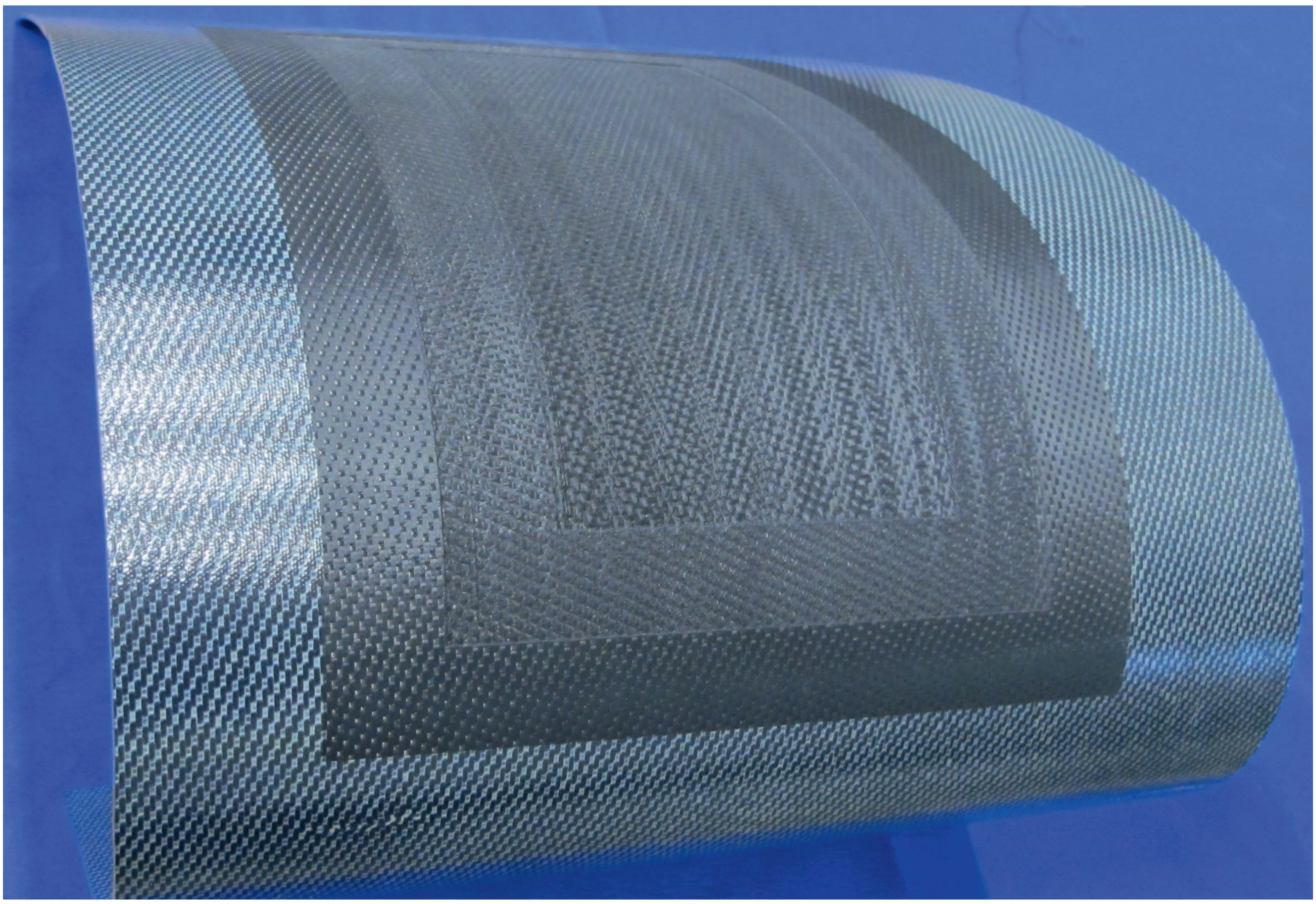
Laser Substitute Manual Work

Automated Repair of Carbon Fiber-Reinforced Plastics

Carbon fiber-reinforced plastics (CFRP) are being used in more and more components. Their production is also becoming more and more effective. In the event of damage, however, business continues to be carried out manually. For this reason, greater automation is desirable when repairing CFRP. Automated laser processes could be one way of doing this.



