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Laser cutting of carbon fiber fabrics

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Abstract

Due to their high weight-specific mechanical stiffness and strength, parts made from carbon fiber reinforced polymers (CFRP) are increasingly used as structural components in the aircraft and automotive industry. However, the cutting of preforms, as with most automated manufacturing processes for CFRP components, has not yet been fully optimized. This paper discusses laser cutting, an alternative method to the mechanical cutting of preforms. Experiments with remote laser cutting and gas assisted laser cutting were carried out in order to identify achievable machining speeds. The advantages of the two different processes as well as their fitness for use in mass production are discussed.

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Keywords: Laser Cutting; Carbon Fiber; CFRP; Preform; Non-Crimp Fabric; RTM

1. Introduction

Due to legislative requirements, increasing customer demand for eco-friendly products, and the limited availability of fossil fuels, alternative drive concepts for passenger cars are needed. In the future, electrified vehicles are expected to play an important role in clean and energy efficient individual transportation. Additionally, the goal of the European Commission to lower the CO_2 fleet average to 95 g/km by 2020 will require car manufacturers to increase the development and production of electrified vehicles [1, 2]. The downsides of electrifying vehicles are the increase in weight and the limited range due to the battery. Therefore, it is advantageous to use carbon fiber reinforced polymers (CFRP) to reduce the overall weight of the car body. As a rule of thumb, using components made from CFRP can save up to 30 % of the weight

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compared to aluminum and up to 70 % compared to steel [3]. By reducing the weight of the vehicle body, fewer battery cells need to be used for the same distance. Since the battery significantly increases the price of electrified vehicles, this step is worthwhile for both manufacturers and customers. Reducing the overall weight also allows other system components like brakes and bumpers to be downsized, and therefore additional cost and weight can be saved. In the automotive industry CFRP is currently used for niche markets and luxury products. To date, high energy and production costs as well as the high price of carbon fiber have discouraged mass market roll-out. According to SUZUKI AND TAKAHASHI [4], both the energy used to produce CFRP body parts and the energy costs can be reduced to that of steel parts, if the "3 Rs" (reduce, reuse, recycle) are effectively applied to the process chain. By the use of the Resin Transfer Molding (RTM) process, CFRP production can be automated and the components can be mass produced with short cycle times. For example, BMW is using the RTM process for their project "BMW i", to realize the first mass-produced electrified vehicle with a CFRP passenger compartment on the market; see as an example "Life-Module" (Figure 1).

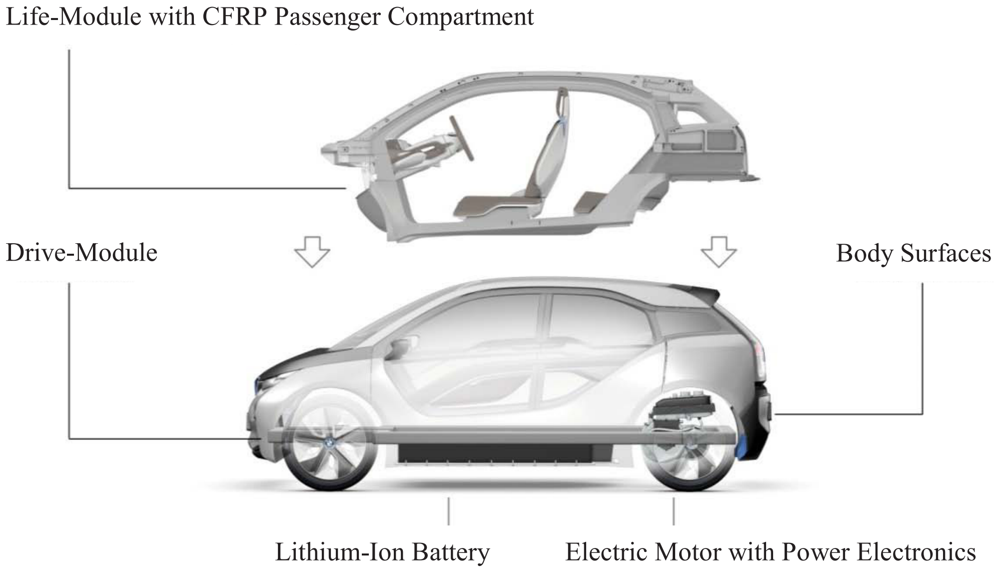


Fig. 1. BMW i3, CFRP passenger compartment (courtesy of BMW Group)

