Technologies for Lightweight Structures 3(1) (2019), pp. 34–41
Special issue: 4th International MERGE Technologies Conference (IMTC),
18th–19th September 2019, Chemnitz

Influence of the edge quality to the water sorption of remote laser and mechanically cut carbon fibre reinforced polymer

Michael Rose[1,2], Alexander Mickan[2], Jan Hauptmann[2], Andreas Wetzig[2], Martina Zimmermann[1,2]

[1] Institute of Materials Science, michael.rose3@tu-dresden.de, Technische Universität Dresden, Helmholtzstraße 7, 01069 Dresden, Germany

[2] Business Unit Laser Ablation and Cutting, alexander.mickan@iws.fraunhofer.de, Fraunhofer Institute for Material and Beam Technology, Winterbergstraße 28, 01277 Dresden, Germany

Keywords

CFRP Processing, Edge Treatment, Materials Testing, Remote Laser Cutting, Water Sorption

Abstract

The processing of carbon fibre reinforced polymers (CFRP) is complex due to the heterogeneous material structure and the hard and brittle fibres. For the creation of the final contour during component manufacture, the trimming of semi-finished products is necessary. For these processing steps, multiple cutting processes are available. Depending on the chosen process, the structure of the edges can show considerable differences [1]. Reference [2] proves that the surface condition of CFRP influences the diffusivity, maximum moisture content and concentration. The cutting edge forms part of the component surface.

The aim of the present study is an evaluation of the influence of the cutting edge condition on the moisture uptake of CFRP. A systematic analysis of the water sorption behaviour of CFRP with edges generated with thermal remote laser and mechanical processing technologies was performed. Also, the effect of edge sealing was considered. Depending on the applied process, differences in the moisture uptake of CFRP could be shown. Several remote laser cut samples with a distinct heat-affected zone (HAZ) absorbed water rapidly. Thermally exposed fibre ends may form capillaries. By choosing suitable laser processing parameters or edge sealing, this effect could be avoided, resulting in inconspicuous water sorption behaviour.

1 Introduction

Due to their excellent mass-specific mechanical properties, fibre composites offer a high potential to meet lightweight construction requirements. Their inhomogeneous layer structure and the possibility of designing the textile architecture of the reinforcing fibres provide a good adaptability of the material characteristics to the specific application.

Nevertheless, there are challenges in manufacturing and machining these materials. The generation of the final component contours makes an appropriate separation processes necessary. Despite continuous development of tools for mechanical machining technologies, such as milling or drilling, they are subject to wear. The reason for this is the high hardness and brittleness of the technically most relevant carbon and glass fibres, which lead to a high abrasion of the tools [1, 3]. Remote laser cutting with galvanometrically driven scanner heads allows the use of light as a tool for the separation process and is therefore an alternative for mechanical machining. Unlike classic gas-assisted laser cutting, cutting is performed without the support of a gas. In addition, the cut here is performed by several high-speed exposure cycles and not by a single pass. Laser cutting is force- and contact-free, so that tool wear does not occur. This enables a reproducible quality of the cutting edge.

The remote technology with continuous wave (cw) lasers shows a smaller HAZ and thus better production results for the processing of CFRP in comparison to gas assisted laser cutting. This is due

Digital Object Identifier: http://dx.doi.org/10.21935/tls.v3i1.116
www.lightweight-structures.de

to the short interaction times between the laser beam and the material resulting from the higher laser spot velocities and the cyclic material ablation [4].

However, the formation of the HAZ has a measurable influence on the load-bearing behaviour of CFRP [5, 6]. Besides the purely mechanical aspects for the construction and design of structural parts, the material behaviour under different environmental conditions is of interest. For example, the polymer component of inhomogeneous composite materials is hygroscopic in most cases. Absorbed water deteriorates the glass transition temperature, shear stiffness and strength, especially at high temperatures [7].

