCr coatings we found Cr_3C_2 and the binder phase. The finer WC carbide grains from the W1 powder are also visible after spraying (Fig. 4b).

Most of the coatings showed hardness values above 1000 HV0.3. This either meets or exceeds the performance of typically used coatings. The Young's moduli ranged from 150 – 200 GPa, which is an excellent result for Cr_3C_2-NiCr coatings. The use of finer carbide grains and WC additives has a positive effect on the coatings.

The liquid fuel HVOF and HVAF processes achieved high deposition rates of up to 4 kg h^{-1}, which implies substantial time savings for coating production. On the other hand, the gaseous fuel HVOF process implies higher deposition efficiencies (Fig. 5). The WC alloyed powder process achieved a deposition efficiency of 70 percent. For liquid fuel HVOF processes the deposition efficiency could be improved to almost 50 percent when using experimental powders Cr_3C_2-(WC)-Ni (C5 and W2).

Deposition efficiency for used coating powder and spray processes



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Abrasive wear test results showed that the wear resistance highly depends on the material. The addition of WC leads to an improved wear resistance for all temperatures. The improvement was about 100 percent compared to pure Cr_3C_2-NiCr coatings. This is especially remarkable for applications at high temperatures and loads since hard metals, which are purely based on WC, typically fail under these conditions. Another important result is the increase of the wear resistance at room temperature after the coatings had been heat treated for 8 h at 800 °C in argon atmosphere. This simple post treatment can significantly broaden the application spectrum of Cr_3C_2-NiCr coatings.

The results presented here were part of a binational Cornet research program. In Germany the IGF project 91EBR was performed in cooperation with Fraunhofer IKTS and it was funded by the Research Association for Welding and Related Processes of the DVS. In Austria the Austrian Society for the Promotion of Research mbH supported the project 839126 at the AC2T GmbH.

1 *Cr_3C_2-NiCr powder*

2 *Equipment to spray hard metal powders*

4 *SEM image of a Cr_3C_2-NiCr (a) and a WC-Ni coating (b)*

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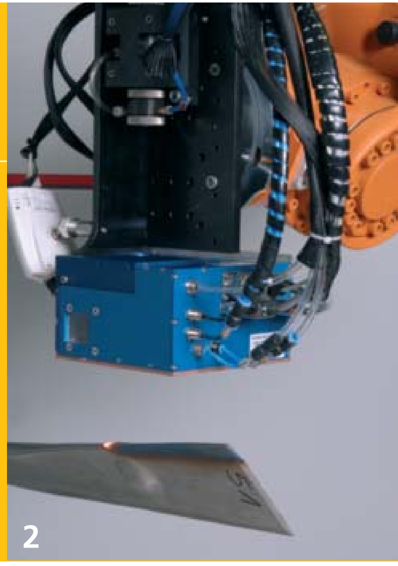

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IMPROVED CAVITATION WEAR RESISTANCES OF TURBINE MATERIALS

THE TASK

Modern high performance materials in power plant machinery are exposed to high temperatures and wear loadings. For example, the leading edges of steam turbine blades, located in the lower temperature stage of the turbine, face direct erosion from the impact of condensing water droplets, which can reach sound velocity. Special steps for wear protection are required to increase the service life of these blades in addition to selecting appropriate base materials. It is also essential to test the wear resistance of the components under real operating conditions to prove the effect of material and process optimizations.

OUR SOLUTION

At the Fraunhofer IWS various wear protection technologies have been developed for high performance materials as they are used in the energy sector. A suitable tool is the high power diode laser with laser powers in the multi kilowatt range.

In principle there are three technological variants:

- martensitic surface hardening of hardenable steels,
- laser solution annealing of the surface region of precipitation hardening steels with subsequent low temperature precipitation hardening in a furnace without affecting the bulk material,
- laser gas alloying (e. g. of titanium materials) by remelting the surface region in a suitable gas environment.

To implement these technologies, several machine designs have been developed which are based on robot-handling of the processing optics and include optional shield gas chambers, which are designed to fit special parts. With the help of additional axis for turning and swiveling the workpiece, it is possible to generate very flexible 3D processing tracks on the workpiece surface. The process has to be stable and safe to produce quality results. This is supported by performing temperature-controlled treatments using the temperature control unit "LompocPro" and the thermal imaging camera "E-FAqS" to capture the temperature fields. Fraunhofer IWS engineers also adapted a test stand to measure the cavitation wear resistance of the processed materials (Fig. 3). The test conditions are standardized. An ultrasonic sonotrode is applied to erode the surface material. The volume removed per time delivers precise results about the wear performance of the materials.

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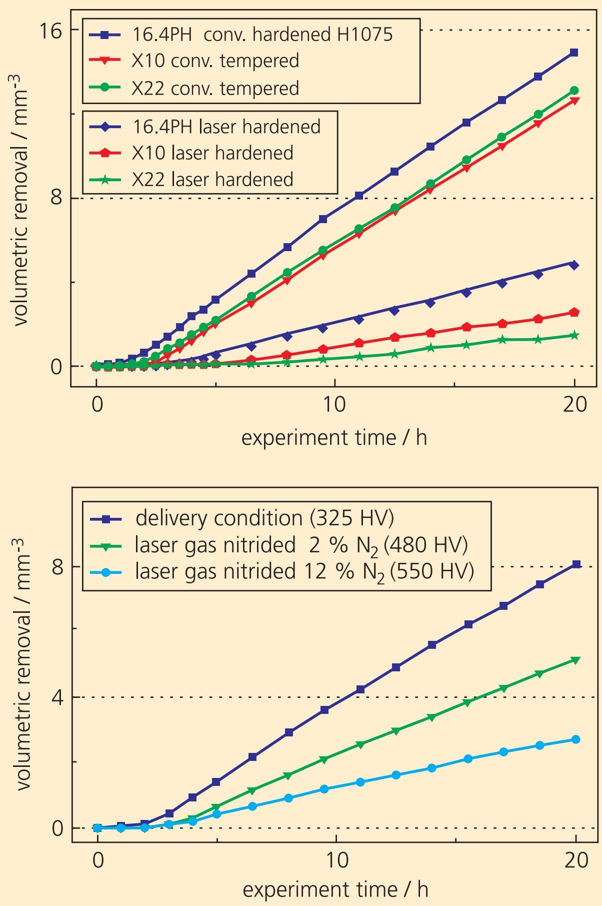
Cavitation wear of various turbine blade steels (upper) and titanium alloys (lower)



specification of the test stand:
Ultrasonic homogenizer VC 501

Test conditions according to ASTM G 32-92:

Test tip diameter:	*Ø 15,9 mm ± 0,05 mm*
Penetration depth:	*12 mm ± 4 mm*
Amplitude:	*100 %*
Frequency:	*20 kHz*
Distilled water	*22 °C + 4 °C*

4

RESULTS

Compared to the conventionally treated material surfaces, laser hardened surfaces show clearly increased hardness values. For steels it is usually possible to realize the material specific maximum hardness. For titanium one has to find a good compromise between high hardness combined with high fatigue strength.

By means of laser hardening, the volumetric material removal for high performance steels under cavitation wear conditions was reduced to 1/3rd or even 1/8th. For titanium alloys the data led to identifying correlations between the wear resistance properties, material hardness and the nitrogen concentration in the gas atmosphere during laser gas alloying. The volumetric material removal for the titanium alloy Ti6Al-4V was reduced to about 1/3rd. Thus one can expect a clear increase of the service life of the laser treated component surfaces, even if the cavitation wear test stand is just a model for the real-world wear conditions.

Using the cavitation wear test is relatively inexpensive and a suitable addition to hardness measurements and microstructure analysis of the materials. It supports the evaluation of the wear resistance of materials and surfaces.

1 Selected turbine blade types for laser processing

2 Laser hardening of a turbine blade with scanner optics (type “LASSY”)

3 cavitation wear test stand

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CHEMICAL SURFACE AND REACTION TECHNOLOGY

Editor: Professor Kaskel, why do you continue to focus on lithium-sulfur batteries?

Prof. Kaskel: This is quite obvious. The lithium-sulfur battery is currently the system with the highest potential for increasing energy density. Up to now the record for classic lithium-ion batteries is about 250 Wh kg^{-1}. So far, this was achieved only in isolated cells. The lithium-sulfur battery has the potential to reach at least 350 to 450 Wh kg^{-1}, so that a significant increase of energy density is given.

Editor: But why is it not possible to buy these batteries yet?

Prof. Kaskel: Well, there are already companies that market this type of battery. Despite this, these systems are not available on the open market. There is also still a considerable need for innovation in the selection of appropriate materials and components. This ranges from porous carbon materials for cathodes, to separators, all the way to appropriate electrolytes and anode materials. Here, the considerable need for further development persists, especially in order to improve cycle stability. During the last three years, we have succeeded in building a complete process line for the production of such batteries and moreover to advance the development of more innovative production processes. The dry production of electrodes, in which the use of toxic solvents can be eliminated, is especially worth mentioning.

Editor: This is surprising. Do you really see such high innovation potential in the development of carbon materials?

"Technology always develops from primitive to complex to the simple"

Antoine de Saint-Exupéry

BUSINESS UNIT MANAGER

PROF. STEFAN KASKEL

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Prof. Kaskel: The generation of new carbon materials plays a key role in many energy-relevant technologies. Think about carbon fibers. Here, we are currently developing new carbonization processes which use plasma, and thereby clearly reduce carbonization times. At the moment, many companies are working on the development of more cost-effective base polymers for carbon fibers, for example from renewable raw materials. In part, the classic carbonization processes fail there whereas the plasmas work very efficiently at atmospheric pressure. In the area of power electronics, however, carbon materials might play a significant role. Diamond-based electronics is considered to have great potential.

Editor: You are also working on modern process monitoring procedures, for example the "Hyperspectral Imaging" (HSI). Which applications does this technology offer?

Prof. Kaskel: Correct! This is a novel technology to image chemical analysis. For example, different impurities next to each other on surfaces are detectable by imaging. The technology is used in process control, in the sorting of materials with different chemical compositions for example. Fruits and vegetables can be sorted with it, since the bruises can be seen under the surface very well with HSI. Additionally, HSI has a promising future in medical technology for tissue studies on tumors and other diseases. So overall, this is a fairly broadly applicable technology. We have now developed it in such a way that controlled measurements of spatial distributions of layer thicknesses can be taken in the range of a few nanometers and imperfections in organic solar cells, or OLEDs. We therefore see a promising application potential in the process control.

COMPETENCES AND CONTACTS

Dr. Holger Althues, division manager chemical surface technology
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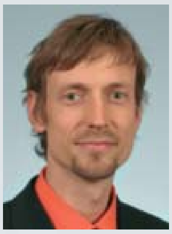
»In the department "Chemical Surface Technology", functional materials and coatings are being developed for a wide range of applications. Besides functional thin films, electrodes put a thematic focus for energy storage. Through the three workgroups, the key processes in the development of next-generation batteries (especially lithium- and sodium-sulfur-batteries) from the material to the coating processes and up to the production of prototype cells, are covered.«



Dr. Philipp Thümmler, group manager battery technology
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»Methods for constructing prototype battery cells and their testing are the foci of this group. Lithium-sulfur cells with 4 Ah and specific energies of > 300 Wh kg^{-1} are fabricated, tested and improved across groups. A process line to automate production of battery cells in local dry room atmosphere was installed at IWS. Key processes are the remote laser cutting "on the fly", the remote laser welding and the automated cell stacking, which were integrated into the process chain.«

Dr. Benjamin Schumm, group manager chemical coating processes
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»Water-based coatings and solvent-free processes for the manufacturing of electrodes are being developed as a roll-to-roll process for the cost-effective production of double-layer capacitors and batteries. Vapor-phase (CVD) and liquid-phase processes for the deposition of functional thin films for conductive, scratch-proof, optical or self-cleaning surfaces are another focus of the group.«

Dr. Susanne Dörfler, group manager battery- and electrochemistry
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»The development of tailored materials (especially carbon and silicon nanomaterials) and the electrochemical characterization of electrodes for battery storage are the focus of this group. Thus the foundations are created to develop new lithium- and sodium-batteries as the next generation of high capacity energy storage devices.«

Dr. Gerrit Mäder, group manager plasma technology and nanomaterials
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» The plasma technology and nanomaterials workgroup develops large area atmospheric pressure plasma sources for custom applications. Application areas are the pretreatment of surfaces for adhesive bonding, the application of adhesion promoters and powder deposition by means of plasma technologies. Another area is the development of gas phase reactors for the production of nanoparticles and metallic conductive carbon nanotubes (CNTs). A flexible, cost-effective high-rate synthesis method was developed especially for the synthesis of single-walled, low-defect CNTs. «

Dr. Wulf Grählert, group manager process monitoring
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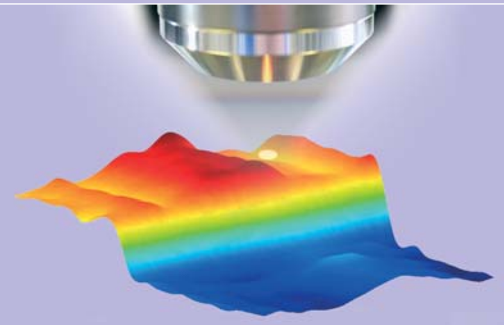
» Optical spectroscopy methods are an excellent process monitoring tool in the characterization of industrial production processes, as well as their products, during or after production. Depending on the methods used, relevant information about the process atmospheres (gas composition) and product characteristics (surfaces, layers, composition, porosity, etc.) can be determined. The methods operate in a contactless manner and are highly sensitive. Some of them even offer spatial resolution. The obtained results can be used for the automated monitoring, control and optimization of the processes. «

2015 PROJECT EXAMPLES

imanto imaging tools



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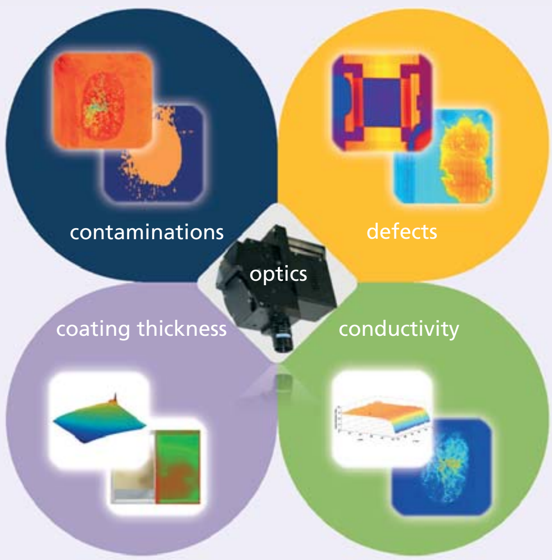
CONTACTLESS HYPERSPECTRAL COATING ANALYSIS

THE TASK

Functional coatings have a key role in many production processes and applications. However, a significant production engineering aspect for many application areas is still completely unresolved: How can the quality of the critical film properties be monitored continuously and reliably over the entire processed surface? This is especially true for coating properties that cannot be determined directly, or only with a relatively high expenditure of time. Thus, in many coating processes one would like to know the thickness, the conductivity, or the stability of other process parameters. There are currently no established methods providing 100 percent process control with spatial resolution.

Overview of the application fields for the contactless hyperspectral coating analysis method



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OUR SOLUTION

The "Hyperspectral Imaging" (HSI) denotes a class of imaging spectrometers that have been developed in the last few years. The optical method works in a contactless manner, which is an essential advantage over invasive inspection and monitoring methods. The recording of spectra in turn offers a considerably greater depth of information than the recording of color pictures. Thus, RGB pictures are coded with a maximum of $(2^8)^3$ color values per pixel, whereas hyperspectral images with 1000 wavelengths are coded with $(2^8)^{1000}$ tonal values. With this, considerably more information about the sample, or product characteristics, are available for an industrial inspection. It is of central importance that this large amount of information is meaningfully processed and interpreted at speeds of a gigabyte per second. This can happen in different ways:

(i) direct interpretation of the spectra, analogously to the classic spectroscopy,
(ii) use of the data for a multivariate, statistical (chemometrical) data analysis aimed at the target quantity (e. g. determination of a substance concentration),
(iii) evaluation of the image information from the spatially resolved image.

At Fraunhofer IWS, approaches were developed that made the acquisition of information possible, both by a direct physical calculation ("hard modeling") and by the use of multivariate algorithms, as well as the image analysis methods that provide correlations with individual process variables ("soft modeling"). In particular, the latter method allows the implementation of fast inline-analysis solutions.

3

RESULTS

The technology of hyperspectral imaging could be established for a variety of application scenarios for coating technologies. The evaluation of the spectra by means of "hard modeling" – the physical description of the layer thicknesses, refractive indexes, absorption coefficients and resistances, or conductivities – offers the possibility to calculate the desired information with high precision for every single sample point.

Starting with known material properties, the determination of different layer properties can be undertaken for a variety of substrates and layers.

Substrates and coating materials for hyperspectral analysis

possible substrates	possible coatings
- metals - wafer - glass - polymers - foils	- inorganic thin films (e. g. Al_2O_3, SiO_2, TiO_2) - metallic thin films (e. g. Au, Ag) - transparent conductive coatings (e. g. FTO, ITO, ATO) - polymers

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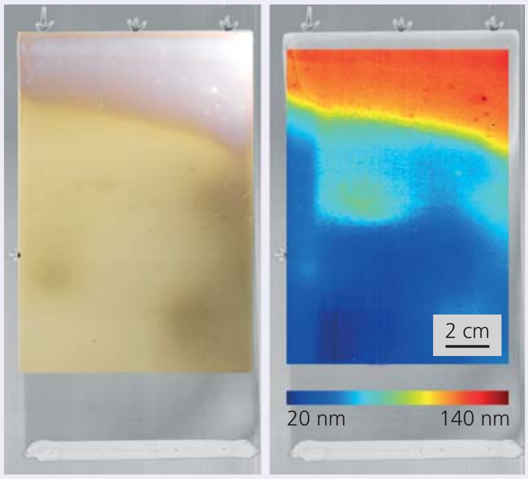
A faster and therefore inline-capable approach offers the evaluation by means of "soft modeling". Here the spectra are directly correlated with one of the target quantities such as one of the listed coating properties. But also process parameters such as the line speed, the deposition quantity of the precursor and the drying time, among other things, serve as target quantities. Overall the HSI technology significantly expands the existing possibilities for process monitoring and related process control technologies.

Aluminum oxide thin film on steel;
left: visual image,
right: calculated thickness distribution



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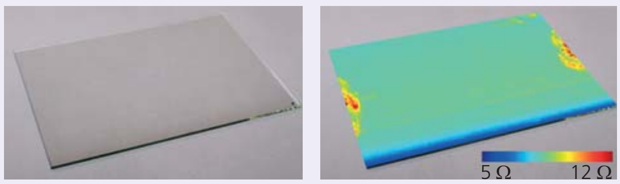
Indium tin oxide thin film on glass;
left: visual image,
right: calculated resistance distribution



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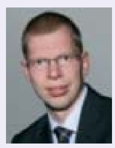
1 *Microscopic investigation of conductive substrate*

3 *Integration sphere (in-house development) for macroscopic coating measurements*

CONTACT



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1

SYSTEMS TECHNOLOGY FOR COST-EFFECTIVE AUTOMATED CELL PRODUCTION

THE TASK

As before in battery research, technical solutions are being researched in order to reduce the production costs of lithium-based batteries and thus, to force a more intensive market penetration of this storage technology. Within the scope of the Federal Ministry of Education and Research (BMBF)-supported research project DryLIZ (KIT 02PJ2302), IWS together with project partners has set itself the task of shortening the process time of electrode assembly and optimizing the transport of the electrodes toward the stacking stage. Electrode cutting and storage should be performed in a minimized dry air volume in order to keep process costs low.

Another research focus is the development of innovative electrode concepts that go beyond familiar electrode production routes. In addition to developing wet coated electrode materials based on water instead of organic solvents, dry processed electrodes with new electrode designs are being developed. Their performance compared to standard electrode systems is investigated (see pp. 70-71).

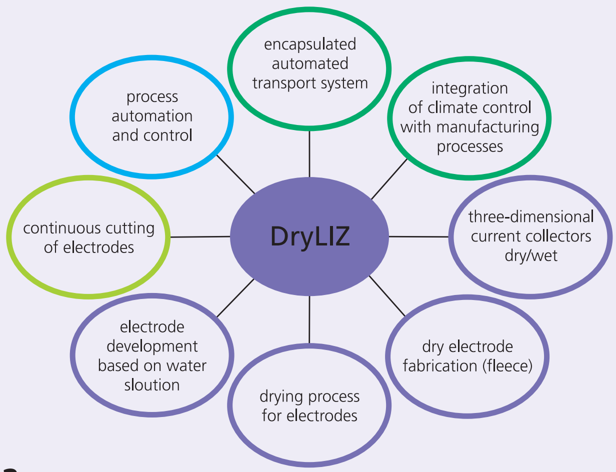
OUR SOLUTION

A fast, interruption-free assembly and packaging of the electrodes increases the throughput of cell production. Continuous electrode cutting processes were evaluated with respect to processing speed, quality of the cutouts, process stability, and tooling costs. Roll stamping technologies with continuous feed of different electrode materials were compared to laser cutting with scanner technology.

The target of fabricating one cutout per second and transferring it both quickly and damage-free posed a big challenge. For the nearly contactless electrode transport, an ultrasound-based transport system was installed, by which the electrodes float on an air cushion.

The handling of dry processed or wet coated and subsequently dried electrodes required defined environmental conditions in order to avoid an irreversible loss of usable electrode capacity. Through the dry air technology developed in the project and the process-customized housing, the applied dry air with a dew point of -40 °C prevents rewetting the electrodes.

Development foci within the DryLIZ project



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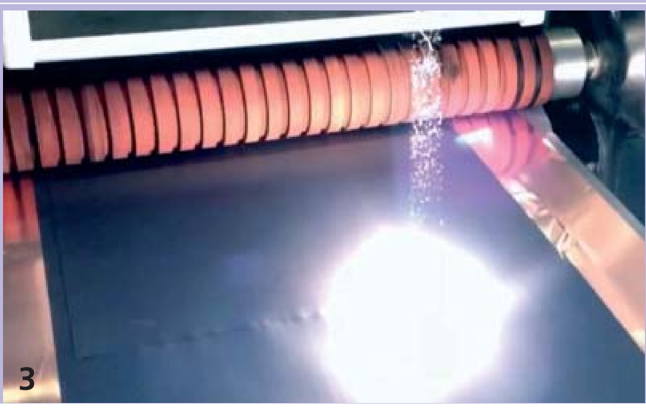

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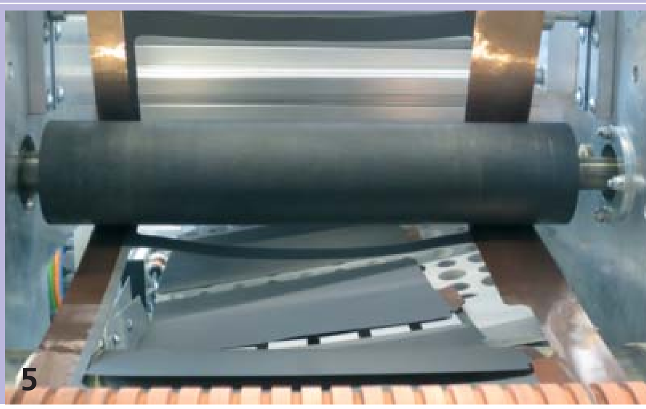

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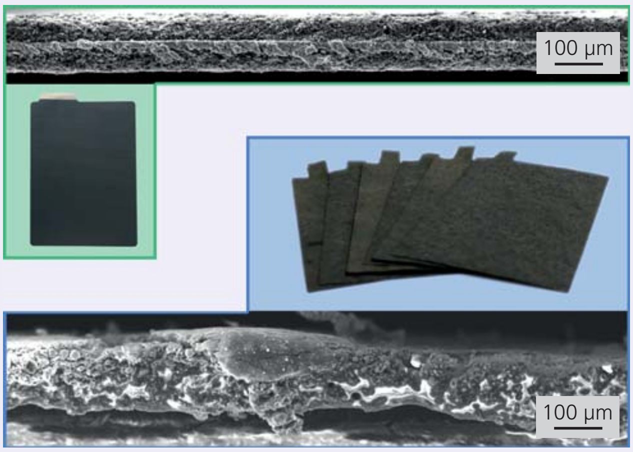
RESULTS

It was impossible to realize reproducible continuous electrode cutting based on roll stamping processes. The laser remote-cutting process on the other hand worked very well with an inexpensive cw single mode laser. This technology achieved good cutting results and high processing speeds. At a transport speed for the electrode material of 200 mm s^{-1} the A5 format cutouts were generated with a cycle time of under a second.

The dry-processed electrodes originating from the project's material development could likewise be cut with the laser. With these electrodes, a conductive 200 µm thick fleece serves as carrier and current collector for the pressed active material. At this point of the development, the new design still cannot be processed by continuous laser cutting "on the fly". However, the smaller format sheets of this material were statically cut by laser and provided evidence of the basic functionality of this new electrode system.

Laser cutouts and SEM images of laser cut edges of the electrode materials (green: water-based coated electrode material, laser cut "on the fly"; blue: dry processed fleece cathode, cut statically)



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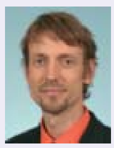
The successful transport of the electrodes was demonstrated. The individual cutouts were picked up by an ultrasound conveyor system without demonstrable damage or contamination. They were transported either freely hanging or floating to another transport element and transferred into magazines.

Within the scope of the DryLIZ project the entire packaging and transport process was demonstrated in a dry air volume that was minimized for the respective processes. Compared to large dry air rooms, the costs of air treatment were reduced significantly. With regard to the laboratory operations of Fraunhofer IWS, the reduction is about 90 percent, only 10 percent of the entire room volume was air-conditioned. The plant operators work in natural room air.

The entire demonstrator for electrode and cell manufacturing is available for further research with partners from science and industry after the successful completion of the project.

1 System overview of cutting and transporting in dry air
3 Laser cutting of fleece cathodes
5 Transportation of cutouts

CONTACT



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1

FROM POWDER TO THE ROLL: DRY-COATED BATTERY ELECTRODES

THE TASK

The standard industrial process for the production of battery electrodes is currently based on wet chemical coating processes in which the active material in the form of suspensions is applied to a metal foil. To ensure that the electrodes produced are of high quality, the removal of the partially toxic solvents used is of great importance. For this, very long and expensive drying sections are needed, which means an immense use of energy.

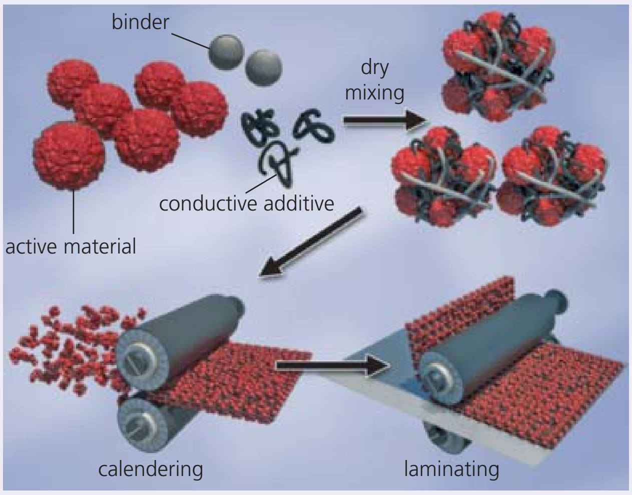
New environmental regulations and increased energy costs demand a rethinking of the concept for new production technologies for battery electrodes. A method of electrode production that does not require the use of solvents therefore has great potential for the saving of production costs.

OUR SOLUTION

Fraunhofer IWS starts here with the dry coating processes, with which the powder is converted in a solvent-free manner to layers and free-standing dry films. Within the collaborative projects DryLIZ (FKZ: 02PJ2302) and BaSta (FKZ: 0325563A) the foundation for the dry materials processing of battery electrodes is laid. Cathode materials for lithium-ion technology (lithium iron phosphate LFP; DryLIZ) and carbon-sulfur composites for room temperature sodium/sulfur batteries (BaSta) were investigated. Within BaSta, an experimental system emerged which was technically expanded for continuous operation. The process of dry coating includes two essential steps. First the powders of the active materials, additives and binders were blended in a dry-mix process. The structure and distribution of the polymer binders are of decisive importance. With optimal distribution of polymer fibrils, with a low binder proportion below 5 % wt., mechanically stable, freestanding films are obtained.

The mixing process yields a powdery material, which is now pressed into thin electrode films of around 50 – 100 µm thickness. These films are either freestanding or bonded to a current collector substrate. The uniform distribution of the powdery material is here of high importance. IWS engineers developed a special applicator system for this step. The IWS has flexible systems so that the powders can be continuously processed into coiled electrode films. In future work, the processes and system components can be adjusted to special customer requirements and further developed.

Process schematic to fabricate dry films



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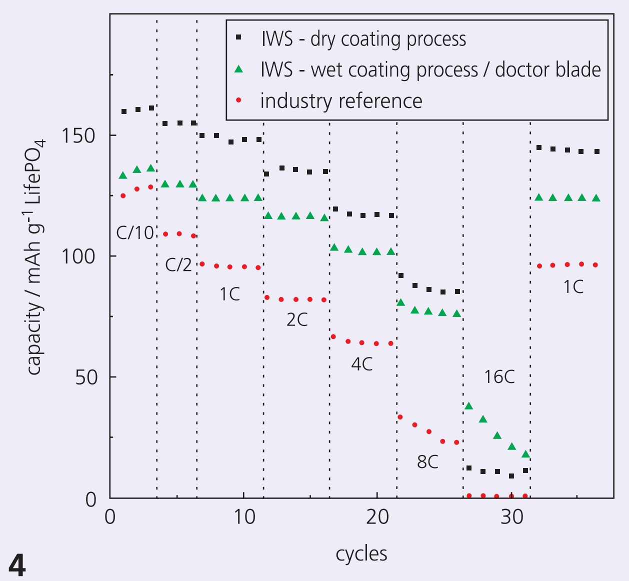
RESULTS

The lithium iron phosphate cathodes manufactured by dry coating were electrochemically investigated and then compared to conventionally processed cathodes. Both for the active material utilization as well as the rate capability (the capacity at increased C-Rate), higher values were obtained with the dry film electrodes than for the reference electrodes.

Likewise, dry-produced carbon/sulfur cathodes are superior to the carbon/sulfur cathodes produced by doctor blade processes. Thus, a specific capacity of over 1,100 mAh g^{-1}-sulfur in the Li-S battery can be achieved with a surface load of over 3 mg cm^{-2}.

Comparison of $LiFePO_4$ cathodes produced by different methods



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By means of an experimental setup used for the conception of demonstration equipment, already 100 µm thick cathode layers could be produced on an aluminum foil with a line speed of 1 m min^{-1}. The enormous potential of the new dry film process, which can be used for different electrode materials in the future, could be revealed.

From the results the following advantages of the dry coating process can be deduced:

- cost savings through the elimination of solvents and drying process,
- environmentally-friendly through the elimination of toxic solvents,
- defect-free application of thick coatings,
- capability to process additives and active materials that are difficult to disperse,
- prevention of negative interference from solvents / drying process.

1 Roll-to-roll process for dry coating

3 Fabrication of a freestanding $LiFePO_4$ cathode

5 Dry coating machine

CONTACT

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1

PLASMA TECHNOLOGY FOR THE EFFICIENT PRODUCTION OF CARBON FIBERS

THE TASK

The growing need for carbon fibers and their composites is based on the sensational lightweight construction properties of these materials. Aside from their high strength at concurrently low densities, they also exhibit a high resistance to corrosion as well as a good damping capability. The price of carbon fibers is determined by the production process and the system costs. The carbonaceous fibers (primarily made from polyacrylonitrile, PAN) must be oxidized and carbonized in order to develop a graphite-like structure. Through the carbonization, the fibers reach a higher strength and stiffness.

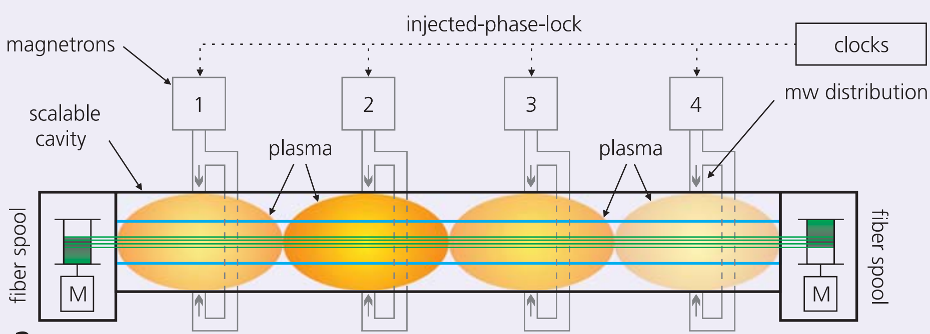
With increasing treatment temperature, the relative carbon content of the fibers rises. At the same time, the efficiency of industrial installations and thus the process efficiency decreases. Alternative treatment methods are therefore important variables for cost reduction and the increase in the efficiency of carbon fiber production. The greatest potential is seen in a reduction of the duration of treatment at concurrent reduction of system dimensions.

OUR SOLUTION

Conventional carbonization is associated with very low heat-up rates in the lower temperature region, because oxygen, nitrogen, hydrogen and their compounds diffuse out from the material, and thus the carbon content in the material increases. With an increase in the heat-up rate through an alternative heating method and the associated increase in the diffusion rate, a considerable increase in efficiency is possible. However, a requirement for this is that no damage to the fibers is sustained and the carbonization process takes place under inert atmospheres. If oxygen enters during treatment in the process room, the fiber quality significantly deteriorates.

At Fraunhofer IWS Dresden, a new low-pressure microwave plasma system was developed in a publicly funded project. It enables the carbonization of pre-oxidized PAN-fibers within 10 minutes. The core of the system is a linearly extended cavity with a present length of 400 mm. Inside, it houses a quartz glass tube with a diameter of 70 mm, through which the fibers are fed. On two opposite sides of the cavity, microwave radiation is coupled into the quartz glass tubes filled with a nitrogen-argon mixture. Through this, it is possible to generate a microwave plasma in the cavity, which carbonizes the fibers through a combination of radiation of various wavelength ranges. The special feature of the developed process is the short processing time of the fibers through the interaction with the microwave plasma.

Sketch of the system capable of inline fiber processing



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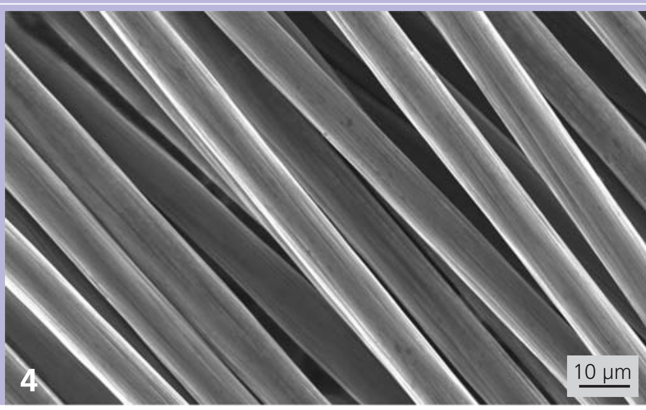

In conjunction with the small size of the system, the fiber throughput is considerably increased and the costs are minimized. Argon and nitrogen are used as process gases.

A further development of this system concept for inline capable fiber processing is currently being built and investigated at IWS. The new system works with the "Injected Phase Locking" process, which enables a phase-synchronous coupling of microwave radiation. This is necessary for scaling up the plasma source. The plasma power density can be controlled and thus, depending on the degree of carbonization, generate the optimum energy input into the fibers.

