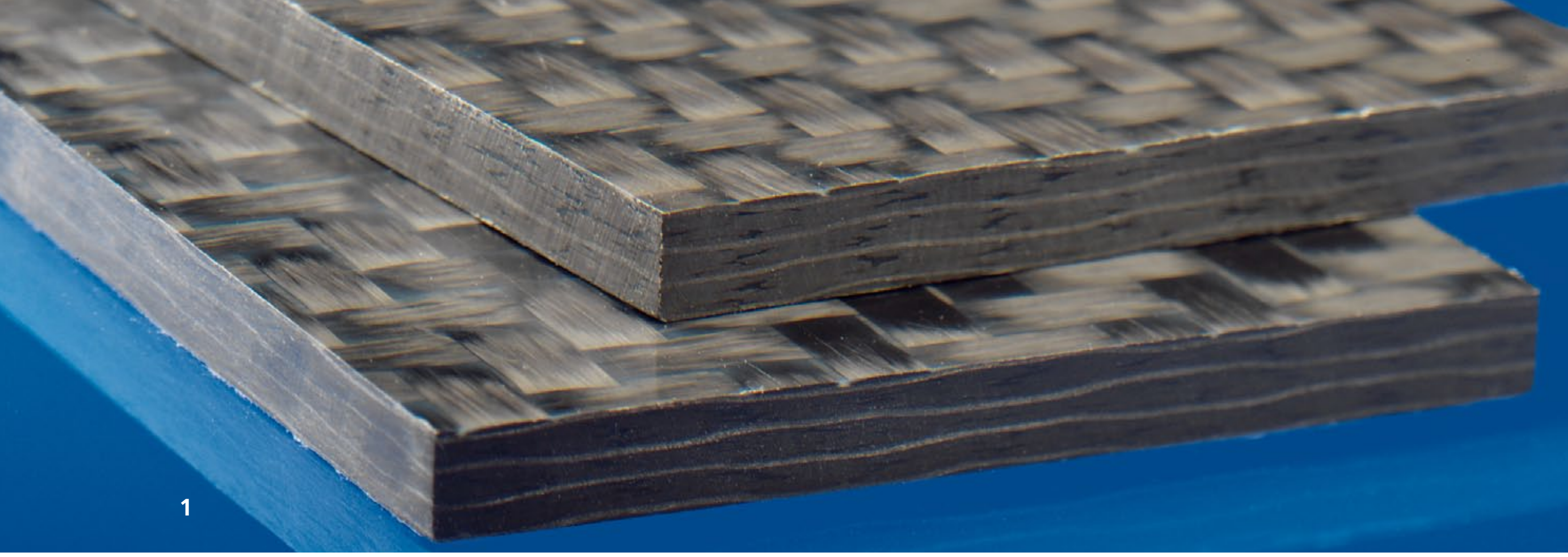


1

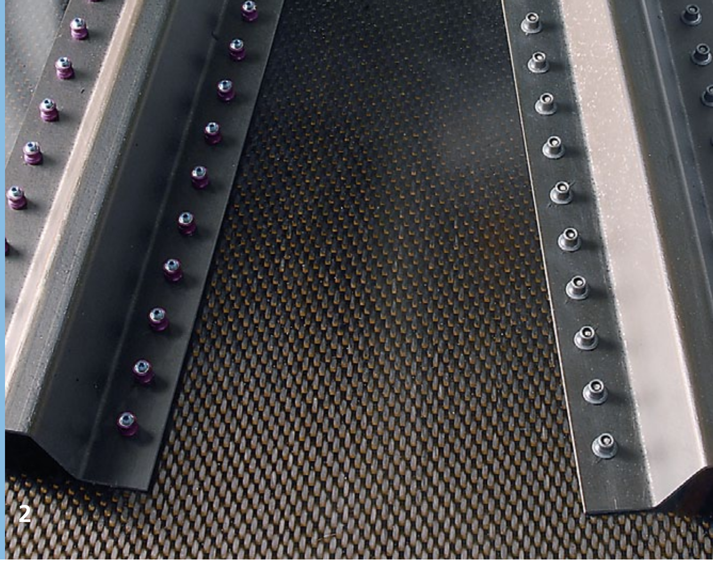
ALL EXPERTISE UNDER ONE ROOF: FRAUNHOFER IFAM HAS EXTENSIVE KNOW-HOW IN THE AREA OF FIBER REINFORCED PLASTICS

Industry favors these unique materials: Fiber composites. In general, fibers of carbon, glass, or other materials are embedded in a resin matrix. The advantage: Depending on the requirements, several layers of the fibers can be positioned on top of one another in different orientations. After curing, the resulting laminate or component has low weight but enormous strength. Light, very stable, and customizable for the relevant application: Fiber reinforced plastics (FRPs) are justifiably very popular, despite their comparatively complex manufacturing processes.