Gupta and Pawar showed that the specimen geometry and the surface condition of fibre reinforced polymers have an influence on the speed and amount of the water absorption [2]. For this reason it is assumed that the occurrence of a HAZ also affects the water sorption of the material. This may be due to matrix degradation and the irregular surface of the polymer component interspersed with the exposed filaments. The existence of such a relationship was investigated for CFRP. The aim of the present study is the clarification of the influence of the remote laser cutting on the water sorption behaviour of CFRP. Furthermore, the effect of an edge sealing after cutting was considered.

2 Materials and methods

2.1 Properties of CFRP samples and their storage in a water bath

The material used for the tests was CFRP with non-woven unidirectional plies. For remote laser cut and waterjet cut samples the stacking sequence was $[0/90_2/\bar{0}]_S$. In contrast, the stacking sequence of the milled specimen was $[0_2/90/0]_S$. Each individual layer had a thickness of 0.3 mm, i.e. 2.1 mm or 2.4 mm for the whole laminates. The CFRP was pressed from epoxy resin prepregs with standard high-tenacity fibres. The fibre volume content was specified by the manufacturer as 60 %.

For the determination of the water absorption behaviour the CFRP specimens were stored in a water bath and weighed over a defined period of time. The geometry of all specimens for the tests was set to a circular shape. In this way the filaments were cut at any angle. The specific diameter of the samples and the water bath temperature were determined by preliminary tests. The applied conditions of the experiments are summarised in Table 1. Before their storage in a water bath, all of the rounds were preconditioned at an air temperature of 23 °C and a relative humidity of 30 % in order to keep the variation of the mass of each individual specimen below ±1 mg.

Table 1: Test conditions: specimen geometry and water bath temperatures

	Preliminary tests	**Main experiments**
Water bath temperature	Room temperature and 60 °C	60 °C
Specimen diameter	40 mm and 60 mm	40 mm

2.2 Precise scale weighing of the CFRP samples

Following the results of the preliminary tests, the weighing procedure of the specimen had to be precisely defined, since the free water, which was deposited especially on the CO_2 laser-cut specimen, evaporated during the measurement. This circumstance made consistent mass determination difficult. For the measurements, a vapour-tight vessel was used in accordance with DIN EN ISO 62. Before the weighing, the water covering the surface of the samples was removed. Subsequently, they were individually stored in the vessel and weighed one by one under reproducible conditions. For the main experiments, a high-precision scale with a repeatability of 0.015 mg and a reading accuracy of 0.1 mg was used.

2.3 Laser cutting and reference cutting processes

For the remote laser processing of the samples, a CO_2 laser and a fibre laser were used. The CO_2 laser offered a nominal power output of 3.5 kW in combination with a post-objective scanner system with 50 mm aperture. Because of the low focusability of this wavelength in comparison to the fibre laser radiation and the long focal length of the system, the cutting result was not optimal due to the lack of intensity. But the distinct HAZ at the cutting edge generated in this way was well suited to study its possible effects on the material behaviour. The nominal power output of the single-mode fibre laser was 5.0 kW. The optical system consisted of a post-objective scanner with an aperture of 50 mm. The parameters of remote laser cutting are shown in Table 2.

Table 2: Remote laser cutting parameters

	CO_2 laser	Fibre laser
Wavelength λ in µm	10.6	1.07
Spot diameter d_f in µm	416	54
Nominal laser power P_L in W	3500	5000
Spot velocity v_s in ms^{-1}	1.0	5.0
Number of passes n	19	16

For the preliminary tests, waterjet cutting was chosen as the mechanical reference process because it generates almost no thermal stress to the material and thus no HAZ [3]. Re-drying tests showed that no residual moisture from the cutting process was present in the samples. In order to obtain a more complete picture of the influence of common mechanical separation methods of CFRP, milling was used as the reference method for the main experiments.

2.4 Edge sealing method

For the evaluation of the edge sealing effect, additional specimens with sealed and untreated edges were compared. The polymer for the sealing was applied by a rotary device as shown in Figure 1. In this way, consistent and reproducible manufacturing conditions were provided.