Figure 2 shows a sequence of the RTM process chain, using binder technology for non-crimp fabrics. Dry carbon fiber filaments are processed into non-crimp fabrics with unidirectionally aligned fibers. These fabrics are stacked on top of each other (step 1), resulting in a multidirectional alignment of the fiber layers (step 2). The stack is then cut to the desired shape. A thermoplastic binder that was applied to the fabric earlier is plasticized by heating the stack. Next, the stack is pressed into the three dimensional shape of the component using a process called preforming (step 3). As the binding agent cools and solidifies, cohesion between the fibers is generated. Then, the 3D textile preform has to be trimmed (step 4) [5, 6]. In an automated production line this is usually done by mechanical knife cutting (wedge effect), ultrasonic knife cutting, die cutting, or abrasive water jet cutting [3]. Next, the trimmed preform is transferred to an RTM press, where the resin is injected and the component is cured (step 5). By using a highly reactive resin the cycle time of the RTM process can be reduced significantly in order to meet the requirements for mass production [6]. After the infiltration and the consolidation of the part, the final outer contour is cut. This is usually done by milling or abrasive water jet cutting.

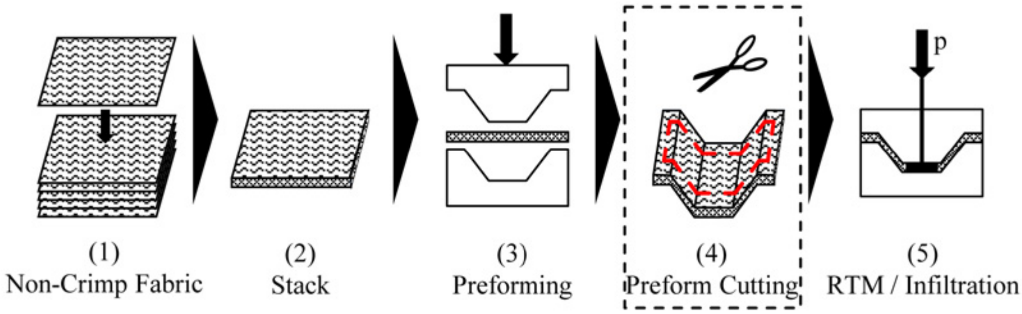


Fig. 2. Process chain for the manufacturing of CFRP components by the RTM Process (based on [6])

2. Cutting of Carbon Fiber Textiles

In summary, three cutting steps are needed within the process chain: the cutting of stacked non-crimp fabrics (2D), the cutting of preforms (3D), and the cutting of consolidated components (3D). Mechanical cutting processes are currently employed at all of these steps. In the following, the cutting of textiles and preforms will be looked at in detail. A major disadvantage of the mechanical cutting of textiles is the physical contact between the cutting tool and the fiber material. Due to the applied cutting force, the fibers are bent and displaced resulting in an unwanted change in the structural properties near the cut edge. Additionally, the abrasive nature of the carbon fiber causes wear, and thus the cutting tool must be frequently exchanged, resulting in an increase in cycle time and tooling cost. Furthermore, the quality of the cut decreases throughout the life of the tool. The cutting of textiles with mechanical processes, like ultrasonic knife cutting, lacks accuracy and process speed especially when cutting complex 3D contours. Extensive clamping fixtures are needed to keep the preform in place during cutting because of the applied force. These factors result in high costs and long cycle times. An alternative process to cut carbon fiber textiles is laser cutting. Laser cutting is a widely used method for cutting both metals and non-metals. According to STEEN [7] laser cutting has various advantages. Since it is contact free, no extensive clamping devices are required and no tool wear is generated. The process is flexible with regard to the component contour and cutting direction. It is highly automatable and offline path planning is commercially available. An additional advantage of laser cutting of carbon fiber textiles is that the edge is thermally fused, which prevents the fibers from being pulled out during handling [3]. The disadvantages of laser cutting of carbon fiber textiles are that there is a heat-affected zone (HAZ) and that emissions are generated. Usually a finish, the so-called avivage, specifically matched for the resin, is applied onto the fibers to improve the adhesion between fiber and resin and to protect the fibers during the manufacturing and handling processes [5]. By evaporation of the avivage in the HAZ the adhesive strength is decreased [8]. The aerosols generated during laser cutting of the carbon fiber are a potential health hazard. Especially for mass-production, effective workplace controls, such as fume and dust collection and filtration, have to be installed to protect the workers and the environment [9, 10].

