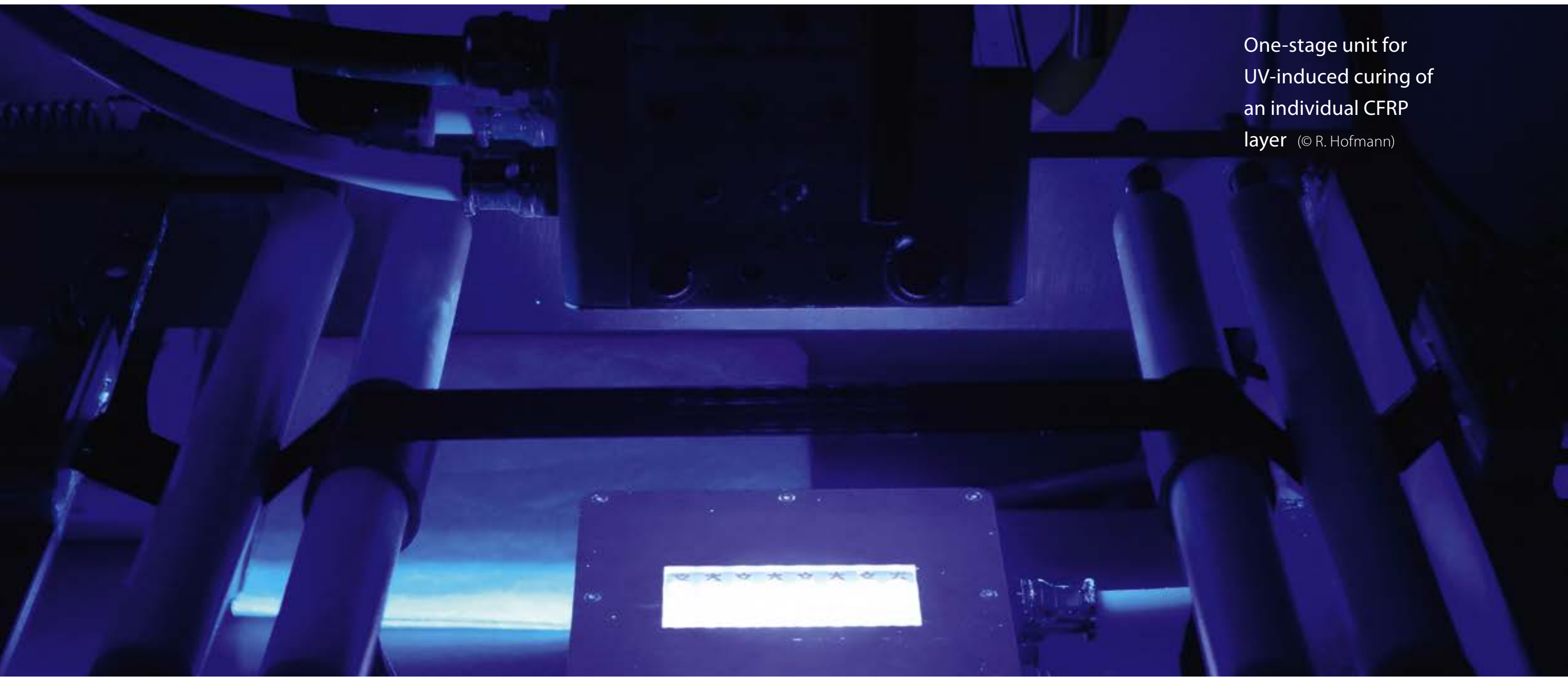

One-stage unit for UV-induced curing of an individual CFRP layer (© R. Hofmann)

Mastermind in the Fiber Placement Head

Additive Manufacture of Carbon-Fiber-Reinforced Components Using UV Radiation

The manufacture of carbon-fiber-reinforced plastic components for automotive serial production must be fast and cost-competitive. The ideal solution would be a one-stage process. In a potential study, a selective fiber placement unit was tested that combines fiber placement, resin injection, and curing in a single process step – with placement rates of up to 1 m/s.

