OPTICAL DEFORMATION ANALYSIS OF THE FAILURE BEHAVIOR OF FIBER REINFORCED POLYMERS CAUSED BY LASER PROCESSING

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ABSTRACT

Near net shape preforms with a minimum of material consumption are required to increase the acceptance of fiber reinforced polymers (FRP) in the industry. This should be accompanied by appropriate, fast and flexible processes. The remote laser process expands the area of possible processing strategies, wherefore the laser can be a tool for the future. However the development of remote laser processing is accompanied with the understanding of the interaction between tool and material as well as the influence of laser irradiation to the failure behavior of FRP, to which this paper contributes. A tensile testing procedure with an adapted specimen is introduced. Hence, the testing procedure is able to correlate the failure mode of inter fiber fracture as a function of laser cutting parameters. The investigations are accompanied by an optical deformation analysis to clarify the geometrical influences of the laser cutting contour.

1 INTRODUCTION

One of the main challenges in the field of composite materials is to improve and optimize existing production processes and procedures. For instance, near net shape preforms are used to minimize the material consumption. In addition thermoplastic matrices are used to decrease the cycle time of the production processes [1]. Mechanical machining like drilling or milling of CFRP is still challenging due to high tooling costs as a result of wear. Furthermore, delamination of the material can occur near the processing area as a consequence of processing at the wear limit of the tools. This damage can be the initiation for progressive crack growth. Hence, the application of a laser beam as a wear and force free tool is appropriate to face the mentioned limitations of conventional processing of fiber-reinforced polymers. The material is thermally affected while laser processing and that may lead to a huge heat affected zone (HAZ) [2]. Therefore, high speed beam deflection systems are used to minimize the interaction time between laser beam and material surface. Thus, the thermal load is reduced. A fast mirror system based on galvanometer scanners, shown in Figure 1, rapidly projects the laser beam onto the material with laser spot velocities up to 20 m/s [2]. A complete thru cut is performed by a cyclic material removal until the cutting kerf is formed.

The size of the HAZ depends on processing parameters like laser power and spot velocity [3]. It has been demonstrated that the residual load bearing capacity correlates with the degree of the material damage induced by laser beam in the area of the cutting kerf [6-8]. Consequently, the material performance also depends on the parameters of the laser treatment.

The aim of the investigations is to provide a mechanical characterization procedure which allows to directly verifying the influence of these parameters to the residual load bearing capacity of FRP. The procedure is based on a quasi-static tensile test. The failure mode is limited to inter fiber failure to obtain basic findings about damage mechanisms of laser cut FRP. Extensive testing series show a relation between factors of laser cutting and mechanical damage for different composite materials. A digital image correlation system is additionally used to consider the deformation behavior of the test specimen.

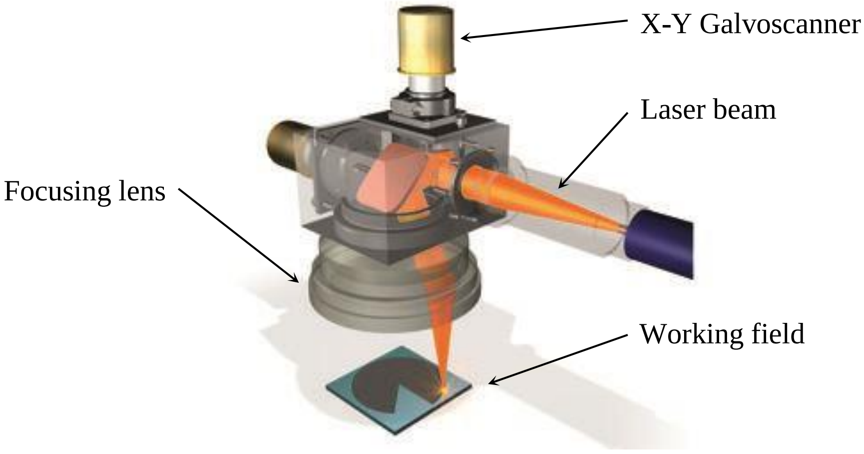

Figure 1: Principle of high-speed beam deflection

2 CHALLENGES OF REMOTE LASER CUTTING

The development of remote laser processing is strongly connected to knowledge about the degradation of the material through laser irradiation. The laser cutting procedure of FRP is an ambitious process due to the big temperature differences - on the one hand with high fiber sublimation temperatures (carbon fiber ≈ 3700 °C) and heat conductivity along the fibers up to 49 W/m/K and on the other hand with low decomposition temperatures of the matrix material and the coating of the fibers (300 – 700 °C). Laser cutting of FRP is an ablation process including melting, sublimation and decomposition of matrix and reinforcement material. The mentioned damage is typically analyzed by the visual examination of cross sections (Figure 2) [3]. However, it is assumed that the HAZ is more outspread than the cross sections, which indicate matrix and fiber decomposition, show.