RESULTS

The PAN-fibers are pulled in a lengthwise manner through the cavity with defined tension. This pre-tension provides a preferred direction for the development of the graphite layers, which increases the strength of the fiber.

The fiber strength is characterized by measuring the tensile strength of single fiber filaments. By varying the microwave power, the spread of the plasma, and thereby also its effective range, can be influenced. By changing the pressure, the intensity of the plasma is varied, which has effects on the temperature in the cavity. The total gas flow and the gas composition influence the fiber characteristics as well. Through the microwave plasma treatment, the strength of the fibers can be substantially increased in comparison to the untreated raw material. At a microwave power of 1150 W applied for 7 minutes, the strength of the raw material could be increased from approximately 300 MPa to a medium tensile strength from 1200 MPa up to 1800 MPa.

The work was carried out in the project "Energy-Efficient Production of Carbon Fibers by Means of Microwave Plasmas" (FKZ: 100154468/2894) in cooperation with SITEC Automation GmbH, financed by funds from the European Union and the Free State of Saxony.

1 Linearly extended low pressure microwave plasma to produce carbon fibers

3 T-distributer at LIMAPP source

4 SEM-image of carbon fibers, which were produces with microwave plasma process

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POWER ELECTRONIC DEVICES BASED ON SINGLE-CRYSTALLINE DIAMOND

THE TASK

For the development of efficient power electronic devices, semiconductor materials with bandgaps larger than silicon are of particular importance. If diamond can be used instead of silicon, the electrical resistance and thereby the power loss of devices would be reduced by a factor of thousand and enable substantial energy savings in power electronics applications.

The next generation of power electronic devices following silicon, is based on silicon carbide (SiC) and gallium nitride (GaN). The intrinsic characteristics of diamond relevant for power electronic applications once again substantially exceed those of SiC and GaN (Fig. 1). If the isolation of 10 kV requires 1000 µm thick silicon devices and approximately 100 µm thick SiC or GaN devices, only 20 µm thick diamond devices are sufficient for the isolation of this voltage.

Currently, the expectations of diamond electronics are based on the comparison of intrinsic material characteristics and the possibilities derivable from them. The task therefore is to manufacture real power electronic devices from diamond and to practically demonstrate the theoretically expected advantages.

Selected properties of semiconductors with large bandgaps

	Si	6H-SiC	GaN	diamond
bandgap / eV	1.12	3.03	3.45	5.45
electric breakdown field strength / kV cm^{-1}	300	2500	2000	10000
thermal conductivity / W cm^{-1} K	1.5	4.9	1.3	22

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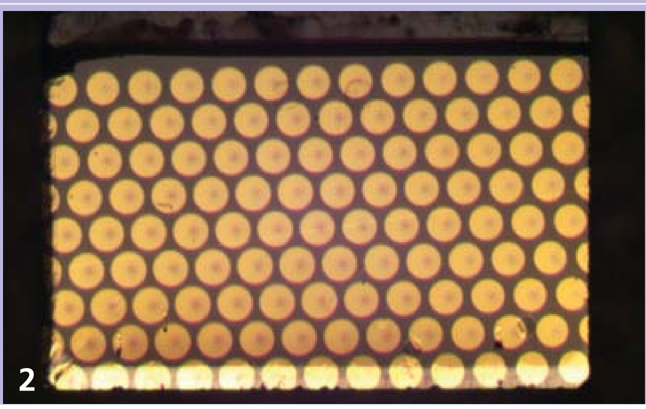
OUR SOLUTION

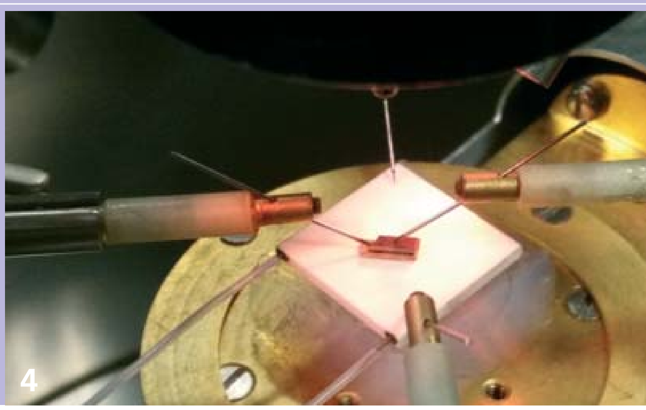
At the Fraunhofer Center for Coatings and Diamond Technologies CCD (see also p. 128), diamond diodes for power electronic applications are developed and fabricated in close collaboration with Michigan State University. The focus lies on vertical Schottky and Schottky pn junction diodes.

In the fabrication of diodes, the processes for the p- and n-doping of diamond are particularly challenging. At CCD the doping occurs during the plasma-based homoepitaxial growth of diamond crystals with boron as p-dopant and phosphorous as n-dopant. In a project financed by the U. S. Department of Energy (DE-AR0000455) the fabrication steps to produce diamond diodes are researched and optimized based on the achieved diode characteristics.

Three doping processes based on plasma-assisted CVD are currently the main focus. Two of the processes produce highly doped n- and p-type semiconducting regions. The third process produces lowly doped p-type regions. These doped regions were analyzed with diagnostic methods in order to determine their dopant concentration and electrical properties.

In a Hall effect measurement system, the electrical properties of the semiconductor are studied from room temperature up to 700 K. Measurements at these high temperatures are important, since special performances are expected of diamond devices in this range.



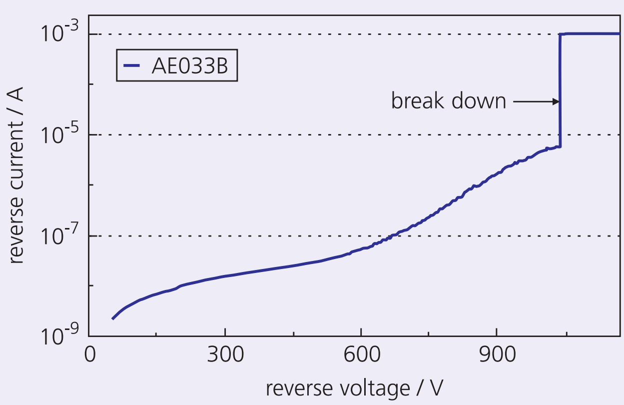


RESULTS

At 0.36 eV and 0.58 eV the activation energies of boron and phosphorous for the release of charge carriers are so high that at lower temperatures (e. g. room temperature), few charge carriers are available. Thus, the electrical resistance and the power loss in the forward direction of such doped regions are high.

Figure 2 shows a field of Schottky diodes produced at CCD, each with a diameter of 150 µm. The diamond region lightly doped with boron (dopant level = 1016 atoms cm^{-3}) is 10 µm thick. Many of these diodes achieved a breakdown voltage (voltage in reverse direction) of more than 1000 V in the test (see Fig. 3).

Current flow of a diamond Schottky diode biased in reverse direction; the breakdown occurs at 1040 V



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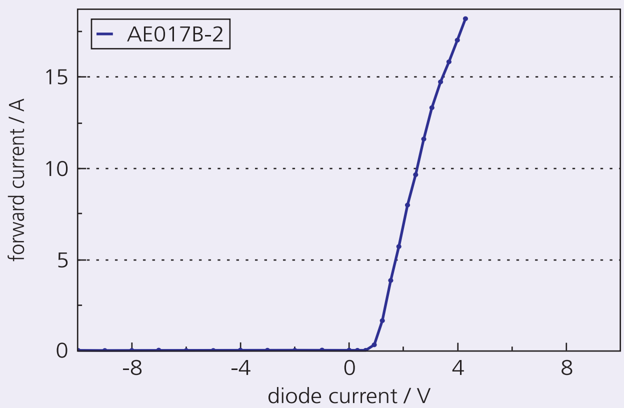
In highly doped diamonds, the activation energies are considerably lower. Furthermore, more charge carriers are released at higher operating temperatures (e. g. through heating). Simultaneously, diamond has a very large bandgap so that the material functions as a stable semiconductor at high temperatures. These considerations are taken into account in the design of electronic devices from diamond. Figure 4 shows another diamond Schottky diode with a contact surface of 1 mm x 2 mm.

Figure 5 is the associated current – voltage graph. The diode has a lightly doped region of 10 µm thickness with a dopant level of 5 x 10^{17} atoms cm^{-3}. The forward current reaches up to 18 A.

Current-voltage graph of a diamond Schottky diode (1 mm x 2 mm) with a forward current of 18 A



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The results demonstrate the fabrication of diamond Schottky diodes as well as first promising voltage and current data. Present work focuses on building diodes that combine the properties of high forward currents with high breakdown voltages in one and the same device.

2 *Diamond Schottky diodes with 150 µm diameter each*

4 *1 mm x 2 mm diamond Schottky diode being*

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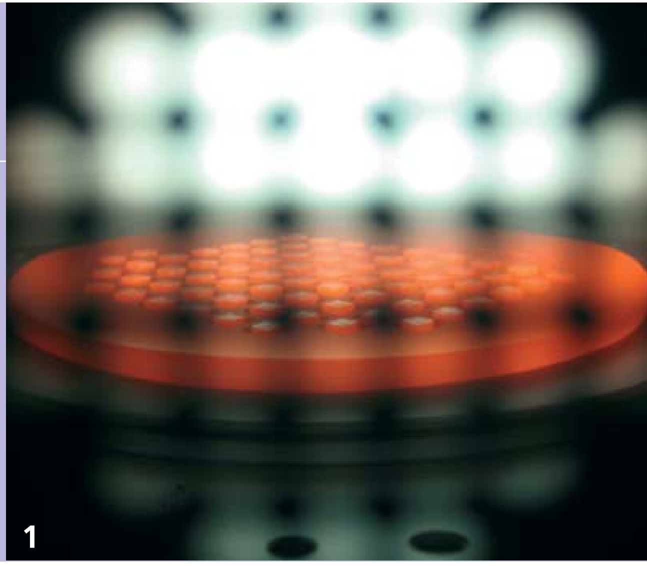
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SEPARATION OF SINGLE-CRYSTALLINE DIAMOND PLATES BY MEANS OF ION IMPLANTATION

THE TASK

Large single-crystalline diamond plates, SCD for short, (<40 µm to 500 µm thick) are of considerable interest for applications in optical and X-ray optical components, radiation detectors and electronic devices. Currently, high quality diamond plates are available up to only about 10 mm edge length, since they are cut and polished from grown diamond crystals. Diameters of at least 50 mm are in particular demand for the production of diamond wafers for the semiconductor industry.

Natural jewelry diamonds are traditionally cut with rotating copper blades. This is a comparably imprecise process and not suited for high-tech applications. Increasingly, laser cutting is being used with good results for smaller cut depths (<10 mm), but there are also disadvantages. For one, the laser cutting profile is V-shaped, which causes considerable material losses at large cut depths. For another, the laser cutting creates a defect zone of several tens of micrometers, which must be removed by polishing after the cutting.

With respect to future developments of diamond plates with significantly larger dimensions, current separation technology is insufficient. The task therefore lies in the development of processes that allow the separation of large surface plates of diamond crystals without much loss of material and with minimum defect zones.

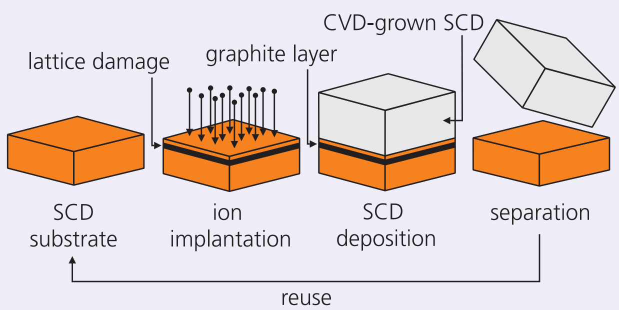
OUR SOLUTION

At the Fraunhofer Center for Coatings and Diamond Technologies CCD (see also p. 128), in close collaboration with Michigan State University and Western Michigan University, technologies are being developed that exploit ion implantation for the separation of diamond plates (Fig. 2).

The initial diamond substrate is first irradiated with highly energetic ions in order to produce a thin damage zone located a few micrometers underneath the crystal surface. This process is scalable to substrate sizes typical of the semiconductor industry. The crystal surface remains intact in the process, so that the following plasma CVD process can grow new diamond homoepitaxially.

Due to the high process temperature (900 °C) during CVD the damage zone inside the crystal graphitizes. After the growth process, the graphitized layer is removed through chemical etching in order to separate the newly grown diamond crystal from the substrate. The substrate is polished and used again for the next cycle.

Process schematic to separate diamond plates by means of ion implantation



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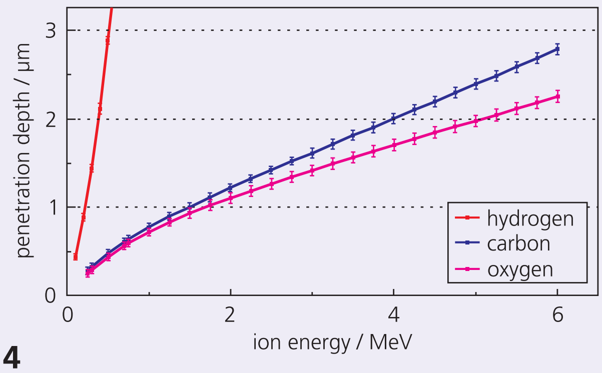
RESULTS

In preparation for the experiments, Monte Carlo simulations were carried out first, in order to find suitable ion energies. The energy must be sufficient to achieve a damage zone in the desired depth within the substrate crystal. The desired penetration depths are a few micrometers.

For the experiments, ion energies of 500 keV for protons, 3 MeV for carbon ions and 3.25 MeV for oxygen ions were chosen. The use of carbon ions has the advantage that no additional chemical elements are introduced into the diamond crystal. Oxygen ions, on the other hand, assist and accelerate the subsequent etching process. Protons have an essentially higher penetration depth in comparison to the heavier ions of comparable energy. This is of interest for further applications of the implantation technology.

Penetration depths of hydrogen, carbon and oxygen ions in diamond crystals as a function of the ion energy (SRIM Monte Carlo Simulations, Stopping Range of Ions in Matter)



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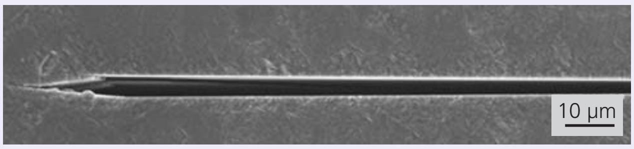
The ion implantation experiments were carried out with a 6 MeV Van de Graaff tandem accelerator at Western Michigan University. A special sample holder allows the stepwise irradiation of substrates with dimensions up to 75 mm x 75 mm (Fig. 3).

Immediately after the ion implantation process, the irradiated substrates appear dark. If the substrate remains dark after the CVD diamond growth, the experiment was successful and the damage zone could be removed. This happens, for example, through thermal oxidation at temperatures of 550 – 580 °C. In this temperature range, the graphitic carbon phase oxidizes to CO and CO_2 while the diamond phase does not oxidize. Figure 4 shows an SEM picture of the etched damage zone after the oxidation process. Figure 3 shows CVD diamonds of various shapes and sizes that are separated through the described process.

SEM image of a diamond substrate crystal. The dark horizontal line is the area of the damage zone, which was removed by chemical etching.



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1 Fabrication of 70 diamond crystals in plasma CVD process

3 CVD Diamonds of different sizes and shapes, separated by ion implantation and thermal oxidation

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LASER ABLATION AND CUTTING

Editor: Your business unit Ablation and Cutting has been reshaped at the beginning of the year. Can you provide some information about the background and the intentions?

Dr. Wetzig: The "old" business unit covered a large bandwidth of topics, which reached from the classic cutting of thick metal sheets with high power lasers to the development of microfluidic modules. Over the past 5 to 6 years the business unit grew by more than 50 percent. Though there were many common elements, it now made sense to split up the department and to introduce microtechnology as a business unit in its own right. Each of the two business units can now better focus on their strengths, which led to positive developments in 2015.

Editor: What other changes occurred?

Dr. Wetzig: I am very glad that the Process Design and Analysis group is now part of our business unit. For many years we have been working closely together in the fields of cutting of thick metal sheets and remote processing. Now we have the chance to offer an even broader spectrum to our customers, which includes the simulation of laser based processes and bridges over several business fields.

Editor: Where do you see future research foci in laser beam cutting?

Dr. Wetzig: It is well known that laser beam cutting is the most industrially relevant process among all laser materials processing technologies. We get approached with a number of interesting research questions concerning cutting and high speed processing with lasers. Frequent topics are quality improvements for classic laser cutting, systems for process monitoring and control, cutting of non-metals by laser and the further development of highly dynamic cutting processes.

"Today's insight may be the daughter of yesterday's error."
Marie von Ebner-Eschenbach

BUSINESS UNIT MANAGER
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Editor: At this year's Laser World of Photonics, you, together with your partners, presented highly dynamic MEMS mirrors. When will these systems be commercially available?

Dr. Wetzig: At this point these mirrors are still under development while initial tests are being performed. I cannot provide a precise date yet. Our industry partners are very much interested in using MEMS mirrors. In 2016 we will offer research and development projects to them.

Editor: What about the laser processing of magnetically soft materials?

Dr. Wetzig: This area is still very successful. One application is the treatment of grain-oriented electrical sheets, which are used in transformers. We implement new scientific and technical ideas to further increase the efficiency of transformers. Simultaneously we are in the process of acquiring new customers, also in Germany. Another application is the laser processing of magnetically soft materials that are not grain-oriented. These are needed to build motors and generators. Here the goal is also to increase the efficiency of electric machines. So far the technology development was primarily funded through public projects. In 2015 we acquired the first larger industry contract from a renowned major German company. The chances are good that this collaboration will continue.

COMPETENCES AND CONTACTS

Dr. Jan Hauptmann, division manager high-speed laser processing
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»Research foci are process and system technological developments for high speed applications. Profound process understanding forms the basis for the successful implementation of the different tasks in technology and system development for industrial applications. The offered processes and solutions are characterized by highest processing speeds. The portfolio includes technology development of remote processes for cutting, ablation, surface treatment and joining of metals and nonmetals as well as the designing, building and qualifying of highly dynamic processing systems.«

Dipl.-Ing. Peter Rauscher, group manager laser systems technology
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»The group's competence is the development of new, and improvement of existing, system technology with a focus on laser cutting, surface treatment and welding. Software and hardware components are being developed for applications that require fast beam scanning and shaping. A process development focus is the laser structuring of grain-oriented electrical sheets for highly efficient transformers.«

Dr. Jan Hauptmann, group manager laser cutting of nonmetals
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»The group focuses on classic polymer cutting and the laser processing of composite materials. Under development are remote cutting processes for fiber-polymer composites. The specialty of these processes is the simultaneous application of different laser wavelengths. Laser cutting process development also addresses other nonmetallic materials such as novel hybrid materials and high performance textiles.«

Dr. Patrick Herwig, group manager laser cutting
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»Research in the area of laser cutting focuses on obtaining a better understanding of the process and on process developments in the areas of laser melt and flame cutting. Topics include the improvement of the cutting quality with solid state lasers or the optimization of the laser beam cutting of electrical sheets without disturbing magnetic properties. Beyond this we qualify novel cutting processes such as the remote laser cutting and its integration into productions processes. To work on these topics, we have at the IWS all typical lasers with various wavelengths, powers and beam qualities, which can be combined with highly dynamic 2D and 3D cutting machines.«

Dr. Achim Mahrle, group manager process design and analysis
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»Based on the laws of thermodynamics and state equations we evaluate the principle energy balance of the studied laser material processing technologies. By comparing the real process and competing technologies we draw conclusions with respect to energy efficiency and obtainable process efficiencies. An additional focus is process analysis. The aim is to describe the functional dependencies between control variables, influencing factors, disturbance variables and target quantities of a given laser material treatment process. Numerical as well as experimental methods are being applied.«

2015 PROJECT EXAMPLES

BUSINESS UNIT
LASER ABLATION AND CUTTING

1

EFFICIENT PROCESSING OF FIBER REINFORCED POLYMER COMPOSITE MATERIALS

THE TASK

High performance materials based on fiber reinforced polymers (FRP) are currently finding many applications in industry. In addition to applications in aerospace and automotive industries, FRPs are increasingly being used in general mechanical engineering applications. The focus here is to develop functionally integrated components.

One of the largest challenges in the area of FRP is the improvement and optimization of the manufacturing process. The carbon fiber is highly abrasive, which causes extreme tool wear during milling as well as water jet cutting operations. There is also the mechanically damaging impact to consider that the tools have on the component, in particular when the tools or the used abrasives approach the end of service life. Based on this situation the laser as a contactless tool with a high automation potential appears to be an excellent choice to efficiently process FRP without tool wear.

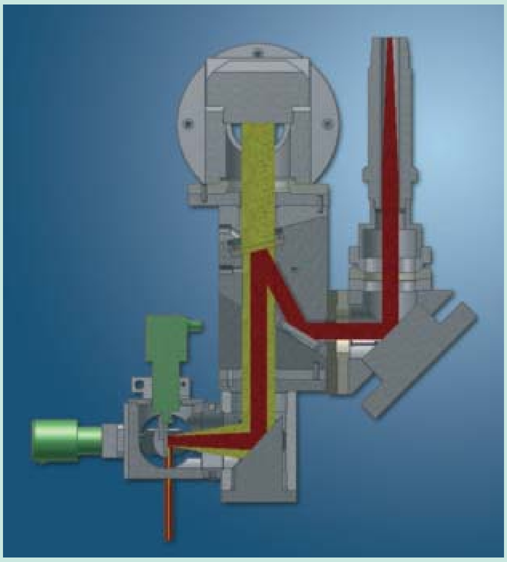
OUR SOLUTION

FRP usually consist of a fiber material embedded in a thermosetting- or thermoplastic matrix. Both base materials have vastly different thermal conductivities, evaporation temperatures and absorption properties. The differing properties of the individual material have to be considered during laser material processing in order to efficiently process the material with high quality results.

Remote laser cutting processes with continuously operating beam sources were already qualified for the treatment of FRP. The high speeds of the laser spot significantly reduce the interaction time between laser and material. This minimizes the influence of the thermal conductivity of the fiber component.

The Fraunhofer IWS joined forces with TU Dresden in a collaborative research program 639 and developed a laser beam combination module (Fig. 1 and Fig. 2). The module was developed so that the specific properties of the individual material in the FRC could be considered. The concept is to coaxially superimpose laser radiation from two beam sources with the emission wavelengths λ =10.6 µm and λ=1.07 µm. The process makes use of the optimal absorption of the CO_2 (10.6 µm) laser radiation by the polymer matrix to evaporate the same. Simultaneously the solid state laser (SSL, 1.05 µm) has good focusing capability to achieve intensities that sublimate the reinforcing fiber component. The laser power for each wavelength can be independently selected, which provides novel possibilities for parameter variations.

Principle of the coaxial beam superposition



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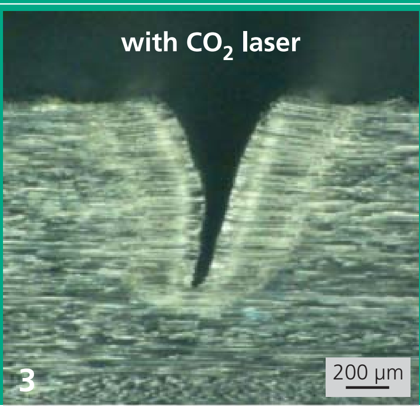
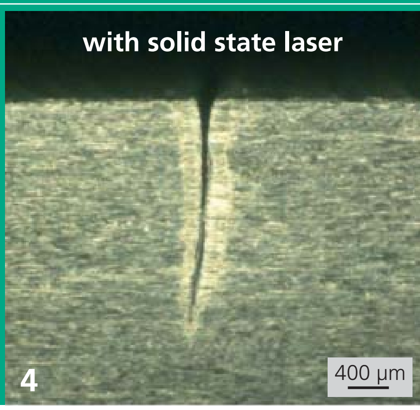
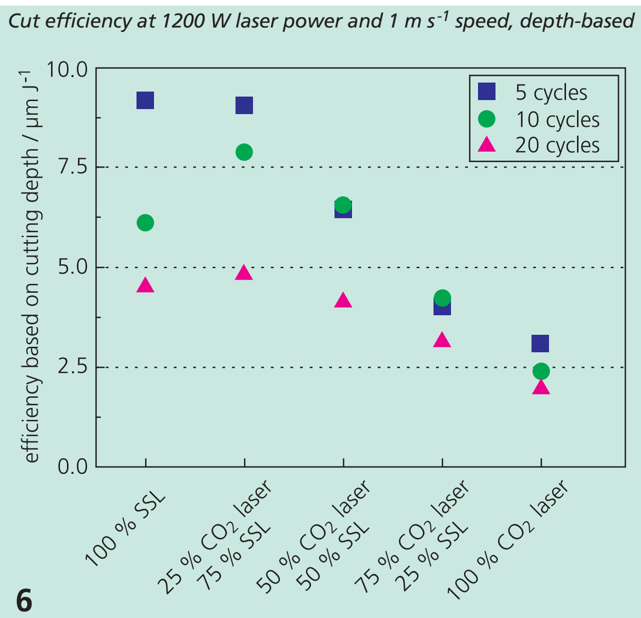




RESULTS

The radiation from the solid state laser can be focused very well, which yields a focal point diameter that is ten times smaller compared to the CO_2 laser radiation using the same optical setup. This translates to a smaller interaction zone and reduced interaction times between laser beam and material. The improved efficiency was demonstrated by cutting carbon fiber reinforced polymer with high modulus carbon fibers and a fiber volume content of 60 percent. The high intensity and short interaction time led to very high quality cuts compared to processing with CO_2 radiation only (Fig. 3 and Fig. 4).

The depth-specific cutting efficiency can be further improved by using synchronous laser radiation with about 25 percent of CO_2 laser radiation (Fig. 6). The cut widens due to the CO_2 laser radiation component, which increased the ablation of material.



The CO_2 radiation interacts with the matrix material and disintegrates the same thermally. Thus the local fiber volume fraction increases, which in turn leads to a higher absorption of solid state laser radiation within the interaction zone. It can also be assumed that the widening cut will reduce the interaction between solid state laser radiation and the sidewalls in the cut. This leads to a more straightened cut and to increased the cutting depths (Fig. 5 and Fig. 6).

The combination of solid state and CO_2 laser radiation expands the parameter field for processing FRP. The increased effort that is necessary on the system side is justified by the improved cutting results.

1 Laser beam combination module with scanner

3-5 Polished cross sections of cuts in FRP after remote cutting with CO_2 laser (3), solid state laser (4) and a combined laser radiation with 25 percent CO_2 fraction

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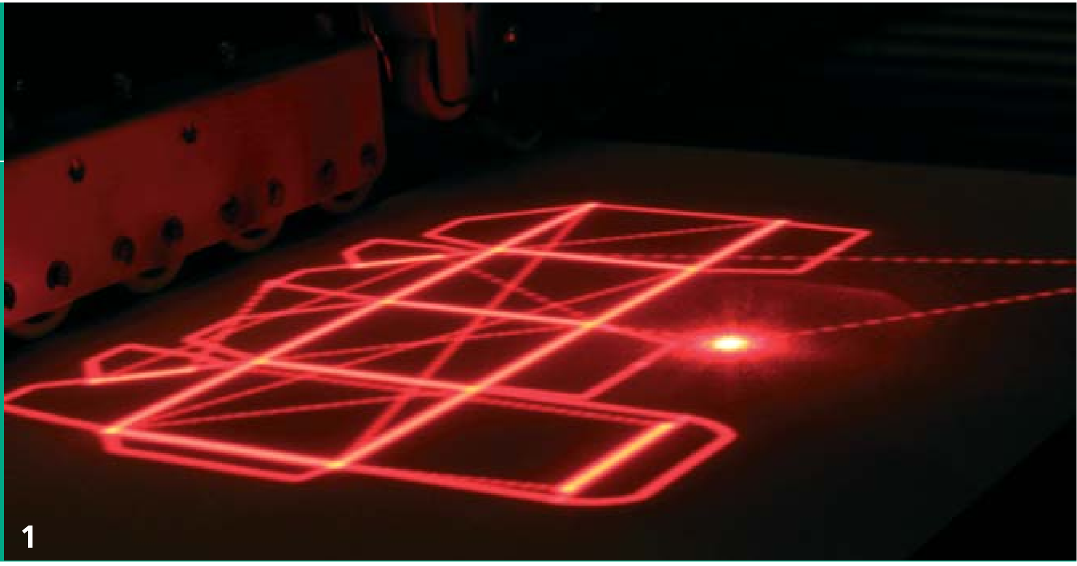

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MULTIFUNCTIONAL CONTROL PLATFORM FOR LASER REMOTE APPLICATIONS

THE TASK

Galvanometer scanners have outstanding dynamic properties. In the field of laser materials processing they are used for fast contour cutouts as well as high frequency beam shaping. The use of these beam positioning techniques increase the efficiency and flexibility of joining and cutting processes. This in turn leads to reduced manufacturing costs. If laser remote processes replace the conventional stamping, it is not necessary to build shape specific stamping tools. Substantial time is saved throughout the overall process from the drawing to the prototype, since the laser beam positioning can be freely programmed.

Highly dynamic galvanometer scanners also enable certain processes such as the welding of mixed material joints. This opens up new possibilities in laser materials processing since without scanners these materials could not be welded. A high frequency scanner based beam shaping optics with small oscillation amplitudes allows for the tailored adjustment of melt pool size and dynamics, which is used to optimize outgassing and solidification processes.

An essential component for this application is a powerful and application-specific control software. The requirements strongly vary, depending on customer and process. Thus the control software has to be flexible and scalable. The challenge lies in the integration of the scanners into a broad spectrum of control systems for various processes and solutions.

OUR SOLUTION

At the Fraunhofer IWS most modern object oriented software development tools and scalable software architectures were deployed to develop a software platform, which abstracts the control and process logic layers so that they are separated from the hardware components. The development of complex processing steps and process control regimes is thus possible, independent from hardware.

In industry many different systems from various manufacturers are used. This includes control systems, galvanometer scanners and even the cameras for image processing. To interact with such components, it is impossible to avoid the need for adaptation. However, by decoupling the hardware it is possible to limit the adaptation to the implementation of a few interfaces, which keeps costs and development times low while flexibility and quality improve due to the standardized approach and software modules. The method makes it possible to reuse, modify and expand previously developed laser remote applications for nearly any customer system with reasonable time and adaptation effort.

RESULTS

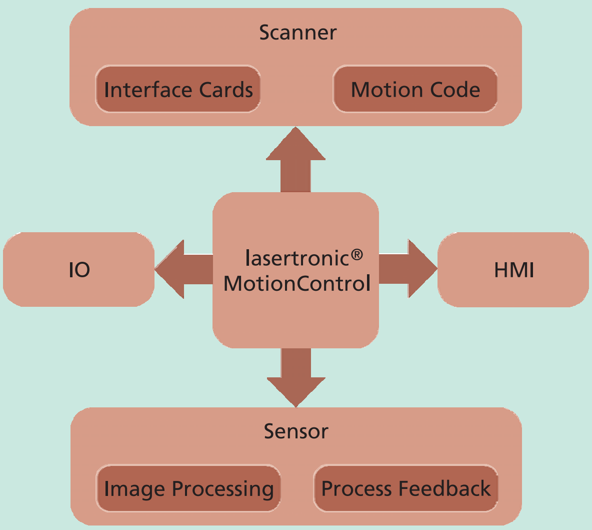
The IWS application platform "lasertronic®MotionControl" consist of 4 basic building blocks (Fig. 2). The "Scanner" module controls the scanner electronics via control boards from various manufacturers. The hardware is connected dynamically via plug-in, which makes the software completely independent from the specific product.

The scanning path is programmed and graphically visualized. Several command sets are already implemented such as the G-Code, which is common in the world of NC programming. Expansions are possible based on specific customer requirements.

The communication with peripheral components such as memory programmable controllers, is handled by the "IO" submodule. All common bus systems are supported as well as digital and analog inputs and outputs.

Another software is called "Sensor", which supports the connection to process sensors ("Process Feedback") and the control of cameras as well as the evaluation of the acquired camera images ("Image Processing"). The information can be used for path correction or for process verification.

Module overview of the platform "lasertronic®MotionControl"



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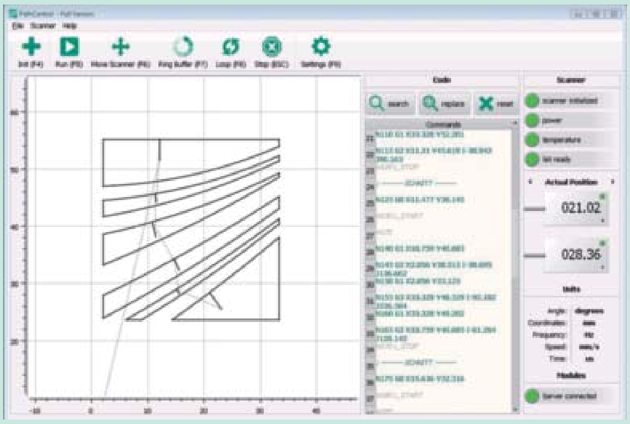
The "HMI" module offers editors for manipulating the command lists. It also has interactive graphics elements to visualize the cut patterns. Camera images can be integrated and the corresponding data from image processing can be displayed. The Fraunhofer IWS Dresden software "PathControl" was developed to realize laser remote applications. It implements functionalities to create, visualize and edit processing programs as well as their execution on the used galvanometer scanner (Fig. 3). The use of the software for various applications with many products from established manufacturers have demonstrated the multifunctional capability of this control platform and realized the strict and successful decoupling of hard- and software.

Software system for the implementation of laser remote applications



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1 Highly dynamic laser cutting and laser grooving of cardboard

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LASER BEAM FUSION CUTTING WITH DYNAMIC BEAM SHAPING

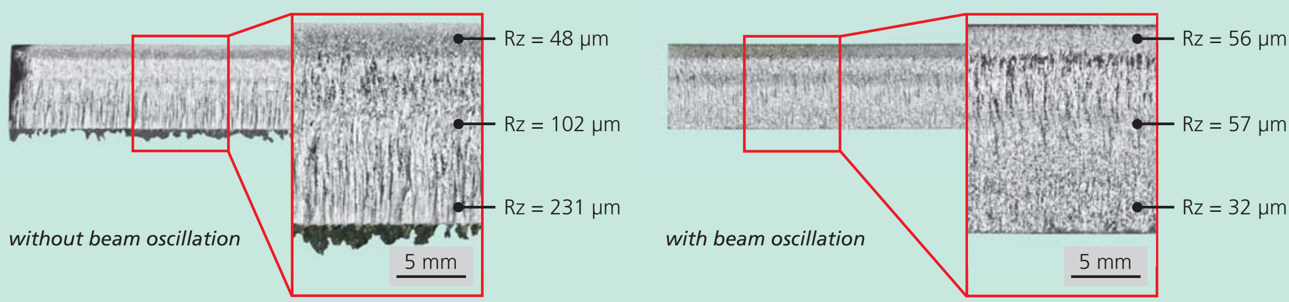
THE TASK

The decisive argument for purchasing a laser cutting machine is the optimal combination of good cut quality, maximum feed rate, low investment and operating costs. Fiber and disk lasers are the leading laser sources for the cutting of thin metal sheets. They offer high cutting speeds and the possibility to use optical fibers. The need for optimization emerges for sheet thicknesses exceeding 4 mm. Compared to CO_2 lasers, the solid state lasers cause an increase in surface roughness and burr formation. In particular, the issue of burr formation has to be addressed by process optimization in order to consolidate and expand the leading position of the solid state lasers as universal laser beam source for the cutting market. One approach to optimize the process is to exploit the incident angle dependence of the absorption on the melt front. It is possible to modify the beam geometry and the intensity distribution to adjust the absorption conditions. Previous approaches worked with static beam shaping for specific applications and were based on adjusting the intensity profile by scaling the laser beam. The aims were to improve process efficiency and/or cut quality. Extensive parameter studies, however, showed only minor improvements compared to standard cutting machines.