The demand and need for carbon-fiber-reinforced plastics (CFRP) have been steadily increasing in recent years. The automotive and aerospace industries, in particular, rely on fiber-reinforced composites for certain components, since they permit substantial weight savings (30–50 %) to be gained as compared with the use of metals, while offering similar mechanical properties [1]. An urgent requirement for the further development of new fiber composite technologies is a considerable increase in material efficiency. It is also essential to achieve an optimum degree of lightweighting through free fiber orientation, localized reinforcement, topological geometry optimization, and the perfect integration of inserts, by placing rovings in loops around the insert.

At the present time, the development and use of CFRP is largely confined to purely thermal curing processes [2]. The above-mentioned demand for a significantly cheaper production process than familiar processes such as resin transfer molding (RTM), wet compression molding, etc., can be addressed by additive manufacture. To meet this requirement, placement rates of 0.06 m/s up to 1 m/s must be attained, so reducing the present very high production costs. The online partial curing of laminate layers at exposure rates of 30 ms to 500 ms achievable with radiation curing was not previously possible with thermally induced curing processes. UV radiation-induced curing (**Title figure**) opens up the possibility of generating degrees of hardness that can be defined by the duration of radiation exposure. In this way, unlike with thermal reaction mechanisms, the progress of the reaction can be timed to give a constant degree of partial cure.

The content of this article is the first part of fundamental studies with UV radiation being conducted in the MAI SFE project by the University of Augsburg in collaboration with BMW AG. (MAI = Munich Augsburg Ingolstadt region of the Carbon Leading-edge Cluster; SFE = Selective fiber placement).

Production Concept with Selective Fiber Placement Unit

Selective fiber placement is being developed as a new additive manufacturing process (**Fig. 1**) in which long and continuous fibers may be impregnated with resin at speeds of up to 1 m/s. The resin reaction is initiated in a controlled way and the consolidated fiber-resin mixture placed with the desired degree of gelling in a one-sided mold. With this method, it should be possible to produce a molding with load-optimized fiber orientation and localized wall thicknesses from dry fibers and resin in a single stage. Cost-competitive implementation of this process depends on consistent fiber orientation, three-dimensional placement, and the avoidance of any cutting. This is possible if the resin-wetted fibers are placed in the mold in a load-optimized way, e.g. in the direction of the force lines, and can be fixed without being limited by technical restrictions of the production process [3].

In the present state of the art, technical restrictions of the production process include:

- The size of the placement head, which limits near-net-shape 3D placement,
- reduction of placement rates at cutouts,
- bridging of the roving in 3D geometry due to poor adhesion of the roving to the substrate or mold.

The intention is to start with the continuous fiber strand or roving with all the required process steps being carried out by a robot-controlled unit before placement in the mold. These steps include feeding and spreading the fibers and resin impregnation with adjustment of fiber volume content. Partial cure of the impregnated carbon fiber tape (b-stage) is induced by radiation. Complex machines such as presses are no longer required. The layers are bonded by contact pressure during placement, and final curing is carried out by annealing.

The process steps required in previous technologies such as the production of non-crimp fabrics, stacking, preforming, and resin injection are no longer necessary, so also eliminating the logistics and transport costs involved in these steps, which should not be underestimated. Compared with the current production system (RTM), material use can be greatly reduced (**Fig. 1**). Plant investment is also considerably reduced (no press, no preforming unit, no stacking unit), while at the same time the process offers faster cycles, increased use of robots, and commercial feasibility through a short process chain, sensor technology, and control circuits. Further potential lies in the higher degree of integration and elimination of machining processes.

Generic Approach

Since the selective fiber placement method is still largely unresearched, a generic approach was chosen, which can be divided into a potential study, a feasibility study, and an implementation phase. In each phase, the requirements were phase-appropriately analyzed and evaluated. Non-fulfillment of a requirement without a solution would lead to discontinuation. The approach can be broken down as follows into:

- State of the art/market screening,
- patent situation,
- product,
- process,
- potential/risk analysis,
- economic viability study, and
- planning the next phase.

While, in the potential phase, evidence can be determined from basic operation on test installations, in the feasibility phase evidence is gathered under near-production conditions (e.g. production speed). The data obtained from this phase then permit a near-production-scale pilot plant to be constructed in the implementation phase (**Fig. 2**).