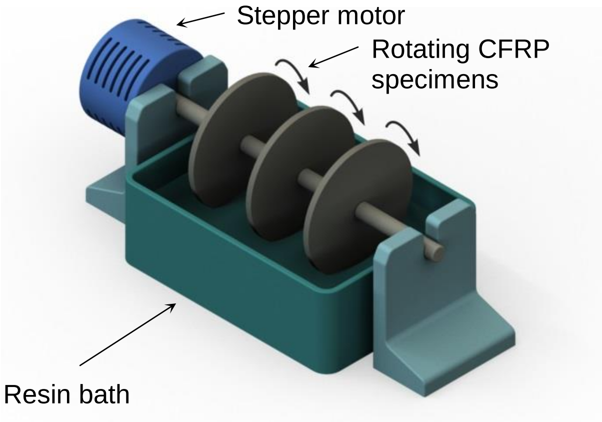

Figure 1: Rotary device for constant resin application conditions

An epoxy resin was used as sealing material. Polypropylene and polyamide proved to be unsuitable for the described method due to their poor processability. The handling and the lack of adhesion to the base material also ruled out the use of thermoplastic polymers for the tests. Unsaturated polyester resin was not used because of its pronounced shrinkage. This effect led to detachments of the sealant, which occurred during the cross-linking of the thermosetting resin. The epoxy resin used was the system consisting of resin L and hardener GL 2. Corresponding to the recommendations of the supplier, the epoxy resin was cured at 60 °C for 24 h. In this way a high degree of cross-linking of the resin was achieved. As a result, the resin did not post-crosslink during the water bath tests and its glass transition temperature of 85–87 °C was significantly higher than the water bath temperature of 60 °C.

3 Results

3.1 Preliminary tests for the specification of the experimental conditions

For the waterjet cut specimens it was necessary to exclude water deposits introduced by the separation process, which could have an influence on the measurements. Therefore, a randomly controlled drying test with subsequent remoistening under normal ambient conditions, which were similar for all specimens, was carried out. For drying, the specimens with a diameter of 40 mm were stored in an oven at a temperature of 60 °C. The results are shown in Figure 2.

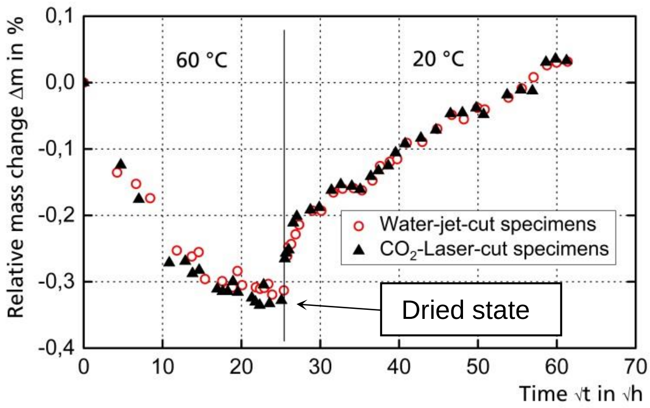

Figure 2: CFRP [0/90₂/0̄]ₛ drying test with subsequent adsorption

The measurements showed that there was no significant measurable difference in the drying and remoistening behaviour of the laser and waterjet cut specimens. The samples showed similar changes in mass increase and equilibrium for both processing technologies. After remoistening, the samples were 0.03 % heavier than before drying. This means that no water could be measured that was bound in the material because of the waterjet-cutting. Preconditioning was therefore sufficient. Furthermore, the influence of the specimen size and the water bath temperature was studied. Figure 3 illustrates the measured values of waterjet cut samples. The continuous lines indicate the minimum and maximum limits resulting from five individual measurements for each data point. Figure 4 shows an exemplary cross-section of an edge of such a waterjet cut specimen.

