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Analytical Model for Laser Cutting of Carbon Fiber Fabrics: Maximum Cutting Speed and the Heat Affected Zone

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Abstract

Laser cutting of carbon fiber reinforced plastics (CFRP) and carbon fiber textiles offers various advantages over conventional machining methods such as milling, water jet cutting, and ultrasonic knife cutting. The process is force and wear free, highly automatable and offers a high quality cut. Yet, it is not used on a large scale in industry. This is partially due to the anisotropic behavior of the material, which makes it hard to predict the cutting speed and the heat affected zone in relation to the angle between the fibers and the direction of the cut.
In the presented study, an analytical model is developed, which predicts the heat affected zone and the maximum cutting speed for cutting non-crimp fabrics made from carbon fiber. The temperature distribution is modeled using a modified line heat source model which accounts for the anisotropic behavior of the fibers. The cutting speed is calculated by using an energy balance. The results of the analytical modeling are compared to those of an empirical analysis. The model will also be suitable for consolidated CFRP consisting of fiber and resin.

Keywords: Analytical Model; Laser Cutting; Carbon Fiber; CFRP; Non-Crimp Fabric

1. Introduction

Laser cutting of carbon fiber (CF) fabrics [1][2] and carbon fiber reinforced polymers (CFRP) [3][4] has been the focus of research for the past few years. This movement has been driven by the increasing number of industrial applications for CFRP in the automotive and aircraft industry. The conventional methods for

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machining CFRP, like milling or abrasive water jet cutting, and for cutting CF fabrics, like ultrasonic knife cutting or stamping, have certain drawbacks. Due to the abrasive nature of carbon fibers the tools wear rapidly, resulting in a decrease in the quality of the cut edge. The dissimilar mechanical properties of fiber and resin cause delamination, cracks, and fiber pull out when machining CFRP. When cutting CF textiles like non-crimp fabrics, woven fabrics, or 3D preforms, the industry often struggles with incomplete cuts. As a consequence manual reworking is required. Laser cutting has been known to be a reliable and cost efficient process for cutting metals. It is contact, force, and wear free, flexible in regard to the contour to be cut, and highly automatable [5][1]. However, laser cutting has not been widely used for CFRP and CF fabrics yet, partially due to an insufficient scientific understanding of the process. Mathematical models can help to better understand and improve the process. Existing analytical models for laser cutting of metals do not account for the anisotropic behavior of the fiber. In this study, an analytical model with anisotropic behavior is presented. This model predicts the maximum cutting speed and the width of the heat affected zone for laser cutting multi-layer carbon fiber fabrics and CFRP using a continuous wave (cw) laser.

2. Nomenclature and parameters

Table 1: Nomenclature and parameters

Parameter	Formula symbol	Unit	Value
Beam parameter product (86 %)	BPP	mm*mrad	3.53
Kerf width	b	m	-
Specific heat capacity	c	J/(kg K)	-
Specific isobar heat capacity of air [6]	$c_{p,Air}$	J/(kg K)	1007
Specific isobar heat capacity of carbon fibers [7]	$c_{p,Fiber}$	J/(kg K)	710
Specific isobar heat capacity of the textile	$c_{p,t}$	J/(kg K)	-
Focus diameter (measured at $1/e^2$)	d_f	µm	174
Heat affected zone	HAZ	mm	-
Latent heat of sublimation [8]	H_{Sub}	J/g	43000
Thermal conductivity	k	W/(mK)	-
Thermal conductivity perpendicular to the fiber direction	$k_{\perp}$	W/(mK)	-
Thermal conductivity parallel to the fiber direction	$k_{\parallel}$	W/(mK)	-
Thermal conductivity of air [6]	k_{Air}	W/(mK)	0.02569
Thermal conductivity of the fibers [7]	k_{Fiber}	W/(mK)	50
Thermal conductivity of the textile	k_t	W/(mK)	-
Thermal conductivity of the textile in x-direction	$k_{x,t}$	W/(mK)	-
Thermal conductivity of the textile in y-direction	$k_{y,t}$	W/(mK)	-
Absorbed laser power	P_{abs}	W	-
Power absorbed as heat conduction losses	P_{HC}	W	-
Laser power	P_L	W	-
Reflected laser power on the surface	$P_{ref,O}$	W	-
Reflected laser power in the kerf	$P_{ref,S}$	W	-
Power absorbed for sublimation	P_{Sub}	W	-
Radius	r	m	-