Characteristic Results of the Potential Phase

Additive manufacture using a programmable control system permits layerwise build-up of the laminate. In this way, the technology differs from conventional CFRP production, in that the complete laminate structure, consisting, for example, of ten individual layers, is first injected with resin and then cured and if necessary post-cured to achieve the necessary glass transition temperature and degree of conversion/final curing.

While spreading and infiltration processes are no longer a challenge at the target production rates of 1 m/s, radia- »

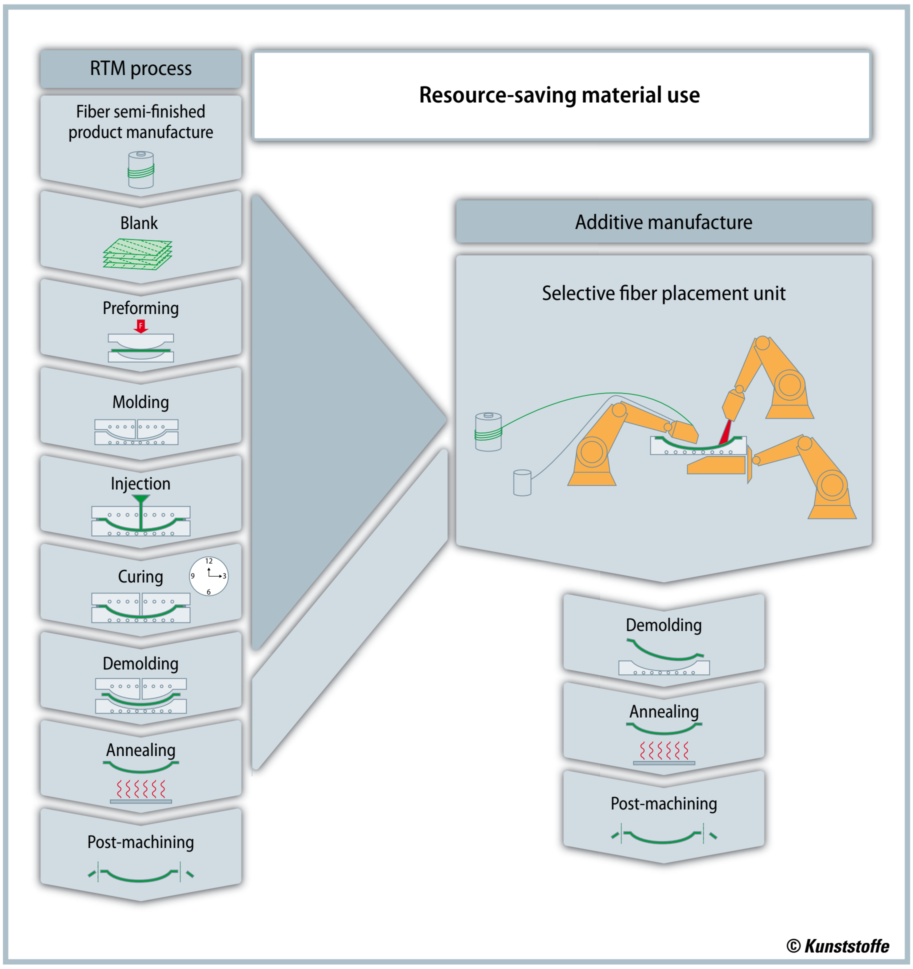

Fig. 1. Comparison between the CFRP manufacturing processes of resin transfer molding (RTM) and selective fiber placement: from the roving directly to the component (source: R. Hofmann)