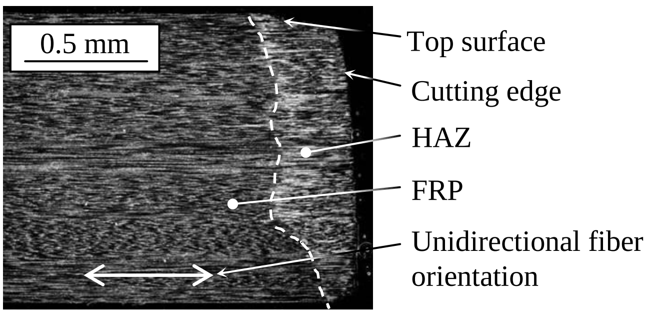

Figure 2: Cross section of a HAZ (CFRP, φ= 60 %, CO_2 Laser, d_f= 400 µm, P_L= 2.9 kW, v_V= 1m/s)

Visualization by scanning electron microscopy (SEM) can be a tool for investigation of the HAZ. Figure 3 shows images of a distinctive HAZ. It is recognizable that matrix material is removed from the cutting zone. With increasing magnification a section is detected with existing but damaged matrix material. Thus there is no clear separation between damaged and undamaged material. For this reason the reduction of the residual load bearing capacity of the material is difficult to detect with cross sections.

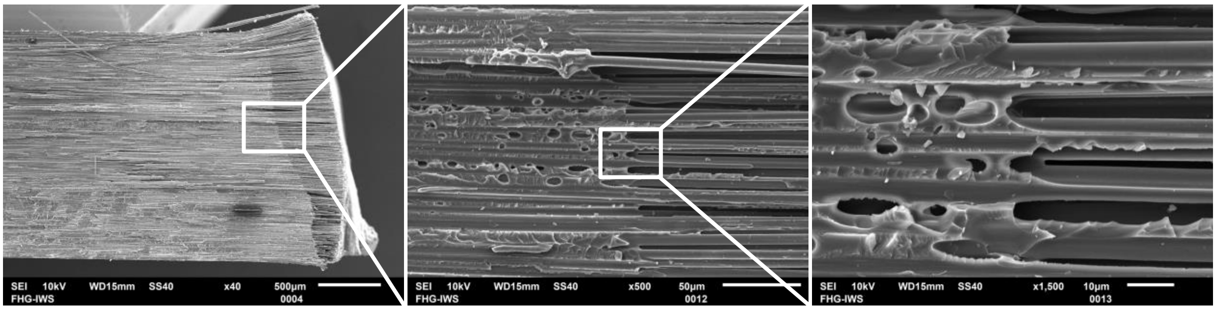

Figure 3: SEM picture of a distinctive HAZ, visible in a fracture surface (CFRP, φ= 60 %, CO_2 Laser, d_f= 400 µm, P_L= 2,9 kW, v_V= 1m/s)

The reduction of the load bearing cross section of the material has to be considered for the investigation due to damage of the material which cannot be detected by visual analysis of polished cross sections. Potential degradation concerning the interface between fiber and matrix can be the exceeding of the glass transition temperature of the matrix material as well as vaporization and thermal decomposition of the coating of the reinforcement fibers [4, 5].

3 EXPERIMENTAL SET UP

3.1 Design of an adapted specimen

Tensile testing as a destructive method is practical and already carried out to clarify the influence of laser cutting on the reduction of the load bearing cross section [6-8]. The mentioned literature citations constitute a dependency on the dimension of the heat affected zone to the maximum breaking strength. Thereby, the used materials are quasi isotropic multi-layer composites and the specimen contours are completely cut by laser. The effects caused due to those layer set ups are to be evaluated critically. There is a known influence of the peripheral zone due to the disabled transverse elongation of individual orientated single layers that can superpose the measurements [9]. One possible approach to prevent geometrical overlay is to determine the influence of laser radiation on interlaminar shear strength [10]. The present investigations are carried out on specimen with an unidirectional layer set up (Figure 4). The fiber orientation is arranged perpendicular to the direction of force. That limits the failure behavior of the specimen to inter fiber fracture [9, 11]. Furthermore, the measurements are not affected by overlaying geometrical effects caused by the layer set up. The main contour of the shoulder tensile specimen including the clips was cut by water jet cutting. This method was chosen because of its low thermal influence on the material. The final geometry of the specimen is achieved by laser trimming of the clips. The fiber orientation supports the thermal damage of the material due to the high thermal conductivity longitudinal to the fiber orientation, especially for carbon fiber reinforced plastics (CFRP).