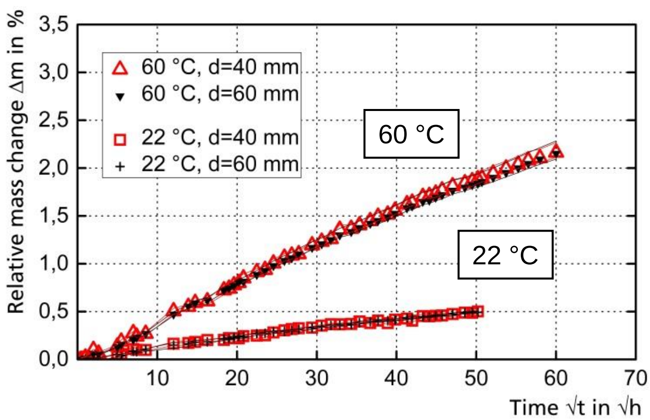

Figure 3: Effect of temperature on the water absorption behaviour of waterjet cut CFRP $[0/90_2/\bar{0}]_S$ with different sample diameters d

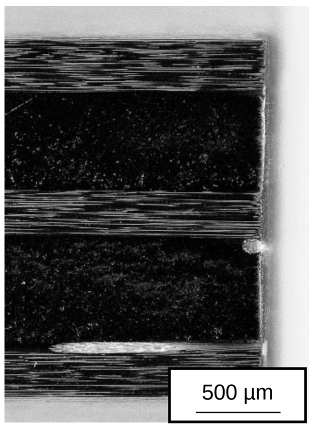

Figure 4: Cross-section of waterjet cut CFRP $[0/90_2/\bar{0}]_S$ edge

It was observed that for the water bath temperature of 60 °C diffusion was much higher than at room temperature. Therefore, this was a useful way of shortening the time required for the tests, especially as the temperature does not affect the maximum saturation of the epoxy resin [8]. It also became obvious that there is no significant influence of the diameter of the waterjet cut specimens on the absorption process. However, as Figure 5 shows, in the case of laser cutting a correlation between sample diameter and water absorption could be observed. An example of an edge generated by CO_2 laser with non-optimal parameters is shown in Figure 6.

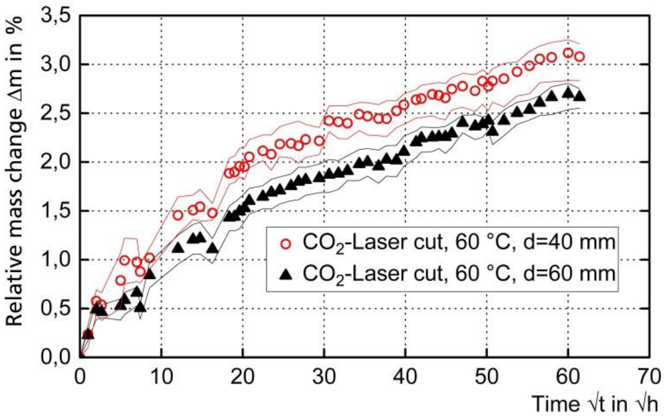

Figure 5: Effect of the specimen diameter d on the water absorption behaviour of remote CO_2 laser cut CFRP $[0/90_2/\bar{0}]_S$ with different sample diameters d

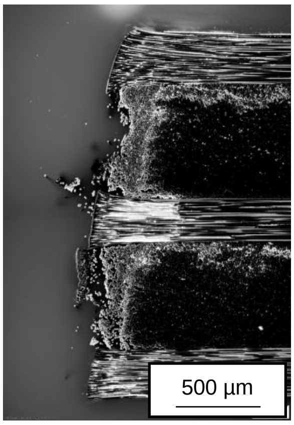

Figure 6: Cross-section of remote CO_2 laser cut CFRP $[0/90_2/\bar{0}]_S$ edge (non-optimal parameters)