During laser cutting, the laser beam heats the fibers until they sublimate at approximately 4000 K [15]. Since carbon has no liquid phase at atmospheric pressure, no molten material is generated (Figure 3). Continuous wave (cw) and pulsed mode laser sources can be used for laser cutting. For mass production cw-laser radiation is more appropriate, due to its higher effective cutting speed, even though it usually generates a larger HAZ than pulsed mode laser radiation. The most commonly used laser sources for cutting emit at a wavelength of 1064 nm (Nd:YAG lasers) or 10.6 µm (CO_2 lasers). Elemental graphite shows a higher absorptance at a wavelength of 1064 nm than at 10.6 µm [11, 12]. Therefore the usage of fiber or disc lasers, which emit at approximately 1064 nm, is more effective for cutting carbon fibers. Two principles of laser cutting with cw-lasers can be used for cutting carbon fiber fabrics, gas assisted laser cutting (GALC) and remote laser cutting. For metals, it is known that during gas assisted laser cutting (fusion cutting), the laser beam heats the material, while the gas jet blows the molten material out of the cut kerf [7]. However, since carbon fiber sublimates at atmospheric pressure, the physics behind this process have to be described differently. The laser directly sublimates the fibers, and the generated aerosol is blown out of the kerf by the gas. There are two types of remote laser cutting processes, remote ablation cutting (RAC) and remote fusion cutting (RFC) [13]. Since carbon does not have a liquid phase at atmospheric pressure, only the term RAC can be used for cutting preforms. In remote laser cutting, the laser beam is usually positioned with scanner optics, and the beam is focused by lenses and moved using mirrors. The laser beam can cut thin textiles with just one pass (single-pass RAC), but thicker textiles might require several passes, or scans (multi-pass RAC). In remote cutting, the pressure generated by the sublimation of the material blows out debris from the cut kerf.

While laser cutting of consolidated CFRP has been widely investigated in the literature, cutting of textiles has not been fully considered. KLOTZBACH ET AL. [14] cut single layers of non-crimp fabrics with remote technology, resulting in high cutting speeds. However, research has yet to be carried out on cutting of multi-layered stacks. HINDERSMANN ET AL. [8] cut preforms using gas assisted laser cutting and showed that the permeability of laser cut preforms is slightly lower than that of conventionally cut preforms.

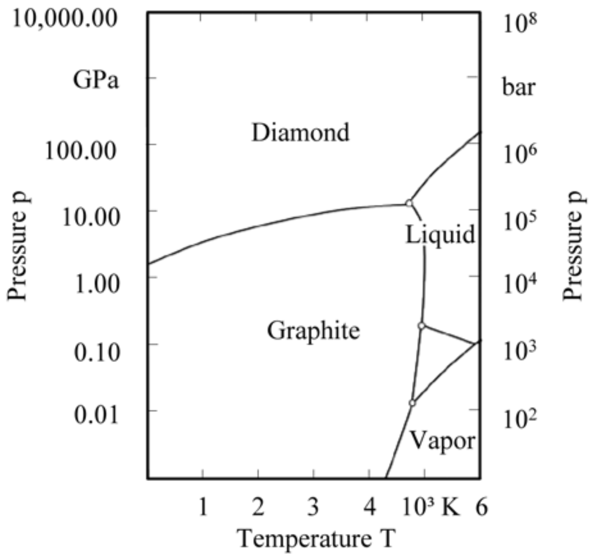


Fig. 3. Pressure-temperature phase diagram of elemental carbon (based on [15])

