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Laser-based approach for bonded repair of carbon fiber reinforced plastics

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Abstract

This paper describes a laser-based approach for the bonded repair of fiber reinforced plastic (CFRP) parts. According to CFRP's material properties and sensitivity to thermal loads, short pulsed UV laser radiation is deployed to realize a precise ply by ply removal for preparation of the repair geometry. The influence of different process parameters like hatch distance and number of cycles on the ablation depth and throughput is discussed. Finally, a full shear strength testing conformable to DIN 65148 is successfully conducted and demonstrates a maximum of material strength combined with a significant drop in total process time.

Keywords: bonded repair; laser-machining; selective matrix removal

1. Motivation / State of the Art

Bonded repair of fiber reinforced specimen is still a very difficult and time consuming process. As the application of composite materials for the manufacturing of aeronautical parts becomes more extensive, the need for repair of damaged composite parts gets higher. The aim of the investigations is to develop a technique for bonded repair that provides high geometrical accuracy, reduces processing time and most importantly, enables fully automated control, thus reducing requirements for skilled personnel and eliminating human errors.

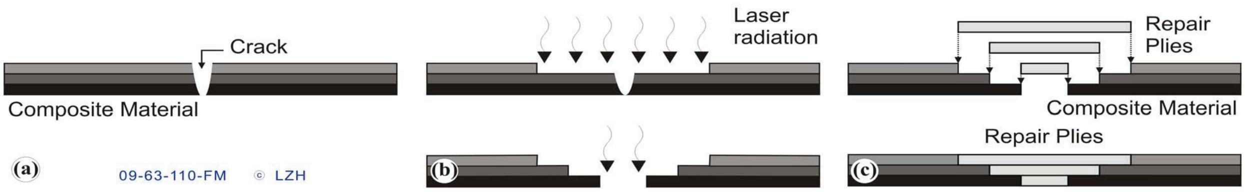

Figure 1. Principle of laser-based preparation for bonded repair of composite materials. (a) cracked CFRP specimen; (b) laser-based ply-by-ply removal; (c) refilling and consolidation with (e.g. laser-cut) fiber plies.

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Figure 1 describes the basic principle of the technique. An exact layer by layer removal of the damaged vicinity has to be realized by appropriate laser machining, Figure 1b. The main concern is the possibility of damaging the underlying ply, which decreases the structural strength of the part. This results in adhesion reduction and might lead to a catastrophic failure in bonding strength. The resulting typical stepped structure has then to be filled with appropriate fiber plies and is finally consolidated by resin infusion with a vacuum consolidation technique [1].

2. Laser – Material interaction

Due to its heterogeneous character, composite material is known to be very difficult to machine [2]. Due to the robust fiber material, a strong wear on the deployed expensive diamond-coated tools causes high costs in production. Even contact-less laser machining is problematic, since a very high intensity in the range of MW/cm² to GW/cm² is required for a thorough degradation of carbon fibers, while the polymeric matrix material has a low ablation threshold and shows a high transparency for a wide range of relevant laser wavelengths [3].