OUR SOLUTION

A new approach to influence the cutting process for thick metal plates is based on dynamic beam shaping. The basic idea is to modify the spatial and temporal energy deposition so that the advantages of high focal intensities remain while the absorption increases. For this purpose, a standard cutting head is combined with a high performance scanner system (Fig. 1). The Fraunhofer IWS Dresden developed a special controller solution, which allows for the programming of freely definable functions of the scanner system in the kilohertz range. Numerous degrees of freedom modulate the oscillation of the laser beam (Fig. 3) and add possibilities to the conventional cutting parameters such as laser power, feed rate, focal plane, and gas pressures.

Cut edge of steel X5CrNi18-10, sheet thickness of 12 mm, cut with a 3 kW fiber laser



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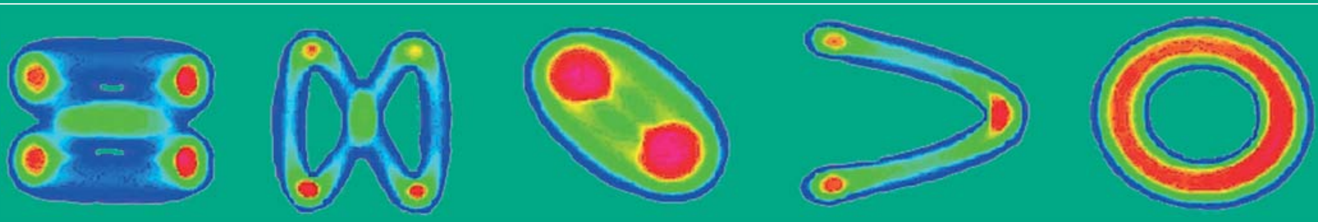

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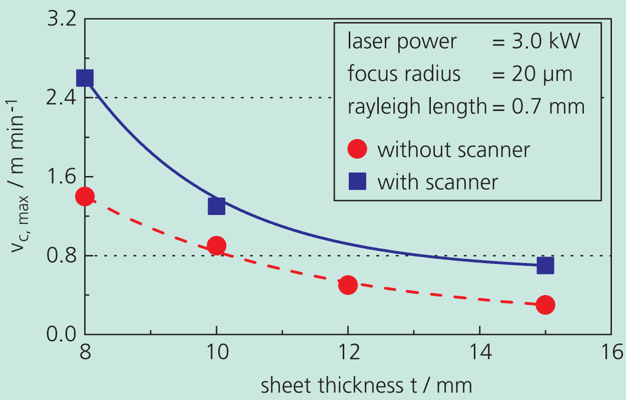
RESULTS

The use of the dynamic beam shaping features clearly improves the cutting performance. Important targets are the achievable cutting speed, the cut kerf geometry and the quality criteria including the surface roughness of the cut edge and the burr formation. Parameter studies with commonly available 3 kW laser sources demonstrate a significant reduction of the burr (Fig. 2) and a changed striation structure. A comparison of the conventionally static and the dynamical beam oscillation with equivalent laser power, exhibits a homogenization of the surface roughness across the entire cut edge as well as a reduction of the absolute roughness depth. Similar results as described for the dynamic beam shaping are only possible with conventional cutting machines if the laser power is significantly increased. In addition to the improved quality and depending on the optical setup it is also possible to increase the cutting speed (Fig. 4) and/or to influence the cut kerf geometry (Fig. 5) with enhanced parallelism of the cut edges. Scanner assisted laser processes achieve good performances for thin as well as thick metal sheet cutting with a single focal length. So far, this was not possible for standard cutting machines without physical adaptation of the focal length. The challenge of the dynamic beam shaping process is the determination of optimized scanner parameters for each application. Available process sensors reduce the analytical effort to adjust the cutting results for customer specific tasks.

Comparison of the cutting speeds during laser beam fusion cutting with and without dynamic beam shaping



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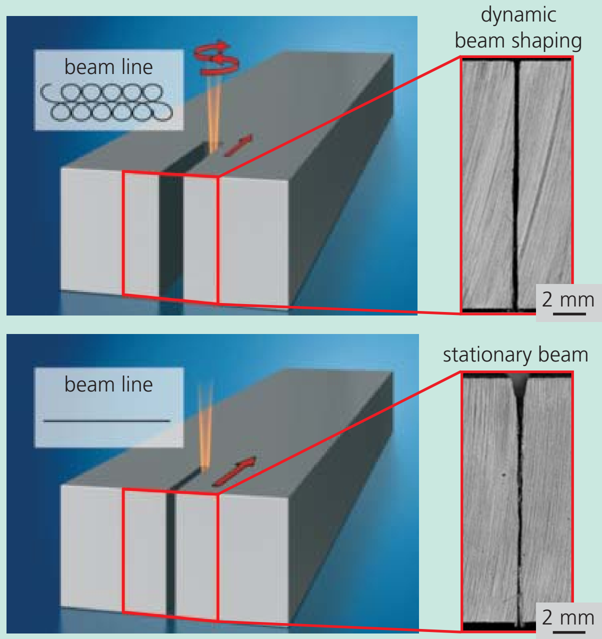
Cut geometry as a function of the oscillation function



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1 *Cutting head with scanner system*

3 *Beam measurement of various oscillation functions*

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FLUIDIC OPTIMIZATION OF PROCESSES AND SYSTEMS

THE TASK

Gases are used for many tasks in laser materials processing. Shielding gases protect the processing zone from the surrounding atmosphere. Process gases support the technical realization of many processes, such as the blow-out of molten material during laser beam cutting. Often they are used as secondary gases to protect processing optics or to purify the air in the process cabin. The latter aspect is important from a standpoint of health issues but also to maintain process stability and quality.

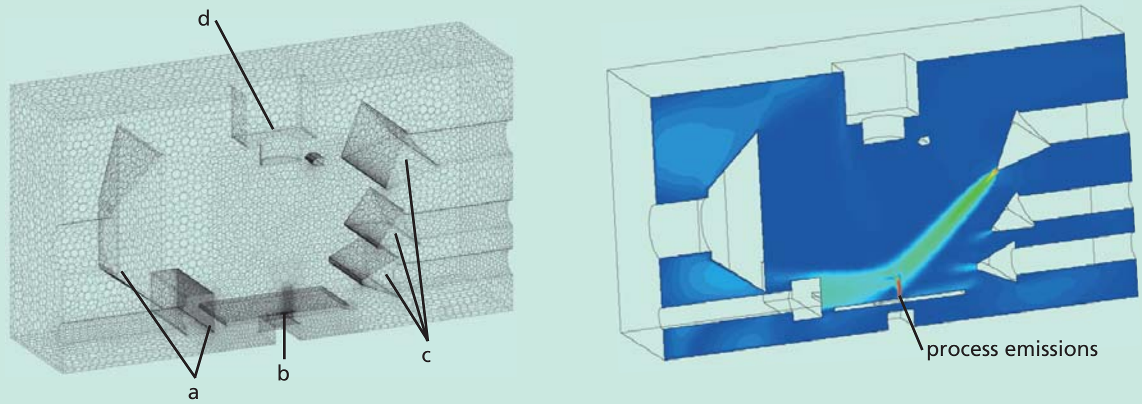
All these applications have in common the need to optimize gas flows depending on the particular circumstances. In addition to the desired functionality the gas consumption is an important cost consideration and of high interest. The technical dimensioning of machining stations and the analysis and optimization of the resulting gas flows are often difficult due to their complexity. The possibilities to visualize them are limited and it is often difficult to measure directly in the process zone. Alternative solutions are sought.

OUR SOLUTION

One possibility is the simulation of the flow conditions with problem adapted numerical models and powerful commercial CFD software. The state behavior of gases is sufficiently known. Thus the simulation predicts quite accurately the flow conditions and one expects good agreement with experimental data.

Figure 1 shows an example of a CFD model of a demonstrator processing station for remote laser welding. This model is used at the Fraunhofer IWS Dresden to study the effect of various ventilation components on the propagation and distribution of the process emissions. The simulation process can be automatically controlled and allows for the parametric setting of geometries and CFG meshing routines. This is useful for the design-of-experiment approaches that extensively analyze dependencies and study the effect of parameters.

Model of a remote laser processing station with a CFD mesh adapted to the problem: (a) exhaust air components, (b) process zone, (c) air supply components, (d) remote laser processing head



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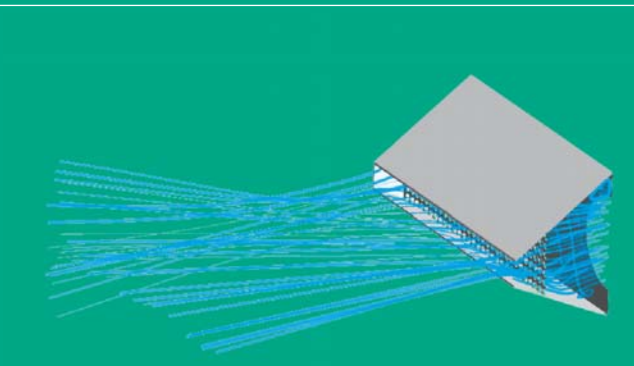

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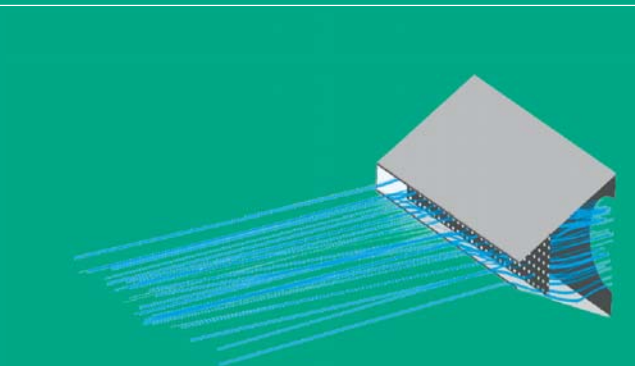

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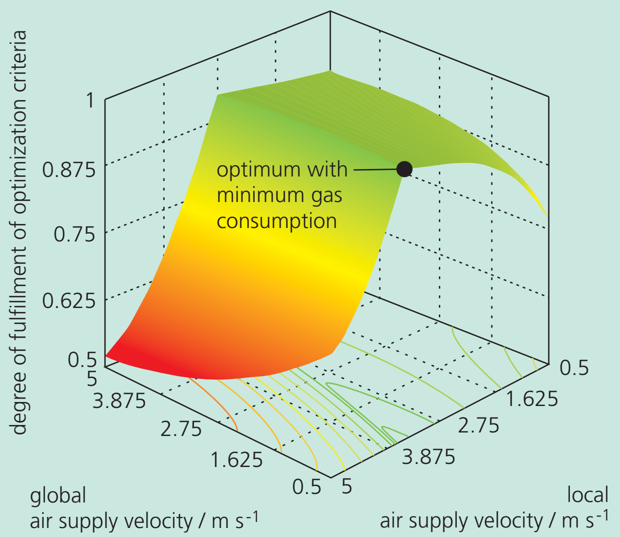
RESULTS

The process gases are modeled using a multi component model. The supplied air is modeled matching the surrounding conditions (atmospheric pressure, room temperature). The process emissions are considered as an iron vapor at evaporation temperature that is introduced to the calculation region. Figure 1 shows an application considering the species transport through the process cabin as well as the heat transfer processes. What is not modelled are phase transitions, particle formation and chemical reactions. The target response is the spatial expansion of the process emissions within the laser beam, which helps to qualitatively judge the effect of different parameter constellations (Fig. 1, right).

Optimization of process criteria as a function of the flow velocity of supply air components



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Of special importance for the accuracy of the prediction of such global air flows is the detailed analysis of the used components (Fig. 2). The results serve both to optimize the individual components and to provide input data for the cabin simulation. The presented model was used to perform extensive statistically designed simulation experiments.

In the first phase numerous geometric and fluid-dynamical factors were studied with respect to their influence on the system behavior and the main factors were identified. The second phase focused on the statistically significant formulation of the system behavior with a complex nonlinear regression model. This model was used to optimize the process parameters (Fig. 3). Assuming an acceptable expansion of the process emissions, the model showed clear potential to reduce the gas consumption compared to existing machine concepts.

2 Supply air nozzle with integrated perforated plate (a) 8 mm, (b) 4 mm

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1

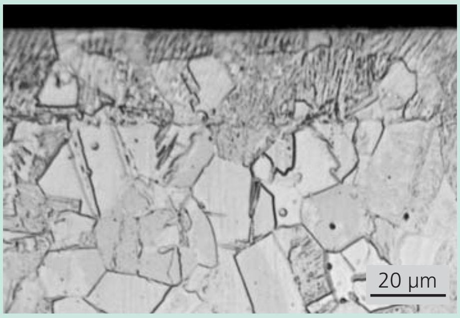
INFLUENCE OF THE LASER BEAM CUTTING ON FATIGUE STRENGTH

THE TASK

The laser beam cutting is a highly efficient process, which is based on efficient use of materials, cutting speeds, the flexibility and the minimal material deformations in the cutting region. However, with increasing metal sheet thickness a significant relief forms on the cut surfaces. The heat deposition into the material also causes microstructural changes in surface-near regions (Fig. 2). If the cutting parameters are not optimized, a part of the melt is not ejected by the shielding gas and solidifies to form macroscopic burrs.

These issues limit the use of the process to components, which are subjected to static and/or cyclic load conditions and have to fulfill safety relevant functions. The micro- and macroscopic grooves and burrs on the sidewalls of the cut cause local stress peaks and affect the classic fatigue resistance as much as the original state of the material. Currently there are no experimental data which allow for a reliable prediction as to what influence the surface relief and burr formation has on the cyclic strength of the material. Research work at the Fraunhofer IWS Dresden tries to address this gap.

Heat affected zone at the cutting edge



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OUR SOLUTION

The influence of the laser cutting process on the fatigue behavior of sheet metal was studied with sheets of various cut qualities made from the metastable austenitic stainless steel material 1.4301. Laser beam cutting is a cost- and time efficient process to machine this material. The geometric and metallurgical changes at the cutting edges are affected by the formation of high melting point oxide phases on the surfaces. These properties of the oxide phases depend on the particular composition of the steel alloy. To improve the fatigue behavior by process optimization requires to understand the interdependencies between geometric non-uniformities (burr formation), hardness gradient (due to heat deposition and microstructural transformations) and the effects of the surface quality.

A particular challenge for understanding the fatigue behavior of laser cut samples lies in the comparatively large scatter of the experimental data. This can be related mostly to the irregularly roughened surface structure of the cutting edges. At the Fraunhofer IWS this problem is addressed by analyzing a sufficiently large number of samples. However, this is only possible if one has high frequency fatigue test stands such as those available at the IWS.

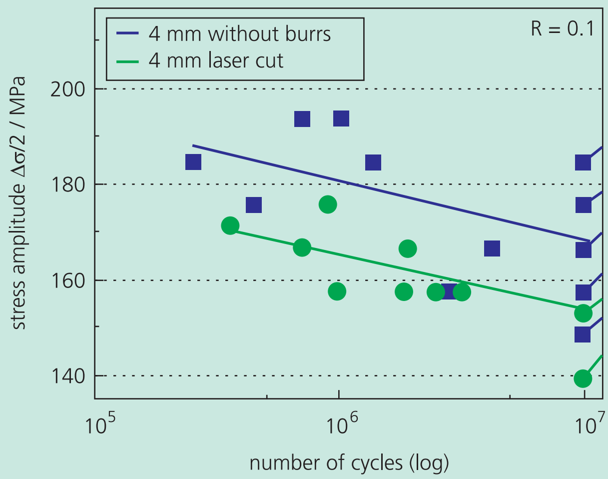
3

RESULTS

The surface roughness of the cutting edge changes with the metal sheet thickness. This directly translates to a different fatigue behavior. The fatigue test experiments were performed under cyclic tension-tension stresses. Here the fractured surfaces usually allow for an unambiguous conclusion about the causes of the crack initiating features. Laser cut metal sheets of 2 to 6 mm thickness showed a fatigue strength in the range from 154 to 166 MPa for a load cycle limit of N =10^7 at 50 percent failure probability. The cracks generally initiated from the burrs (Fig. 5), their geometry often resembles a technical crack right from the beginning.

To simulate a process optimization, an additional experiment was performed, in which the burr was removed after cutting a 4 mm sheet. Now the remaining factors that could influence the fatigue behavior were the surface relief and the heat affected zone. This step led to an increased fatigue strength by 10 percent (Fig. 4).

Fatigue strength of laser cut fatigue test specimen from 1.4301 material with and without burrs



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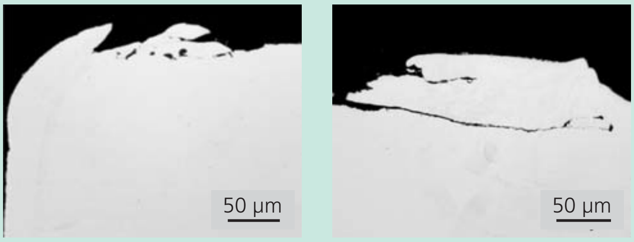
A novel Suisse high frequency fatigue tester was used for the first time to obtain the here presented data for the fatigue strength of 1.4301 steel sheets representing the properties of laser cut sheet edges. This machine is a resonance pulsator, the so called Gigaforte, which can test with frequencies of about 1000 Hertz.

Burrs at the cutting edge



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This test stand concept is not yet commercially available, but it allows for a significant reduction in testing time due to the high testing frequency. Up to 100 million load cycles can be reached within 1 to 2 days. So far such reduced experiment times were only possible with ultrasonic fatigue testing (also available at IWS), which is limited to certain sample shapes.

1 Laser melt cutting

3 1000 Hz resonance pulsator test stand

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ADDITIVE MANUFACTURING AND PRINTING

Editor: Prof. Leyens, additive manufacturing methods are trailblazing toward industrial manufacturing. Where do you see particular challenges?

Prof. Leyens: During additive manufacturing the workpiece and the material it is made from are created simultaneously. In earlier years the purpose of "rapid prototyping" was to create geometric models. The introduction of additive manufacturing into industrial production means that the fabricated parts are fully functional. This poses special requirements to the manufacturing process and process control. It also requires profound knowledge of the possibilities to influence materials and component properties with the generative fabrication process. Currently, throughout the world, there are only few examples that have demonstrated the complete knowledge of the additive process chain which led to products of highest quality. At IWS, in collaboration with partners from science and industry, we are working on product solutions for highly complex parts, which can demonstrate performance suitable for industrial use.

Editor: Recently you have launched the Center for Additive Manufacturing. What will be the purpose of this center?

Prof. Leyens: There is an almost unmanageable variety of additive manufacturing methods. Some of them are exclusive to special applications, others are useful for several applications. In addition, there is the entire palette of structural and functional materials in the form of plastics, metals and ceramics, which may be suitable for a potential application. The Center for Additive Manufacturing Dresden collaborates closely with the Technische Universität Dresden within the DRESEDN concept initiative. We offer clients our expertise in process and materials to develop the best possible product solutions. This way our

"It ist not enough that technology works well it also has to fit perfectly into the world."

Gero von Randow

BUSINESS UNIT MANAGER

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customers and partners have access to the latest research equipment. Components can be manufactured, characterized and tested; including, for example, using non-destructive computer tomography.

Editor: What progress have you been able to make in the field of printing functional materials?

Prof. Leyens: Just recently we have managed to use a dispenser printing method to print an entire thermoelectric generator on a flexible carrier foil. The generator produces an electrical voltage already at small temperature gradients. This voltage is sufficient to supply sensors with electrical energy. These sensors can be mounted to components in machinery and thus form the basis of a sensor network to improve the communication between the individual machine components. This is an important contribution to Industry 4.0.

Editor: Such a network will generate huge amounts of data. How will this problem be solved?

Prof. Leyens: The real-time analysis of large amounts of data, comparing them with existing databases and saving them in a form allowing for fast access is a major challenge for our research activities in the field of "Big Data". Currently we are learning from other specialist disciplines, for example, medical research. They also deal with enormous amounts of data obtained from complex medical diagnostics methods. The methods used in medicine are being further developed and adapted to technical processes. Here we contribute to the improvement of patient care and open new doors for data processing and management in technical areas.

COMPETENCES AND CONTACTS

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»New, integrated 2D and 3D printing solutions are realized by combining printing technologies. To offer one stop solutions, the group develops materials, printing processes and post-treatment processes such as sintering methods. A focus is on functional printing, which integrates and expands the functionalities of the printed product beyond just creating its shape. It is, for example, possible to integrate electrical conduction paths into 3D bodies during the printing process. One area of research addresses the printing of thermoelectric materials in form of pasts and inks. This enables the industrial use of printing technology to produce thermoelectric generators. The goal is to create flexible thermoelectric generators for use in sensorics, such as "Structural Health Monitoring" and other low power applications in the mW to W power range.«

Prof. Karol Kozak, group manager image processing and data management
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»"Big Data" means amounts of data (image or alphanumerical data), which are too huge or complex or which may quickly change, so that they cannot be analyzed with classic data processing methods. Classic visual image processing software, relational databases as well as statistics and visualization software are often incapable to process such large amounts of data. Thus Big Data handling requires new platforms, data storage and machine learning methods which can run in parallel on up to hundreds or thousands of processors or servers. Companies hope that the analysis of Big Data will open possibilities to obtain competitive advantages, to find cost savings and to create new business fields.«

Dr. Frank Brückner, group manager additive manufacturing
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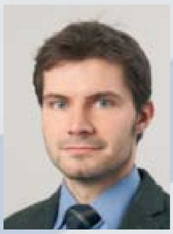


»The group Additive Manufacturing develops generative fabrication technologies for the flexible and efficient fabrication of individualized products which are based on functional components and structures made from modern metallic and nonmetallic construction materials. The processes serve for repair tasks as well as the creation of new parts, which often have to meet complex performance criteria. The unique selling point is a fabrication approach that spans broad ranges of scale and materials. Thus customers from a diverse portfolio of industry branches can benefit from tailored solutions.«

2015 PROJECT EXAMPLES

BUSINESS UNIT
ADDITIVE MANUFACTURING AND PRINTING

1

GENERATION OF POROUS STRUCTURES WITH LASER POWDER BUILDUP WELDING

THE TASK

The aerospace, energy, medical device and automotive industry sectors all have an enormous innovation potential from lightweight and load-adapted components, which are designed to exactly meet the requirements of their application.

Manufacturing such structures with conventional methods often requires substantial efforts or is not even possible. Generative processes promise an enormous freedom of design. Additive manufacturing methods can build up complex freeform bodies by sequentially depositing the material. Examples of such methods are the generative laser powder buildup welding and laser beam welding in powder beds.

A lightweight materials example from nature is the bone in the (human) body. Bones have a branched internal structure with open and closed cavities that are enveloped by a dense bone skin.

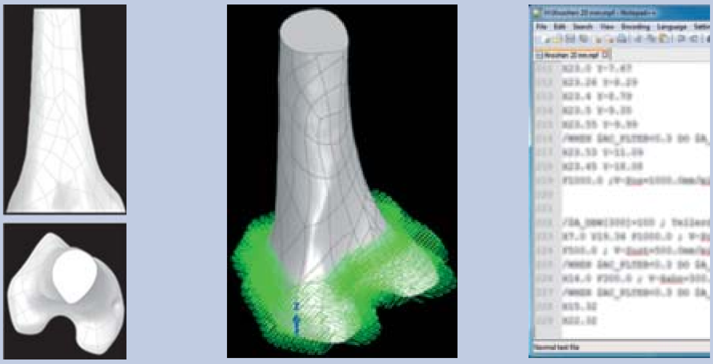
This design principle has great potential for numerous technical applications if it is possible to build separated cavities free of powder. Additive manufacturing is an advantageous method for this task as it creates near-net-shape structures without using more material than needed.

OUR SOLUTION

Bonelike structures are fabricated at the Fraunhofer IWS Dresden using laser powder buildup welding technology with coaxial powder nozzles (Fig. 1). A cavity-forming agent is added in-situ to the raw powder material to froth it up. The delivery and mixing of metal powder and cavity-forming agent occurs via two separated and completely automated delivery channels. The composition of both components can be continuously adjusted, which allows for the local variation of the cavity density and thus the adaptation of the structure to match the needs of the designated application.

The cavities are directly produced during the fabrication of the part. A fast solidification is typical for the laser powder buildup welding process, which prevents the process gas from escaping. Thus closed cell structures can be produced.

Planning of the buildup strategy and obtaining the NC code



CAD data | slicing of the data file | NC program

2

3

4

RESULTS

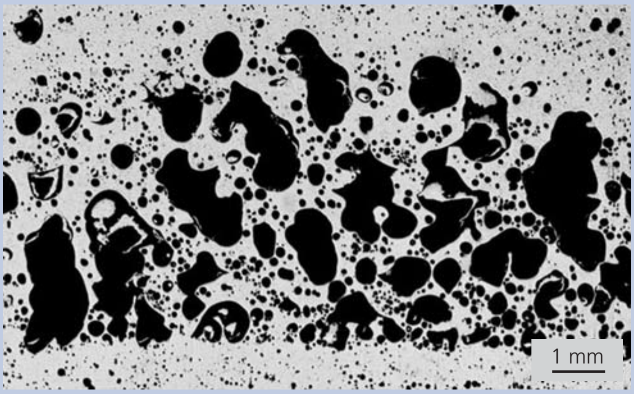
The generative fabrication approach builds up the component layer by layer. This makes it possible to build inner structures with powders. So far we were able to produce cavity-to-material ratios of about 1:1.

But the process is capable of much more than just simply producing porous materials. It is possible to spatially alternate between porous and dense structures, to create density gradients and, thereby, to vary local mechanical properties.

The systems are very much automated so that such alternating density and cavity structures can be readily adapted to the requirements of different applications (Fig. 4). This way it is possible to create steep as well as gradient density transitions (Fig. 5).

This technique adds design possibilities to typical hybrid processes, which combine generating and finishing steps. This in turn leads to new applications of the technology. Lightweight manufacturing is one application area, but new functionalities can be developed such as hidden breaking points or regions with large surface areas to enhance biocompatibility for example.

Polished cross section of a solid body with local variation of the pore density



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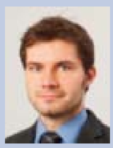
1 *Process picture of generating the bone structure*

3 *Bone section generated with laser powder buildup welding process*

4 *Cut of a bone section with porous inner structure and dense skin*

CONTACT



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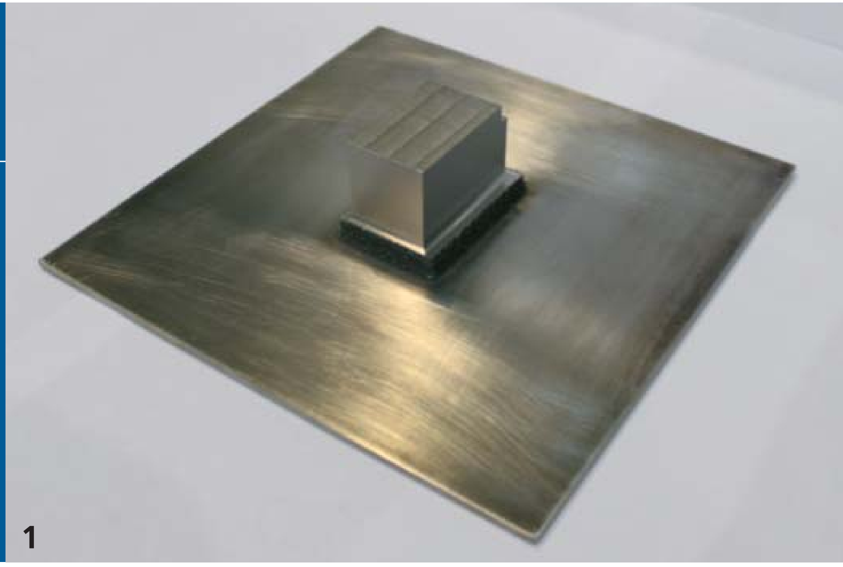


1

GENERATION OF SOLID BODIES ON THIN-WALLED PARTS

THE TASK

The automotive, energy and aerospace industries have similar requirements with respect to reducing the required resources to process hard-to-machine high performance materials while simultaneously performing such processes at lesser costs. Alternatives are explored by moving away from pure subtractive processes. Hybrid processes such as the combination of additive generative laser processing with milling offer the potential to substantially improve material utilization.

A special requirement is the deposition of large volumes of material on thin-walled parts. A key requirement is the control of thermally introduced stresses. These lead to warpage of low stiffness structures that are not fitted with any special countermeasures. To avoid this issue many industrial parts are machined from bulk material. If the material is hard to machine this approach quickly leads to the need for time consuming, technologically challenging and expensive efforts.

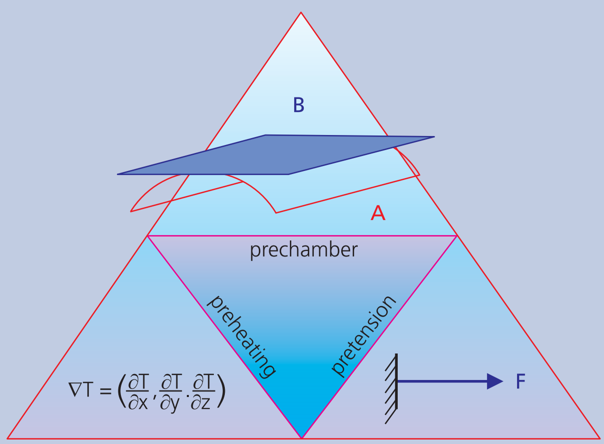
Of special interest are thin-walled structural components, which often have local thickness variations for increased stiffness requirements due to assembly reasons. Depending on the shape of these transition regions or their maximum thickness, these parts may require substantial machining efforts. Machining exerts mechanical forces which may have to be considered during part design, especially for very thin-walled cross sections.

Addressing these challenges involves the development of special processing strategies, which allow for the generative buildup of large material volumes on thin-walled parts with minimum change of the part's shape.

OUR SOLUTION

Laser powder buildup welding is an additive process that, under special processing conditions, is capable of depositing material directly onto thin-walled components. This can be achieved if the part is thermally precambered in combination with precisely aligned laser energy deposition and precamber temperature as well as suppression of any plastic deformation due to the pretension (Fig. 2). This approach enables the buildup of large material volumes at low structural stiffness.

Interaction between thermal and mechanical impact factors



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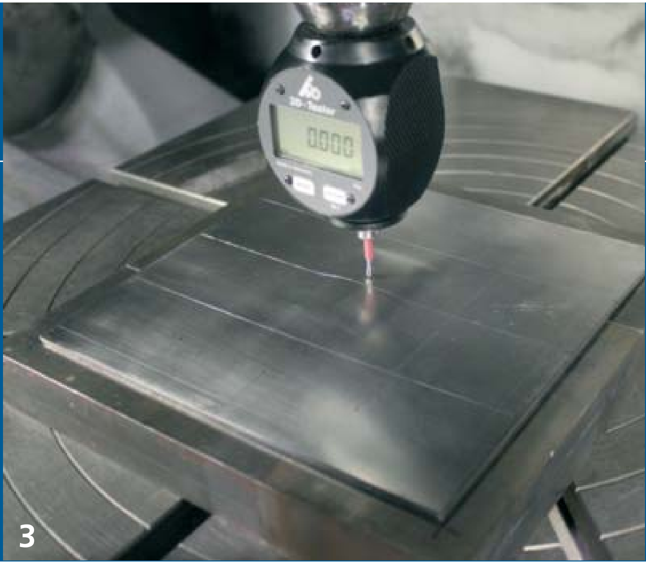

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RESULTS

A solid cuboid with a height exceeding 40 mm was generatively fabricated on top of a 2.4 mm thick substrate using a laser powder buildup welding process. The thickness ratio of the deposited shape to the substrate was about 1:17 (Fig. 1). The lateral dimensions of the part were 200 mm for the quadratic substrate and 60 or 40 mm for the deposited volume. The material was a high temperature stable nickel base alloy.

The tailored process minimized the changes to the original shape to less than 2 mm (Fig. 4). Outside of the area of material deposit the shape change remained below 0.56 mm.

Changes of the substrate geometry compared to original shape

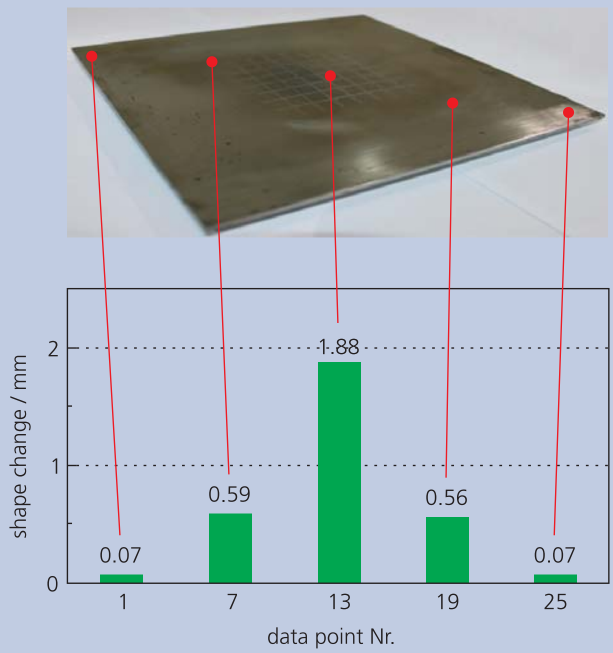

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Figure 3 shows the measurement setup to detect local shape changes as it was used during the process to perform tactile measurements.

This method substantially reduces the traditionally required milling effort, which is in particular true for difficult to machine materials. It is also possible to build complex shapes while enormously reducing the required material. This promises economic advantages, especially when costly materials are required.

1 Volume deposition on thin-walled substrate (isometric)

3 Tactile measurement of shape changes

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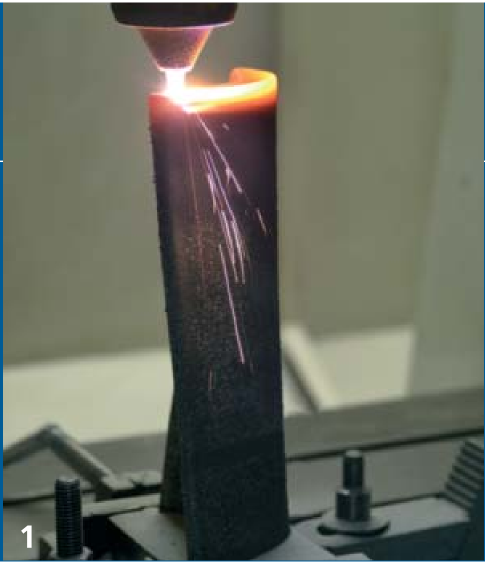
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2

ADDITIVE MANUFACTURING OF LARGE-SIZED SOLID BODIES

THE TASK

Today we have flexible and efficient additive manufacturing technologies that use modern metallic and nonmetallic construction materials to build functional components and structures. The unique selling point is a fabrication approach that spans broad ranges of scale and materials. Thus customers from a diverse portfolio of industry branches can benefit from tailored solutions.