The smaller samples with a diameter of 40 mm had a greater relative mass change than the larger ones. The main difference between the laser and waterjet cut specimens was the presence of a HAZ in the laser-cut samples. In conclusion, this was the reason for the specimen size dependent water absorption behaviour. This appeared plausible because the absolute width of the HAZ was similar in all of the CO_2 laser cut samples, which were all cut with the same parameters. But its volume in relation to the total specimen volume was larger for the small diameter. It was assumed that the exposed and narrow filament ends of the HAZ formed capillaries, which were capable of taking up water. The exemplary SEM photograph of a fracture surface of a remote fibre laser cut unidirectional CFRP in Figure 7 demonstrates the exposure of the filament ends in more detail.

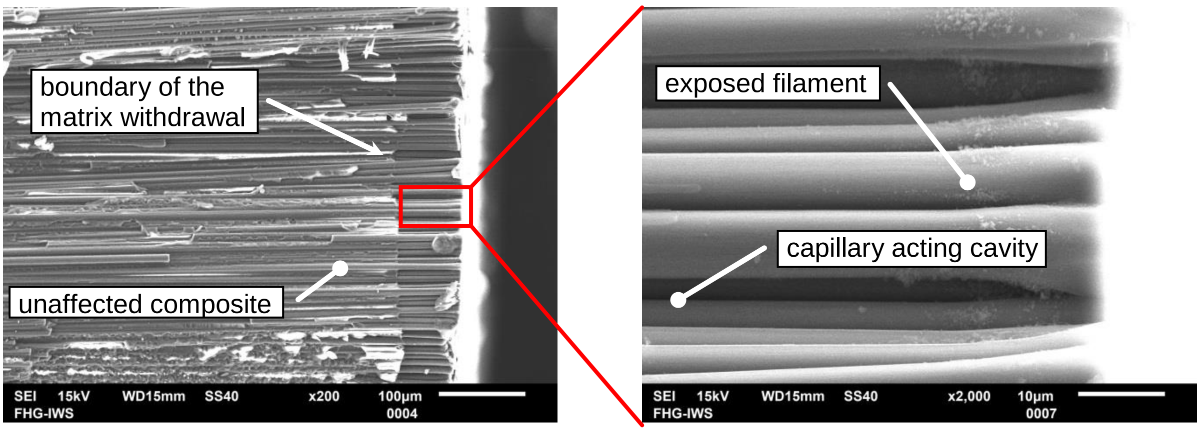

Figure 7: Exemplary SEM photograph of remote fibre laser cut CFRP with exposed filament ends

After 20 √h the curves of the samples with different diameters showed an approximately constant difference of 0.44 % mass increase on average, as depicted in Figure 5. Therefore, it was assumed that after saturation of the capillaries, water absorption took place only in the polymer matrix. Another indication was the increased deviation of each individual measurement in comparison to the waterjet cut samples. The free water that was stored in the capillaries at the laser-cut edges could escape more easily during the measurement process than the water captured in the polymer matrix. The specimens with a diameter of 40 mm were more sensitive to influences of the HAZ than those with a diameter of 60 mm. For this reason, this geometry was chosen for the further investigations.

3.2 Influence of the cutting process and an edge sealing on the water absorption

The water absorption of remote CO_2 laser cut, remote fibre laser cut and milled CFRP samples was investigated. As shown before, laser cutting of CFRP can have an effect on its water absorption behaviour. Therefore, an edge sealing was considered as a barrier against water. Each data point in the following diagrams represents the average value from the measurements of three specimens. Figure 8 shows the water absorption behaviour of the sealed and unsealed samples cut with the CO_2 laser. Figure 9 shows the cross-section of such a sealed edge. The sudden water absorption of the samples cut by the CO_2 laser could be reproduced. As already described in the preliminary tests, the increase in relative mass followed an uneven course for the unsealed samples. This indicated unbound water in the capillaries of the HAZ, which however could be sealed successfully.