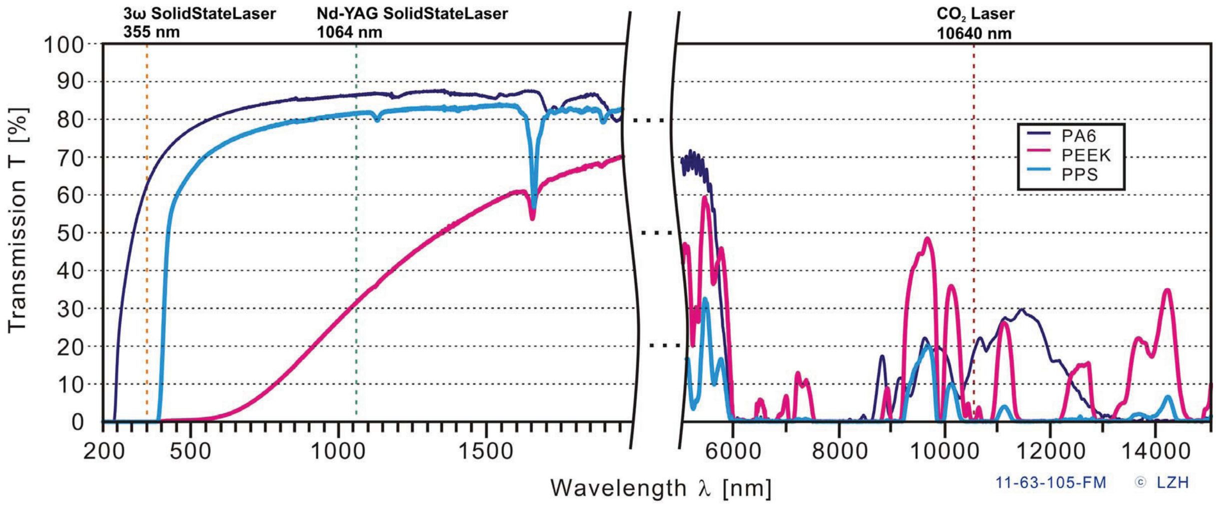

Figure 2. Transmission characteristic of selected thermoplastic matrix materials with indication of relevant laser wavelengths.

The transmission spectra of several thermoplastic matrix materials displayed in Figure 2 explain this phenomenon. Near the typical infrared (IR) wavelength of solid state lasers ($\lambda \approx 1000$nm) the transmission is very high, which means that a defined ablation of bulk material is not possible. Close to the mid wavelength IR, as emitted by CO_2-lasers ($\lambda \approx 10600$nm) the transmission drops but the strong thermal characteristic of the radiation creates a high risk of composite damage like delamination [4]. The photo thermal behaviour of this laser source derives from the low photon energy of approximately 0.12 eV ($\lambda \approx 10640$nm). This energy is not sufficient for direct intermolecular bond breaking of the treated materials, since the typical bonding energy of polymeric matters (e.g. C-N: 3.04 eV or C-C: 3.62 eV) exceed this quantum drastically [5]. Thus, for this wavelength regime the major degradation impact on CFRP is induced by heating, which causes carbonization and delamination within the laminate.

Accordingly, UV-laser radiation with wavelength $\lambda < 400$nm features low transmission and therefore good results for precise material ablation. With a photon energy of 3.49 eV ($\lambda = 355$nm), the process is characterized predominantly by a photo chemical mechanism, since most polymeric bonds can be cracked by a single photon. Industrially available UV-laser sources provide a low average power < 50W. Hence, to insure the high intensity necessary for sublimation of the carbon fibres, short pulsed radiation ($\tau \leq 30$ns) is required.

3. Experimental

The experimental setup consists of a 3ω solid state laser (SSL; $\lambda = 355$nm, $\tau \approx 30$ns, $f_p \leq 300$kHz), which can be guided by a highly dynamic laser galvano-scanner. This setup enables an easy modification of the test geometry by a CAD/CAM interface and appropriate adaptation of relevant parameters, like hatch width and number of hatch cycles. The detailed machine setup has been described in a separate paper [6].

For generating the desired repair geometry, initially a removal of fibers and matrix material is necessary. The physical process requests high intensity of the radiation to cut the fibers but also requires a precisely controlled ablation depth, so as to not damage underlying plies.

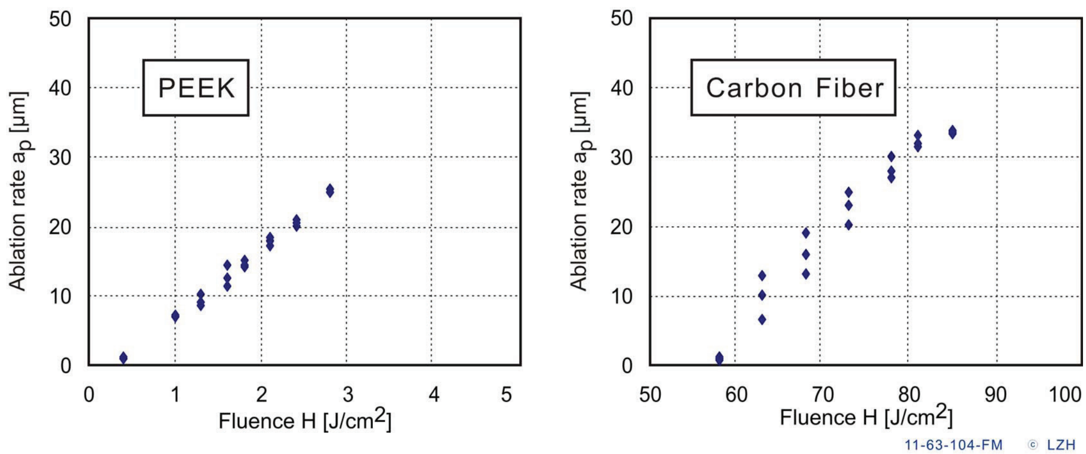

Figure 3. Ablation rate of the matrix material PEEK and carbon fibers vs. fluence (wavelength $\lambda = 355$nm; pulse duration $\tau_p = 30$ns) [3].

