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Physics Procedia 83 (2016) 1037 – 1043

Physics Procedia

9th International Conference on Photonic Technologies - LANE 2016

Efficiency of laser cutting of carbon fiber textiles

Alexander N. Fuchs[a,]*, Michael F. Zaeh[a]

[a]iwb – Institute for Machine Tools and Industrial Management, Technical University of Munich, Boltzmannstr. 15, 85748 Garching, Germany

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Abstract

Laser cutting of carbon fiber textiles has various advantages over conventional processes like ultrasonic knife cutting: It is wear free, no fibers are left uncut in the kerf, it is able to cut complex contours, and the cut edge is clearly defined. To ensure a complete cut under variable conditions, e.g. the thickness of the material, line energy has to be applied at a higher level than theoretically necessary to account for those variations. This energy is transilluminated through the kerf. In addition, not all laser energy is absorbed by the fibers but reflected and transmitted within the space between the fibers. Experiments were carried out to measure the percentage of laser power transilluminated through multi-layered carbon fiber textiles during laser cutting with maximum speed. To do so, blocks of poly(methyl methacrylate) (PMMA) were placed underneath the samples and the mass of the sublimed material was measured. Depending on the angle of the fiber, between 9 % and 40 % of the laser power was transilluminated.

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Keywords: laser cutting; carbon fiber; PMMA; efficiency

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1. Introduction

To decrease the mass of automobiles and airplanes, fiber reinforced polymers are increasingly used for structural components. Carbon fiber reinforced polymers (CFRP) play a special role in this context, due to high weight-specific mechanical stiffness and strength. However, the manufacturing processes for structural components made from CFRP are not as mature and cost-effective as for metals. One of these process steps, the cutting of carbon fiber textiles, cannot yet be fully automated. Not all fibers are separated when using conventional mechanical techniques; as a consequence the process cannot be automated economically. Laser cutting of textiles is a highly promising

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* Corresponding author. Tel.: +49-89-289-15505 ; fax: +49-89-289-15555 .
E-mail address: alexander.fuchs@iwb.tum.de

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2016.08.109

technique that can overcome the aforementioned issues. However, the process is not yet fully qualified for industrial use. Previous studies have shown the following:

- The material responds highly anisotropic to the cutting process (Klotzbach et al. 2011, Fuchs et al. 2015).
- A linear trend exists between laser power P_L and feed rate v when keeping the other parameters constant. Thus, the line energy E_s can be kept constant (Fuchs et al. 2013).
- The use of assist gas has little to no influence on the results of the cutting process (Fuchs and Zaeh 2014).
- The focus diameter has a strong influence on the line energy which is required to cut the textile (Ziermann et al. 2011).
- Sealing the cut edge has little to no effect on the infiltration of the textile in a vacuum molding process (Hindersmann et al. 2011).
- A cut edge, which is strongly thermally damaged by applying an excess of line energy, has a negative effect on the mechanical strength of the laminate (Priess et al. 2015).

To cut with a given speed, the laser power has to be adjusted to separate the material completely. Variations occurred during previous studies due to the inhomogeneities of the material. As a consequence, the parameters can only be determined with a limited accuracy. Excessive power has to be applied in an industrial setting to achieve a complete cut.

Nomenclature

α	fiber orientation of the carbon fiber textile
CFRP	carbon fiber reinforced polymer
d_f	focus diameter of the laser beam
E_s	line energy
l	length unit
λ	wavelength
Δm	ablated mass
P_{abs}	power, absorbed by the workpiece
P_L	laser power
P_{ref}	power, reflected by the workpiece
$P_{ref,k}$	power, reflected on the surface of the kerf
$P_{ref,s}$	power, reflected on the surface of the workpiece
P_{trans}	power, transmitted through the workpiece
$P_{trans,k}$	power, transilluminated through the kerf
$P_{trans,m}$	power, transmitted through the matter
PMMA	poly(methyl methacrylate)
v	feed rate

2. Power losses during laser cutting of carbon fiber textiles

During laser cutting, laser radiation is absorbed, reflected, and transmitted when interacting with the workpiece. Thus, the power balance between the laser power P_L, the absorbed power P_{abs}, the reflected power P_{ref}, and the transmitted power P_{trans} can be written as (Steen and Mazumder 2010):

$$P_L = P_{abs} + P_{ref} + P_{trans} \tag{1}$$

When the minimum line energy to cut a textile is applied, the different portions of the power are absorbed as shown in Figure 1 a). A portion of the power is reflected on the surface of the textile ($P_{ref,s}$), reflected in the kerf