It is important to realize at the outset that fiber composites would not be possible without adhesive bonding technology. The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM has built up outstanding knowledge over many decades, ranging from the understanding of processes at the molecular level to the joining of fiber reinforced plastics on an industrial scale. The institute has actively supervised many development projects.

Both carbon fiber reinforced plastics (CFRPs; fig. 1) and glass fiber reinforced plastics (GFRPs) have become established in industry. The applications for these materials vary tremendously and range from canoes, molded from resin-soaked glass fiber mats, to the wings of the latest Airbus aircraft. Other applications include those in high-performance sports and in high-tech areas: CFRPs are used to make tennis racquets, the frames of racing cycles, and skis, while GFRPs are used in shipbuilding and wind turbines. In the aviation industry, glass fiber reinforced aluminum (GLARE®) plays an important role: Alternating layers of aluminum and glass fibers laminated together.

The sections of the Department of Adhesive Bonding Technology and Surfaces at the Fraunhofer IFAM are involved in key issues relating to the manufacture and application of fiber composites. More often than not, the transitions are seamless: Close collaboration between the individual sections guarantees comprehensive and effective project work and appraisal from different points of view.



Dimensioning, design, and manufacture of fiber composites

The section Material Science and Mechanical Engineering is involved with the dimensioning and design of fiber composites, as well as with their manufacture, mechanical testing, and issues regarding bonding and riveting of these materials. Resin infusion and prepreg methods are preferred for the manufacture of fiber composite laminate sheeting up to a size of two square meters. Here, either dry fiber mats are placed in a mold and soaked with resin during the further processing, or – as in the prepreg method – pre-soaked mats are placed on molds and then cured in an autoclave under pressure and heat. The latter method requires extensive know-how, but gives particularly high-quality products, as required, for example, by the aviation industry.

Also important is the institute's long-time experience in testing fiber composites. The specialists at the Fraunhofer IFAM are able to determine the load limit and fatigue strength of fiber composite materials under static or alternating loads, right through to crash tests. These tests are undertaken, for example, on fiber composites used for aircraft, yacht, and wind turbine manufacture. Empirical knowledge is also important for dimensioning and designing components. This is because fiber composites can be manufactured with completely different mechanical properties, namely the layer structure and the properties of the resin can be tailored for the subsequent application.

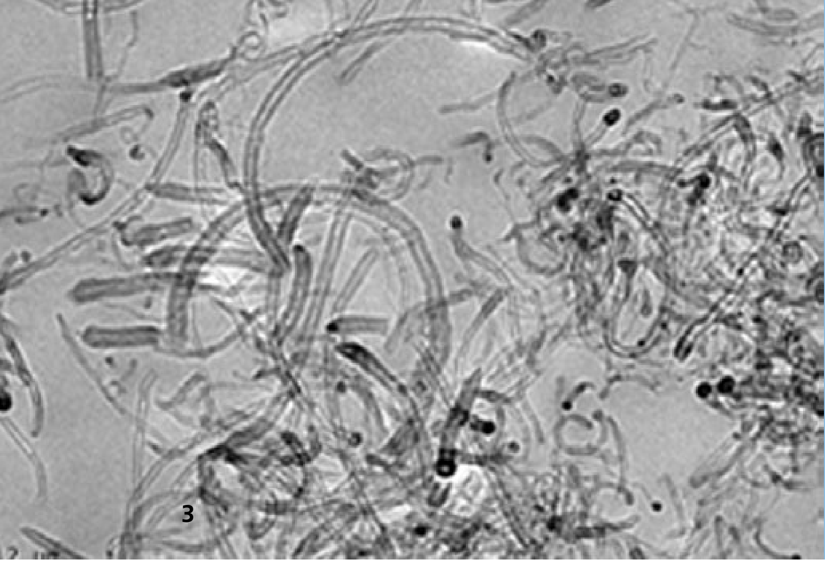
The section Material Science and Mechanical Engineering is also involved with the further processing of fiber composite components. These can be bonded, so giving thin-walled, light structures and a planar load transfer – ideal for the growing area of lightweight construction. Hybrid structures using fiber composites and other materials are also possible. In the aircraft manufacturing sector, where CFRPs are widely used, these materials are still often riveted in structural areas. The riveting of CFRPs and hybrid joining – namely the integration of adhesive bonding technology and riveting – are R&D areas in which the Fraunhofer IFAM has built up extensive knowledge and experience (Fig. 2).

