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Laser Scored Machining of Fiber Reinforced Plastics to Prevent Delamination

Wolfgang Hintze[a,*], Marcel Cordes[a], Tobias Geis[a], Melchior Blühm[a], Claus Emmelmann[b], Marten Canisius[b]

[a] *Institute of Production Management and Technology, Hamburg University of Technology, Denickestr. 17, 21073 Hamburg, Germany*
[b] *Institute of Laser and System Technologies, Hamburg University of Technology, Denickestr. 17, 21073 Hamburg, Germany*

Abstract

Delamination is a major problem in contour milling of fiber reinforced plastics (FRP) causing scrap or rework. Today, delamination avoidance limits overall productivity and tool life. Damage of the top layer of a composite structure is initiated if fibers are not cut during first engagement of the cutting edge, but deflected. Generated cracks propagate due to recurrent contact of fibers with the rotating tool. In contrast, when laser cutting FRP, the heat input often leads to an extensive heat-affected zone (HAZ), particularly in case of large laminate thickness and high energy input. Combination of both processes is a promising approach to overcome the mentioned disadvantages. Experiments indicate that pre-scoring of the top layer is possible with negligible HAZ for FRP materials using proper laser parameters, especially low energy input per unit length. Positioning of the laser scored kerf along the contour to be manufactured by the subsequent milling tool prevents crack propagation along the fiber direction even with a heavily worn milling tool at increased feed rate. Furthermore, laser pre-scoring eliminates protruding fibers and allows for edge chamfering. The process understanding is enhanced using simulation of the laser pre-scoring, particularly considering heat conduction and forced convection, as well as by presenting a model for the mechanism of delamination prevention.

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Keywords: fibre reinforced plastics; contour milling; laser pre-scoring; delamination; heat-affected zone;

* Corresponding author. Tel.: +49-40-42878-3233; fax: +49-40-42878-2295.
E-mail address: w.hintze@tuhh.de

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1. Introduction

Carbon fiber reinforced plastics (CFRP) have become a major material for structural elements in modern aircraft design. FRP components usually have to undergo a processing step to obtain their final contour. For this purpose contour milling or laser cutting are two possible processes. Contour milling is well-established for trimming of FRP. Nevertheless, the occurrence of delamination and fiber protrusion limits the tool life and the feed rate significantly and, furthermore, causes expensive rework or even scrap. Laser cutting avoids delamination because it is a thermal and not a mechanical process. However, the key disadvantage of laser cutting FRP is the HAZ, which is mostly considered unacceptable by the aeronautical industry today.

In contour milling, the occurrence of delamination depends to a considerable degree on the fiber orientation angle ϕ and the fiber cutting angle θ [1,2,3,4,5]. A widely used failure criteria for FRP is the *Puck* inter-fiber fracture criteria. It is divided in three different failure modes A, B and C depending on the ratio between normal stress to shear stress in the material [6]. Another significant factor for the quality of the workpiece edge is the wear condition of the tool. The feed force increases significantly with increasing wear, which is accompanied by a greater degree of delamination [3]. Due to the high abrasiveness of the fibers, polycrystalline diamond (PCD) is recommended as a cutting material [3,7]. In full-groove cuts a better edge quality is achieved at the up-milled surface ply [8].

Two different process approaches for laser cutting are available to pursue either high productivity or high quality. Cutting with continuous wave laser systems with a mean power in the kilowatt range allows feed rates above 10 m/min [9,10]. The inherent HAZ and thermal damage of the laminate´s surface at the edge causes a low relevance of laser processing in commercial applications today. Higher cutting quality can be achieved with pulsed laser systems [11]. However, for typical laminates feed rates are limited to about 1 m/min. Concerning the laser wavelength, CO_2 lasers have a much better absorption behavior in FRP than solid state lasers in the range of 1 µm, especially when cutting glass fibers. A first analysis of the kerf building under the influence of the first exposures during laser remote cutting is done by Schmidt-Lehr et al. [12]. A linear relationship between the kerf depth and the number of exposures is found up to a kerf depth of about 6 mm. For continuous wave laser processes a few approaches for numerical process simulation exist [13,14,15]. 3D finite difference or finite element methods are used to predict the temperature field as well as the HAZ or the kerf geometry. Only Liebelt [13] considered all three phenomena for an orthogonal-anisotropic material with a thickness of 0.24 mm. All simulations are based on the numeric solution of the heat transfer equation that considers the isotropic or orthogonal-anisotropic heat conduction. Phase changes of the material are modeled in each study, while Liebelt included the phase changes of the polymer as well as the fiber material. The fiber reinforced material is considered as a continuum in all studies.

