INFLUENCE OF LASER CUTTING ON HANDLING, DRAPE AND INFUSION CHARACTERISTICS OF PREFORMS

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Summary: Mass production of CFRP parts has lately become reality in the automotive industry, and 5-digit production volumes are feasible in state-of-the-art production technology. However, further automation and a reduction in production steps are needed to be able to compete with other lightweight solutions. Today, higher-volume production processes for CFRP consist of a number of steps, typically including a preform manufacture, followed by a trimming operation on the preform, infusion of the matrix, and a final trimming operation performed on the cured laminate.

In this paper, the influence of the laser cutting process and its key parameters on the handling, drape and infusion characteristics is discussed. Depending on the process parameters, the fibres of single layers were predominantly attaching to each other, but inter-layer connections were rare, which may be favourable for the following handling steps. A simplified drape test has been performed, measuring the forces needed to push a stamp into a circular laser cut specimen. It was observed that the connection between the fibres does only affect the forces to a minimal extent. Laser cut specimens have then been infused in vacuum infusion as well as in RTM with no observable limitation. The process had been transferred from simple 2D specimens to 3D-preforms used in the manufacture of a door for a mobile home. In conclusion, laser cutting of uncured fibres has been found an alternative to conventional cutting methods, allowing for high process speeds, maximum flexibility and an easier handling of the cut material, while still fulfilling drape and infusion requirements.

1 INTRODUCTION

With lightweight solution becoming the centre of interest for more and more applications, CFRP part production volumes and batch sizes are increasing within the last years. However, with today’s part production processes, production time and cost requirements can often not be met. Therefore, automated processes are in the focus of research and development.

To ease handling of the textile and precursor materials, preforms can be manufactured by
use of a binder material and pressing 2D textile layers in a 3D form. Alternatively, these preforms maybe manufactured by sewing or weaving. These preforms keep the basic 3D shape and allow for automated handling e.g. by robots. Figure 1 provides an overview over the production of preforms from initial carbon fibres, and their further use in the RTM and vacuum infusion route to manufacture complex 3D CFRP parts [1].

![Process chain of preforming route for CFRP part production.](image)

The preforming route still involves a fairly large number of processing steps, of which cutting and trimming operations are an essential part. Whereas the cutting process on the textiles is a highly abrasive but otherwise rather simple 2D cutting process, cutting of the preforms in order to make them fit into the RTM or vacuum infusion tools is a complex 3D operation, and can barely be done by mechanical or ultrasound cutting [2, 3].

Laser cutting of textiles and preforms is an interesting, wear- and force-free alternative. Furthermore, laser cutting offers the advantage of a near-net-shape cutting process, which has the potential for avoiding the need for a final trimming operation on the cured part. Therefore, several research groups have investigated the laser cutting of carbon fibre textiles and preforms lately, using pulsed as well as continuous wave (cw) laser systems.

The use of solid state lasers at a wavelength of 1030 – 1070 nm proved to yield better cutting qualities than e.g. CO2 lasers emitting at 10600 nm due to increased absorption [4-6]. From literature, two effects of the laser-material-interaction are well known: Firstly, fibre swelling, i.e. the thickening of the fibres at the cutting kerf and their partial fusing in this area [7], and secondly, fibre bulging caused by the interaction between laser beam and material [8]. However, only few literature exists on the topic of the influence of the laser cutting process on the further process chain [9, 10].

Figure 1 also gives an indication on the processes that follow after the potential laser cutting operation on the textiles and preforms. Directly after laser cutting, the preforms need to be positioned in the RTM or vacuum infusion tool, thus the robust handling of the preforms is of interest, as well as the possibility to drape them into the tools. In addition, the injection or infusion process might be influenced by the cut quality. Thus, the influence of
laser cutting on the handling, drape and infusion characteristics of non-crimp fabrics and preforms is investigated within this paper.

2 MATERIAL AND EXPERIMENTAL SET-UP

For the investigations, a textile material typical for applications in the automotive industry was selected. The textile materials used are described in detail in table 1.