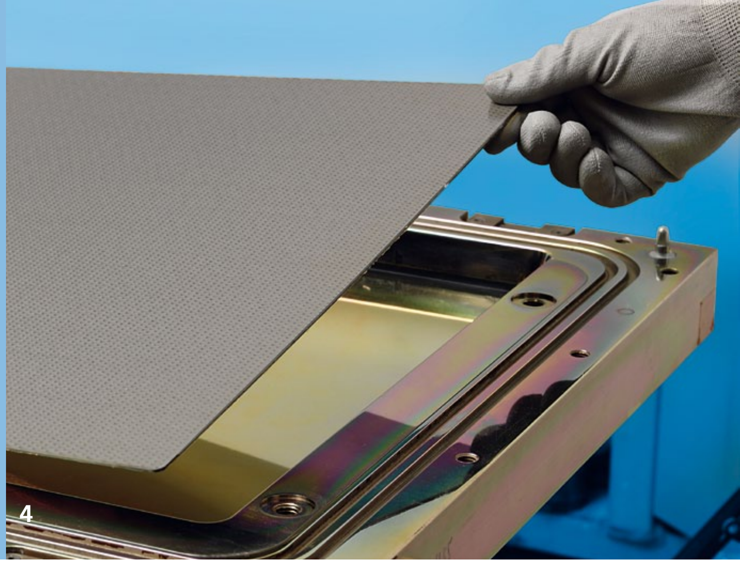
Fibers and resins: The chemistry must be right

A prerequisite for optimum production and the successful use of fiber composites is precise knowledge of the relationships between the fibers and resins, including all their individual features. For example, the weight and strength depend on the composition and structure of the finished CFRP or GFRP material. The section Adhesives and Polymer Chemistry is involved with matrix resins, the optimal attachment of the fibers to the matrix, and the modification of the resins in order to optimize the property profile.

Thermosets or thermoplastics are used as the matrix resins, with the focus at the Fraunhofer IFAM being on thermosets. After curing they often have a certain brittleness which is one of the main causes of damage to fiber composite materials. Although the toughness of the materials can be improved with various additives, these often reduce the strength. Intensive work is being carried out to find ways of overcoming the current limitations. Other important points for optimization regarding the production of fiber composites are the rheological properties of the resins and the curing conditions.

Amongst the additives which are used, special attention is put on modified nanoparticles. These particles have already been proven to have positive effects in adhesive formulations. The main material being used here is silicon dioxide pretreated in various ways, but also elastomanic nanoparticles, aluminum oxide, and carbon nanotubes (CNTs; see fig. 3) are being employed.


3


4

Pre-treatment of surfaces essential

Surface pre-treatment is highly important for fiber composites. The section Plasma Technology and Surfaces – PLATO – devotes itself to this task. The pre-treatment starts with the individual carbon fibers, which may already be affected by the oxidation processes used for their industrial manufacture. The surfaces of the fibers can subsequently be further modified, depending on the particular application, for example via plasma pre-treatment or wet-chemical processes. Together with the aforementioned optimization of the matrix resins, the Fraunhofer IFAM hence creates the preconditions for manufacturing fiber composite products having the best possible properties.

During the manufacture of fiber composite components or laminates in molds, the matrix resin generally acts as an adhesive. This is why thin release layers are necessary, consisting for example of wax or silicone, to enable easy removal of the finished fiber composite parts from the molds. The residues of the release agents which remain behind on the parts are, however, a problem. They prevent effective bonding and/or coating and hence must be removed. PLATO has developed innovative surface pre-treatment methods for cleaning. These include techniques involving the removal of material such as the CO_2 snow jet or vacuum suction blasting. In addition, the surfaces are activated by plasma treatment or with high energy radiation in the vacuum ultraviolet spectral region (VUV). At a molecular level these techniques allow improved attachment of adhesives or paints/coatings.