The laser scored machining (LSM) process combines laser cutting and milling in a way that promises to overcome the disadvantages of the individual processes. Laser cutting is used to score a kerf into the top layer of the laminate. Due to the small depth of the kerf, the thermal impact on the laminate is greatly reduced, which minimizes the size of the HAZ to an extent that can be considered negligible. In the subsequent milling process, the kerf prevents the occurrence and propagation of delamination.

2. Delamination prevention model

During milling, delamination predominantly occurs in the outside layers of the laminate due to the lack of support. Regarding the effect of scoring, two mechanisms have to be distinguished. The first one is the interruption of delamination propagation at the scored kerf. With the tool proceeding along its feed path, delamination propagates along the fiber direction. In order to interrupt the propagation, the depth of the scored kerf d_k has to be larger than the depth d_d in which the delamination is propagating, Fig. 1a. The second mechanism is the prevention of initial delamination, as shown in Fig. 1b. The cutting edge exerts a force F on the workpiece. When the cutting edge reaches the kerf, the outside layers of the laminate above point e support against the acting force.

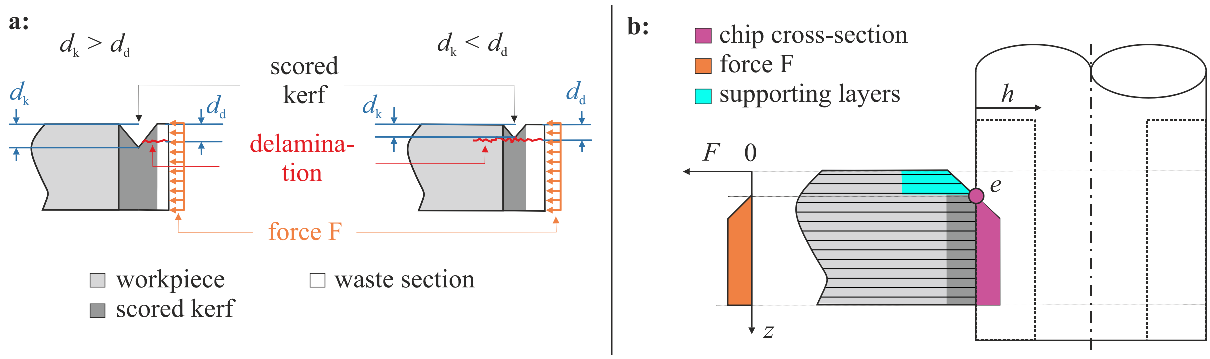


Fig. 1. (a) Interruption of the delamination at the scored kerf; (b) Support of the outside layers during milling.

To show the effect of the supporting layers, a finite element analysis (FEA) has been carried out. Therefore, the cutting force F_c and cutting normal force F_{cn} have been measured as a function of the tool engagement angle φ during machining of CFRP in full engagement. In the FEA, these forces were applied to a 2 x 2 x 1 mm³ specimen, Fig. 2a. The cutting edge is represented by an area of the width twice the cutting edge radius r_n (2 x 28 µm) and the length of the cutting edge in engagement. The material characteristics were adjusted according to the existing fiber cutting angle and fiber orientation angle. The meshing was done as an unstructured mesh of tetrahedron elements with intermediate nodes. In addition, the mesh was refined towards the contact area where the load is applied. The convergence of the resulting stresses and the node displacement was then tested with the h-method [15] to guarantee sufficient accuracy and short simulation time. In fact, the assessment of failure in case of three-axial stress state is yet only possible by experiments. As a first approach, the failure assessment using the modes of *Puck* is based on separate consideration of the stresses acting in the top layer, neglecting stress and strain interactions perpendicular to the laminate plane. The calculated stress for each element of the model was used to determine whether damage occurred based on the failure mode criteria of *Puck*. For a fiber orientation angle ϕ = 135° and a fiber cutting angle θ = 135°, the results are shown in Fig. 2b for an unscored and a scored surface (d_k = 300 µm). Blue marked elements represent *Puck* mode A, yellow elements mode B and red elements mode C. Behind the cutting edge, *Puck* modus A is present due to tensile stress. In the contact area, modus B is present due to high shear stress and compressive stress. In front of the cutting edge, mode C occurs due to high compressive stress. The scored model does not show damage of the outside layer, only a few damaged elements are present at the lower edge of the kerf. The model of delamination prevention by scoring and the support of the outside layers by the kerf will be validated experimentally in Chapter 4.

