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Laser cutting of natural fiber reinforced composites with high speed and minimum damage

Christian Strohl[a,*], Kathrin Placzek[a], Daniel Holder[a], Christian Hagenlocher[a], Johannes Baur[b], Thomas Graf[a]

[a]*Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany*
[b]*Institut für Flugzeugbau (IFB), University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany*

Abstract

Flax fiber reinforced composites Plastik (FFRP) offer a sustainable alternative to synthetic reinforcement fibers like glass or carbon. However, processing of FFRP using conventional machining techniques results in low cut qualities due to fraying and delamination.
Laser cutting of FFRP can avoid these issues with the added benefit of FFRP having a similar decomposition temperature of matrix and fiber when compared to synthetic composites. Avoiding quality decreases from thermal influences while still providing high cutting speeds is a major challenge when cutting FFRP with lasers.
For this purpose, laser cutting of 2.5 mm FFRP plates was investigated using different laser systems. Very high cutting speeds of up to 8000 mm/min with minor thermal damage were achieved using a continuous wave CO_2 laser. High cutting qualities with no thermal damage at cutting speeds of up to 32 mm/min were achieved using a femtosecond laser.

Keywords: natural fiber reinforced composite; laser cutting; laser ablation cutting; cut quality

1. Introduction

Fiber reinforced plastic (FRP) offer lightweight solutions while meeting highest mechanical requirements. Although synthetic fibers like glass or carbon shine with excellent weight-specific mechanical properties during their lifetime, they have significant issues before and after their dedicated use.

Producing these fibers requires a large amount of energy, and recycling the composite material is almost impossible. This leads to an increasing amount of difficult-to-dispose waste. Regarding a more sustainable and environmentally friendly industry, an alternative could be found in natural reinforcement fibers like flax. Flax fibers are cost and energy efficient while still performing on a comparable level with glass fibers as shown by Ku et al., 2011.

Similar to other fiber reinforced composites (FRP), conventional mechanical processing of flax fiber reinforced composites (FFRP) is associated with notable quality concerns. Mechanical cutting relies on the physical contact of material and tool to apply a force. Due to the contrasting mechanical properties of the fiber and matrix material, the cutting process within the material is inconsistent. This results in various types of damage, including fraying of the cut surface. Figure 1 depicts this damage type for mechanical cutting of FFRP for three different tools.

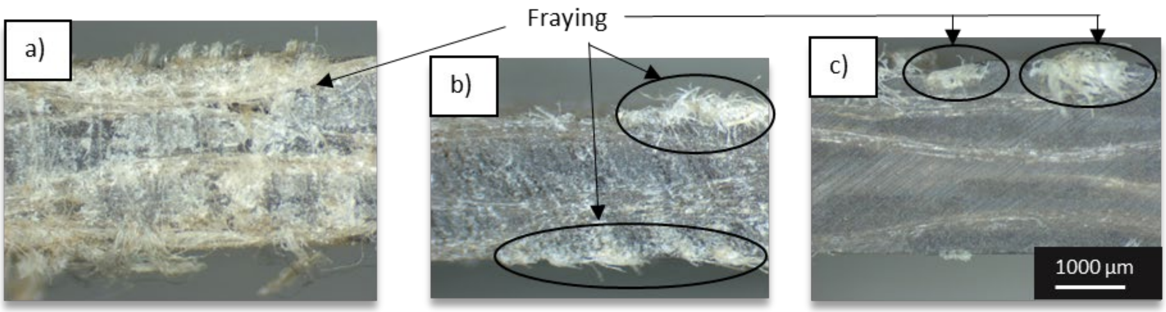

Fig. 1. Examples of mechanical cutting of FFRP with different tools: a) hand saw, b) milling machine, c) wet saw

The images in figure 1 show the results for cutting FFRP with a hand saw in a), a milling machine in b), and a wet saw in c). For the hand saw (a), fraying is seen across the complete surface leading to a very low cut quality. The fraying is reduced by using a milling machine b) or a wet saw c) but is still present, especially at the edges of the cut surface.

