INFLUENCE OF LASER IRRADIATION ON THE FAILURE BEHAVIOR OF UNIDIRECTIONAL FIBRE REINFORCED POLYMERS

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Abstract
To increase the acceptance of fibre reinforced polymers (FRP) in the industry, near net shape preforms with a minimum of material consumption are required. This should be accompanied by appropriate, fast and flexible processes. The remote laser processing expands the area of possible kinds of processing strategies, wherefore the laser can be a tool for the future. But the development of remote laser processing is accompanied with the understanding of the interaction between tool and material and the influence of laser irradiation to the failure behavior of FRP, to which this paper contributes. An tensile test method of an adapted specimen is introduced. Hence the test method is able to allegorize to the failure mode of inter fibre fracture as a function of laser cutting parameters.

1. Introduction

A growing demand for high-strength composite components can be observed in different industries. The largest volumes are provided in the automotive-, aircraft- and wind - industry [1]. A further demand can also be seen in the machinery and plant engineering. Here, the specific properties, such as the low thermal expansion coefficient of carbon fibres can be exploited. For example, this is used for parts in textile machinery, which require maximum accuracy even under varying temperature conditions [1]. The main challenge in the field of composite materials is the improvement and optimization of existing production processes and procedures [2]. Here the laser as a wear and force free process can be a tool for the future.

1.1. Principle of remote laser cutting of FRP

Processing of FRP with the laser is made possible by high-speed beam deflection systems. A fast mirror system based on galvanometer scanners is used to rapidly project the laser beam onto the material (Figure 1). Cutting FRP with high brilliant lasers is an ablation process including melting, sublimation and decomposition of matrix and reinforcement material. Due to the ambitious material behavior caused by the inhomogeneity in heat conductivity and sublimation temperatures for matrix and fibre material, high feed rates and brilliant beam sources are needed to process the material with acceptable heat affected zones (HAZ).

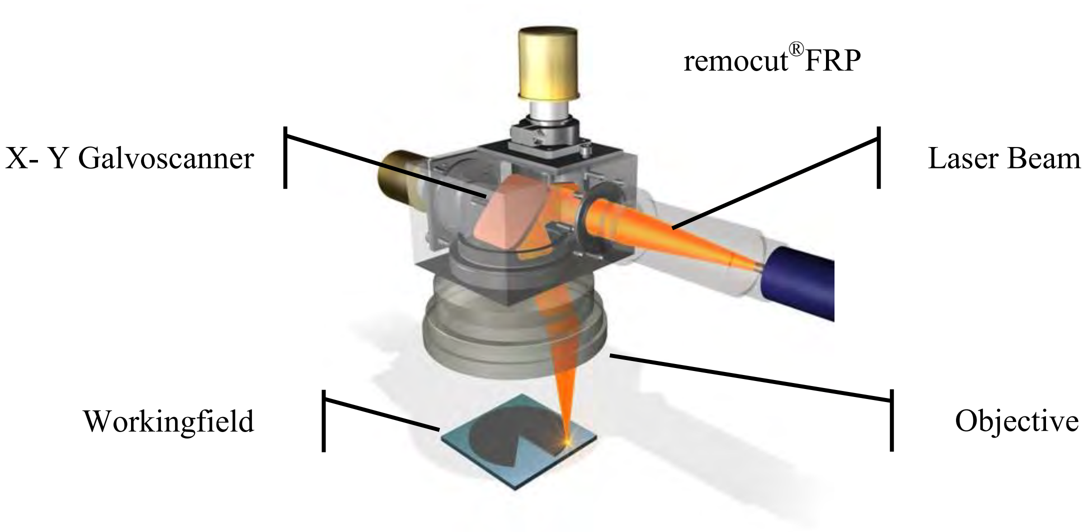

Figure 1. Principle of high-speed beam deflection

A complete thru cut is performed by a cyclic material removal until the cutting kerf is formed (Figure 2). With this technology it is possible to cut pliable reinforcement textiles, semi-finished as well as near-net-shape parts. [3] and [4]