In principle one distinguishes between processes that have a continuous material delivery and those that use a powder bed. Powder bed processes can fabricate parts of virtually any three-dimensional shape. Even parts with undercuts are possible, which cannot be produced using conventional machining and casting manufacturing methods. Thus, the process offers much freedom of part design, the possibility for functional optimization and integration. However, the process limitations of powder bed processes include limited part dimensions and comparatively low processing speeds.

The Fraunhofer USA Center for Laser Applications (CLA) developed an additive manufacturing technology, which is capable to build much larger parts at significantly increased processing speeds.

OUR SOLUTION

CLA's approach relies on the laser powder buildup welding process with continuous powder delivery. Robots and CNC machines are used in combination with various lasers as well as the powder delivery nozzles that were developed at the Fraunhofer IWS Dresden. Robots and CNC machines allow for the fabrication of parts as large as 2 m x 4 m x 2 m.

Laser based additive manufacturing of a demonstration part for the aerospace industry


3

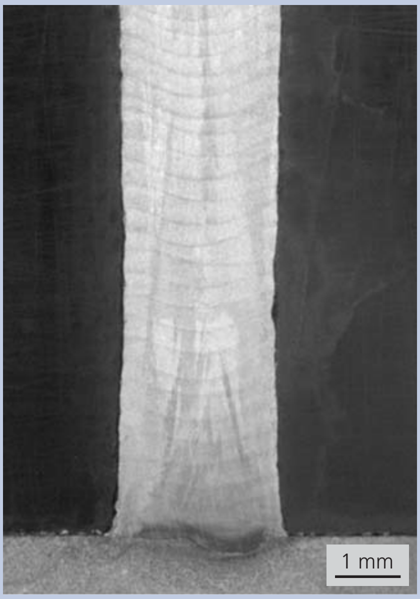
4

RESULTS

Large-sized aerospace application demonstrators were produced using laser systems and the IWS powder nozzles COAX8 and COAX9 (Fig. 1 and Fig. 3). It is also possible to build turbine blades with hollow structure and components of rocket engines.

The rocket nozzle demonstrator in Figure 3 was made from Inconel 625 powder using a 6 kW laser and a robot system. The tool paths were programmed offline using a CAD-CAM software. A typical cross section of a laser generated demonstrator is shown in Figure 5.

Cross section of a laser generated rocket nozzle made from Inconel 625



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CAD-CAM software was used to develop and evaluate various buildup strategies for test parts using powder coating technology. This way deposition rates were achieved of up to 2 kg per hour.

A 6 axes robot system with tilt and turn table and the IWS powder nozzle COAX8 were used to produce an extrusion cylinder made from stainless steel 316L. To do this, a screw thread was deposited onto a standard steel tube (Fig. 2). The part is longer than 1120 mm and has a diameter of 255 mm. The production time was 18 hours.

Fraunhofer CLA is also testing the new Fraunhofer IWS wire head COAXwire for multidirectional buildup of wire material (Fig. 4). The focus of this work is the manufacturing of high-quality titanium components for the aerospace industry.

1 *Laser based additive manufacturing of gas turbine blade*

2 *Laser based additive manufacturing of an extruder screw from stainless steel*

4 *Additive manufacturing with the IWS wire head COAXwire*

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1

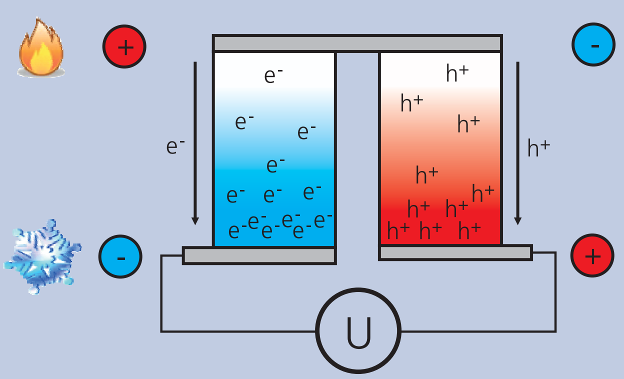
THERMOELECTRIC MODULE OF FLEXIBLE GEOMETRY

THE TASK

The challenge of providing reliable energy to sensor networks will become more important in the future. The digitalization and miniaturization of sensor networks to monitor the condition of components and machinery in combination with the “Internet of Things” and mobile applications lead to an increased demand for autarkic electronics and the associated need for energy supplies.

Energy-autarkic sensor platforms with wireless communication units require operating voltages of only a few 100 mV. This voltage range is suitable for thermoelectric generators, which can contribute substantially to building reliable, durable and autarkic energy supplies. However, for this to happen, the thermoelectric elements need to be cost-effective, efficient and mass producible. Thermoelectrics is based on the Seebeck effect. A temperature gradient within a thermoelectric material leads to diffusion of charge carriers, which results in a usable voltage. The heat flow from warm to cold regions is converted directly into electrical energy.

Schematics of a thermoelectric generator



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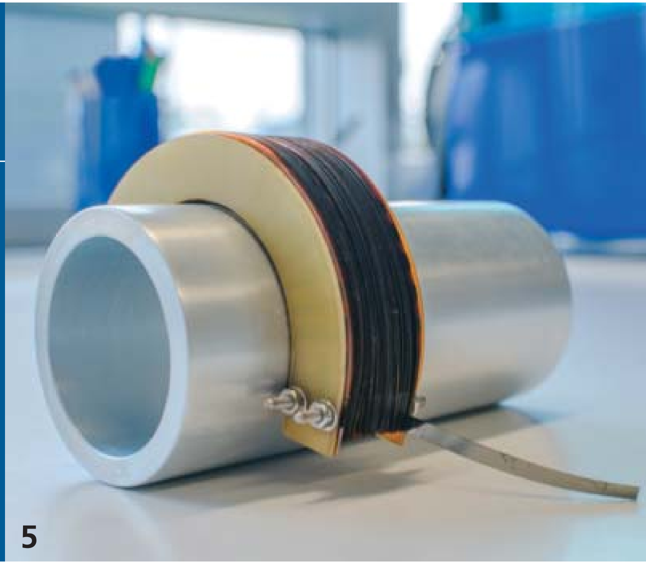
Currently thermoelectric modules are fabricated semi-manually. Compared to automated production the process yield is low. Conventional elements use materials (e. g., bismuth, telluride and germanium), which are often toxic, rare or expensive. A conventional element is also rigid and geometrically inflexible. Thermal stresses between the materials limit the maximum size of the elements. The development of flexible thermoelectric modules, which can be manufactured with a high degree of automation would be desirable.

OUR SOLUTION

With dispenser printing it is possible to efficiently produce thermoelectric modules at low costs. The maskless process can be highly automated at high production throughput and offers great flexibility with respect to geometric parameter variations. Dispenser printing works for different materials in paste form (metals, polymers, composites). The pastelike material is squeezed with defined quantity through a fine capillary and deposits onto the two- or three-dimensional substrate.

The process advantages become especially obvious when producing individual thermoelectric modules that fit a given contour. The substrate is first printed with electrical contacts and the thermoelectric material. Then the contour is laser cut. Such cutouts are then stacked, vertically oriented and electrically contacted. The vertical orientation allows for a large number of thermocouples to be packaged. The height of the thermo-electric material and the resulting temperature gradient can be adjusted to the requirements of a given application.

3



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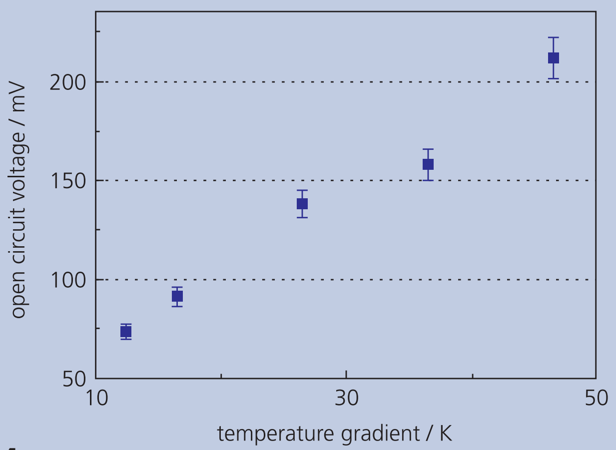
RESULTS

A CAD model is created of the geometry of the heat source so that it can be analyzed for adaptation of the contour of the thermoelectric foil. The model is then used to produce the print images for electrical contacting and the thermoelectric material. The substrate material is often a flexible and temperature resistant polyimide foil.

The electrical contacting of the thermoelectric materials is done with printed silver conduction paths. After drying, the printed silver paste becomes highly conductive and is little prone to cracking when bended.

In a next step, the thermoelectric material is printed onto the carrier foil with the silver contacts. To demonstrate feasibility, only a p-type material (polyethylenedioxythiophene polystyrene sulfonate, PEDOT:PSS) is used as n-type polymers are not yet available commercially. Depending on the application, several layers of PEDOT:PSS are printed and dried to adjust the conduction cross section.

Open circuit voltage of a thermoelectric module as a function of temperature



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The carrier foil is then laser cut to contour. The process yields several small flexible foil pieces. These thermoelectric foils can then be electrically connected, either in series or parallel, to generate the desired voltage or current.

Connected in series, the foils generate a voltage of 125 mV at a temperature gradient of 25 K. The cold side of the module is at room temperature. This voltage is sufficient to supply a commercial microcontroller in a sensor platform.

While maintaining the geometry and the manufacturing process, the voltage or power of such generators can be significantly increased when using materials with higher Seebeck coefficients or combinations of p- and n-type materials. Additional progress for such thermoelectric modules is expected from improving the thermal transport from heat source to heat sink.

1 Printed substrate prior to laser cutting

3 Separate generator foil after cutting

5 Thermoelectric module matching the contour of a pipe

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BUSINESS UNIT
ADDITIVE MANUFACTURING AND PRINTING

1

ADDITIVE MANUFACTURING WITH POWDER BEDS

THE TASK

Additive manufacturing of parts with powder bed processes offers a thus so far unknown level of geometric freedom. The technology enables to redesign existing products so that they have substantially improved properties. Highly complex shaped parts can be manufactured with integrated functions resulting in significant improvements.

The raw material is efficiently utilized due to the near net shape fabrication process. The level of resource efficiency is further increased by applying lightweight construction strategies. One example is the replacement of full density body sections with lattice structures of nearly the same strength. It is also possible to create individually optimized structures, for example to increase the relative surface area for improving the efficiency of cooling systems.

Additive manufacturing processes offer an enormous potential to save resources and energy and to increase ergonomics and efficiency. On the other hand, there are enormous challenges for novel manufacturing processes. Examples include the generation, handling and protection of part data, the reproducibility, speed and precision of the processes as well as the surface quality, detail resolution and material properties of the fabricated objects. Here we need the development of specially adapted process chains and the definition of design guidelines beginning with the creation of the CAD model and continuing with the preparation of manufacturing-ready data all the way to the post-processing of the completed parts to achieve the previously defined surface and structural properties.

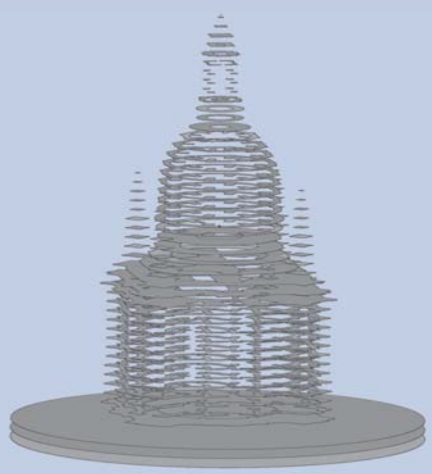
OUR SOLUTION

Selective Laser Melting (SLM) and Electron Beam Melting (EBM) are two additive processes which can produce highly complex parts from powder raw materials.

These processes are based on the iterative areal deposition of powders and selectively melting the material layer by layer. To avoid chemical reactions of the melted powder with the surrounding atmosphere, the SLM manufacturing process is performed in a shielding gas atmosphere, whereas the EBM process operates in vacuum.

Figure 2 shows individual layers of a part which are created with computers prior to processing in the machine.

A sliced layer model



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RESULTS

Beyond the commonly used materials, IWS engineers qualified highly corrosion resistant steels and highly thermally resistant nickel base alloys for the selective laser melting process. Process parameters were developed to optimize the energy deposition into the powder bed for the fabrication of parts that are nearly free of pores.

The resulting part strengths are similar to the strengths of the base materials. In the buildup direction it is possible to even further increase the strength beyond the base materials. Using these materials and processes decisively contributes to establishing the additive manufacturing processes especially for aerospace applications. Novel possibilities emerge for this high technology sector, which make the best possible use of the advantages of additive manufacturing.

A sample structure of a combustion chamber with adapted cooling channels

4

The additive manufacturing of cooling channel structures for combustion chambers is one possible application. For these systems cooling ribs were generated with wall thicknesses in the submillimeter range. Subsequently their surface properties were optimized so that flow behavior and thermal transport improved for the generated cooling channels.

Due to the deposited heat, such thin wall thicknesses often suffer distortions. Support structures were added as a measure to counteract this effect. These structures also contribute to the heat conduction from the inner region of the part toward its mounting point.

Optimizing the creating of the support structure and increasing the building chamber temperature improved the building process. This yielded reduced thermal distortions, which significantly increased the reproducibility.

1 SLM produced model of Dresden's Church of Our Lady

3 Planet gears produced in one step (without joining)

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JOINING

Editor: Laser beam welding is one of the most demanding welding processes. Which applications fields did you develop and what is the current focus of your research?

Dr. Standfuß: For many applications, laser beam welding increasingly becomes more interesting in terms of technology as well as economy. In the past the costs of laser sources limited the application to high volume manufacturing scenarios such as in the automotive industry and their suppliers. Meanwhile the technology has become of interest to small and medium sized companies with very diversified application profiles. A particular challenge, also for other processes, is the welding of pressure cast aluminum. The dissolved gases and other additives cause untight and porous welds. Complex mechanical welding processes with seals often have to be used. However, with the help of new brilliant beam sources and high frequency beam oscillation we developed a process to tight-weld parts made from pressure die cast aluminum. The process was implemented in industry (see page 114). Laser beam welding processes also offer advantages in other areas. One example is the welding of thick-walled parts in steel construction with wall thicknesses of 50 mm. Multilayer welding with high power diode lasers deposit almost three times less energy per unit length than conventional arc welding when it comes to weld walls with thicknesses up to 90 mm (see page 116).

Editor: Since this year you also have established a group for adhesive bonding and fiber reinforced composite technologies. Which research topics does the group address?

"As far as technology is concerned, our world is growing more and more together."

Jawaharal Nehru

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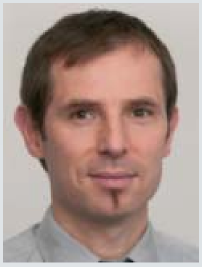
Dr. Standfuß: We added about 400 m^2 of laboratory space in a new building of the 4^{th} expansion phase. Here we concentrate our activities in the areas of adhesive bonding and fiber reinforced composite technologies. The work focuses on plasma and laser processes for the contactless and automated surface pre-processing of parts to be bonded with adhesives. We are also working on bonding metals with plastics. A number of promising technical approaches and results of joining mixed materials are discussed in this report (see pages 120 and 122). Furthermore, the group works on processes to fabricate fiber metal laminates (FML) for future applications in the aerospace industry. These research activities are funded within the current aerospace research program in addition to activities such as laser beam and friction stir welding of metallic fuselage structures.

Editor: Designing highly-stressed parts to exactly match production process and application requirements becomes more and more important. Are you focusing in this topic as well?

Dr. Standfuß: Absolutely. The topics “lightweight construction”, “adaptive manufacturing processes” and “design criteria for joined structures” lie in the focus of all groups of our business unit. They were the primary concerns in most of the research and development work in 2015. I think that this will become evident, if only partially, when describing our research work in this annual report. As an example, I would like to mention the work on mixed material joining of aluminum and steel. Here we are currently EMP welding metal sheet parts (see page 110) and study the corrosion behavior.

COMPTENCES AND CONTACTS



Dr. Axel Jahn, division manager laser beam joining
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»The application field of laser beam joining technologies is increasingly broadening. Laser based processes are especially advantageous when the application demands a combination of high precision, component quality and economics. There are rapidly mounting challenges in terms of the increasing range of desired materials and their combinations. The simultaneously increasing demands for higher part strengths lead to the development of ever more complex joining technology solutions. The department "Laser Beam Joining" performs comprehensive tasks. These range from the design of the parts to meet processing and strength requirements and include welding process development for specific materials as well as the evaluation of the part quality and process efficiencies.«

Dr. Dirk Dittrich, group manager laser beam welding
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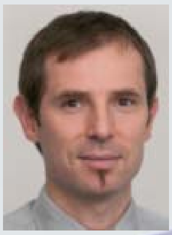
»Process understanding and metal physical background knowledge provide the basis to adapt laser beam welding processes. Processes with integrated short-term heat treatment, with material specific filler materials as well as high frequency beam manipulation enable new approaches to produce crack-free welded joints made from hardenable high strength steels, cast iron, lightweight metal pressure casts and hot-crack prone Al or Ni materials, mixed joints as well as parts of high stiffness. The group follows the credo of "One Stop Solutions", develops tailored welding technologies and supports customers all the way to industrial applications.«



Dr. Axel Jahn, group manager component design
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»Increasing demands for parts, innovative materials and material combinations as well as novel manufacturing processes typically require new design approaches. The group offers structure-mechanical FE simulation tools, thermo-mechanical modeling and experimental verification. The goal is to design parts with the capability to meet the process needs and application requirements requested by the customer. The solutions are developed in close collaboration with in-house process development and materials characterization.«

Dipl.-Ing. Annett Klotzbach,
group manager adhesive bonding and fiber composite technology
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» The group bundles competences which address industrial demands for joining technologies of fiber composite materials in lightweight constructions. Modern laboratories and efficient systems technology are available for example to develop new pre-treatment process for the large area bonding of metals and polymers. Plasma as well as laser pre-treatment processes are deployed. The group also researches the basics of direct thermal bonding of thermoset composite materials. To prove that a produced joint will be sufficiently strong in real-world environments, we apply ageing studies such as climate and spray tests in addition to mechanical testing. «

Dipl.-Ing. Sebastian Schulze, group manager special joining processes
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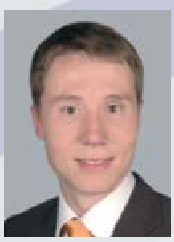
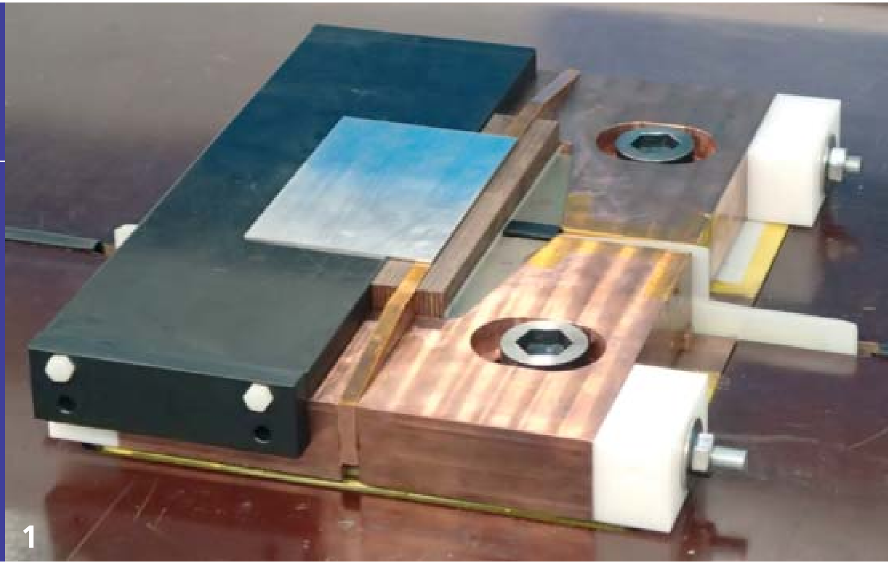


» Often fusion based welding processes are limited in their capability to join modern functional materials. For metals for example, this is so for high strength aluminum alloys. If mixed metal joints are needed, such as welding aluminum and copper, difficulties become even greater since the melt forms intermetallic phases, which strongly reduce strength. The group aims at developing joining processes, which avoid melting and the associated problems. The primary focus is on friction stir welding and electromagnetic pulse welding. We offer process development, prototype welding and system technology developments. «

2015 PROJECT EXAMPLES



1

ALUMINUM-STEEL SHEET JOINTS – ENABLED BY MPW

THE TASK

Electromagnetic pulse welding (MPW) is a new process to bond different types of materials in their solid state phase. The physical principle is to accelerate conductive materials by means of magnetic pressure caused in variable magnetic fields. Due to the strong acceleration, the material deforms and ultimately collides with a second material. During impact the collision zone experiences strong deformation and high collision pressures, which lead to cold welding of the materials.

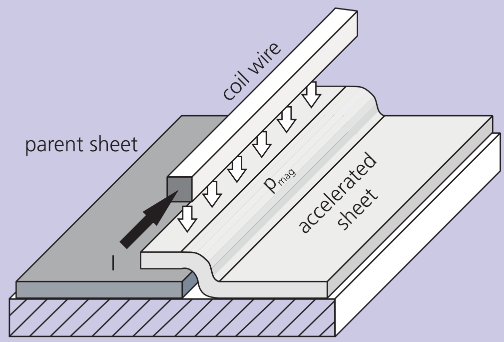
At the Fraunhofer IWS Dresden this principle was applied to develop a joining process for rotationally symmetric parts in overlapping configuration. The process was successfully demonstrated for aluminum-steel, aluminum-copper and copper-steel combinations whereby the welded joints were free of brittle intermetallic phases. The coil dimensions are designed for high mechanical loads so that they accelerate the outer tube to high velocities for forming. Thus the coils can be used for many forming pulse cycles.

It is also possible to apply magnetic pulse welding to join flat metal sheets. However, the design of the coils is a particular challenge. The coil wire needs to be very strong but should also have a small cross section so that it produces high magnetic fields. Resolving these opposing factors requires novel coil designs.

OUR SOLUTIONS

A new coil was developed for electromagnetic pulse welding processes for metal sheets. The coil design considers the required currents as well as the occurring electromagnetic forces. The principle is shown in Figure 2.

Schematics showing the functioning of a flat coil for the electromagnetic pulse welding of metal sheets



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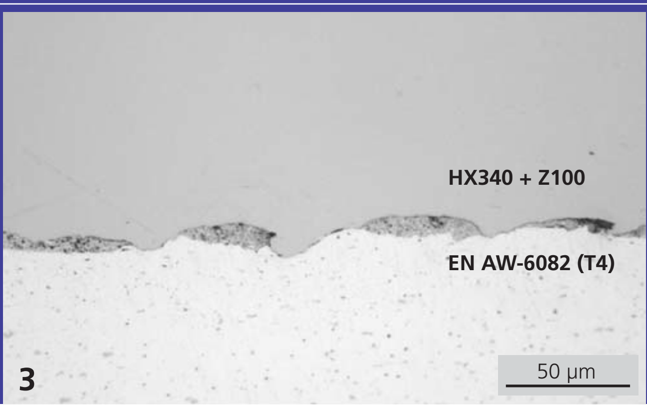
Initial experiments showed that a single welding process takes about 30 µs and that this time is independent from the length of the weld seam. A high speed camera system was used to measure the collision velocities of the sheets (Fig. 4). These were as high as 300 m s^{-1}.

These results served as input data to numerically simulate the expected impact loads, which are transferred to the support structure of the parent sheet. Fraunhofer IWS performed additional FEM simulations to optimize the complex distributions of magnetic pressures and current densities aiming at highest process efficiency.



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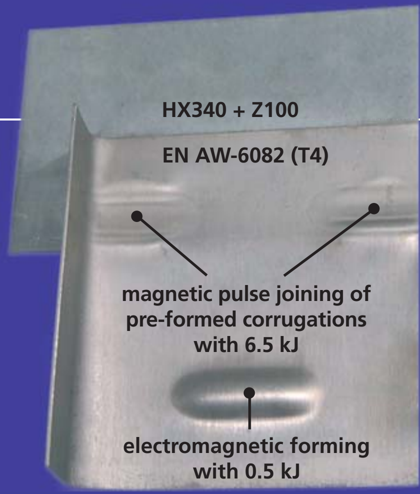

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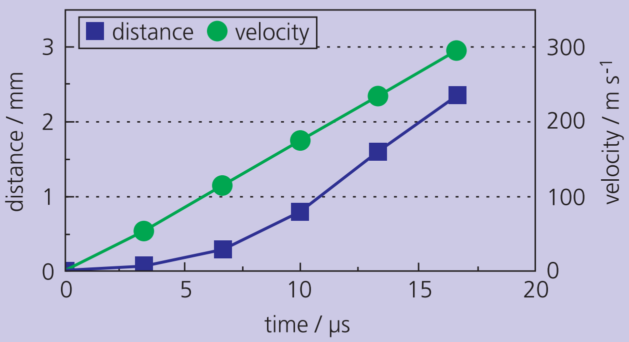
RESULTS

The coils were designed with the required flexibility to adapt them to the particular joining task. The fixture can hold coils of different widths and contours. The magnetic pressure intensity distribution is adjustable to work for the selected material combinations and thicknesses.

The support structure for the parent sheet is designed so that it is possible to weld nearly unlimited lengths of overlapping material. The structure can be adjusted for height so that sheets can be welded with different thicknesses and also joined in combination with profiles.

Figure 3 shows the polished cross section of a linear joining zone between galvanized steel and aluminum sheets. The wavy interface is typical for electromagnetic pulse welding processes. First mechanical tests have shown that the joint strength exceeds the strength of the aluminum. This can be attributed to strain hardening effects that occur during high velocity forming and collision.

Measured position of the accelerated sheet during electromagnetic pulse joining (high speed image with 300,000 images per second)



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The process is very fast and does not require complex pre- and post treatments, which is a great advantage. The method is useful to fabricate semi-finished products as well as for assembling products. The different kinds of materials are welded as lap joints and are immediately ready for further processing.

The process is also useful for car body construction. Here lap joints are typically welded with resistance spot welding of two overlapping steel sheets. Magnetic pulse welding can also firmly bond different materials in this configuration. The welding gap is used for accelerating the material toward the joining zone. Unnecessary positioning efforts are avoided by placing corrugations into the sheet. Subsequently the sheets are placed together without additional gap just like in conventional welding. Finally, the magnetic pulse welds the sheets together where the corrugations are. Figure 4 shows a part with bead-like corrugations as well as the magnetic pulse welded stitched seam between aluminum and steel sheets.

1 Copper coil with centered coil bar

3 Microscope image of the joining zone

5 Steel aluminum hybrid sheet fabricated with dual stage welding processes

CONTACT

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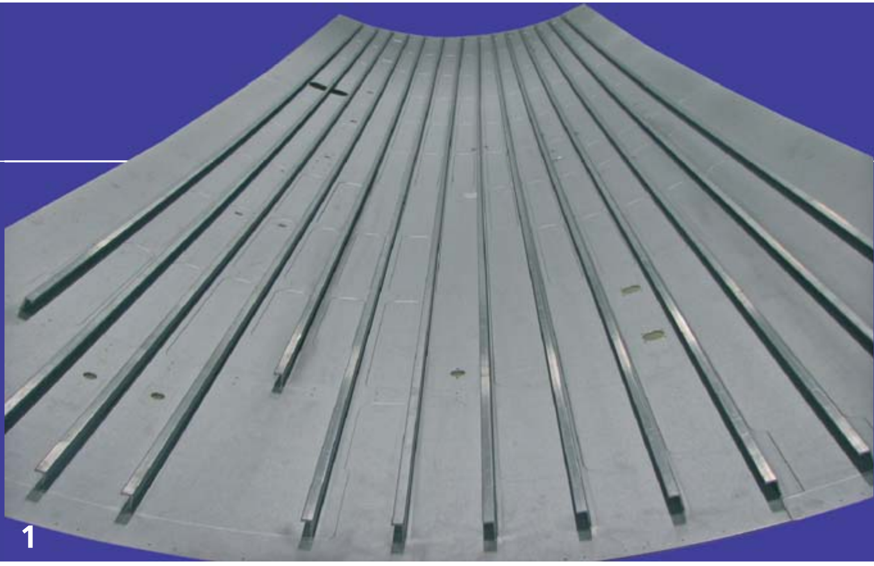


1

FORMING OF SPHERICAL ALUMINUM SHEETS FOR AEROSPACE APPLICATIONS

THE TASK

The steady requirements for lightweight construction and the strong desire for low manufacturing costs of metallic fuselage structures lead to an increasing demand for integral design methods. There are new aluminum alloys based on AlMgSc, which have a lower density, a high strength and better corrosion resistance. They are also very well suitable for laser welding and thus offer reduced weight of the welded parts.

The idea is to manufacture curved fuselage skins with longitudinal stiffening (Fig. 1) by first laser welding the stiffeners to the flat sheets and then bending the sheets to their final shape using a creep-age forming process at elevated temperatures. The new AlMgSc alloys do not show any property degradation when exposed to temperatures in excess of 300 °C, which makes them a good candidate for this manufacturing approach.

Doubly curved or spherical structures pose special challenges. During the forming process they tend to buckle at the edges and thus fail due to tangential compressive stresses. Innovative solutions are needed.

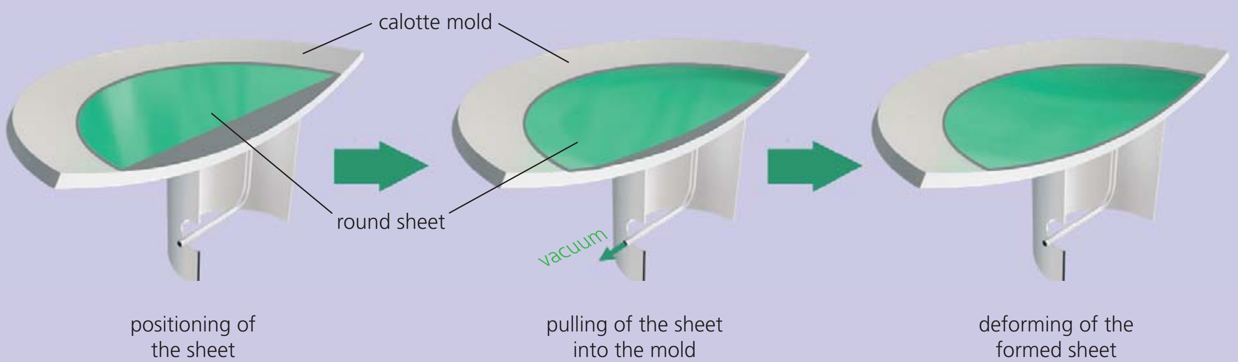
OUR SOLUTION

The Fraunhofer IWS Dresden participates in the aerospace research program “LuFo V” and studies forming technologies of large area, thin-walled and spherical aluminum structures. Solutions are worked on to reduce buckling.

A spherical shell segment serves as a generic model. The shell has the same curvature in both directions. The approach is to iteratively determine critical sheet or round blank diameters above which the sheets buckle. These diameters are determined as a function of curvature and sheet thickness. Round sheets with diameters larger than the determined critical diameter will buckle, smaller diameter sheets will not.

Figure 2 shows schematically how the experiments are performed. Circular round sheets are pulled into the calotte shaped mold.

Experiment to form spherically curved aluminum sheets



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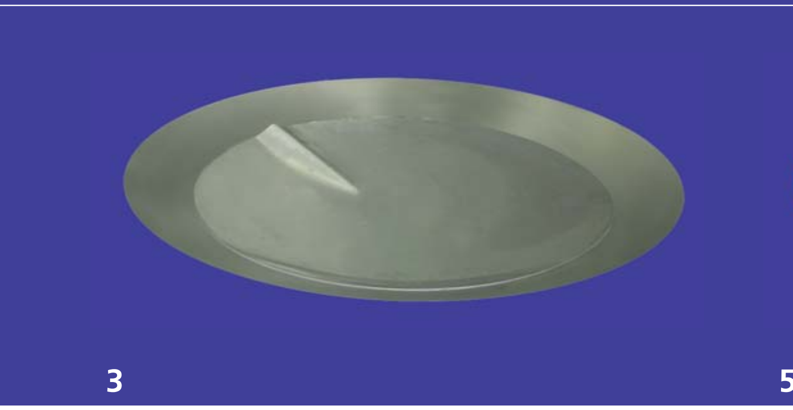

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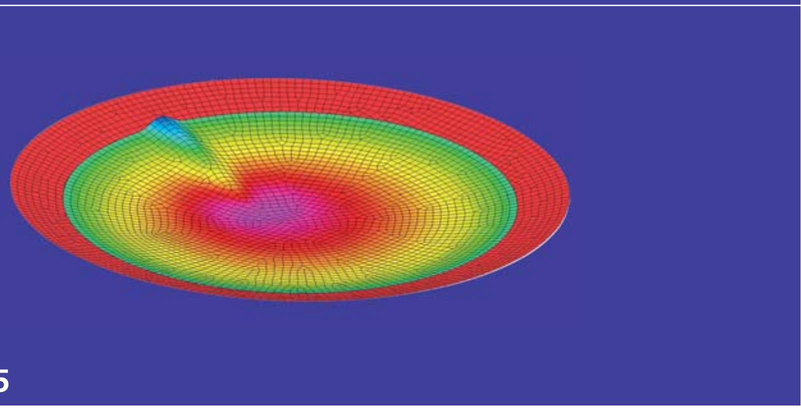

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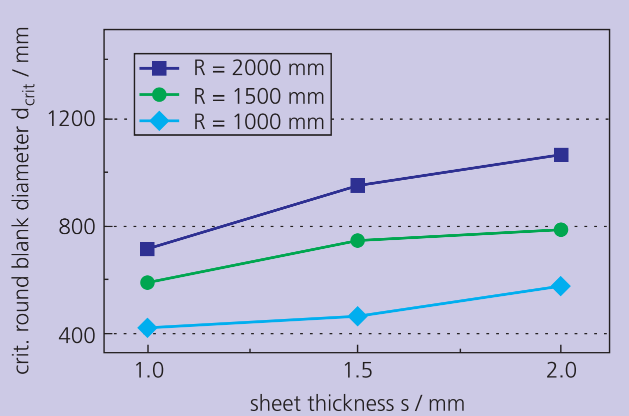
RESULTS

The experiments (Fig. 3) were performed with three sheet thicknesses (s = 1, 1.5 and 2 mm), which are typical for airplane applications. Three calotte-shaped molds had radii of R = 1000, 1500 and 2000 mm. This combination yielded altogether 9 critical round blank diameters $d_{crit} = f(s, R)$ for the buckling threshold. The experimental results showed very good correlation with data obtained from FE simulations (Fig. 5).

The results (Fig. 4) show that thicker sheets as well as larger radii of curvature (i. e., smaller curvature 1/R) yield higher critical sheet diameters.

Comparison of experiments and FE simulations for the forming of spherical aluminum sheets



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Subcritical and thus buckle-free formable aluminum sheets are shaped at elevated temperature (for AlMgSc ϑ_{max} = 325 °C) and constant pressures (vacuum pressure p_{vak} ≈ 1 bar) for about 2 hours. The creep effect or stress relaxation achieves low elastic spring back and small residual stresses. The mechanical properties of the final part are not significantly impaired.

The forming of larger structures without buckling requires additional efforts (e. g. a blank holder). The Fraunhofer IWS Dresden is performing more work on this topic.