Parameter	Formula symbol	Unit	Value
Length of a line section	s	m	-
Temperature	T	K	-
Fiber sublimation temperature [9]	T_{Sub}	K	3923
Ambient temperature	T_{∞}	K	293
Time	t	s	-
Thickness of the textile	t_t	mm	-
Transformed cutting speed	u	m/s	-
Air volume	V_{Air}	m³	-
Fiber volume	V_{Fiber}	m³	-
Textile volume	V_t	m³	-
Cutting speed	v	m/s	-
Maximum cutting speed	v_{max}	m/s	-
Cartesian coordinates	x,y,z	-	-
Rayleigh length (86%)	z_R	mm	2.15
Cutting direction	α	°	-
Absorptance [10]	η_{abs}	-	0.95
Heat conduction coefficient	η_{HC}	-	0.365
Thermal diffusivity	κ	m²/s	-
Wavelength	λ	nm	1070
Density	ρ	kg/m³	-
Density of air [6]	ρ_{Air}	kg/m³	1.188
Density of carbon fiber [7]	ρ_{Fiber}	kg/m³	1750
Density of the textile	ρ_t	kg/m³	-
Fiber volume fraction	φ_{Fiber}	-	-
Fiber mass fraction	Ψ_{Fiber}	-	-
Transformed coordinates of x and y	ξ,ψ	-	-
Heat source	$\dot{\omega}$	W/m³	-

3. Background

Various mathematical approaches are commonly used to model the heat flow in solids. Moving line sources and point sources, which are both based on solutions of the Green's function, can be used to model heat conduction phenomena in laser material processing. Point sources are used for processes in which the laser radiation is absorbed on the surface, e.g. laser hardening; line sources are used for processes with an absorption in-plane, e.g. deep penetration welding or laser cutting. The heat conduction problem is assumed to be two dimensional and the heat flow in the axis of the laser radiation is neglected [11][12][13].

Pan & Hocheng developed a model for the laser grooving of fiber reinforced polymers. Due to the shallow cutting depth, a point source could be used to model the problem. The anisotropic behavior of the material was considered by special substitutions of the thermal conductivity and the heat capacity [7]. Goeke developed a model for laser cutting of fiber reinforced polymers based on a line source model. An average was used for the thermal conductivity in the x and the y axis of the cutting plane. Due to the quasi-isotropic composition of the analyzed material, the error was assumed to be negligible. Thus, temperature fields resulting from strongly anisotropic material properties cannot be predicted using this model [14]. MUCHA ET AL. presented a method to determine the heat conduction losses for laser cutting of CFRP, based on a 1D heat flow model and an empirical measurement of the temperature in the laminate [15]. No models have been developed so far for laser cutting of CFRP and CF-textiles with cw lasers, which properly account for the anisotropic behavior of the material.

4. Analytical model

The model will primarily be developed for cw laser cutting of multi-layer carbon fiber fabrics, but can also be applied to CFRP laminates. Heat conduction in carbon fiber is highly anisotropic, therefore the model has to account for this behavior. The line source will be modified with an expression representing the anisotropic behavior, and an energy balance will be used to determine the maximum cutting speed. The following assumptions and simplifications are made:

- Stationary state of the process
- Temperature-independent material parameters
- No heat conduction in the z-axis (2D heat conduction in the x-y plane)
- The material is a semi-infinite plate and $T=T_\infty$ for $x=\pm\infty$, $y=\pm\infty$, and $z=+\infty$
- No secondary heat source due to oxidation
- No power losses through the beam guidance, the beam shaping, or the plume
- No transmission through the material, and no power losses through the kerf
- Convection and radiation are neglected. By calculation they account for less than 0.05 % of the laser power.

Therefore, the laser power is either absorbed along the cutting front (Figure 1) or reflected.