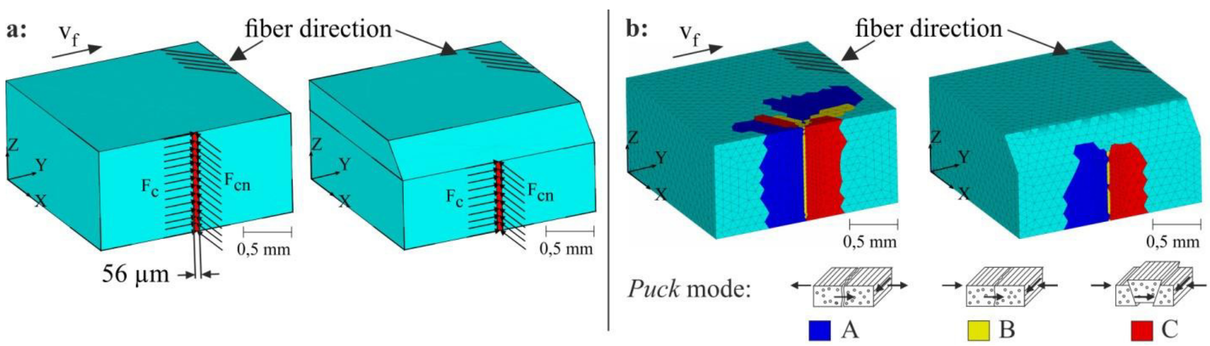


Fig. 2. (a) FEA model for simulation of the FRP material damage; (b) Simulation results for ϕ = 135°

3. Simulation of laser pre-scoring

The minimization of the HAZ and the prediction of the kerf geometry are important goals of laser scoring process development. Due to the plurality of laser process parameters, a simulation of the laser scoring process has been carried out. For this purpose, a model has been developed which consists of a finite difference based simulation of the heat conduction in the yz-plane perpendicular to the feed direction (Fig. 3a left) and a finite volume based simulation of the transient flow of the gaseous process emissions in the kerf (xz-plane) as well as the resulting convective heat transfer (Fig. 3a right).

Regarding the finite difference simulation of heat conduction, as shown in Fig. 3a left, the explicit formulation is chosen due to robustness, stability and speed of the simulation. The transient temperature field is calculated in the yz-plane, while heat conduction in feed direction is neglected. This is admissible, because the heat conduction is very slow compared to the feed rate of the laser beam.