($P_{ref,k}$), absorbed by the workpiece (P_{abs}), or transmitted through the material ($P_{trans,m}$). However, this is an idealized view of the cutting process. Since the edge of a laser beam is never clearly defined in the radial direction and the beam also overlaps the bottom end of the kerf in a through-cut, a portion of the power is also transilluminated ($P_{trans,k}$) through the kerf in a more realistic view (Figure 1 b). The absorption in the plume above the kerf or other losses are neglected in this study.

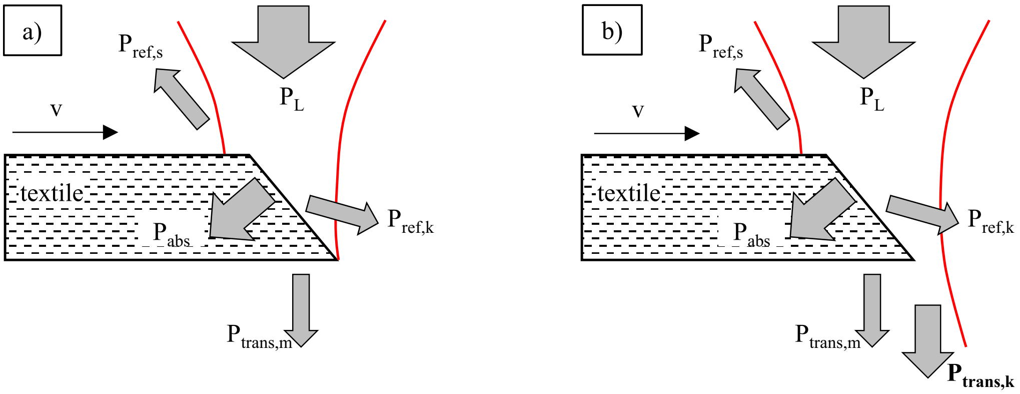

Fig. 1. Power portions at the kerf. Idealized (a) and realistic model (b).

The reflected power P_{ref} can be calculated as shown in equation 2:

$$P_{ref} = P_{ref,s} + P_{ref,k} \tag{2}$$

The transmitted power P_{ref} can be calculated as shown in equation 3, whereas the power transilluminated ($P_{trans,k}$) is not transmitted through the material, but rather transilluminated through the kerf behind the cutting front.

$$P_{trans} = P_{trans,m} + P_{trans,k} \tag{3}$$

Freitag et al. (2014) have shown, that the absorptivity of carbon fiber textiles is approximately 75 % at a wavelength of 1064 nm using ray tracing methods. The rest of the radiation is subsequently transmitted or reflected. Since carbon fiber textiles contain thousands of fibers with diameters of approximately 7 µm, multiple reflections within the textile increase the absorption. Thus, the portion of the transmitted radiation sharply decreases with the thickness of the textile.

3. Scope

The radiation which is transmitted through the textile and transilluminated through the kerf, is an indicator of the efficiency of the cutting process. The transmitted power P_{trans} was indirectly determined in this study using a sample of poly(methyl methacrylate) (PMMA) underneath the workpiece to measure the radiation. By measuring the transmitted power when cutting the anisotropic textiles at different angles, greater understanding can be achieved; in particular, the variations in previous studies and the deviations between an analytical model and the experiments can be analyzed in depth (Fuchs et al. 2015).

4. Experimental study

4.1. Experimental setup

Scintilla et al. (2011) presented a method to measure the transmitted power P_{trans} during laser cutting. A sample of black PMMA is placed at a defined distance underneath the sample. The transmitted and transilluminated radiation forms a kerf in the PMMA by subliming the material. The mass of the sublimed material can be measured and correlated to the transmitted power. The same setup was used in this study, as shown in Figure 2 a). A fiber laser with a maximum output power of P_L = 8 kW and a wavelength of λ = 1070 nm was used for the experiments. The focal plane of the laser beam was on the surface of the textile with a diameter of d_f = 180 µm. The power of the laser beam after the optics was determined using a calibrated power meter prior to the experiments at different power levels. Carbon fiber textiles with six layers and an unidirectional layup were used. Each sample had a size of 40 mm by 40 mm. Black PMMA was placed underneath the carbon fiber textiles. The length of each sample was 25 mm. The ablated mass was measured using a scale which has an accuracy of 0.1 mg. The samples were weighed prior to and after the experiments; they were not cleaned before the final weighing.