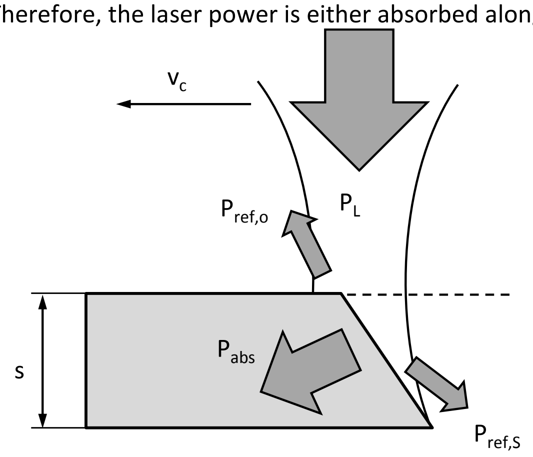

Figure 1: Cutting front and assumptions

The textile is modeled as a composite, consisting of fibers and air. Thus, most of the material's parameters are calculated using the volume or the mass fraction of the single constituents. The fiber volume fraction φ_{Fiber} can be modeled using equation 1, whereas V_{Fiber} and V_{Air} are the volume of the fibers and the air, respectively. V_t, the volume of the textile, is the sum of V_{Fiber} and V_{Air} [14].

$$\varphi_{Fiber} = \frac{V_{Fiber}}{V_t} = \frac{V_{Fiber}}{V_{Fiber} + V_{Air}} \quad (1)$$

The fiber mass fraction Ψ_{Fiber} can be calculated according to equation 2, using φ_{Fiber} and the density of air (ρ_{Air}) and fiber (ρ_{Fiber}) [14]:

$$\Psi_{Fiber} = \frac{1}{1 + \left(\frac{1}{\varphi_{Fiber}} - 1\right) \frac{\rho_{Air}}{\rho_{Fiber}}} \quad (2)$$

The density of the textile (equation 3) is determined by using the volume fraction of the fiber and the density of air and fiber [14]:

$$\rho_t = \varphi_{Fiber}\, \rho_{Fiber} + (1 - \varphi_{Fiber})\, \rho_{Air} \quad (3)$$

The specific isobar heat capacity of the textile can be calculated according to equation 4, using the fiber mass fraction and the heat capacity of the fibers ($c_{P,Fiber}$) and the air ($c_{P,Air}$) [14]:

$$c_{p,t} = \Psi_{Fiber}\, c_{p,Fiber} + (1 - \Psi_{Fiber})\, c_{p,Air} \quad (4)$$

The thermal conductivity (k) of the textile can be modeled analogous to electrical circuits. In the direction parallel to the fibers ($k_\parallel$), the assumption of a parallel connection is made (equation 5). Perpendicular to the direction of the fibers ($k_\perp$), the assumption of a series connection is made (equation 6) [7].

$$k_\parallel = \varphi_{Fiber}\, k_{Fiber} + (1 - \varphi_{Fiber})\, k_{Air} \quad (5)$$

$$k_\perp = \frac{k_{Fiber}\, k_{Air}}{\varphi_{Fiber}\, k_{Air} + (1-\varphi_{Fiber})\, k_{Air}} \quad (6)$$

To model cuts in random directions, the thermal conductivity of the composite has to be transformed to the Cartesian system as a function of the thermal conductivity parallel and perpendicular to the fibers. This is done using a trigonometric function as shown in equations 7 and 8, resulting in the thermal conductivity in the y-direction ($k_{y,t}$) and the x-direction ($k_{x,t}$),respectively [16]:

$$k_{y,t} = (\sin\alpha)^2\, k_\parallel + (\cos\alpha)^2\, k_\perp \quad (7)$$

$$k_{x,t} = (\cos\alpha)^2\, k_\parallel + (\sin\alpha)^2\, k_\perp \quad (8)$$

Heat conduction phenomena are commonly described as partial differential equations, such as the heat equation. The heat equation can be transformed into the coordinate system of the moving laser beam. Given the assumption of a continuous relative movement between the laser spot and the workpiece with a speed $\vec{v}$, the heat equation can be described as shown in equation 9, with κ being the thermal diffusivity (equation 10). A solution to equation 9 can be found by using Green's function for the heat source ω [13][17]:

$$\frac{\partial T}{\partial t} = \kappa\, \Delta T - \vec{v}\, \vec{\nabla} T + \frac{\omega}{\rho\, c} \quad (9)$$

$$\kappa = \frac{k}{\rho\, c} \quad (10)$$

With the model of the moving line source, the heat equation is applied to model laser processes. It is valid for processes like laser cutting and deep penetration welding, where the laser power is not absorbed on the surface, but idealized as a line along the thickness of the workpiece. A temperature gradient in the direction of the inclining laser beam is neglected and the temperature field in the plane of the workpiece (x- and y-direction) can be calculated according to equation 11. K_0 is the Bessel function, t the thickness of the workpiece, and r is the radius of the laser beam [13].

$$T(x,y) - T_\infty = \frac{P_L}{t\, \rho\, c} \frac{1}{2\, \pi\, k}\, K_0\left(\frac{|v|\, r}{2\, k}\right) \exp\left(\frac{v\, x}{2\, k}\right) \quad (11)$$

The model of the line source only accounts for isotropic heat conduction and is therefore not suitable for laser cutting of carbon fiber textiles. Thus, substitutions (12) are used in the derivation of the line source from the heat equation to add anisotropic terms [7][12]. The solution is shown in equation 13 and 14:

$$\xi = \sqrt{\frac{k_C}{k_{x,t}}}\, x;\ \psi = \sqrt{\frac{k_C}{k_{y,t}}}\, y;\ u = \sqrt{\frac{k_C}{k_{x,t}}}\, v;\ k_t = \sqrt{k_{x,t}}\, \sqrt{k_{y,t}} \quad (12)$$

$$T(\xi,\psi) = \frac{\eta_{HC}\, P_L}{\rho_t\, c_{p,t}\, t_t} \frac{1}{2\,\pi\, k_t}\, K_0\left(\frac{|v|\,\sqrt{\xi^2+\psi^2}}{2\, k_t}\right) \exp\left(\frac{u\,\xi}{2\, k_t}\right) + T_\infty \tag{13}$$

$$T(x,y) = \frac{\eta_{HC}\, P_L}{2\,\pi\, t_t\, k_t}\, K_0\left(\frac{\rho_t\, c_{p,t}\, |v| \sqrt{\frac{k_t}{k_{x,t}}} \sqrt{x^2\,\frac{k_t}{k_{x,t}} + y^2\,\frac{k_t}{k_{y,t}}}}{2\, k_t}\right) \exp\left(\frac{v\, x\, \frac{k_t}{k_{x,t}}\, \rho_t\, c_{p,t}}{2\, k_t}\right) + T_\infty \tag{14}$$

Finally, the equation of a moving line source, which accounts for the anisotropic behavior of the carbon fiber textiles, is found in equation 15. This equation can generally be applied to anisotropic heat conduction problems if the model of the moving line source is adequate; t_t is the thickness of the textile and η_{HC} is the heat conduction coefficient (fraction of the power, which is absorbed into heat conduction).

$$T(x,y) = \frac{\eta_{HC}\, P_L}{2\,\pi\, t_t\, \sqrt{k_{x,t}}\, \sqrt{k_{y,t}}}\, K_0\left(\frac{\rho_t\, c_{p,t}\, |v| \sqrt{\frac{x^2}{k_{x,t}} + \frac{y^2}{k_{y,t}}}}{2\,\sqrt{k_{x,t}}}\right) \exp\left(\frac{\rho_C\, c_{p,t}\, v\, x}{2\, k_{x,t}}\right) + T_\infty \tag{15}$$