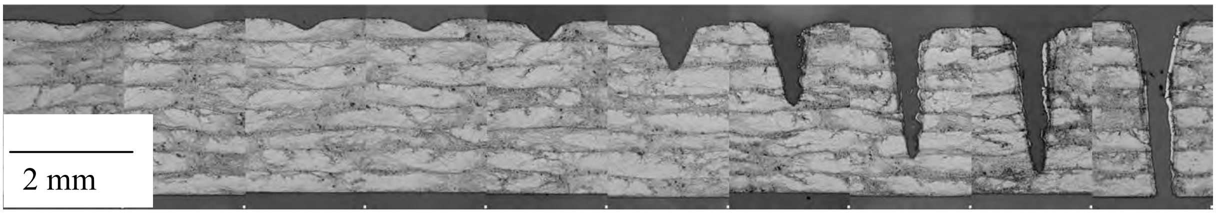

Figure 2. Cyclic removal of CFRP, from left to right increasing number of repetitions

1.2. Challenges of remote laser cutting of FRP

The development of remote laser processing is strongly connected with the knowledge of the degradation of the material due to laser irradiation. As mentioned above the laser cutting procedure of FRP is an ambitious process, because of high fiber sublimation temperatures (carbon fibre ≈ 3700°C) and high heat conductivity along the fibers (up to 49 W/m*K) on one hand and low decomposition temperatures of the matrix material and the coating of the fibres (300 – 700°C) on the other. The influence of laser processing on FRP is executed by the analysis of cross sections of the cutting kerf [3] and [5]. But it is assumed that the HAZ can be more outspread than the evaluation of cross sections (Figure 3) that indicate matrix and fibre decomposition. Investigations have also to consider the minimization of the load bearing cross section of the material, due to damage of the material which cannot be detected by visual analysis of cross sections. Potential degradation concerning the interface between fibre 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 fibre [6] and [7]. A consisting and untouched interface between fibre and matrix material is the key for load transmission between both components [7].

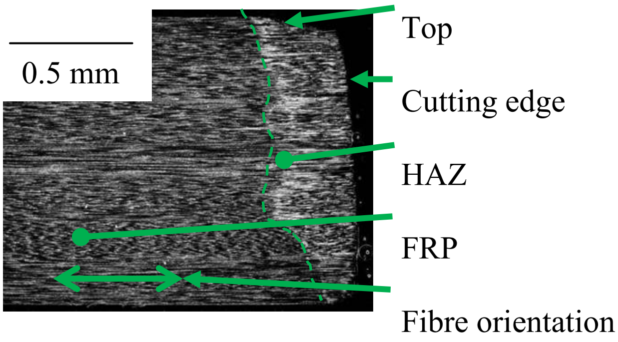

Figure 3. Cross section of laser cut at CFRP φ= 60 %, Dimension of HAZ

1.3 Design of an adapted specimen

Tensile testing as a destructive method is practical and already realized to clarify the influence of laser cutting on the reduction of the load bearing cross section [8], [9] and [10]. 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 laser cut. 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 [11]. The investigations were carried out on specimen with a unidirectional layer (Figure 4). The fibre orientation is arranged perpendicular to the direction of force. That limits the failure behavior of the specimen to inter fibre fracture as a result of modification of fibre matrix adhesion [11] and [12]. The main contour of shoulder tensile specimen including the sacrificial clips is created by water jet cutting. After laser trimming of these clips, the final geometry of the specimen is achieved. The fibre orientation supports the thermal damage of the material due to the huge amount of heat conductivity longitudinal to the fibre orientation.