Non-mechanical processing such as laser cutting allows for an avoidance of such defects as there is no physical contact between tool and material involved, as shown by Masoud et al., 2020.
However, the different decomposition temperatures of matrix and fiber in composites, especially with using carbon reinforcement fibers, may also cause quality issues. Fibers provide a higher thermal resistance and diffusivity, than the matrix material. As a result, the fibers conduct the process heat very quickly into the surrounding material. The high temperature of the fibers in such an extended heat-affected zone damages or evaporates the surrounding matrix material, as described by Hintze et al., 2021. To avoid matrix evaporation and reduce the extent of the heat-affected zone, cutting FRP with ultrashort laser pulses (USP) has proven to be an effective approach, as demonstrated by Freitag et al., 2014 and Weber et al., 2012. Compared to processing with cw-lasers, the thermal load is significantly reduced, since the material is exposed to the laser for a shorter time, as pointed out by Weber et al., 2011 and Holder et al. 2021. The high cut quality comes at the cost of higher processing times as the average power of pulsed lasers is typically lower by two orders of magnitude. Transferring this knowledge to FFRP, the thermal resistance, and diffusivity does not differ as much as for CFRP, as illustrated in Arrakhiz et al. 2013; Kannan et al. 2013. The decreased difference between the material characteristics should reduce the formation of the defects described above, which would positively affect the cw-laser cutting process.

Therefore, both USP- and cw-laser cutting could be viable options for processing FFRP. Within the frame of this work, the experimental results of a cutting process of FFRP with cw- and USP-lasers are presented. The cut surface is analyzed regarding mechanical and thermal damage.

2. Experiment

Figure 2 shows the experimental setup for the cw-laser cut in a) and the USP-laser cut in b). The used parameters are given in table 1.

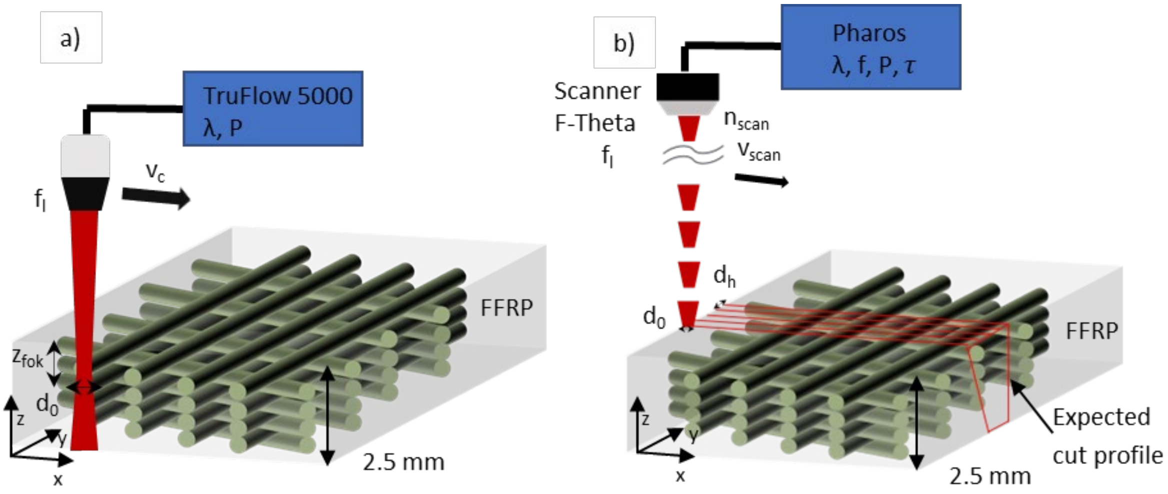

Fig. 2. Experimental setup for cw-laser cut in a) and USP-laser cut in b)

Table 1. Data and parameters for cw- and USP-laser cutting

Parameter		USP-cutting	cw-cutting
name		Pharos	TruFlow 5000
medium		Yb: YAG	CO_2
wavelength	λ	1030 nm	10600 nm
M^2		1.2	2.3
focal length	f_l	163 mm	155 mm
average power	P	12 W	700 W
scan speed	v_{scan}	120 m/min	-
number of scans	n_{scan}	3750	1
cutting speed	v_c	32 mm/min	8000 mm/min
beam waist diameter	d_0	57 µm	230 µm
Rayleigh length	z_r	1630 µm	1704 µm
	τ	250 fs	-
frequency	f	50 kHz	-

The investigated FFRP consists of a thermoplastic matrix and four layers of flax fiber fabric, particularly ampliTex^{tm} 300, twill2/2 produced by Bcomp Ltd. The matrix is composed of ELIUM 188 XO, a thermoplastic, acrylic resin, distributed by Arkema France which can be used explicitly in combination with natural fibers.

The composite was produced by *the Institut für Flugzeugbau* (IFB) at the University of Stuttgart with Vacuum Assisted Resin Injection (VARI). The resulting FFRP plates have a thickness of 2.5 mm.