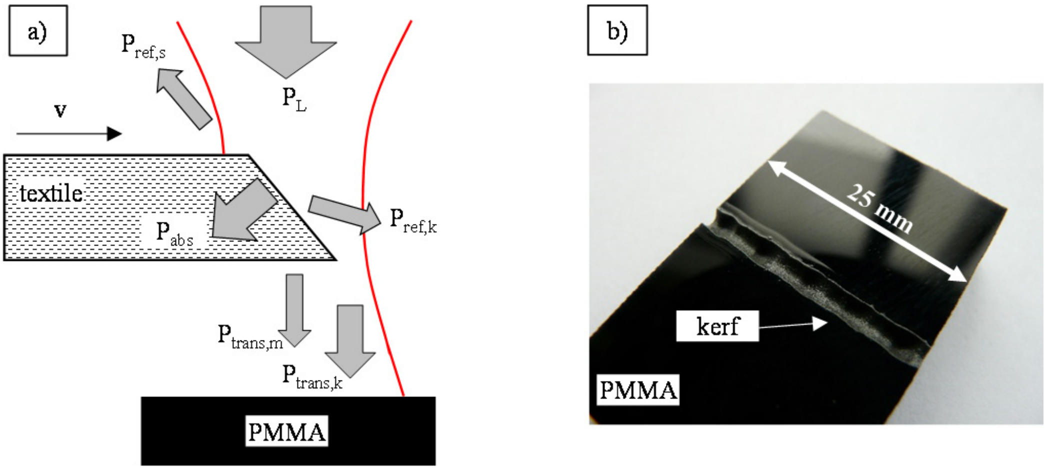

Fig. 2. Experimental setup to measure the transmitted power (a). Sublimed material of a PMMA sample (b).

The transmitted power can be calculated according to Scintilla et al. (2011) by using equation 4:

$$P_{trans} = H_v \cdot \frac{l}{\Delta m} \cdot \frac{\rho}{v} \tag{4}$$

H_v is the sublimation enthalpy of PMMA, l is the length of the cut, Δm the ablated mass, and ρ the density of the PMMA (ρ = 1.18 g/cm³ (Scintilla et al. 2011)).

4.2. Calibration

Preliminary experiments to determine the sublimation enthalpy and to compare the result to values from the literature were carried out. For this purpose, kerfs in the PMMA were formed by the laser. For these experiments only the PMMA was illuminated. A design of experiments was planned and the results were evaluated in a quadratic regression model of the sublimation enthalpy, calculated according to equation 4. The influencing variables were the cutting speed v and the laser power P_L. However, only a very low coefficient of determination could be achieved. The assumption from the literature that the sublimation enthalpy can be assumed to be constant could not be confirmed. As a consequence, formula 4 was not used for the experiments. The sublimation enthalpy would have had to be determined in an elaborate design of experiments. Instead, the mass ablation per length unit $\Delta m/l$ was determined at different feed rates with varying laser powers. The feed rates were the same as those of the experiments to measure the transmitted power during the cutting of the textiles.

At first, experiments at a feed rate of v = 4.5 m/min were carried out with laser powers between P_L = 400 W and P_L = 5000 W. The resulting kerfs using different laser powers can be seen in Figure 4. A uniform kerf was formed and the material was completely sublimed.