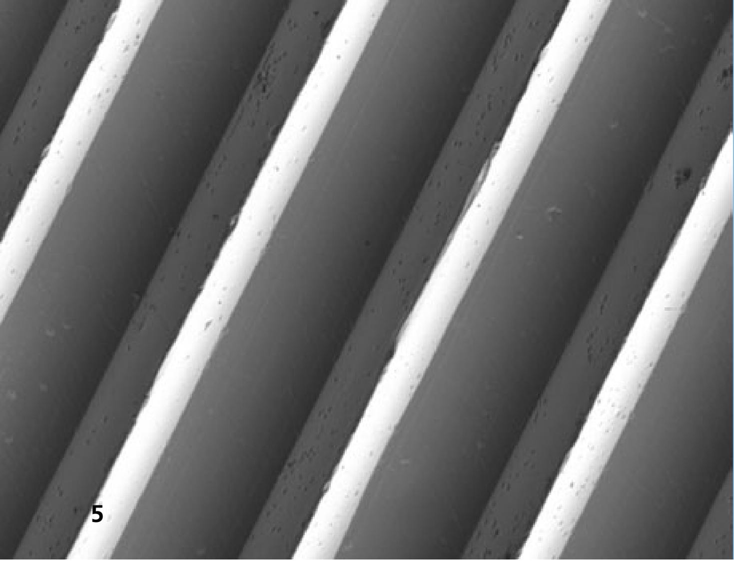
An alternative method for removing fiber composite components from molds is the coating of the molds with a permanently active release layer. In contrast to conventional release agents, the molding tool is coated with a release layer developed by PLATO. Even after many molding cycles this still has very good release properties. After being removed from the molds, the CFRP components show no presence of contaminants, meaning they are "ready-to-paint" or "ready-to-bond". Figure 4 shows a plasma-polymer coated molding tool on removal of a CFRP component.

The expertise of the section Plasma Technology and Surfaces is also relevant for other aspects of the manufacture and processing of fiber composite materials. This is particularly so regarding plasma-etching: In order to be able to monitor the intactness of carbon fiber materials during their everyday use, for example in aircraft components, glass fibers will in the future be incorporated into CFRP components as sensors to indicate the state of the component during usage (structural health monitoring: SHM). When joining such CFRP components, the individual glass fibers must be connected to each other. It is therefore necessary to expose them using a process as gentle as possible, and atmospheric plasma treatment is able to achieve this.

A further research topic of PLATO is corrosion protection when joining fiber composites with other lightweight construction materials, for example aluminum. As damage often occurs due to so-called contact corrosion, corrosion-suppressing plasma-polymer layers are applied in the joint regions.

Coating and modification of CFRPs

Surfaces are also of vital importance in the work of the section Paint/Lacquer Technology. They are investigating ways of measuring and eliminating undesired surface defects. This work concerns a variety of defects. High-quality CFRP components in particular require defect-free surfaces. A component can, however, only be as good as the mold in which it is made. If the mold has "negative" defects, then these appear on the surface of the component as "positive" defects. This gives rise, for example, to so-called voids: Pores which subsequently require extra filling and hence require additional


5


6

surface pre-treatment steps for cleaning, grinding, and activation.

If the resin and fibers expand to different extents due to temperature and humidity fluctuations, then the fiber structures – even after painting/lacquering – may be visible on the surface. The Fraunhofer IFAM is tackling issues like this in order to be able to produce acceptable paint/lacquer surfaces.

It is advantageous for the production if a component can be removed from a mold already painted/lacquered. The Fraunhofer IFAM is therefore working on developing special paints/lacquers which can be directly processed in the mold. This can, for example, be undertaken using a release film into which one of more paint/lacquer layers are integrated. Prior to manufacturing the component, the special films are deep-drawn into the mold. In conjunction with PLATO, the section Paint/Lacquer Technology is working to further improve these in-mold paints/lacquers and optimize them for applications.