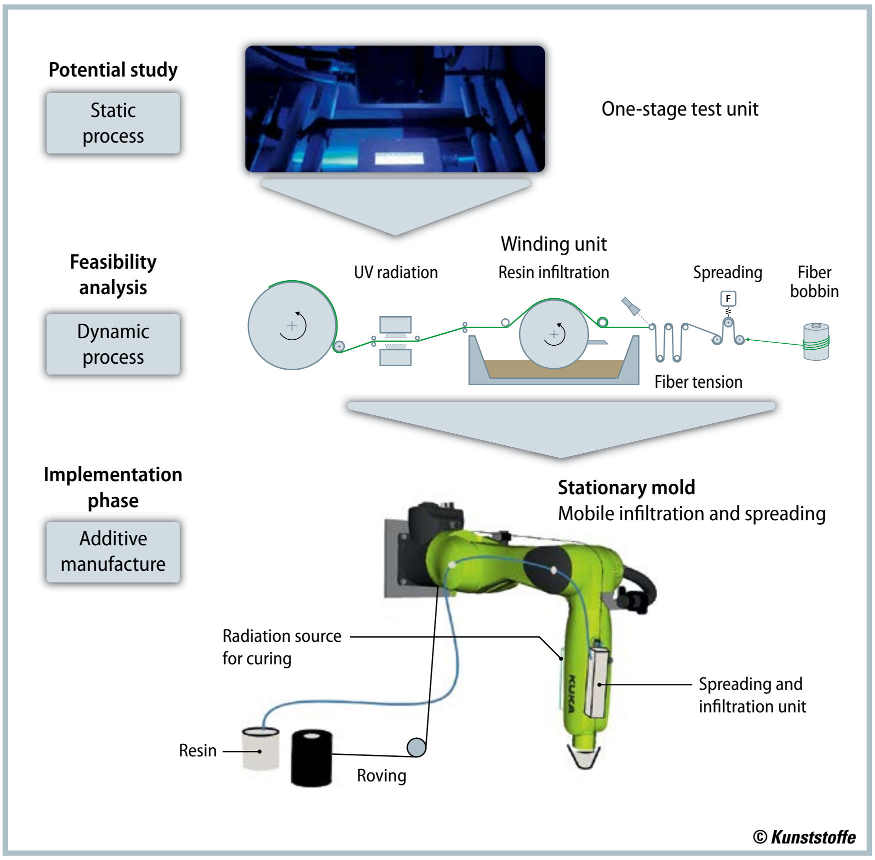

Fig. 2. Test chain from the static process over the dynamic process to the pilot-scale additive manufacture (source: R. Hofmann)

tion curing of CFRP under these boundary conditions is still largely unresearched.

In a cost-benefit analysis, preliminary trials evaluated different radiation sources for their suitability to be used in additive manufacture. UV radiation curing appeared to offer the best chances of implementation in selective fiber placement technology. Factors such as lamp technology, material system, and processing window were prioritized as success criteria for further evaluation of the process.

Lamp Technique

In addition to the established mercury vapor lamp, LED technology has been continually optimized over the last few years. In **Figure 3**, the usual curves for radiation intensity are plotted against the wavelength range. LED-UV systems operate in the UVA range of 315 to 380 nm with a wavelength of 365, 385 or 400 nm and convert energy directly into light. Relative to the 365 range (350–380 nm), a radiation intensity of 3.7 W/cm^2 and more can be applied here.

Besides UV radiation, mercury vapor lamps also emit visible light and infrared radiation, so providing a broader wavelength spectrum but also lower radiation intensity for selected regions than LED. Taking the example of the 365 range (350–380 nm) once again, a radiation intensity of only 0.65 W/cm^2 could be applied [4]. Because of the pulsing nature of fiber placement in the mold, the on-off behavior of the lamps plays a relevant role in relation to cycle time. In view of this, the UV-LED lamp was chosen for this project.

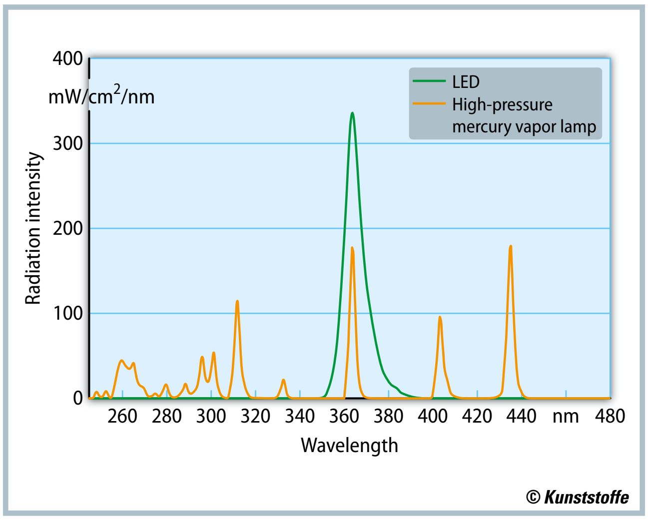

Fig. 3. Comparison between the wavelengths emitted by representative mercury vapor and UV-LED lamps (source: R. Hofmann)