3. Experimental Study

In the following, cw-laser cutting of carbon fiber preforms using both remote laser cutting and gas assisted laser cutting is analyzed. Since these two processes differ significantly in their parameters and cutting principle, a direct comparison is not possible. Nevertheless, a prediction about which process is suitable for the cutting of carbon fiber preforms can be derived. The focus of this study is on the achievable effective processing speeds.

The material assembled for the cutting experiments is an approximately 3 mm thick multi-directional stack, with six layers made from non-crimp unidirectional fabric layers, resulting in a laminate thickness of 2.2 mm. The stack is symmetrical, with fiber orientations of $(45°/-45°/0°)_S$. The cohesion between the single layers in the 2D test specimens was generated by activating the binder in a hot press.

A 3 kW single-mode Ytterbium doped fiber laser with a wavelength of 1070 nm in combination with a post objective scanning system was used for remote laser cutting. For gas assisted laser cutting, an 8 kW multi-mode Ytterbium fiber laser with a wavelength of 1070 nm in combination with conventional cutting optics was used. Since the tolerable laser power of these cutting optics is limited to 4 kW, the maximum power output of the laser source could not be used during the experiments. The parameters for this study are shown in Table 1. The experiments were conducted in an enclosed cell connected to an exhaust system in order to ensure a reproducible air flow over the carbon fiber test specimen and to prevent the operator from being exposed to emissions from the cutting process. For gas assisted laser cutting, the laser beam optics were moved with regard to the work piece by an industrial robot. The preforms were cut with one pass, and nitrogen was used as an assist gas. The gas pressure was set to a relatively low value of 0.4 bar because high gas pressures tend to tear up the cutting edge of the textile preforms. For remote laser cutting the laser beam was positioned by the scanner mirrors, while the scanner itself was standing still. The cutting was done either in one pass or with several scans using multi-pass RAC, thereby removing small amounts of material with each scan. The effective cutting speed for multi-pass RAC is calculated as the ratio between the scan speed and the number of scan cycles required to completely separate the material. During the experiments, a short pause was made between passes to allow the material to cool down. Given that large contour lengths will be cut in mass production, the time from one pass to another will be sufficient for allowing the material close to the kerf to cool, thus the effective cutting speeds were calculated without accounting for the pause between passes.

Straight cuts were performed to determine the maximum cutting speed. The orientation of the cuts was perpendicular to the 0° layers, since it is known from preliminary studies that cutting velocities in this direction are lower than those parallel to the 0° layers. For single pass RAC and GALC, the influence of the focal position of the laser beam was varied, by focusing either on the top or the bottom surface of the test specimen.

Table 1. Parameters used for laser cutting

Parameter	Formula Symbol	Unit	Remote Laser Cutting	Gas Assisted Laser Cutting
Laser Power	P	kW	1 - 3	1 - 4
Beam Parameter Product	BPP	mm*mrad	0.5	6.3
Focus Diameter (86 %)	d_{Focus}	µm	48	210
Rayleigh Length	z_R	mm	1.1	1.6
Nozzle Stand-Off	z_{Nozzle}	mm	-	1
Focus Position	-	-	Top or Bottom Surface	
Gas Pressure	p_{N2}	bar	-	0.4
Scan Speed (multi- pass RAC)	v_S	mm/s	150 - 1000	-

4. Results and Discussion

For single-pass RAC and GALC, maximum cutting speed and laser power have an almost linear relationship (Figure 4). The focus position has an influence on the cutting speed. For GALC, higher cutting speeds can be obtained with the focus on the top surface. With a laser power of 4 kW, the maximum cutting speed is 12 m/min with the focus on the top surface, while a cutting speed of 10 m/min is possible with the focus on the bottom surface. For single-pass RAC, higher cutting speeds can be obtained with the focus on the bottom surface; with a laser power of 3 kW the maximum cutting speed is 10.5 m/min. The maximum cutting speed is about 1 m/min lower when the laser focus is on the top surface.