1 Spherical fuselage shell with laser beam welded reinforcing stringers

3 Forming experiments with round sheets that are supercritical to buckling

5 FE simulation of a forming experiment with round sheet that are supercritical to buckling

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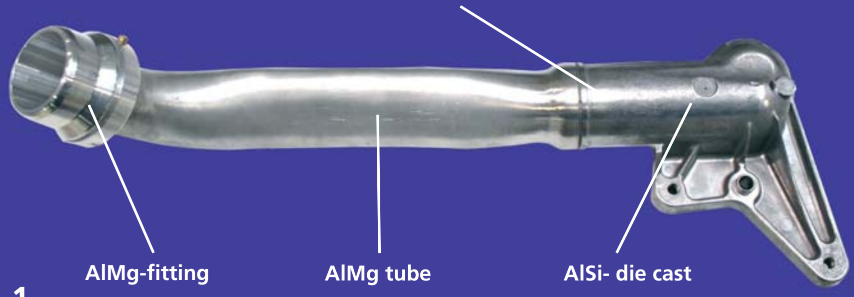


1

TIGHT-WELDING OF DIE CAST MATERIALS WITH FIBER LASER

THE TASK

Die cast aluminum is an exceptional material to cast and thus finds many applications in the automotive industry and in particular to make parts with thin-walled cross sections. Such cast components often need to be connected to profile or tube shaped parts. The weld seam quality needs to be highly reproducible and yield pressure-tight joints. High quality joints are an essential condition for industrial use. It is also necessary to use a welding process free of distortion to meet the tolerance requirements for assembly and fitting.

So far, melt based beam welding processes have not been suitable to produce such demanding joints for die cast components. Pressure casting naturally generates high pressure pores in the material, which cause unstable welding process conditions. Additional difficulties originate from the release agents that are used for die casting and lead to non-uniform weld seams. The weld material has more pores and the material stochastically ejects during the welding process. Conventionally produced die cast components are usually considered to be almost unweldable.

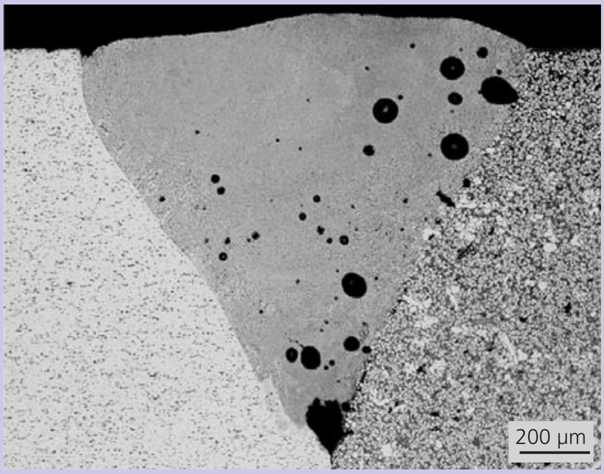
The development of new melt-based welding processes is necessary to tight-weld die cast components with minimal distortion. This process should have significantly reduced ejection probabilities and thus produce less splatter. The melt should be able to outgas.

OUR SOLUTION

To firmly join die cast aluminum parts with an aluminum tube (Fig. 1) Fraunhofer IWS engineers developed a novel welding process. This process utilizes beam sources of highest quality in combination with high frequency beam oscillation.

Geometric keyhole formation is controlled with the scanning frequency in the kHz range. The melt pool dynamics can be adjusted to the materials and allows for a controlled outgassing and homogeneous solidification of the melt. The number of gas inclusions in the weld metal is significantly reduced. The high process stability also increases the yield of welded components.

Laser welded joint produced through high frequency beam oscillation (left: AlMg tube, right: conventional AlSi pressure casting)



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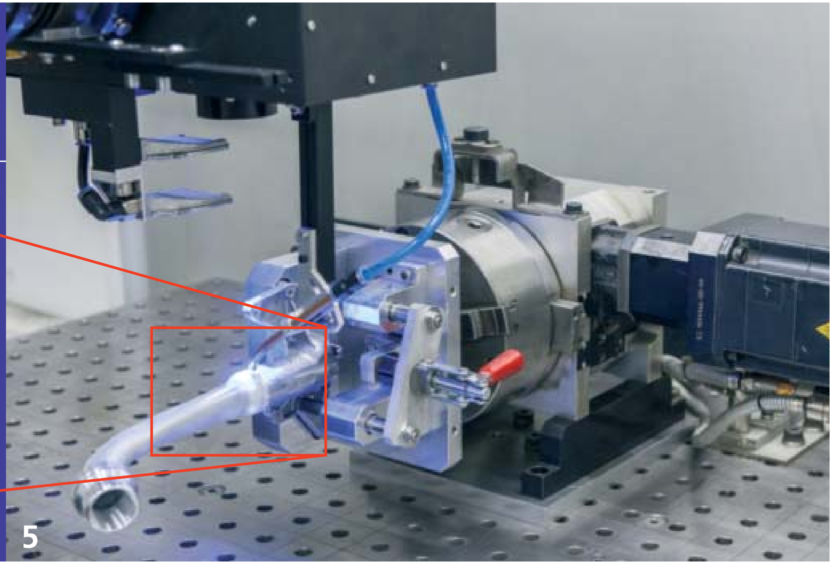

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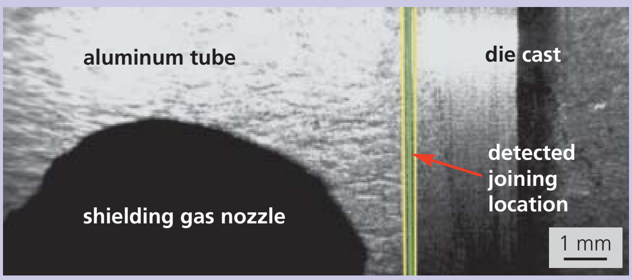
RESULTS

Welding experiments with die cast components in the laboratory showed that high frequency beam oscillation stabilizes keyhole formation. The process runs in a steady and stable manner. The typical ejections and splatter that are observed when welding die cast materials, are suppressed.

The metallographic analysis confirms these observations. The microscope image reveals that the remaining number of pores in the weld metal is low (Fig. 2) and that these are concentrated on the side of the die cast part. Parts were tested under 2.5 bar pressure and weld seams proved stable and pressure-tight.

Due to the low energy deposition (laser power < 1 kW) the 3D-formed part is dimensionally accurate and distortions are barely measurable. Complex assembly situations are therefore possible without the need for additional alignment steps. Welding tests with larger batches of prototypes proved that the process is suitable for series production yielding the desired properties.

Camera view of the joining location for detection and position of the laser beam via the scanner optics. The camera is coaxially aligned with the laser beam path.



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The Fraunhofer IWS service offer included materials analysis, designing the joining location, process development and the characterization of the joint properties.

Based on the obtained results, IWS engineers transferred the welding process into series production at an automotive supplier plant (Fig. 3 and Fig. 5). This step included the technology transfer and also the integration of hardware such as laser, welding optics and an integrated weld seam recognition system into an existing welding machine.

An application specific software was developed to control the scanner optics and to provide automatic image recognition (Fig 4). The software was also integrated into the welding machine. The specially developed welding process in combination with automated image recognition and scanner control software as a package offers a series production-ready solution also for other applications.

1 Laser welded die cast cooling pipe component

3 Laser beam welding process

5 Technical setup at the customer with IWS welding head (above) and active image recognition (right)

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1


2

MULTILAYER WELDING IN STEEL CONSTRUCTION WITH HIGH POWER DIODE LASER

THE TASK

In steel construction conventional welding processes such as submerged arc welding or metal inert gas welding form the backbone of technologies to fabricate thick-walled welded constructions. Opening angles of more than 40 degrees are often required to provide access for the welding tools so that they can deeply penetrate into the welding joint. It is typical in steel construction that the weld joint is prepared by plasma or flame cutting. The cuts provide a very large V-shaped joint cross section, which is problematic with respect to the increasing component distortion with thicker sheet thicknesses.

Laser based processes are currently unusual in steel construction. The classic seam preparation techniques are not suitable for laser welding and mechanical preprocessing of the joint would be too expensive. Modern steel construction requires efficient welding processes that can handle large dimensional tolerances of the parts and do not require expensive post-processing. Fraunhofer IWS engineers developed a laser based process to weld thick sheets for steel construction so that the value added potential in this field remains attractive in Germany.

OUR SOLUTION

Fraunhofer IWS researchers developed a laser based multilayer narrow-gap welding process (MPNG) to offer a new approach for the fabrication of welded constructions with thick metal sheets but also for repair tasks. This process removes the classic limitations of laser beam welding of thick sheets.

An approach was already demonstrated for welding thick aluminum sheets. It had to be slightly modified to also work for steel constructions. Instead of a fiber laser, a 10 kW diode laser is used. Its beam quality in combination with the selected optical components yielded a spot diameter on the workpiece of about 3 mm. The component tolerances are about 2 mm and therefore the laser spot easily covers the tolerances.

The minimum opening angle for the joint depends on the laser beam caustic and can be reduced to less than 15 degrees without melting the flanks in the upper areas of the studied 120 mm double-bevel groove weld. The beam is moved statically through the joint to fill the gap with either one, two or three tracks per layer (Fig. 3). A 1.6 mm diameter wire is dragged along the process zone to provide the filler material.

The melt pool sizes remain small, similar to those in classic welding. The advantage of the laser beam welding is the lower and locally limited energy deposition into the workpiece, which reduces the distortions also for thick-sheet applications. The high power density in the focus of the laser beam simultaneously melts the workpiece edges as well as the filler material.

Principle of the laser multilayer narrow-gap welding process (MPNG)


3

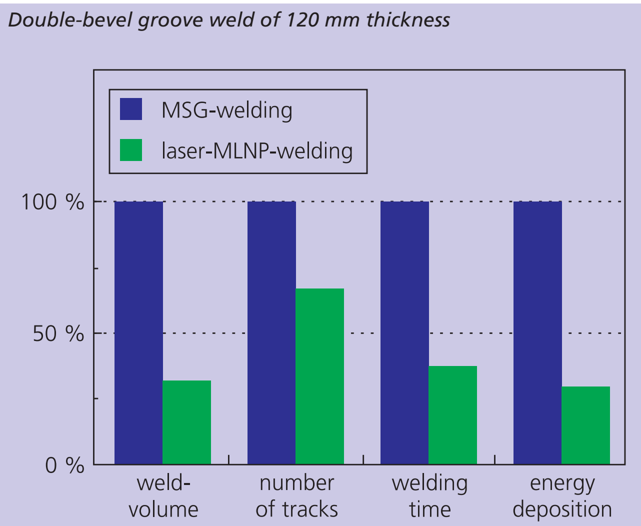
4a

4b

RESULTS

Weld joints were prepared with an opening angle of 12 ° for parts that are similar to actual workpieces. The described optical components were used to weld 800 mm long and 600 mm deep weld seams (Fig. 1, 2, 4). The edges were prepared with plasma cutting methods that are commonly used in the steel construction industry. The special feature is the extremely small opening angle. By doubly welding the single-bevel groove weld it is possible to safely join sheets as thick as 120 mm.

Optimized welding parameters guarantee the reproducible fabrication of homogeneous welds free of cracks and bonding flaws. The laser welded seam has a low pore density similar to that of the conventional weld seam (Fig. 4a and b). It is therefore classified within the best quality level group (B) for imperfections according to DIN EN ISO 13919-1.



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The weld seam volume with the laser multilayer narrow-gap welding process is reduced by 32 percent compared to metal inert gas welding (Fig. 5). This reduces the number of individual tracks that have to be welded. For a 120 mm double-bevel groove weld that means the number is reduced from 105 to 70 tracks, which also reduces the overall process time. The process also achieves melt rates of about 5 kg h^{-1}, which is very high for laser applications. An advantage is that the small cross section of the weld seam also reduces distortion. Contributing factors are also the small opening angle as well as the drastically reduced energy deposition per welded layer.

The experiments confirm the high expectations for the laser multilayer narrow-gap welding process with respect to its efficiency, which is an important decision-making criterion in steel construction. The use of diode lasers also reduces the necessary investment as the costs per kilowatt power have been significantly declining over the past decade.

1,2 Laser multilayer narrow-gap welding of a 60 mm thick single-bevel groove with an opening angle of 12 degrees

4 Polished cross section of conventional (a) and laser welded (b) steel sheets

CONTACT

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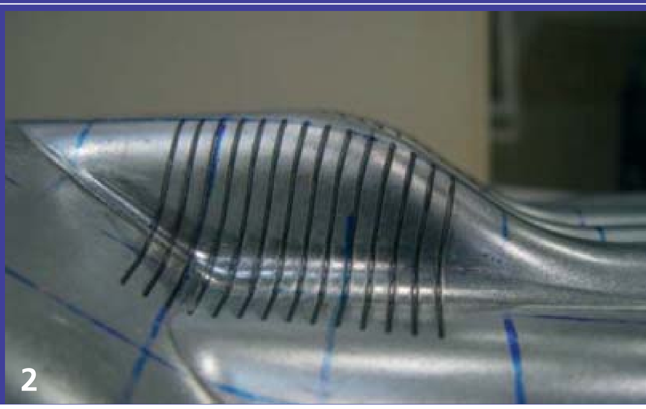


2

LASER-STRENGTHENED STEEL SHEET STRUCTURES – NOW WITHSTANDING HIGH CYCLIC LOADS!

THE TASK

Current laws drastically limit the permissible CO_2 emissions of automobiles. This forces the manufacturers to develop light-weight bodywork construction technologies to reduce the vehicle weight without compromising safety. Components get ever more complex and need to be stronger. Conventional construction principles were based on using homogeneous high strength materials. This approach will not be sufficient in the future.

An innovative approach has been developed to use lasers to locally strengthen steel crash structures used in vehicle bodies. The method tailors the workpiece hardness and strength at selected locations to adjust the material properties for the expected load distribution. Clear improvements of static and dynamic crash performances of steel sheet components were already demonstrated. However, in addition to static and impact loads, automotive chassis and body components are also exposed to cyclic mechanical fatigue loading.

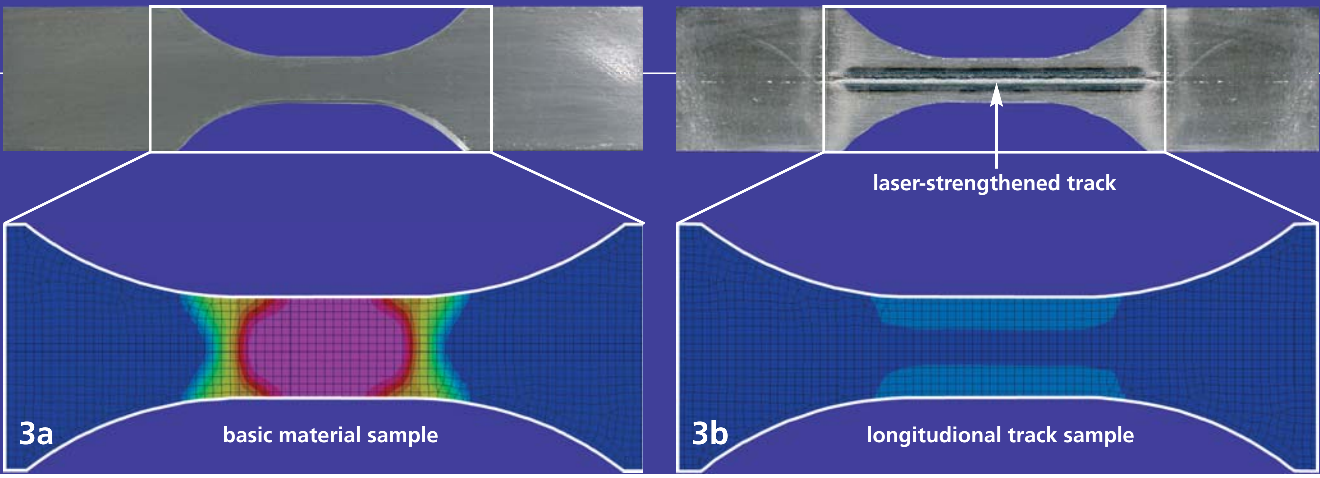
The task was to investigate the influence of the laser-strengthened structures on the fatigue strength of automotive sheet materials. The comparison included the basic sheet material and laser-strengthened sheets. The aim was to estimate the effect of the process and to derive conclusions for future component designs.

OUR SOLUTION

Laser-strengthening of metal sheets principally aims at using cost-effective low strength steel sheets with reduced wall thicknesses. These sheets are laser treated at locations with high loads. The focused laser beam is scanned across the surface at defined speed. The concentrated energy deposition heats or even melts and subsequently solidifies the track (Fig. 2). The subsequent cooling leads to martensitic hardening of such steels that are typically used in the automotive industry. This effect is used to locally strengthen the material. The tensile strength in the treated zones can be 2.5 higher compared to the base material.

How strengthened tracks affect the fatigue strength was researched jointly with the department for materials characterization and testing at the IWS. The test material (S355 J2+N) is typical for automotive chassis applications. A special test program was developed. The effects of shape (track orientation) and surface states were studied with respect to the achievable fatigue strengths and endurance limits.

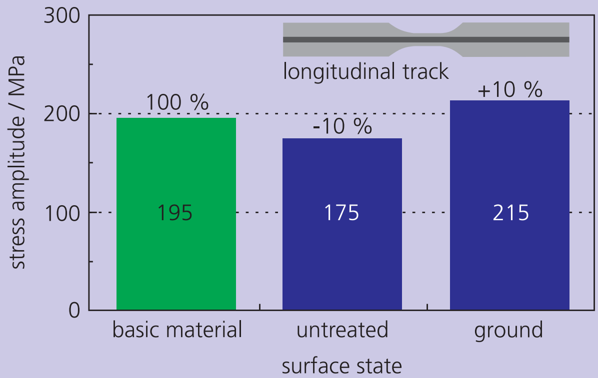
The experimental matrix includes the variations shown in Figure 4. One sample was ground down to remove the weld grooves and to reach a roughness of $R_Z \approx 6$ µm across the entire surface. FE simulations were performed (static nonlinear) to determine plastic deformation as a result of defined loads for various track orientations.



RESULTS

The FE calculations simulated a loading cycle by applying a static tensile load, which was subsequently relieved (1 cycle). As a result, the base material suffers plastic tensile deformation, which is homogeneously distributed (Fig. 3a). Applying the same load to material with longitudinal tracks, the results show no significant residual deformation in the area of the base material (Fig. 3b). The reason for this is the significantly higher yield strength of the laser-strengthened track. This longitudinally oriented tensile band reduces residual deformations so that one can also expect improved fatigue strength.

Results of fatigue strength tests for a cycle number of $N = 2 \times 10^6$



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Untreated (not ground) samples with tracks oriented in parallel to the direction of the loading force experience crack initiation at the edge of the track grooves. At the same loading conditions, the support due to the track reduces the maximum elongation and nearly compensates the detrimental effect of the groove. The fatigue strength only slightly reduces compared to the base material (Fig. 4, blue, untreated).

Ground down samples showed a tendency to improve the fatigue strength (Fig. 4, blue, lapped). The sampling size for these experiments is low. However, principle differences in the levels of fatigue strength and endurance limit became apparent.

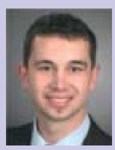
The experiments proved that laser-strengthened tracks are useful for applications, in which the parts are exposed to cyclic loads in addition to static and impact loads. The technology significantly improves the resilience of chassis components especially in situations of impact misuse. The experiments allowed the identification of strategies as to how to apply the technology while maintaining the fatigue strength of the base material. Even further improvements are expected from process optimization, which perhaps renders an additional grinding process obsolete.

1 *Chassis component made from welded sheets*

2 *Laser strengthened steel sheet structure*

3 *Comparison of plastic strain of untreated (a) and laser strengthened (b) fatigue test samples (same scale of strain)*

CONTACT



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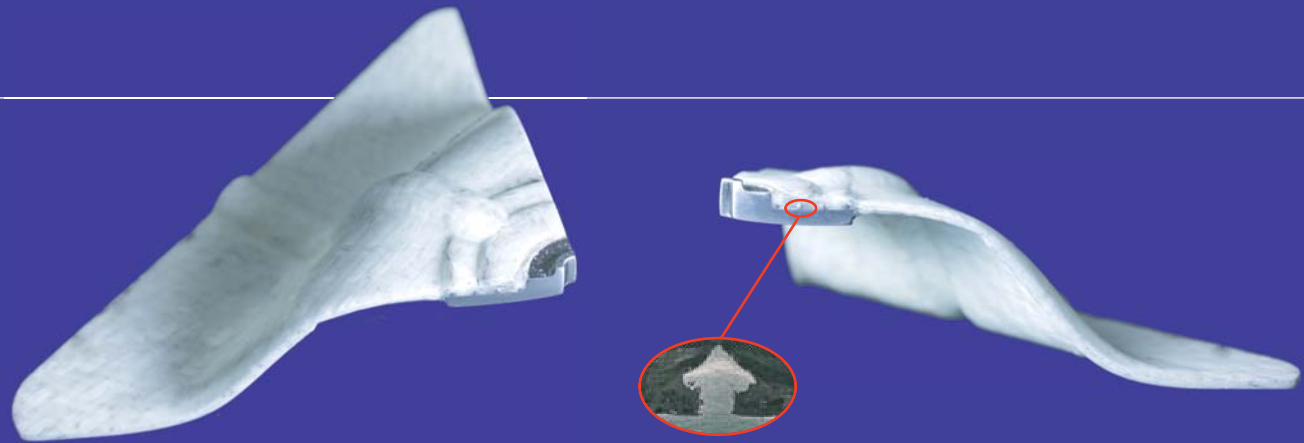


1

THERMAL DIRECT JOINING OF METAL AND THERMOPLASTICS

THE TASK

Tailored mixed material joints which combine the specific advantages of metals and thermoplastics are becoming more important for industrial applications and in particular for lightweight construction. Efficient process chains are required which employ optimized pre-processing and joining technologies, tools and simulations as well as material characterization. The resulting joint properties need to be tailored for specific application environments.

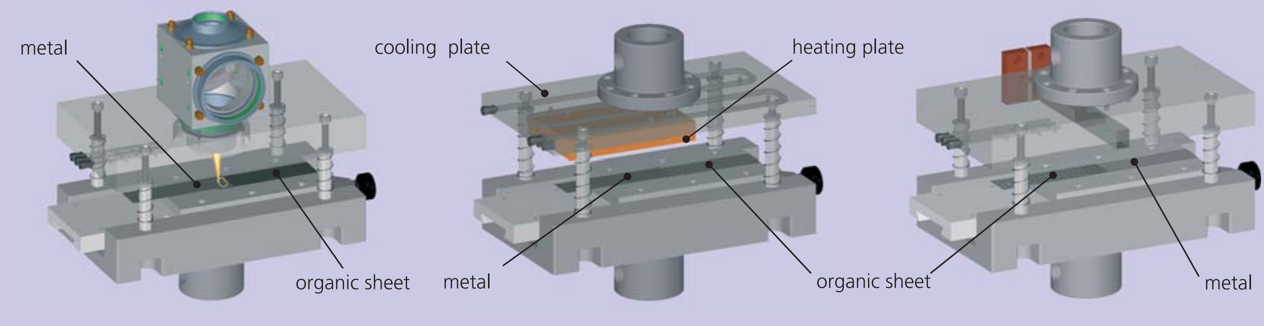
Typical processes to join dissimilar materials are post and inmold assembly, mechanical joining techniques such as bolting, riveting and adhesive bonding. Specific restrictions of these processes result in particular due to:

- limited complexity of shapes,
- locally reduced cross sectional areas with disturbed flow of forces in fiber reinforced plastic composites,
- the necessity to introduce additives and
- increased process times.

OUR SOLUTION

Fraunhofer IWS engineers have substantial materials and process know-how addressing laser and plasma based manufacturing technologies. This capability is applied to develop surface preprocessing and adhesive bonding technologies as well as to study thermally induced joining techniques. Direct thermal joining processes are fast and eliminate the need for additives (e. g. adhesives). To join metals and thermoplastics, IWS engineers apply suitable surface structuring, adhesion promoting layers and different heating concepts. Heat is applied using laser radiation, heating elements or induction (Fig. 2). Another method to deliver a short burst of heat is the use of reactive multilayer coatings (RMS).

Schematics for different heating concepts



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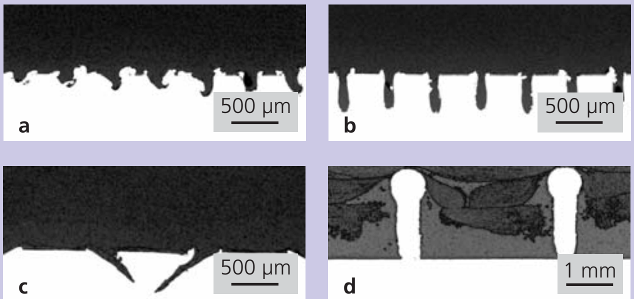
3

RESULTS

The first step is to structure the metal surface (Fig. 4a-c) or to generatively add structures (Fig. 4d). The particular pattern of the surface structure aims at providing the best adhesion for the melted thermoplastic material for a given application. This way the connection between plastics and metal relies on form fitting and non-covalent forces (Van-der-Waals). The strength of thermoplastics-metal joints can be further increased by using adhesion promoting layers, which are selected depending on the materials used. These direct joints combine the effective principles of form fitting and adhesive bonding technologies.

Direct joints with adapted surface structures to improve the joint strength of metal (below) and thermoplastics (a-c) and to fiber reinforced composites (d)



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Engineers of the Fraunhofer IWS in Dresden are studying different heating methods to join thermoplastics and metals of complex geometries. The goal was to identify cost-effective methods and to explore application potentials and limitations of the techniques. Compared to conventional heater elements, laser induced heating has the advantages that the heat can be locally deposited and that the process is suitable to work with more complex part geometries. It is also possible to apply a temperature gradient by integrating pyrometer control.

Heating inductively requires well developed knowledge about the geometry of the joining zone, the material behavior as well as the processing approach in order to dimension the inductor and the generator. This method has the advantages of being very fast and its capability to deliver heat to regions that are optically inaccessible. This is similar for using RMS foils. If the process is designed just right, the heat deposits directly at the contact interface between metal and thermoplastics.

All the described methods rely on heat convection in the contact interface to plasticize the thermoplastic material or the thermoplastic material matrix of pre-consolidated fiber reinforced composites (so-called organic sheets). Under pressure the plasticized material flows into the fabricated structures, which have undercut geometries. There the material solidifies to connect in a form fitting way with the structure or to bond with the adhesion promoter. The process can be as brief as a few seconds. The short processing time is a decisive advantage compared to conventional processes such as adhesive bonding.

1 *Glass fiber polypropylene suspension strut dome with directly connected stainless steel dome bearing*

3 *Fracture surface of metal-thermoplastics joints*

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1

STRUCTURAL ADHESIVE JOINING OF TEXTILE REINFORCED THERMOPLASTIC COMPOSITES

THE TASK

The industrial use of thermoplastic fiber reinforced composites in large series production requires suitable and reproducible joining techniques. Adhesive bonding is here of particular importance since the technique allows for a uniform load distribution over large areas of the complex fiber reinforced composite structure. Compared to thermoset based matrix materials, thermoplastic polymers such as polyamides, polyethylene and polypropylene have advantages for high volume production of fiber reinforced plastic composites. Thus the joining process results must yield high strength and durable joints as well as short cycle times to allow for high volume series production.

OUR SOLUTION

The IWS group addressing bonding and composite technologies works on implementing automated processing steps, which enable the adhesive bonding of flat and curved fiber reinforced thermoplastic composites. The following process steps are studied and developed:

- surface pre-treatment,
- adhesive selection,
- adhesive application and curing,
- documentation of transmission strength and durability.

This work was performed in close collaboration with the TU Dresden and funded within a special research program 639 ”Textile-reinforced composite components for function-integrating multi-material design in complex lightweight applications.“

Surface pre-treatment:
Thermoplastics with low surface energies such as polypropylene provide poor adhesion for adhesives and cannot easily be bonded for the use in structural applications. The adhesion can be improved by physical methods to pretreat the surface or by using special adhesives. Atmospheric pressure plasmas and laser radiation are especially useful to flexibly pretreat such surfaces. Both methods are primarily used to clean the surface (remove softeners, release agents etc.) and sometimes also to functionalize the nonpolar plastics surface. The plasma treatment deposits little heat, is automated and forms functional surface groups. In addition to surface cleaning and activation, laser surface treatments (structuring) can also increase the surface area. This permits the adhesive, in addition to chemical interactions, to also form mechanical anchorage with the polymer surface.

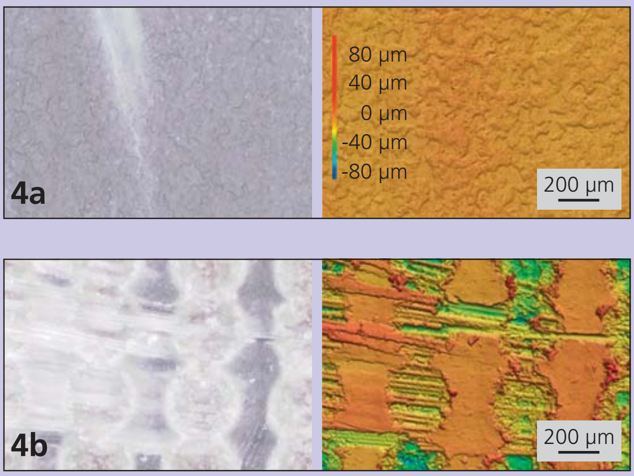
Adhesive selection, application and curing:
The bonding of highly stressed structural joints with fiber reinforced thermoplastic composites requires tailored adhesives based on polyolefins, epoxy resins, polyurethanes and acrylates. These adhesives were evaluated and the quasi static joint strengths were compared. In order to meet production throughput requirements, experiments were performed to accelerate the curing of thermally sensitive glass fiber reinforced polypropylene composites. The aim was to cure larger structures within a few minutes to get them ready for subsequent processing steps.

Ferromagnetic particles were added to industrial one-component and two-component epoxy resin based adhesives and the system was heated via high frequency induction. Curing times reduced from 60 - 90 minutes in conventional ovens to 3 - 5 minutes. The glass fiber reinforced thermoplastic components did not face high heat exposure, which is the case in conventional ovens. The induction heat is locally deposited into the adhesive layer.

RESULTS

Surface treatments with atmospheric pressure plasma and pulsed solid-state laser radiation yielded significant joint strength improvements of adhesively bonded structural fiber reinforced thermoplastic composites. Even after ageing tests, the strength remained high. The reference experiment used solvent cleaned samples. Here the bond failed adhesively at peel forces of 15 N m^{-1}. Laser structured surface were bonded and survived peel forces of up to 3800 N m^{-1} when they failed cohesively by delaminating. The different surface preparations of the reference sample and the laser structure sample are shown in Figure 4.

Surfaces of fiber reinforced thermoplastic composites (left: microscopy, right: surface topology) a) untreated and b) laser structured with local fiber exposure



An accelerated curing of the adhesive was achieved by high frequency induction heating. For this process to work, nanoscale super-paramagnetic particles (iron oxide particles in a shell of silicon oxide) were dispersed into the different adhesives. A motion controlled inductor excites the nanoferrites and cures the adhesive at temperature between 130 °C – 180 °C.

Mechanical testing yielded bonding strengths of the inductively cured adhesives, which were on par with those that were conventionally cured at room temperature or in ovens. In the case of glass fiber reinforced polypropylene the bonding strengths ranged from 8 MPa to 12 MPa depending on pretreatment and adhesive. The bonding process was also automated by coupling the pretreatment system (atmospheric pressure plasma head) and adhesive applicator (two component dispense and application unit) or the induction system with cooperatively working industrial robots (Fig. 2 and 3).

1 Function-integrating vehicle system unit

2 Driver cabin of the vehicle system unit at automated pretreatment and adhesive application station

3 Pyrometer controlled inductively accelerated adhesive curing with industrial robots

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1

PROCESS MONITORING DURING LASER BEAM WELDING OF NONFERROUS MATERIALS

THE TASK

Laser processing of nonferrous metals requires a high level of process control. Especially for the medical device industry, the welding of titanium components requires high precision and high strength joints. Joining processes for materials with medium or low melting points are well established including process analytics. However, currently it is challenging to monitor the welding processes for nonferrous materials with high melting points.

It is important to exactly determine the parameters which lead to process deviations. Measuring the thermal radiation emitted from the joining zone is difficult as it strongly depends on the emission coefficient of the material. The emission coefficient in turn is a function of material surface conditions, the uniformity of the material structure and the wavelength. Processing of titanium materials may also form oxides on the surface (tempering colors), which create optical and structural disadvantages.

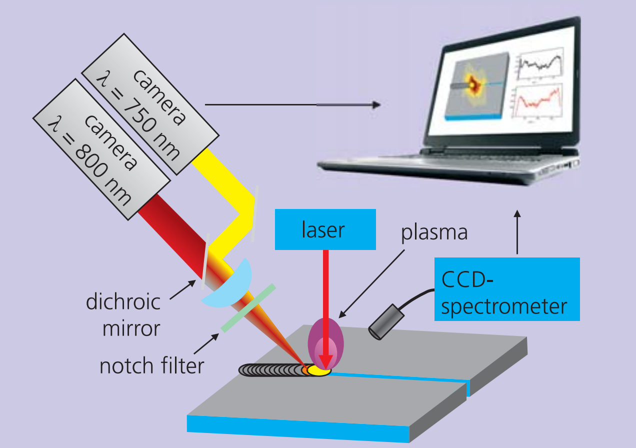
The aim of the project was the development of a camera online process control system that is based on spatially resolved pyrometer measurements of the material's surface temperature. Inhomogeneous temperature profiles were expected to correlate with defects in the joining process.

OUR SOLUTION

The spatially resolved measurement of temperatures up to 2500 °C is implemented with special CMOS camera sensors. It is important to capture very high as well as very low intensities. Two independent camera systems were used so that very high intensity temperature information could be captured from the processing zone.

The pyrometer aligned two cameras of type UI-512SE to detect radiation over well defined wavelength ranges. One camera filters the thermal radiation at 800 nm, the other at 750 nm. The ranges were selected so that the cameras are very sensitive and capture a large number of photons coming from the processing zone over a wide temperature range.

Camera based online process control system to join titanium alloys



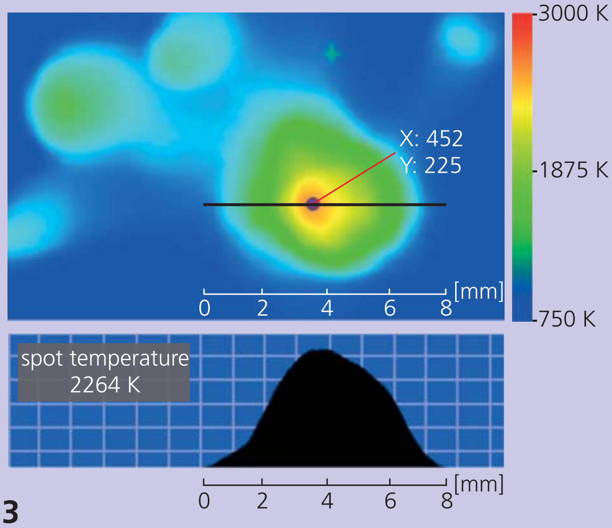
2

RESULTS

The radiation emitted from the sample is focused through imaging elements and then split to reach both cameras. This pyrometer setup measures the thermal radiation independent from influencing factors of the studied object. Prior to each measurement a calibration is performed. An initial sample weld is performed to adjust the system to the anticipated intensities. The software has a location correction algorithm for the captured intensity information and overlays the images of both cameras.

Figure 3 shows the user interface at the analysis computer. The picture presents a welding process which developed weld beads on the surface of the seam due to an error with the delivery of the shielding gas. The live image of the pyrometer system shows ejections from the welding process.