Selection of a Suitable Material System

The commercial focus of the project leaves no latitude in the selection of the carbon fiber rovings (50 k). The curing mechanism of the UV resin systems is initiated by the photoinitiators used and defined by their specific absorption behavior. It is characteristic of the photoinitiator that its absorption of UV radiation takes place within a narrowly defined wavelength range. The curing rate of radiation-induced processes is essentially dependent on three factors: the match between the wavelength emitted by the UV lamp and the photoinitiator's absorption spectrum, the radiation intensity of the lamp, and the mass content of photoinitiator in the resin system. If the absorption wavelength of the photoinitiator and the wavelength of the lamp do not match, no relevant degree of conversion can be achieved [5].

Besides the better-known issues of spreading and infiltration, three sub-processes are relevant:

- Initial curing before placement: at the start of the study, a working value of at least 60 % based on empirical values was used as a basis, i.e. only partial curing of the roving before placement is necessary. The partial curing of 60 % had to be achieved at the maximum production rate (of 1 m/s) within 30 ms.
- Final bonding of the new individual layer with the previously placed mate-

rial (the compression molding process should be avoided).

- Annealing to achieve the final glass transition temperature (depending on the expected service temperature of the component, generally about 120 °C for automotive applications) and a degree of conversion must be > 95 %.

The requirements and stepwise approach in the evaluation are shown in **Figure 4**. In the first step, pure resin characteristics were determined. If these met specifications, individual laminate layers were produced in a static process and evaluated with established test methods (degree of conversion, glass transition temperature, fiber volume content, laminate quality) (**Fig. 5**). On a further test installation, multilayer laminates were then produced and similarly evaluated [6].

Process and Production Parameters

Since the serial-production process comprises a number of sub-steps linked together in a compact environment, an exact knowledge of the interactions between each individual step is required. For this reason, in the first place, a static test installation was used to produce test specimens of individual laminate layers. With this setup, it was possible to vary the input parameters (spread quality of the roving, areal weights and thickness, different resin systems), processing parameters (fiber tension, exposure time, distance from the laminate), and hardware (UV lamps) and evaluate the test specimens so produced (laminate quality, degree of conversion, glass transition temperature, mechanical properties).

Market screening for this process identified the availability of epoxy and acrylic systems with curing times of 1 to 3 s. In the initial tests, an epoxy resin »