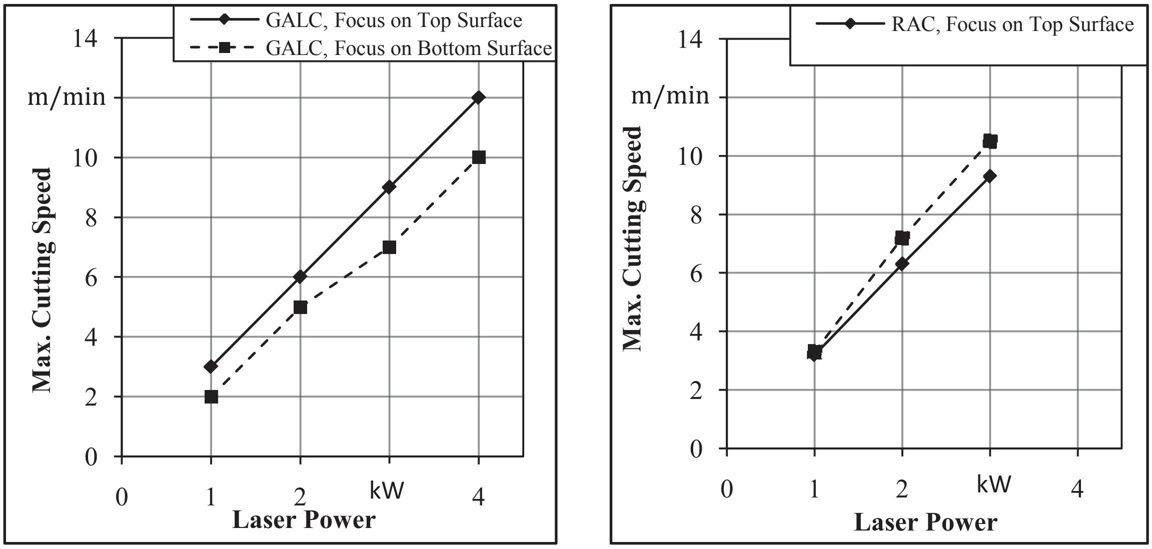
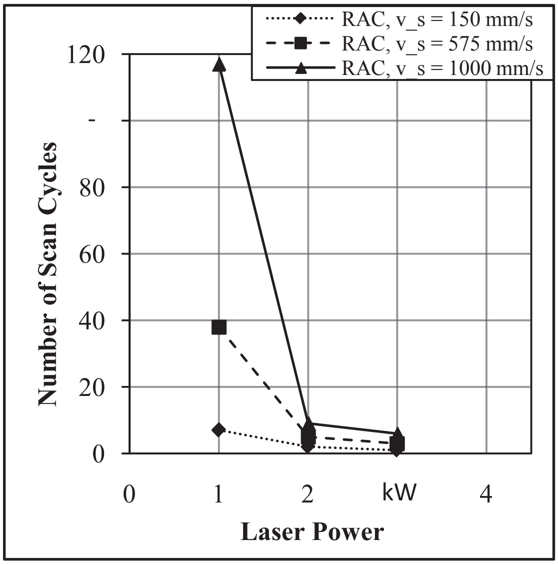


Fig. 4. Maximum cutting speed depending on the focus position. Gas assisted laser cutting (left) and single-pass remote ablation cutting (right)

For multi-pass RAC, scanning speed and number of cycles are highly interdependent (Figure 5). With a laser power of 1 kW, 117 passes are required at a scanning speed of 1000 mm/s, while it takes 7 passes to separate the material at a scanning speed of 150 mm/s. On the other hand, the resulting cutting velocities do not significantly differ at this power level. With increasing laser power, fewer passes are required to cut the material. With a laser power of 3 kW, the influence of the scan speed on the number of cycles is less significant than at 1 kW. The cutting velocities at this power level are dependent on the scan speed, and the highest cutting velocity was found at a scan speed of 575 mm/s. Higher effective cutting speeds can be expected to be found by applying a design of experiments (DOE) to determine the most appropriate scan speed.