The absorbed power P_{abs} can be described as the sum of the power for the sublimation of the material P_{Sub} and the power for heat conduction P_{HC} (equation 16), or as the product of the laser power and the absorptance η_{abs} (equation 16):

$$P_{abs} = P_{Sub} + P_{HC} \tag{16}$$

$$P_{abs} = \eta_{abs}\, P_L \tag{17}$$

The power required for the sublimation of the material can be calculated using equation 18 [13]:

$$P_{Sub} = \varphi_{Fiber}\, b\, t_t\, v\, \rho_{Fiber}\, H_{Sub} \tag{18}$$

When equation 18 is inserted into equation 16 and 17, the maximum cutting speed can be calculated according to equation 19:

$$v = \frac{\eta_{abs}\, P_L - P_{HC}}{\varphi_{Fiber}\, b\, t_t\, \rho_{Fiber}\, H_{Sub}} \tag{19}$$

with

$$P_{HC} = \eta_{HC}\, P_L \tag{20}$$

5. Experimental validation

The results of the analytical model, given in equation 15 for the temperature field and in equation 19 for the cutting speed, were validated via experimentation. A 8 kW multi-mode fiber laser (wavelength 1070 nm) with a fixed optics was used. The process was performed without shielding gas. Unidirectional carbon fiber textiles with varying numbers of layers were used. For the model, the width of the kerf was assumed to be identical to the diameter of the laser beam. A central composite design (CCD) was used to plan the experiments to validate the temperature field calculations. The thickness of the textile, laser power, cutting direction in regard to the fiber direction, and relative cutting speed (ratio between cutting speed and maximum cutting speed) were varied. When altering the laser power, the cutting speed was changed accordingly in order to keep the line energy constant. The heat affected zone was measured and correlated to a specific temperature. The factor η_{HC} was calibrated to a value of 0,365. By doing so, a good agreement between experiment and model in the center of the CCD was found. The material parameters taken from the literature, as well as the parameters used for the experiments can be found in table 1. The results of the validation are shown in Figure 2. While there are differences between the values predicted by the model and those of the experiment, the model accurately predicts the behavior of the experiments. The anisotropic behavior of the material is considered accurately, as it is being shown by the results for the cutting direction.