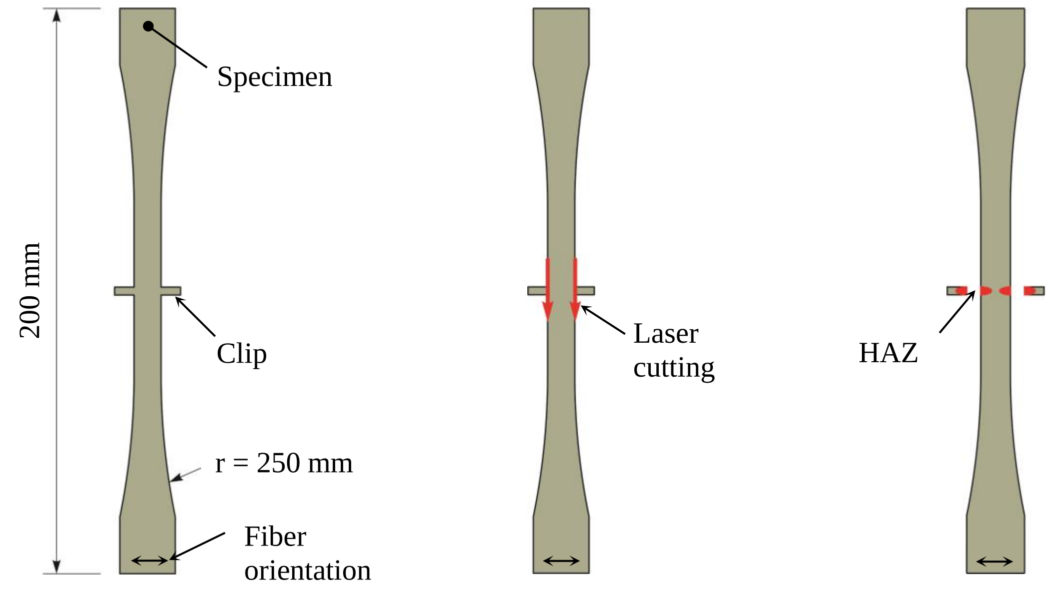

Figure 4: Design of specimen with sacrificial clips (left), laser cutting path (middle) and final specimen contour with HAZ (right)

The design of the tensile test specimens is similar to the geometry, proposed by the German standard DIN EN ISO 527-4. Because of the unidirectional orientation of the reinforcing fibers perpendicular to the direction of the tensile load, the usage of tensile test specimens with shoulders is suitable. The mechanical properties of the material are dominated by the matrix in this orientation. Thus there is no need to take care about problems of load introduction into the fibers, as it is done with specimens with bonded stiffeners. The chosen design simplifies the manufacturing of the specimens and improves the reproducibility of the experiments in this way. Preliminary tests showed that the specimens made of the tested material do not fail within the gauge length reliable, if the exact geometry of the standard is used. Instead of that, they tear near the outlet of the fillets predominantly. This behavior leads to problems, because it may superimpose the mechanical influence of the local HAZ to the residual load bearing capacity of the specimens. A mechanical FEM analysis of the problem shows stress concentrations at the critical areas, as seen in Figure 5 for a tension load of 1000 N and a specimen with an increased fillet radius in comparison to the standard. The optimization of the geometry by the FEM and the enlargement of the radius from 60 mm to 250 mm cause a reduction of the mechanical stress peak of about 70 % as well as an average gain of 40 % of valid trials. A further increase of the radius seems to be inappropriate, because it does not improve the numerical results considerable. Instead, at a constant gauge length, it raises the size of the specimens and leads to an unnecessary material consumption.

