Analysis of the remote laser cutting process induced damage in carbon fibre reinforced polymers

Benjamin Schmidt1,∗, Markus Husert1, Michael Rose2, Martina Zimmermann2, and Markus Kästner1,3

1 Institute of Solid Mechanics, TU Dresden, Dresden Germany
2 Institute of Materials Science, TU Dresden, Dresden Germany
3 Dresden Center for Computational Materials Science (DCMS), TU Dresden, Dresden Germany

In this contribution a modelling approach for the laser cutting process simulation of carbon fibre reinforced polymers is introduced. The cutting process is modelled in a 3D thermal simulation, the material is modelled layer-wise orthotropically. For the evaporation of matrix and fibre phase transitions are utilised. The laser spot is modelled with its gaussian distribution as a heat input on the upper side.

1 Introduction

Due to their high specific strength and stiffness, combined with an excellent material damping, Carbon Fibre Reinforced Polymers (CFRP) have been established in many lightweight construction areas. Nevertheless, the high fibre strength leads to increased tool wear and frayed cutting edges during mechanical processing.

Here remote laser cutting is a fast and tool-wear free alternative, but the heat input in the material causes a Heat Affected Zone (HAZ) [1], which also influences the mechanical parameters of the material [2]. The aim of this contribution is the analysis of the cutting process with a process simulation. Since the cutting process parameters are direct inputs to the simulation, this allows for the analysis of different configurations without expensive experiments.

2 Laser cutting of CFRP

Material characterisation. The laminates of the composite material were pressed from Sigrapreg C U150-0/NF-E340/38% prepegs. The fibre type is Torayca T700 and the matrix is an E340 epoxy. In this analysis plates with a [0/90]6s stacking sequence and a thickness of 1.9 mm are used. A fibre volume content of \( V_f = 0.54 \) was measured.

| Parameter          | Unit | Matrix | Fibre | CO2  |
|--------------------|------|--------|-------|------|
| Thermal conductivity \( \lambda \) | W/(m K)\(^{-1} \) | 0.21   | \( \lambda || = 26.64 \) | 0.0774 |
| Heat capacity \( c \) | J/(kg K)\(^{-1} \) | 940    | 711   | 1277 |
| Density \( \rho \) | kg m\(^{-3} \) | 1200   | 1800  | 0.9  |

Table 1: Material parameters for thermal process simulation.

Process description. In remote laser cutting, the laser spot is deflected by two tilt-able mirrors. This allows for a high spot velocity, which minimises the interaction time with the laser and thus reduces the HAZ. The laser source is a fibre laser with a wave length of 1070 nm, a laser power \( P_l = 4650 \) W and a focal diameter (86 %) \( d_f = 36 \) \( \mu m \). In the analysed configuration a spot velocity of \( v = 1 \) m s\(^{-1} \), 1 s rest time between the different cutting cycles and four cycles for the complete cutting gap were used.

3 Process modelling approach

A thermal simulation with the domain given in Figure 1a is used for the modelling of the laser cutting process. The hollow cylinder is discretised with 48 elements in radial, 48 elements in peripheral and 24 elements in thickness direction. For the simulation a user element in the simulation software FEAP is used. The material is modelled on a macroscopic level orthotropically with parameters given in Table 1. The effective material parameters are calculated from rules of mixtures, Springer [3] in longitudinal direction and Chamis [4] in transverse direction. The laser spot is modelled as a heat input on the element surfaces assuming gaussian intensity distribution. Evaporation of matrix and fibre are modelled with phase transitions, analogously to an approach introduced by Canisius [5]. The phase variables start at \( p = 0 \) for intact material and end at \( p = 1 \) for complete evaporation.

∗ Corresponding author: e-mail Benjamin.Schmidt@tu-dresden.de
For the matrix evaporation a rate dependent Arrhenius approach
\[ \dot{p}_{\text{mat}} = (1 - p_{\text{mat}}) \cdot a \cdot e^{bT} \]
is used, the parameters \( a = 1.7110^{-7} \) and \( b = 0.021 \) were identified in a thermogravimetric analysis. For the fibre sublimation an alternative approach is used. Here, after reaching the sublimation temperature \( T = T_{\text{fib}} \), the temperature can not rise further, but the additional energy is absorbed until the sublimation enthalpy is reached, see Figure 1b.

After phase transitions, CO\(_2\) is assumed to occur as hot process gas, thus the associated constituents in the rules of mixture are replaced by parameters for CO\(_2\).

The process gas is also assumed to absorb a part of the laser power, thus, according to the Beer-Lambert law, the applied heat flux
\[ q = q_0 \cdot e^{-\Delta z \cdot V_{\text{rel}} \cdot \varepsilon'} \]
is reduced from the initial heat flux \( q_0 \), depending on the cutting depth \( \Delta z \), the ratio of gas and solid volume \( V_{\text{rel}} \) and the adsorption coefficient of CO\(_2\) \( \varepsilon' \).

Figure 1c shows a cross section of the cutting gap after the process with visible matrix evaporation zone and gap.

![Simulation Domain](a) Simulation domain of the laser cutting process simulation with the cutting contour (red).  
![Temperature and Phase Variable](b) Temperature and phase variable for a constant energy input during the fibre sublimation.  
![Cross Section](c) Cross section after the cutting process, with intact material, complete matrix evaporation and complete fibre and matrix evaporation.

**Fig 1:** Visualisations of the simulation domain, fibre evaporation and the cutting gap.

## 4 Conclusion and outlook

In this contribution a modelling approach for the laser cutting process of CFRP is presented. The implementation in FEAP allows for high parallelisation and thus the simulation of detailed structures. A validation of the results is possible with the comparison of the cutting gaps with micro-sections, where the gap and HAZ are visible.

The aim of this cutting process analysis is the identification of its influence on the structural properties. For this purpose a further goal is the mapping of the process simulation results on the mechanical models [2] for a closed process-structure-property linkage.

**Acknowledgements** This work was supported by the Deutsche Forschungsgemeinschaft (DFG, KA 3309/6-1 and ZI 1006/12-1). The authors gratefully acknowledge the support.

The authors are grateful to the Centre for Information Services and High Performance Computing (Zentrum für Informationsdienste und Hochleistungsrechnen (ZIH)) TU Dresden for providing its facilities for high throughput calculations.

Open access funding enabled and organized by Projekt DEAL.

**References**

[1] M. Rose, S. Niverty, B. Schmidt, M. Kästner, M. Zimmermann, and N. Chawla, Engineering Fracture Mechanics p. 107820 (2021).
[2] B. Schmidt, M. Rose, M. Zimmermann, and M. Kästner, Journal of Materials Processing Technology 295, 117162 (2021).
[3] G. S. Springer and S. W. Tsai, Journal of Composite Materials 1(2), 166–173 (1967).
[4] C. C. Chamis, Simplified composite micromechanics equations for hygral, thermal and mechanical properties, in: 38th Ann. Conf. of the Society of the Plastics Industry (SPI) Reinforced Plastics/Composites Inst., 7-11 Feb. 1983, (NASA, Houston, Texas, 1983), pp. 1–12.
[5] M. Canisius, Prozessgüte für das Laserstrahltrennen kohlenstofffaserverstärkter Kunststoffe (Springer, 2018), ISBN: 9783662562086.