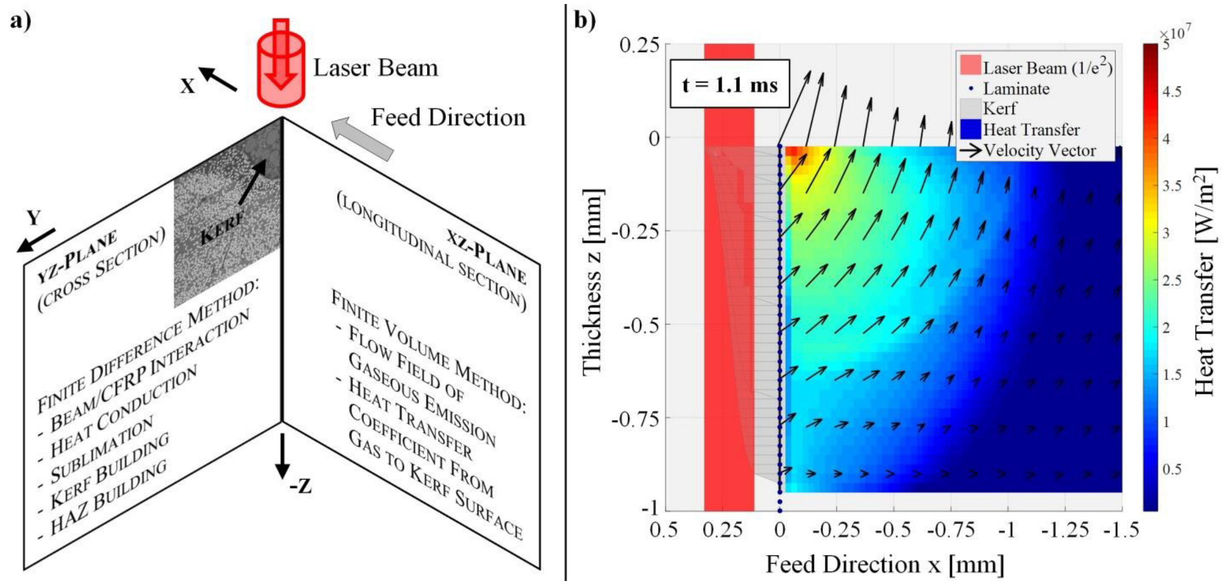


Fig. 3. (a) Coordinate system and modeled phenomena; (b) Gaseous process emission flow field and heat transfer to kerf surface

Based on the changing kerf geometry during the laser exposure, the boundary conditions and material properties of the finite difference mesh are adapted. Thus, the model includes the phenomenon of non-linear kerf depth development with further exposure repetitions. The parametrical material model considers the laminate´s setup such as number of layers, their particular thickness and fiber orientation, fiber volume fraction as well as the thermal conductivity, capacity and latent heat of matrix, fiber and the HAZ. The material properties used in the simulation are summarized in Table 1.

Table 1. Material characteristics of the examined CFRP laminate

Resin type	Epoxy	Fiber volume fraction	60 %
Carbon fiber type	HT (high tenacity)	Thermal conductivity fiber / epoxy	10 / 0.54 $Wm^{-1}K^{-1}$
Laminate structure	[135°, 45°, 135°,...]	Specific heat fiber / epoxy	710 / 1,900 $Jkg^{-1}K^{-1}$
Laminate thickness	5 mm	Latent heat fiber / epoxy	43,000 / 1,020 Jg^{-1}
Lamina thickness	250 µm (UD tape)	Sublimation temp. fiber / epoxy	3,825 / 393-497 °C

The reinforced material is considered as a continuum based on the rule of mixture with orthogonal-anisotropic properties [13]. The HAZ is treated as a combination of solid polymer and fiber with a weighting according to the local degradation of the polymer. The two phase changes during the sublimation of the polymer as well as the carbon fibers are considered [14]. The material model is based on measured data of temperature gradient analysis as well as of differential scanning calorimetry. The heat source is calculated using laser parameters such as power, feed rate, number of exposure repetitions, repetition delay and beam intensity profile.

The convective heat transfer in the xz-plane is considered (Fig. 3a right), because the gaseous process emission from sublimation transports a huge amount of thermal energy that cannot be neglected. The gas flows with very high velocity, pressure and temperature out of the kerf after passing its surface. A process simulation that just considers the heat conduction is not sufficient to calculate the temperature field and HAZ during continuous wave laser scoring or cutting of FRP properly. The convection model is formulated based on the explicit finite volume method. It considers the compressibility of the gas, the flow resistance and the heat transfer of the forced convection at the existing kerf geometry, which is known from the interaction between laser beam and material calculated in the yz-plane. The simulation enables the calculation of the transient temperature, pressure and velocity field in the kerf. The field coupling between the yz-plane and the xz-plane is realized by iterative, alternate calculation.

Based on this model, the forced convection for the entire kerf surface can be calculated, Fig. 3b. The first velocity component of the flow field is oriented opposite to the feed direction of the laser beam and its second velocity component opposite to the beam direction. Especially for high kerf depth (in the range of several beam diameters), the flow takes a long way along the kerf surface, resulting in a considerable amount of thermal energy transferred to the laminate by forced convection. Ultimately, the kerf geometry as well as the HAZ are known.