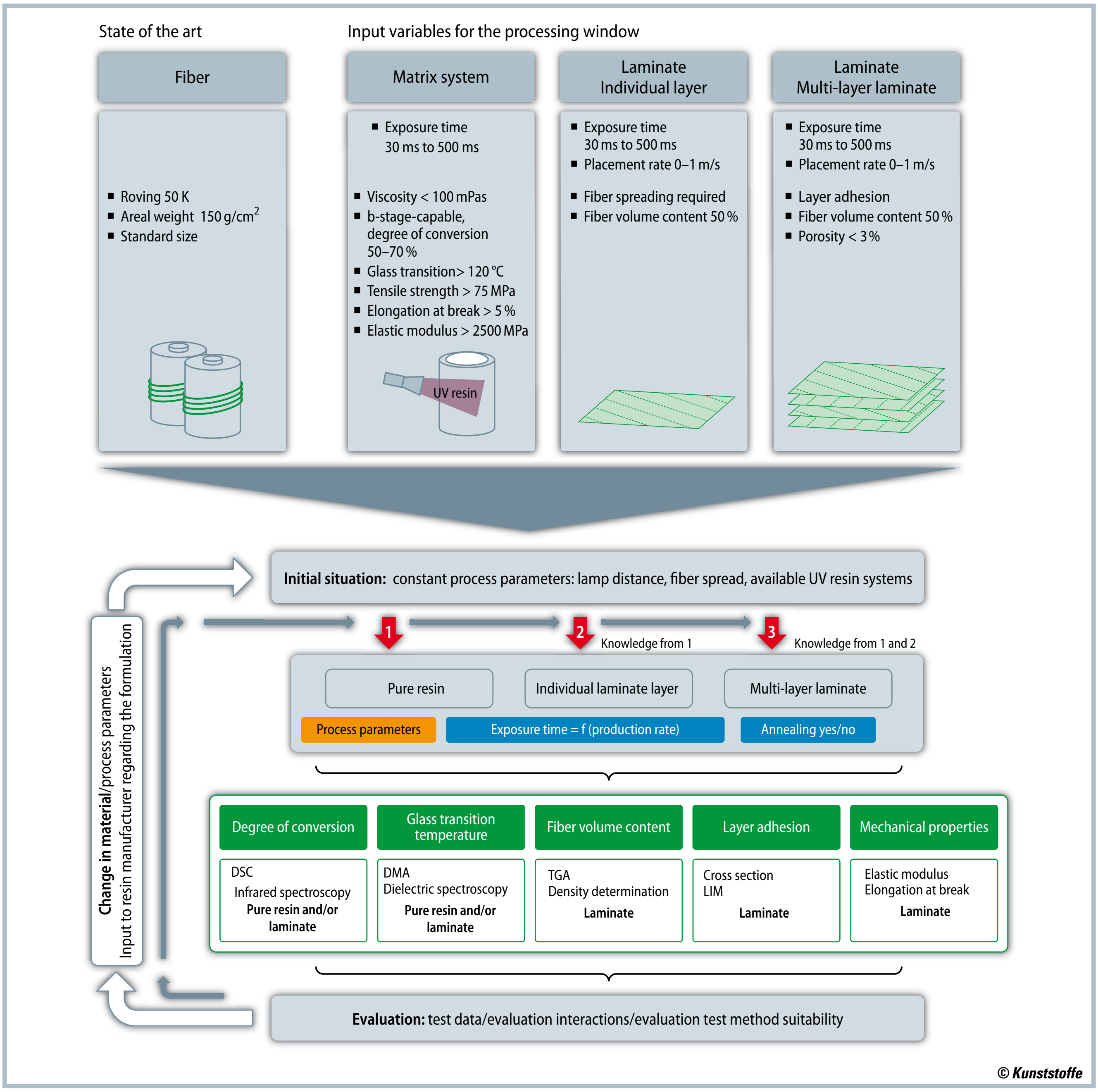

Fig. 4. Material requirements and selection system to meet the necessary process criteria (source: R. Hofmann)

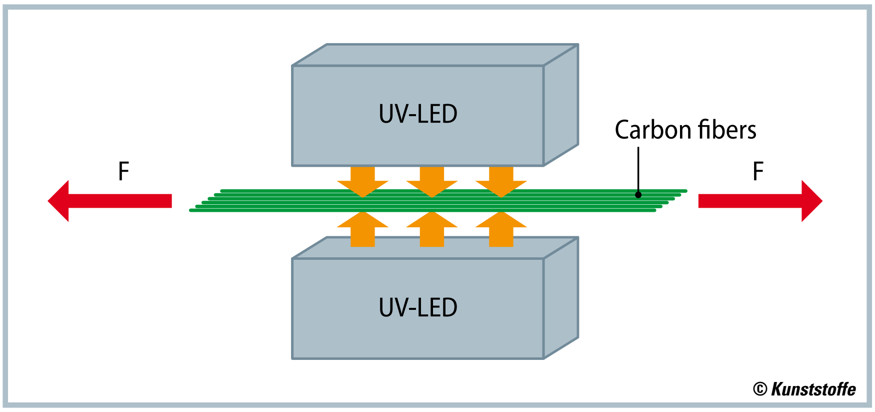

Fig. 5. Static test installation for the production of single laminate layers using UV curing (source: R. Hofmann)

system at the trial stage was used (type: Delo Katiobond VE113740, manufacturer: Delo Industrie Klebstoffe GmbH & Co. KGaA, Windach, Germany), as it seemed to have the most potential when compared to other commercial systems. Representative results are shown in **Figure 6**. The degree of conversion was determined by infrared spectroscopy (instrument: Bruker Equinox 55 Research Grade FTIR with ATR unit) and the glass transition temperature by DMA (instrument: Q800, TA Instruments), with the exposure time being varied (30, 100, 500 ms). The