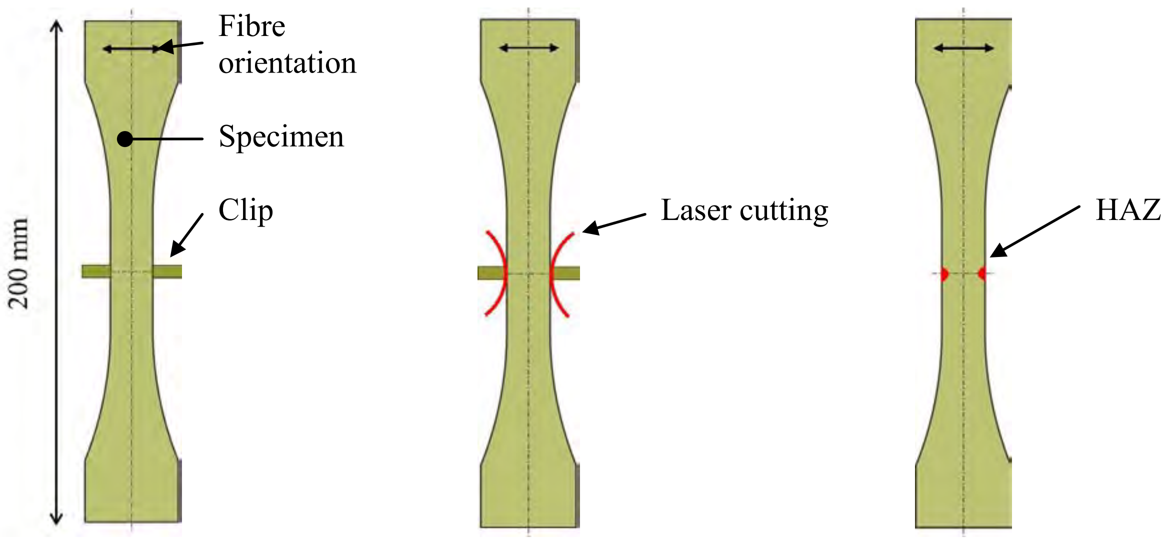

Figure 4. Design of specimen with sacrificial clips (left), laser cutting path (middle) and final specimen contour with HAZ (right)

2. Experimental Set up

Previous investigations have shown a dependency of wavelength of the beam source on the absorption behavior of the material. Therefore different beam sources whose wavelengths differ by the factor of app. 10 were used to process the material. Additional the shorter wavelength of 1.09 µm leads to a hundred times higher intensity of the beam, which is needed to vaporize carbon fibre. The used beam sources and scanner systems are shown in Table 1. [4] and [13]

Table 1. Beam sources and beam scanning systems

Parameter	CO_2 - Laser	Yb - Laser
Wavelength λ [µm]	10.6	1.09
Power P_L [kW]	1-3	1-5
Spot radius ω_0 [µm]	195	25
Scannersystem	Powerscan 50 (ScanLab AG)	Pro Series 2 (CTI Inc.)
Spot velocity v_v [$^m/_s$]	0.5-5	1-5

The influence of heat conductivity to the measurements is provided by the usage of high modulus (HM) carbon fibres and high tenacity (HT) carbon fibres. The key differences are the thermal properties caused by higher degree of orientation as a result of the rate of graphitization of the fibre material [2] and [4]. A glass fibre reinforced polymer is taken into account to complete the test series. The materials and calculatively determined thermal properties are summarized in
Table 2.

Table 2. Calculated thermal properties of glass and carbon fibre reinforced polymers (GFRP, CFRP) [2], [11]

Material	Type of fibre	φ	λ_{II} [W/m*K]	$\lambda_{\perp}$ [W/m*K]
GFRP	M 40	0.5	0.71	0.63
CFRP HT	SGL Sigrafil C30	0.6	3.02	0.44
CFRP HM	M 40 J	0.6	41.28	1.09

$\lambda_{\|}$ Thermal heat conductivity longitudinal to fibre orientation
$\lambda_{\perp}$ Thermal heat conductivity perpendicular to fibre orientation
φ fibre volume content

Within the investigations the influence of laser cutting parameters like laser power (P_L) and laser spot velocity (v_v) on the failure behavior of the specimen has to be carried out. Both parameters are summarized to energy per unit length:

$$E_S = \frac{P_L}{v_v} \tag{1}$$

Previous investigations have shown a minimized damage of the material, when using high laser power and high spot velocities, which lead to a low energy per unit length [3]. The testing method that is introduced requires being referenced. Therefore laser cutting parameters have to be taken in consideration that leads to a minimum as well as a maximum thermal damage of the material. The variation of parameters occurs within these boundaries.

3. Results

The specimens are stressed to failure by a Z050 testing device (Zwick GmbH & Co. KG). All tested specimens failed due to inter fibre fracture, which is to be seen exemplarily in Figure 5. The laser cut specimens are compared to a water jet cut reference.

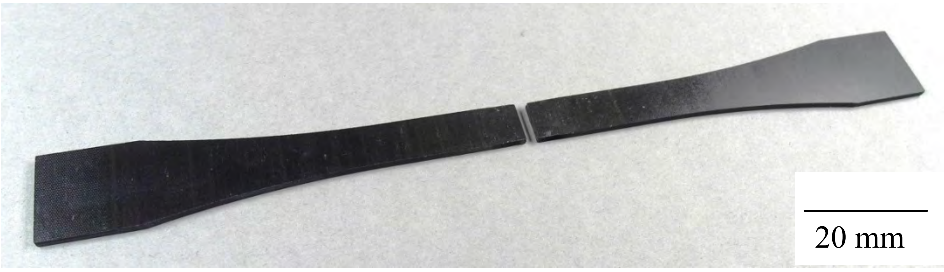

Figure 5. Fracture of specimen in the area of HAZ

An area of thermal influenced fibre and matrix material can be characterized due to visual analysis of the cross sections (Figure 6). It is assumed that the discolored area is similar to the area of destroyed fibre and matrix material. Therefore this area is considered as no longer load bearing. The remaining portion of the cross section is regarded as the remaining load bearing cross section A_{Res}. The monitored maximum load (F_{max}) at failure is referred to the cross section A_{Res} and follows:

$$R_z = \frac{F_{max}}{A_{Rest}} \tag{2}$$

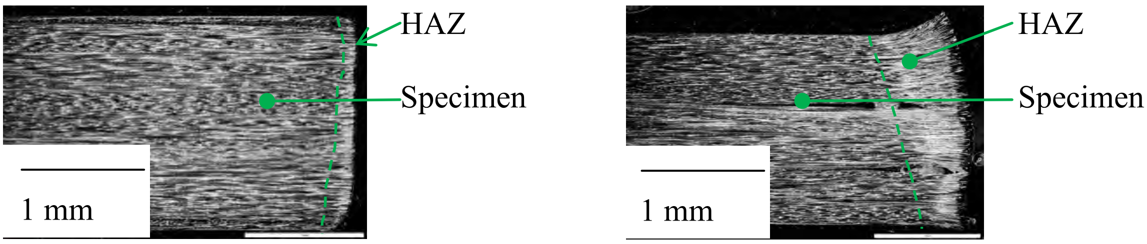

Figure 6. Characteristic HAZ, Parameter YAG-HT-5-5 (left), CO2-HT-2,9-0.5

Both, Figure 7 and Figure 8, show the tension at failure as a function of energy per unit length. The grid points are declared as laser process parameters, for example CO_2-GF- 2.9-5 means CO_2 Laser, laser power of 2.9 kW and a spot velocity of 5 $^m/_s$. The error indicator of each grid point shows the 95% confidence level. A test series consists of 10 specimens. A test series is taken into account if 7 of 10 specimens failed in the area of the HAZ. As mentioned before, the design of the specimen contributes failure due to constriction of the load bearing cross section area as a result of destroyed inter fibre fracture and thermal decomposition of fibre and matrix material. As to be seen in the cross sections (Figure 6) there is a dependency between process parameters (P_L and v_v) and dimension of HAZ, which constricts the load bearing cross section area. Hence it can be shown that the testing method is suitable to constitute the influence of laser process parameters on the failure mechanism of inter fibre fracture of CFRP. Within the investigation different types of carbon fibres were used, whose thermal heat conductivity differs by the factor of 10. A more distinguished HAZ was expected, when processing specimen with high modulus carbon fibre. But the analysis of the measurements provides no significant decrease of the tension at failure comparing to high tenacity carbon fibre with low thermal heat conductivity. In contrast the influence of inapplicable beam sources and process parameters (Figure 7 compared to Figure 8) is much more pronounced. It is known that processing of composite materials with laser is possible, if the laser ray will be absorbed at the material [4]. The results, shown in Figure 8 maintain this statement. Additional the test method can assist clarifying the suitability of the beam sources linked with the scanning system. While the damage of the CFRP specimen at rising energy per unit length lead to a decreasing tension at failure, GFRP seems to be unoffended (Figure 8).