Figure 6 shows pictures taken of a cut preform under an optical microscope. The samples show a clean cut contour with no fibers hanging over. On the surface of the preform the HAZ can be seen. The HAZ is largest on the surface layers and smaller on the layers inside the preform. On the top and bottom surface, black residue can be found. This is believed to be caused by smoldering, which can be observed on the surface of the preform very shortly after processing. Due to their low melting point, the threads close to the kerf are partially evaporated and partially molten. Less residue is found at the locations where the threads were prior to cutting. The thermoplastic binder is evaporated close to the kerf on the layers inside of the preforms. The edges of the preforms are thermally fused and the surface of the kerf is grey and shiny.



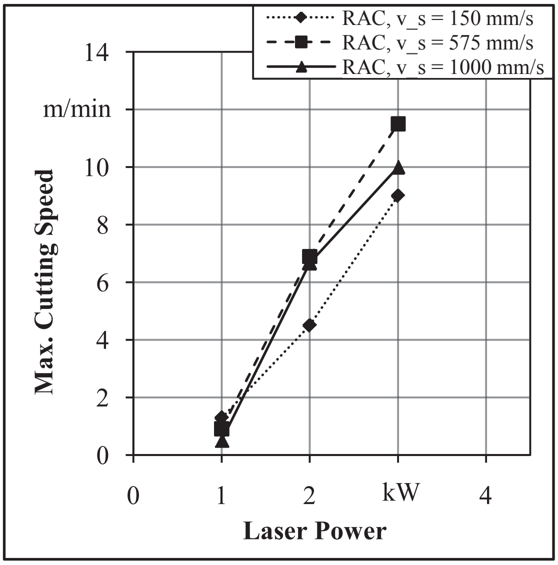


Fig. 5. Number of scan cycles for a complete cut (left) and the resulting maximum cutting speed (right) for multi-pass remote ablation cutting, depending on the scan speed with the focus on the top surface

Using a scanning electron microscope (SEM) it can be observed that the fibers thicken towards the kerf (Figure 7). This effect is called fiber swelling and was previously described by VOISEY ET AL. [16]. At their ends, the fibers are completely fused together. The fusing of the fiber ends occurred with conventional as well as remote processing. In multi-pass RAC with a high number of passes, the fiber ends tend not to fuse over the whole kerf width, thus a partially open surface remains after cutting. A possible explanation for this observation is that when less material is ablated per pass, the sublimated material has more space and time to discharge from the kerf and cannot resolidify on the remaining fibers.

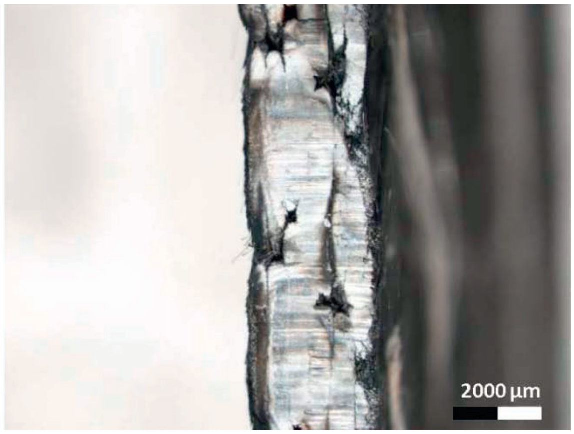


Fig. 6. Microscopic pictures of a laser cut preform. Surface of the preform (left) and a view of the edge (right)