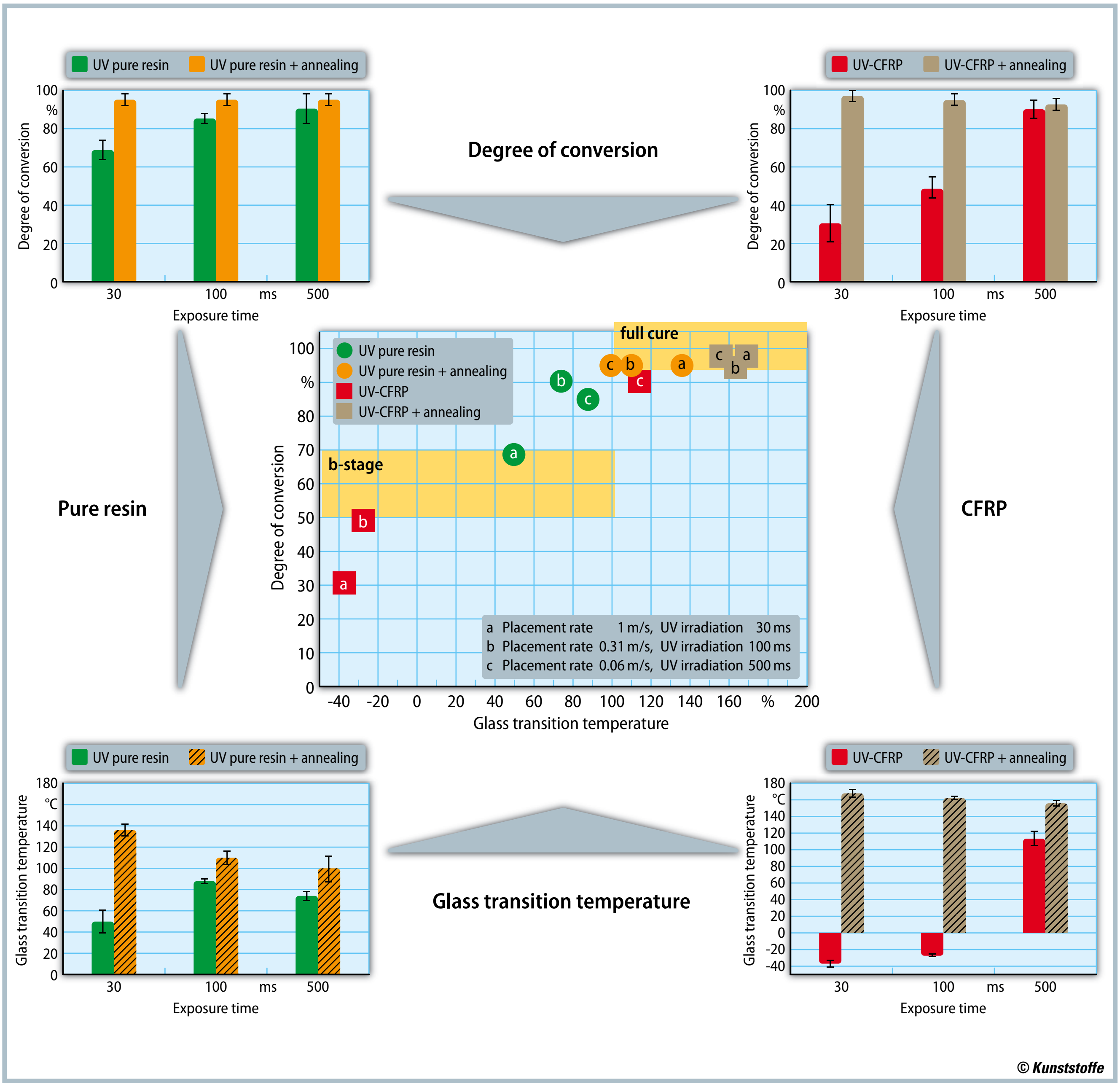

Fig. 6. Graphic representation of the different pure resin and laminate results for placement speeds of 1 m/s, 0.31 m/s and 0.06 m/s. The middle graph shows the degree of conversion as a function of exposure time (a, b, c) and glass transition temperature. The target states for the placed laminate layers (b-stage) and final CFRP laminate (full cure) are indicated in yellow (source: R. Hofmann)