Stepped scarfing on slat demonstrator: scarfing is a challenging step in CFRP repair © LZH

Carbon fiber-reinforced plastics (CFRP) have become increasingly established in lightweight construction. It is used extensively, especially in aviation. Modern aircraft already have a structural weight percentage of over 50% CFRP. In addition to secondary structures, this material is also found in more and more load-bearing primary structures. The increasing need for CFRP has led to increasing production. However, the production of CFRP components is prone to errors and often requires rework. So far, this has been carried out mainly by hand. However, it requires qualified personnel and takes time. For this reason, automated processes should be used in many cases.

Rework is divided into three phases: repair preparation, patch application and consolidation. Well-trained personnel usually use compressed air-powered angle grinders to prepare for repairs, with which the CFRP is removed in layers around a damaged area in the component. This creates a scarfing in a stepped (**Title figure**) or conical shape. Afterwards, so-called patches are inserted into these scarfings. The patches can be applied as a hard patch or in the wet laminate process. The goal is to restore the original layer structure. The repair is then completed by consolidation of the repair site using heat treatment [1, 2].

Scarfing is a particular challenge when it comes to repairs. The carbon fibers have a strong abrasive effect on conventional machining tools. This leads to continuous wear and lowers process efficiency, which is why a regular tool change is necessary. The manufacturing process of the components is also difficult. Lateral displacements of the rovings can occur when the fiber fabric is laid on top of one another. When pressurized during curing or pre-compacting, these displacements sometimes also occur normal to the intended layer. Such undulations of the fiber layers must be taken into account when scarfing to prevent intact fiber layers from being damaged during the repair. This would result in a need for larger repair that was previously unnecessary. In addition, the conventional scarfing tools require the application of contact forces to the CFRP component to be repaired. Often, however, these are thin-walled structures with material thicknesses of few millimeters, which are therefore susceptible to deformation, especially in the progressive milling process.

Short Laser Pulses Protect Material

While the manual process for preparing for repairs remains state of the art, various institutions are working on its automation. This applies to conventional, mechanical processes such as milling and grinding as well as newer technologies such as machining using a water or laser beam. The engineers at Laser Zentrum Hannover e.V. (LZH), Hanover, Germany, are working with various partners to investigate methods for automating the laser-based material processing of CFRP surfaces. The focus is on linking laser use with modern process monitoring technology.

During the laser process at the LZH, the desired material thickness, which usually corresponds to the CFRP layer thickness, is successively removed with the laser by scanning the CFRP surface several times with a galvanometer scanner. Short-pulsed laser beam sources are used for this. Compared to continuously emitting laser beam sources, the interaction time between laser energy and material can be significantly reduced with nanosecond pulses. This prevents thermal overloading of the CFRP, which can lead to degradation of the plastic matrix and component failure. This should also be taken into account when directing the beam across the surface. The excess energy must remain below the degradation threshold of the plastic and be dissipated via the fibers before there is a critical heat accumulation in the matrix material. Therefore, one should avoid beam guidance along the carbon fibers and use an orthogonal guide [3].