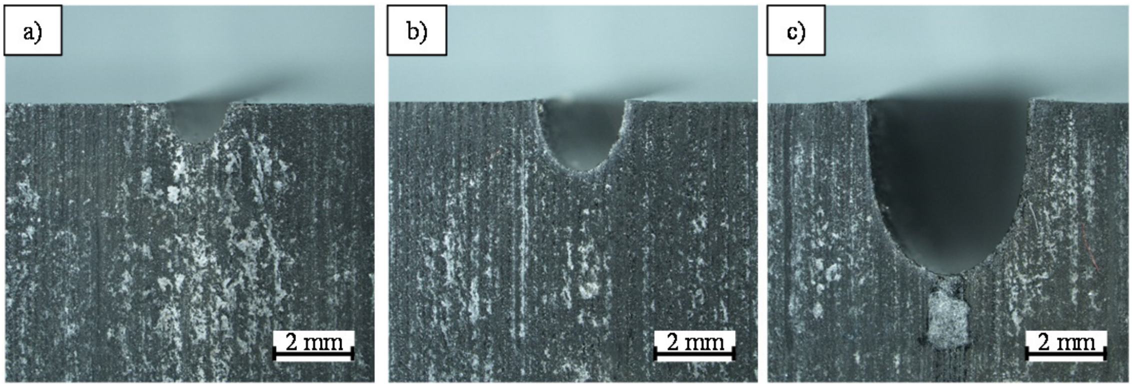

Fig. 3. Cross section of the kerf in the PMMA. $v = 4.5$ m/min. a) $P_L = 800$ W; b) $P_L = 1500$ W; c) $P_L = 5000$ W.

The experiments were repeated four times and the ablated mass was determined. The results were highly reproducible and the standard deviation was lower than 1 %. A linear trend between the mass ablation per length unit and the laser power can be observed. This offers advantages when determining the transmitted power in the experiments with the carbon fiber textiles, since the required values can easily be interpolated. Subsequently, experiments using different feed rates were conducted analogous to the previous tests at $v = 4.5$ m/min. The results are shown in Figure 4. For most experiments, the standard deviation is so small that it cannot be shown in Figure 4. The linear regression lines for all feed rates were determined.

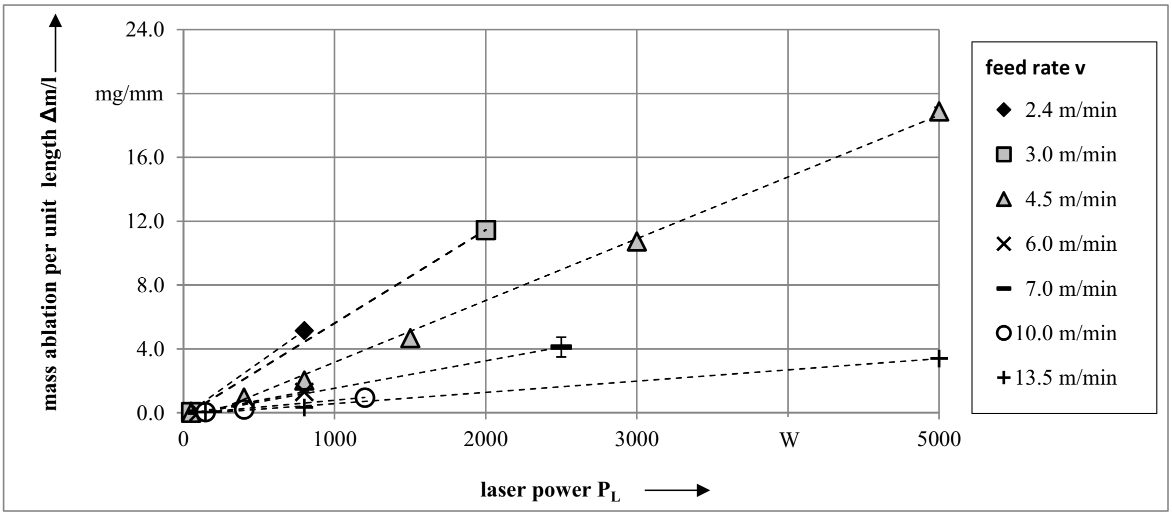

Fig. 4. Calibration experiments, mass ablation per unit length of the PMMA $\Delta m/l$ vs. laser power P_L.