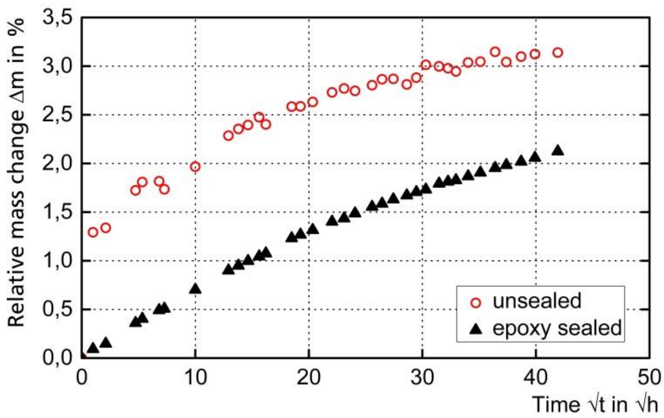

Figure 8: Water absorption behaviour of remote CO_2 laser cut CFRP $[0/90_2/\bar{0}]_S$

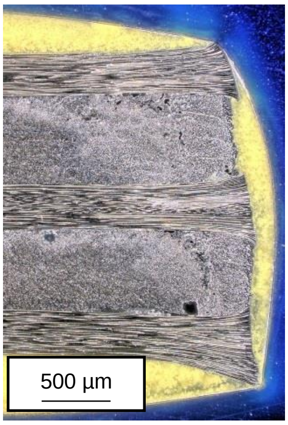

Figure 9: Remote CO_2 laser cut CFRP edge with yellow sealant

The course of mass increase of unsealed samples cut with the fibre laser, as shown in Figure 10, did not display any conspicuous water absorption behaviour. A rapid increase of the relative mass change after the first measurement was not detectable. Nor was a significant quantitative difference between the relative mass changes of the sealed and unsealed specimens observed. The moisture uptake pattern appeared somewhat more irregular in the unsealed samples, which could also be explained here by the presence of, albeit small, capillaries and surface irregularities at the cutting edge. These could also be sealed by the epoxy coating.

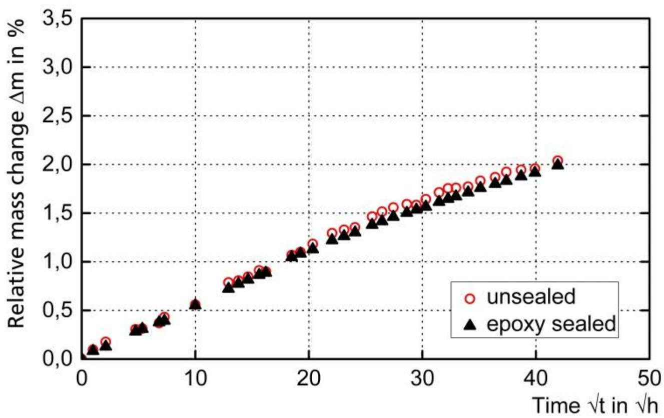

Figure 10: Water absorption behaviour of remote fibre laser cut CFRP $[0/90_2/\bar{0}]_S$

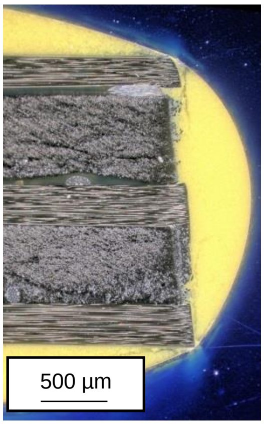

Figure 11: Remote fibre laser cut CFRP edge with yellow sealant

Figure 12 shows a comparison of the characteristics of the HAZs of remote laser cut CFRP for both laser systems. The visible thermal material damage caused by the CO_2 laser system is much more pronounced. In contrast to the CO_2 laser, whose radiation was absorbed by all components of the composite, the radiation of the fibre laser only had a high degree of absorption for the carbon fibres, but not for the epoxy polymer of the matrix [9]. Nevertheless, the advantage of the smaller beam focus of the fibre laser prevailed. The smaller spot was generated due to the given configuration of the optical systems of both lasers and the shorter wavelength of the fibre laser. Because of the smaller focus and the higher nominal power, the fibre laser could cut with a higher power density. This allowed higher spot velocities to be used, which led to a reduction of the interaction time between laser beam and CFRP and thus to a lower expansion of the HAZ. By cutting with the fibre laser, the expansion of the HAZ was reduced to such an extent that sudden water absorption could no longer be detected with the methods applied.