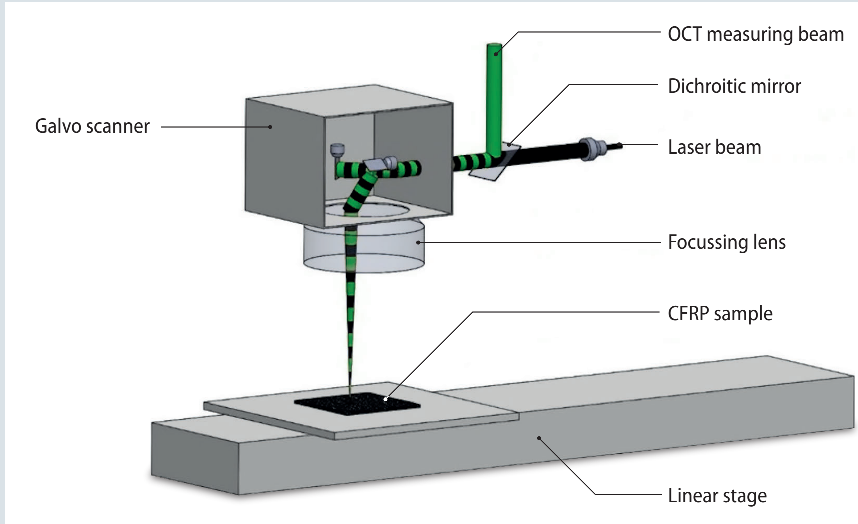


Fig. 1. The setup combines laser material processing with an optical measurement technique to automate the laser process Source: LZH, graphic: © Hanser

Optical Measurement for Automation

In order to provide an automatically controlled process, the laser process was linked with the short optical coherence tomography (OCT) from Precitec Optronik GmbH, Neu-Isenburg, Germany, in the joint project "ReWork" (**Fig. 1**) [4]. It is a very precise method for measuring path length differences. The measuring principle is based on a laser beam that is split. One half of the laser beam is guided along a reference path, the other to the measurement object. There, the partial beams are reflected, returned and the path length difference of the two beams is determined. The height of the removed material thickness can be monitored by continuous measurement during laser ablation and comparison with a reference plane recorded before the start of the process.

A great advantage of this optical measuring principle is that it can be easily combined with laser processing. Both systems can be configured to work with a similar wavelength ($\Delta\lambda \leq 30$ nm). This enables beam guidance via the same beam path. Excessive differences between the wavelengths would lead to aberrations in the processing plane, so-called color errors. They are due to different refrac- »

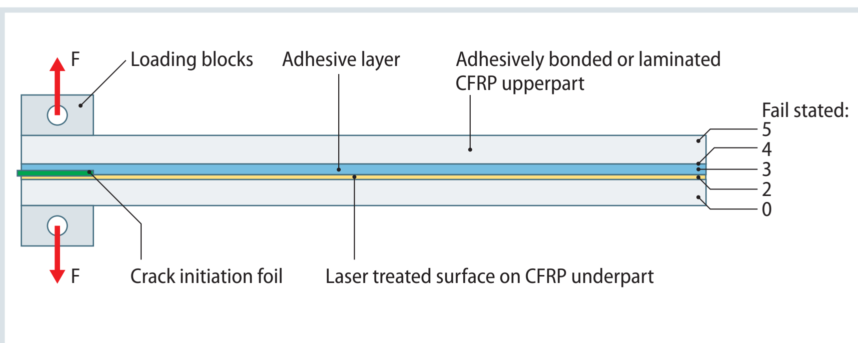


Fig. 2. Schematic principle of G_{Ic} coupon with highlighted positions of five fail-states Source: LZH, graphic: © Hanser