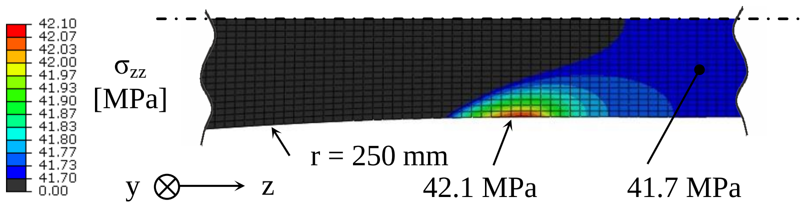

Figure 5: Numerical FEM analysis of the tensile test specimen

Figure 6 illustrates the final specimen contour that is used for the investigations. The thickness of the specimens is about 1.8 or 2 mm, dependent on the material.

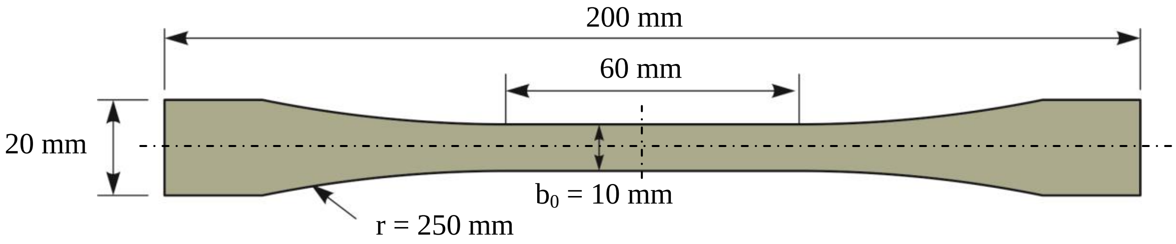

Figure 6: Final geometry of the tensile test specimen

3.2 Remote Laser System Equipment

Previous investigations have shown a dependency of wavelength of the beam source on the absorption behavior of the material [4, 13]. Therefore different beam sources whose wavelengths differ by the factor of 10 were used to process the material. Additional the shorter wavelength of 1.07 µm leads to a hundred times higher intensity of the beam, which is needed to vaporize carbon fiber. The used beam sources and scanner systems are shown in Table 1.

Parameter	CO_2 Laser	Solid State Laser (SSL)
Wavelength λ [µm]	10.6	1.07
Power P_L [kW]	1-3	1-5
Spot radius ω_0 [µm]	195	25
Scannersystem	Aperture 50 mm	Aperture 50 mm
Spot velocity v_v [m/s]	0.5-5	1-5

Table 1: Beam sources and beam scanning systems

Laser radiation in the range of the wavelength of mid-infrared, such as emitted by CO_2 lasers, is particularly suitable for the processing of glass fiber reinforced polymers (GFRP) because of the absorption behavior of the material. For the processing of carbon fiber reinforced polymers (CFRP) solid state lasers are preferable, also because of a higher focusability [13]. Figure 7 shows the processing stations for the remote laser cutting of the specimens. The CO_2 station allows the alignment of the laser cuts with the help of a camera system. It monitors the working field coaxial with the laser beam by the scanning mirrors. The positioning of the cuts made by the solid state laser was carried out by fitting the contour with the help of test specimens. The focal spot of the laser was placed on the top surface of the specimen at both systems.

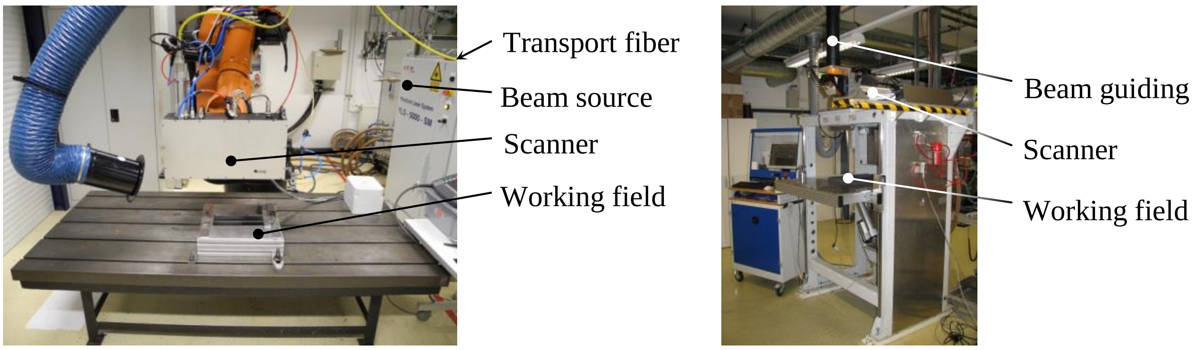

Figure 7: Laser processing stations for the laser cutting of the specimen. Left: SSL system Right: CO_2-Laser system