4. Experimental results and model validation of laser scored machining

4.1. Geometry of the kerf and HAZ when laser pre-scoring

The top layer of the laminate is initially scored with a CO_2 laser, which has a maximum laser output power of 650 W and a wavelength of 10.6 µm. The beam is guided by a 2D-Scanner with an F-Theta lens and a focal length of 200 mm. The resulting focus diameter was approx. 220 µm. In order to validate the above mentioned laser cutting and delamination models and to investigate the influence of the kerf geometry on the edge quality after milling, the process parameters feed rate $v_{f,l}$ of the laser, laser power P and number of exposures n_{exp} are varied. For the experiments, the same CFRP material is used as for the simulation of pre-scoring, Table 1.

The kerf geometry is characterized based on cross sections of the pre-scored specimens. Fig. 4 shows specimens with different energy input per unit length S, which is calculated as follows:

$$S = \frac{P}{v_{f,l}} \cdot n_{\mathrm{exp}} \qquad (1)$$

As expected, higher energy input per unit length leads to an increase in kerf depth. The maximum resulting kerf depth is 670 µm, thus penetrates up to the third lamina (Fig. 4d). The HAZ is visible as a result of different light reflection. For maximum S, the width of the HAZ is 357 µm at the surface. Compared to laser-only cutting of such CFRP materials the HAZ width is significantly reduced [16].

The cross sections that were obtained using the simulation described in Chapter 3 are presented in the lower part of Fig. 4. In order to fit the experimental results, the simulated laser power was multiplied by a constant factor of 0.53. The discrepancies may be attributed to the self-shielding of the laser process due to emissions. Furthermore, the mesh is comparatively coarse, which causes increased accumulation of thermal energy at the grid elements at the kerf surface compared to the real process. In addition, free convection and radiation between ambience and surface are neglected.

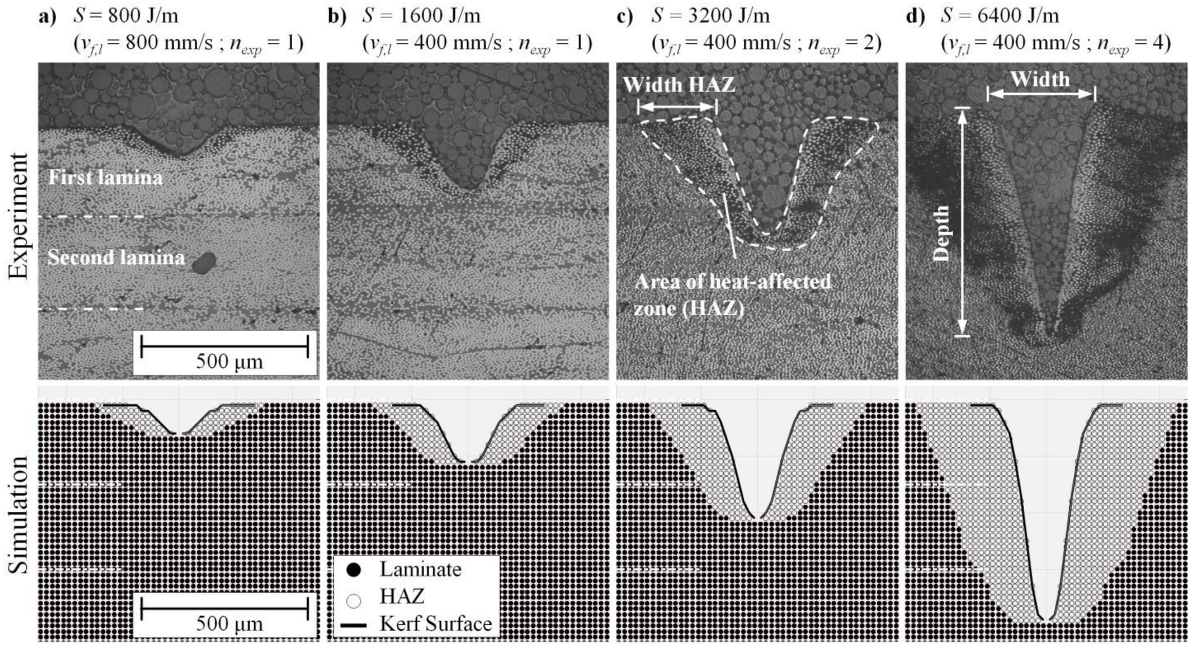


Fig. 4. Cross sections and simulation of CO_2-laser pre-scoring with laser power P = 640W