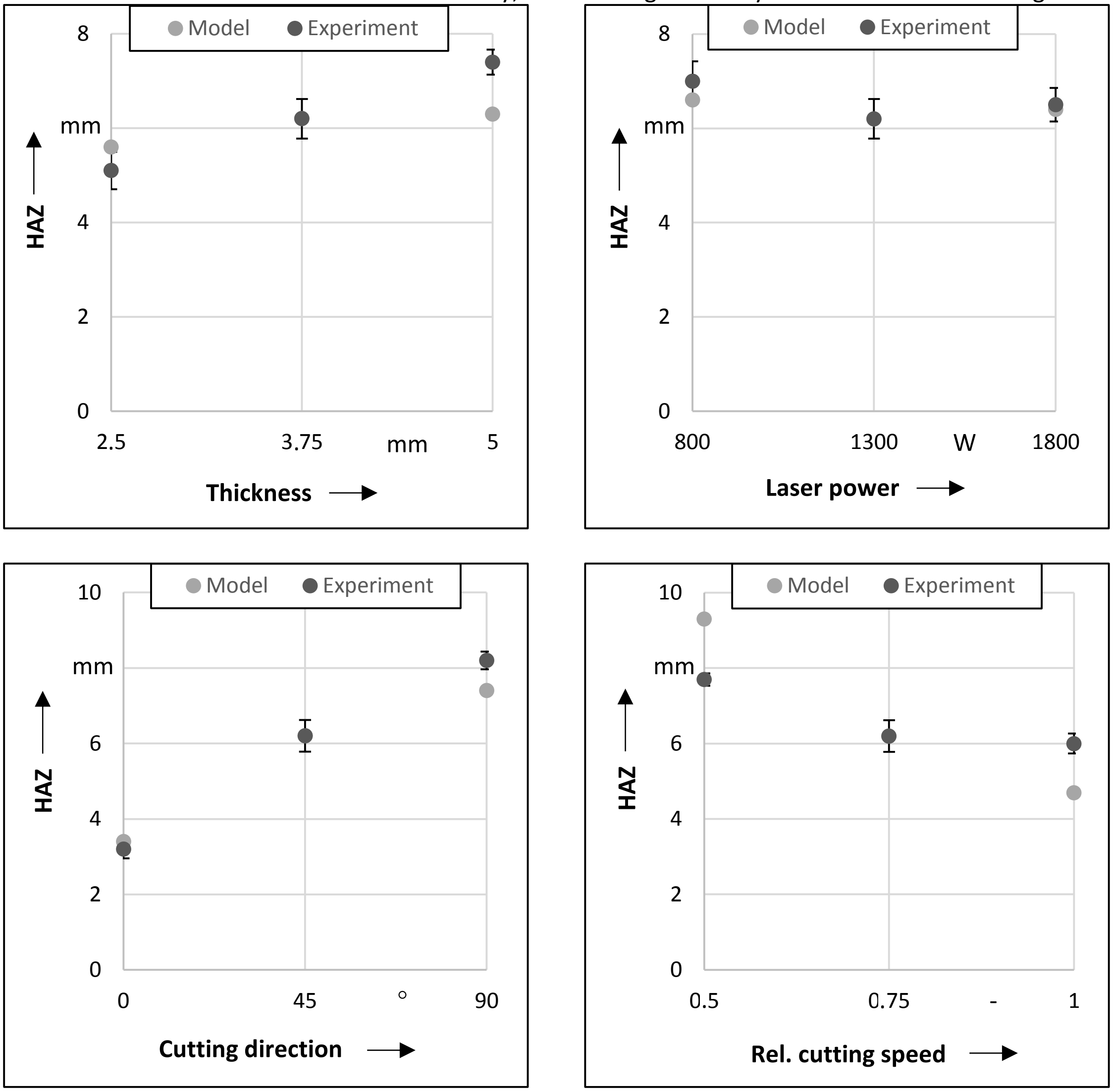

Figure 2: Validation of the model for the temperature field. Variation of the textile thickness (left top), the laser power (right top), the cutting direction (left bottom), and the relative cutting speed (right bottom)

In order to validate the model at the maximum cutting speed, experiments with the central point of the CCD and varying cutting directions with regard to the fiber orientation were performed. As shown in Figure 3, the cutting speed decreases when the cutting angle is increased in the model. Even though this behavior is similar to the experiment, the model depicts the anisotropic behavior significantly too low.

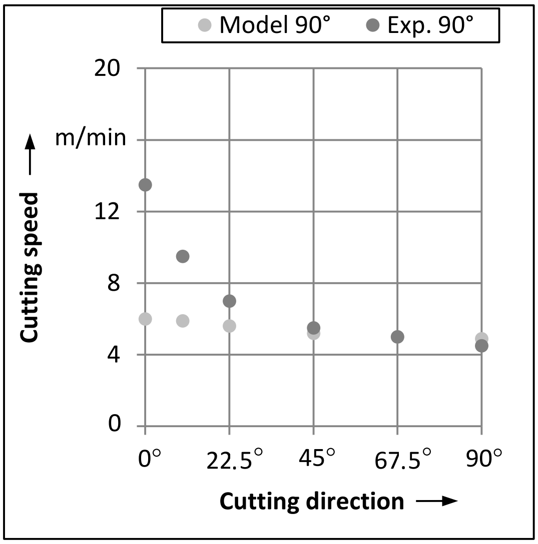

Figure 3: Validation of the model for the maximum cutting speed. Cutting direction vs. cutting speed

6. Conclusions and outlook

An analytical model was presented to predict the temperature field and maximum cutting speed for the laser cutting of carbon fiber textiles. The moving line source model was modified to account for the anisotropic behavior of the material and to model the temperature field. To predict the maximum cutting speed, an energy balance was developed and used. An experimental validation of the model with unidirectional multi-layered carbon fiber textiles was performed. The behavior of the process in regard to the temperature field could be predicted fairly well, as long as the coefficient of heat conduction was calibrated by the experiments. The maximum cutting speed was not predicted equally well by the model.

By accounting for the anisotropic behavior in the model, a major step towards modeling the laser cutting of carbon fiber textiles, CFRP, and other anisotropic materials was made. Nevertheless, the model needs to be developed further. Currently, calibration of the model is required to determine the portion of the laser power which is transformed into heat conduction. This calibration could be overcome and more universal results could be achieved, if the power for heat conduction would be extracted from the temperature fields. The geometry of the kerf is currently assumed to be uniform, resulting in a high volume of the sublimated material and therefore in a high sublimation power. A more realistic contour of the kerf has to be implemented into the model.

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