3.3 Material

Three different FRP materials were chosen for the experiments. On the one hand they involve two carbon fiber reinforced polymers (CFRP) with epoxy matrices. These materials are widespread in application within the field of composites due to the fact that the Prepreg and RTM technologies provide viable opportunities to produce FRP. Furthermore, the thermoset resin has good mechanical properties [1]. On the other hand a GFRP is examined. It is made of Twintex hybrid yarn. GFRP provide adequate mechanical properties for a lot of applications at low costs in comparison to CFRP. In addition, the thermoplastic matrix enables high production rates. It is expected that the material gets more importance in the future [1].

The influence of heat conductivity to the measurements is provided by the usage of high modulus (HM) carbon fibers and high tenacity (HT) carbon fibers. The key differences are the thermal properties caused by a higher degree of orientation as a result of the rate of graphitization of the fiber material[12, 13]. The materials and calculatedly determined thermal properties are summarized in Table 2.

Material	Type of fiber	φ	$\lambda_\parallel$ [W/m/K)]	$\lambda_\perp$ [W/m/K]
GFRP	E-Glass	0.5	0.71	0.63
CFRP HT	SGL Sigrafil C30	0.6	3.02	0.44
CFRP HM	M 40J	0.6	41.28	1.09

Table 2: Calculated thermal properties of glass and carbon fiber reinforced polymers [9], [12]

$\lambda_\parallel$ Thermal heat conductivity longitudinal to the fiber orientation
$\lambda_\perp$ Thermal heat conductivity perpendicular to the fiber orientation
φ fiber volume content

3.4 Tensile Testing Equipment and Specifications

The tensile tests were carried out by an universal testing machine with a maximum load capacity of 50 kN. The used load cell has a relative display error of 1 % from a tensile force of 100 N. The extension speed of the displacement controlled tests was 1 mm/min. By measuring the crosshead travel, the current global strain of the specimens was determined. This is sufficient, since the failure load is of interest solely in the studies which allows the calculation of the desired residual load bearing capacity. The use of a mechanical extensometer does not seem to be appropriate, because it delivers unnecessary information. Instead, it may damage the sensitive unidirectional material of the specimen for transverse tension or it may influence the failure behavior.

For the local strain measurement in the heat affected area of the specimens a digital image correlation system was used. It was done with the *Aramis 5M* system (GOM GmbH). The cameras have a resolution of 5 megapixels and objectives with a fixed focus length of 50 mm. The measuring area was 18 x 20 mm^2.

After water jet cutting of the initial contour of the hygroscopic specimens, they were dried and stored for at least two weeks under the same climate conditions like the tensile tests before accomplishment. To obtain the cross sectional dimensions of the specimens the thickness was measured by an outside micrometer. The width was determined optically using a microscope in the laser cut area, where the failure is expected. Thereby, damages due to the handling during mechanical measurements were avoided. Each individual measurement was done three times and then averaged so that attention was paid to material fluctuations and inaccuracies.

4 EXPERIMENTAL INVESTIGATIONS

4.1 Design of Experiments

To prove the respective suitability of the different laser systems for CFRP and GFRP also in mechanical aspects, both were used for the treatment of all materials. Beside the wavelength and focal diameter, the laser power P_L and spot velocity v_S represent adjustable process variables that influence the cutting result. Table 3 gives a complete overview of the parameters used for the experiments.

Laser system	Material	P_L [kW]	v_S [ms^{-1}]
SSL	HM-CFRP	3; 4; 5	1; 2; 5
	HT-CFRP	3; 4; 5	1; 2; 5
CO_2	HM-CFRP	2.9	0.5; 1
	HT-CFRP	2.9	0.5; 1
SSL	GFRP-PP	3; 4; 5	1; 2; 5
CO_2		1.5; 2; 2.5	0.5; 1; 2

Table 3: Processing parameters for the laser cutting of the specimen

They were determined by cutting trials on the test materials and selected from the following aspects. First there have to be three different levels of laser power and spot velocity each. All of the combinations of both variables must lead to a complete thru cut. Moreover the combinations must be within the widest possible range of the total energy per unit length, emitted to the material due to the laser with a cyclic ablation. This quantity is defined by the equation [14]

$$E_{S,eff} = n\ (P_L / v_S), \tag{1}$$

where n is the number of ablation cycles to form the complete cutting kerf. By this means, a full factor experimental design is generated. In application of the CO_2 Laser on the CFRPs, only two setups could be found that produce complete cuts. In this case, the experimental design is fractional factorial.