To conduct the cw-laser cuts a TruFlow 5000 by Trumpf was used, with the parameters given in table 1 and an image of the setup shown in figure 2 a). A CO_2 laser with a wavelength of 10.6 µm was chosen because of the high absorption of 80-90% in polymers, as shown by Mittal et al.,2014.

For the USP-ablation cutting a Pharos laser from Light Conversion in combination with an intelliSCAN 30 was used to perform the experiments. The cutting parameters are listed in table 1 and an image of the setup is shown in figure 2 b). To reach the required cutting depth of 2.5 mm and reduce the thermal load into the material, five parallel lines with a hatch distance of 50 µm were scanned. 750 x 5 scans, resulting in a total of 3750 scans were necessary to completely cut through the sample. The maximum effective cutting speed

$$V_c = \frac{v_{scan}}{n_{scan}} = \frac{120\,\frac{m}{min}}{3750} = 32\,\frac{mm}{min} \qquad (1)$$

results from the division of the scan speed v_{scan} by the number of scans n_{scan}.

To estimate the roughness R_{max} of the cut surfaces, z-stacked images of the resulting cw- and USP-cut surfaces were taken with a Leica DMC 5400 microscope. The R_{max} value represents the maximum height difference of a profile of the cut surface. The surfaces were investigated without any form of post-processing.

3. Results

3.1 Cw-laser cut

The cut surface of the cw-laser cut is shown in Figure 3 at a magnification of 30x for image a) and 200x for image b).

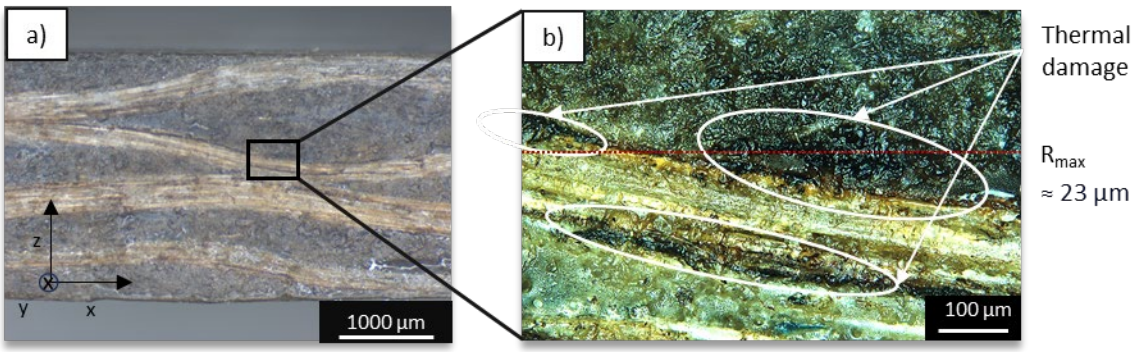

Fig. 3. cw-cut surface at 30x magnification in a) and 200x Magnification in b); cw process parameters: λ = 10.6 µm, P = 700 W, v_c= 8 m/min, M^2 =2.3, d_0 =230 µm, z_{fok}= - 0.5 mm

The four light-brown stripes in Figure 3a show the fibers which are aligned parallel to the cut, the darker regions show the fibers oriented perpendicular to the cut surface. Notably, no fraying is observed, and even the edges of the cut show no indication of damage.

Figure 3b shows a close-up of an area located in the middle of the cut surface. In the lower half of the image, the fibers are oriented parallel to the cut surface indicated by a lighter coloring. Conversely, the fibers in the upper half are oriented perpendicular resulting in a darker shade. No fraying or single loose fibers can be observed, confirming the results of picture a). However, areas in which the material has significantly darkened were identified. The energy of the laser has slightly burned the composite resulting in thermal damage to the cut surface. The thermal damage results in a rather rough surface. With the z-stack analysis (y-axis in the coordinate system), a height profile along the dotted red line was created resulting in a R_{max} value of 23 µm. This gives the height difference between highest and lowest point within the profile.

3.2 USP-laser ablation cut

Figure 4 shows the cut surface of the USP-ablation cut. Figure 4a shows the cut at a magnification of 30x, the images Figure 4b and Figure 4c depict different regions of the cut surface at a magnification of 200x.