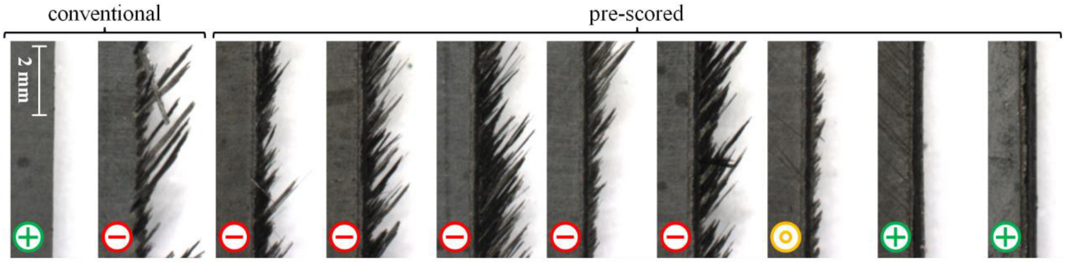
4.2. Milling of the pre-scored specimens

Afterwards, the pre-scored specimens are milled on a 5-axis-machining center. The machining is carried out in full groove cuts (slotting) with a PCD end mill, which has a cutting edge radius (CER) of 60 µm. Hence, the cutting edges are heavily worn and at the end of their industrial usage [2,17]. In contrast to the industrial practice, the feed per tooth is set high to 0.09 mm in order to show the high potential of the laser scored machining. For comparison with the conventional contour milling, reference grooves with the worn and a sharp (CER=12 µm) tool are milled without pre-scoring. The cutting parameters are summarized in Table 2. Since in general a better quality is achieved at the up-milled edge [8], only the up-milled edge of the top lamina is assessed. The relative position of the milled groove to the pre-scored kerf was chosen in a way that the trimmed edge runs in the center of the kerf. Thus, laser pre-scoring simultaneously allows for edge chamfering, which is often required for subsequent processing steps like handling or painting.

Table 2. Properties of tool and cutting conditions used in the experiments.

Diameter (mm)	12.7
Number of teeth, z	2
Helix angle (deg)	0
Cutting edge radius CER (µm)	12 (sharp); 60 (worn)
Feed per tooth, f_z (mm)	0.09
Cutting velocity, v_c (m/min)	798

Fig. 5 shows microscopic images of the resulting edge quality depending on the laser process parameters. First of all, without pre-scoring the heavy impact of tool wear in terms of CER on delamination becomes apparent. On the other hand, with increasing energy input per unit length the pre-scoring results in a complete prevention of delamination. Both, fiber protrusions and surface damage extending into the material are not evident.



CER [µm]	12	60	60	60	60	60	60	60	60	60
P [W]	-	-	80	80	320	640	320	640	640	640
$v_{f,l}$ [mm/s]	-	-	200	100	400	800	200	400	400	400
n_{exp}	-	-	1	1	1	1	1	1	2	4
S [J/m]	-	-	400	800	800	800	1600	1600	3200	6400

Fig. 5. Comparison of edge quality after milling with and without laser pre-scoring for fiber orientation angle 135°

4.3. Influence of kerf geometry on edge quality

The influence of the kerf geometry on edge quality after milling is shown in Fig. 6. The geometrical characteristics depth and width of the kerf as well as the area of the HAZ have been extracted from the cross sections, compare Fig. 4. For each specimen, two cross sections have been prepared and the measured values averaged. The depth of the kerf is increasing virtually linear with increasing energy input per unit length, whereas the width remains almost constant. The delamination is prevented starting with a scoring depth of approximately 250 µm, which corresponds with the thickness of one lamina.