4.2 Experimental procedure

A tensile test of a laser treated specimen is rated as valid in the case of failure within the area the clips have been located. There the material is heat affected and a HAZ exists. During the tensile tests the stress strain curves were recorded. Because of the matrix dominated material behavior in load direction, the specimen crack brittle. As a result, a clear stress at failure is detectable. It is defined as the maximum reached stress before the value drops suddenly because of the fracture and it is called as the residual load bearing capacity in this paper. Since the inhomogeneous state of the FRP within the area of the HAZ it is not a characteristic value of the material and do not correspond to the strength. The measured residual load bearing capacities ($F_{res,theoretical}$ / A_0) were referred to measurements on completely water jet cut specimen σ_{Ref}.

4.3 Results

HM-CFRP

In this material, a noticeable reduction of the residual load bearing capacity is detectable by increasing the total energy per unit length, as Figure 8 indicates. This applies to the processing with both of the laser systems. Thus the mechanical damage of the HM-CFRP depends on the chosen laser parameters. It is found that cutting with parameters that lead to a low energy per unit length are beneficial under mechanical aspects and can lead to residual load bearing capacities near the reference. The given error bars represent the confidence interval of 95 %. They are calculated on the basis of student's t-distribution because of the relative small sample size. The intervals are very large partially because of a low amount of valid trials in some test series. If no confidence interval is specified, only one specimen within the series failed valid. By increasing the total energy per unit length, also a growth of the HAZ occurs as shown in Figure 9 for the laser cutting with solid state laser.

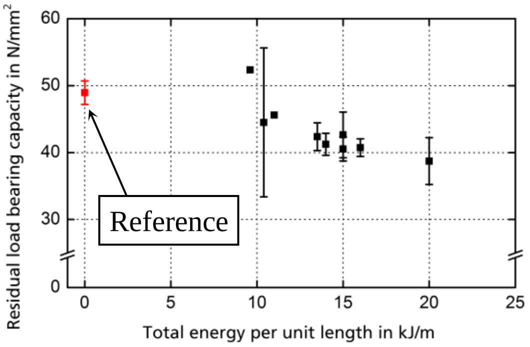

Figure 8: Residual load bearing capacity of SSL cut HM-CFRP dependent on the total energy per unit length

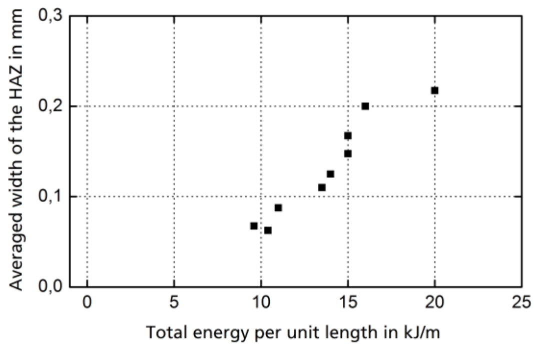

Figure 9: Averaged width of the HAZ of SSL cut HM-CFRP dependent on the total energy per unit length

The mean width $b_{HAZ,av}$ of the HAZ for every sample series has been determined by measuring the visible thermal influenced cross sectional areas at both sides of one specimen. Subsequently the values were averaged and divided by the mean thickness of the specimen to ensure comparability between the different materials. Figure 10 illustrates the measurement method exemplary. If the residual load bearing capacities are set as function of the assigned averaged widths of the HAZ, an interesting aspect emerges. Equation (2) allows calculating theoretical residual load bearing capacities with the assumption that the visible thermal influenced areas do not have any material cohesion. The SEM pictures of Figure 3 support this hypothesis because of the completely exposed fiber ends that cannot transport any loads in transverse direction. Figure 11 illustrates the supposed interrelations. The theoretical residual load bearing capacity is marked as a solid line.