The variation of the ablation rate for the matrix material PEEK and carbon fibers in dependence on increasing fluence is shown in Figure 3. It is obvious, that the ablation threshold of carbon is about two orders of magnitude higher than the threshold for PEEK. This circumstance enables a selective removal of the matrix material from the non-damaged fiber layer by appropriate setting of laser parameters. However, due to the required high fluence, the risk of damaging the underlying plies is evident. A detailed discussion of the investigations has been published in [3].

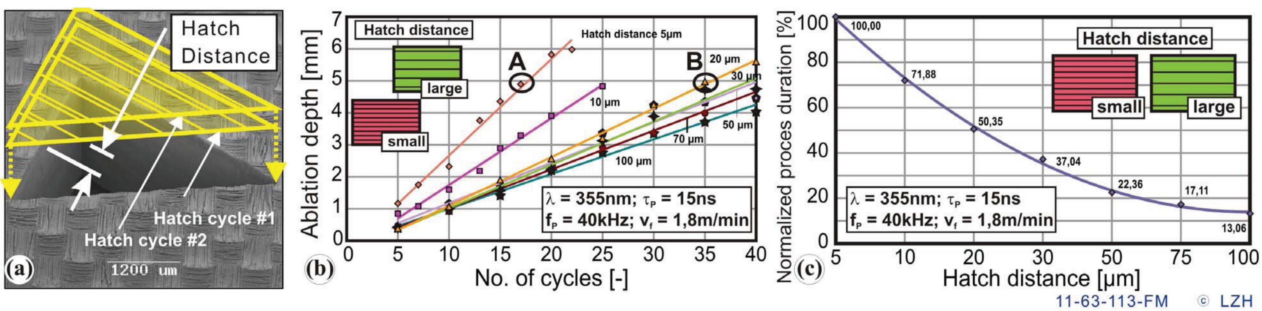

Figure 4. Influence of hatch distance and number of cycles of the affective ablation depth: (a) definition of hatch distance and number of cycles; (b) influence of hatch distance on the ablation depth; (c) potentials for increased throughput in dependence on hatch distance.

The ply-by-ply removal is realized by a linear laser hatching of the area to be removed, Figure 4 (a). In addition to general process parameters like pulse energy and feed rate the distance between the laser lines (hatch distance) has been identified as an important factor for throughput. To average the effects of a preferred direction of heat conduction along the fiber orientation, the parallel hatch lines of two adjacent hatch cycles are positioned perpendicular to each other. A precise depth control is possible by applying an appropriate number of hatch cycles.

Evidently, a smaller hatch distance results in increased laser energy per area and will lead to larger ablation depth. Figure 4 (b) displays an analysis of the ablated depth of a square shaped structure in relation to the number of hatch cycles as well as the hatch distance. It is obvious that the total ablation depth increases with the number of cycles and shorter hatch distance. However, considering the time scale of the laser process for two particular test scenarios with identical total ablation depth, indicated as A (17 cycle; 5µm hatch distance) and B (35 cycle; 20µm hatch distance) in Figure 4 (b), a distinct difference can be derived for the total process duration. For scenario B the "duration factor" *hatch cycle* would result in an approximately doubled duration compared to scenario A, while the factor *hatch distance* would result in a four times shorter duration per cycle. This means, that the overall process time for a certain ablation depth is faster with the set of process parameters for scenario B. Accordingly, a "normalized process time" has been calculated, which describes the duration for ablation of a defined volume of material in relation to the hatch distance, Figure 4 (c). For the displayed graph, the process time for a hatch distance of 5 µm has been normalized to 100%. A continuous drop of total process time can be observed from the analysis which runs into a saturation with hatch distance > 100µm.

This effect can be explained by the fact that the ablation characteristic for larger hatch distance moves towards the expulsion of close-cropped fiber clusters instead of vaporizing of the bulk material. This technique increases the material removal rate, but leads to slightly rougher surfaces. However, from this relation an optimization of the process speed can be derived up to a certain degree.