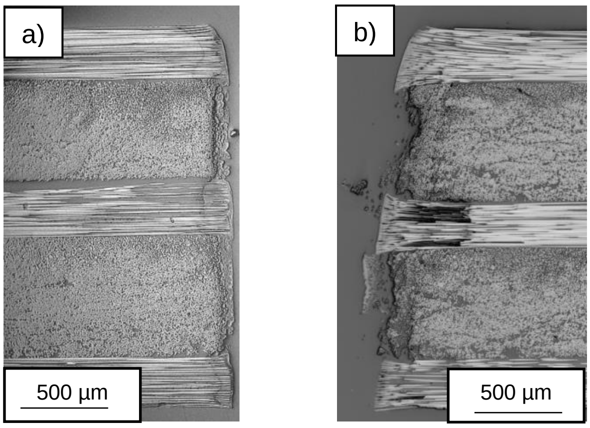

Figure 12: Characteristics of the HAZs of CFRP $[0/90_2/\bar{0}]_S$ a) remote fibre laser cut and b) remote CO_2 laser cut CFRP

Due to the divergent laminate stacking sequence, the absolute numbers of measurements of the material processed by milling were not directly comparable to the laser-cut material. Nevertheless, a sudden increase in mass was not noticeable either (Figure 13). The moisture uptake for the unsealed CFRP seemed to be very smooth in comparison to the irregular data point sequences of the laser-cut specimens. The milled edges were very even and no capillaries were suspected. In addition, it became obvious that all data points of the measurements on the blank milled samples without sealing were below the values of the sealed ones. The small volume of the epoxy coating takes up additional water due to the lack of reinforcing carbon fibres, which have no significant water absorption capacity [7].

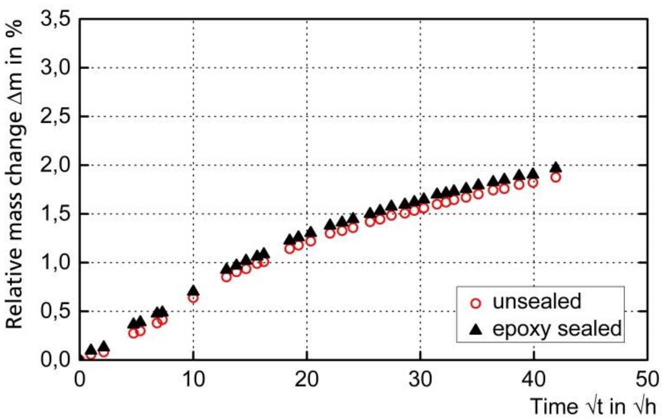

Figure 13: Water absorption behaviour of milled CFRP $[0/90_2/\bar{0}]_S$

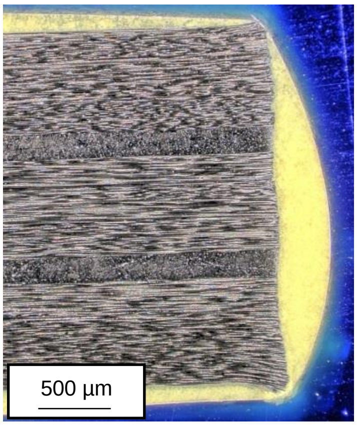

Figure 14: Milled CFRP edge with yellow sealant

4 Conclusion

An influence of remote laser cutting on the water absorption behaviour of CFRP was detectable. The use of unsuitable cutting parameters led to sudden moisture uptake of the specimens stored in a water bath. Within the HAZ the filaments were exposed and not surrounded by the polymer due to thermal decomposition. It was assumed that these closely spaced filament ends form capillaries which absorb the water very quickly. In contrast to the water stored within the polymer, the water in the capillaries was unbound. However, it is possible that these capillaries store water and release it to the polymer while the actual water source is not present.