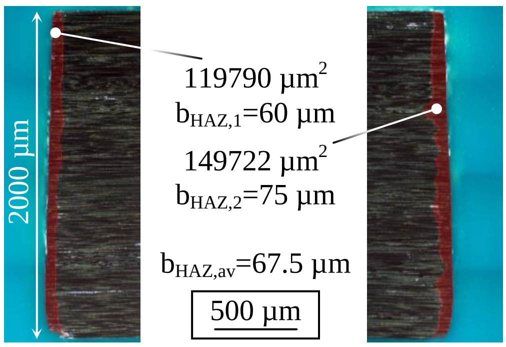

Figure 10: Microscopically determination of the averaged width of the HAZ (SSL, P_L=3 kW, v_S=5 ms^{-1}, HM-CFRP)

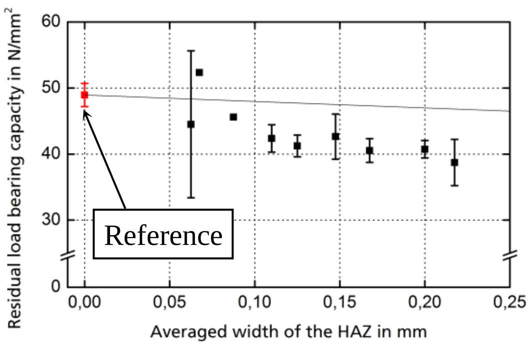

Figure 11: Residual load bearing capacity of SSL cut HM-CFRP dependent on the averaged width of the HAZ

$$(F_{res,theoretical} / A_0) = \sigma_{Ref} (1 - (2\, b_{HAZ,av}) / b_0) \quad (2)$$

With one exception, all of the measured values are clear below this curve. One reason for this behavior can be the circumstance that the HAZ induces a mechanical notch effect that causes early failure of the specimen. Another possibility is a material damage that is extended beyond the optical detected areas. For example a damage of the fiber-matrix interface due to the thermal load is conceivable because of an initial decomposition of the size. Or the release of residual thermal stresses after reaching the glass transition temperature of the matrix cause detachments of the fibers.

In order to estimate a possible notch effect of the HAZ, the digital image correlation system was used. Figure 12 contains a false color plot that illustrates the local strain ε_{yy} in the direction of the tensile load y. Significant peaks can be recognized in the edge region of the double-sided HAZ. This is an indication of a present notch effect thereof. The question about the extent of the mechanical damage beyond the visible HAZ thus remains unclear. However the notch effect may be the reason for the sensitivity of the tensile testing method for the influences of the various HAZs that differ in very small ranges from each other.

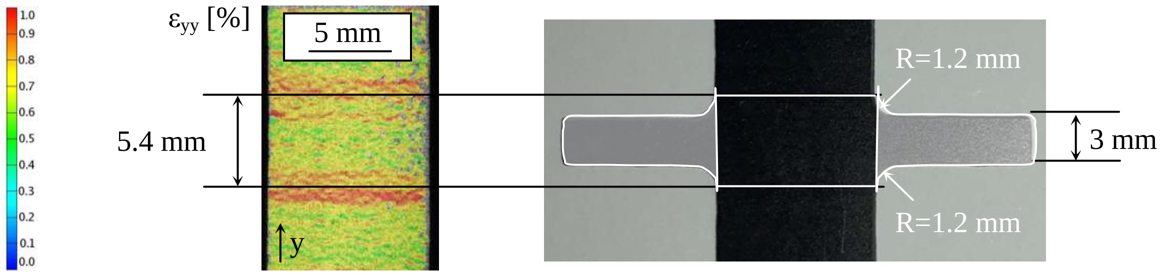

Figure 12: Optical grey scale correlation measurement (left) at a tensile of 922 N (SSL, P_L=5 kW, v_S=1 ms^{-1}, HM-CFRP) and specimen with clips for laser cut (right)

The usage of the CO_2 laser system for cutting the HM-CFRP led to a residual load bearing capacity of 37.54 MPa at a total energy per unit length of 43.5 kJ/m and 34.89 MPa at 40.6 kJ/m. Necessary high specific energies and the fact that almost the entire specimens failed within the HAZ emphasizes the low suitability of the CO_2 system for cutting the material.

HT-CFRP

Tests at solid-state-laser cut HT-CFRP yielded some different results. On the one hand side increasing total energies per length unit also generate growing HAZ as shown in Figure 13. But on the other hand side the residual load bearing capacities do not react significantly to the increasing quantity. Figure 14 proves the described material behavior.