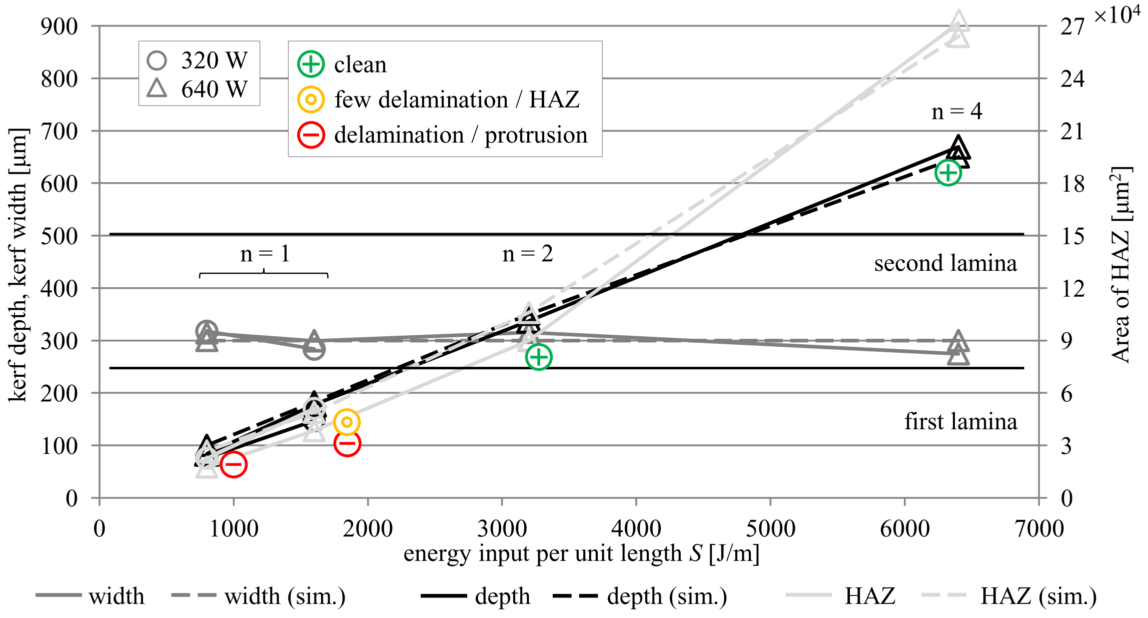


Fig. 6. Influence of kerf geometry on edge quality

The experimental milling result is in accordance with the FEA, which predicts no surface damage for a scored depth of 300 µm (compare Fig. 2b). In addition, the modeled kerf depth, width and HAZ determined based on the simulated cross sections are shown in Fig. 6. They show a good quantitative agreement with the experiment.

5. Conclusions

A novel edge trimming process for FRP, consisting of a laser pre-scoring and a milling step, has been introduced. The process aims at preventing delamination and fiber protrusion at the top lamina. The process and its principles have been examined theoretically and verified through experiments.

- A model for the mechanism of delamination prevention at the top layer through pre-scoring has been presented. Two effects are involved: the interruption of the propagation of delamination at the kerf and the prevention of initial delamination based on a better support of the relevant layers against the cutting force. A finite element analysis of the cutting area is used to demonstrate the impact of the kerf on top layer damage.
- Simulation can be used to predict the kerf geometry and the HAZ resulting from the laser pre-scoring. This is shown using a finite difference and finite volume simulation incorporating heat transfer by conduction as well as forced convection from gaseous process emission to the kerf surface. After calibration, a good agreement between simulation and experimental results is found.
- Cross sections of laser pre-scored kerfs show that the HAZ is considerably reduced compared to laser-only cutting. Moreover, the position of the HAZ is favorably located at a small area around the upper kerf edge. The kerf depth as well as the size of the HAZ increase with the energy per unit length applied.
- Experimental results show that laser pre-scoring can effectively prevent top layer delamination during contour milling. For this purpose, a sufficient kerf depth has to be achieved. In the current experiments, the minimum depth was found to be around 250 µm, which corresponds to the thickness of one lamina. As a small kerf depth is sufficient to achieve delamination prevention, the HAZ as well as the required laser power can be kept small.

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