With appropriate suitable process design, this effect could be suppressed to a degree that it could no longer be measured with standard equipment. But even with optimised parameters it was assumed that capillaries are still present. Free outer edges cut by laser could be closed with elastomeric sealing lips, for example. Milled and waterjet cut edges did not exhibit the behaviour of sudden water uptake.

Another approach is the application of a polymer sealing layer. The effect of such an edge sealing on the moisture absorption of CFRP was analysed. It could be demonstrated that the used epoxy sealant prevents the excessive water absorption of the remote laser cut CFRP samples. In the milled specimens, the sealant caused a slight increase in their relative mass in comparison to the untreated milled samples. This may be due to the lack of reinforcing fibres in the additional epoxy layer, which results in an increased water absorption capacity of the specimen volume.

The aim of this study was to identify a possible effect of the remote laser cutting technology of CFRP to its moisture absorption behaviour, which could actually be detected. Optimised parameters had to be found for the processing of the specific material to reduce the width of the HAZ. In this way, negative effects in the water absorption behaviour could be avoided. Also an edge sealing could improve the moisture resistance of remote laser cut CFRP. Further investigations should quantify the moisture uptake of CFRP depending on the cutting technology by direct comparison of different methods.

References

[1] Caggiano, A.: Machining of Fibre Reinforced Plastic Composite Materials. J. Materials, 11 (2018) 3, no. 442. doi: 10.3390/ma11030442

[2] Gupta, K. M.; Pawar, S. J.: A nonlinear diffusion model incorporating edge and surface texture effects to predict absorption behaviour of composites. J. Materials Science & Engineering A, 412 (2005) 1, pp. 78–82. doi: 10.1016/j.msea.2005.08.034

[3] Ahmad, J.: Machining of Polymer Composites, New York: Springer, 2009.

[4] Klotzbach, A.; Hauser, M.; Beyer, E.: Laser Cutting of Carbon Fibre Reinforced Polymers using Highly Brilliant Laser beam Sources. j. Physics Procedia, 12 (2011) 1, pp. 572–577. doi: 10.1016/j.phpro.2011.03.072

[5] Zaeh, M. F.; Byrne, G.; Stock, J. W.: Peak stress reduction in the laser contouring of CFRP. J. CIRP Annals - Manufacturing Technology, 66 (2017) 1, pp. 249–252. doi: 10.1016/j.cirp.2017.04.126

[6] Herzog, D.; Jaeschke, P.; Meier, O.; Haferkamp, H.: Investigations on the thermal effect caused by laser cutting with respect to static strength of CFRP. J. International Journal of Machine Tools and Manufacture, 48 (2008) 12, pp. 1464–1473. doi: 10.1016/j.ijmachtools.2008.04.007

[7] Schürmann, H.: Konstruieren mit Faser-Kunststoff-Verbunden. Berlin, Heidelberg, New York: Springer, 2007.

[8] Zhou, J.; Lucas, J. P.: Hygrothermal effects of epoxy resin. Part I: the nature of water in epoxy. J. Polymer, 40 (1999) 20, pp. 5505–5512. doi: 10.1016/S0032-3861(98)00790-3

[9] Fürst, A.; Klotzbach, A.; Hühne, S.; Hauptmann, J.; Beyer, E.: Remote Laser Processing of Composite Materials with Different Opto–Thermic Properties. J. Physics Procedia, 41 (2013), pp. 389–398. doi: 10.1016/j.phpro.2013.03.092