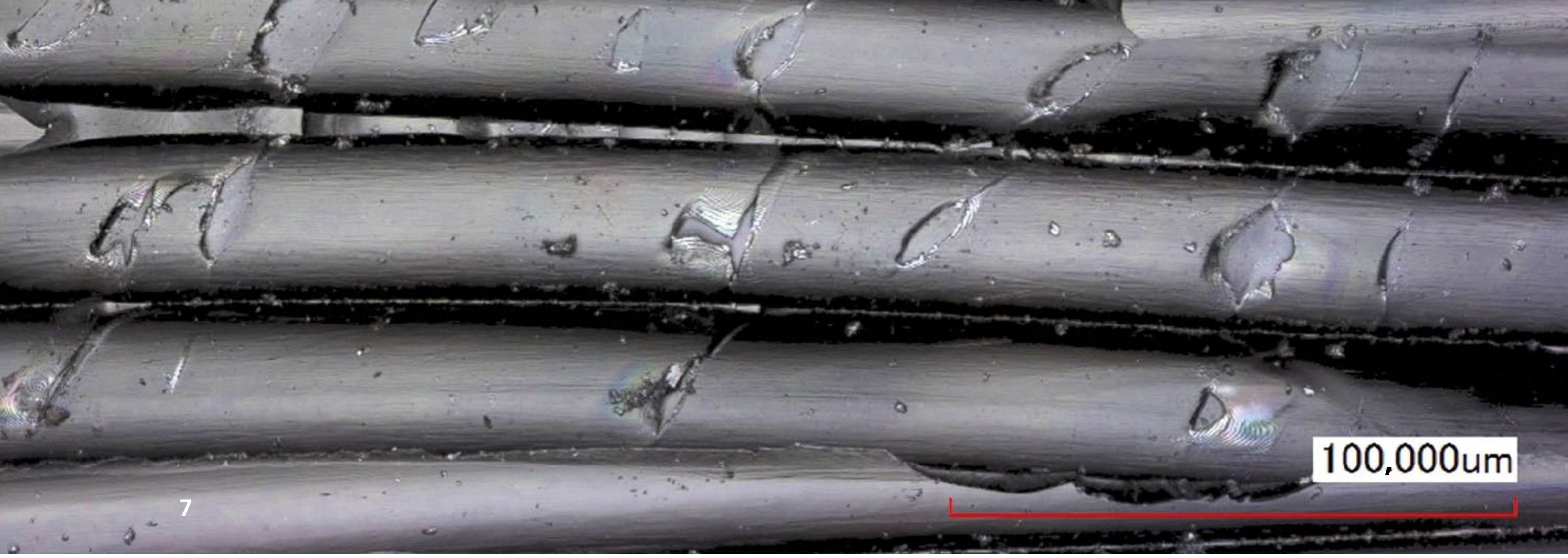
The Paint/Lacquer Technology section has extensive know-how for coating carbon fiber composites. This includes the qualification of paint and lacquer systems and also cleaning, pre-treatment, and lacquering processes. The quality of the surface can be analyzed and evaluated for its color, gloss, dust inclusions, run, and many other parameters. In addition, the functional modification of surfaces with systems such as self-repairing coatings, anti-fouling and anti-icing coatings, anti-erosion coatings, and riblet structures ("sharkskin structures"; fig. 5) are possible. The latter are particularly interesting due to the aerodynamic benefits for aviation and the wind energy industry.

The right joining technique: A lot of adhesives, with some rivets

In order to join components made of fiber composite materials to each other for a particular application such that the joints can withstand high loads, one needs an optimized and also economical joining method. This is true for both very small and very large structures: Until the day arrives when Fraunhofer IFAM can manufacture "a one-piece aircraft", wings have to be joined to the fuselage, and the tailfin to the undercarriage – ideally using adhesive bonding technology, which has always been the core competence of the Fraunhofer IFAM.

Fiber composite materials are generally joined after surface activation using film adhesives or hot curing adhesives. The bonding processes are often undertaken with the help of an autoclave in which the joints cure under the influence of pressure and heat (Fig. 6). One of the problems is that the size of the pressure vessel limits the size of the components which can be joined: There are no autoclaves which have the size of aircraft fuselages and it would not be economically viable to construct such large autoclaves. The Fraunhofer IFAM is hence developing adhesives for this purpose, which cure at lower temperatures. It is also desirable, for example, to be able to apply an adhesive to long joints with variable thickness – depending on the size of the gap between the individual substrates.

The section Adhesive Bonding Technology of the Fraunhofer IFAM is actively tackling these challenges. It is currently investigating, for example, the ideal composition of adhesives for joining fiber composites and is optimizing the flow properties and processing temperature. The section also develops complete process chains: Taking into account the relevant production environment and the given boundary conditions for the adhesives and components, the necessary personnel, machine, and space requirements are determined.



7

In addition, adhesive application, namely the actually applying of the adhesive, is a focus of the work. The need for gap size dependent adhesive application and minimum overdosing is being met by a newly developed system. The components and their contours are scanned by a laser scanner and after data transformation the components are virtually assembled on the PC. The varying gap width is measured. This information can be programmed into the robot and the adhesive can be finally applied according to need.