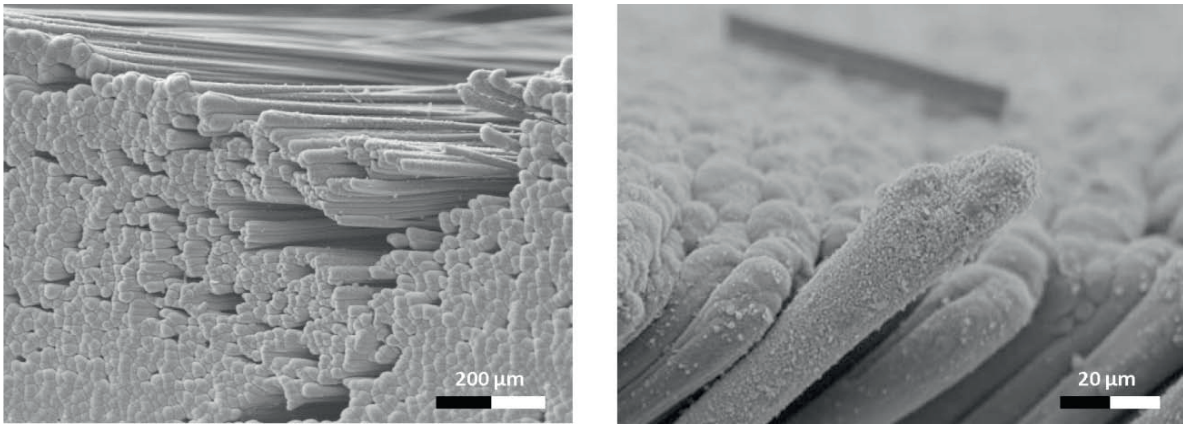


Fig.7. SEM pictures of the laser cut kerf. Fused surface of the kerf (left). Fiber swelling and fused fiber ends (right)

5. Conclusion and future works

Due to the increased use of CFRP in mass production, new, efficient and highly automatable manufacturing processes are required. In this study the laser cutting of carbon fiber preforms was analyzed. Experiments were carried out to determine the maximum processing speeds for gas assisted laser cutting and remote laser cutting. Using the described system technology, it was shown that cutting speeds of up to 12 m/min can be achieved for a material with six layers and a thickness of approximately 3 mm. With both processes, cuts with a high edge quality can be generated. The laser cut kerfs are fused, and the fibers show geometric changes within the HAZ. Laser cutting seems to be an alternative for the currently employed mechanical cutting processes, but there are still some open questions regarding the fitness for use in mass production. In future works the following points should be addressed to derive the fitness for use for laser cutting carbon fiber preforms:

- Unlike with metals, no standardized procedure has been established for measuring the HAZ of laser cut preforms. A major question regarding the HAZ concerns the heat-induced change of the fiber surface and how it affects the interface between the resin and the fiber. By determining the influence of laser cutting of preforms on the mechanical properties of the CFRP parts, a definition of the HAZ can be derived and an acceptable width of the HAZ can be determined.
- The fused edge can be advantageous for handling the preforms, but the lack of permeability could be an obstruction. Experiments using the RTM process with different laser parameters have to be conducted to test the permeability of the preforms. As mentioned above, using RAC with high scan speeds and a high number of passes can reduce fiber fusing. By varying laser parameters in different areas of the preform, a balance between permeability and processing speed is possible.
- During this study, only 2D specimens were cut. The results have to be transferred to 3D contours; therefore suitable clamping devices have to be developed. Especially for GALC, where a low nozzle stand-off is required, the position of the work piece should not vary too much. Capacitive distance sensing could be used with carbon fiber preforms, but because the fibers at the kerf move when blown by the assist gas jet, the distance between the fabric and the nozzle cannot be reliably determined.
- Path planning systems for multi-pass RAC cutting are currently not commercially available. There are two options; the first is to position the scanner at the initial cutting position by using an external

manipulator, perform the cut within the scan field, and then move to the next cutting position. This option is rather easy to implement, but productivity is not high because the laser has to be turned off when moving from position to position. The second option is "on the fly" processing, where the laser beam is deflected to perform multiple passes over the material while an external manipulator, an industrial robot, for example, moves the scanner. This option requires extensive path planning, but offers the highest productivity. HATWIG ET AL. [17] developed an automated programming system for "on the fly" multi-pass RAC, the effectiveness of which was shown in a laboratory environment.
- Last but not least, effective workplace controls have to be developed and tested to collect and filter emissions in order to protect the workers and the environment.

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