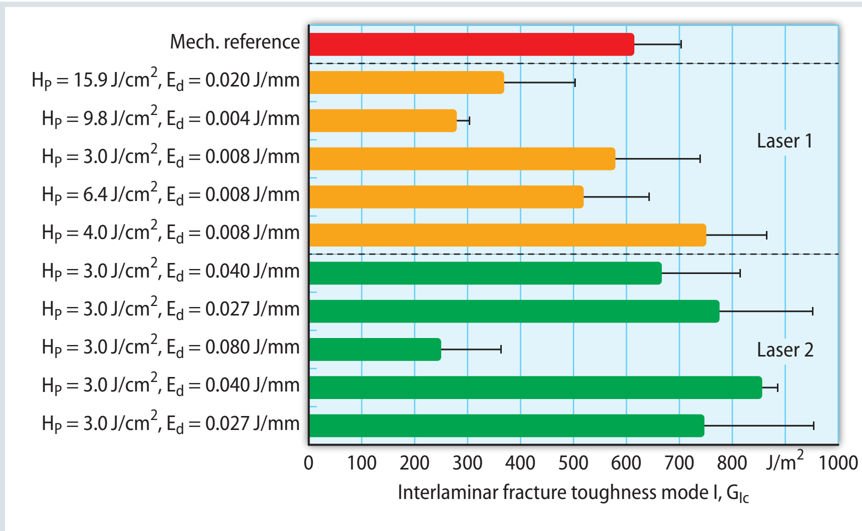


Fig. 3. Depiction of interlaminar fracture toughness realized by two near-infrared laser sources in comparison to mechanically milled references Source: LZH, graphic: © Hanser

tive indices on the optical lenses and mirrors. The almost congruent wavelengths, on the other hand, produce only minimal color errors. By precisely adjusting the two processing lasers and measuring beams, position errors in the processing plane can be achieved in the single-digit micrometer range.

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Acknowledgments
The research in project "ReWork" was supported within the fifth Federal Aeronautical Research Program (grant ID: 20Q1521B) of the German Ministry of Economic Affairs and Energy (BMWi), based on a resolution of the German Parliament.

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This measurement technology and the laser process are combined with a numerical process model. In this model, the relationships between the process parameters laser power, scanning speed, line spacing and size of the surface to be processed as well as their influence on the depth of ablation per surface crossing are stored. During the successive removal of the CFRP, the current depth is compared pixel by pixel with the target layer thickness of the respective CFRP layer. By comparing these two sizes, areas can be detected that have not yet reached the required removal depth. The sizes of non-contiguous areas are then determined and the processing parameters are automatically modified using the process model [5]. In this way, an automatically controlled laser process can be implemented.

Determination of Repair Quality

As part of "ReWork", the LZH engineers also examined the influence of the laser process on the repair quality. In cooperation with Invent GmbH, Brunswick, Germany, the interlaminar energy release rate Model (G_{Ic}) was determined in accordance with the test standard AITM 1–0053 for carbon fiber reinforced plastics, i.e. the energy required per area for crack opening or the start of delamination. To do this, the scientists removed the resin top layer on the CFRP surface with the laser radiation. The second half of the coupon was laminated to the exposed fiber surface in the same way as a CFRP repair. A separating film was inserted as the predetermined breaking point and crack formation was initiated there. The scientists then loaded the connection on the laser-treated surface for peeling. For the analysis, they examined the applied tensile forces and the development of crack growth. As the crack progresses, a distinction is made between up to five fail-states, depending on the areas of the test specimen in which the crack spreads (**Fig. 2**).

These states range from 0 (failure within the treated sample) to 2 (failure at the interface between the treated surface and the adhesive layer), 3 (failure within the adhesive layer) and 4 (failure in the interface between the adhesive layer and untreated sample) to state 5, in which the sample fails within the untreated half of the specimen. A pure failure in state 0 is problematic, since this indicates laser-induced damage to the matrix material below the surface. This can lead to component failure due to delamination.

As part of the project, test specimens were processed using two laser beam sources and with different parameter settings. Conventional, mechanically machined test specimens were used as a reference. The results in **Figure 3** show that with suitable process parameters, interlaminar fracture toughness can be achieved that corresponds to or even exceeds conventional processing.

Mixed Failures

With one exception, the fracture patterns of the coupons tested showed mixed failure cases, which had proportions of fail-states 0, 3, 4 and 5. Only the third parameter set processed with laser 2 failed completely in state 0. The dominant fail-state for laser 2 was state 4, a failure in the connection of the adhesive film to the CFRP coupon half not treated with the laser. Precise repair preparation with laser radiation can therefore lead to good results if optimal process parameters are selected.

Automatic control of the laser process is an important step towards automated, laser-based repair of CFRP. There is still further need for optimization for laser technology. Next, the engineers at the LZH plan to improve the speed of data processing and overall process speed. ■