Principle of spatially resolved temperature profil to detect anomalies during spot welding of titanium



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By capturing these events it is possible to not only control the process but to also perform quality monitoring. The central temperature of the processing zone is measured via spot detection. The measured temperature profile shows a homogeneous heat affected zone. The system can be integrated with machine control systems to perform real-time testing and controlling of the welding process of nonferrous materials.

The camera pyrometer has the following parameters:

- control of pyrometer adjustments,
- real-time measurements,
- semiautomatic calibration,
- imaging scaling with up to 3:1 magnification,
- 50 images per second to record at corresponding welding speeds,
- online analysis of the welding region with spot and line measurements.

1 Laser welding with online process control

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CENTERS

SYNERGIES VIA GLOBAL NETWORKS THE CCL-GROUP IN MICHIGAN, USA

The US market is one of the most important innovation drivers for application-oriented research and development. This is the reason why, for more than a decade, the Fraunhofer IWS has developed its daughter operations in Michigan, USA. Primary business goals in the USA are technology transfer, the expansion of scientific competences through intensive collaboration with research centers of international excellence and the qualification of colleagues in an international environment.

Since 1994 the Fraunhofer Gesellschaft has been operating a wholly-owned subsidiary in the USA. Fraunhofer USA Inc. is the umbrella organization for seven research centers and additional units. Fraunhofer IWS is the mother institute and research partner of these research centers which have been operating independently since 2015. The Center for Coatings and Diamond Technologies (CCD) is closely connected with the Michigan State University (MSU) in East Lansing, Michigan. The Center for Laser Applications (CLA) is located in Plymouth, Michigan.

Sustaining the success of the centers requires the knowledge of customer demands, continuous scientific research and maintaining a competitive innovation potential. Therefore both centers jointly performed strategic technology audits on August 17th and 18th 2015 in East Lansing and Plymouth. Research and financial aims as well as joint development foci for the centers were defined for the coming years and presented to the auditors. The auditing panel consisted of 8 experts from the USA and Germany, of which six were industry representatives and two came from research institutions. They acknowledged to the stakeholders a clear strategy and development perspective of the centers. The comprehensive and bilateral exchange of scientists was unanimously considered to be the basis for past and future successes. CCD and CLA solidified their good positions in the American research market in 2015 and had a successful business year. The following table lists selected results of the 2015 business year.

COORDINATION

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BUDGET CCL-GROUP	**$5.5 MILLION**
EMPLOYEES	**Number**
Staff	22
Associated MSU employees (CCD)	7
Interns and students	22
TOTAL	**51**
PUBLICATIONS	**Number**
Dissertations	3
Master's theses	6
Journal papers	7
TOTAL	**16**
PATENTS (first filing)	3

CENTER FOR COATINGS AND DIAMOND TECHNOLOGIES (CCD)

The Fraunhofer Center for Coatings and Diamond Technologies (CCD) is one of the two newly founded centers in the USA. The CCD is located in East Lansing, Michigan, on the campus of Michigan State University (MSU). For twelve years MSU and the IWS daughter have collaborated in the research fields of thin film and diamond technologies. Fraunhofer CCD offers custom-tailored technology solutions through combining process, materials and systems technology know-how with scientific excellence, quality and project management.

In 2014 researchers at Fraunhofer CCD and Michigan State University were awarded an ARPA-E research grant in the field of diamond electronics. The project aims at developing a diamond based diode that combines a reverse breakdown voltage of 1200 V with a forward current of 100 A (see pages 74-77). With respect to electronic applications, diamond possesses extraordinary properties, which include for example a dominating thermal conductivity, high charge carrier mobilities and the high electrical field breakdown strength. With respect to diamond synthesis and the processing of high quality single-crystalline diamond materials, Fraunhofer CCD and MSU have a profound process know-how and patented systems technology.

Jointly with the Mackinac Technology Company and the University of Michigan, researchers at the Fraunhofer CCD work on a project funded by the US Department of Transportation. The objective is to create an antireflective coating of windshields for transit busses (SBIR project) with the goal to improve traffic safety by reducing reflections caused by internal lighting, which is necessary for passenger transport.

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In Phase I of the project the team demonstrated that an innovative coating made from amorphous diamond-like carbon (DLC) reduces reflections and perceptively improves driver visibility. Phase II has the goal to advance the technology toward commercialization for passenger bus windshields.

In a new project CCD collaborates with CLA and an industry partner to develop a cost efficient retrofit solution to make existing window installations more energy efficient. The concept is based on a very thin, lightweight, optically transparent and UV stable polymer film, which is coated with a wavelength-selective nonmetallic coating. In the range of visible light, the coated polymer film is completely transparent. It can be mounted to the inside of windows with lightweight metal framing and is as easily removable.

CENTER FOR LASER APPLICATIONS CLA

The Fraunhofer Center for Laser Applications (CLA) is a result of bundling all laser activities at Fraunhofer USA into a joint center. The activities focus on offering laser technologies and systems for industrial applications. The CLA is located in Plymouth, Michigan near Detroit. The laser applications laboratory of 1200 m^2 is equipped with the latest laser and systems technology.

Fraunhofer CLA offers a wide spectrum of laser processes including welding, cutting, drilling, coating, heat treating, surface marking and structuring as well as additive manufacturing. An additional expertise is the development of systems technology for process monitoring and control as well as processing heads for buildup welding and generating.

A new innovation of 2015 was the development of an inner diameter coating head for high deposition rates, which can be used with diode lasers of up to 6 kW power. The coating can be used to perform depositions up to 1 m deep inside tubes starting at 100 mm diameter.

Fraunhofer CLA has developed successful processes for the additive manufacturing of large parts (see page 100-101). The processes are performed with robots and CNC motion systems in combination with IWS powder nozzle technology. The direct deposition processes offer advantages over powder bed based technologies in that they coat larger parts faster and have fewer restrictions with respect to part sizes.

Over the past 7 years the lithium ion-battery technology has become a core competence at Fraunhofer CLA. The center performed numerous projects with several large industrial customers to develop laser welding technologies for lithium-ion battery manufacturing. Some of the results were already transferred successfully to production. This work will be continued in the coming years.

The center participates in trade fairs and conference as these present proven opportunities to acquire new customers. During the next ALAW from June 6th – 8th 2016 the Fraunhofer CLA will invite conference participants to visit its laboratories and exchange experiences with Fraunhofer researchers. In 2015 150 participants made use of the opportunity to attend the Open House.

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FRAUNHOFER PROJECT CENTER AND WROCLAW CENTER OF EXCELLENCE FOR MANUFACTURING

The Fraunhofer Project Center Laser Integrated Manufacturing (PCM) was founded in 2008. Its research work focuses on three main areas:

- contract research and development for industrial customers,
- publically funded research projects on the level of national, bilateral and European research and development programs,
- internal projects to strengthen the competences of both partners.

The expertise of the Project Center is based on the core competences of the laser oriented business units at the Fraunhofer IWS Dresden:

- cutting, ablation and joining,
- micromachining and thermal coating,
- BigData platform for production and medicine,
- surface technology,

as well as on the fundamental areas of the CAMT (Center for Advanced Manufacturing Technologies) of the Wroclaw University of Technology:

- manufacturing technologies, including additive manufacturing,
- production management and quality testing system,
- production automation and control.

The establishment of the Wroclaw Center of Excellence (WCE) was and will be the focus of the work in 2015 and 2016. The Wroclaw University of Technology is successfully expanding the existing network by closely collaborating with the National Center for Research and Development and renowned German research institutions such as the University of Würzburg and the Fraunhofer IWS in Dresden. WCE's vision encompasses innovative state-of-the-art technology and device development, business activities through interactions with established Polish and European companies and the starting of spin-off companies. Special foci are new materials, nanophotonics, additive laser-based technologies and new management and organization systems.

WCE will combine manufacturing technology developments with nanophotonics to create novel designs, more efficient system solutions and the associated services in the following areas:

- manufacturing of multi-material elements, components with interesting mechanical/thermal/chemical properties and complete multifunctional products,
- creation of properties, which cannot be achieved by conventional micromachining systems,
- image processing for process and quality control, monitoring and controlling of laser processes,
- integrated systems for customer-specific designs and additive manufacturing of individual products,
- commercial and affordable systems for production planning and control for modern industry,

Partner consortium of the Wroclaw Center of Excellence

- real-time simulation of manufacturing processes based on 3D hall layout,
- automated manufacturing processes for sensors and device networks based on the Internet of Things,
- development of infrared photon devices and systems based on new materials to replace toxic ingredients such as mercury and cadmium,
- low power solutions with photonic components for portable gas sensors,
- new semiconductor devices, immune to external conditions such as temperature, pressure or mechanical shock,
- durable photonic components for more efficient sensor systems and their application in hard-to-reach remote areas,
- development of epitaxial and post-growth process technologies to manufacture novel photonic and optoelectronic devices, which exceed the performance of existing devices.

The second important activity is the project "MedMODEL" (2016-2018). This project is eligible for funding from the INTEREG-program for the bilateral cooperation between Lower Silesia and Saxony. The aim of this project is the development and integration of unified standards into daily practice for the planning of surgical processes based on pre-operative models made by additive manufacturing technologies.

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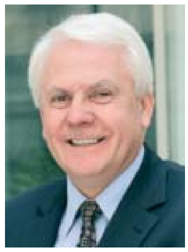

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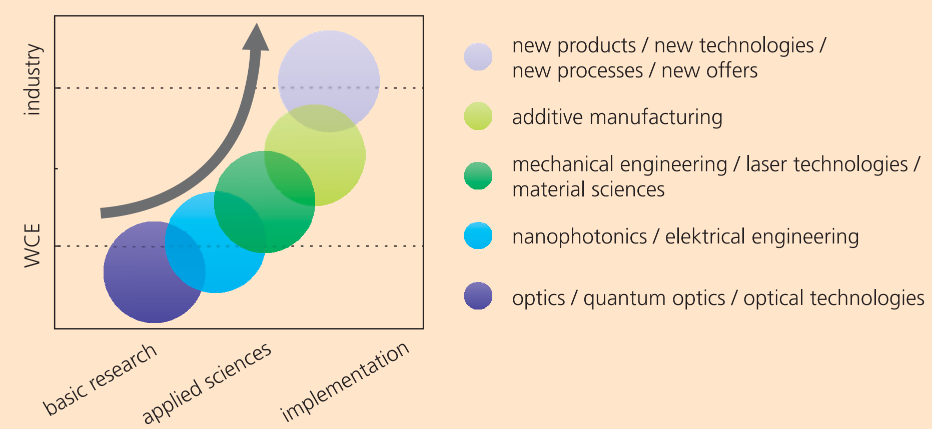
The consortium consists, among others, of the Wroclaw University of Technology (CAMT), Fraunhofer IWS, University Hospital Dresden, Technische Universität Dresden, Marshall Office of the Voivodship Lower Silesia and the specialized clinic Alfred Sokolowski in Walbrzych.

Technology transfer and utilization in WCE



SURFACE TECHNOLOGY CENTER DORTMUND – DORTMUNDER OBERFLÄCHENCENTRUM (DOC®)

For flat and other steel products, surface technologies are of prominent significance and will become ever more important in the future. Therefore, Thyssen-Krupp Steel Europe AG (TKSE) is concentrating its surface technology research in Dortmund. At the Dortmunder OberflächenCentrum DOC® (Surface Technology Center in Dortmund, Germany) a team of world leading research institutions collaborates in the field of surface technologies for steel materials. Here researchers develop tailored coating solutions that can be applied to continuous steel strip processes. Customer-focused development goals include novel surface treatment concepts that lead to superior properties, such as ,for example, increased corrosion resistance, scratch resistance, electrical conductivity, formability or cleaning properties. Current research activities also address the development of flat steel products with entirely new functionalities based on solar thermal or photovoltaic properties as well as the development of novel lightweight materials.

The Fraunhofer IWS cooperates as a partner at the DOC® with a project group. The group's development portfolio includes surface coatings based on PVD, PACVD and spray processes and laser materials processing activities.

Current foci in the field of thin film coatings are:

- development of conductive carbon coating systems with good forming properties,
- graphite-like carbon (GLC) and plasma nitro carburized surfaces for electro mobility, e. g. for steel bipolar plates used in fuel cells, as well as Al and Cu electrodes for batteries and super capacitors (e. g. conductivity comparable to gold without degradation in fuel cell stack test, see page 34),
- Diamor® coating systems (ta-C: tetrahedral amorphous carbon) for wear protection based on short pulsed arc (spArc®) technology (e. g. successful transfer to production for self-sharpening kitchen knives),
- novel PVD high performance processes at pressures above 30 mbar, which are used to refine continuous steel strip with corrosion protection based on zinc alloys, e. g. for highly corrosion resistant metallic coatings (e. g. ZnMg) and metallic coatings for hot working (e. g. ZnFe).

Current foci in laser materials processing and spray technologies are:

- development of joining processes based on laser MIG hybrid welding for lightweight construction, e. g. for the welding of mobile crane components made from high-strength fine-grained structural steels (see Figure on page 132),
- low splatter and high speed laser welding with solid state lasers of high beam quality,
- arc wire spraying,
- combination of joining and arc spraying processes for example to post-galvanize welding seams,
- remote welding of vehicle components,
- continuous laser surface processing of steel strips.

The Fraunhofer project group has a laboratory of 1100 m^2 and offers a number of additional complementary surface refinement processes. Using the latest machine technology in combination with solid-state lasers, the group offers arc wire spray deposition under vacuum conditions, that is, the deposits are not exposed to oxygen during the processes. Furthermore, it is possible to wear-proof highly stressed areas on components and tools by laser cladding or the deposition of millimeter thick protective coating with laser buildup welding. Meter-sized and ton-heavy parts can be coated in vacuum with nano- to micrometer thick high performance layers such as Diamor® coating systems using the cost-effective and robust spArc® process. These coatings have superior hardness and excellent friction properties. They are deposited at high rates and substrate temperatures below 150 °C. More coating materials with additional corrosion protective properties are under development.

The Fraunhofer project group at DOC® has the following systems at its disposal:

- modular spArc® evaporator technology with a large-sized industrial PVD chamber. The useful chamber diameters as well as the coating height are 1.2 m each. The substrate weight limit is 1.2 metric tons,
- in-house developed PVD technology to refine steel strip under rough vacuum conditions,
- modern arc wire spray technology with cabin, vacuum chamber and the possibility to combine the process with a laser,
- 3D capable laser and laser-MIG hybrid welding machines (cantilever gantry unit, robot systems) with mobile 8 kW fiber laser,
- remote welding technology.

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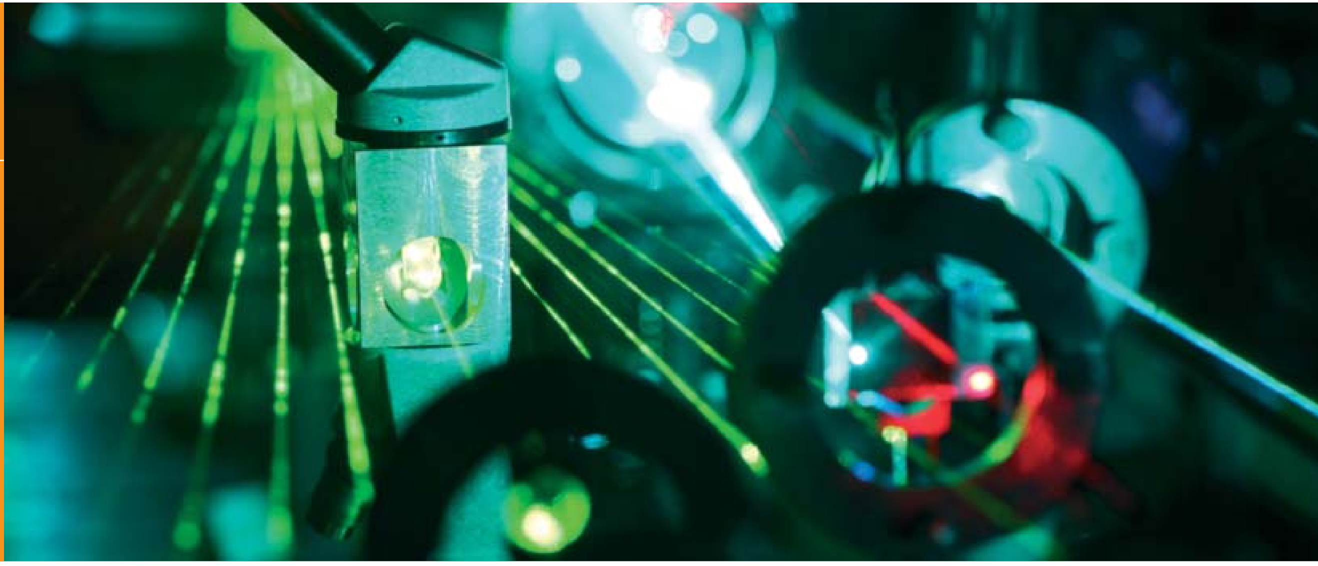
Within joint projects it is also possible to use machinery owned by Fraunhofer IST and TKSE. For example, the Fraunhofer IWS project group collaborates with IST and TKSE on researching vacuum deposition processes for the continuous refinement of thin sheet metal strip. This work is performed on TKSE's 80 m long steel strip pilot line located at DOC®.

The processes cover a wide range of technologies, which often can be combined using Fraunhofer IWS know-how to provide economically sound and technically optimized solutions to TKSE, TKSE's customers and other industry clients. Novel, compact and mobile 8 kW solid-state lasers are not only used for process development but also for trouble-shooting on-site, directly at the customer's location, at short notice and close to production.



APPLICATION CENTER FOR OPTICAL METROLOGY AND SURFACE TECHNOLOGIES

The new Fraunhofer IWS Application Center for Optical Metrology and Surface Technologies (AZOM) launched operations in August 2015. The center is located near the West Saxon University of Applied Sciences of Zwickau (WHZ) and forms a bridge between the Fraunhofer IWS and the regional industries in Western Saxony.

Currently the IWS as well as the partner WHZ have numerous industrial customers in Saxony and its bordering regions of Eastern Thuringia and Upper Franconia. The application center will enable both institutions to bundle their research and development services as well as their educational opportunities in the region. The new application center is in the position to substantially contribute to strengthen the economy in the southwest region of Saxony.

The Fraunhofer application center's technical orientation intersects with the needs of the typical industries of the region, these are mechanical, automotive and medical engineering. The competences of the application center complement those of Fraunhofer IWS business fields in the areas of optical metrology, sensorics and surface technologies. The work foci and competences of the new Fraunhofer application center include particularly the following areas:

IMAGE PROCESSING AND OPTICAL PROCESS CONTROL

- industrial process monitoring
- non-destructive characterization of components
- optical imaging methods in medical technology
- high speed imaging of thermal processes
- application specific automation solutions

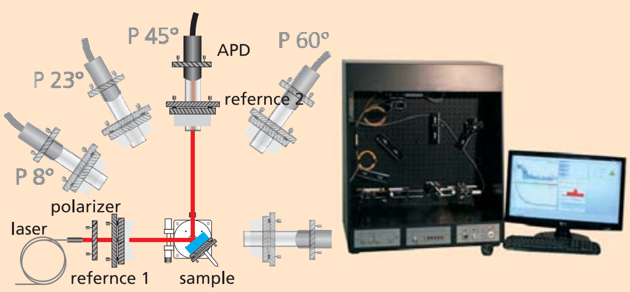
PHOTONIC SYSTEM COMPONENTS, FIBER TECHNOLOGIES AND OPTICAL METROLOGY

- laser beam characterization and stability studies
- nonlinear optics technologies
- development of special light sources
- measurement of human functional parameters
- optic sensor elements for bio micro sensorics
- fiber measurement technologies (dispersion measurements)
- fiber sensorics
- coating analysis techniques (e. g. CRD measurement system, see figure below)

SURFACE AND MATERIALS TECHNOLOGIES

- interferometric surface and coating analysis
- optical analysis of materials parameters in surface processes
- surface modification of implants
- optical measurement techniques in the field of quality of life
- laser based spectroscopy techniques
- color and texture measurement techniques

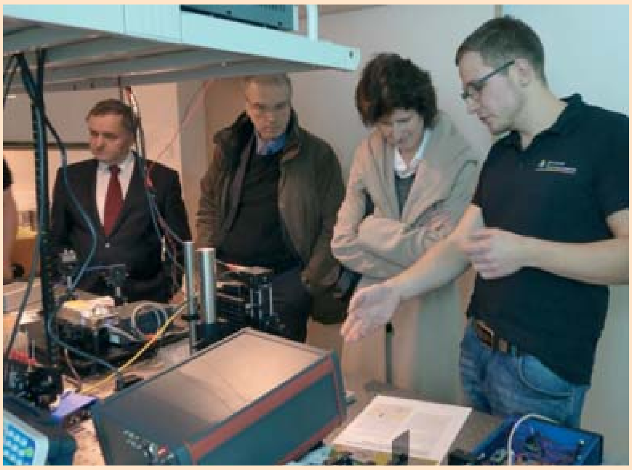
Cavity ring down measurement system to determine optical losses of high-end coatings



The close contact to the WHZ is an essential part of the concept of the new Fraunhofer IWS application center. In parallel to starting scientific research at the new center, several WHZ students commenced work on their bachelor and master theses. The AZOM will also intensify its integration into teaching activities at the WHZ. In the coming winter semester, the Fraunhofer IWS and WHZ will offer joint lectures.

The close collaboration of AZOM with IWS was expressed during a joint booth at the Laser World of Photonics 2015 tradeshow in Munich. The team presented a technology for monitoring laser welding processes, which was developed at AZOM. In 2016 AZOM will participate in the "Innovation Evening for Industry – Industry@Fraunhofer IWS" as well as in the laser symposium "Fiber, Disc & Diode" and the joining technology symposium "Tailored Joining". Additional tradeshow participations are being planned.

Visit of the Saxon Minister of State for Science and Art Dr. Eva-Maria Stange (3. f. l.), Head of Division Hermann Jaekel, SMWK (2. f. l.) and the Rector of the WHZ Prof. Dr. Gunter Krautheim (1. f. l.) at the project group AZOM at the WHZ



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FRAUNHOFER APPLICATION CENTER FOR OPTICAL METROLOGY AND SURFACE TECHNOLOGIES AZOM

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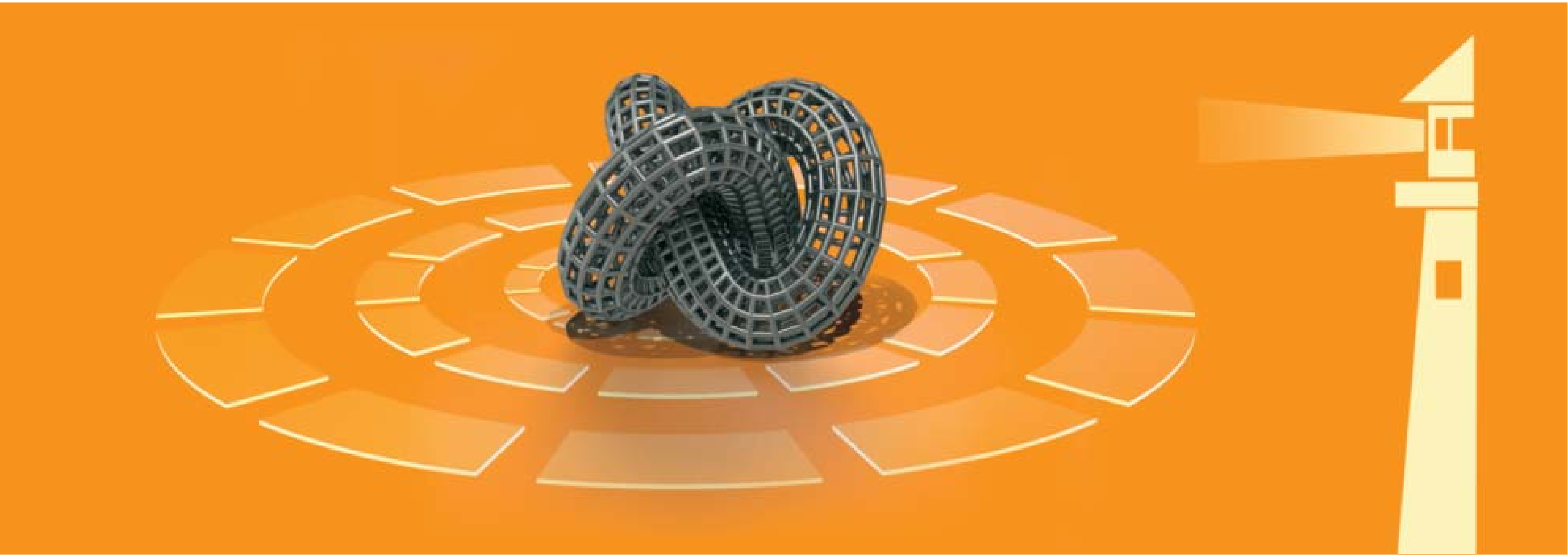
AZOM is located near the inner city campus of the WHZ. Over the coming months laboratory and office space of 472 m^2 will be built out. In parallel, modern measurement systems and laboratory equipment are being acquired, installed and paid using state funding. The Free State of Saxony supports the creation of the Fraunhofer application center with 2.6 million euros over the period from 2015-2020.

Essential to the success of the IWS application center will be the establishment of successful research collaborations with industry. AZOM researchers are already working on projects for partners from the automotive industry, where they are working to implement optical metrology for manufacturing processes.



ADDITIVE MANUFACTURING – COMPETENCE IN MATERIALS AND MANUFACTURING ENGINEERING

The additive manufacturing of components leads to a paradigm shift in manufacturing technologies. When building a part layer-by-layer materials are only used where they are needed. Furthermore, additive manufacturing concepts allow new degrees of freedom, which surpass the limitations of conventional manufacturing with respect to optimizing parts for their function, realizing new design geometries and in terms of production flexibility. Accordingly, industry is very much interested in the qualification of additive manufacturing processes for the manufacturing of products with industrial quality.

While additive manufacturing offers great potential there are also numerous unsolved questions. These can only be answered through close collaboration between industry and science. One of such initiatives is the project "Additive generative manufacturing" (in short Agent-3D), which was initiated by Fraunhofer IWS. A consortium of more than 80 partners drives forward the development of additive manufacturing methods and builds a network between industry and research organizations.

The Fraunhofer IWS together with the TU Dresden established an internationally recognized competence Center for Additive Manufacturing within the framework of "DRESDEN-concept". The center uses a wide range of process technologies to work on manufacturing processes and materials solutions to fabricate challenging products. Current foci are in the aerospace, automotive, energy, tool ,die and medical industries. The center offers the ideal networking platform for industry with basic research at universities and applied research in a rapidly developing high technology field.

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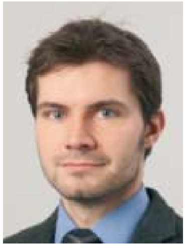

www.iws.fraunhofer.de/additivemanufacturing

The available range of processes includes among others:
- laser buildup welding with powder and wire,
- selective laser and electron beam melting,
- 3D printing

for metallic and nonmetallic materials, plastics, functional materials as well as multi material systems. In addition to process development current efforts address the development of systems technology, sensorics and process diagnostics. The research at the Center for Additive Manufacturing focuses on typical process chains for products in different industries. This starts with component design and includes the actual manufacturing process as well as post-processing steps, repair and recycling. Another competence of the center is the evaluation and testing of the generated materials and components.

ENERGY EFFICIENCY – WE ARE NOT FINISHED YET!

Economical energy use and resource-conserving technologies are of central concern at Fraunhofer IWS. Since its establishment the institute has developed and deployed numerous technologies, which have provided substantial energy savings to industry and society. One example was the development of a novel and locally applied heat treatment process, which increased the energetic efficiency of steam turbines. Likewise, a laser treatment was developed to increase the efficiency of transformers.

The IWS also deployed a laser welding technology for the lower fuselage structures of several airbus models, which allowed for a significant weight reduction of the structure. In the case of the A340-600 the weight savings are about 100 kilograms. Laser welding of primary structures provides weight savings of about 10 percent.

Another example is the mass production of automotive transmission parts. Here laser welding processes are indispensable. Aims are to reduce fuel consumption and to improve the overall energy balance. IWS' low friction coatings offer another way to further reduce fuel consumption. This IWS technology is on its way to broad industrial use in combination with the systems technology for Diamor® deposition.

Energy efficiency is a future topic, which will be further expanded in the region of Dresden. The "Dresden Innovation Center Energy Efficiency DIZE^{EFF}" was established in 2009 to drive forward and accelerate innovations for industry beyond institutional boundaries. Fraunhofer IWS coordinates this center. Researchers of the TU Dresden and Dresden's Fraunhofer institutes collaborate on numerous research tasks in the fields of high performance solar cells, fuel cells and energy efficient manufacturing as well as energy saving display technologies.

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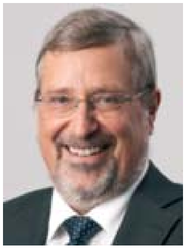

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www.iws.fraunhofer.de/energy

Current IWS developments focus on capturing thermal energy via thermoelectric generators and on the reduction of magnetic losses in electromotors. Each year IWS presents latest results in the field of energy efficiency at the Hannover Trade Fair as well as at the "Future Energy" conference.
See www.zukunftenergie-dresden.de/en

BATTERY RESEARCH AT IWS – TECHNOLOGIES FOR NEW ENERGY STORAGE SYSTEMS

Research on electro mobility and stationary energy storage are central topics at IWS Dresden. IWS engineers develop know-how on numerous manufacturing technologies and thus provide essential contributions and innovations to many processing steps in battery manufacturing. The IWS Center for Battery Research was established to offer solutions to industry based on the latest equipment available.

IWS goals are to develop battery solutions ranging from materials development and electrochemistry to cell and module production. Jointly with partners from industry and research institutions, IWS engineers work on research tasks along the value-added chain and implement processes to fabricate and evaluate prototype cells.

Currently the IWS works on publically funded projects to develop materials and technologies:

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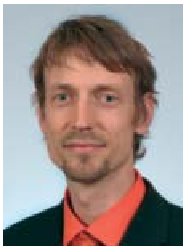

www.iws.fraunhofer.de/battery

DEVELOPMENT OF LITHIUM-SULFUR BATTERIES FOR MOBILE STORAGE

Lithium-sulfur batteries offer high gravimetric energy densities and low material costs compared to lithium-ion batteries. The cell chemistry is very attractive for future storage solutions especially for increasing the driving range of electric vehicles. IWS produces prototype cells with 3 Ah capacity, which can be used to evaluate new material and cell concepts. The EU project ALISE began in 06/2015 to develop Li-S cells for automotive applications with the participation of high level European partners.

DEVELOPMENT OF SODIUM-SULFUR BATTERIES FOR STATIONARY STORAGE

Sodium-sulfur based batteries provide energy storage with low cost raw materials that are available worldwide. This provides an ideal situation for energy storage systems that are designed to relieve the power grid and to support the further expansion of using renewable energy sources. The development of a room temperature sodium-sulfur battery is funded in the BaSta project (BMWI: FZJ 0325563A). First prototype cells for 1000 charging cycles and are now being deployed in a first battery module.

"TAILORED JOINING" – JOINING TECHNOLOGY COMPETENCES IN DRESDEN

Joining is a central production challenge and often a significant cost factor. Current joining technology developments may often offer important improvements and impulses. Fraunhofer IWS, TU Dresden and additional partners established the joining technology center "Tailored Joining". The center offers an overview of possibilities and limitations of the various joining techniques and provides an unbiased comparison of possible solutions. The basis of the center is the internationally exceptional bandwidth of joining processes, which are intensively researched and developed in Dresden.

In the area of IWS industry-focused applied research these processes include:

- laser beam welding,
- laser hybrid welding (plasma, arc, induction),
- brazing with laser and reactive multilayers,
- magnetic pulse welding (forming and welding),
- friction stir welding,
- interlocking laser beam welding (web-slot connections),
- diffusion welding (laser induction roll plating),
- adhesive bonding and direct thermal joining of metal-plastic mixed joints.

Our TU Dresden partner (chair for joining technology) focuses on processes and tools in the areas of thermal joining (arc processes, soldering), forming-based and mechanical joining (screwing, pressing) as well as hybrid joining. This includes the overall planning of assembly, handling and joining processes.

Since 2014, Dresden's University of Applied Sciences has supported the collaboration with know-how in the area of electron beam welding. All partners pay special attention to providing an unbiased comparison of various solutions to support the user's decision making process.

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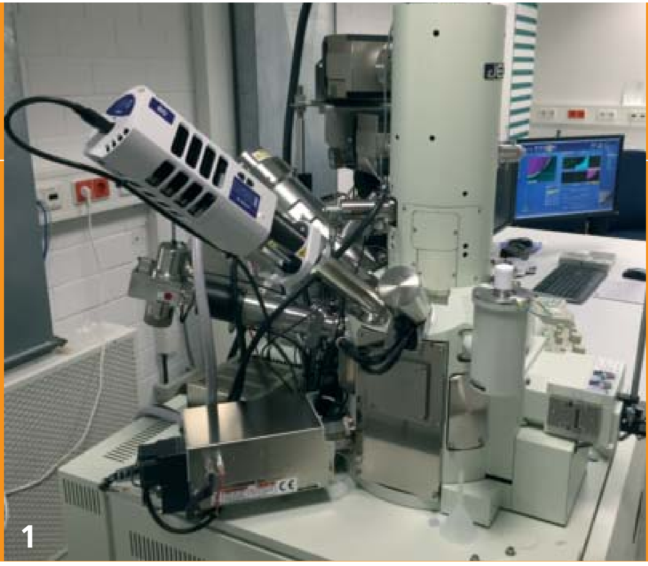
The joining technology symposium "Tailored Joining" is a proven forum to exchange experiences. The symposium was run in parallel with the international laser symposium "Fiber, Disc & Diode" on February 23rd and 24th 2016. A wide range of modern joining processes and current developments will be presented. Basic courses are offered on selected processes, which are combined with practical demonstrations in the laboratories of participating partners. Novices can use these opportunities to quickly familiarize themselves with the technology and to evaluate its possibilities and limitations. More information is provided here: www.fuegesymposium.de/en



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COMPETENCE FIELD MATERIALS CHARACTERIZATION AND TESTING

New high performance materials are the foundation and the driver for the development of reliable and innovative products of tomorrow's world. A broad spectrum of experimental experiences and a deep understanding of the physical processes inside materials are required to fully exploit the potential of classic as well as novel structural and functional materials. This is the only way to advance sustainable innovation in the areas of product design, systems development and process optimization.

The competence field Materials Characterization and Testing faces this challenge and offers services to all IWS business fields as well as to external industry customers. New materials with better properties almost always require adapted processing technologies and the evaluation of the relating component properties. Highest quality standards are achieved by establishing a timely feedback loop between materials characterizaion and application tailored processing technologies. The close integration of materials analytics with testing is one of the cornerstones of the powerful IWS team.

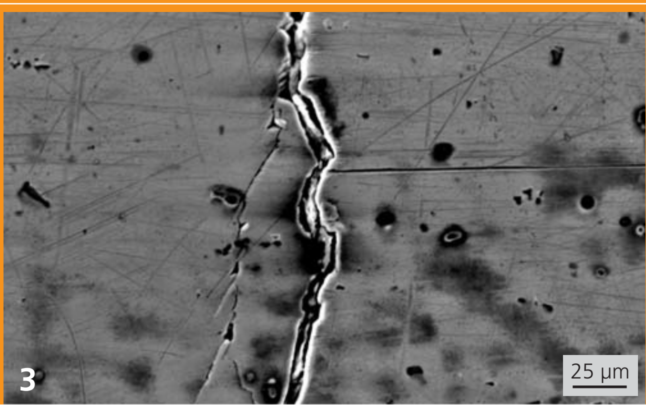
The offer includes the determination of mechanical parameters of materials and material composites, the establishment of characteristic curves to evaluate the fatigue strength in particular with timesaving high frequency testing and the high resolution imaging and analytic characterization of laser modified surfaces, joining interfaces, thin film systems, nanotubes and nanoparticles.