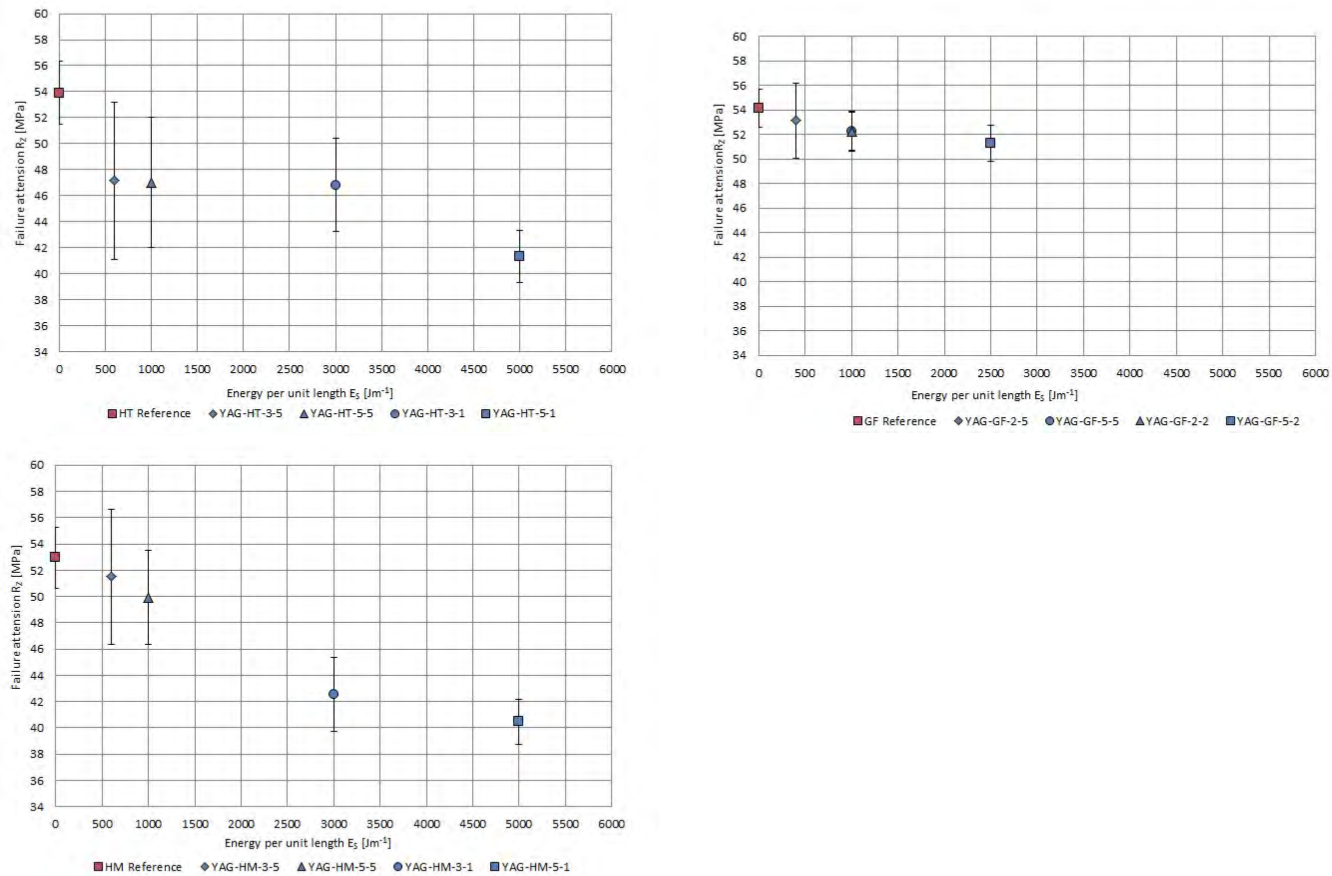

Figure 7.Decrease of tension at failure Rz as a function of energy per unit length ES (Yb - Laser)

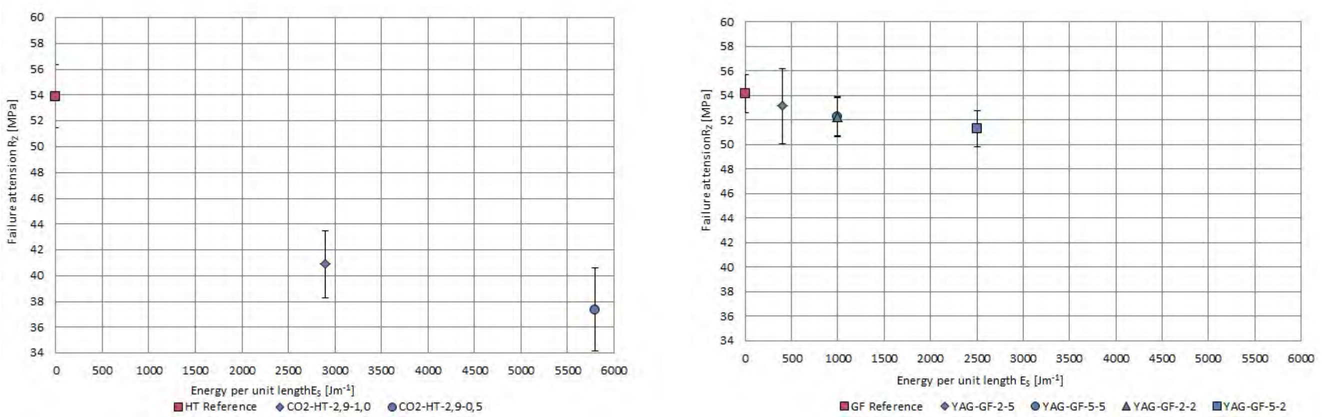

Figure 8. Decrease of tension at failure Rz as a function of energy per unit length ES (CO2 - Laser)