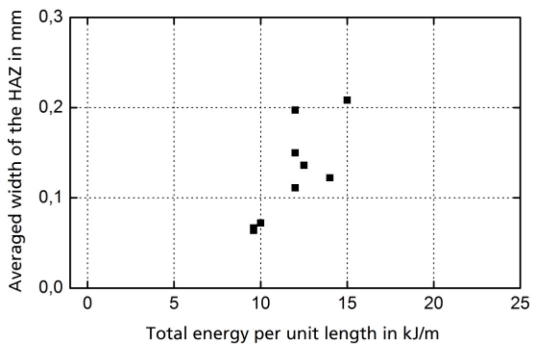

Figure 13: Averaged width of the HAZ of SSL cut HT-CFRP dependent on the total energy per unit length

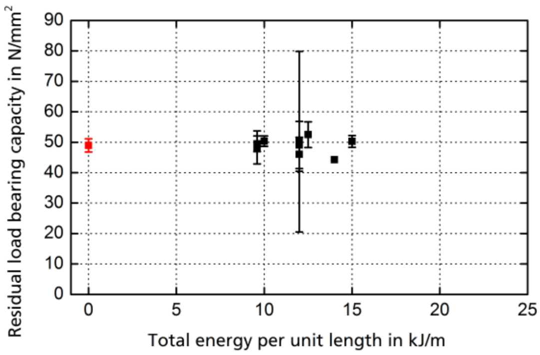

Figure 14: Residual load bearing capacity of SSL cut HT-CFRP dependent on the total energy per unit length

As a consequence, there is no clear noticeable correlation between the extent of the HAZ and the residual load bearing capacity for the solid-state beam source treated material as shown in Figure 15. But the values are near the theoretical trend of the residual load bearing capacity. Because of the obvious difference in thermal heat conductivity (Table 2) between both of the CFRPs this quantity is identified as the reason for the apparently better cutting ability of the HT fiber reinforced material.

Paradoxically the material behaves similar to the HM-CFRP if machining is done with the CO_2 laser system. A total energy per unit length of 34.8 kJ/m led to 31.94 MPa respectively 33.07 MPa. All of the specimens tore within the HAZ unexceptional.

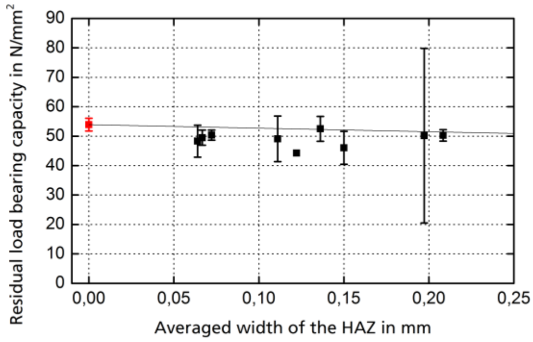

Figure 15: Residual load bearing capacity of SSL cut HT-CFRP dependent on the averaged width of the HAZ

GFRP-PP

The evaluation of the tests on the GFRP specimens is not possible with the current system. The specimens tore only occasional within the HAZ. Because the load bearing capacities always were near the reference value it is attributed to accidently events. GFRP is thus well suited for laser cutting. Because of the good absorption behavior for mid-infrared radiation, CO_2 lasers are preferable.

5 CONCLUSION

Within this paper a correlation between laser process parameters and their influence on mechanical properties was shown. Therefore a specimen for tensile testing was introduced, whose failure mechanism is limited to inter fiber fracture. The design of the specimen supports the heat propagation in the material without any effects of the fiber layup that can superpose the measurements. It has been shown, that reinforcement materials, like glass fiber or HT carbon fiber do not show any recognizable impact, when processing with tailored beam sources and system technology. In that case, the determined extent of the HAZ constitutes low narrowing of the load bearing cross-sectional area of the specimen. When processing on thermal sensitive materials, like HM carbon fiber the increasing extent of the visible HAZ correlates with the decreasing residual load bearing capacity. By the usage of galvanometer scanning systems the spot velocity can set to a maximum. This substantially reduces the interaction time between laser and material and leads to a minimized HAZ that can be detected with the measurement method. Even when processing on HM carbon fiber, laser cutting parameters could be found whose tensile failure are quiet close to the water jet cut reference. Accompanying optical deformation analysis investigations have considered the strain in the laser-processed area. Local strain peaks superpose the measured values. Further investigations have to consider that difficulty.

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