Recent highlights included the upgrading of in-house experimental capabilities with a focused-ion-beam (FIB) analytics, which is used concurrently with SEM as well as EDX and EBSD analytics (Fig. 1). A prototype of a 1000 Hz resonance pulsator test stand was added to the high frequency fatigue testing laboratory (Fig. 2). In addition to a well equipped and modern metallographic laboratory the materials competence team has the following systems:

- ultra high resolution field emission scanning electron microscope (FE-SEM),
- high resolution scanning electron microscope for "low vacuum" operation with large sample chamber,
- analytical 200 kV transmission electron microscope,
- ion beam preparation, sputter and evaporation systems,
- axial/torsional fatigue test system with a torsional moment of 8 kNm and a maximum axial load of 40 kN,
- ultrasonic fatigue tester with preload (f = 20 kHz).

Current research foci in materials testing and failure analysis are:

- the characterization of low friction and wear resistant coatings such as ta-C carbon films, which often have complex and multiphase transition zones between substrate and ta-C coating that are critical to the reliability of the coating. The analysis of such substrate/coating interfaces requires special preparation routines for TEM foils so that the true microstuctural compositions can be made visible,
- the high resolution electron microscopic analysis of intermetallic phases in mixed material joints (e. g. Al-Cu joints that are of significant importance to electro mobility) studies the influence of the often very brittle intermetallic phases on the electrical properties of the joint and on its operational safety.



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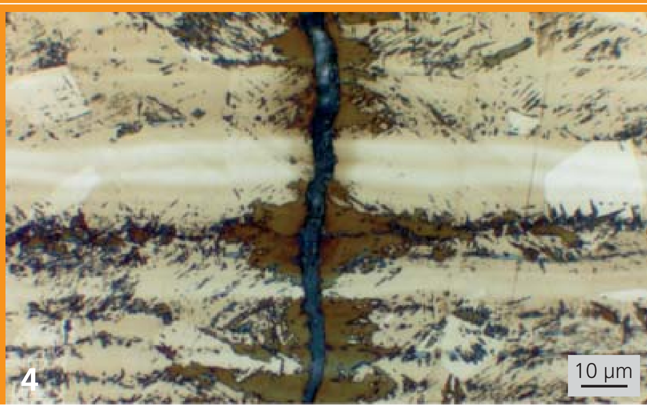

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Failure analysis is another area that benefits from the experience, materials and process know-how of the IWS team. In addition to identifying the cause of failures, IWS experts consult customers with respect to alternative materials solutions, design optimizations and process improvement to prevent future damage. Projects benfit from the close collaboration of experts from metallography, analytics and materials testing.

Current analysis foci in the area of materials and component testing are:

- fatigue testing of mixed material joints (e. g. those made from hard-to-weld material combinations such as case hardened steel and cast iron) as they are used in powertrain applications, the development of test specimen similar to components and the development of testing strategies where the joint is the most stressed structure, which enables early estimates about the reliability of joined components,
- the determination of materials parameters to predict the failure-critical areas of laser processed structures, such as for example for laser-strengthened sheet metal constructions as they are used in crash-stressed components, here it was evaluated what influence geometric and structural notches have on the static and cyclic fatigue strengths,
- the fatigue behavior of various materials and composites for very large numbers of load cycles (beyond the classic fatigue limit), including stainless steel, aluminum and nickel-based alloys as they are supposed to be used in the future in highly efficient power plants.

Determining the key material parameters to predict the deformation behavior, strength properties and crack growth behavior (Fig. 3) of materials and structures is only one central element of the many activities of the materials competence team. As a rule, experimental results will be complemented with comprehensive fractography, often also applying electron microscopy to reveal texture characteristics, which could be responsible for crack initiation (Fig. 4). These results are used to derive materials and process strategies to improve the application-related requirements. One example was the identification of the importance of burr minimization for the fatigue strenght of laser cut structures.

The department Materials Characterization and Testing is intensively engaged in the education of materials testers and thus contributes to making this thrilling profession accessible to young people. Through personnel appointments the department is closely connected to the Professorship of Mechanics of Materials and Failure Analysis at the TU Dresden. This ensures steadily growing know-how through basic research as well as the targeted development of young people for the field.

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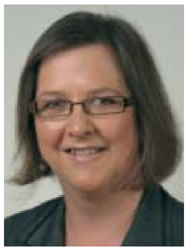

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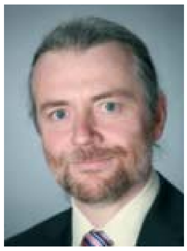
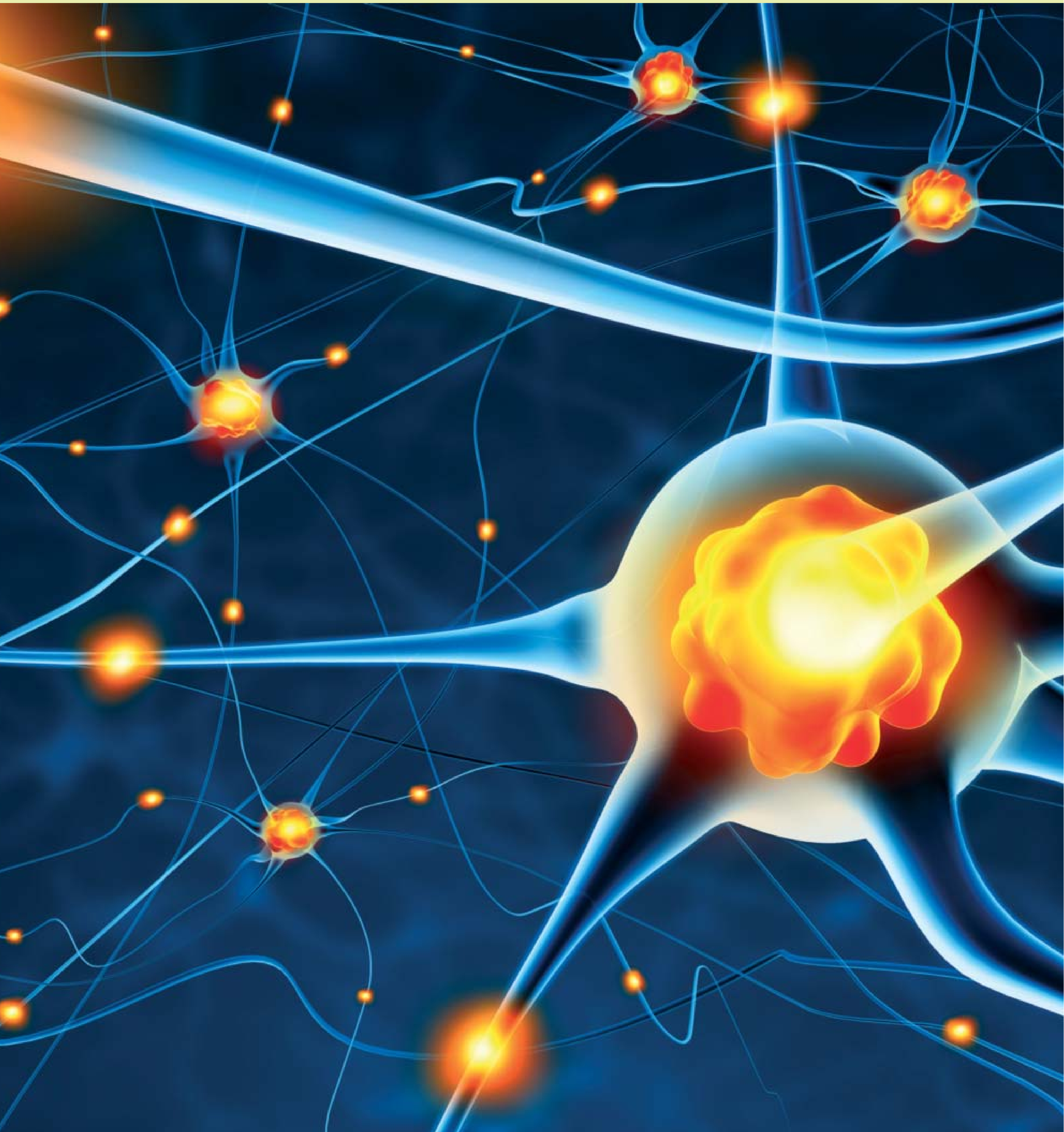


www.iws.fraunhofer.de/characterization

NETWORKS



Joseph von Fraunhofer

THE 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.

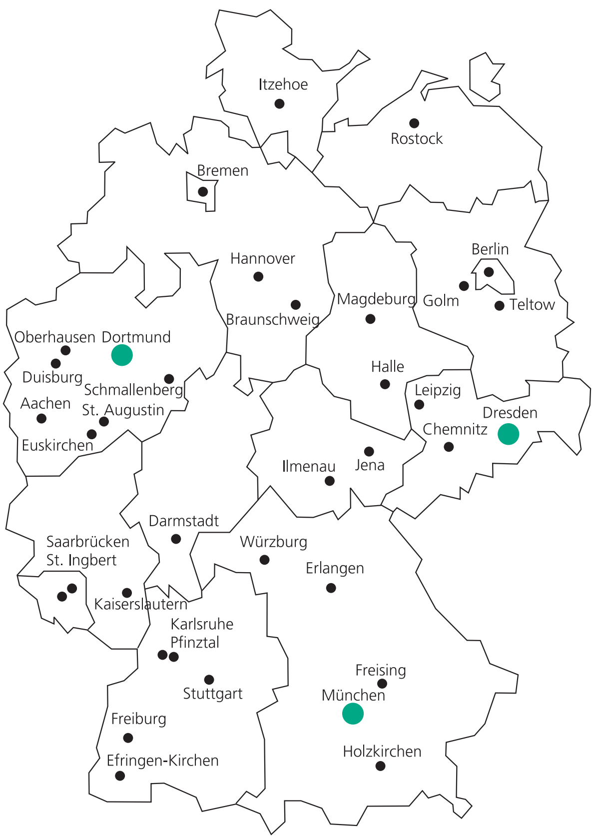
At present, the Fraunhofer-Gesellschaft maintains 67 institutes and research units. The majority of the nearly 24,000 staff are qualified scientists and engineers, who work with an annual research budget of more than 2.1 billion euros. Of this sum, more than 1.8 billion euros is generated through contract research. More than 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Almost 30 percent is contributed by the German federal and Länder 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.

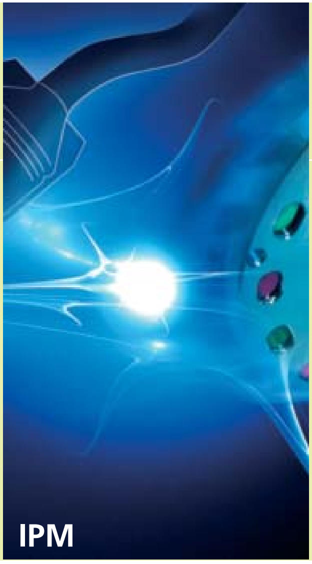
International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

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.





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

CONTACT

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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, the 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 APPLIED OPTICS AND PRECISION ENGINEERING IOF, JENA

The 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 SURFACE ENGINEERING AND THIN FILMS IST, BRAUNSCHWEIG

As an industry oriented R&D service center, the 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 MATERIAL AND BEAM TECHNOLOGY IWS, DRESDEN

The Fraunhofer Institute for Material and Beam Technology is known for its innovations in the business units joining and cutting as well as in the surface and coating technology. Across all business units our interdisciplinary topics include energy storage systems, energy efficiency, additive manufacturing, lightweight construction and big data. Our special feature is the expertise of our scientists in combining the profound know-how in materials engineering with the extensive experience in developing system technologies. Every year, numerous solutions with regard to laser material processing and coating technology have been developed and have found their way into industrial applications.

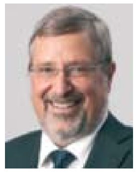
www.iws.fraunhofer.de

EXCELLENT COOPERATION PARTNER TU DRESDEN

The cooperation with the TU Dresden began in 1997. Since then the Fraunhofer IWS has continuously expanded the cooperation with various university chairs. Such collaboration enables the combination of the broad basic science know-ledge of the university with the applied development work performed at the IWS. Professors and coworkers at the TU Dresden are closely involved in IWS research projects and have access to the technical equipment and infrastructure at the institute. IWS management and coworkers support the university in educating students and graduate students. Junior scientists emerge from this pool. This effort is driven by these scientists:

FACULTY OF MECHANICAL SCIENCE AND ENGINEERING INSTITUTE OF MANUFACTURING TECHNOLOGY

CHAIR OF LASER AND SURFACE TECHNOLOGY
PROF. DR.
ECKHARD BEYER



Topics:
- laser systems technology
- laser machining processes
- plasma in manufacturing
- surface technologies
- manufacturing technologies
- laser robotics

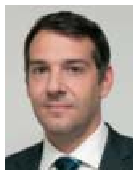
FACULTY OF MECHANICAL SCIENCE AND ENGINEERING INSTITUTE OF MANUFACTURING TECHNOLOGY

CHAIR OF NANO- AND COATING TECHNOLOGY
PROF. DR.
ANDREAS LESON

Topics:
- nanotechnology
- thin film technology

FACULTY OF MECHANICAL SCIENCE AND ENGINEERING INSTITUTE OF MANUFACTURING TECHNOLOGY

CHAIR FOR LARGE AREA BASED SURFACE MICRO/NANO-STRUCTURING
PROF. DR.
ANDRÉS-FABIÁN LASAGNI



Topics:
- fabrication of large area 2- and 3D micro and nanostructures
- surface functionalization
- laser structuring
- two photon polymerization
- simulation of structuring processes
- process development

"There is joy in work. There is no happiness except in the realization that we have accomplished something.«
Henry Ford

FACULTY OF MECHANICAL SCIENCE AND ENGINEERING
INSTITUTE OF MATERIALS SCIENCE

CHAIR OF MATERIALS SCIENCE
PROF. DR.
CHRISTOPH LEYENS

Topics:
- metallic and intermetallic high temperature materials
- ferrous and nonferrous materials
- surface and coating technologies
- relationships between microstructure and properties of metallic materials

FACULTY OF MATHEMATICS AND NATURAL SCIENCES
DEPARTMENT OF CHEMISTRY AND FOOD CHEMISTRY

CHAIR OF INORGANIC CHEMISTRY
PROF. DR.
STEFAN KASKEL

Topis:
- synthesis, characterization and application of porous materials
- inorganic nanoparticles
- nanocomposites and hybrid materials

FACULTY OF MECHANICAL SCIENCE AND ENGINEERING
INSTITUTE OF MATERIALS SCIENCE

CHAIR OF MECHANICS OF MATERIALS
AND FAILURE ANALYSIS
PROF. DR.
MARTINA ZIMMERMANN

Topics:
- mechanical properties and microstructure
- fatigue (high frequency test engineering)
- failure analysis and prevention
- structure and component reliability

FACULTY OF MEDICINE
CLINIC FOR NEUROLOGY

CHAIR OF DATA MANAGEMENT
AND EVALUATION
PROF. DR.
KAROL KOZAK

Topics:
- imaging
- machine learning
- BigData

DRESDEN LIGHT YEAR 2015

The UNESCO declared 2015 as the "International Year of Light and Light-Based Technologies". In this context the Fraunhofer IWS participated with numerous partners in events related to the "Dresden Light Year 2015". The importance of light was underlined as an elemental condition for the life of humans, animals and plants. Thus light is an essential and central component of science and culture. Highlights of the "Dresden Light Year 2015" were:

January 19th, 2015

Opening event of the "Dresden Light Year 2015" festivities. The Dresden artist group KAZOOSH! developed the media art installation "TALKING TOWER" at the Ernemann building of the Technical Collections Dresden.

February 25th-26th, 2015

The International Symposium "Additive Manufacturing" at Fraunhofer IWS Dresden connects additive manufacturing experts with more than 150 potential users of this fascinating technologies and shows laser light in action.

April 23rd, 2015

During Girls' Day IWS researchers introduce young girls to the diversity of laser technology. The girls were eagerly and excitedly experimenting with light and laser technology.

April 29th, 2015

Third through fifth grade students are guests at the Fraunhofer IWS as part of the City of Dresden's "JUNIORDOKTOR" program. The topic of the event is "Let there be light". The children learn how laser light is created, why it may be red or green and how one uses light to cut metals.

June 19th, 2015

The exposition "Hi Lights" opens at the Technical Collections Dresden. This is a very special highlight of the "Dresden Light Year 2015" activities of the Fraunhofer IWS and Dresden's research, education and cultural institutions. The exposition offers hands-on experiments to introduce the history of the sciences related to light and tells the story of the development of the laser. The "Photonics Arena" shows the most important applications of current photonics research (page 149 bottom) in the form of experimental setups, prototypes and interactive exhibits. The exhibition at the Technical Collections Dresden facilities remains open to the public until June 30th 2016.

June 27th, 2015

Premiere of the the research theatre "Light!" at the Technical Collections Dresden. The play asks about the fascination with a natural phenomenon, its scientific research and its modern technical developments. The coproduction invites to dive into a world of illusions, of seeming and being and inspires enthusiasm, especially in young people, for one of the most important and simultaneously dynamic areas of current technology research.

July 3rd, 2015

Fraunhofer IWS opens its doors to visitors to attend the "Long Night of the Sciences" event. The new buildings at Winterbergstraße 31f house the "Center for Resources-Saving Energy Technologies" and are opened to the public for the first time. Local residents and interested visitors use the opportunity to look over the shoulders of researchers in the new building.

August 24th-28th, 2015

4th International Summer School "Trends and new developments in laser technology":

The one-week event gathers international junior scientists for intensive studies of the basics and applications of laser technology.

November 5th, 2015

At the Technical Collections Dresden, the Dresden Center of Science and Art awards the 2nd Science-Art prize. The awardee of the "KuWiDresden 2015" is Detlef Schweiger for his CD sculpture. The award acknowledges achievements in the interdisciplinary interaction with novel technologies and scientific topics in the field of optical effects and systems.

January - December, 2015

The Thalia cinema runs the film series "Lichtspiel" in cooperation with Dresden's science institutions and companies. The series includes documentaries and feature movies addressing all facets of the topic "light". A highlight is the presentation of the movie "Interstellar" at the the stage of the "Movie nights at the banks of the river Elbe" at which about 3000 people participated (page 148 above).

The screening of the movie "Hugo Cabret" on December 28th 2015 is the closing event of the "Dresden Light Year 2015" festivities. More than 50 events delight numerous children, adolescents and adults, novices as well as experts.

www.dresdner-lichtjahr.de/en

AWARDS AND HONORS

A researcher team from Dresden received the Green Photonics Award 2015 at the PHOTONICS West 2015 SPIE international optics and photonics conference in San Francisco. Prof. **Andrés Lasagni** and Mr. **Sebastian Eckhardt**, both employees of Fraunhofer IWS and the Institute of Manufacturing Technology at the TU Dresden, Lars Müller-Meskamp from the Institute of Applied Photo Physics as well as Dr. **Mathias Siebold** and **Markus Löser** from Helmholtz Center Dresden Rossendorf received the award for their joint work on the topic "Manufacturing of highly efficient, transparent metal thin film electrodes with direct laser interference patterning" in the category of laser assisted manufacturing and micro/nano manufacturing.

On March 18th, 2015 Prof. **Eckhard Beyer** received the AILU International Award 2015 from the Association of Laser Users (AILU) to honor his extraordinary contributions to the field of industrial laser materials processing. Prof. Beyer received this award as a pioneer and international leader in laser materials processing. The director of the Fraunhofer IWS in Dresden and director of the Institute of Manufacturing Technology has supported AILU (Association of Laser Users) as an active member for many years. The AILU awarded the prize to Prof. Beyer to thank him for numerous contributions and presentations, which were provided to laser users in the UK.

On June 9th, 2015 Prof. **Andreas Leson**, Dr. **Hans-Joachim Scheibe** and Dr. **Volker Weihnacht** received the Joseph-von-Fraunhofer Prize 2015 for the development of the Laser-Arc process and the application of ta-C coatings in series production. The award was issued during the Annual Meeting of the Fraunhofer-Gesellschaft. The researchers modified the Laser-Arc

process so that the desired coatings can be deposited precisely controlled and with high deposition rate. The new technology meets to a high degree the industrial quality and cost requirements for wear resistant coatings. The process is already being used by numerous companies in the automotive, supplier and tool manufacturing industries to produce high value components.

On April 29th, 2015 Dr. **Susanne Dörfler**, Mr. **Markus Piwko** and Mr. **Patrick Strubel**, all employees of Fraunhofer IWS and the Institute of Inorganic Chemistry at the TU Dresden, were recognized by winning 1st place with their poster about new materials and cell concepts for lithium-sulfur batteries. The award from the Federal Ministry of Education and Research was presented during the conference i-Wing 2015.

The IWS-Award winners were recognized on December 18th, 2015.

Marius Boden and **Karsten Zenger** developed a multi-functional control platform for laser remote applications, lasertronic®MotionControl. Their work was recognized with an IWS-Award for the best scientific-technical performance. They developed a software framework consisting of four components, which provide an abstract programming interface separated from project specific software modules. The framework reduces the required programming efforts when implementing customer specific control solutions for laser processes using scanners. It provides a software architecture as well as libraries and functionalities (see pages 84/85).

The prize for the best innovative product idea to open a new business field went to Mr. **Stefan Grünzner**. He significantly advanced the development of universal microfluidic platforms for cell based studies by implementing numerous detailed engineering solutions. Especially noteworthy is his optimization of the fabrication process the multilayer based devices, which is scalable and offers great design freedom and thus is of high potential for applications (see pages 46/47).

Mr. **Michael Kohl** received the award for the best scientific performance of a junior scientist. His dissertation addressed the development of room temperature Na-S batteries. New anode concepts were developed and cathode, electrolyte and processes steps were adapted to reduce the operating temperature of Na-S batteries from 300 °C to room temperature. The approach is based on low cost raw materials and simple processing steps and yields significantly increased discharge capacities and higher charging efficiency. He demonstrated for the first time more than 1000 charging/discharging cycles for Na-S batteries at room temperature.

The research works of Mr. **Robert Pautzsch** on "Joining of metal and thermoplastics with reactive multilayer coatings" were recognized as an outstanding performance by a student. By influencing the interface between metal polymer and optimizing the joining process it is now possible to explore new applications in the electronics and optical component manufacturing industries.

Mr. **Martin Zawischa** was likewise recognized for his outstanding performance as a student. Mr. Zawisch analyzed and classified failure modes of ta-C coatings and defined a new characteristic parameter to quantify adhesive failure during scratch testing. This parameter is useful for standard process characterization.

The special award of the institute went to Dr. **Anja Techel**, Dr. **Günter Wiedemann** and Dr. **Dieter Pollack** for their commitment throughout the "Dresden Light Year 2015" festivities (page 148/149).

Andreas Leson, Dieter Pollack, Anja Techel, Günter Wiedemann, Stefan Grünzner, Martin Kohl, Marius Boden, Karsten Zenger, Eckhard Beyer (f.l.t.r.)

PUBLICATIONS

PRP = peer-reviewed papers

[L01] PRP
T. Abendroth, H. Althues, G. Mäder, S. Kaskel, E. Beyer

»Selective absorption of carbon nanotube thin films for solar energy applications«

Solar energy materials and solar cells 143 (2015), S. 553-556
DOI: 10.1016/j.solmat.2015.07.044

[L02]
T. Abendroth, J. Liebich, P. Härtel, B. Schumm, H. Althues, S. Kaskel, E. Beyer

»Transparente und leitfähige Veredelung von Kunststoffoberflächen: Antistatische und elektrooptische Anwendungen«

Vakuum in Forschung und Praxis 27 (2015), Nr. 3, S. 36-40
DOI: 10.1002/vipr.201500583)

[L03] PRP
M. A. Adam, P. Strubel, L. Borchardt, H. Althues, S. Dörfler, S. Kaskel

»Trimodal hierarchical carbide-derived carbon monoliths from steam- and CO_2-activated wood templates for high rate lithium sulfur batteries«

Journal of materials chemistry A, Materials for energy and sustainability 3 (2015), Nr. 47, S. 24103-24111
DOI: 10.1039/C5TA06782K

[L04] PRP
A. I. Aguilar-Morales, J. A. Álvárez-Chávez, A. Morales-Ramirez, M. Panzner, M. A. Ortega-Delgado, L. M. Rosales-Olivares

»Photomechanical ablation in obsidianus lapis via Q-switched 1064-nm laser energy«

Optical engineering 54 (2015), Nr. 9, Art. 097101
DOI: 10.1117/1.OE.54.9.097101

[L05] PRP
R. R. Ahmed, O. Ali, O. N. H. Faisal, N. M. Al-Anazi, S. H. Al-Mutairi, F.-L. Toma, L.-M. Berger, A. Potthoff, M. F. A. Goosen

»Sliding wear investigation of suspension sprayed WC-Co nanocomposite coatings«

Wear 322-323 (2015), S. 133-150
DOI: 10.1016/j.wear.2014.10.021

[L06] PRP
R. R. Ahmed, N. H. Faisal, N. Al-Anazi, S. Al-Mutairi, F.-L. Toma, L.-M. Berger, A. Potthoff, E. K. Polychroniadis, M. Sall, D. Chaliampalias, M. F. A. Goosen

»Structure property relationship of suspension thermally sprayed WC-Co nanocomposite coatings«

Journal of thermal spray technology 24 (2015), Nr. 3, S. 357-377
DOI: 10.1007/s11666-014-0174-2

[L07]
T. Baselt, C. Taudt, A.-F. Lasagni, P. Hartmann

»Dispersion characterization of large mode-area YB^3+ doped double-clad fibers implemented in a laser cavity during operation«

4th International Summer School »Trends and new developments in Laser Technology 2015«, 24.-28. August 2015, Dresden
URL: http://publica.fraunhofer.de/documents/N-366369.html

[L08] PRP
T. Baselt, C. Taudt, A.-F. Lasagni, P. Hartmann

»Experimental measurement of group velocity dispersion during operation in cladding-pumped large-mode-area Yb-doped fibers«

Lehmann, P.; Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: Optical Measurement Systems for Industrial Inspection IX: 22.-25. Juni 2015, München
Bellingham, WA: SPIE, 2015, Paper 95253Z (Proceedings of SPIE 9525)
URL: http://publica.fraunhofer.de/documents/N-356614.html,
DOI: 10.1117/12.2184803

[L09] PRP
R. Baumann, R. Siebert, P. Herwig, A. Wetzig, A., E. Beyer

»Laser remote cutting and surface treatment in manufacturing electrical machines: High productivity, flexibility, and perfect magnetic performance«

Journal of laser applications: JLA 27 (2015), Supplement 2, Art. S28002
DOI: 10.2351/1.4906383

[L10]
J. Bellmann, J. Lueg-Althoff, A. Leigh-Lorenz, S. Schulze, S. Gies, A. E. Tekkaya, E. Beyer

»Influence of axial workpiece position in the coil for electromagnetic pulse joining. Shed some light on the black box«

I2FG / PAK 343 Workshop on Electromagnetic Pulse Forming and Joining 2015, 5.-6. Oktober 2015, Dortmund
URL: http://publica.fraunhofer.de/documents/N-366368.html,
DOI: 10.17877/DE290R-16373

[L11]
L.-M. Berger, R. Trache, F.-L. Toma, S. Thiele, J. Norpoth, L. Janka

»Entwicklung wirtschaftlich effizienter Hartmetallbeschichtungslösungen für Hochtemperaturanwendungen. Teil 1: Beschichtungspulver, Wirtschaftlichkeit und Schichteigenschaften«

Thermal spray bulletin 8 (2015), Nr. 2, S. 126-136

[L12]
L.-M. Berger

»Tribology of thermally sprayed coatings in the Al_2O_3-Cr_2O_3-TiO_2 system«

Thermal sprayed coatings and their tribological performances, Hershey/Pa.: Engineering Science Reference, 2015, S. 227-267
DOI: 10.4018/978-1-4666-7489-9.ch008

[L13]
L.-M. Berger

»Application of hardmetals as thermal spray coatings«

International journal of refractory metals and hard materials 49 (2015), S. 350-364
DOI: 10.1016/j.ijrmhm.2014.09.029

[L14] PRP
M. Bieda, C. Schmädicke, T. Roch, A.-F. Lasagni

»Ultra-low friction on 100cr6-steel surfaces after direct laser interference patterning«

Advanced engineering materials 17 (2015), Nr. 1, S. 102-108
DOI: 10.1002/adem.201400007

[L15] PRP
T. Biemelt, K. Wegner, J. Teichert, S. Kaskel

»Microemulsion flame pyrolysis for hopcalite nanoparticle synthesis: A new concept for catalyst preparation«

Chemical communications 51 (2015), Nr. 27, S. 5872-5875
DOI: 10.1039/c5cc00481k

[L16] PRP
G. Bolelli, L.-M. Berger, T. Börner, H. Koivuluoto, L. Lusvarghi, C. Lyphout, N. Markocsan, V. Matikainen, P. E. Nylén, P. Sassatelli, R. Trache, P. Vuoristo

»Tribology of HVOF- and HVAF-sprayed WC-10Co4Cr hardmetal coatings: A comparative assessment«

Surface and coatings technology 265 (2015), S. 125-144
DOI: 10.1016/j.surfcoat.2015.01.048

[L17] PRP
V. Bon, N. Klein, I. Senkovska, Irena, A. Herwig, J. Getzschmann, D. Wallacher, I. Zizak, M. M. Brzhezinskaya, U. C. Müller, S. Kaskel

»Exceptional adsorption-induced cluster and network deformation in the flexible metal-organic framework DUT-8(Ni) observed by in situ X-ray diffraction and EXAFS«

Physical chemistry, chemical physics: PCCP 17 (2015), Nr. 26, S. 17471-17479
DOI: 10.1039/c5cp02180d

[L18]
S. Bonß

»Abteilung Wärmebehandeln und Plattieren des Fraunhofer IWS Dresden«

Elektrowärme international (2015), Nr. 3, S. 115-118

[L19] PRP
S. Bonß, J. Hannweber, U. Karsunke, S. Kühn, M. Seifert, D. Pögen, E. Beyer

»Laser heat treatment with latest system components«

Heat Treating Society -HTS-; ASM International: Heat Treating 2015, 28th ASM Heat Treating Society Conference, 20.-22. Oktober 2015, Detroit, Michigan, USA; Materials Park, Ohio: ASM International, 2015, S. 15-20

[L20]
M. Borkmann, A. Mahrle, E. Beyer, J. Walter, C. Hennigs, M. Hustedt, S. Kaierle

»Optimierte Luftströmungsführung beim Remote-Laserstrahlschweißen. Teil II: Numerische Untersuchungen«

Czarske, J.; Deutsche Gesellschaft für Laser-Anemometrie e.V -GALA-: Lasermethoden in der Strömungsmesstechnik: 23. Fachtagung, 8.-10. September 2015, Dresden
Karlsruhe: Deutsche Gesellschaft für Laser-Anemometrie GALA, 2015, S. 25/1-25/8
URL: http://publica.fraunhofer.de/documents/N-360123.html

[L21]
M. Borkmann, A. Mahrle, A. Wetzig, E. Beyer, J. Walter, C. Hennigs, A. Brodeßer, M. Hustedt, S. Kaierle, H. Exner

»Optimierung der Luftströmungsführung in Bearbeitungskabinen zum Remote-Laserstrahlschweißen«

9. Mittweidaer Lasertagung 2015. Lasertechnik: Im Rahmen der 24. Wissenschaftlichen Konferenz der Hochschule Mittweida (IWKM), 19.-20. November 2015, Mittweida (Scientific Reports 4/2015)

[L22]
F. Bouchard

»2-Photonen-Polymerisation für das 3D-Generieren einer verzweigten Hohlfaser zur Anwendung in Mikrofluidiksystemen«

Dresden, TU, Dipl.-Arb., 2015

[L23] PRP
S. Braun, A. Kubec, P. Gawlitza, M. Menzel, A. Leson

»Low-stress coatings for sputtered-sliced Fresnel zone plates and multilayer Laue lenses«

R. Hudec, Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: EUV and x-ray optics: Synergy between laboratory and space IV: 13.-14. April 2015, Prag, Tschechische Republik
Bellingham, WA: SPIE, 2015, Paper 95100L, 9 S. (Proceedings of SPIE 9510)
DOI: 10.1117/12.2178851

[L24]
S. Braun, A. Leson

»Optical elements for EUV lithography and X-ray optics«

Fecht, H.-J.: »The nano-micro interface. Bridging the micro and nano worlds. Vol. 2«
Weinheim: Wiley-VCH, 2015, S. 613-628
DOI: 10.1002/9783527679195.ch30

[**L25] PRP**
M. F. Broglia, D. F. Acevedo, D. Langheinrich, H. R. Perez-Hernandez, C. A. Barbero, A.-F. Lasagni

»Rapid fabrication of periodic patterns on poly(styrene-co-acrylonitrile) surfaces using direct laser interference patterning«

International journal of polymer science (2015), Art. 721035
DOI: 10.1155/2015/721035

[L26] PRP
F. Brückner, T. Finaske, R. Willner, A. Seidel, S. Nowotny, C. Leyens, E. Beyer

»Laser additive manufacturing with crack-sensitive materials: Temperature monitoring system for defect-free material build-up«

Laser-Technik-Journal 12 (2015), Nr. 2, S. 28-30
DOI: 10.1002/latj.201500015

[L27]
F. Brückner, A. Seidel, A. Straubel, R. Willner, C. Leyens, E. Beyer

»Laser-based manufacturing of components using materials with high cracking susceptibility«

Laser Institute of America -LIA-: ICALEO 2015, 34th International Congress on Applications of Lasers & Electro-Optics. Conference Proceedings: 18.-22. Oktober 2015. Atlanta, Ga., USA
Orlando, Fla.: LIA, 2015, S. 586-592, Paper 1001

[L28]
F. Brückner, M. Riede, T. Finaske, A. Seidel, S. Nowotny, C. Leyens, E. Beyer

»AM with high-performance materials & lightweight structures by Laser Metal Deposition & Laser Infiltration«

LIA Today 23 (2015), Nr. 2, S. 10-13

[L29]
M. Busek, A. Rudolph, S. Grünzner, F. Schmieder, F. Sonntag, K. Hofmann, U. Grätz

»Design and regulation of complex microfluidic systems with simulationX«

Gesellschaft für Ingenieurtechnische Informationsverarbeitung -ITI-, Dresden: ITI-Symposium 2015. Conference Proceedings of the 18th ITI Symposium, 9.-11. November 2015, Dresden
URL: http://publica.fraunhofer.de/documents/N-370244.html
DOI: 10.13140/RG.2.1.2859.9761

[L30] PRP
A. Chamas, M. Giersberg, K. Friedrich, F. Sonntag, D. Kunze, S. Uhlig, K. Simon, K. Baronian, G. Kunze

»Purification and immunodetection of the complete recombinant HER-2[neu] receptor produced in yeast«

Protein expression and purification 105 (2015), S. 61-70
DOI: 10.1016/j.pep.2014.10.004

[L31]
I. Dani

»Additive manufacturing of electrical functionalities«

1st International Symposium on Additive Manufacturing (ISAM), 25.-26. Februar 2015, Dresden
URL: http://publica.fraunhofer.de/documents/N-364395.html

[L32] PRP
N. Danz, A. Sinibaldi, P. Munzert, A. Anopchenko, E. Förster, S. Schmieder, R. Chandrawati, R. Rizzo, R. Heller, F. Sonntag, A. Mascioletti, S. Rana, T. Schubert, M. M. Stevens, F. Michelotti