To post a failure analysis, it is assumed that the visible HAZ (Figure 6) is mechanically completely destroyed. The remaining cross section area is set as (A_{Rest}). To compare the results, the ratio between tension at failure $(\bar{\sigma}_{Ver})$ of the thermal damaged specimen and tension at failure of the reference series $(\bar{\sigma}_{Ref})$ are presented as a function of remaining cross section area (A_{Rest}) and the average cross section area $(\overline{A_{Ges}})$ of the specimen of each measurement serie (3), (Figure 9).

$$\frac{\bar{\sigma}_{Ver}}{\bar{\sigma}_{Ref}} = \frac{A_{Rest}}{\bar{A}_{Ges}} \tag{3}$$

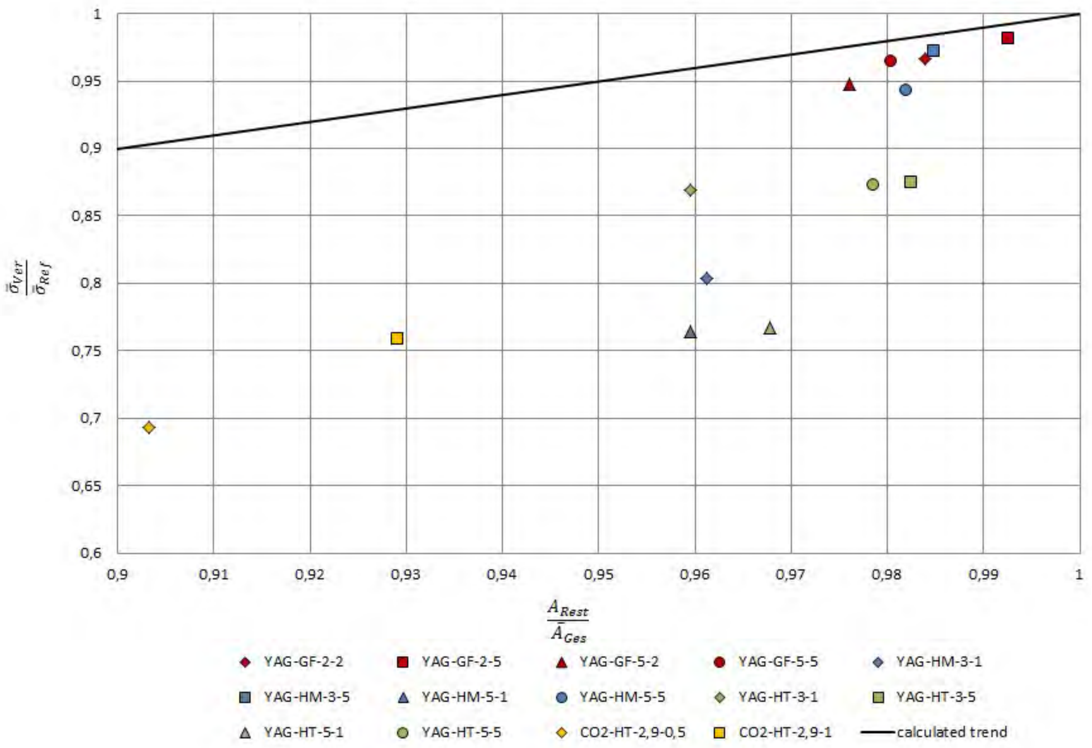

Figure 9. Tension at failure relative to proportionately remaining cross section area

The results are shown in Figure 9. Due to the fact, that the actual determined average values are below the calculated, one can assume that the HAZ is more distinctive than a visual analysis can provide. However the influence of a notch effect, caused by matrix withdrawal is not considered and may superpose the results.

4. Conclusion

Within this paper a correlation between laser process parameters and their influence on mechanical properties was shown. A specimen for tensile testing was introduced, whose failure mechanism is limited to inter fibre fracture. The design of the specimen supports the heat propagation in the material without any geometrical effects that can superpose the measurements. 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 minimized HAZ that can be detected with the measurement method. Process parameter could be found, whose tensile at failure are quiet close to a water jet cut reference. Further investigations have to consider the elongation at stress in the laser processed area, which can clarify the notch effect that can superpose the measurements.

Acknowledgements

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