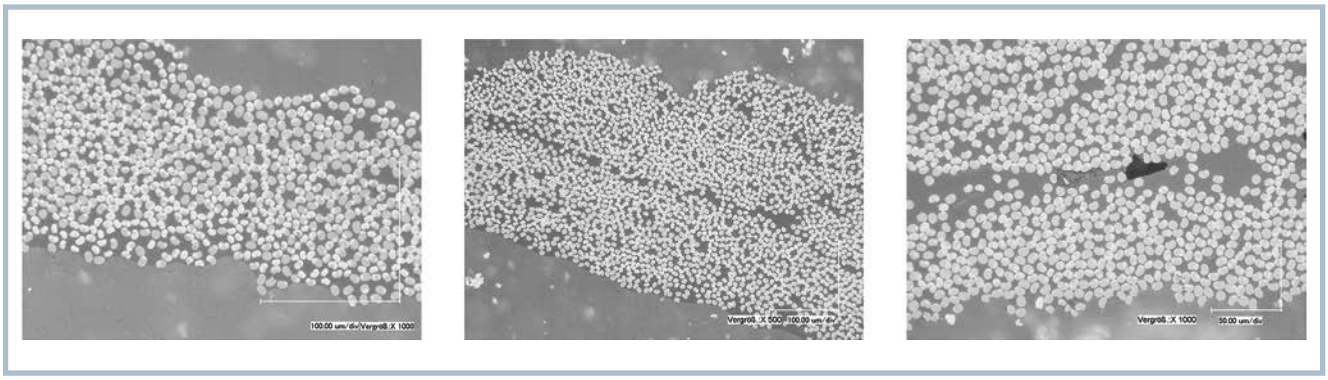

Fig. 7. Light micrographs of a UV-cured individual laminate layer, a multi-layer laminate (b-stage/b-stage) and a multi-layer laminate (b-stage/full cure). The samples were produced without a press (from left to right) (© R. Hofmann)

tests were carried out on both the pure resin and the individual CFR layer [6].

Figure 6 is divided into four quadrants with a summary in the center. The top bar graphs show the degree of conversion and the lower graphs the glass transition temperature. On the left are the results for the pure resins and on the right those for the laminates. The colored bars show the properties on placement, while the hatched bars show them after an additional annealing step. In each graph, the results are given for the relevant UV exposure times (30, 100, 500 ms).

When the degree of conversion is plotted against exposure time (a, b, c) and glass transition temperature, the graph in the center is obtained. Here, in addition, the target state of the placed laminates (b-stage) and the final CFRP laminates (full cure) are identified in yellow.

Figure 6 shows by way of example the results for the test resin, which were used as a basis for optimization of the resin formulation and the process:

- Radiation exposure time is the control lever for setting the degree of conversion.
- The characteristic values for the individual laminate layers are considerably lower than those for the pure resins.
- Complete conversion cannot be achieved with UV radiation alone.
- Post-annealing enables the target degree of conversion and glass transition temperature to be reached and is absolutely essential.
- The test resin does not meet the requirements for the b-stage at 30 ms. Exposure times greater than 100 ms must be planned.

Although the target requirements were not met, the state achieved at 100 ms was an order of magnitude better than the market norm and could lead to the desired result with modification of the lamp (exposure area/number of LEDs). On the basis of these data, a corresponding process model can also be created and confirmed. This approach can also be applied to other resin systems.

Once material systems and individual CFRP layer production had been examined in the initial tests described above and interactions identified, the first preliminary trials with the production of a multi-layer laminate followed (**Fig. 7**). These will make it possible to construct another test installation in future.

Summary and Outlook

The results of this potential study into a new one-stage additive manufacturing process for CFRP components show that alternatives to thermally induced CFRP production processes exist. A controlled UV-induced resin reaction was demonstrated at the required placement rate of up to 1 m/s for pure resin and up to 0.31 m/s for single tow placement. These results represent the first key milestone in establishing this process. Component production can be simplified and made considerably more cost-competitive. In the next step, the interactions occurring during fiber placement must be determined and bonding with the previously placed layer examined to avoid the need for a compression molding process.

With the above knowledge, implementation of the process on a machine with integrated process control, including a curing sensor, can be started. This is the next step in the commercialization of this additive manufacturing process. ■

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