<table>
<thead>
<tr>
<th>fibre type</th>
<th>carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>filaments per roving</td>
<td>24k</td>
</tr>
<tr>
<td>yarn count</td>
<td>1,650 g/km</td>
</tr>
<tr>
<td>areal weight</td>
<td>317 g/m², 0°, 90°</td>
</tr>
<tr>
<td>areal weight</td>
<td>319 g/m², 45°, -45°</td>
</tr>
<tr>
<td>fabric type</td>
<td>non-crimp fabric</td>
</tr>
<tr>
<td>sewing thread</td>
<td>polyamide</td>
</tr>
</tbody>
</table>

Table 1: Specifications of the textiles.

The preforms consist of 6 layers from the textile materials defined in table 1, also in a set-up typical for automotive applications. After infusion, the laminates manufactured from the preforms have a thickness of 1.3 to 1.5 mm, which is the desired thickness for the application in the final demonstrator, a door of a mobile home. 2D preform specimens have been manufactured for the investigations, as well as 3D preforms of the door of a mobile home to transfer the results to an industrial application. The preform set-up is defined in table 2.

<table>
<thead>
<tr>
<th>Textiles</th>
<th>as defined in table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of layers</td>
<td>6</td>
</tr>
<tr>
<td>orientation of layers</td>
<td>0°/90°/+45°/-45°/90°/0°</td>
</tr>
<tr>
<td>Binder</td>
<td>epoxy resin powder</td>
</tr>
<tr>
<td>Thickness</td>
<td>2.47 mm</td>
</tr>
<tr>
<td>(thickness after infusion)</td>
<td>1.3 – 1.5 mm</td>
</tr>
</tbody>
</table>

Table 2: Specifications of the preforms.

Regarding the experimental set-up, a disk laser is used and the laser beam is directed through a 2D scanner system in order to allow for high cutting speeds. The characteristics of the laser and scanner system are given in table 3.

<table>
<thead>
<tr>
<th>laser system manufacturer</th>
<th>TRUMPF GmbH + Co. KG, Ditzingen, Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>central emission wavelength</td>
<td>1030 nm</td>
</tr>
<tr>
<td>maximum output power</td>
<td>6 kW</td>
</tr>
<tr>
<td>beam parameter product</td>
<td>4 mm mrad</td>
</tr>
<tr>
<td>process fiber core diameter</td>
<td>100 µm</td>
</tr>
<tr>
<td>scanner system manufacturer</td>
<td>TRUMPF GmbH + Co. KG, Ditzingen, Germany</td>
</tr>
<tr>
<td>maximum speed</td>
<td>10 m/s</td>
</tr>
<tr>
<td>focal length</td>
<td>255 mm</td>
</tr>
<tr>
<td>resulting spot diameter @ 1 kW</td>
<td>172 µm</td>
</tr>
<tr>
<td>rayleigh length @ 1 kW</td>
<td>1.9 mm</td>
</tr>
<tr>
<td>resulting spot diameter @ 6 kW</td>
<td>195 µm</td>
</tr>
<tr>
<td>rayleigh length @ 6 kW</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>working area</td>
<td>elliptical, 104 mm x 180 mm</td>
</tr>
</tbody>
</table>

Table 3: Specifications of laser and scanner system.
For positioning of the textiles and 2D preform specimens, a 2D clamping device is used which holds the specimens by low-pressure generated from a laval nozzle in order to keep a high constant flow rate. In order to take care of emissions, an extraction system was designed fitting to the elliptical working area and is attached to the scan head. For the demonstrator part, a clamping device was constructed by company Bergmann & Steffen, Spenge, that can hold the mobile home door preforms as well as the cured laminate. Figure 2 gives an overview of the 2D set-up (for planar specimens) and the 3D set-up (for the mobile home door) used for the investigations.

![Image](image_url)

**Figure 2:** 2D set-up (left) and 3D set-up (right).

### 3 RESULTS

In first investigations, the influence of key laser parameters on the cut quality was determined, and the process was optimized for maximum efficiency. Afterwards, cut specimens were applied to the following steps of the process chain: handling, draping and infusion.