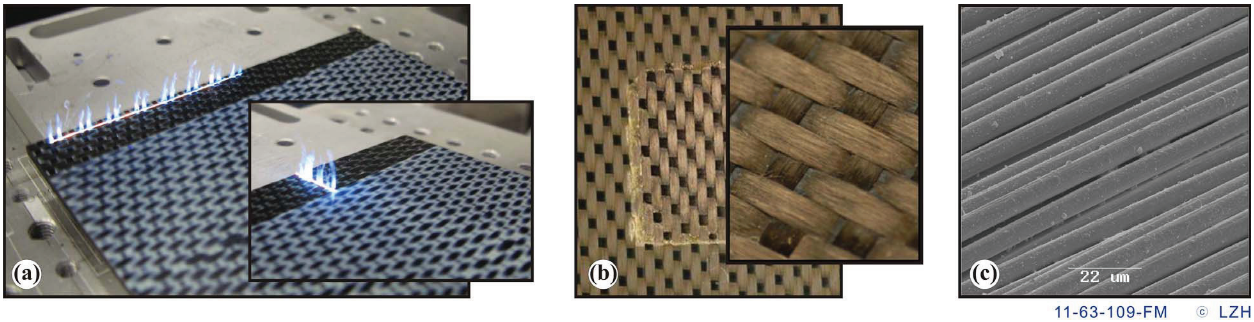

Figure 5. Selective ablation of the matrix material without damaging the fibers: (a) areal ablation principle (in x- and y-direction); (b) partly removed matrix from fabric; (c) SEM picture of cleanly exposed and non-damaged carbon fibers.

A further step of the preparation is the selective removal of matrix without damaging the underlying fiber plies. Due to the aforementioned drastically different ablation threshold of polymer and carbon, this technique can be implemented by reducing intensity or minimizing number of cycles. Fig. 5 (a) shows the strategy of perpendicular line scans by a 2-D scanner. Cleanly exposed fabric was achieved by this technique, fig. 5 (b), which did not show any evidence of fiber damage but a significant activation of the surface for bonding. Examination by SEM proved, that the polymeric matrix material could be removed precisely even between the still undamaged fibers. This supports the resin infiltration during the successive vacuum consolidation process and therefore increases the final bonding strength, fig. 5 (c).

4. Results and Discussion

Based on the knowledge gained from the initial experiments a full composite repair scenario has been realized to investigate the influence of the scarf ratio on the shear strength. For this reason, stepped structures were fabricated using the laser-basted technique described in section 3. The material used for the mechanical testing was unidirectional CF-PEEK (Tape Toho-Tenax, P-Yarn/Vestakeep). According to DIN 65148, the interlaminar shear strength of repaired laminates and 20 reference-specimens were measured and evaluated during the investigations.

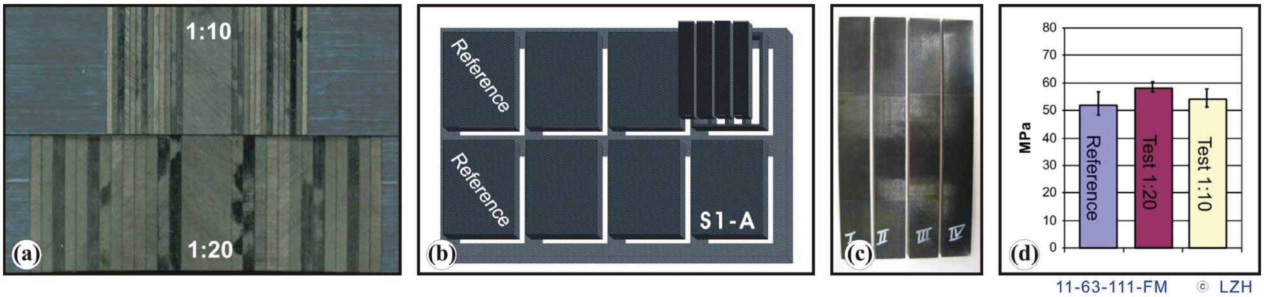

Fig. 6. Bonded repair: (a) size of area with different step width; (b) test pattern according to DIN 65148; (c) separated test specimen; (d) results of shear strength tests in comparison to non-machined specimen (reference).