4.3. Measurement of the transmitted power

Finally the experiments for the carbon fiber textiles were carried out. The transmitted power was measured using the PMMA blocks underneath the textiles. Two different fiber orientations $\alpha = 0°$ and $\alpha = 90°$ were used. Thus, the cut was either parallel or perpendicular to the fibers. The maximum cutting speed was used at every power level. The kerfThe results are shown in Table 1 and Figure 5. The transmitted power increases linearly with increasing laser power. A higher inclination can be observed for a fiber angle of $\alpha = 90°$ than for $\alpha = 0°$. Within the analyzed parameters, the transmitted power is higher for $\alpha = 90°$ at equal laser powers. Thus, the efficiency is lower. This can be due to the anisotropic heat flow within the fibers. If a cut is made parallel to the fibers, the heat flows along the direction of the cut. This preheats the process zone, so that less power is required to cut the material and the process is more efficient. Higher variations of the transmitted power can be observed for a fiber orientation of α = 90°. This can be caused by variability when determining the cutting speed with this fiber orientation. Since the fiber rovings have a periodic structure, the absorbed power as well as the transmitted power also vary. Thus, the results for the experiments with a fiber orientation of α = 90° are scattered. In general, the quality of the kerfs in the PMMA with and without a texile above were comparable. However, the periodic structure of the fiber rovings can be seen in the kerf in the PMMA, if a textile cut.

Table 1. Results for the measurement of the transmitted power.

P_L in W	v in m/min	α in °	$\Delta m/l$ in mg/mm	P_{trans} in W
400	3.0	0	0.059	50
800	6.0	0	0.092	117
1200	10.0	0	0.072	151
1500	13.5	0	0.060	143
800	2.4	90	0.959	175
1500	4.5	90	1.288	387
2500	7.0	90	1.478	945
5000	13.5	90	1.405	2064

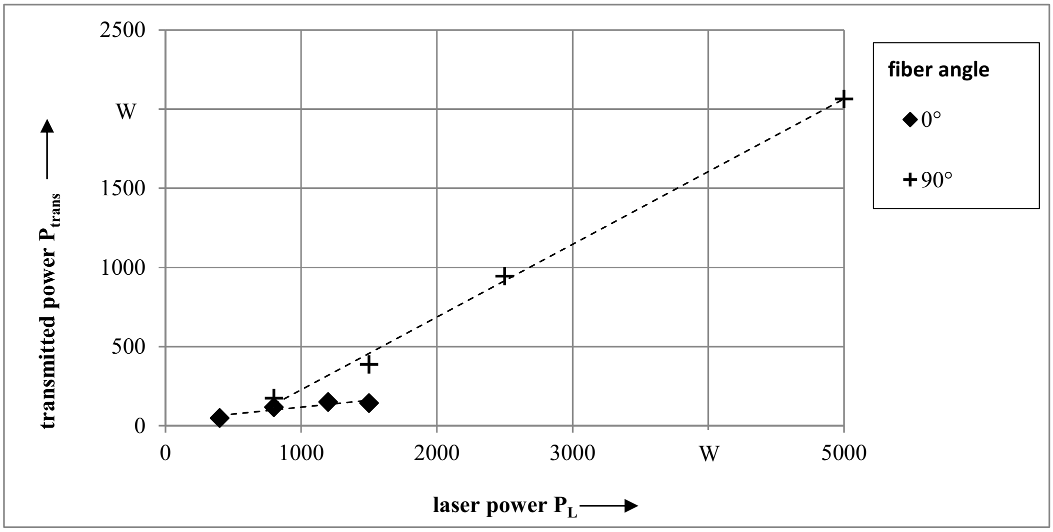

Fig. 5. Results for the measurement of the transmitted power.

5. Conclusions

An analysis to determine the transmitted laser power during laser cutting of carbon fiber textiles was carried out. To measure the transmitted power, samples of PMMA were placed underneath the carbon fiber textiles; the ablated mass in the PMMA correlates to the transmitted power. In the literature, an equation using a constant value for the sublimation enthalpy is commonly used. The assumption of a constant value for the sublimation enthalpy could not be confirmed in preliminary experiments within this study. Thus, the experimental setup was calibrated by determining the mass ablation per length unit in the PMMA for different laser powers and feed rates. The experiments were highly reproducible and an accurate linear model for the mass ablation per length unit depending on the laser power and the feed rate could be developed. Subsequently, experiments with carbon fiber textiles were conducted and the transmitted power was measured. Depending on the fiber angle, between 9 % and 40 % of the laser power was lost, as measured using PMMA underneath the textiles. The results will be used to further improve an analytical model for the cutting process of carbon fiber textiles, which is currently being developed.

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