A special challenge when joining fiber composites is the riveting of these materials. This is currently common practice in the aircraft manufacturing sector: When the wings and fuselage of an aircraft are joined, the aircraft manufacturers do not trust adhesive bonding alone, and also always require rivets. The selection of the correct types of rivets and the drilling of the holes for the rivets are areas where the Fraunhofer IFAM is actively engaged. One task is to minimize adverse effects on the properties of composite materials due to material damage. The combined use of adhesives and rivets – so-called hybrid joining – is also a key area of work of the institute.

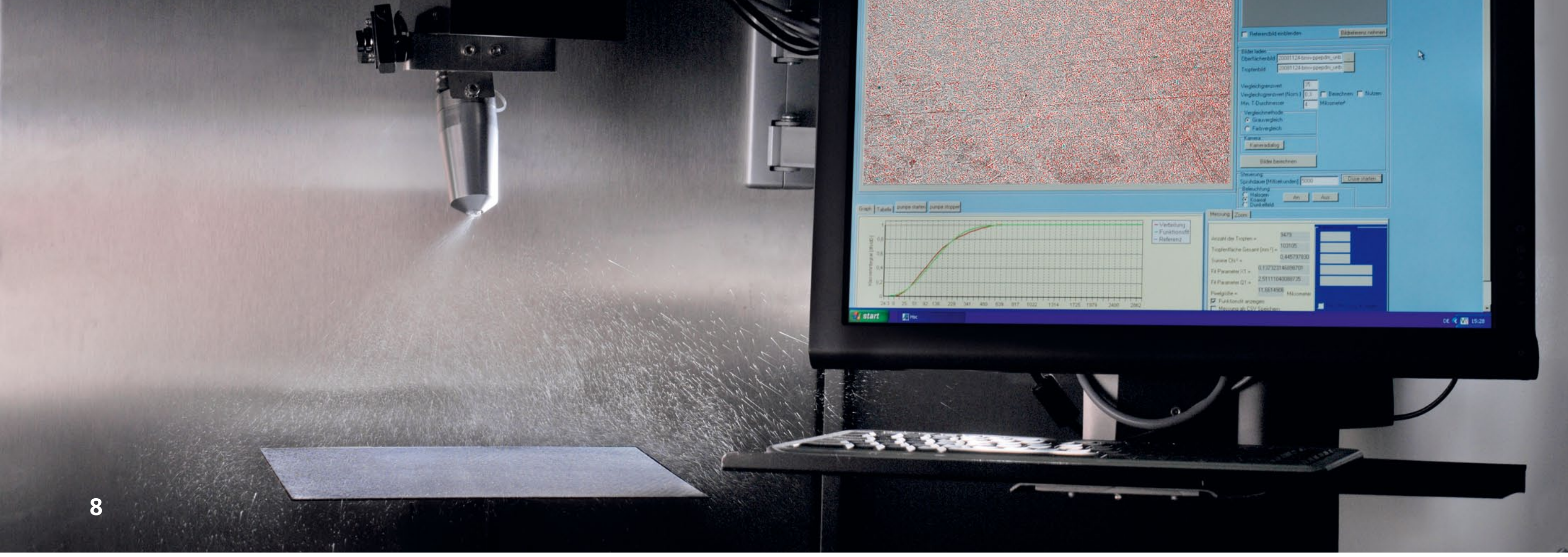
Know-how for material and process optimization: Adhesion and Interface Research

The aviation industry puts major challenges on adhesive bonding technology for the bonding of load-bearing parts, so-called structural bonding. For safety reasons it must be ensured that the bonded joint remains intact, namely does not suddenly fail. This can be tested using non-destructive test methods. Here one often encounters the problem of "kissing bonds": These material-fit joints which appear to be bonded perfectly, and yet satisfactory adhesion forces do not develop. The reason for this is a poor connection and poor interaction of the adhesive with the substrates at a molecular level.

Another means of demonstrating product safety is via process monitoring. The actual bonding process and joining process are closely monitored: Is the quality of the surface pre-treatment acceptable? Has the correct amount of the correct adhesive been applied at the correct place? Is the contact pressure acceptable and have optimum conditions such as temperature and air pressure been observed? This monitoring can also be very effectively integrated into the production process and is one of the tasks of the Adhesion and Interface Research section of the Fraunhofer IFAM. After the surface pre-treatment and before the application of the adhesive it is determined whether the surface is in an optimal state for being bonded (Fig. 8).