»Biosensing platform combining label-free and labelled analysis using Bloch surface waves«

Baldini, F.; Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: Optical Sensors 2015: 13.-16. April 2015, Prag, Tschechische Republik
Bellingham, WA: SPIE, 2015, Paper 95060V (Proceedings of SPIE 9506)
DOI: 10.1117/12.2178444

[L33]
G. Dietrich, E. Pflug, M. Rühl, S. Braun, A. Leson, E. Beyer

»Neuartige reaktive Multilayersysteme für die Mikroverbindungstechnik«

Schweißen und Schneiden 67 (2015), Nr. 8, S. 456-457

[L34] PRP
I. Dirnstorfer, N. Schilling, S. Körner, P. Gierth, A. Waltinger, B. Leszczynska, D. K. Simon, J. Gärtner, P. M. Jordan, T. Mikolajick, I. Dani, M. Eberstein, L. Rebenklau, J. Krause

»Via hole conditioning in silicon heterojunction metal wrap through solar cells«

Energy Procedia 77 (2015), S. 458-463
DOI: 10.1016/j.egypro.2015.07.065

[L35]
D. Dittrich, R. Schedewy, R. Strohbach, B. Brenner, J. Standfuß

»Laser-Mehrlagenengstspaltschweißen (Laser-MES) für Bauteildicken in Aluminium bis 50 mm und Stahl bis 60 mm«

Deutscher Verband für Schweißen und Verwandte Verfahren e.V. -DVS-: Große Schweißtechnische Tagung 2015: DVS-Studentenkongress, DVS Congress und DVS Expo, 15.-17. September 2015, Nürnberg
Düsseldorf: DVS Media, 2015, S. 777-782 (DVS-Berichte 315)

[L36]
D. Dittrich, R. Schedewy, B. Brenner, E. Beyer

»Laserstrahl-Mehrlagen-Engstspaltschweißen zum verzugsarmen und heißrissfreien Fügen von Aluminiumlegierungen im Dickblechbereich«

Schweißen und Schneiden 67 (2015), Nr. 3, S. 114-117

[L37]
D. Dittrich, R. Schedewy, B. Brenner, E. Beyer

»Multi-pass narrow-gap (MPNG) laser welding process for the low-distortion and hot-crack-free joining of thick plates made of aluminium alloys«

Welding and cutting 14 (2015), Nr. 3, S. 174-177

[L38] PRP
S. Eckhardt, L. Müller-Meskamp, M. Löser, M. Siebold, A.-F. Lasagni

»Fabrication of highly efficient transparent metal thin film electrodes using direct laser interference patterning«

Klotzbach, U.; Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: Laser-based Micro- and Nanoprocessing IX: 10.-12. Februar 2015, San Francisco, California, USA
Bellingham, WA: SPIE, 2015, Paper 935116 (Proceedings of SPIE 9351)
DOI: 10.1117/12.2082537

[L39]
J. Fichtner

»Druckbare Kohlenstoffnanoröhren – Polymerpaste«

Saarbrücken: AV Akademikerverlag, 2015
ISBN 978-3-639-72663-3, ISBN 3-639-72663-4

[L40] PRP
R. Frenzel, T. Schiefer, I. Jansen, F. Simon, A. Calvimontes, K. Grundke, L. Häußler, E. Beyer

»Polyelectrolytes to promote adhesive bonds of laser-structured aluminium«

International journal of adhesion and adhesives 61 (2015), S. 35-45
DOI: 10.1016/j.ijadhadh.2015.05.001

[L41]
V. Fux, T. Fiebiger, A. Berger, J. Kaspar, S. Kühn, B. Brenner

»Laserwalzplattierte Bimetalle«

Deutscher Verband für Schweißen und Verwandte Verfahren e.V. -DVS-: Große Schweißtechnische Tagung 2015: DVS-Studentenkongress, DVS Congress und DVS Expo, 15.-17. September 2015, Nürnberg
Düsseldorf: DVS Media, 2015, S. 741-745 (DVS-Berichte 315)

[L42] PRP
A. Ganvir, N. Curry, N. Markocsan, P. E. Nylén, F.-L. Toma

»Comparative study of suspension plasma sprayed and suspension high velocity oxy-fuel sprayed YSZ thermal barrier coatings«

Surface and coatings technology 268 (2015), S. 70-76
DOI: 10.1016/j.surfcoat.2014.11.054

[L43] PRP
W. Garkas, M. Fröhlich, K. D. Weltmann, C. Leyens

»Oxidation and decomposition of Ti_2AlN MAX phase coating deposited on Nickel-based super alloy IN718«

C. Edtmaier: 20th Symposium on Composites 2015, 1.-3. Juli 2015, Wien, Österreich
Durnten-Zurich: TTP, 2015, S. 628-635 (Materials Science Forum 825-826)
DOI: 10.4028/www.scientific.net/MSF.825-826.628

[L44]
C. Goppold, T. Pinder, P. Herwig, A. Mahrle, A. Wetzig, E. Beyer

»Beam oscillation - periodic modification of the geometrical beam properties«

Wissenschaftliche Gesellschaft Lasertechnik -WLT-: Lasers in Manufacturing, LiM 2015: International WLT-Conference on Lasers in Manufacturing, LIM 2015, 22.-25. Juni 2015, München, Paper 112

[L45] PRP
S. Grigoriev, T. Nikolaevich, V. Tatyana, G. O. Gvozdeva, S. Nowotny

»Solidification behaviour during laser microcladding of Al-Si alloys«

Surface and coatings technology 268 (2015), S. 303-309
DOI: 10.1016/j.surfcoat.2014.08.001

[L46]
A. Grimm, S. Schulze, A. F. Silva, G. Gunther, J. Standfuß, B. Brenner, E. Beyer, U. Füssel

»Friction stir welding of light metals for industrial applications«

Materials today. Proceedings 2 (2015), Supplement 1, S. S169-S178
DOI: 10.1016/j.matpr.2015.05.007

[L47]
D. Günther, R. Heß, B. Beutner, S. Subhani, M. Masroor, X. Wang, C. Zwahr, A. Welle, T. Weingärtner, D. Scharnweber, A.-F. Lasagni

»Einfluss von Topographie und Chemie auf das Verhalten von lebenden Zellen«

Werkstoffwoche 2015, Kongress für innovative Werkstoffe, Verfahren und Anwendungen, 14.-17. September 2015, Dresden
URL: http://publica.fraunhofer.de/documents/N-370226.html

[L48]
D. Günther, R. E. Alves, S. Dani, S. Eckhardt, M. Bieda, T. Roch, I. Cestari, A.-F. Lasagni

»Anpassung von Polyurethan durch direkte Laserinterferenzstrukturierung«

Werkstoffwoche 2015, Kongress für innovative Werkstoffe, Verfahren und Anwendungen, 14.-17. September 2015, Dresden
URL: http://publica.fraunhofer.de/documents/N-370225.html

[L49]
J. Haag, T. Mertens, M. Kolb, L. Kotte, S. Kaskel

»Plasma enhanced chemical vapour deposition (PECVD) at atmospheric pressure (AP) of organosilicon films for adhesion promotion on $Ti_{15}V_3Cr_3Sn_3Al$ *and* Ti_6Al_4V*«*

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URL: http://publica.fraunhofer.de/documents/N-364205.html,
DOI: 10.17265/2161-6213/2015.7-8.004

[L50]
J. Hannweber, S. Bonß, S. Kühn, M. Seifert, U. Karsunke, D. Pögen, B. Brenner, E. Beyer

»Systems engineering for laser heat treatment«

Japan Laser Processing Society: LAMP 2015, 7th International Congress on Laser Advanced Materials Processing: LPM 2015, the 16th International Symposium on Laser Precision Microfabrication; HPL 2015, the 7th International Symposium on High Power Laser Processing; 26.-29. Mai 2015, Kitakyushu, Fukuoka, Japan, Paper A160

[L51] PRP
G.-P. Hao, N.-R. Sahraie, Q. Zhang, S. Krause, M. Oschatz, A. Bachmatiuk, P. Strasser, S. Kaskel

»Hydrophilic non-precious metal nitrogen-doped carbon electrocatalysts for enhanced efficiency in oxygen reduction reaction«

Chemical communications 51 (2015), Nr. 97, S. 17285-17288
DOI: 10.1039/c5cc06256j

[L52]
J. Hauptmann, A. Fürst, P. Rauscher, P. Herwig, A. Wetzig, E. Beyer

»Hochleistungs-Remote-Bearbeitung – Applikationen und Systemtechnik«

9. Mittweidaer Lasertagung 2015. Lasertechnik: Im Rahmen der 24. Wissenschaftlichen Konferenz der Hochschule Mittweida (IWKM), 1 9.-20. November 2015, Mittweida, S. 60-63 (Scientific Reports 4/2015)

[L53]
J. Hauptmann, R. Michael, A. Fürst, A. Klotzbach, A. Wetzig, E. Beyer

»Laser cutting of fiber reinforced polymers and its applications«

11th International Conference Advances in Plastics Technology, APT 2015. Conference Papers. CD-ROM: Sosnowiec, Poland, 13.-15. Oktober 2015 Sosnowiec, 2015, Paper 19

[L54]
J. Hauptmann, P. Herwig, A. Wetzig, D. Dittrich, E. Beyer, U. Hofmann, F. Senger

»System technology for dynamic beam shaping«

Laser Institute of America: ICALEO 2015, 34th International Congress on Applications of Lasers & Electro-Optics. Conference Proceedings: 18.-22. Oktober 2015. Atlanta, Ga., USA
Orlando, Fla.: LIA, 2015, S. 930-939, Paper 2003

[L55] PRP
S. Helten, B. Sahoo, P. Müller, D. Janßen-Müller, N, Klein, R. Grünker, V. Bon, F. Glorius, S. Kaskel, I.Senkovska

»Functional group tolerance in BTB-based metal-organic frameworks (BTB - benzene-1,3,5-tribenzoate)«

Microporous and mesoporous materials 216 (2015), S. 42-50
DOI: 10.1016/j.micromeso. 2015.02.055)

[L56]
P. Herwig

»Prozesssichere Laserbearbeitung hochreflektiver Werkstoffe«

Aachen: Shaker, 2015, 141 S.
Zugl.: Dresden, TU, Diss., 2015
ISBN 978-3-8440-3861-3

[L57]
D. Höche, J. Kaspar, P. Schaaf

»Laser nitriding and carburization of materials«

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DOI: 10.1016/ B978-1-78242-074-3.00002-7

[L58]
C. Hoffmann, P. Plate, A. Steinbrück, S. Kaskel

»Nanoporous silicon carbide as nickel support for the carbon dioxide reforming of methane«

Catalysis science & technology 5 (2015), Nr. 8, S. 4174-4183
DOI: 10.1039/c4cy01234h

[L59]
A. Jahn, M. Wagner, J. Bellmann, J. Standfuß, B. Brenner, E. Beyer

»LBW of steel-aluminum corner joints generated by selected laser material melting«

Laser Institute of America: ICALEO 2015, 34th International Congress on Applications of Lasers & Electro-Optics. Conference Proceedings : 18.-22. Oktober 2015, Atlanta, Ga., USA
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A. Jahn, J. Bellmann, M. Wagner, J. Standfuß, E. Beyer

»Metallische Mischverbindungen für automobile Anwendungen«

Deutscher Verband für Schweißen und Verwandte Verfahren e.V -DVS-: Große Schweißtechnische Tagung 2015: DVS-Studentenkongress, DVS Congress und DVS Expo, 15.-17. September 2015, Düsseldorf: DVS Media, 2015, S. 481-486 (DVS-Berichte 315)

[L61]
A. Kabardiadi, T. Baselt, P. Hartmann

»Designing of measurement for fast alternative method for measuring the wavefront of lithography exposure systems«

4th International Summer School »Trends and new developments in Laser Technology 2015«, 24.-28. August 2015, Dresden
URL: http://publica.fraunhofer.de/documents/N-366370.html

[L62] PRP
M. Kästner, S. Müller, F. Hirsch, J.-S. Pap, I. Jansen, V. Ulbricht

»XFEM modeling of interface failure in adhesively bonded fiber-reinforced polymers«

Advanced engineering materials (2015), Online First
DOI: 10.1002/adem.201500445

[L63]
C. Katsich, J. Norpoth, M. Rodriguez Ripoll, L. Janka, L.-M. Berger, S. Thiele, F.-L. Toma, R. Trache

»Wear properties of chromium carbide based HVOF and HVAF thermal spray coatings up to 800°C«

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Aachen: GfT, 2015, Paper 31

[L64]
J. Köckeritz

»Herstellung und Charakterisierung einer thermoelektrischen Dispenserdruckpaste«

Dresden, HTW, Bachelorthesis, 2015

[L65]
T. Köckritz, F. Wehnert, J.-S. Pap, I. Jansen

»Increasing the electrical values of polydimethylsiloxane by the integration of carbon black and carbon nanotubes: A comparison of the effect of different nanoscale fillers«

Nihon-setchaku-gakkaishi = Journal of the Adhesion Society of Japan 51 (2015), Supplement 1, S. 221-222
DOI: 10.11618/adhesion.51.221

[L66] PRP
M. Kohl, J. Brückner, I. Bauer, H. Althues, S. Kaskel

»Synthesis of highly electrochemically active Li_2S nanoparticles for lithium-sulfur-batteries«

Journal of materials chemistry A, Materials for energy and sustainability 3 (2015), Nr. 31, S. 16307-16312
DOI: 10.1039/C5TA04504E

[L67] PRP
M. S. Komlenok, V. V. Kononenko, E. V. Zavedeev, V. D. Frolov, N. R. Arutyunyan, A. A. Chouprik, A. S. Baturin, H.-J. Scheibe, M. L. Shupegin, S. M. Pimenov, M. Sergei

»Laser surface graphitization to control friction of diamond-like carbon coatings«

Applied physics. A 121 (2015), Nr. 3, S. 1031-1038
DOI: 10.1007/s00339-015-9485-5

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L. Kotte, J. Roch, G. Mäder, J. Haag, T. Mertens

»Large area atmospheric pressure plasma processes: Applications of the LARGE plasma source«

Bogaerts, A; Sanden, R. van de; University of Antwerp: ISPC 22, 22nd International Symposium on Plasma Chemistry. Proceedings: 5.-10. Juli 2015, University of Antwerp, Stadscampus, Antwerp, Belgium, Paper P-III-6-26

[L69]
L. Kotte, J. Roch, M. Julius, G. Mäder

»Mobile Plasmaquelle jetzt industriereif«

Maschinenmarkt. MM, das Industriemagazin (2015), Nr. 7, S. 56-58, 60

[L70]
A. Krause, J. Brückner, S. Dörfler, F. M. Wisser, H. Althues, M. Grube, J. Martin, J. Grothe, T. Mikolajick, W. Thomas, W. M. Weber

»Stability and performance of heterogeneous anode assemblies of silicon nanowires on carbon meshes for lithium-sulfur battery applications«

G. Koblmüller, Materials Research Society: Semiconductor nanowires - growth, physics, devices and applications: 30. November - 5. Dezember 2014, Boston, Massachusetts, USA; Symposium LL: Semiconductor Nanowires - Growth, Physics, Devices and Applications; held at the 2014 MRS fall meeting, Red Hook, NY: Curran, 2015, S. 19-24 (Materials Research Society Symposium Proceedings 1751)
DOI: 10.1557/opl.2015.196

[L71] PRP
A. Kubec, N. Kujala, R. Conley, N. Bouet, J. Zhou, T. M. Mooney, D. Shu, J. Kirchman, K. Goetze, J. M. Maser, A. T. Macrander

»Diffraction properties of multilayer Laue lenses with an aperture of 102 µm and WSi_2/Al bilayers«

Optics Express 23 (2015), Nr. 21, S. 27990-27997
DOI: 10.1364/OE.23.027990

[L72]
F. Kubisch, M. Pfennig, F. Brückner, S. Nowotny

»Internal laser cladding of barrels with the newly developed Mini-ID cladding head«

Associazione Italiana di Metallurgia -AIM-; International Federation for Heat Treatment and Surface Engineering: Heat treatment and surface engineering. CD-ROM: From tradition to innovation. European Conference on Heat Treatment 2015 & 22nd IFHTSE congress, 20.-22. Mai 2015, Venice, Italien
Milano: AIM, 2015, S. 60-63

[L73]
T. Kunze, T. Roch, T. Hoffmann, E. Fedyna, V. Konovalov, D. Oulianov, A.-F. Lasagni

»High resolution direct laser interference patterning by high energy q-switched lasers«

Fotonika : Naucno-techniceskij zurnal = Photonics Russia 53 (2015), Nr. 5, S. 34-41

[L74]
T. Kunze, F. Böttcher, V. Lang, A. Gärtner, A.-F. Lasagni

»Surface functionalization of forming using direct laser interference patterning for dry forming applications«

Dry metal forming open access journal 1 (2015), S. 108-112
URL: http://nbn-resolving.de/urn:nbn:de:gbv:46-00104815-13

[L75]
A.-F. Lasagni, E. Beyer

»Fabrication of periodic submicrometer and micrometer arrays using laser interference-based methods«

Lawrenc, J.: Laser surface engineering. Processes and applications, Cambridge: Woodhead Publishing, 2015, S. 423-439 (Woodhead publishing series in eletronic and optical materials 65)
DOI: 10.1016/B978-1-78242-074-3.00017-9

[L76] PRP
A.-F. Lasagni, T. Roch, J. Berger, T. Kunze, V. Lang, E. Beyer

»To use or not to use (direct laser interference patterning), that is the question«

Klotzbach, U.; Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: Laser-based Micro- and Nanoprocessing IX: 10.-12. Februar 2015, San Francisco, California, USA
Bellingham, WA: SPIE, 2015, Paper 935115, 7 S. (Proceedings of SPIE 9351)
DOI: 10.1117/12.2081976

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A. Leifert, N. Mohamed-Noriega, A. Meier, G. Giovanni, S. Dörfler, J. Grothe, S. Kaskel, B. Schumm, C. Nowka, S. Hampel, E. L. Cuéllar

»Mechanical reinforcement of copper films with ceramic nanoparticles«

Kriven, W. M.; American Ceramic Society -ACerS-, Westerville/Ohio: Developments in Strategic Materials and Computational Design V: A collection of papers presented at the 38th International Conference on Advanced Ceramics and Composites, 27.-31. Januar 2014, Daytona Beach, Florida, USA
Hoboken, NJ, USA: John Wiley & Sons Inc., 2015, S. 361-366 (Ceramic engineering and science proceedings Vol. 35, Nr .8)
DOI: 10.1002/9781119040293.ch31

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A. Leson, G. Englberger, D. Hammer, S. Makowski, C.-F. Meyer, M. Leonhardt, H.-J. Scheibe, V. Weihnacht

»Diamantartige Kohlenstoffschichten steigern die Effizienz: Laser-Arc-Verfahren zur Abscheidung von ta-C-Schichten«

Vakuum in Forschung und Praxis 27 (2015), Nr. 4, S. 24-28
DOI: 10.1002/vipr.201500588

[L79]
C. Leyens, E. Beyer

»Innovations in laser cladding and direct laser metal deposition«

Lawrence, J.: Laser surface engineering. Processes and applications, Cambridge: Woodhead Publishing, 2015, S. 181-192 (Woodhead publishing series in eletronic and optical materials 65)
DOI: 10.1016/B978-1-78242-074-3.00008-8

[L80]
J. Liebich, H. Althues, S. Kaskel

»Leitfähige Polymeroberflächen durch CNT Dünnschichten«

Galvanotechnik 106 (2015), Nr. 7, S. 1378-1381

[L81] PRP
C.-H. Lu, M. Beckmann, S. Unz, D. Glöß, P. Frach, E. Holst, A.-F. Lasagni, M. Bieda

»Heat transfer model of dropwise condensation and experimental validation for surface with coating and groove at low pressure«

Heat and mass transfer (2015), Online First
DOI: 10.1007/s00231-015-1641-0

[L82] PRP
A. T. Macrander, A. Kubec, R. Conley, N. Bouet, J. Zhou, M. J. Wojcik, J. M. Maser

»Efficiency of a multilayer-Laue-lens with a 102 µm aperture«

Applied Physics Letters 107 (2015), Nr. 8, Art. 081904
DOI: 10.1063/1.4929505

[L83]
J. Marx

»Herstellung und Evaluierung eines n-leitenden Polymers für thermoelektrische Anwendungen«

Dresden, 2015, 92 S., Ilmenau, TU, Masterthesis, 2015

[L84] PRP
I. Maschmeyer, T. Hasenberg, A. Jaenicke, M. Lindner, A. K. Lorenz, J. Zech, L. A. Garbe, F. Sonntag, P. J. Hayden, S. Ayehunie, L. Seyoum, R. Lauster, U. Marx, E. M. Materne

»Chip-based human liver-intestine and liver-skin co-cultures: A first step toward systemic repeated dose substance testing in vitro«

European journal of pharmaceutics and biopharmaceutics 95, Part A (2015), S. 77-87
DOI: 10.1016/j.ejpb.2015.03.002

[L85] PRP
I. Maschmeyer, A. K. Lorenz, K. Schimek, T. Hasenberg, A. P. Ramme, J. Hübner, M. Lindner, C. Drewell, S. Bauer, A. Thomas, N. S. Sambo, F. Sonntag, R. Lauster, U. Marx

»A four-organ-chip for interconnected long-term co-culture of human intestine, liver, skin and kidney equivalents«

LAB on a chip 15 (2015), Nr. 12, S. 2688-2699
DOI: 10.1039/C5LC00392J

[L86] PRP
E. M. Materne, I. Maschmeyer, A. K. Lorenz, R. Horland, K. Schimek, M. Busek, F. Sonntag, R. Lauster, U. Marx

»The multi-organ chip – A microfluidic platform for long-term multitissue coculture«

Journal of visualized experiments : JoVE. Online resource (2015), Nr. 98, Art. e52526
DOI: 10.3791/52526

[L87] PRP
L. Müller-Meskamp, S. Schubert, T. Roch, S. Eckhardt, A.-F. Lasagni, K. W. Leo

»Transparent conductive metal thin-film electrodes structured by direct laser interference patterning«

Advanced engineering materials 17 (2015), Nr. 8, S. 1215-1219
DOI: 10.1002/adem.201400454

[L88] PRP
S. Nowotny, F. Brückner, S. Thieme, C. Leyens, E. Beyer

»High-performance laser cladding with combined energy sources«

Journal of laser applications: JLA 27 (2015), Supplement 1, Art. S17001
DOI: 10.2351/1.4817455

[L89] PRP
M. Oschatz, M. Leistner, W. Nickel, S. Kaskel

»Advanced structural analysis of nanoporous materials by thermal response measurements«

Langmuir. The ACS journal of surfaces and colloids 31 (2015), Nr. 13, S. 4040-4047
DOI: 10.1021/acs.langmuir.5b00490

[L90]
J.-S. Pap, J. Schiefer, I. Jansen

»Adhesively bonded structures with hybrid yarn textile-reinforced plastics«

Nihon-setchaku-gakkaishi = Journal of the Adhesion Society of Japan 51 (2015), Supplement 1, S. 229-230
DOI: 10.11618/adhesion.51.229

[L91]
D. F. Pessoa, A. Mahrle, P. Herwig, A. Wetzig, M. Zimmermann

»Einfluss des Laserschneidens auf das Ermüdungsverhalten eines metastabilen austenitischen Stahls«

Borsutzk, M.; Deutsche Gesellschaft für Materialkunde -DGM-: Fortschritte in der Werkstoffprüfung für Forschung und Praxis: 33. Vortrags- und Diskussionstagung Werkstoffprüfung 2015, 3.-4. Dezember 2015, Bad Neuenahr
Düsseldorf: Verlag Stahleisen, 2015, S. 273-278

[L92]
M. Piwko, H. Althues, B. Schumm, S. Kaskel

»Confocal microscopy for process monitoring and wide-area height determination of vertically-aligned carbon nanotube forests«

Coatings 5 (2015), Nr. 3, S. 477-487
DOI: 10.3390/coatings5030477

[L93]
A. Rank, T. Kunze, T. Hoffmann, A.-F. Lasagni

»Fabrication of surface architectures on metallic stamps for hot embossing of polymers«

4th IWS Summer School »Trends and new developments in Laser Technology 2015«, 27. August 2015, Dresden
URL: http://publica.fraunhofer.de/documents/N-369992.html

[L94] PRP
A. Roch, M. Greifzu, E. Talens, L. Stepien, T. Roch, J. Hege, N. V. Nong, T. Schmiel, I. Dani, C. Leyens, O. Jost, A. Leson

»Ambient effects on the electrical conductivity of carbon nanotubes«

Carbon 95 (2015), S. 347-353
DOI: 10.1016/j.carbon.2015.08.045

[L95] PRP
T. Roch, D. Benke, S. Milles, A. Roch, T. Kunze, A.-F. Lasagni

»Dependence between friction of laser interference patterned carbon and the thin film morphology«

Diamond and Related Materials 55 (2015), 55, S. 16-21
DOI: 10.1016/j.diamond.2015.02.002

[L96]
M. Rose, A. Fürst, J-S. Pap, A. Klotzbach, J. Hauptmann, I. Jansen, E. Beyer

»Optical deformation analysis of the failure behavior of fiber reinforced polymers caused by laser processing«

20th International Conference on Composite Materials 2015, Proceedings, 19.-24. Juli 2015, Kopenhagen, Dänemark
Kopenhagen, 2015, Paper 1206-1
URL: http://publica.fraunhofer.de/documents/N-370061.html

[L97] PRP
G. Rotella, M. Alfano, T. Schiefer, I. Jansen

»Enhancement of static strength and long term durability of steel/epoxy joints through a fiber laser surface pre-treatment«

International journal of adhesion and adhesives 63 (2015), S. 87-95
DOI: 10.1016/j.ijadhadh.2015.08.009

[L98] PRP
F. Sandra, N. Klein, M. Leistner, M. R. Lohe, M. Benusch, M. Wöllner, J. Grothe, S. Kaskel

»Speeding up chemisorption analysis by direct IR-heat-release measurements (infrasorp technology): A screening alternative to breakthrough measurements«

Industrial and Engineering Chemistry Research 54 (2015), Nr. 26, S. 6677-6682
DOI: 10.1021/acs.iecr.5b01404

[L99] PRP
F. J. Sanza, D. Langheinrich, J. Berger, A. L. Hernandez, S. Dani, R. Casquel, A. Lavin, A. Oton, B. Santamaria, M. Laguna, A.-F. Lasagni, M. Holgado

»Direct laser interference patterning (DLIP) technique applied to the development of optical biosensors based on biophotonic sensing cells (BICELLs)«

Klotzbach, U.; Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: Laser-based Micro- and Nanoprocessing IX: 10.-12. Februar 2015, San Francisco, California, USA
Bellingham, WA: SPIE, 2015, Paper 935114 (Proceedings of SPIE 9351)
DOI: 10.1117/12.2077292

[L100] PRP
S. Scheitz, F.-L. Toma, T. Kuntze, C. Leyens, S. Thiele

»Surface preparation for ceramics functionalization by thermal spraying«

McDonald, A.; ASM International; The Thermal Spray Society: Thermal spray 2015. International Thermal Spray Conference ITSC 2015. Proceedings: Innovative Coating Solutions for the Global Economy; 11.-14. Mai 2015, Long Beach, Ca., Materials Park, Ohio: ASM International, 2015, S. 684-688

[L101]
T. Schiefer, I. Jansen, M. Bieda, J.-S. Pap, A.-F. Lasagni

»Large area surface structuring by direct laser interference patterning for adhesive bonding applications«

Nihon-setchaku-gakkaishi = Journal of the Adhesion Society of Japan 51 (2015), Supplement 1, S. 223-224
DOI: 10.11618/adhesion.51.223

[L102] PRP
N. Schilling, N. Wiegand, U. Klotzbach

»Laser assisted electrical contacting in multifunctional GF/PP composites«

C. Edtmaier: 20th Symposium on Composites 2015: 20th Symposium on Composites, 1.-3. Juli 2015, Wien, Österreich
Durnten-Zurich: TTP, 2015, S. 541-547 (Materials Science Forum 825-826)
DOI: 10.4028/www.scientific.net/MSF.825-826.541

[L103] PRP
N. Schilling, B. Krupop, U. Klotzbach

»Laser processing of glass fiber reinforced thermoplastics with different wavelengths and pulse durations«

Klotzbach, U.; Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: Laser-based Micro- and Nanoprocessing IX: 10.-12. Februar 2015, San Francisco, Ca. USA
Bellingham, WA: SPIE, 2015, Paper 93510N (Proceedings of SPIE 9351)
DOI: 10.1117/12.2081903

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N. Schilling, D. Linaschke, I. Dani

»Laserdotieren als mögliche Alternative zur Ionenimplantation zur Erzeugung definierter Dotierprofile«

Wetzig, K.; Europäische Forschungsgesellschaft Dünne Schichten e.V. -EFDS-: Morphologie und Mikrostruktur Dünner Schichten und deren Beeinflussung, 12. März 2015, Dresden; Tagungsband, Dresden: EFDS, 2015

[L105]
S. Schulze, A. Grimm, G. Göbel, J. Standfuß, B. Brenner, E. Beyer

»Konzept zum Fügen zukünftiger metallischer Flugzeugrumpfstrukturen«

Deutscher Verband für Schweißen und Verwandte Verfahren e.V. -DVS-: Große Schweißtechnische Tagung 2015: DVS-Studentenkongress, DVS Congress und DVS Expo, 15.-17. September 2015, Nürnberg
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[L106] PRP
F. Senger, U. G. Hofmann, T. von Wantoch, C. Mallas, J. Janes, W. Benecke, P. Herwig, P. Gawlitza, M. A. Ortega Delgado, C. Gruhne, J. Hannweber, A. Wetzig

»Centimeter-scale MEMS scanning mirrors for high power laser application«

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Bellingham, WA: SPIE, 2015, Paper 937509 (Proceedings of SPIE 9375)
DOI: 10.1117/12.2079600

[L107]
R. Siebert

»Bestimmung der magnetischen Flussdichteverteilung in nichtkornorientiertem Elektroblech nach dem Laserschneiden mittels Neutronen-Dunkelfeld-Bildgebung«

Aachen : Shaker, 2015, VI, 116 S., XXIX
Zugl.: Dresden, TU, Diss., 2015
ISBN 978-3-8440-3956-6, ISBN 3-8440-3956-2,
DOI: 10.2370/9783844039566

[L108]
A. Sinibaldi, N. Danz, A. Anopchenko, P. Munzert, S. Schmieder, R. Chandrawati, R. Rizzo, S. Rana, F. Sonntag, A. Occhicone, L. Napione, S. de Panfilis, M. M. Stevens, F. Michelotti

»Label-free detection of tumor angiogenesis biomarker angiopoietin 2 using bloch surface waves on one dimensional photonic crystals«

Journal of Lightwave Technology 33 (2015), Nr. 16, S. 3385-3393
DOI: 10.1109/JLT.2015.2448795

[L109] PRP
F. Sonntag, S. Grünzner, F. Schmieder, M. Busek, U. Klotzbach, V. Franke

»Multilayer based lab-on-a-chip-systems for substance testing«

Klotzbach, U.; Society of Photo-Optical Instrumentation Engineers -SPIE-, Bellingham/Wash.: Laser-based Micro- and Nanoprocessing IX : 10.-12. Februar 2015, San Francisco, Ca., USA
Bellingham, WA: SPIE, 2015, Paper 93510C, (Proceedings of SPIE 9351)
DOI: 10.1117/12.2083100

[L110]
J. Standfuß, A. Jahn, M. Wagner, J. Bellmann, E. Beyer

»Innovative laser processes for lightweight constructions«

Industrial laser solutions for manufacturing 30 (2015), Nr. 4
URL: http://www.industrial-lasers.com/articles/print/volume-30/issue-4/features/innovative-laser-processes-for-lightweight-constructions.html

[L111]
J. Standfuß, E. Beyer, B. Brenner, R. Schedewy, D. Dittrich, R. Strohbach

»Laser-multi-pass-welding of aluminium and steel with sheet thickness above 50mm«

Laser Institute of America: ICALEO 2015, 34th International Congress on Applications of Lasers & Electro-Optics. Conference Proceedings, 18.-22. Oktober 2015, Atlanta, Ga., USA
Orlando, Fla.: LIA, 2015, S. 626-631, Paper 1201

[L112]
L. Stepien, A. Roch, S. Schlaier, I. Dani, A. Kiriy, F. Simon, M. v. Lukowicz, C. Leyens

»Investigation of the thermoelectric power factor of KOH-treated PEDOT: PSS dispersions for printing applications«

Energy harvesting and systems (2015), Online First
DOI: 10.1515/ehs-2014-0060

[L113]
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»Betriebsbewährung von Alloy 617 in Gasturbinen«

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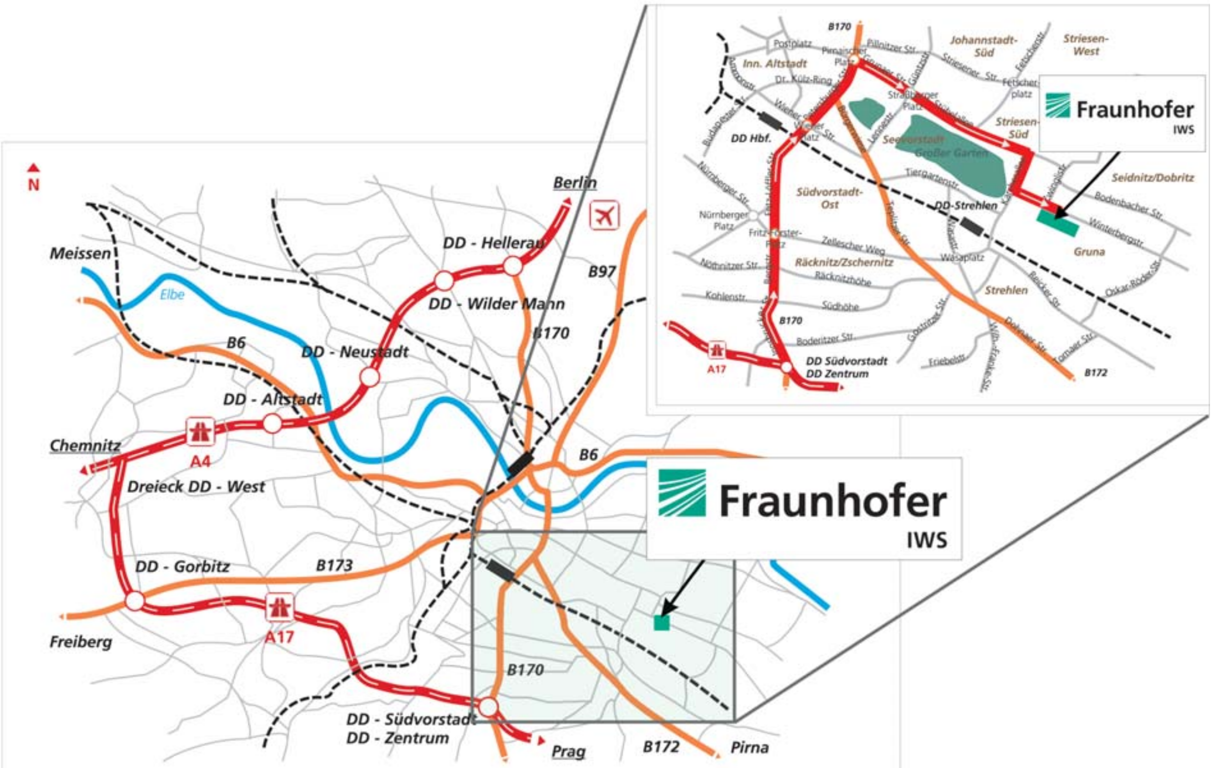

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