The motivation for the lower scarf ratio of 1:10 can be easily derived from fig. 6 (a), which shows an obviously reduced total area needed for repair compared to that of the standard ratio of 1:20. This is relevant for composite parts with a curved or small-area surface to be repaired. All laser scarfed laminates have been consolidated by standard procedures and prepared and separated according to DIN 65148, fig. 6 (b). The emerged bonded test specimens, Figure 6 (c), have been shear strength tested. Fig. 6 (d) shows the results of the investigations. It is obvious, that within the margin of uncertainty the reference as well as the consolidated specimen show similar strength behavior. This implies that the difference in resulting total shear strength is minor. Hence, reducing the step width of the structure is definitely an option for repair of damaged parts with geometrical restrictions on the area of repair.

The even more remarkable result of the tests is that all laser repaired specimens showed at least the same strength behavior compared to the non-repaired reference samples, which proves the high potential of the described new technical approach including the ability for activation of the surface. Furthermore, the total process time for a repair cycle could be decreased from 40h (for mechanical standard repair) to 12h. A detailed description of the investigations can be found in [7].

5. Conclusion and Outlook

These investigations describe a new approach for bonded repair for CFRP parts. The results demonstrate that a reliable repair process can be established by the use of laser technology.

Main advantages of the novel technique are:

- A precise, high resolution ply-by-ply removal of the damaged vicinity.
- A selective ablation of the matrix material without damaging the underlying fiber layer.
- A high potential for automation and resulting from this fact, a possibility of certification (e.g. for aerospace parts)
- A clear decrease of process duration for the bonded repair cycle with comparable bonding strength

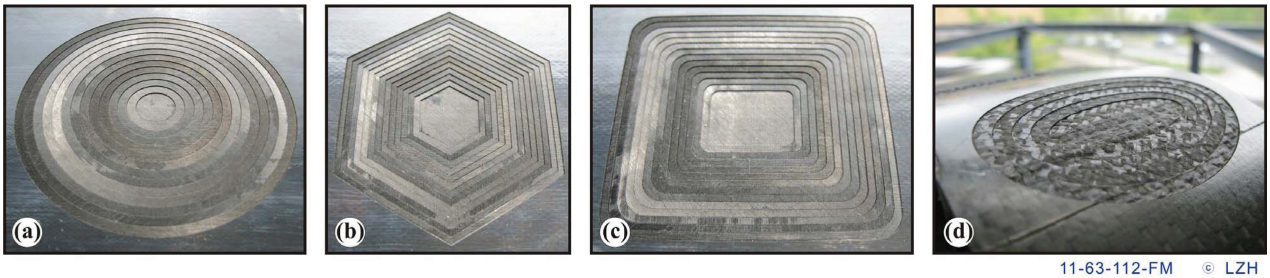

Figure 7. (a)-(c) Various geometries for bonded repair; (d) Laser machined step structure on curved surface.

The deployment of a flexible laser-scanner technology allows a very easy adaption of shape for the repaired area as well as the step width to depth ratio, Figure 7 (a)-(c). Furthermore, the machining of curved surfaces can be realized, Figure 7 (d).

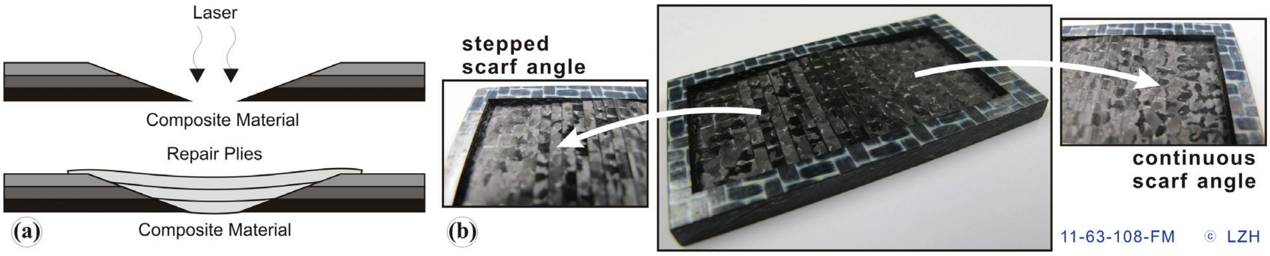

Figure 8. (a) Principle for bonded repair with continuous scarf angle; (b) laser-machined part for demonstration of a continuous scarf angle.

Finally, a continuous scarf angle of the ablated structure can be reproducibly realized on the damaged vicinity by further reduction of the step width, Figure 8. The advantage of this structure is a minimum of required total area for the repair. This opens up new capabilities of damaged parts which are difficult to repair, due to limited clear surface, complex overall geometry or strong curvature.

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