#### 3.1 Efficiency and cut quality in dependence of key laser parameters

Laser power was varied between $P_L = 0.5 \text{ kW}$ and $6 \text{ kW}$. For each value of laser power, the cutting speed was initially set to a low value and then increased in steps of $\Delta v_s = 0.1 \text{ m/s}$, if there was still a full cut through the material. This was then iterated, in order to identify the maximum speed $v_{s,max}$ for which a full cut of the material was still observed. Then, the energy per unit length $E_s$ was calculated from

$$E_s = \frac{P_L}{v_{s,max}}$$

which is a measure for the efficiency of the process. The energy per unit length in dependence of the laser power is shown in figure 3.
Figure 3: Energy per unit length in dependence of laser power for the non-crimp fabric consisting of two layers (left) and six layers as well as of the preform manufactured from six layers (right).

In addition to the experiments, the theoretical energy per unit length \( E_{s,th} \) needed for evaporation of the carbon fibres in the cut zone was calculated. According to literature, the energy for sublimation of carbon fibres is \( E_{\text{sub,fibre}} = 85 \) J/mm\(^3\) [11]. With the focal spot diameter \( d_{\text{spot}} \) (as a function of laser power, comp. table 3), the aerial weight of the non-crimp fabric \( m_{\text{fabric}} \) (comp. table 1) and the density of the carbon fibres of \( \rho_{\text{fibre}} = 1.85 \) g/cm\(^3\) [12], the theoretical energy needed for evaporation of the carbon fibres during the process can be calculated as:

\[
E_{s,\text{th}}(P_L) * 1 \text{ m} = E_{\text{sub,fibre}} * d_{\text{spot}}(P_L) * 1 \text{ m} * m_{\text{fabric}} / \rho_{\text{fibre}}
\]

Due to losses e.g. from heat conduction and shielding by emissions, it can be expected that the actual energy input needed for the cutting process is higher than the theoretical value calculated from solely looking at the evaporation energy. This can be confirmed by the experiments except for cutting in 0°/90° direction at lower laser power below \( P_L < 1.5 \) kW. Also, cutting in 0°/90° orientation needs considerably less energy than cutting in 45°/−45° orientation. This can be explained, as in case of e.g. a cut direction of 0°, only the fibres perpendicular to the cut direction and the sewing thread need to be evaporated, whereas the fibres parallel to the cut direction are already separated. In case of a cut direction of 45°, both layers from the non-crimp-fabric need to be evaporated in order to fully cut through the material.

When cutting six layers of non-crimp fabric (figure 3, right), approximately three times the amount of energy for cutting two layers (figure 3, left) of the same material is needed. If preforms are used, the evaporation of the binder needs additional energy input.

For all materials and orientations investigated, the process loses efficiency towards higher laser power, or higher process speed, respectively. To identify the reason for this behaviour, the cut specimens were studied in detail, using light microscopy. Bulging of fibres was identified. In order to quantify this behaviour, the ratio between the thickness of the cut edge (thickness after cut, \( t_{\text{ac}} \)) and the original thickness (thickness before cut, \( t_{\text{bc}} \)) of the fabric have been calculated from the images. The results are presented in figure 4.
Figure 4: Cut quality depending on laser power, measured by the thickness after and before the cut as a measure of bulging behaviour.

It can be derived from figure 4, that the ratio of thickness increases with the laser power both for the non-cramp fabric as well as for the preform. Obviously, process forces from the evaporation are increasing with higher speed, which in the first instance results in the bulging behaviour, which in turn leads to fibres bulging further away from the focal plane, and finally results in a loss of process efficiency.

In comparison with a conventional cutting process with a hand cutter, six layers of non-cramp fabric of the given orientation may be cut with a laser power of up to $P_L = 2$ kW (or a feed rate of $v_{s,\text{max}} \approx 0.2$ m/s), and the preform manufactured from the same layers of non-cramp fabric may be cut with a laser power of up to $P_L = 3$ KW (or a feed rate of $v_{s,\text{max}} \approx 0.3$ m/s), keeping bulging of fibres below typical values achieved with conventional processes.

3.2 Influence of laser cutting on handling characteristics

Handling of cut-out textile parts can be difficult, due to insufficient stiffness of the material and non-existent cohesion of the fibres at the cut edge. This may cause unwanted unravelling of fibres or other types of loss of form. However, during laser cutting of CFRP, residues of evaporated material condense on the fibres and form a deposit, holding fibres together [13], thus easing the handling process to some extent. The dependence of this deposit-formation on the laser power is shown in figure 5. For quantification of this effect, the total length of cohesion was calculated, as described in figure 5, left.
It can be concluded, that the cohesion along the cut surface is decreasing with laser power. As shown in section 3.1, increased laser power leads to an increase in bulging. Therefore, the assumption is that the deposit formed on the bulging fibres cannot form homogenous areas, but rather condenses on single fibres. If cohesion of fibres at the cut edge is wanted in order to ease the handling process, laser cutting at lower laser power of up to $P_L = 3.5$ kW is found to be advantageous.