The surface characterization, namely analysis of the surface chemistry as well as macro- and microstructures, plays a key role regarding the adhesion of adhesives and coatings. It is hence important, prior to the surface pre-treatment, to acquire fundamental information about the microscopically thin interfacial layer in which the actual adhesion of the adhesive or coating occurs (Fig. 7).

With the help of adhesion and interface research, surface pre-treatments can be analyzed and evaluated – for example



8

the use of release agents, the degree of contamination, and the effects of release agent residues on the strength of the bonded joints. At the microscopic and sub-microscopic levels tests are carried out to investigate the adhesive interactions between the carbon fibers and the matrix resins which are important for the mechanical properties of CFRP materials. These tests are carried out at the Fraunhofer IFAM using state-of-the-art analytical methods and computer-aided simulation methods.

In addition, the evaluation and optimization of concepts for preventing galvanic corrosion when joining CFRPs with light metals, including the required long-term electrical insulation of the materials, is another important task of the section, especially directed at the aircraft manufacturing industry.

From the laboratory to 1:1 scale

All the expertise of the Fraunhofer IFAM mentioned up until now regarding the manufacture and application of fiber composite materials is also very important for the manufacture of large structures, for example for aircraft manufacture. The newly established Fraunhofer Project Group Joining and Assembly FFM has started its work for the Forschungszentrum CFK Nord (Research Center CFRP North) in Stade which is currently under construction. Together with various partners from the aviation sector they will develop assembly methods for CFRP components on a 1:1 scale.

The background to this is the current drive towards weight reduction via the increased use of lightweight materials, leading to fuel savings of up to 20 percent for aircraft. Other advantages are lower service costs and longer service life of CFRP structures, excellent corrosion resistance, and easier inspection.

Examples such as the Boeing 787 (Dreamliner) or the Airbus A350 demonstrate that the use of CFRP lightweight materials is advancing rapidly. For economical series production of such aircraft it is, however, necessary to maximize the degree of mechanization and automation by a variety of parallel process steps.

As the Fraunhofer-Gesellschaft – and in particular the Fraunhofer IFAM – has expertise in the whole process chain for CFRP processing, the Project Group FFM is a vital partner for the aircraft industry. Together with Airbus, Premium Aerotec, and other suppliers the Project Group FFM will further develop the automated and parallel-machining and assembly of large CFRP structures on a scale which guarantees a seamless transfer of the newly developed production processes to industry (Fig. 9). The wide use of CFRP materials in different sectors of industry – not only in the aviation sector – will increase if the costs can be reduced via automation. The car manufacturing industry, commercial vehicle sector, rail vehicle industry, and shipbuilding industry will then use CFRP materials to an ever increasing extent.

Workforce training – an important prerequisite

No innovation will achieve a break through and exhausts all the potential of a new technology if it is incorrectly used. This is why the training and further training of the people who work with and use fiber composite materials is very important. The Fraunhofer IFAM recognized this more than 15 years ago, when adhesive bonding technology was starting to boom. The Center for Adhesive Bonding Technology of the Fraunhofer IFAM is the leading training organization in the area of adhesive bonding technology.