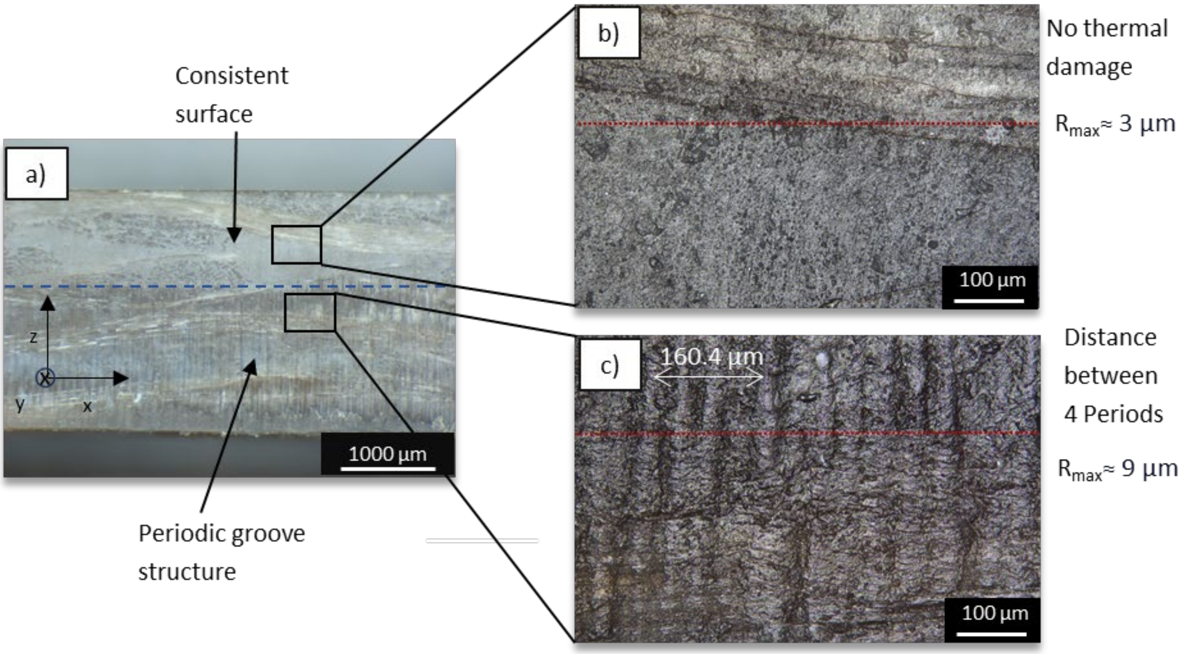

Fig. 4. USP- cut surface at 30x Magnification a); 400 x Magnification of homogeneous region b); 200 x magnification of periodic groove structure ; USP process parameters: λ = 1030 nm, P = 12 W, f = 50 kHz, □ = 250 fs, v_s = 120 m/min, M² =1.2, d_0 = 57 µm, d_h= 50 µm, N_s = 3750, z_{fok}= 0 mm;

In Figure 4a of the USP-cut surface, no evidence of fraying or any other form of mechanical damage is observed. The surface is divided into two different zones, separated by the dotted blue line. While the upper zone shows a mainly consistent cut surface, the lower zone consists of a periodic groove structure.

Figure 4b shows a close-up Image of the cut surface of the upper zone. As expected, a smooth surface with minor irregularities can be observed. No loose fiber ends or thermal damage is visible. A R_{max} value of 3 µm was determined along the dotted red line.

Figure 4c shows the grove structure of the lower zone. As in the upper zone, no loose fibers or thermal damage can be seen. The z-stack imaging gives a depth of 9 µm for the grooves. The distance between four grooves was measured to 160.4 µm resulting in a single period length p_{groove} of 40.1 µm, which agrees well with the period of the applied laser pulses.

$$\lambda_{pulse} = \frac{v_{scan}}{f} = \frac{120\ \text{m/min}}{50\ \text{kHz}} = 40\ \mu\text{m} \tag{2}$$

From this agreement, one can assume, that the groove structure results from the distance between individual laser pulses. Due to the Gaussian intensity distribution of laser pulses the ablation rate is higher in the center of the laser pulse. The decreasing ablation at the edges of a laser pulse can explain the appearance of the groove structure.

4. Conclusion

2.5 mm flax fiber reinforced composites were cut with a cw-laser and a USP-laser. A high processing speed of 8 000 mm/min without fraying but with thermal damage and a R_{max} value of 23 µm of the cut surface was achieved with cw-cutting. USP-cutting achieves excellent cut quality with no, fraying or thermal damage. The cut surface was divided into a smooth zone in the upper third with a R_{max} of 3 µm and a zone with a groove structure with a R_{max} of 9 µm in the lower region of the cut surface. However, the cutting speed is low with a maximum of 32 mm/min. Overall, the shown cut quality of both cw- and USP-laser cuts surpass mechanical cuts of FFRP, identifying the laser as a well-suited tool for cutting FFRP.

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