### 3.3 Influence of laser cutting on drape characteristics

For the manufacture of 3D CFRP parts, the cut fabrics need to be placed into the form tool, e.g. the RTM mould. A 2D cut-out fabric is therefore draped into the form. In order to investigate the influence of laser cutting on the draping behaviour of the material, a drape test was performed, in a simplified version to the approach suggested by Christ et al. [14]. The set-up consists of a piston which is draping a specimen into a hole by moving downwards as a result of a defined spring force of approx. 5 N, as shown in figure 6, left and middle.

![Diagram of drape test set-up and results](image)

Figure 6: Schematic (left) and actual set-up (middle) for drape test; and drape depth in dependence of laser power (right).
The main concern regarding the influence of laser cutting on the drapability is that the partial cohesion of fibres might interfere with the necessary movement of fibres when draped. Therefore, simply the resulting drape depth was monitored and the results are given in figure 6, right. No negative influence of the laser cut on the drapability was observed. Actually, even though cohesion of fibres was found to be more pronounced at lower laser powers, there seems to be no influence on the drape depth at all.

3.4 Influence of laser cutting on vacuum infusion process

For the vacuum infusion route, the infiltration of the textile with the matrix system follows the placement of the material in the form. Here again, the concern regarding the applicability of laser cutting is that the cohesion of the fibres might interfere with the infusion of the matrix. Therefore, specimen cut with different laser power have been infused. The resulting infused parts have been investigated in the area of the former laser cut by light microscopy. Figure 7 shows two exemplary specimens, as well as the misalignment resulting from vacuum forces and burr, if present.

All specimens could be infused without problems. Values for the burr are scattering between -0.3 and +0.3 mm, irrespective of the material. The misalignment from the vacuum forces however is more prominent for the non-crimp fabric. Infused preform specimens show comparatively low values for misalignment.

3.5 Influence of laser cutting on RTM injection process

Same as for the vacuum infusion process, the main concern for applying laser cut fabrics to the RTM process is that the cohesion of the fibres might interfere with the resin injection. Planar specimens of the preform were cut by laser, and then infused with epoxy resin in an RTM tool. The result is a uniform CFRP plate, shown in figure 8. No problems were observed during the infusion process.
3.6 2D and 3D cutting of preforms

A major advantage of laser cutting is the process’ flexibility and ability to cut complex 3D structures. Therefore, the process has been applied to 2D, as well as 3D preforms to show its industrial potential, figure 9.

The 3D mobile home door was cut by the scanner adapted to a robot, compare set-up shown in figure 3. With this set-up, it is possible to cut parts of up to approx. 2 m x 1 m.

4 CONCLUSIONS

Laser cutting has been investigated as an alternative method for the cutting of uncured textiles and preforms. The laser power has been varied, and the maximum cutting speed for each value of laser power has been identified. Maximum speed to cut a two-layer non-crimp fabric in 0°/90° orientation was around 1 m/s, for six layers of non-crimp fabric in 0°/90°/45°/-45°/90°/0° orientation and a preform manufactured of it was around 0.5 m/s. However, for all materials it was observed that the efficiency is decreasing with increasing laser power, due to an increase in fibre bulging and fibres diverging from the focal plane.

A pronounced cohesion of fibres due to the formation of a deposit on the cut edge was observed for specimens cut with laser power below 3.5 kW, easing the handling of parts. This effect is also decreasing with increasing laser power, probably due to the bulging behaviour. Regarding the drapability, no effect on the drape depth from the laser cutting process was observed in a simplified drape test. For the vacuum infusion as well as RTM of laser cut specimens, no limitations have been found. Especially when preforms are used, the cured
parts only show minor deviations from the target geometry, showing a potential for near net-shape manufacturing. The preform cutting process was successfully transferred from 2D specimens to a complex, full-scale 3D demonstrator.

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