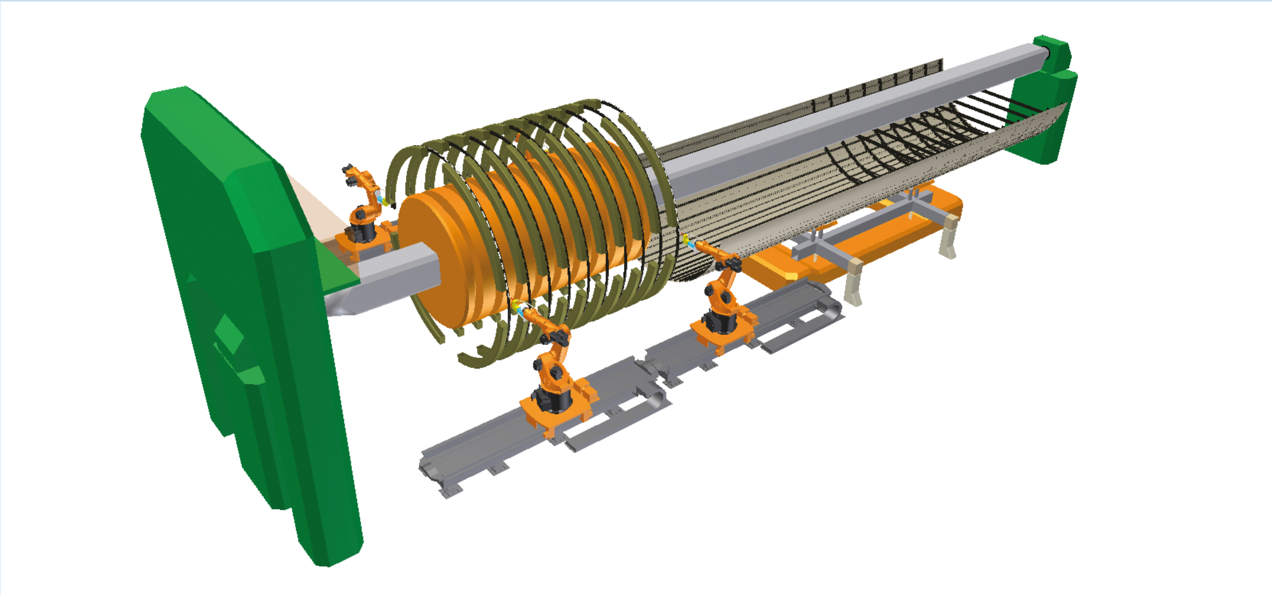


Fig. 9: Assembly plant on a 1:1 scale for bonding CFRP aircraft fuselages.

As the processing and joining of fiber composites cannot be separated from adhesive bonding, yet does have its own special features, the Fraunhofer IFAM and partners established the Plastics Competence Center. The Fiber Reinforced Plastic Technician training course is one of the activities carried out there (Fig. 10). This training course is becoming increasingly important for the plastic processing industries: The wind turbine construction industry and the shipbuilding, car manufacture, aviation and aerospace sectors require well trained employees. Such trained employees are available thanks to the Fraunhofer IFAM: To date, more than 340 people have successfully passed the Fiber Reinforced Plastic Technician training course in Bremen, Bremerhaven, and Brake.

CONTACT

Dr. Markus Brede
Material Science and Mechanical Engineering
Phone +49 421 2246-476
markus.brede@ifam.fraunhofer.de

Dr. Stefan Dieckhoff
Adhesion and Interface Research
Phone +49 421 2246-469
stefan.dieckhoff@ifam.fraunhofer.de

Prof. Dr. Andreas Groß
Workforce Training and Technology Transfer
Phone +49 421 2246-437
andreas.gross@ifam.fraunhofer.de

Priv.-Doz. Dr. Andreas Hartwig
Adhesives and Polymer Chemistry
Phone +49 421 2246-470
andreas.hartwig@ifam.fraunhofer.de

Dr. Dirk Niermann
Fraunhofer Project Group Joining and Assembly FFM
Phone +49 421 2246-439
dirk.niermann@ifam.fraunhofer.de

Dipl.-Ing. Manfred Peschka
Adhesive Bonding Technology
Phone +49 421 2246-524
manfred.peschka@ifam.fraunhofer.de

Dr. Volkmar Stenzel
Paint/Lacquer Technology
Phone +49 421 2246-407
volkmar.stenzel@ifam.fraunhofer.de

Dr. Ralph Wilken
Plasma Technology and Surfaces – PLATO –
Phone +49 421 2246-448
ralph.wilken@ifam.fraunhofer.de

Institute

Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM,
Department of Adhesive Bonding Technology and Surfaces,
Bremen

1 *Carbon fiber reinforced plastic (CFRP).*
2 *Hybrid joined CFRP component.*
3 *Adhesive with dispersed carbon nanotubes (CNTs).*
4 *Permanent release layer to allow molded CFRP components to be easily removed from molds.*
5 *Scanning electron micrograph of a riblet-structured paint surface developed by the Fraunhofer IFAM (top view).*
6 *Autoclave for manufacturing fiber reinforced plastics.*
7 *Laser scanning microscopy image of carbon fibers at the surface of a CFRP component manufactured by the resin transfer molding process (RTM).*
8 *Evaluation of the wetting properties of surfaces using the aerosol wetting test developed at the Fraunhofer IFAM.*
10 *Workforce training: Fiber Reinforced Plastic Technician training course at the Plastics Competence Center.*